The latest results from the Daya Bay

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on behalf of the Daya Bay collaboration

Laboratory of Nuclear Problems,
Joint Institute for Nuclear Research

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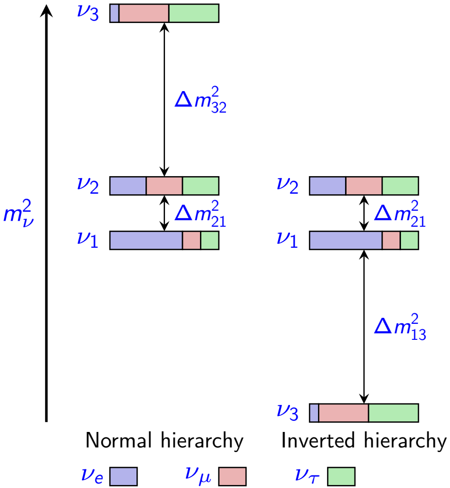
Moscow, October 23, 2018

Neutrino mixing



Neutrino mixing

Weak and mass eigenstates are mixed:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}|\nu_i\rangle$$

Mixing is parametrized by three mixing angles and phase:

- $\theta_{12} \approx 34^\circ$, $\theta_{13} \approx 8^\circ$, $\theta_{23} \approx 45^\circ$
- $\delta_{CP} \sim \frac{3\pi}{2}$ only hints

Mass splitting

From oscillation experiments:

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
- $|\Delta m^2_{32}| = (2.42 \pm 0.06) \times 10^{-3}$ eV^2
- $|\Delta m^2_{32}| / \Delta m^2_{21} \sim 32$

Reactor electron anti-neutrino disappearance

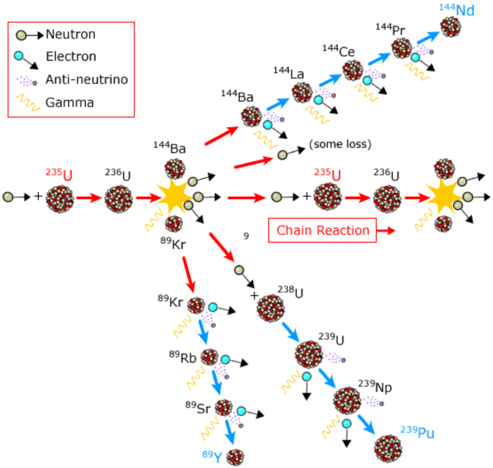
Reactor as $\overline{\nu}_e$ source

- **Strong**:
  Produces $\sim 10^{20}\ \overline{\nu}_e/\mathrm{s}/\mathrm{GW_{th}}$;
- **Clean**:
  Produces only $\overline{\nu}_e$.
- **Controllable**:
  "Free" artificial antineutrino source.
- **Complex spectrum**:
  a lot of constituents, time dependence.
- $E_\nu < 10$ MeV

Reactor $\overline{\nu}_e$ production

in beta decays of fission products of

- $^{235}\mathrm{U}$, $^{239}\mathrm{Pu}$ and $^{241}\mathrm{Pu}$ (slow n)
- $^{238}\mathrm{U}$ (fast n)
- $\sim 6\ \overline{\nu}_e$/fission



Reactor electron anti-neutrino disappearance

$\overline{\nu}_e$ disappearance

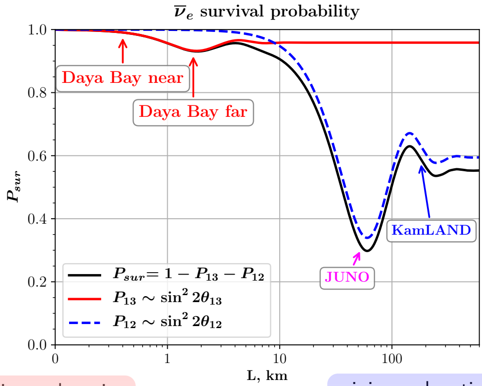
- **No side effects**:
  Negligible matter effects, no δ_{CP} dependence.

$\overline{\nu}_e$ detection

- Inverse beta decay (IBD):

$$\overline{\nu}_e + p \longrightarrow e^+ + n$$

- Treshold $E_\nu \sim 1.8\,\text{MeV}$



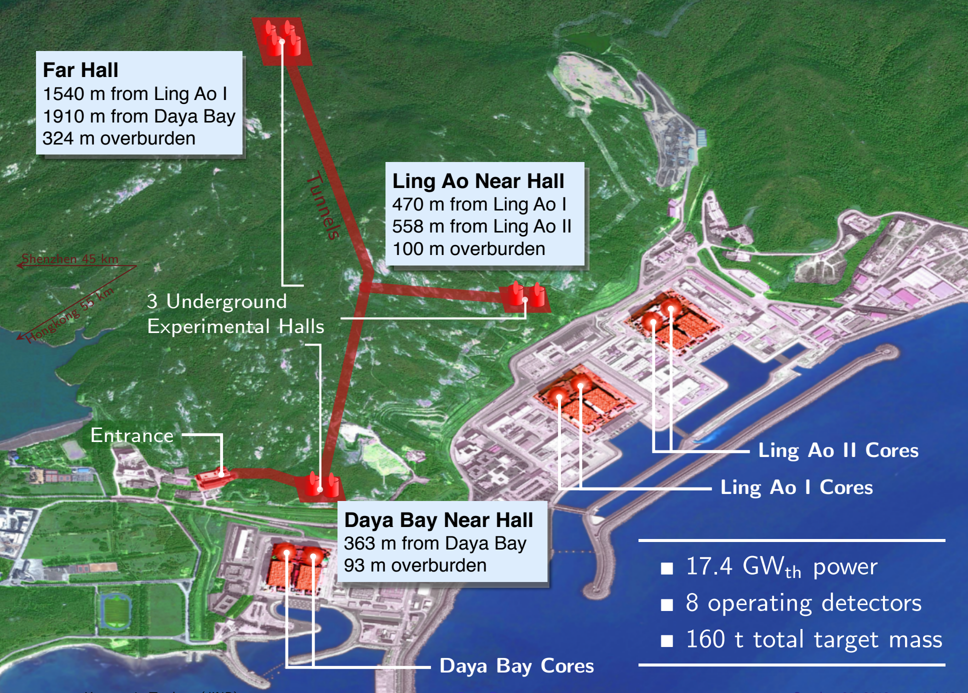
deficit value — minimum location — minimum location (solar)

$$1 - P_{\nu_e \to \nu_e} = \sin^2 2\theta_{13} \left(\sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} + \cos^2\theta_{12} \sin^2 \Delta_{31} \right) + \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \Delta_{21}$$

$$\approx \sin^2 \frac{L \Delta m^2_{ee}}{4E}$$

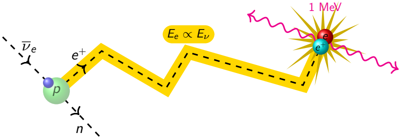
effective reactor mass splitting

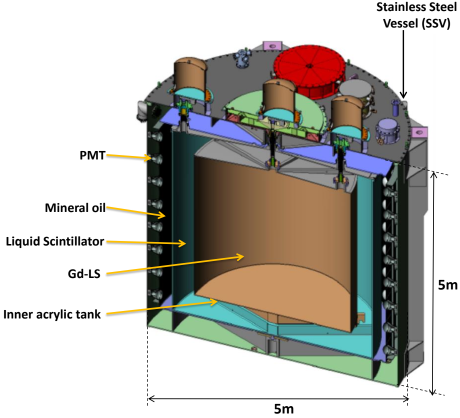
$$\Delta_{jk} = 1267 \cdot \frac{\Delta m^2_{jk}}{\text{eV}^2} \frac{L}{E} \left[\frac{\text{MeV}}{\text{km}}\right]$$


Far Hall
1540 m from Ling Ao I
1910 m from Daya Bay
324 m overburden
Ling Ao Near Hall
470 m from Ling Ao I
558 m from Ling Ao II
100 m overburden
Tunnels
Shenzhen 45 km
Hongkong 55 km
3 Underground Experimental Halls
Entrance
Daya Bay Near Hall
363 m from Daya Bay
93 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

Antineutrino detection

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





Antineutrino detection

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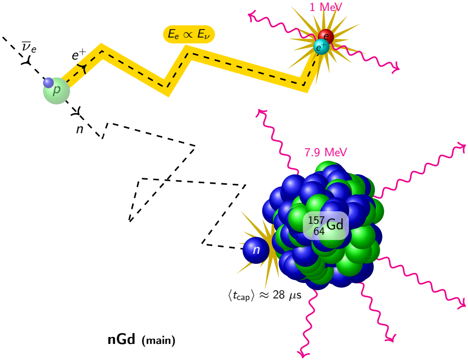
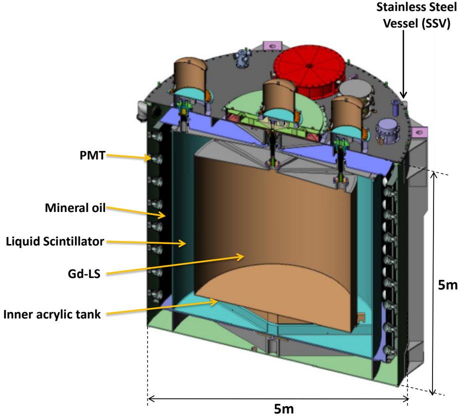


nGd (main)



$\hookrightarrow$ $_{64}$Gd: $^{155}_{64}$Gd, $\mathbf{^{157}_{64}Gd}$ and some others.

Antineutrino detection

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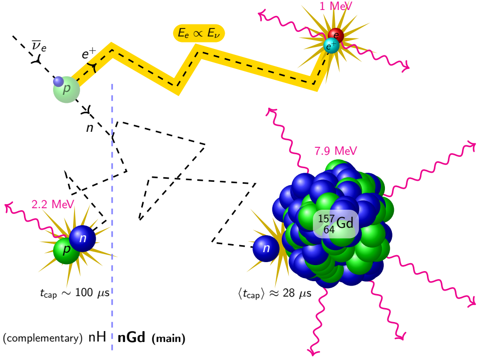
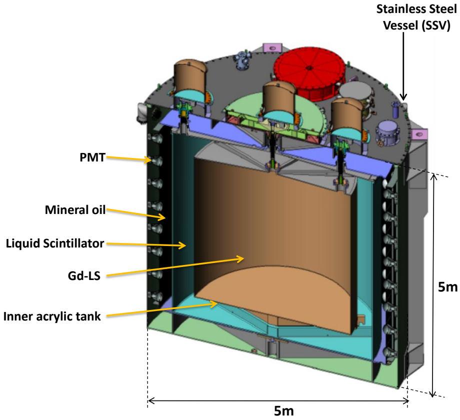
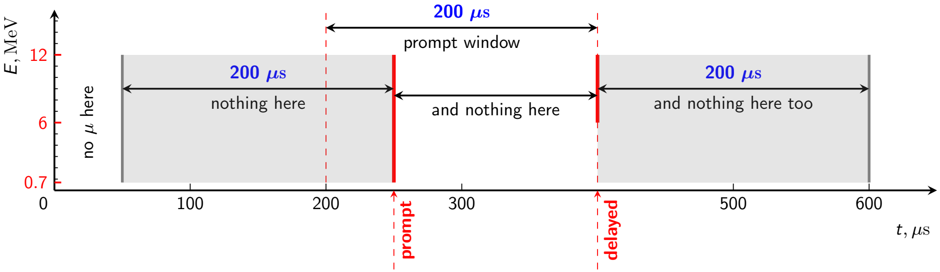




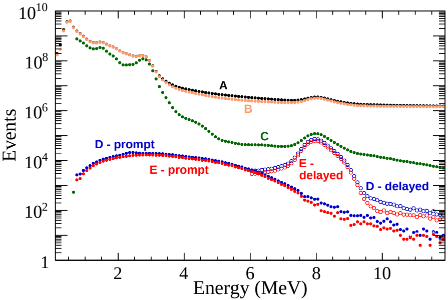
$\hookrightarrow$ ${}_{64}\mathrm{Gd}$: ${}^{155}_{64}\mathrm{Gd}$, $\mathbf{{}^{157}_{64}Gd}$ and some others.

IBD selection



Selection criteria

- Two signals within 200 μs window
  - Prompt: 0.7 MeV to 12 MeV
  - Delayed: 6 MeV to 12 MeV
- No other signals around $\pm$ 200 μs and in between
- No muons within 0.6 ms – 1 s before delayed
- Flashes from PMTs are removed



Data set: 1958 DAQ days

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	830036	964381	889171	784736	127107	127726	126666	113922
DAQ live time (days)	1536.621	1737.616	1741.235	1554.044	1739.611	1739.611	1739.611	1551.945
$\varepsilon_\mu \times \varepsilon_m$	0.8050	0.8013	0.8369	0.8360	0.9596	0.9595	0.9592	0.9595
Accidentals (day^{-1})	8.27 ± 0.08	8.12 ± 0.08	6.00 ± 0.06	5.86 ± 0.06	1.06 ± 0.01	1.00 ± 0.01	1.03 ± 0.01	0.86 ± 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})	2.38 ± 0.66		1.59 ± 0.49		0.19 ± 0.08			
Am-C correlated(day^{-1})	0.17 ± 0.07	0.15 ± 0.07	0.14 ± 0.06	0.13 ± 0.06	0.06 ± 0.03	0.05 ± 0.02	0.05 ± 0.02	0.04 ± 0.02
^{13}C(α, n)^{16}O (day^{-1})	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02
$\overline{\nu}_e$ rate (day^{-1})	659.36 ± 1.00	681.09 ± 0.98	601.83 ± 0.82	595.82 ± 0.85	74.75 ± 0.23	75.19 ± 0.23	74.56 ± 0.23	75.33 ± 0.24

New data set

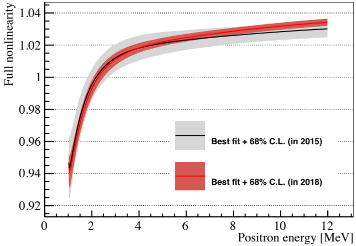
- 1958 days of DAQ data.
- Above 3.9M IBD candidates, 0.5M of them are on a far site. (high statistics)
- Statistical uncertainty in $\overline{\nu}_e$ rates: 0.1% – 0.3%.
- Background contribution to $\overline{\nu}_e$ rate: 1.5% – 2%. (low background)
- Background uncertainty in $\overline{\nu}_e$ rates 0.1%. (low systematics)

(+highly redundant)

Major systematics improvements

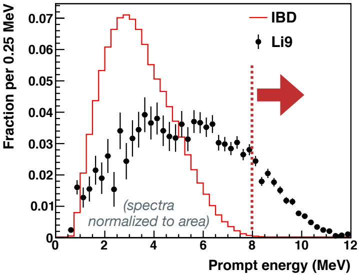
Energy scale

- Need a model to convert reconstructed positron energy to true energy
- Nonlinear response due to:
  - Quenching + Cherenkov light yield
  - Response of electronics
- FADC studies + dedicated calibration campaign → positron energy scale nonlinearity uncertainty: 1% → 0.5%



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

- Based on high statistics $^{9}Li/^{8}He$ rate uncertainty reduced from 50% → 30%

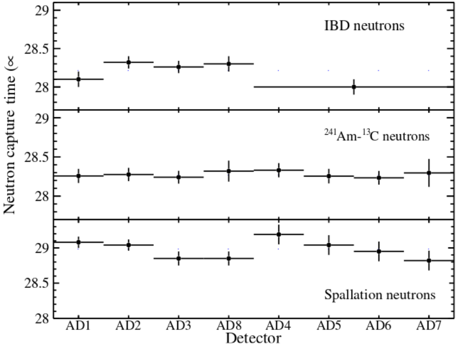


Spent Nuclear Fuel

- SNF rate uncertainty significantly reduced 100% → 30% (SNF contribution: 0.3%).

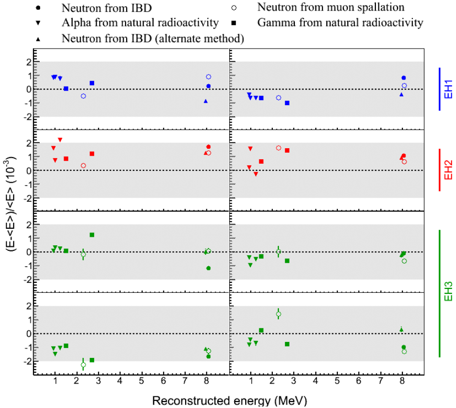
Relative efficiency and relative energy scale

- Relative efficiency $\rightarrow \sin^2 2\theta_{13}$ uncertainty.



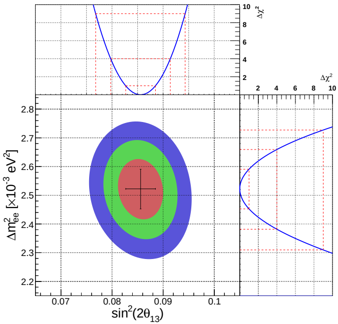
- Dominated by relative Gd capture fraction unc. $< \mathbf{0.10\%}$.
- Relative efficiency uncertainty $< \mathbf{0.13\%}$.

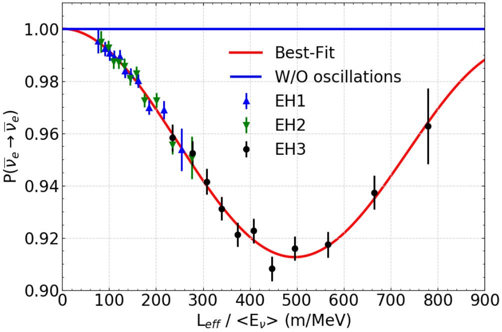
- Relative energy scale $\rightarrow \Delta m^2_{32}$ uncertainty.



- Relative energy scale uncertainty $< \mathbf{0.2\%}$.

Daya Bay oscillation result: 500K/4M events





$\sin^2 2\theta_{13} = 8.56 \pm 0.29$	$\times 10^{-2}$	3.4%	12%	60%
$\lvert\Delta m^2_{ee}\rvert = 2.522^{+0.068}_{-0.070}$	$\times 10^{-3}$ eV^2	2.8%	13%	50%
$\chi^2/\mathrm{NDF} = 148.0/154$		precision	improvement	stat. uncertainty

$$\left|\Delta m^2_{32}\right| = \begin{pmatrix} 2.471\ (\mathrm{NH}) \\ 2.575\ \ (\mathrm{IH}) \end{pmatrix} {}^{+0.068}_{-0.070} \times 10^{-3}\ \mathrm{eV}^2$$

$$P_{\mathrm{dis}} \approx \sin^2 2\theta_{13} \frac{\Delta m^2_{ee} L}{4E}$$

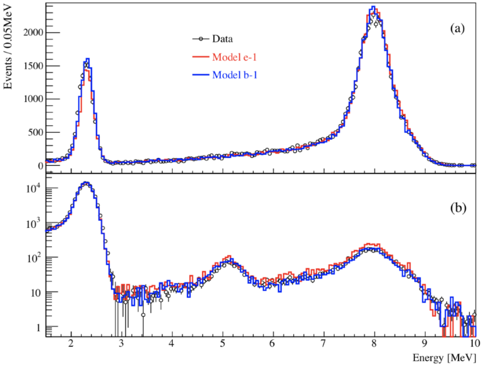
1958 days, arXiv:1809.02261

Absolute reactor antineutrino flux

1230 days, 1808.10836

Updates

- New neutron calibration data: $^{241}\mathrm{Am}$-$^{13}\mathrm{C}$ and $^{241}\mathrm{Am}$-$^{9}\mathrm{Be}$ sources deployed along 3 axes.
- New estimation of neutron related efficiency: $\varepsilon_n = (81.48 \pm 0.60)\%$
- Uncertainty improvement: ε_n: 57%, R(exp): 30%



Reactor antineutrino yield

$$\sigma_f = (5.91 \pm 0.09) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$

ILL+Vogel

$$R = \mathbf{1.001 \pm 0.015} \pm 0.0026$$

(exp) (model)

Huber+Mueller

$$R = \mathbf{0.952 \pm 0.014} \pm 0.023$$

(exp) (model)

Huber+Mueller (global)

$$R = \mathbf{0.945 \pm 0.007} \pm 0.023$$

(exp) (model)

Summary

Current status

- Planned data taking till 2020:
  - achieve $\sin^2 2\theta_{13}$ precision below 3%.
- Near detector EH1 AD1 is taken down permanently:
  - negligible impact on $\sin^2 2\theta_{13}$ precision ($< 0.05\%$).
  - GdLS is replaced by LS for JUNO studies.

Prospects

- Use improvements on energy nonlinearity from FADC for reactor shape measurement.
- Prospects on combined analysis with PROSPECT experiment (reactor spectrum and sterile).
- Studies to be updated:
  - $\sin^2 2\theta_{13}$ and Δm^2_{32} measurement on nH.
  - Reactor antineutrino spectrum shape measurement.
  - Sterile neutrino search.
  - Fuel evolution measurement.

- New oscillation result:

$$\sin^2 2\theta_{13} = 8.56 \pm 0.29 \times 10^{-2}$$

$$|\Delta m^2_{ee}| = 2.522^{+0.068}_{-0.070} \times 10^{-3}\ \mathrm{eV}^2$$

- New reactor flux measurement:

$$R = \mathbf{0.952 \pm 0.014}_{(exp)} \pm 0.023_{(model)}$$

Recent publications:

1603.03549	**PRD**	$\overline{\nu}_e$	osc. pars. (nH)
1607.01174	**PRL**	$\overline{\nu}_s$	
1607.01177	**PRL**	$\overline{\nu}_s$	DB+MINOS
1607.05378	**CPC**	$\overline{\nu}_e$	flux+spectrum
1608.01661	**EPJC**	$\overline{\nu}_e$	(de)coherence
1704.01082	**PRL**	$\overline{\nu}_e$	reactor evolution
1708.01265	**JCAP**	μ	seasonal variation
1711.00588	**PRD**	n	production

New publications:

1808.10836	$\overline{\nu}_e$	reactor flux
1809.02261	$\overline{\nu}_e$	osc. pars. (nGd)
1809.04660	$\overline{\nu}_e$	time variation

Thank you for your attention!

Спасибо!

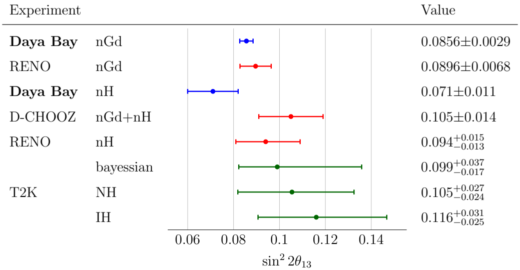
Backup slides...

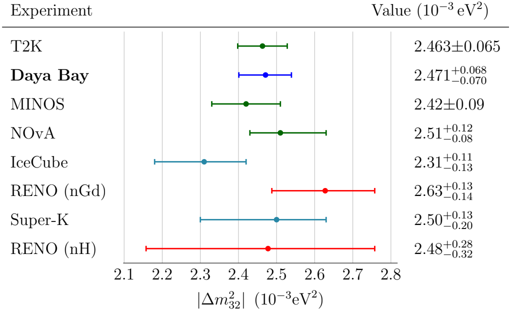
Daya Bay oscillation result

nH, 621 days, arXiv:1603.03549, PRD

nGd, 1958 days, arXiv:1809.02261

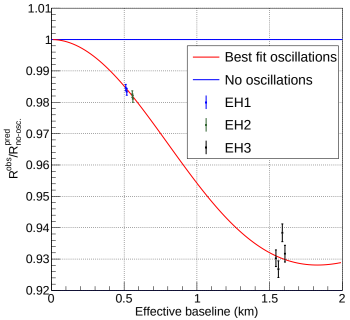
- Most precise $\sin^2 2\theta_{13}$ measurement.
- $\sin^2 2\theta_{13} = 0$ is excluded at almost 30σ.
- nH $\sin^2 2\theta_{13}$ measurement is world's third in precision.
- Second world's measurement of Δm^2_{32}.
- Δm^2_{32} is consistent with and complementary to accelerator measurements.
- Negligible correlation between $\sin^2 2\theta_{13}$ and Δm^2_{ee}.

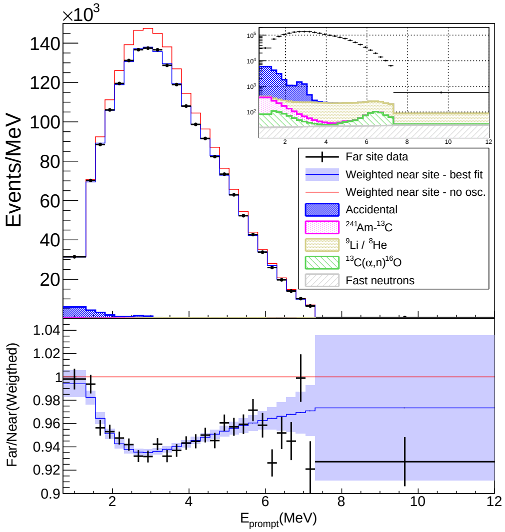




Far vs. near comparison: 500K/4M events

1958 days, arXiv:1809.02261



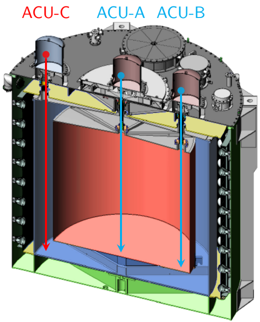


The observed
event rate deficit
and
relative spectrum distortion
are highly consistent with oscillation interpretation.

Energy response calibration

Automated calibration units (ACU)

- Three automated calibration units installed.
  Each equipped with: $^{60}\mathrm{Co}$, $^{68}\mathrm{Ge}$, $^{241}\mathrm{Am}$-$^{13}\mathrm{C}$, LED.
- Weekly energy scale calibration with $^{60}\mathrm{Co}$.
- Continuous energy scale calibration spallation neutrons.
- $\sim$ 160 p.e./MeV.



Energy response nonlinearity

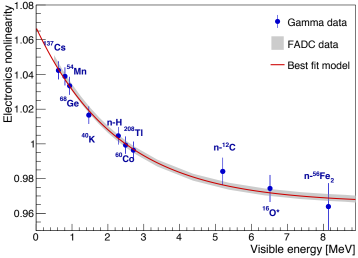
- LS nonlinearity: quenching and Cherenkov light contribution
- Electronics nonlinearity.
- ✗ Difficult to disentangle.

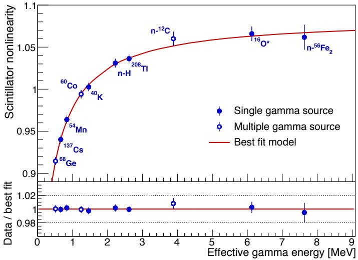
Updates

- ✓ Simultaneous readout by both ADC and FADC in a EH1-AD1 detector (since 2016)
  $\hookrightarrow$ measurement of electronics nonlinearity.
- ✓ Deployment of $^{60}\mathrm{Co}$ calibration sources with different coating material (early 2017)
  $\hookrightarrow$ measurement of shadowing effects.
- ✓ MC simulation of energy loss in $^{60}\mathrm{Co}$ coating material.

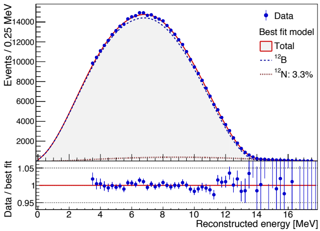
Energy response calibration

✓ Decoupled electronics and scintillator nonlinearity

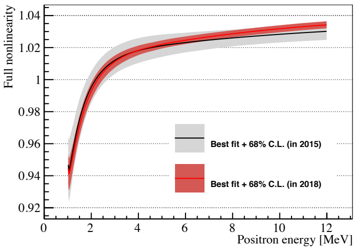




✓ Continuous ^{12}B spectrum

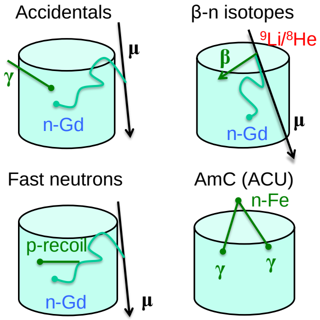


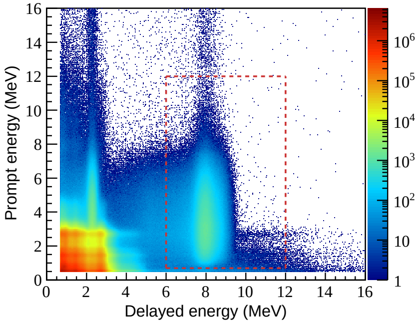
✓ Combined positron energy nonlinearity. (uncertainty 1% → 0.5%)



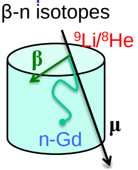
Background events

	Near Halls B/S, %	Far Hall B/S, %	Unc.	Estimation method
Accidentals	1.3	1.6	1%	Calculated based on uncorrelated signals
$^{9}\mathrm{Li}/^{8}\mathrm{He}$	0.3	0.2	30%	Measured with after-muon events
Fast neutrons	0.08	0.07	17%	Measured with tagged muon events
$^{241}\mathrm{Am}$-$^{13}\mathrm{C}$	0.03	0.07	45%	MC, benchmarked with single γ and strong $^{241}\mathrm{Am}$-$^{13}\mathrm{C}$ source
$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$	0.01	0.07	50%	Calculated from measured radioactivity



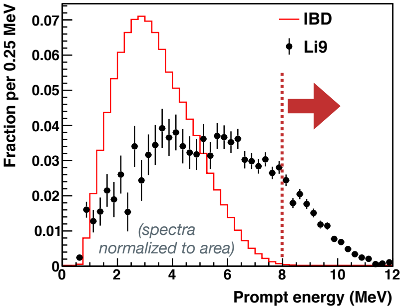


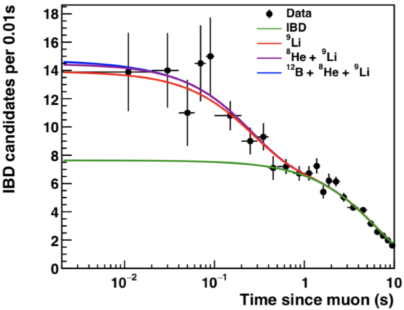
^{9}Li/^{8}He update and more



- New large statistics ^{9}Li/^{8}He rate estimation.
- Step 1: Select high-energy events (negligible contribution of IBDs).
- Step 2: Fit the time-since-last muon distribution.

✓ ^{9}Li/^{8}He rate uncertainty reduced from 50% $\longrightarrow$30%.





SNF update

- SNF rate uncertainty significantly reduced 100% $\longrightarrow$30% (SNF contribution: 0.3%).

Systematics

	Parameters	Uncorr.	Uncertainty	Comment
Free	Oscillation parameters (reactor)	P		
	Oscillation parameters (solar)	P		negligible
Reactor	Thermal power	R	0.5%	
	Fission fractions	RI*	5%	
	Average fission energy	I	0.12% – 0.25%	
	Off-equilibrium correction	RI	30%	
	SNF contribution	R	30%	
	$\overline{\nu}_e$ spectra	IE	2% – 30%	
Detector	**Relative efficiency**	D	**0.13%**	**dominant** (part. correlated)
	Relative energy scale	D	**0.2%**	**dominant** (part. correlated)
	Energy scale non-linearity	P	<1%	
	Energy resolution	P	30%	negligible
	IAV energy distortion	D	4%	
Background	Accidentals rate	D	0.4%	
	$^{9}Li/^{8}He$ rate	S	30%	**secondary**
	^{9}Li contribution to $^{9}Li/^{8}He$		5%	negligible
	Fast neutrons rate	S	10% – 17%	
	^{241}Am-^{13}C rate		40% – 45%	
	$^{13}C(\alpha, n)^{16}O$ rate	D	50%	
	Background spectra shape		no	negligible

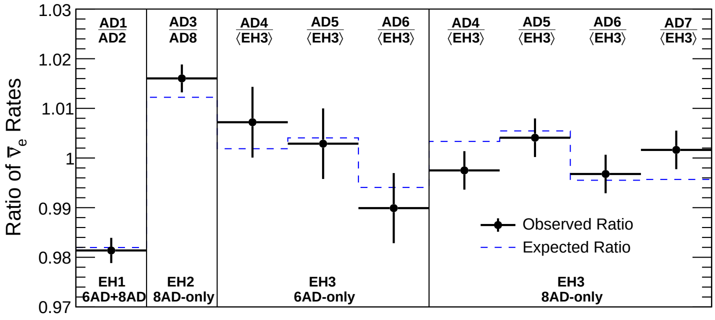
Uncorrelated groups

- **P**arameter
- **R**eactor
- Fissile **I**sotope
- **S**ite
- **D**etector
- **E**nergy bin
- ***** — part. correlation

Side-by-side Comparison

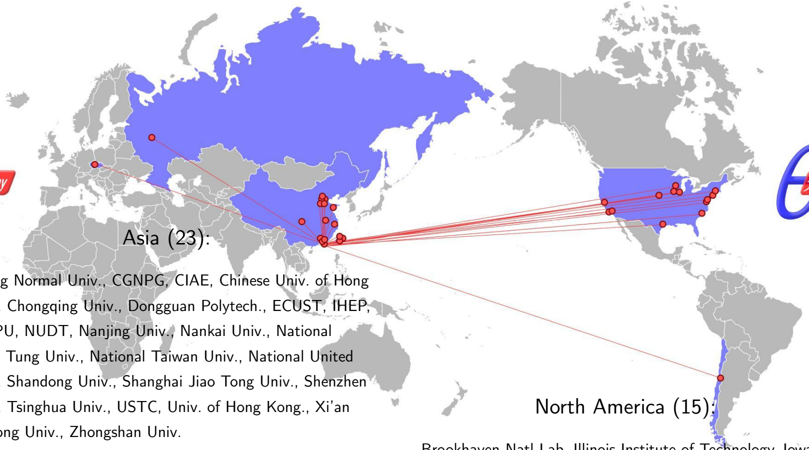
1230 days, arXiv:1610.04802, PRD

- One of the most significant improvements was the reduction of the relative detection efficiency uncertainty from 0.2 % to 0.13 %.
- Side-by-side rates are consistent with expectations:



- $\sin^2 2\theta_{13}$ uncertainty is dominated by statistics and relative detection efficiency uncertainty.

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.

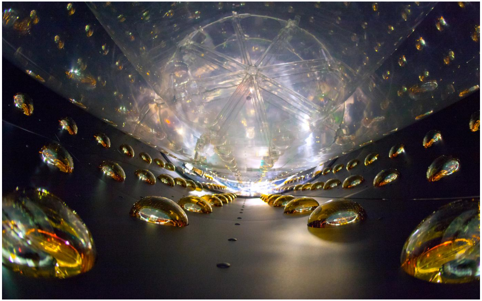
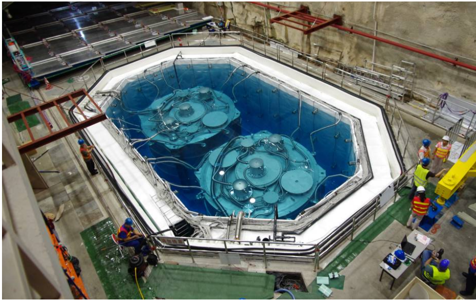
Europe (2) and Sourth America (1):

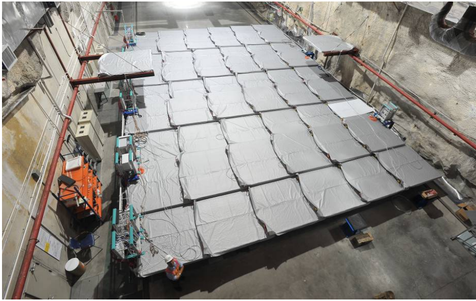
Charles University, **Joint Institute for Nuclear Research**, Catholic Univ. of Chile.

North America (15):

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

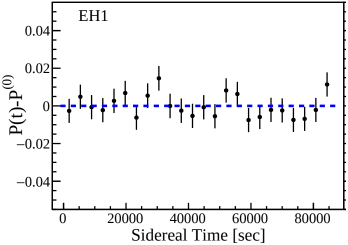
Detector photos

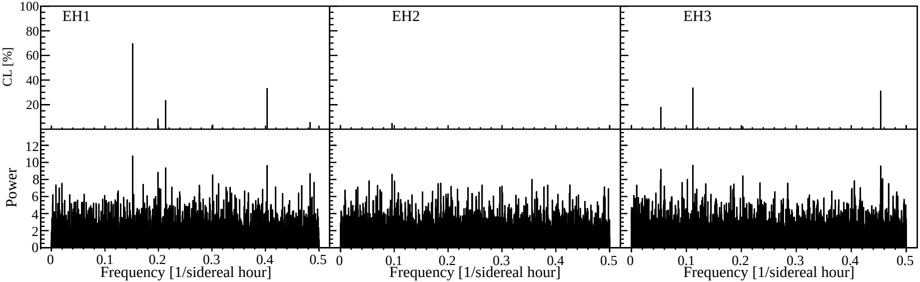
Time-variation of antineutrino signal

704 calendar days, 1809.04660



- Ultra-light DM coupling to neutrino or Lorentz/CPT violation may lead to time variation of $\overline{\nu}_e$ signal.
- Search for any periodicity with Lomb-Scargle (LS) periodogram.
- Performed search for sidereal modulation in context of Standard Model Extension (SME):
  first simultaneous constraint from neutrino experiment.

No Signal!



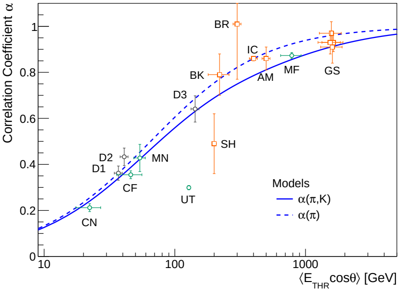
Cosmic ray results

621 days, arXiv:1711.00588, PRD

Muon flux seasonal variation

- ✓ Observe clear correlation between atmosphere temperature and variations of muon flux.
- ✓ Correlation coefficients:

	EH1	EH2	EH3
$\langle E_{\rm thr}\cos\theta\rangle$	37±3	41±3	143±10
α	0.362±0.031	0.433±0.038	0.641±0.057

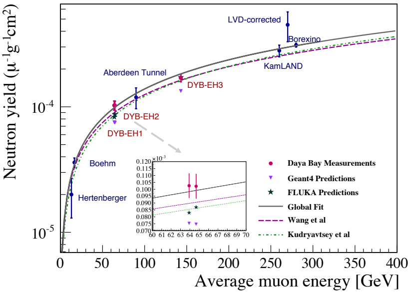


Neutron production

- ✓ Measurement of neutron yield in LS.

	EH1	EH2	EH3	
$\overline{E}_\mu$	63.9±3.8	64.7±3.9	143.0±8.6	GeV
Y_n	10.26±0.86	10.22±0.87	17.03±1.22	

$\times 10^{-5}\ \mu^{-1}\mathrm{g}^{-1}\mathrm{cm}^2$



621 days, arXiv:1708.01265, JCAP

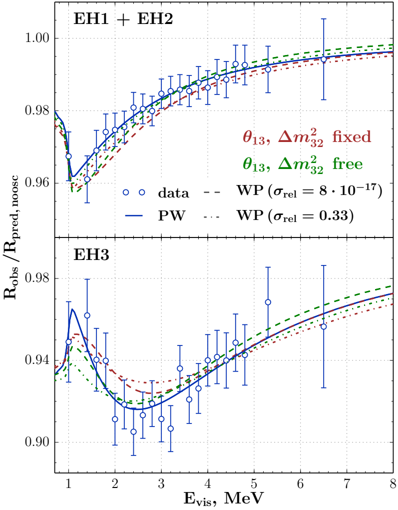
Wave packet effects

621 days, arXiv:1608.01661, EPJC

- 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

621 days, arXiv:1608.01661, EPJC

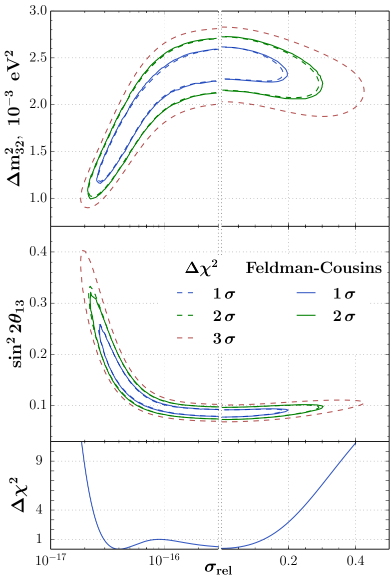
- The obtained limits read

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

- taking into account the reactor/detector sizes:

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

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



Independent nH oscillation analysis

621 days, arXiv:1603.03549, PRD

Key points:

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

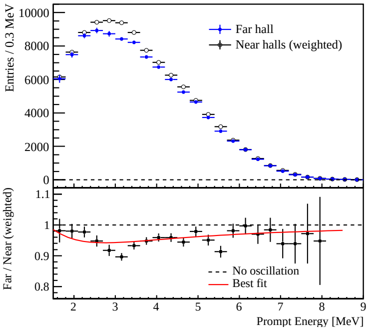
nH

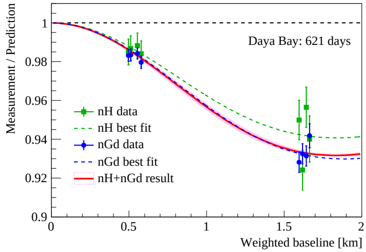
$$\sin^2 2\theta_{13} = \mathbf{0.071} \pm \mathbf{0.011}$$

nH+nGd

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

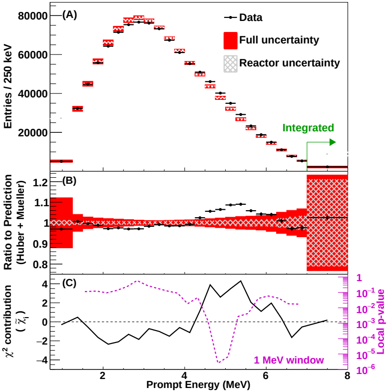
- Observed significant rate deficit.
- Spectral distortion consistent with oscillations.
- Third world precise measurement after Daya Bay (nGd) and RENO (nGd).





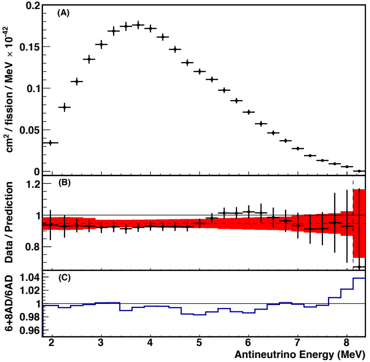
Reactor antineutrino spectrum

Observed positron spectrum



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

Extracted antineutrino spectrum



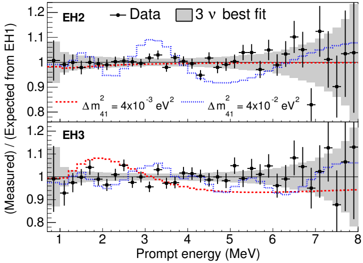
- **Global significance:** **2.9σ.**
- **Local significance:** **4.4σ.**

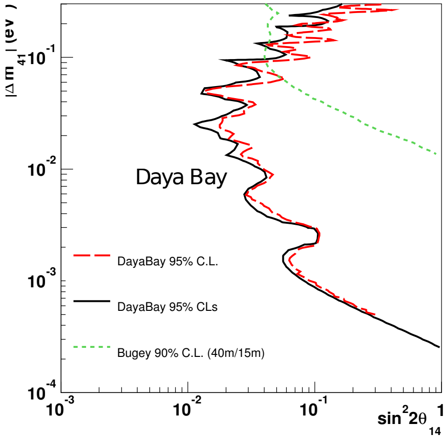
621 days, arXiv:1607.05378, CPC

Light sterile neutrino search

217 days, arXiv:1407.7259, PRL

- Sterile neutrino will cause spectral distortions at the near and far sites.
- Relative measurement independent of reactor related systematics.
- **Result is consistent with 3-flavor oscillations.**

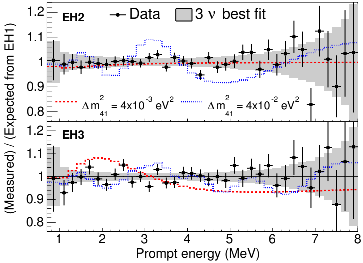


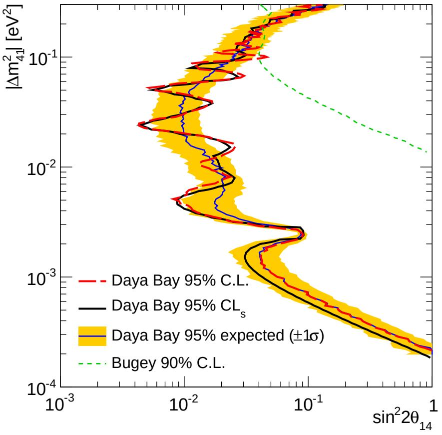


Light sterile neutrino search

621 days, arXiv:1607.01174, PRL

- Sterile neutrino will cause spectral distortions at the near and far sites.
- Relative measurement independent of reactor related systematics.
- **Result is consistent with 3-flavor oscillations.**

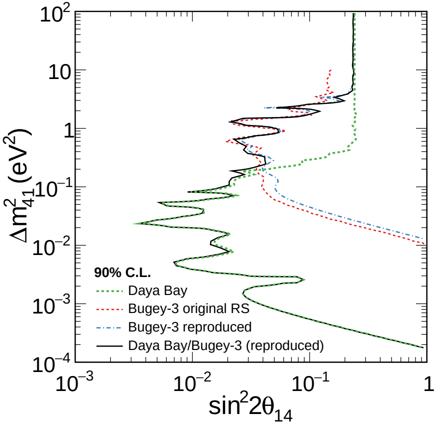




Light sterile neutrino search with Bugey-3 and MINOS

621 days, arXiv:1607.01174, PRL

- 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**.



Light sterile neutrino search with Bugey-3 and MINOS

621 days, arXiv:1607.01174, PRL

+MINOS, arXiv:1607.01177, PRL

- 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**.