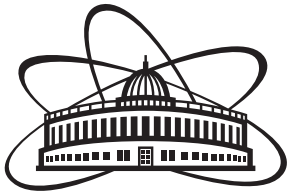


New Results from the Daya Bay Reactor Neutrino Experiment

Dmitry Naumov
on behalf of the Daya Bay collaboration

JINR

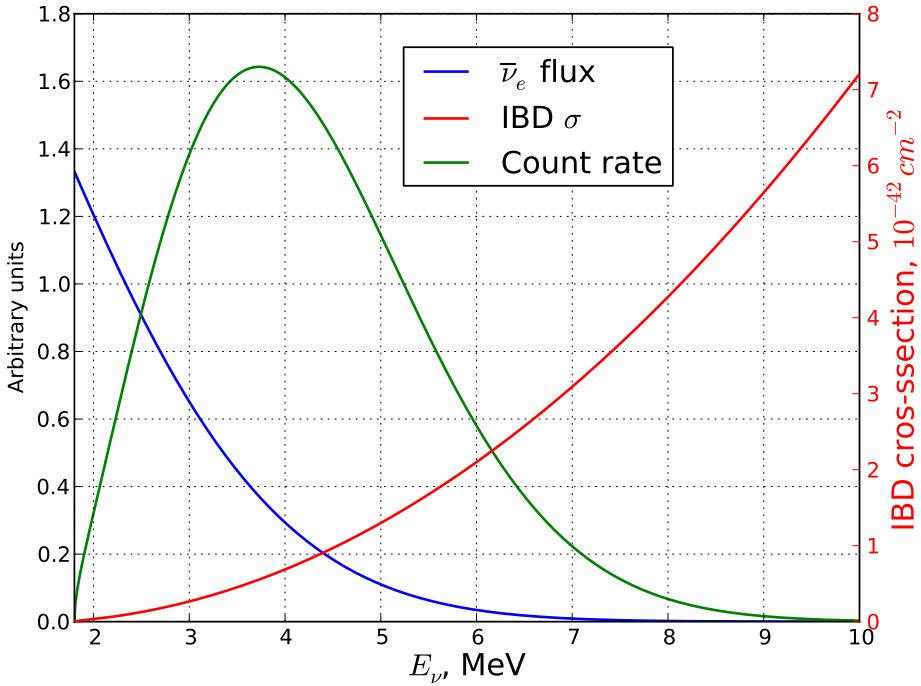
Neutrino Telescopes,
March 14, 2017,
Venice

Analyses to be discussed

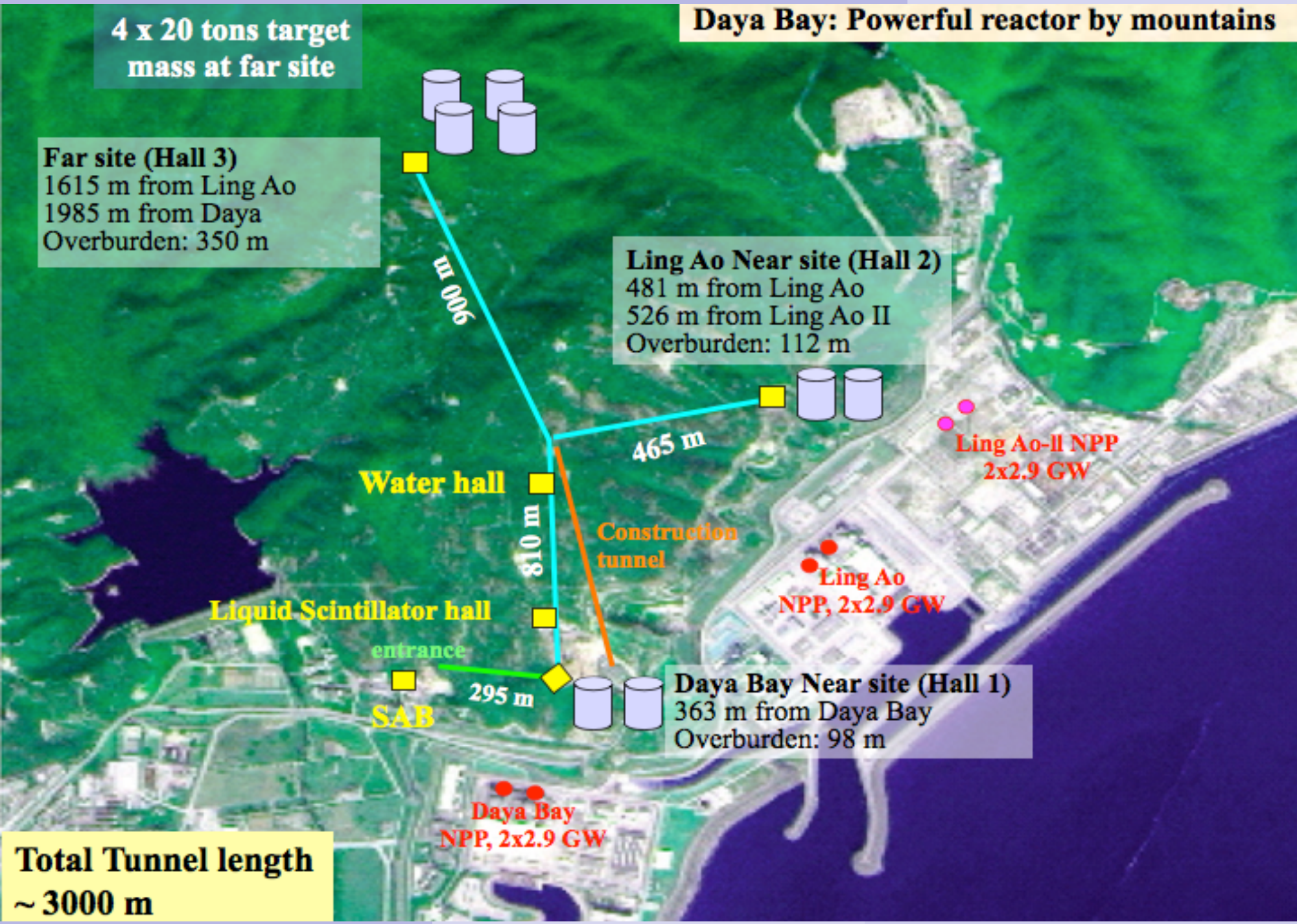
- Reactor $\bar{\nu}_e$ flux and energy spectrum measurement.
- Precision measurement of θ_{13} and Δm^2_{32}.
- Search for sterile neutrino admixture in ν_e state.
- Study of wave packet effects in neutrino oscillations.

Reactor as a source of electron anti-neutrinos

- **Strong**:
  Produces $\sim 10^{20}$ $\overline{\nu}_e$/s/GW$_{\text{th}}$.
  $\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.


4 x 20 tons target mass at far site
Daya Bay: Powerful reactor by mountains
Far site (Hall 3)
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
Ling Ao Near site (Hall 2)
481 m from Ling Ao
526 m from Ling Ao II
Overburden: 112 m
Ling Ao-II NPP
2x2.9 GW
Water hall
Construction tunnel
Ling Ao
NPP, 2x2.9 GW
Liquid Scintillator hall
entrance
SAB
Daya Bay Near site (Hall 1)
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP, 2x2.9 GW
Total Tunnel length
~3000 m

Antineutrino detector (AD)

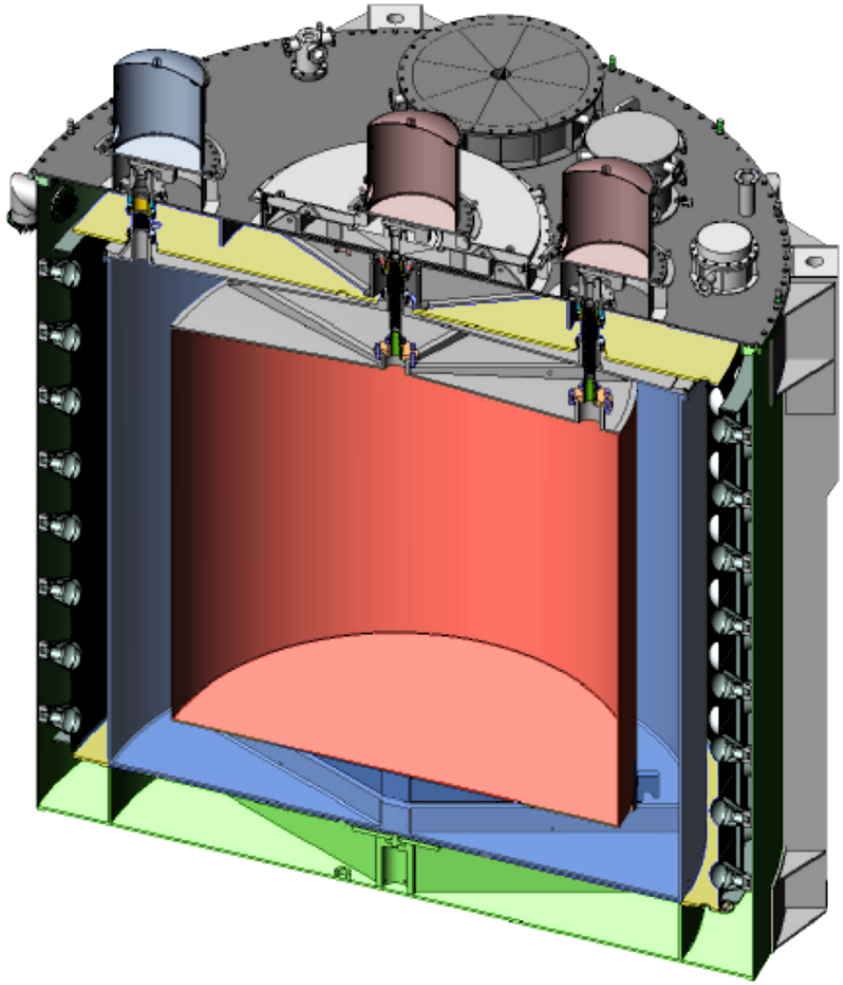
3-zones antineutrino detector:		
Inner zone	20 t	Gd-doped LS
Middle zone	20 t	LS
Outer zone	40 t	Mineral oil

Inner zone:

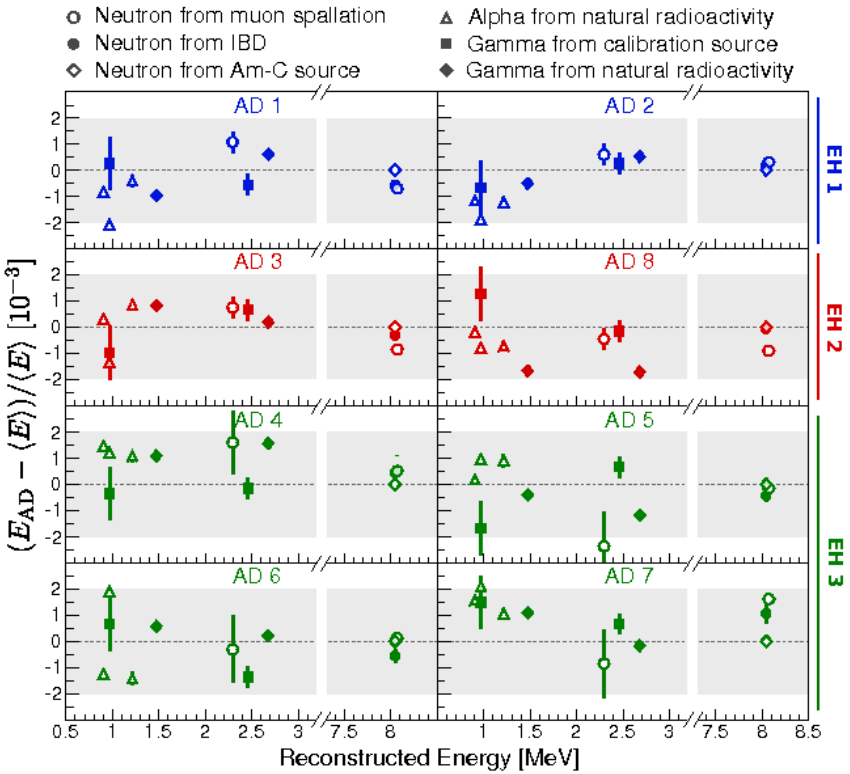
- $\overline{\nu}_e$ target.
- fixes the fiducial volume.
- contained in acrylic vessel.

Inverse beta decay:

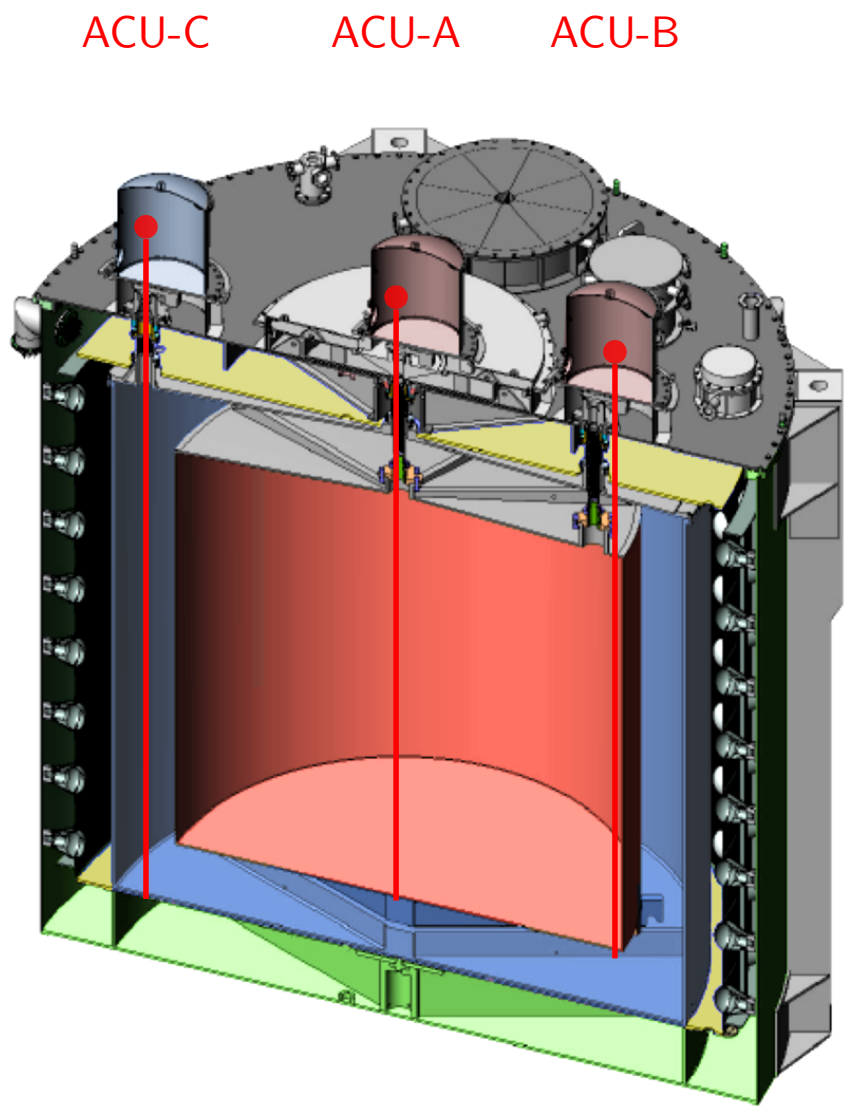
- $\overline{\nu}_e + p \longrightarrow e^+ + n$
- $e^+ + e^- \longrightarrow 2\gamma$
- $n + Gd \longrightarrow Gd + \sum \gamma$ (8 MeV)
- Prompt energy $\simeq E_\nu - 0.8$ MeV
- Delayed energy: $\simeq 8$ MeV



Calibration

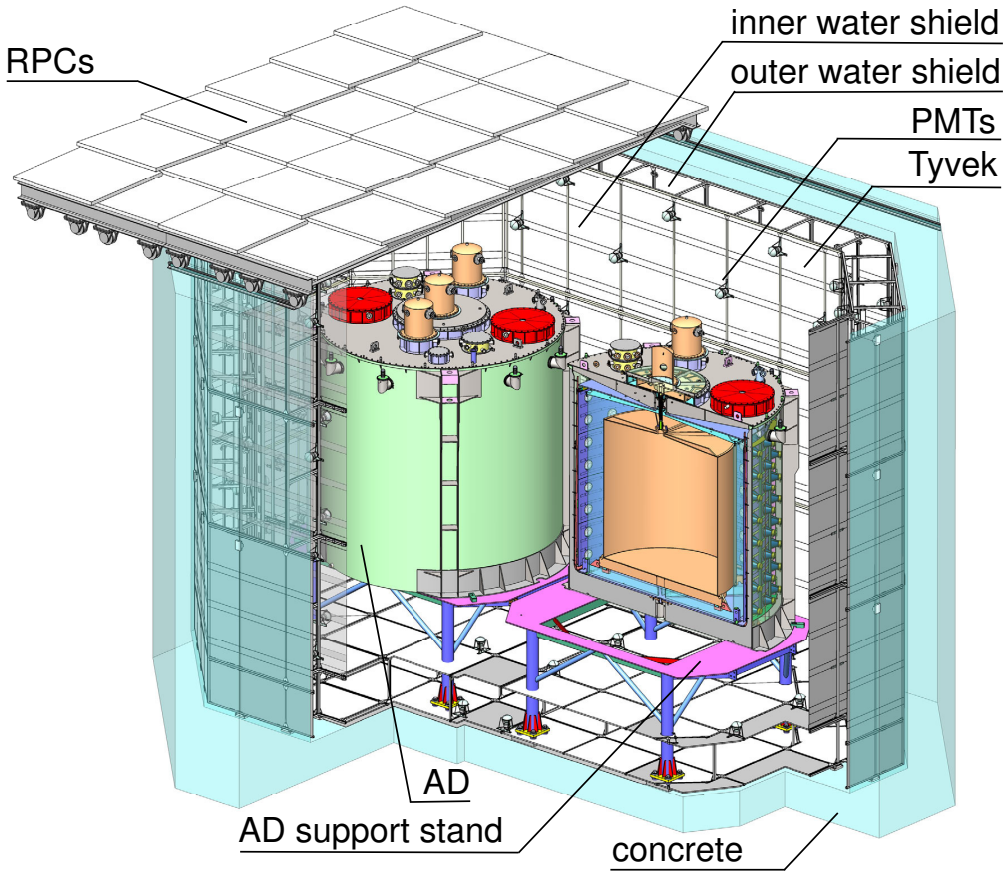


Relative energy scale uncertainty for nGd analysis: 0.2%.



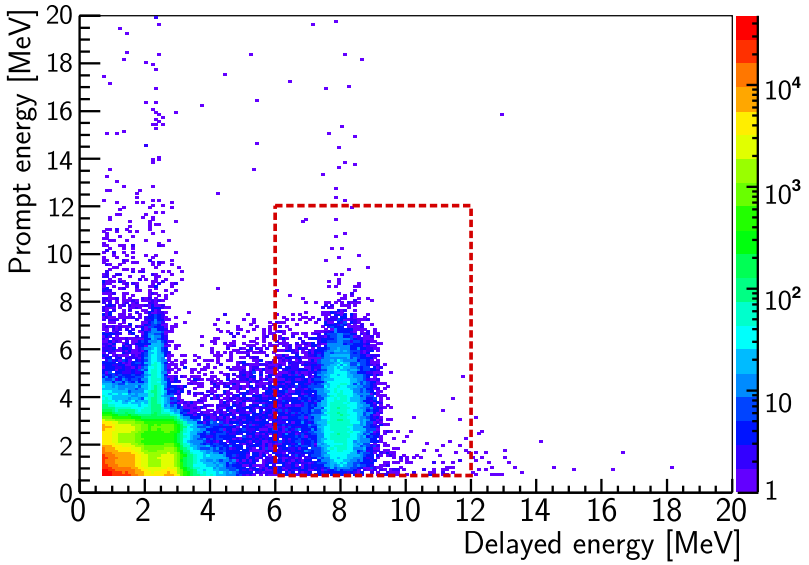
Muon veto system

- 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 $< 0.25\%$.



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



Uncertainties summary

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.92%	**0.03%**
Flasher cut	99.98%	0.01%	**0.01%**
Prompt energy cut	99.8%	0.10%	**0.01%**
Delayed energy cut	92.7%	0.97%	**0.08%**
Capture time cut	98.7%	0.12%	**0.01%**
Multiplicity cut		0.02%	**0.01%**
Gd capture fraction	84.2%	0.95%	**0.10%**
Spill-in	104.9%	1.00%	**0.02%**
Livetime	100.0%	0.002%	**0.01%**
Combined	**80.6%**	1.93%	**0.13%**

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 ($\sim$1%).
- Influence of uncorrelated reactor systematics is reduced by far/near measurement.

Data periods

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

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

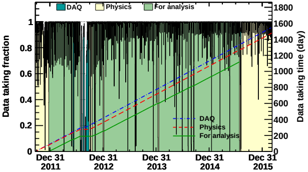
C. Rate-only update, 126 days, 6AD:
   CPC, nGd, [1210.6327]

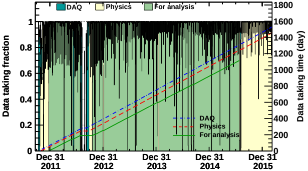
D. Spectral analysis, 217 days, 6AD:
   PRL, nGd, [1310.6732]
   PRD, nH, [1406.6468]
   PRL, ν_s, [1407.7259]
   PRL, reactor, [1508.04233]

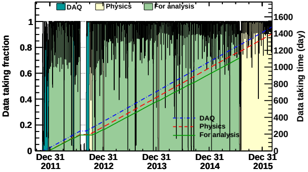
E. Summer 2012 shutdown

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

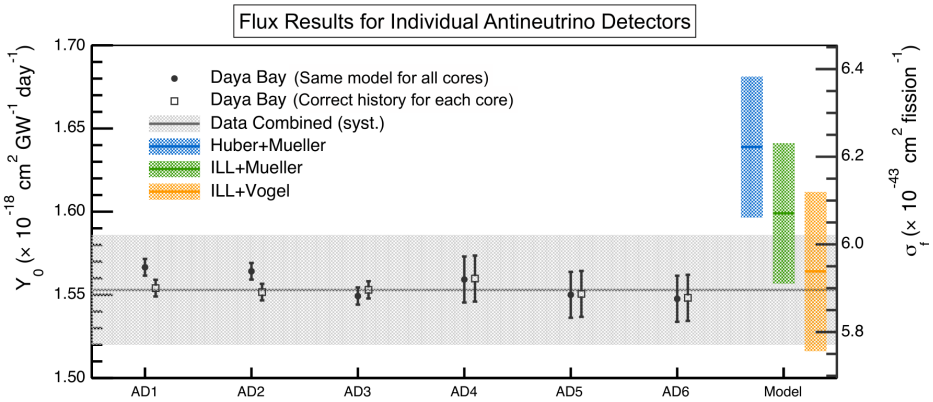






Absolute reactor antineutrino flux

- 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

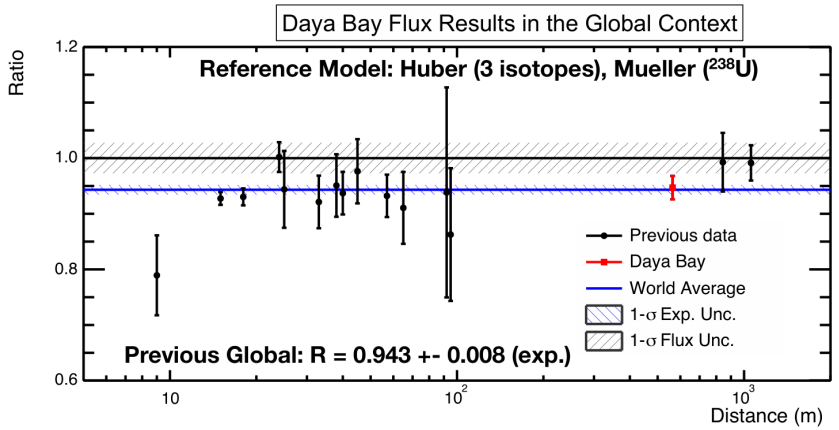


Huber+Mueller

Data/prediction: $\mathbf{0.946 \pm 0.022}$

ILL+Vogel

Data/prediction: $\mathbf{0.991 \pm 0.023}$



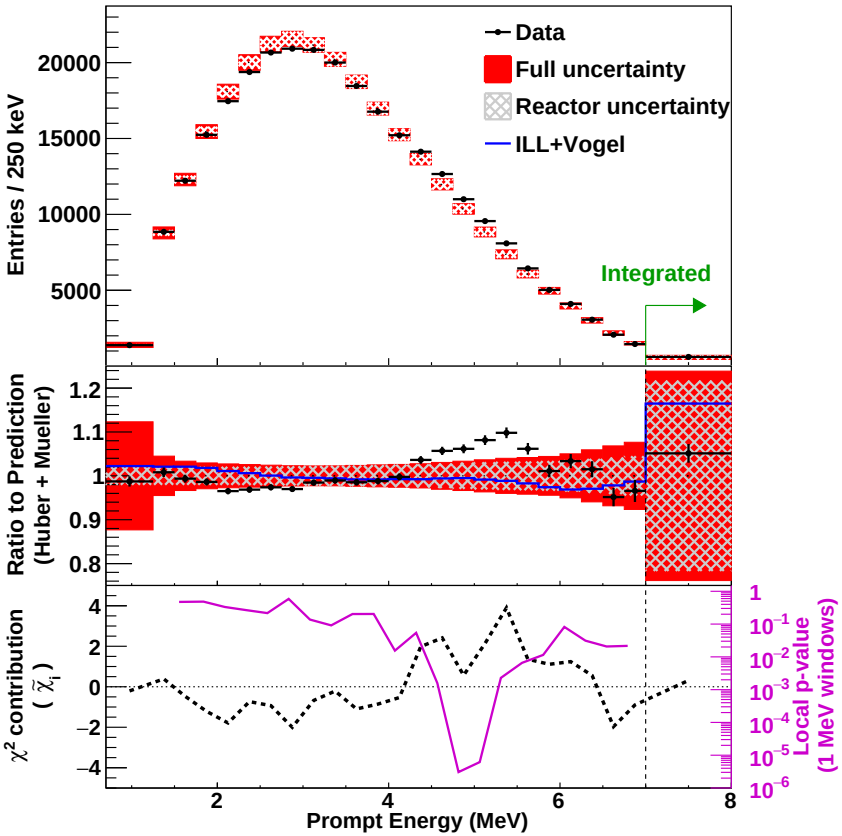
Huber+Mueller (global)

Data/prediction:
$\mathbf{0.943 \pm 0.008}$ (exp) $\pm \mathbf{0.025}$ (model)

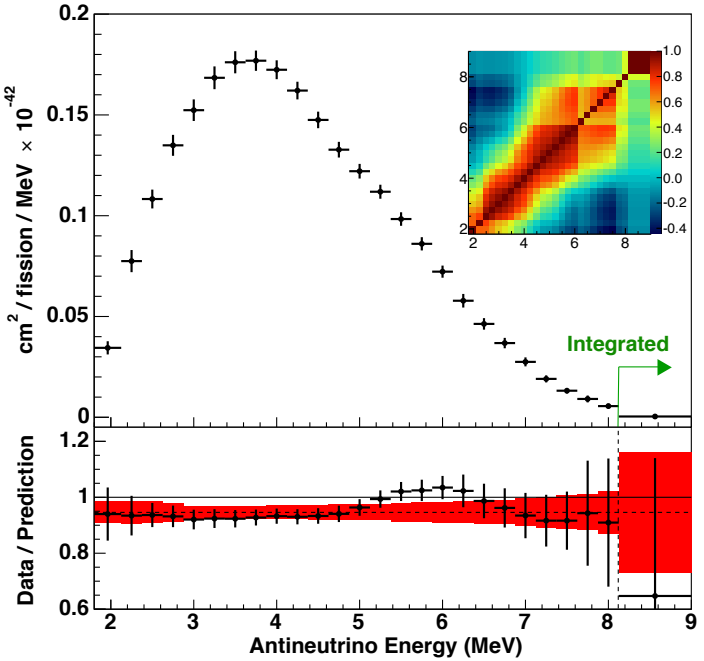
[1508.04233]

Reactor antineutrino spectrum

Observed positron spectrum



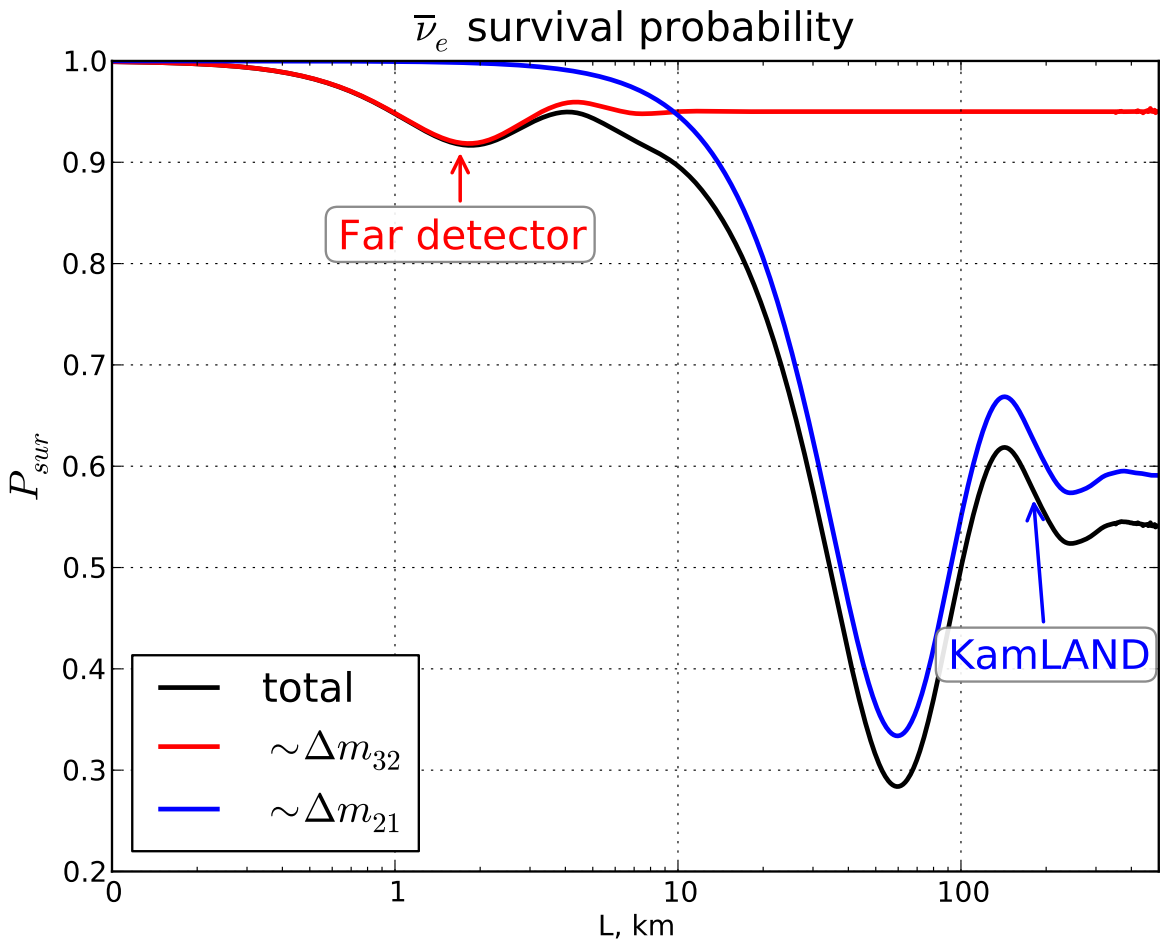
Extracted antineutrino spectrum



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

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

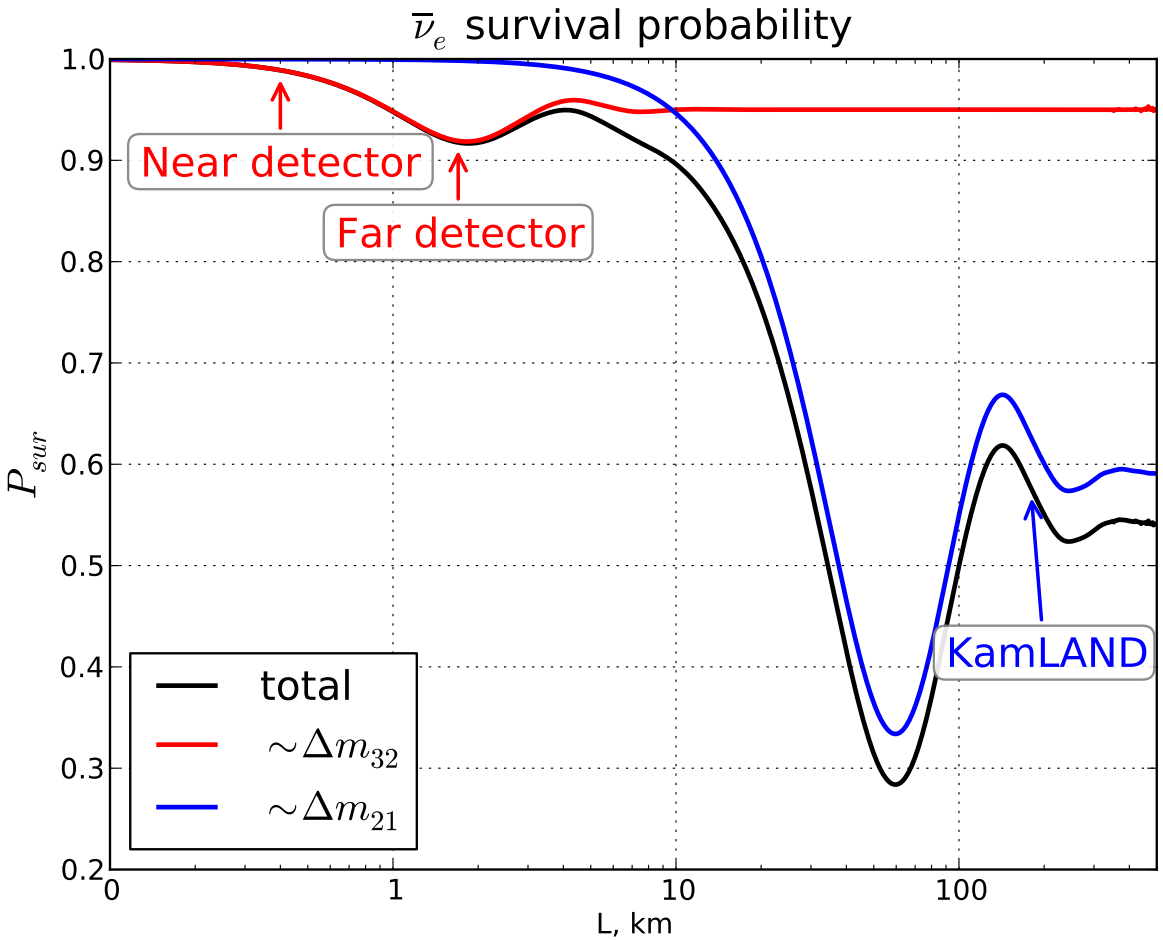
Oscillation analysis



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

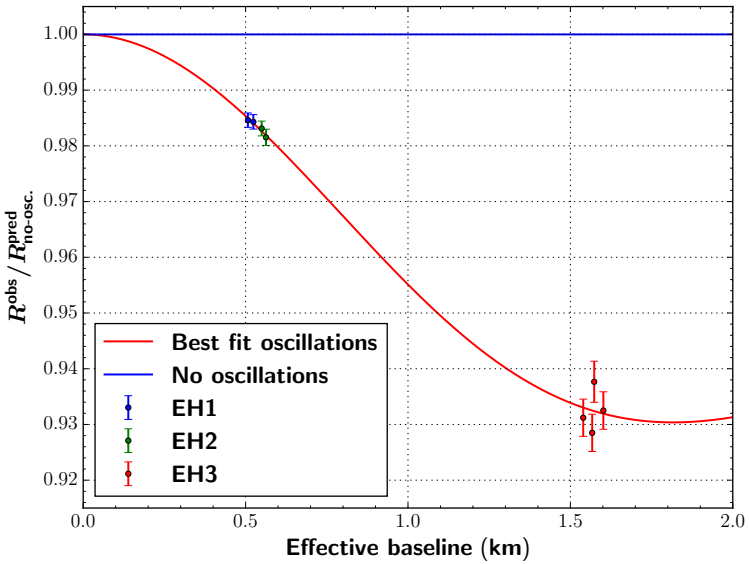
$$= \sin^2 2\theta_{13}\sin^2\Delta_{\text{ee}} + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}, \quad \Delta_{jk} = 1267\cdot\frac{\Delta m^2_{jk}}{\text{eV}^2}\,\frac{L}{E}\,\left[\frac{\text{MeV}}{\text{km}}\right]$$

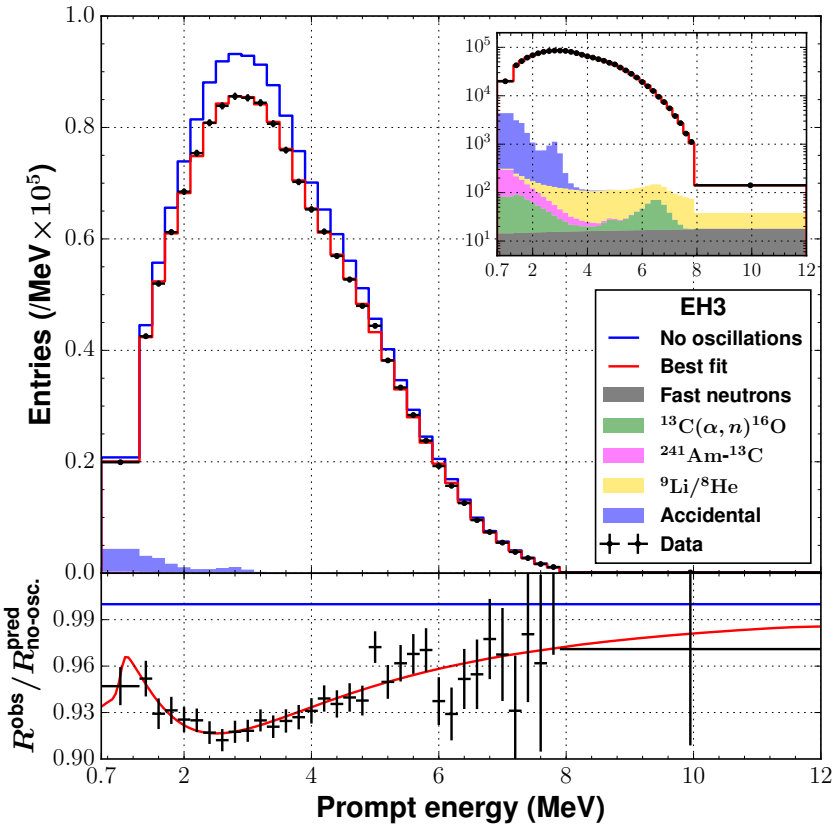
Oscillation analysis



$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{p,\mathrm{f}}}{N_{p,\mathrm{n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left(\frac{P_{\nu_e\to\nu_e}(E,L_{\mathrm{f}})}{P_{\nu_e\to\nu_e}(E,L_{\mathrm{n}})}\right)$$

Far vs. near comparison

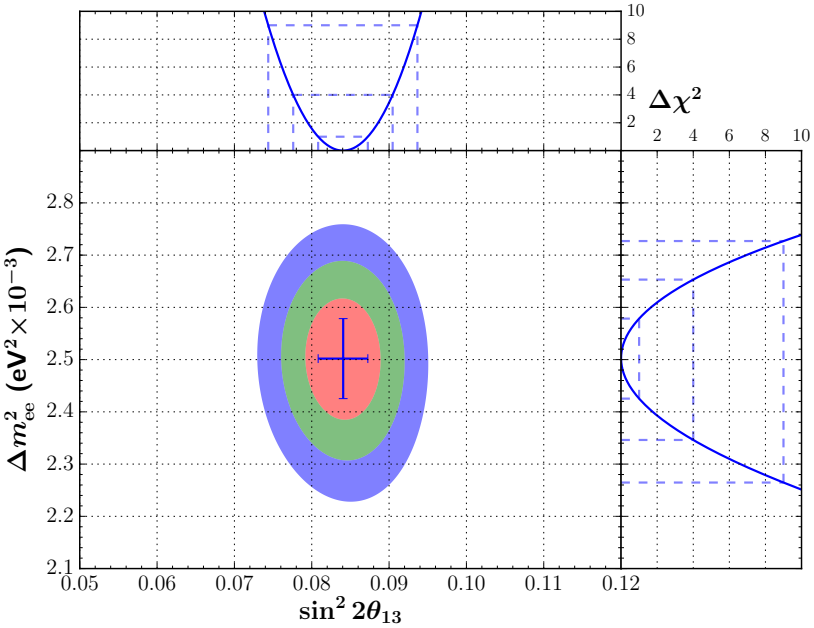


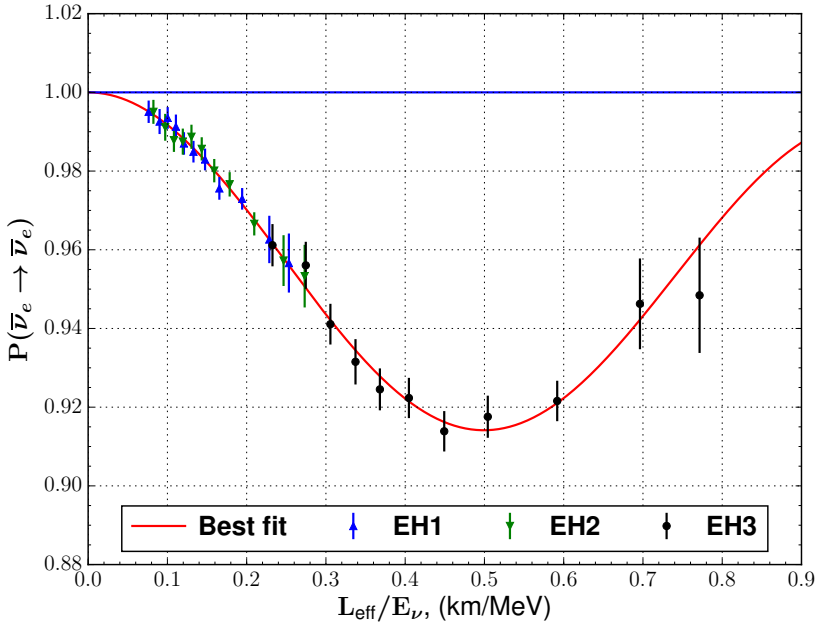


The observed **event rate deficit** and **relative spectrum distortion** are highly consistent with oscillation interpretation.

[1610.04802]

Daya Bay oscillation result





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

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

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

[1610.04802]

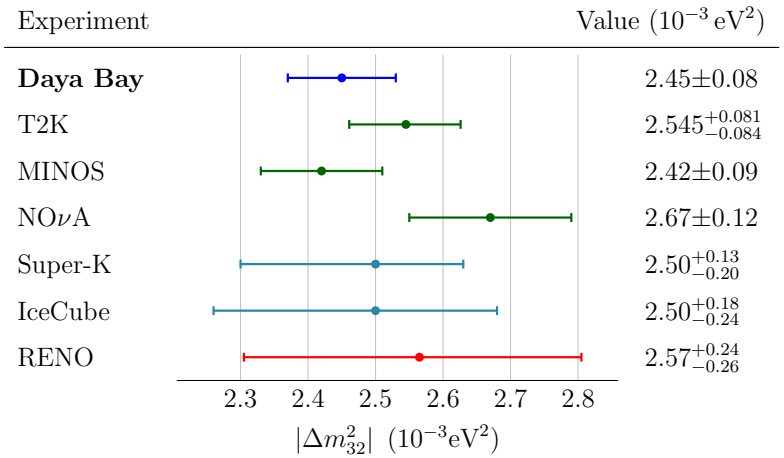
Daya Bay oscillation result

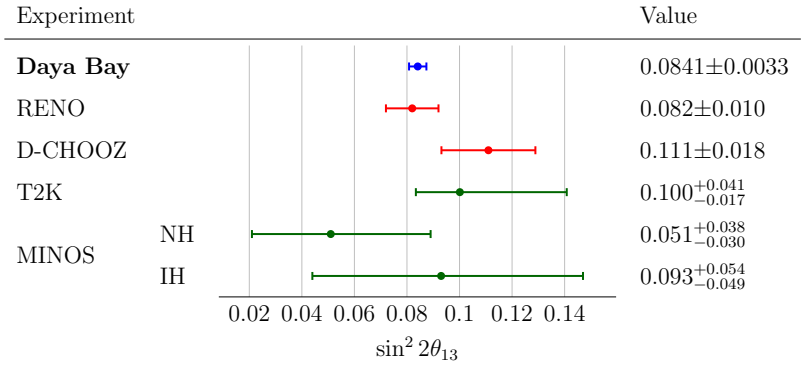
- Most precise $\sin^2 2\theta_{13}$ measurement. The non-zero value is excluded at $> 25\sigma$
- Most precise measurement of Δm^2_{ee}
- Normal Hierarchy:

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

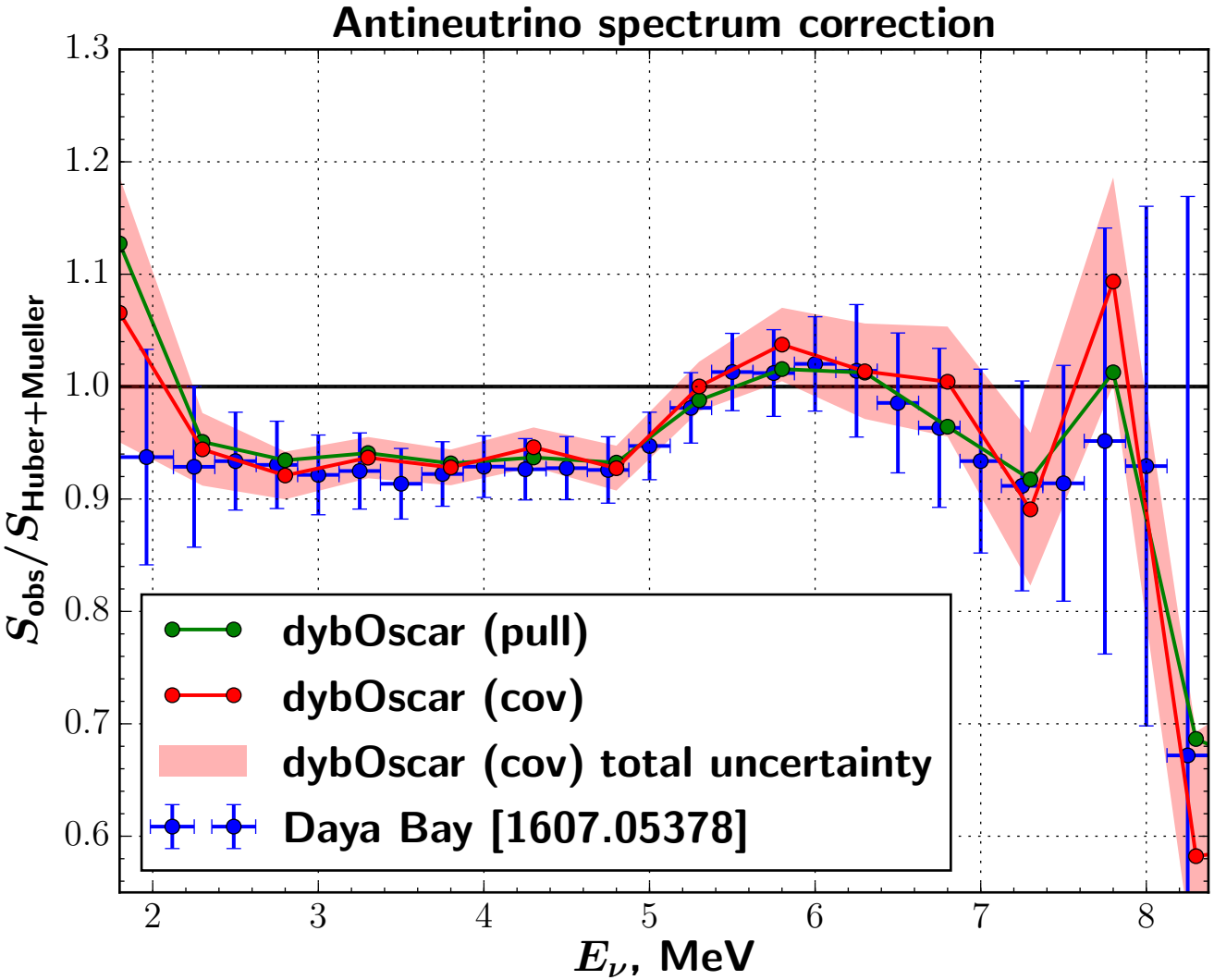
- Inverted Hierarchy:

$$\Delta m^2_{32} = (-2.56 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})) \times 10^{-3}\ \text{eV}^2$$





[1610.04802]



- Shape of reactor spectrum is fitted simultaneously with oscillation parameters. Good agreement with a dedicated analysis of the reactor spectrum.
- Correlation of oscillation and spectral parameters is negligible.

Independent nH oscillation analysis (NEW!)

Key points:

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

nH

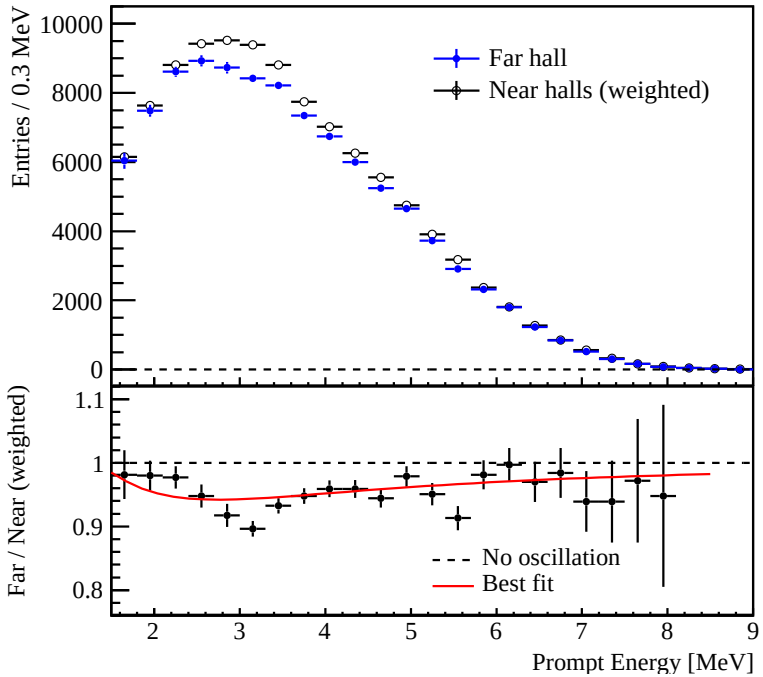
$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

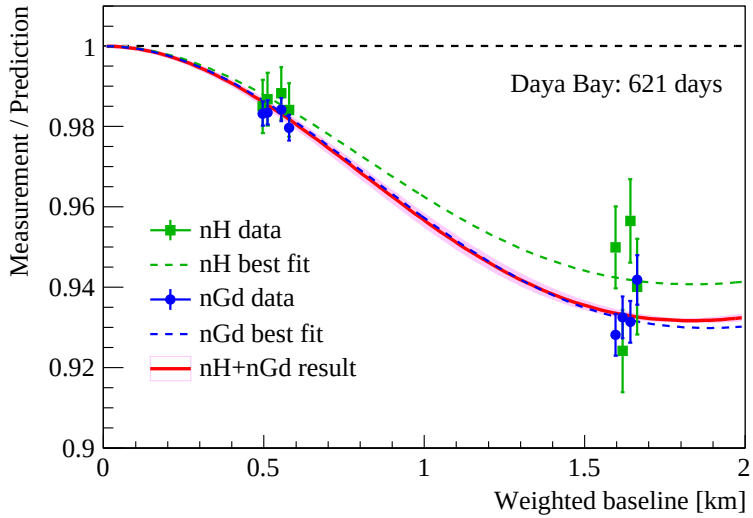
nH+nGd

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

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

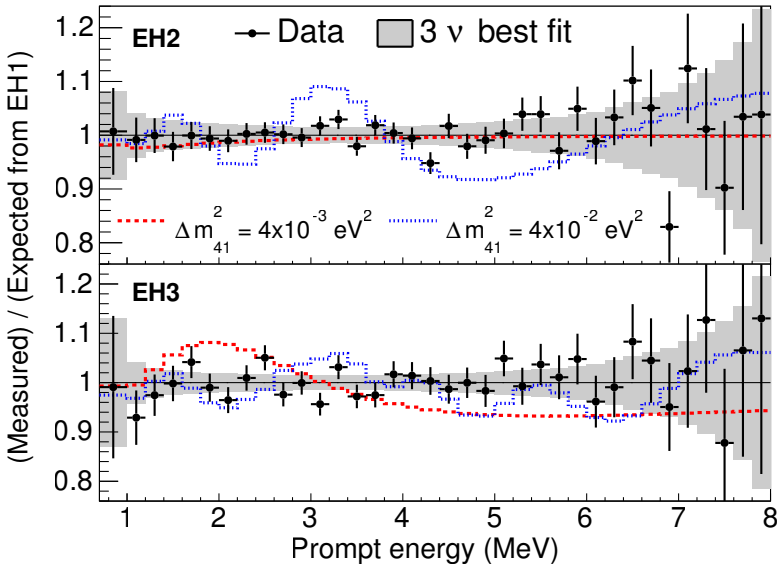
[1603.03549]

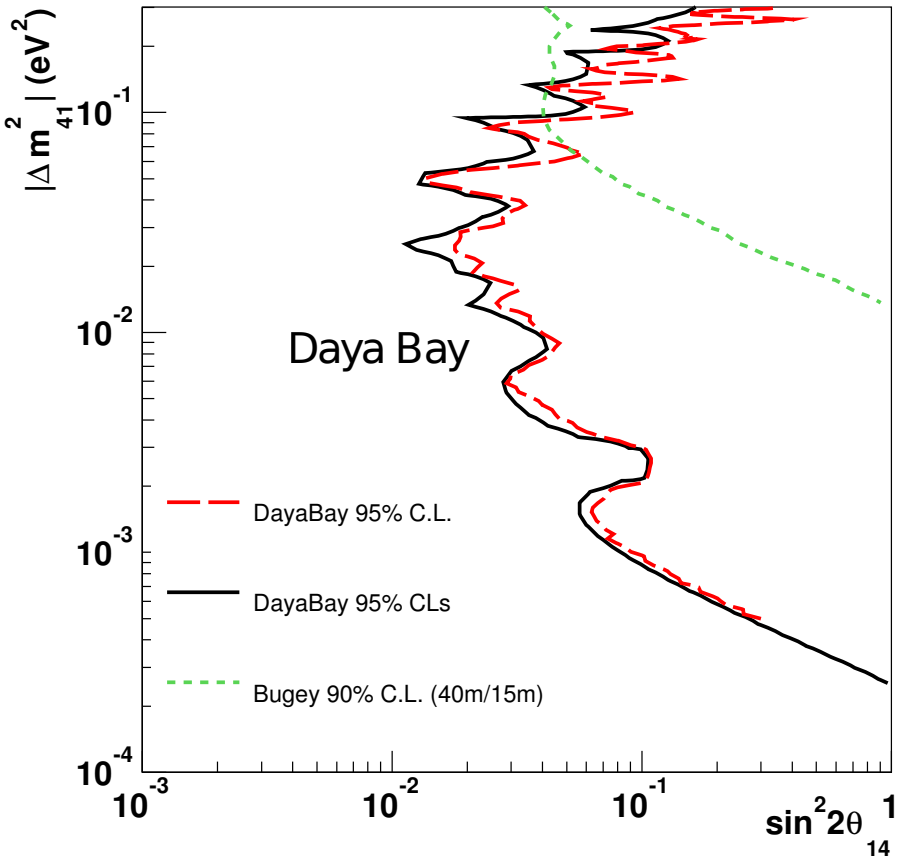




Light sterile neutrino search

- 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**

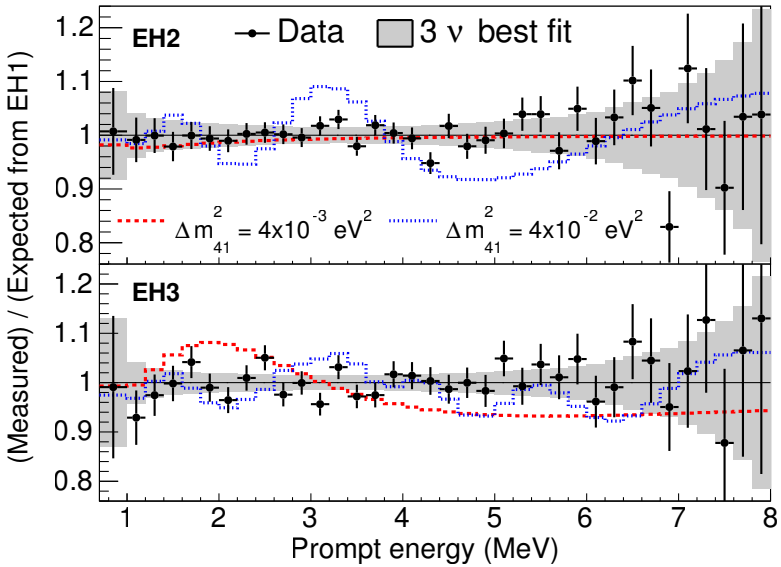


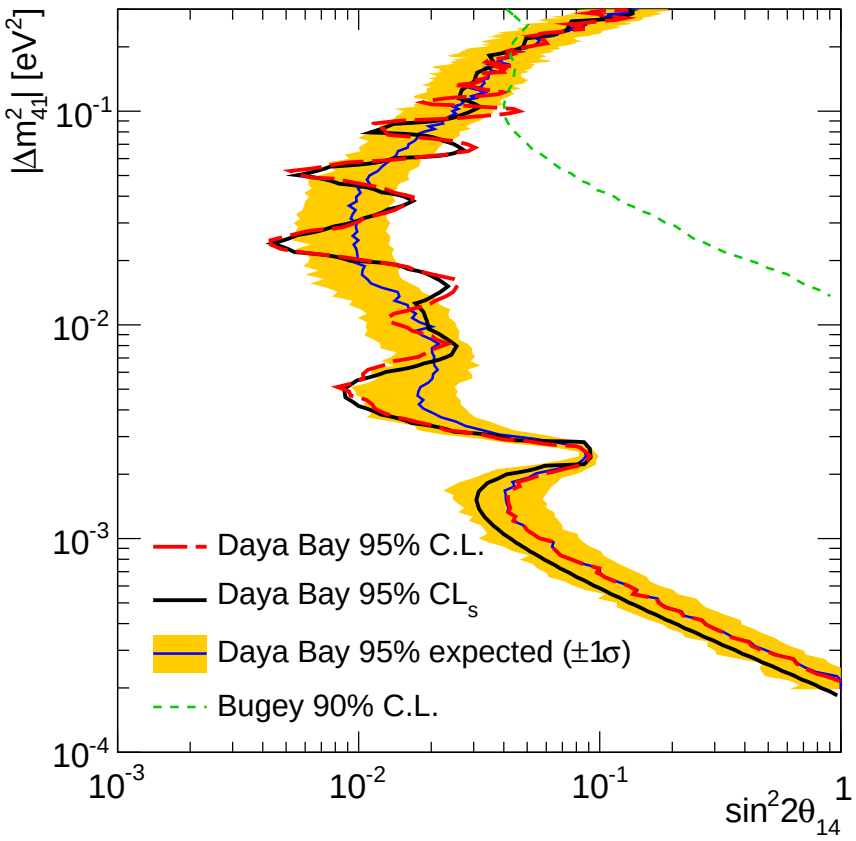


[1407.7259]

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**

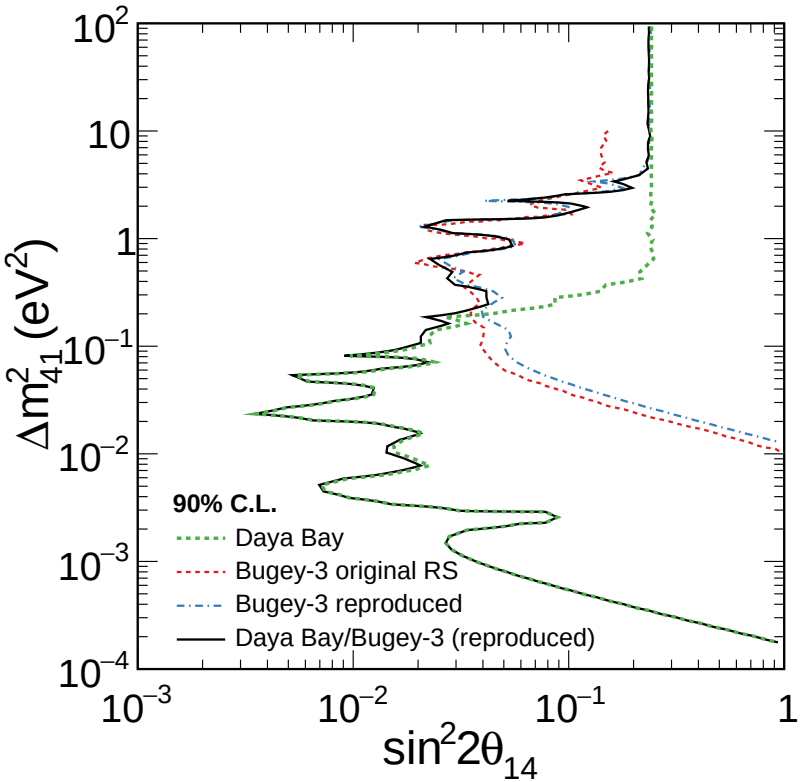




[1607.01174]

Light sterile neutrino search with Bugey-3 and MINOS

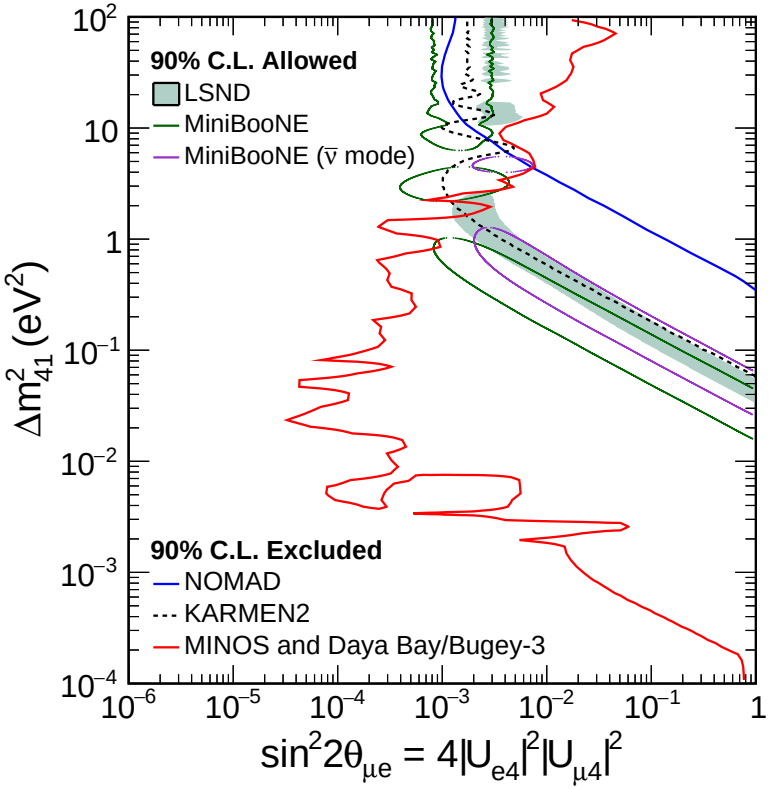
- Combining Daya Bay and Bugey-3 data strongly constrains Δm^2_{41} and $\sin^2 2\theta_{41}$
- Combining Daya Bay and Bugey-3 and MINOS data allows to constrain Δm^2_{41} and $\sin^2 2\theta_{41}\sin^2 2\theta_{42}$
- Joint analysis strongly suggests that LSND results is not due to **sterile neutrino**



[1607.01177]

Light sterile neutrino search with Bugey-3 and MINOS

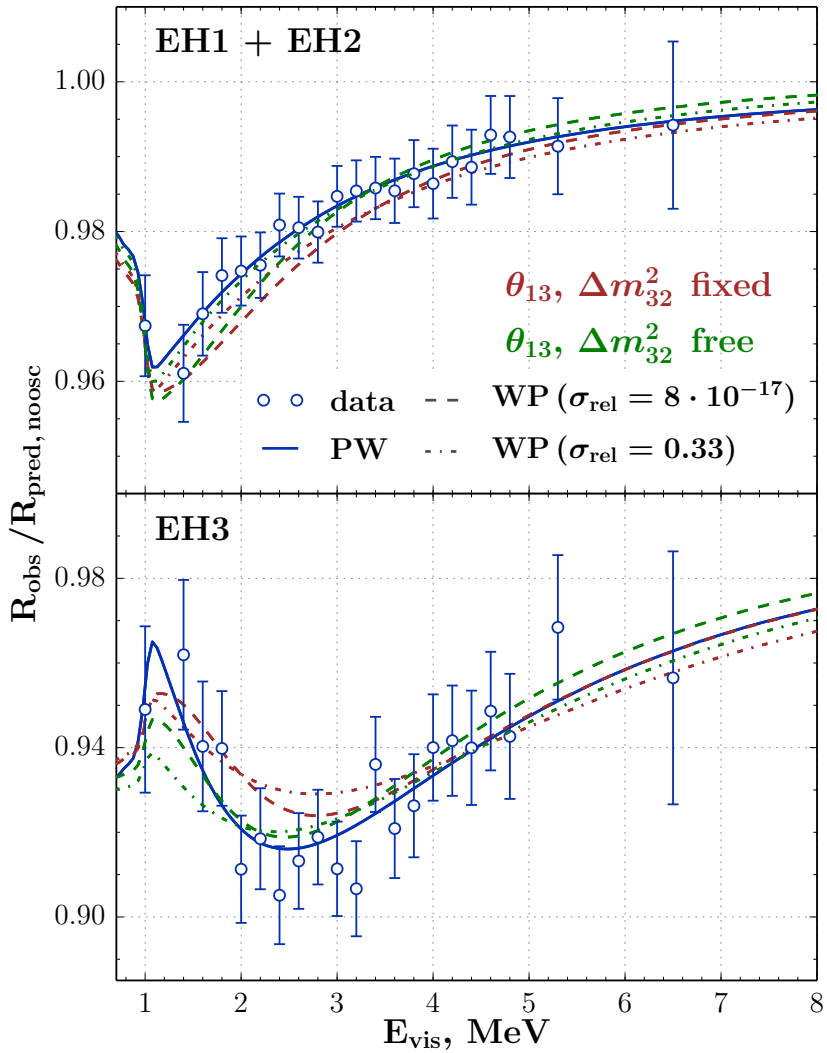
- Combining Daya Bay and Bugey-3 data strongly constrains Δm^2_{41} and $\sin^2 2\theta_{41}$
- Combining Daya Bay and Bugey-3 and MINOS data allows to constrain Δm^2_{41} and $\sin^2 2\theta_{41}\sin^2 2\theta_{42}$
- Joint analysis strongly suggests that LSND results is not due to **sterile neutrino**



[1607.01177]

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** $L^{\text{coh}} = \frac{L^{\text{osc}}}{\sqrt{2}\pi\sigma_{\text{rel}}}$, where $\sigma_{\text{rel}} = \sigma_p/p$.
  - if $\sigma_x \gg L^{\text{osc}}$, where $\sigma_x = 1/2\sigma_p$.



Wave packet effects

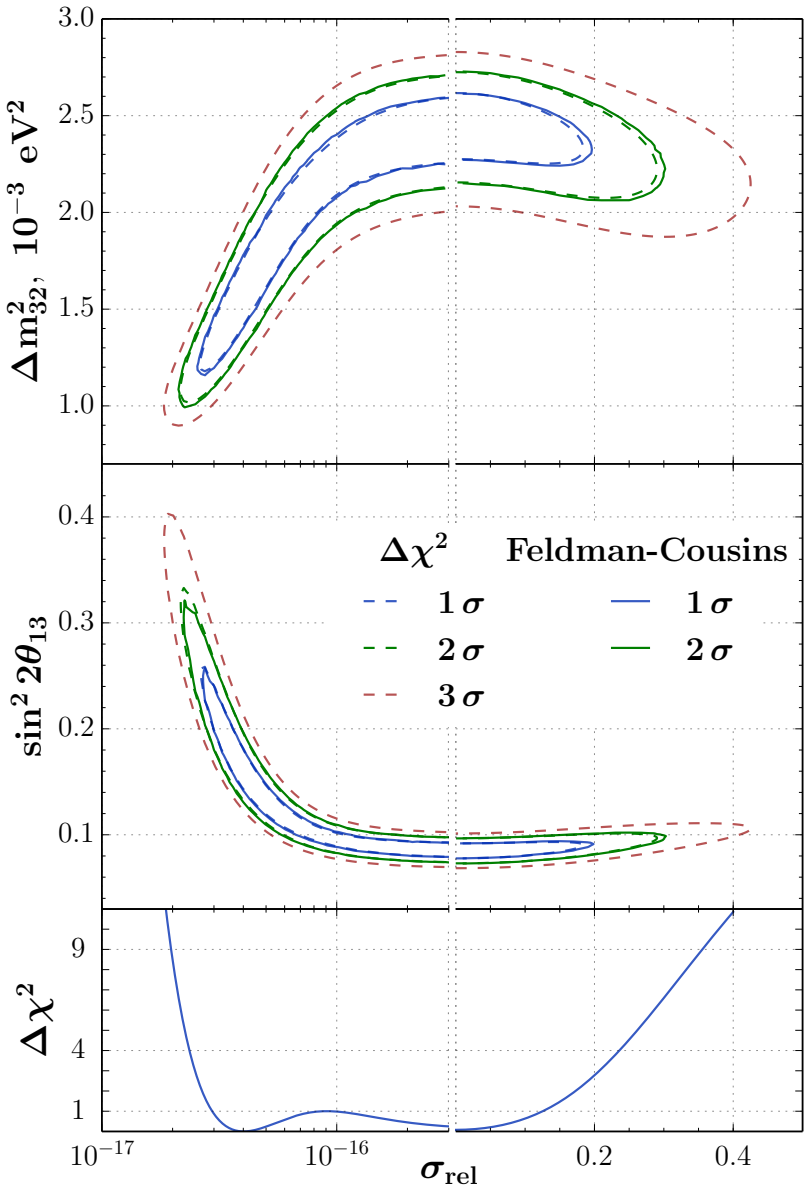
- The obtained limits read

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

- 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:

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

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

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:

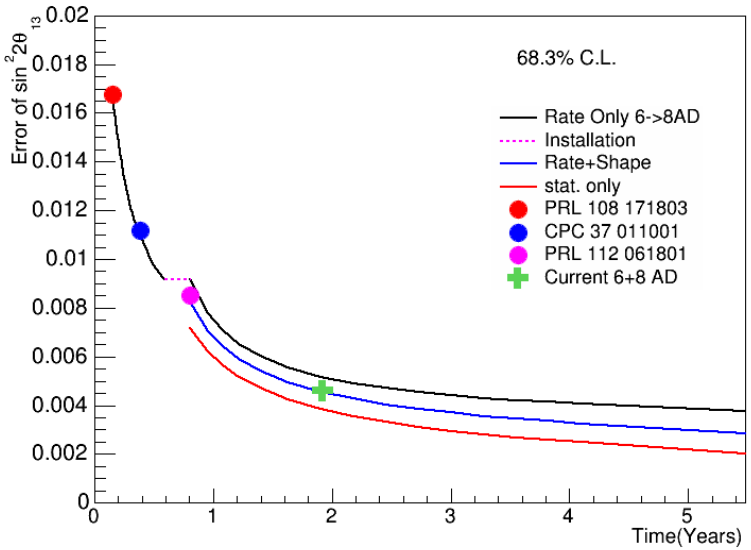
$$\sin^2 2\theta_{13} = 0.082 \pm 0.004$$

- Reactor antineutrino flux $\sim$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.

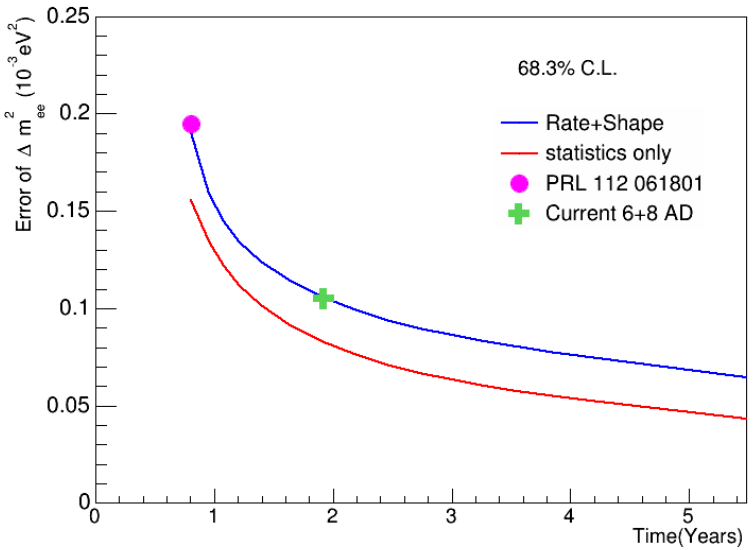
Backup slides...

Daya Bay sensitivity

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



Δm^2_{ee} error projection



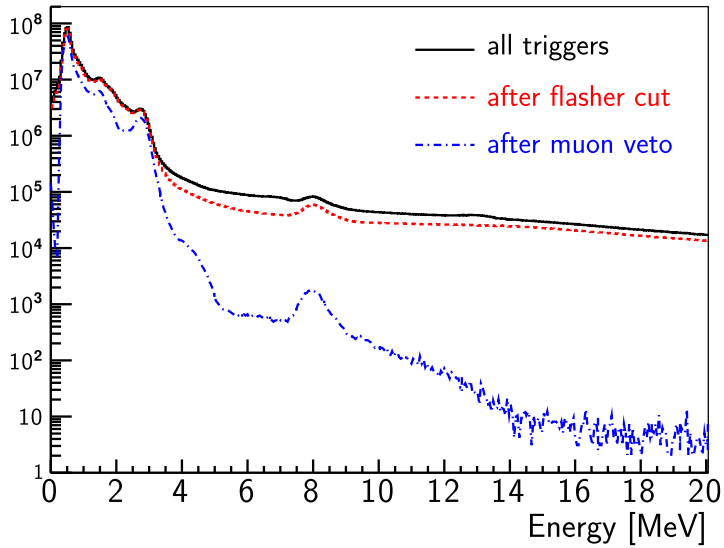
IBD selection criteria

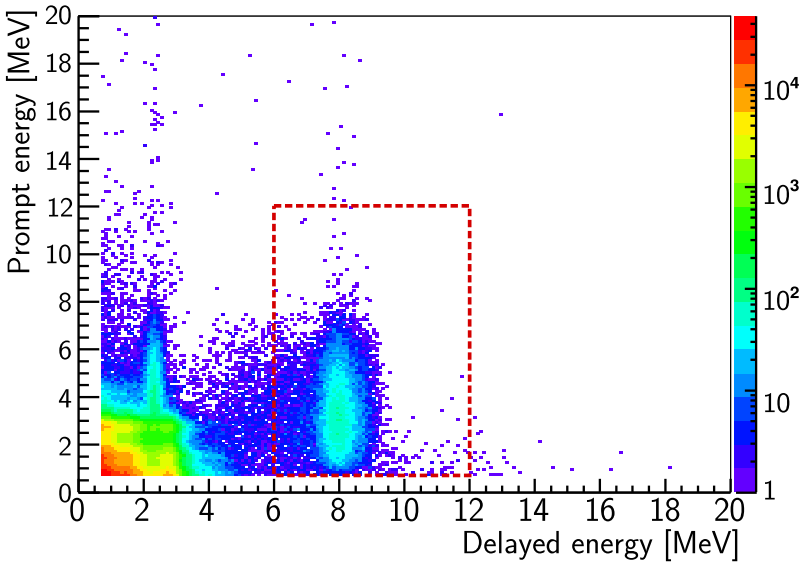
Inverse beta decay:

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

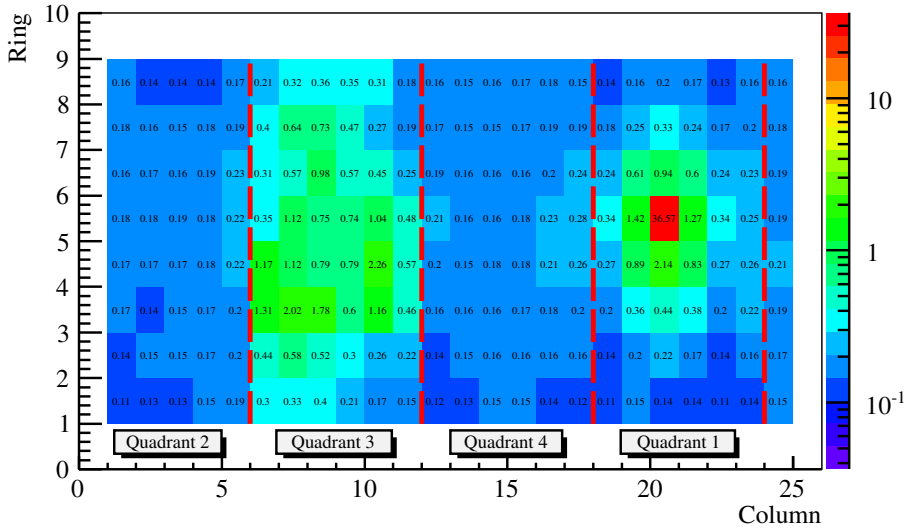
Selection:

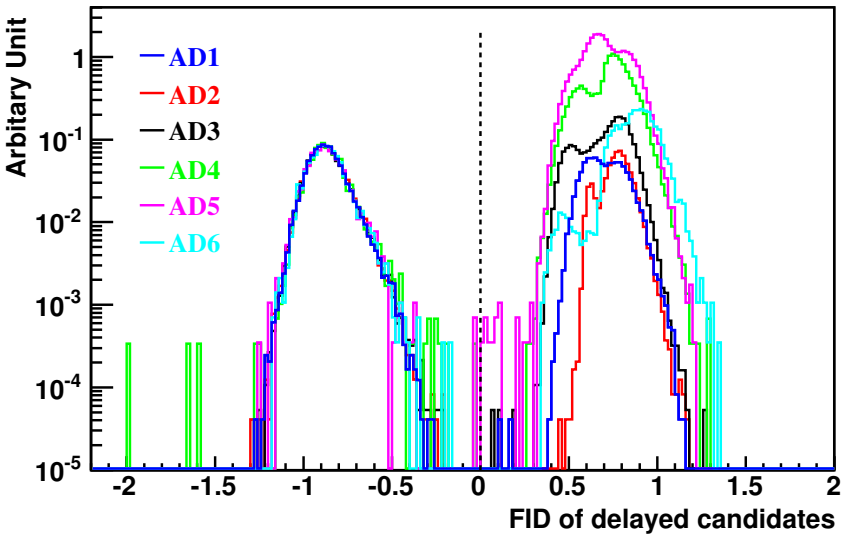
1. Reject spontaneous PMT light emission (99.98%).
2. Prompt energy (positron):
   $0.7\ \text{MeV} < E_p < 12\ \text{MeV}$ (99.88%).
3. Delayed energy (neutron capture):
   $6\ \text{MeV} < E_p < 12\ \text{MeV}$ (90.9%).
4. Neutron capture time:
   $1\ \mu s < \Delta t < 200\ \mu s$ (98.6%).
5. Reject 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
   $E > 0.7\ \text{MeV}$ 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

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

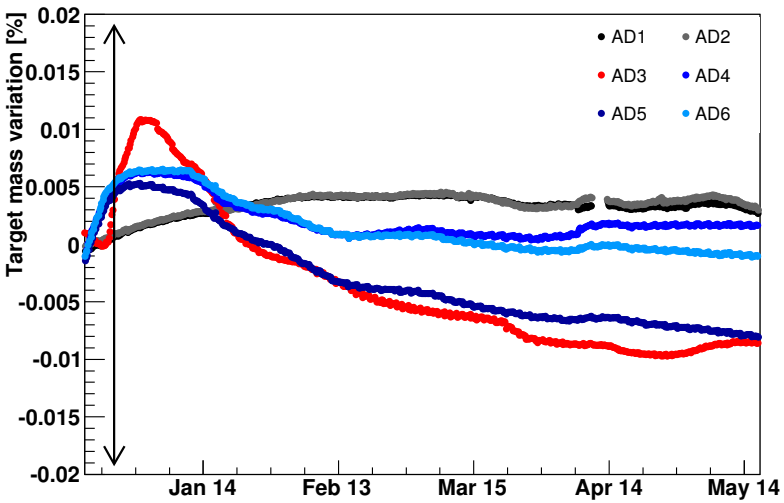
$d_{quad} = Q_3/(Q_2 + Q_4)$

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

AD liquids

Target mass:

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

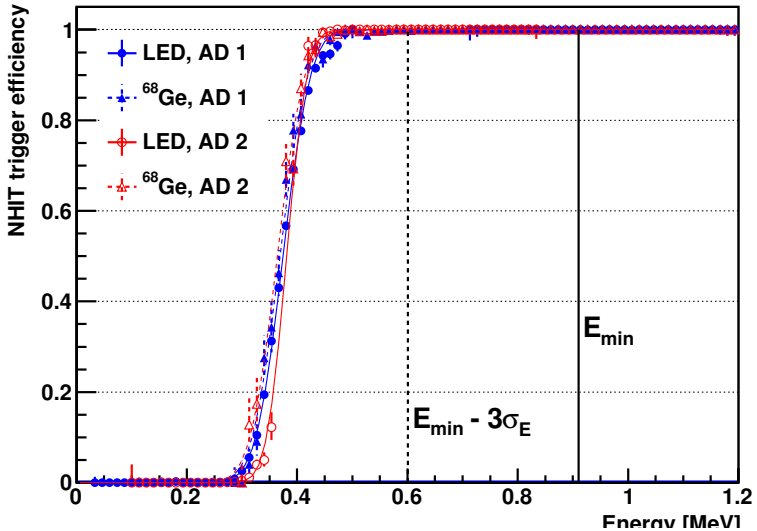
Liquids storage and filling:

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

Trigger

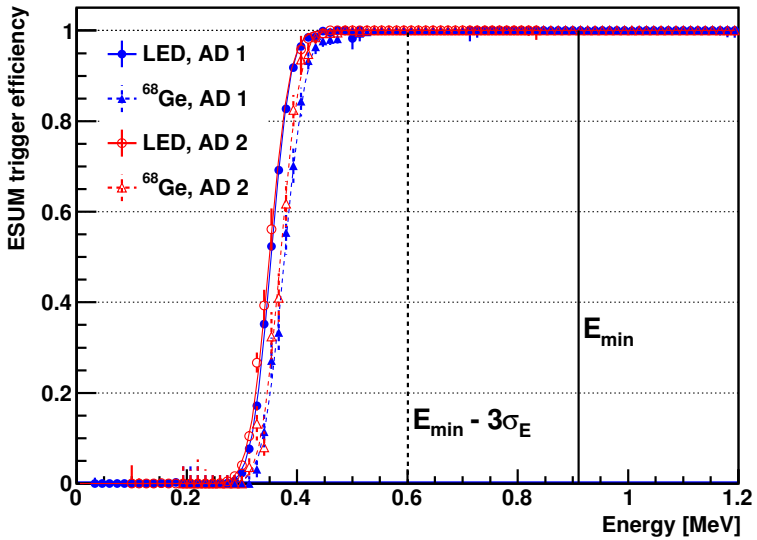
Trigger criteria:

- 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.

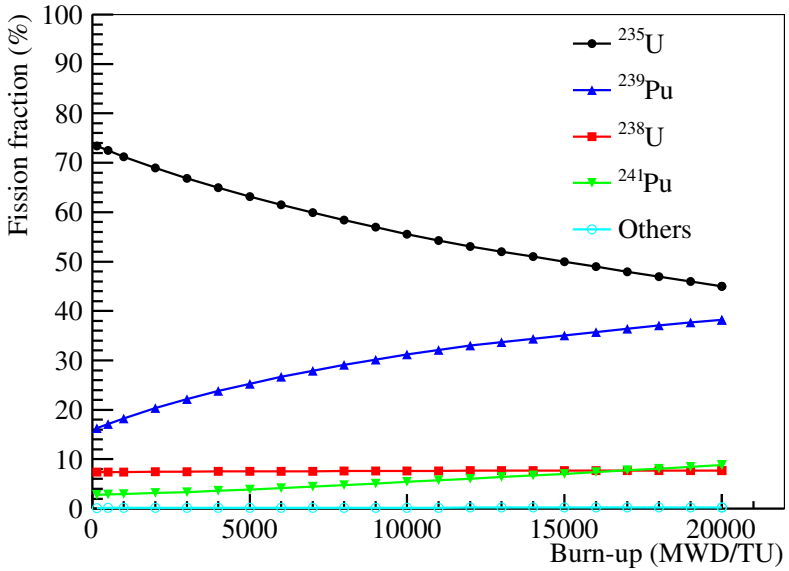


Reactor flux expectation

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

Information provided by the NPP:

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

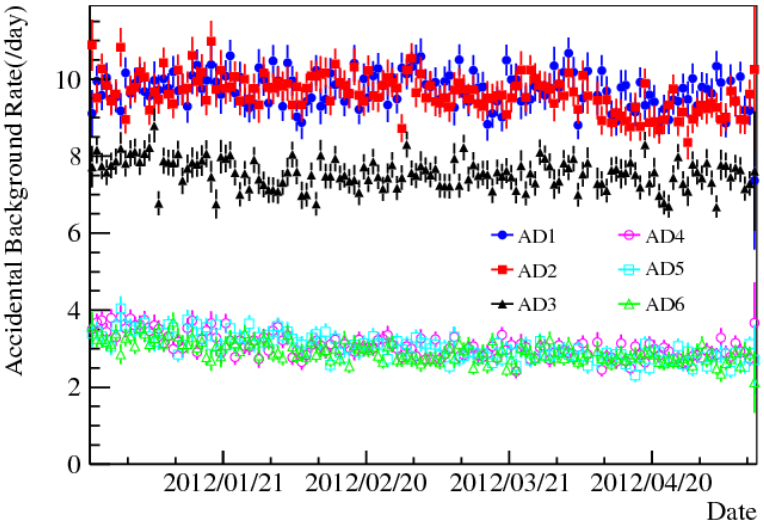


Neutrino data:

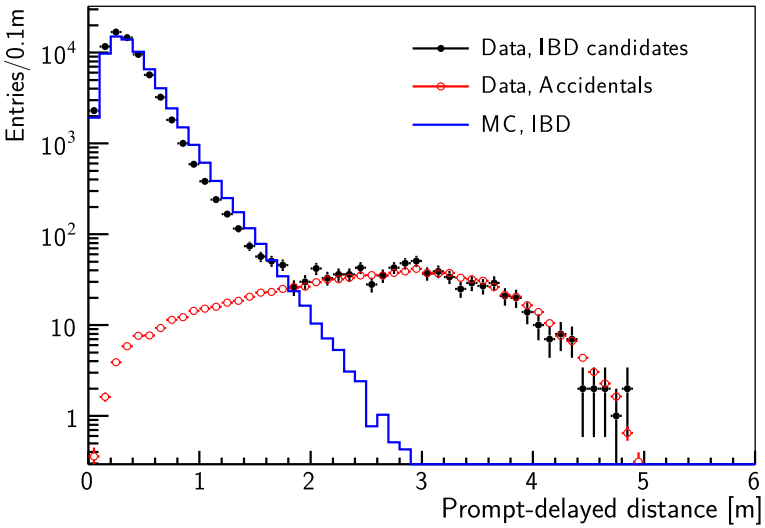
- E_i — energy released per fission:
  - V. Kopeikin, L. Mikaelyan, and V. Sinev, Phys. Atom. Nucl. **67**, 1892 (2004).
- $S_i(E)$ — antineutrino spectra per fission:
  - W. G. K. Schreckenbach, G. Colvin and F. von Feilitzsch, Phys. Lett. **B160**, 325 (1985).
  - A. F. von Feilitzsch and K. Schreckenbach, 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

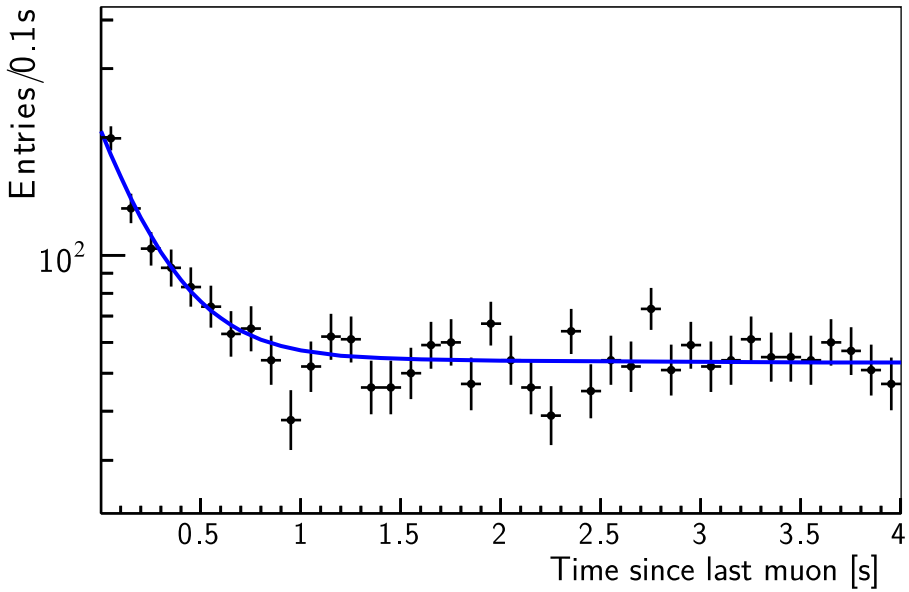


Figure

- 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.

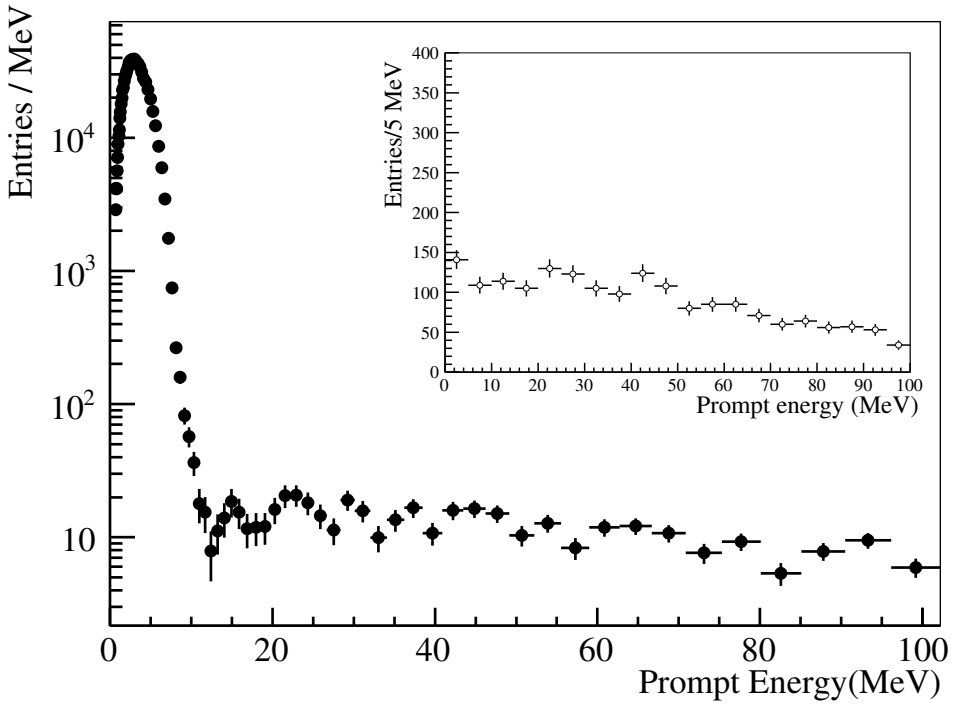


Figure

- 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.

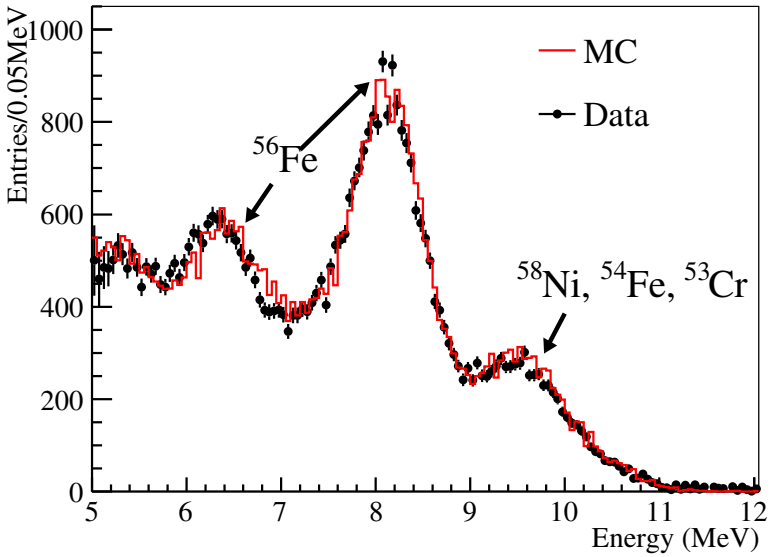


Figure: Energy spectrum of the events near the top of ADs in the Far Hall.

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.

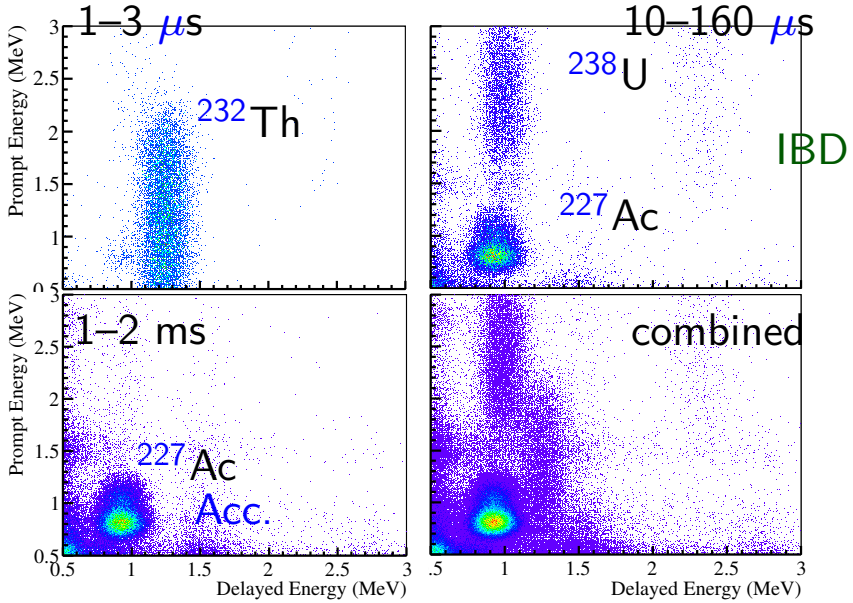


Figure: Correlations of prompt and delayed energy for cascade decay chains.