Latest Results from the Daya Bay Reactor Neutrino Experiment

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on behalf of the Daya Bay collaboration

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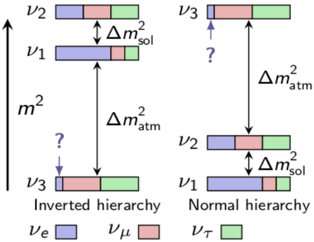
Budva, Becici

Neutrino mixing



Weak and mass eigenstates differ:

$$|\nu_\alpha\rangle = \sum_i V^*_{\alpha i}|\nu_i\rangle$$

α — flavor states

i — mass states

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

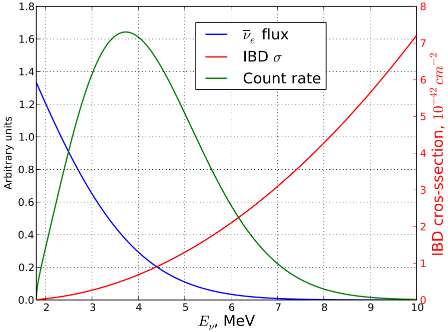
$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12}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

- $\theta_{23} \approx 45^\circ$ established through atmospheric and accelerator experiments.
- $\theta_{12} \approx 12^\circ$ established through solar experiments and KamLAND.
- $\theta_{13} \approx 8^\circ$ discovered by Daya Bay in 2012 and confirmed later by RENO, Double-Chooz, NOVA, T2K.

Reactor electron anti-neutrino disappearance

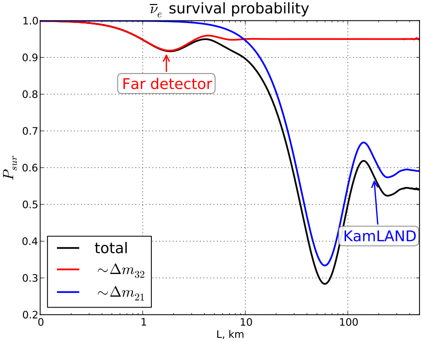
Reactor as $\overline{\nu}_e$ source:

- **Strong**:
  Produces $\sim 10^{20}$ $\overline{\nu}_e$/s/GW$_{th}$.
  $\sim$6 $\overline{\nu}_e$'s per nuclear fission
- **Clean**:
  Produces only $\overline{\nu}_e$.
- **Independent**:
  Free artificial antineutrino source.



- Detection via inverse β-decay (IBD) $\overline{\nu}_e + p \longrightarrow e^+ + n$
- **No side effects**:
  Negligible matter effects, no δ_{CP} dependence.

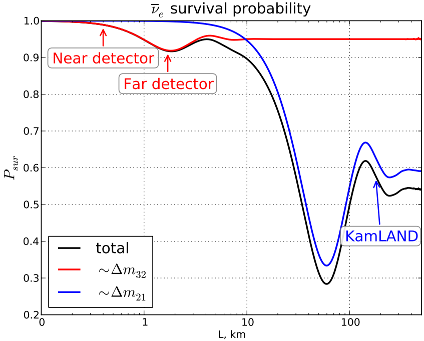
Reactor electron anti-neutrino disappearance



$$P_{\text{dis}} = \sin^2 2\theta_{13} \left(\sin^2\theta_{12}\sin^2\Delta_{32} + \cos^2\theta_{12}\sin^2\Delta_{31}\right) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

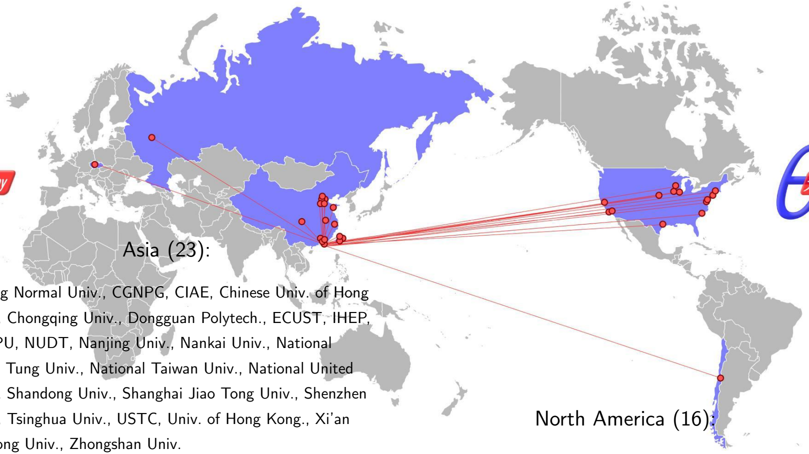
$$\Delta_{jk} = 1267 \cdot \frac{\Delta m^2_{jk}}{\text{eV}^2}\;\frac{L}{E}\;\left[\frac{\text{MeV}}{\text{km}}\right]$$

Reactor electron anti-neutrino disappearance



$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left(\frac{P_{\nu_e\to\nu_e}(E,L_f)}{P_{\nu_e\to\nu_e}(E,L_n)}\right)$$

Daya Bay collaboration



Asia (23):

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

Europe (2) and Sourth America (1):

Charles University, **Joint Institute for Nuclear Research**, Catholic Univ. of Chile.

North America (16):

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

Daya Bay: Powerful reactor by mountains

Antineutrino detector (AD)

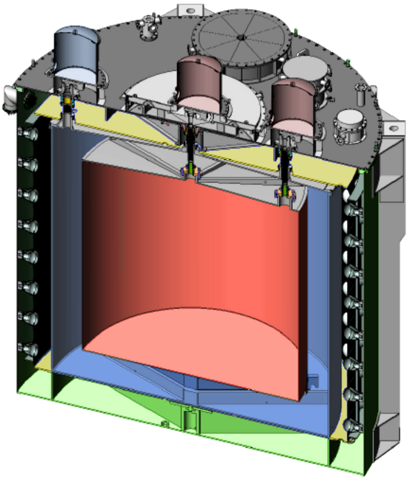
3-zones antineutrino detector:		
Inner zone	20 t	Gd-doped LS
Middle zone	20 t	LS
Outer zone	40 t	Mineral oil

Inner zone:

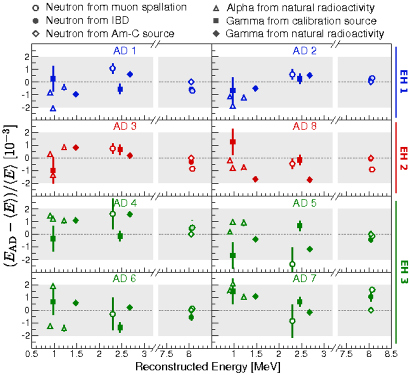
- $\overline{\nu}_e$ target.
- fixes the fiducial volume.
- contained in acrylic vessel.

Inverse beta decay:

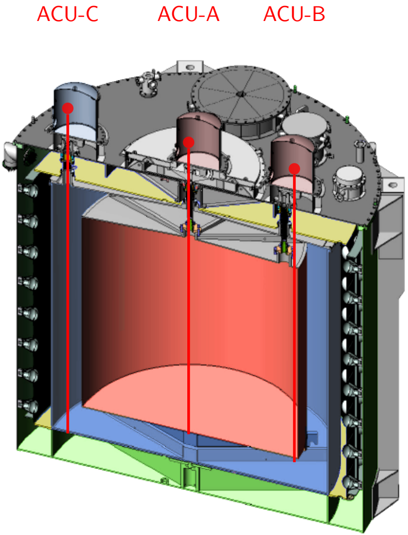
- $\overline{\nu}_e + p \longrightarrow e^+ + n$
- $e^+ + e^- \longrightarrow 2\gamma$
- $n + Gd \longrightarrow Gd + \sum \gamma$ (8 MeV)
- Prompt energy $\simeq E_\nu - 0.8$ MeV
- Delayed energy: $\simeq 8$ MeV



Calibration

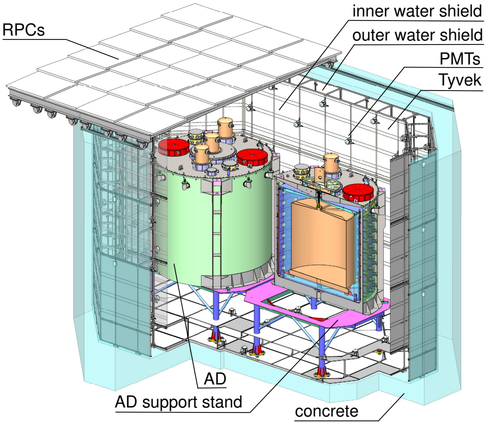


Relative energy scale uncertainty for nGd analysis: 0.2%.

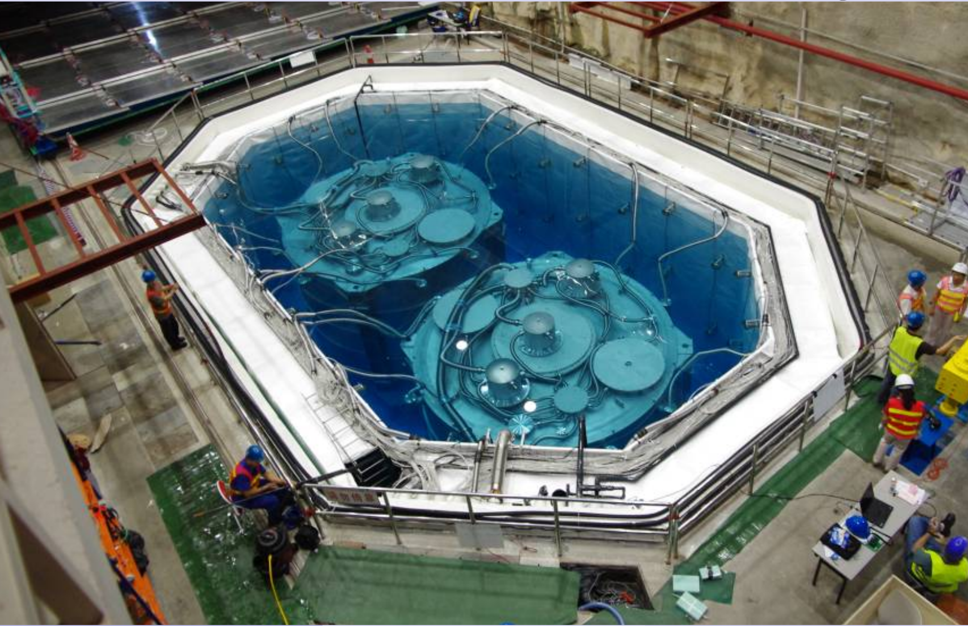


Muon veto system

- Water pool:
  - Shield against the external radioactivity and cosmogenic background.
  - Cherenkov muon tracker.
  - 288 8'' PMTs in each Near Hall.
  - 384 8'' PMTs in each Far Hall.
  - Outer water shield (1 m).
  - Inner water shield (>2.5 m).
- 4-layer RPC veto:
  - Muon tracker.
  - 54 modules in each Near Hall.
  - 81 modules in the Far Hall.
- Goal efficiency 99.5% with uncertainty $< 0.25\%$.

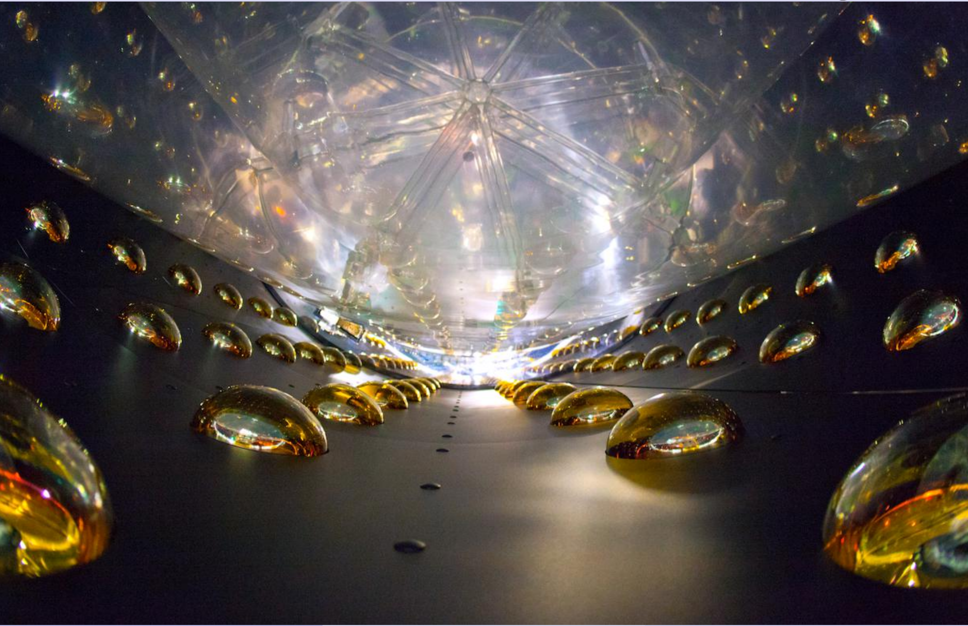


Experimental hall 1



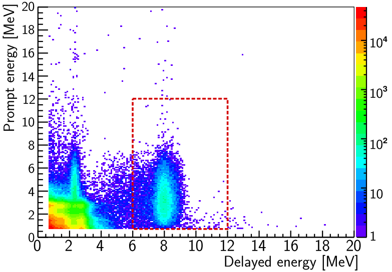
Experimental hall 3

Inside the AD



Background summary

	Near Halls B/S, %	Far Hall B/S, %	Uncertainty	Estimation method
Accidentals	1.4	2.3	$\sim 1\%$	Calculated based on uncorrelated signals
^{9}Li/^{8}He	0.4	0.4	50%	Measured with after-muon events
Fast neutrons	0.1	0.1	50%	Measured with tagged muon events
^{241}Am-^{13}C	0.03	0.2	50%	MC, benchmarked with single γ and strong ^{241}Am-^{13}C source
$^{13}C(\alpha, n)^{16}O$	0.01	0.1	50%	Calculated from measured radioactivity



Data periods

A. AD comparison, 90 days, 2AD:
   NIM, nGd, [1202.6181]

B. Rate-only analysis, 50 days, 6AD:
   PRL, nGd, [1203.1669]

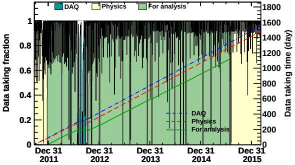
C. Rate-only update, 126 days, 6AD:
   CPC, nGd, [1210.6327]

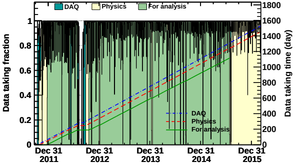
D. Spectral analysis, 217 days, 6AD:
   PRL, nGd, [1310.6732]
   PRD, nH, [1406.6468]
   PRL, ν_s, [1407.7259]
   PRL, reactor, [1508.04233]

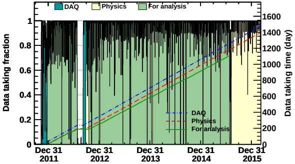
E. Summer 2012 shutdown

F. 6+8AD, 621 days of data:
   $>$ 1M ν interactions
   PRL, nGd, [1505.03456]
   PRD, nH, [1603.03549]

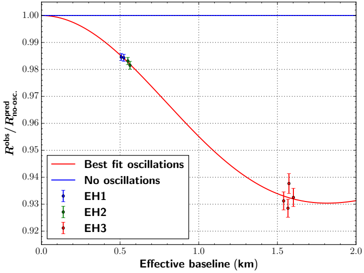
G. 1230 days of data:
   $>$ 2.5M ν interactions
   nGd most precise oscillation results



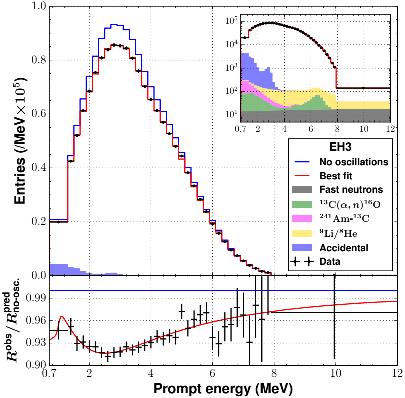




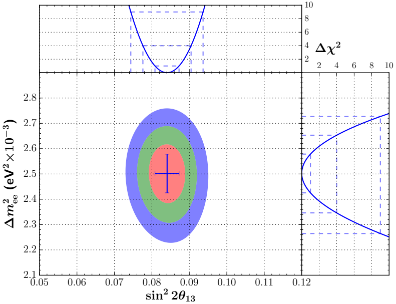
Far vs. near comparison

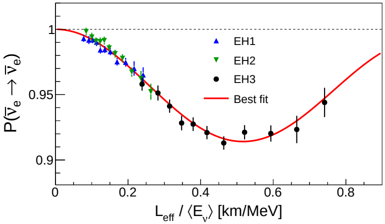


The observed **event rate deficit** and **relative spectrum distortion** are highly consistent with oscillation interpretation.



Daya Bay oscillation result





$$\sin^2 2\theta_{13} = (8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})) \times 10^{-2}$$

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

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

- Due to a short baseline the Daya Bay data are not sensitive to the neutrino mass hierarchy.
- It is accurate to fit the data with $P_{\text{sur}} \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$
- where Δ_{ee} is a flavour average $\Delta m^2_{ee} \simeq \cos^2\theta_{12}\left|\Delta m^2_{31}\right| + \sin^2\theta_{12}\left|\Delta m^2_{32}\right|$ [0607284].

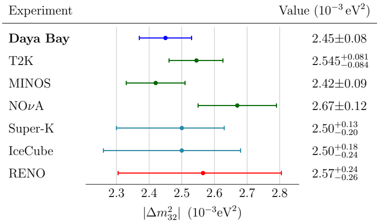
Daya Bay oscillation result

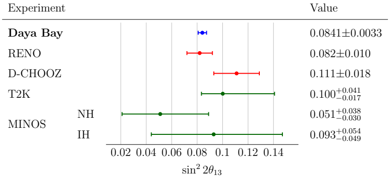
- Most precise $\sin^2 2\theta_{13}$ measurement. The non-zero value is excluded at $> 25\sigma$
- Most precise measurement of Δm^2_{ee}
- Normal Hierarchy:

$$\Delta m^2_{32} = (2.45 \pm 0.06(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})) \times 10^{-3}\ \mathrm{eV}^2$$

- Inverted Hierarchy:

$$\Delta m^2_{32} = (-2.55 \pm 0.06(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})) \times 10^{-3}\ \mathrm{eV}^2$$





Independent nH oscillation analysis (NEW!)

Key points:

- ✓ Additional statistics (+20 ton/AD)
- ✓ Largely independent systematics
- ✗ Lower delayed energy (∼2.2 MeV)
- ✗ More accidentals

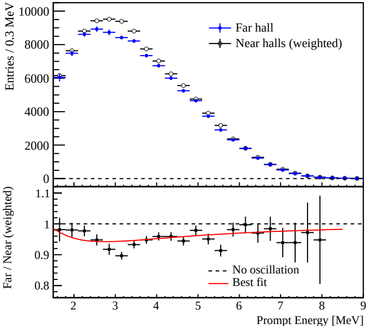
nH

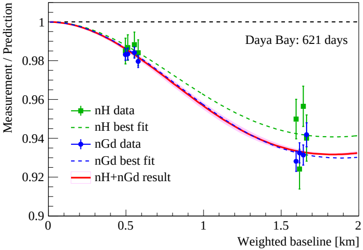
$$\sin^2 2\theta_{13} = \mathbf{0.071 \pm 0.011}$$

nH+nGd

$$\sin^2 2\theta_{13} = \mathbf{0.082 \pm 0.004}$$

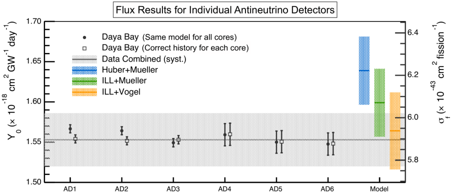
- Observed significant rate deficit.
- Spectral distortion consistent with oscillations.
- Third world precise measurement after Daya Bay (nGd) and RENO (nGd).





Absolute reactor antineutrino flux

- 217 days of data (6AD period)
- Results are consistent within ADs
- Result is consistent with world average
- Daya Bay supports the existence of reactor antineutrino anomaly



Huber+Mueller

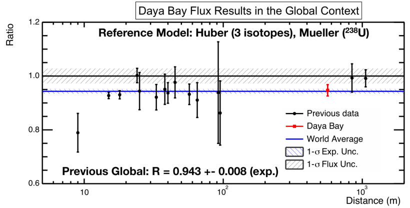
Data/prediction: **0.946** ± **0.022**

ILL+Vogel

Data/prediction: **0.991** ± **0.023**

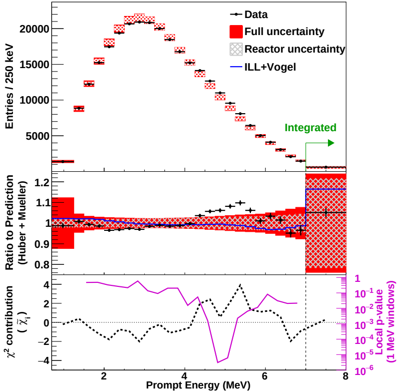
Huber+Mueller (global)

Data/prediction:
0.943 ± **0.008** (exp) ± **0.025** (model)

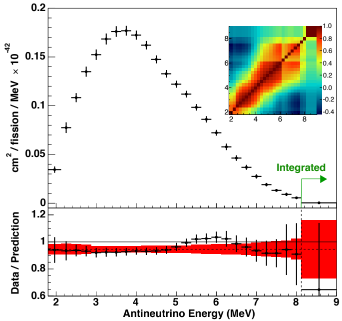


Reactor antineutrino spectrum

Observed positron spectrum



Extracted antineutrino spectrum

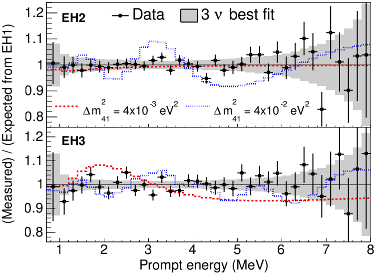


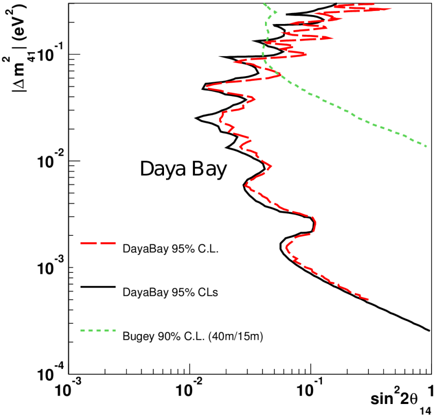
- Bump feature around 5–6 MeV.
- Consistent with other experiments.
- Seen for both Huber+Mueller/ILL+Vogel.

- **Global significance: 2.6σ.**
- **Local significance: 4σ.**

Light sterile neutrino search

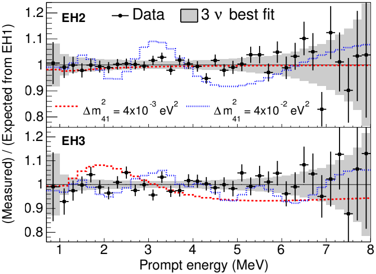
- Sterile neutrino will cause spectral distortions at the near and far sites
- 217 days of data (6AD period)
- Relative measurement independent of reactor related systematics
- **Result is consistent with 3-flavor oscillations**

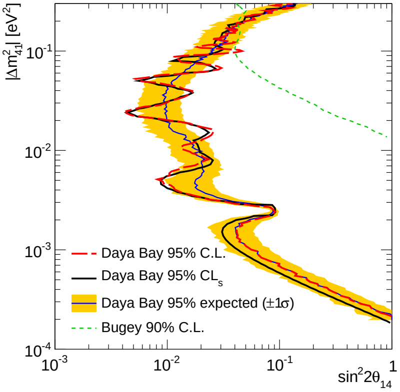




Light sterile neutrino search

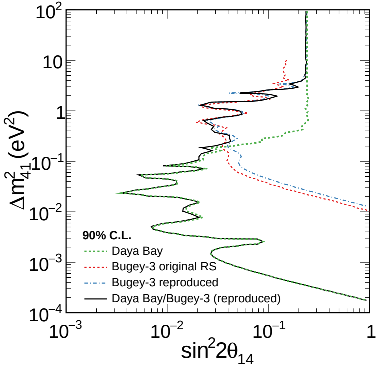
- Sterile neutrino will cause spectral distortions at the near and far sites
- 621 days of data (6+8AD period)
- Relative measurement independent of reactor related systematics
- **Result is consistent with 3-flavor oscillations**





Light sterile neutrino search with Bugey-3 and MINOS

- Combining Daya Bay and Bugey-3 data strongly constrains Δm^2_{41} and $\sin^2 2\theta_{41}$
- Combining Daya Bay and Bugey-3 and MINOS data allows to constrain Δm^2_{41} and $\sin^2 2\theta_{41}$ $\sin^2 2\theta_{42}$
- Joint analysis strongly suggests that LSND results is not due to **sterile neutrino**



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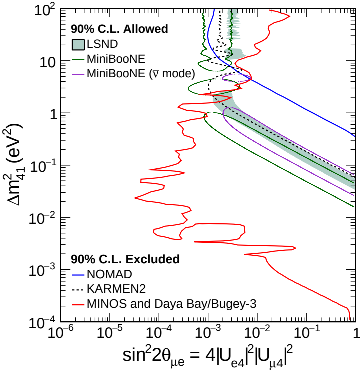
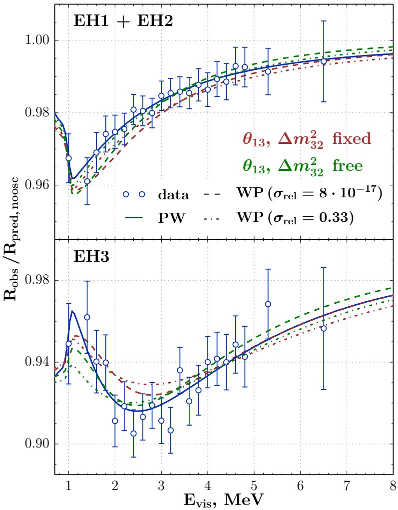


Wave packet effects

- Plane-wave (PW) model of neutrino oscillations is not self-consistent
- A wave-packet (WP) model modifies the oscillation probability formula
- It depends on σ_p –effective dispersion of neutrino wave-packet and predicts suppression of oscillations:
  - at distances exceeding the **coherence length** $L^{coh} = \frac{L^{osc}}{\sqrt{2}\pi\sigma_{rel}}$, where $\sigma_{rel} = \sigma_p/p$.
  - if $\sigma_x \gg L^{osc}$, where $\sigma_x = 1/2\sigma_p$.



Wave packet effects

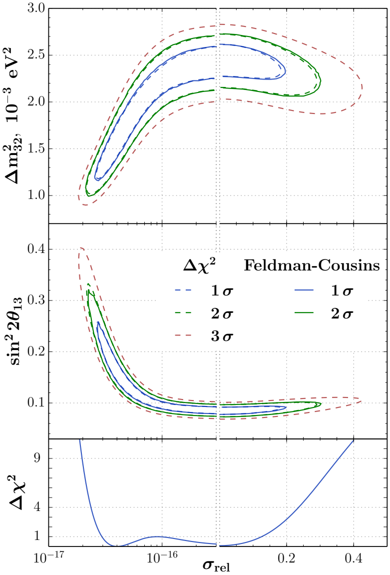
- The obtained limits read

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

- taking into account the reactor/detector sizes:

$$10^{-11}\ \text{cm} \lesssim \sigma_x \lesssim 2m.$$

- These results ensure unbiased measurement of $\sin^2 2\theta_{13}$ and Δm^2_{32} within the PW model



Summary

- Most precise oscillation result:

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

based on 1230 days of data.

- Operation till 2017: $\sin^2 2\theta_{13}$ and Δm^2_{ee} precision $\rightarrow$ 3%.
- Planned operation till 2020.

✓ Updated independent nH rate-only analysis is consistent with nGd:

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

✓ Combined nH+nGd analysis yields:

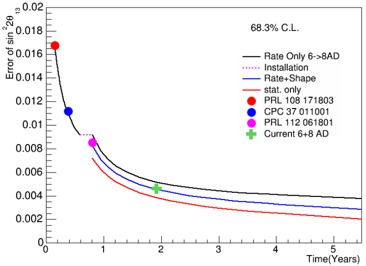
$$\sin^2 2\theta_{13} = 0.082 \pm 0.004$$

- Reactor antineutrino flux ∼5% deficit.
- Significant spectral distortion comparing to theories around 5–6 MeV.
- Stringent limits for sterile neutrinos for $2 \cdot 10^{-4}\ \text{eV}^2 < \Delta m^2_{41} < 0.2\ \text{eV}^2$.
- First constraints of wave-packet impact
- In SuperNova Early Warning System since end of 2014.

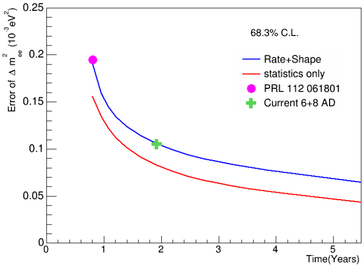
Backup slides...

Daya Bay sensitivity

$\sin^2 2\theta_{13}$ error projection



Δm^2_{ee} error projection



Uncertainties summary

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	**0.03%**
Flasher cut	99.98%	0.01%	**0.01%**
Prompt energy cut	99.81%	0.10%	**0.01%**
Delayed energy cut	92.70%	0.97%	**0.12%**
Capture time cut	98.70%	0.12%	**0.01%**
Multiplicity cut		0.02%	<**0.01%**
Gd capture fraction	84.20%	0.95%	**0.1%**
Spill-in	104.9%	1.5%	**0.02%**
Livetime	100.0%	0.002%	<**0.01%**
Combined	**80.6%**	2.1%	**0.2%**

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	**0.8%**

- Only uncorrelated uncertainties are relevant for Near/Far oscillation analysis.
- Largest systematics smaller than Far site statistics (∼1%).

- Influence of uncorrelated reactor systematics is reduced by far/near measurement.

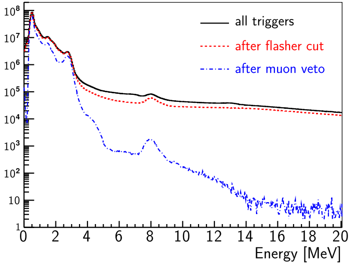
IBD selection criteria

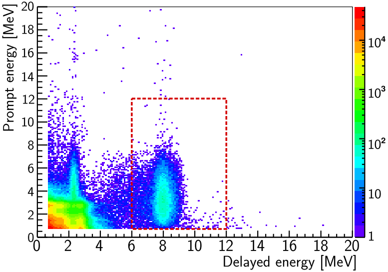
Inverse beta decay:

- $\overline{\nu}_e + p \longrightarrow e^+ + n$
- $\sim 28\ \mu s:\ n + Gd \longrightarrow Gd^* \longrightarrow$
  $\longrightarrow Gd + \sum \gamma$ (8 MeV)

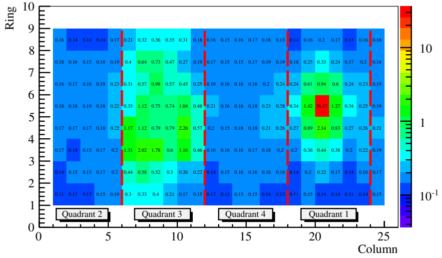
Selection:

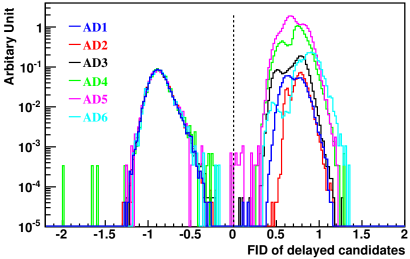
1. Reject spontaneous PMT light emission (99.98%).
2. Prompt energy (positron): 0.7 MeV $< E_p <$ 12 MeV (99.88%).
3. Delayed energy (neutron capture): 6 MeV $< E_p <$ 12 MeV (90.9%).
4. Neutron capture time: $1\ \mu s < \Delta t < 200\ \mu s$ (98.6%).
5. Reject muons:
   - Water pool muons Nhits>12: 0.6 ms
   - AD muons with E>12 MeV: 1 ms
   - AD shower muon E>2.5 GeV: 1 s
6. Multiplicity: no other signal with $E > 0.7$ MeV in $\pm 200\ \mu s$ of IBD





Flashers identification





Flashers — PMTs spontaneously emitting light:

- $\sim 5\%$ of PMTs
- $\sim 5\%$ of the events
- Rejected based on the topology

$$d_{max} = Q_{max}/Q_{sum}$$

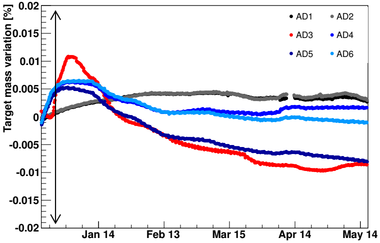
$$d_{quad} = Q_3/(Q_2 + Q_4)$$

$$\text{FID} = \log_{10}\left[\left(\frac{d_{quad}}{1}\right)^2 + \left(\frac{d_{max}}{0.45}\right)^2\right] < 0$$

AD liquids

Target mass:

- Target mass is measured during filling by the load cell with precision of ~ 3kg, 0.015%.
- Cross-checked by the Coriolis meters with precision of 0.1%.
- $M_{\text{target}} = M_{\text{fill}} - M_{\text{overflow}}$



Liquid scintillator composition:

- LAB + Gd (0.1%) + PPO (3 g/L) + bis-MSB (15mg/L)
- One year 1-ton prototype monitoring on GdLS stability.

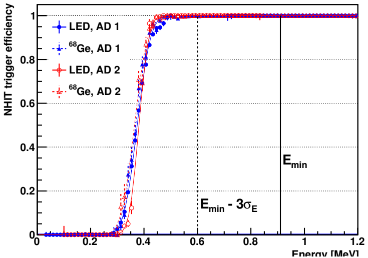
Liquids storage and filling:

- Fill each AD from all 5 storage tanks.
- Fill ADs in pairs.
- Recirculate storage tanks.

Trigger

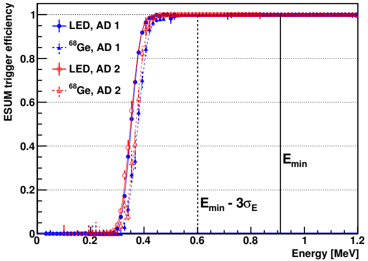
Trigger criteria:

- Signal > 0.25 p. e.:
  - Nhit > 45.
  - Esum > 0.4 MeV.
- Water pool:
  - Nhit > 12.



Trigger efficiency:

- Measured from LED light and ^{68}Ge source.
- No measurable inefficiency above 0.7 MeV.
- Minimal $E_p \approx 0.95$ MeV.

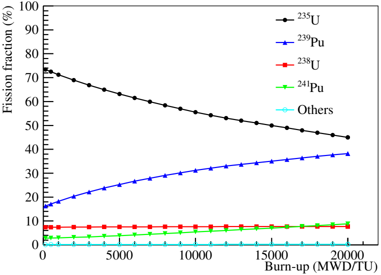


Reactor flux expectation

$$S(E) = \frac{W_{\mathrm{th}}}{\sum_k f_k E_k} \sum_i f_i S_i(E)$$

Information provided by the NPP:

- W_i — thermal power.
- f_i — relative isotope fission fraction.

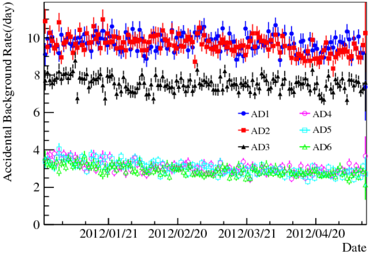


Neutrino data:

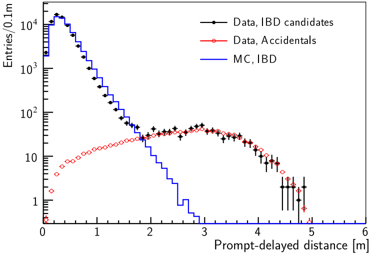
- E_i — energy released per fission:
  - V. Kopeikin, L. Mikaelyan, and V. Sinev, Phys. Atom. Nucl. **67**, 1892 (2004).
- $S_i(E)$ — antineutrino spectra per fission:
  - W. G. K. Schreckenbach, G. Colvin and F. von Feilitzsch, Phys. Lett. **B160**, 325 (1985).
  - A. F. von Feilitzsch and K. Schreckenbach, Phys. Lett. **B118**, 162 (1982).
  - A. A. Hahn *et al.*, Phys. Lett. **B218**, 365 (1989).
  - P. Vogel, G. K. Schenter, F. M. Mann, and R. E. Schenter, Phys. Rev. C**24**, 1543 (1981).
  - T. Mueller *et al.*, Phys. Rev. C**83**, 054615 (2011).
  - P. Huber, Phys. Rev. C**84**, 024617 (2011) [Erratum-ibid. **85**, 029901(E) (2012)].

Backgrounds: accidentals

Accidental event — two independent signals accidentally satisfy event selection criteria.



Figure

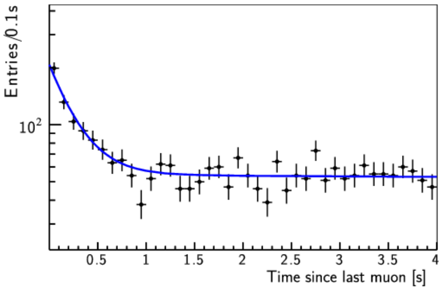


Figure

- Calculated based on prompt and delayed rates.
- Cross-checks:
  - Prompt-delayed distance distribution.
  - Off-window coincidence.

Backgrounds: $^{9}Li/^{8}He$

Long-lived cosmogenic isotopes of $^{9}Li/^{8}He$ decay with both β and neutron emission.

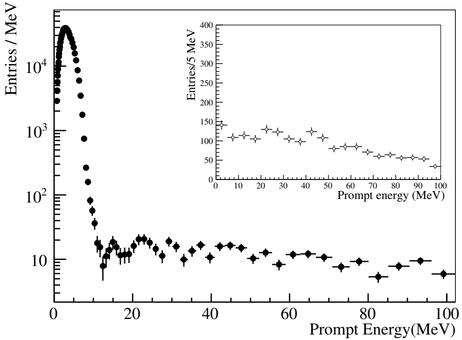


Figure

- Calculated by fitting the time-after-last-muon events distribution. Based on known half-life times:
  - ^{9}Li $\lambda = 178ms$
  - ^{8}He $\lambda = 119ms$
- Cross-checks:
  - Analyze muon samples with and without followed neutrons.

Backgrounds: fast neutrons

Fast neutrons can produce recoil protons, which mimic prompt signal. Neutron capture itself is the delayed signal.



Figure

- Method I:
  - Collect events with $12\text{ MeV} < E_p < 100\text{ MeV}$
  - Extrapolate the spectrum to the $E_p < 12\text{MeV}$
- Method II:
  - Use water pool and RPC to determine the number of fast neutrons.

Backgrounds: ^{241}Am-^{13}C and ^{13}C$(\alpha, n)^{16}$O

Correlated background from ^{241}Am-^{13}C sources (ACU):

- Neutron inelastic scattering on ^{56}Fe + neutron capture on Fe/Cr/Mn/Ni.
- Estimated based on simulation.
- Cross checked with data.

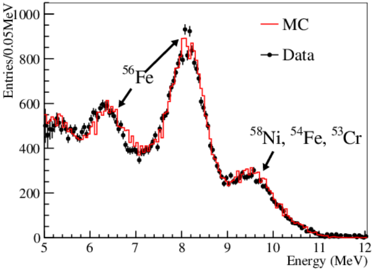


Figure: Energy spectrum of the events near the top of ADs in the Far Hall.

Correlated ^{13}C$(\alpha, n)^{16}$O background:

- ^{238}U, ^{232}Th, ^{227}Ac and ^{210}Po α rates are measured.
- Neutron yield is calculated with MC.

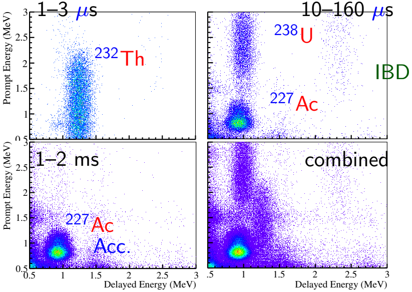


Figure: Correlations of prompt and delayed energy for cascade decay chains.