Recent results of Daya Bay

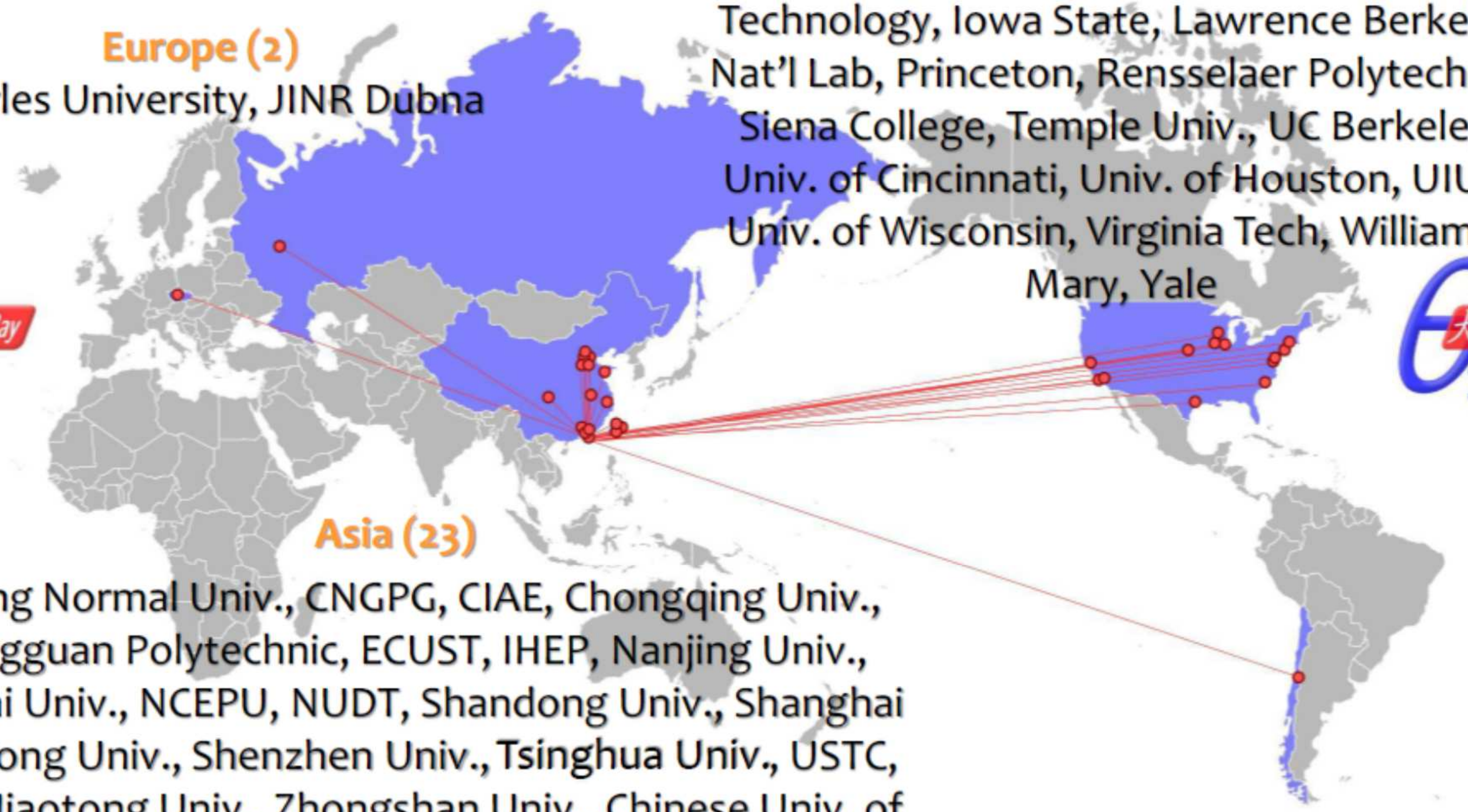
Rupert Leitner, Charles University, Prague

on behalf of the Daya Bay collaboration

1. Daya Bay experiment
2. Results on θ_{13} and Δmee
3. Searches for light sterile neutrinos
4. Precise measurement of reactor neutrino spectra
5. Importance of Daya Bay results
6. Summary

Daya Bay Collaboration

256 collaborators from 42 institutions:



Europe (2)

Charles University, JINR Dubna

North America (16)

Brookhaven Nat'l Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Nat'l Lab, Princeton, Rensselaer Polytechnic, Siena College, Temple Univ., UC Berkeley, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Asia (23)

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

South America (1)

Catholic Univ. of Chile

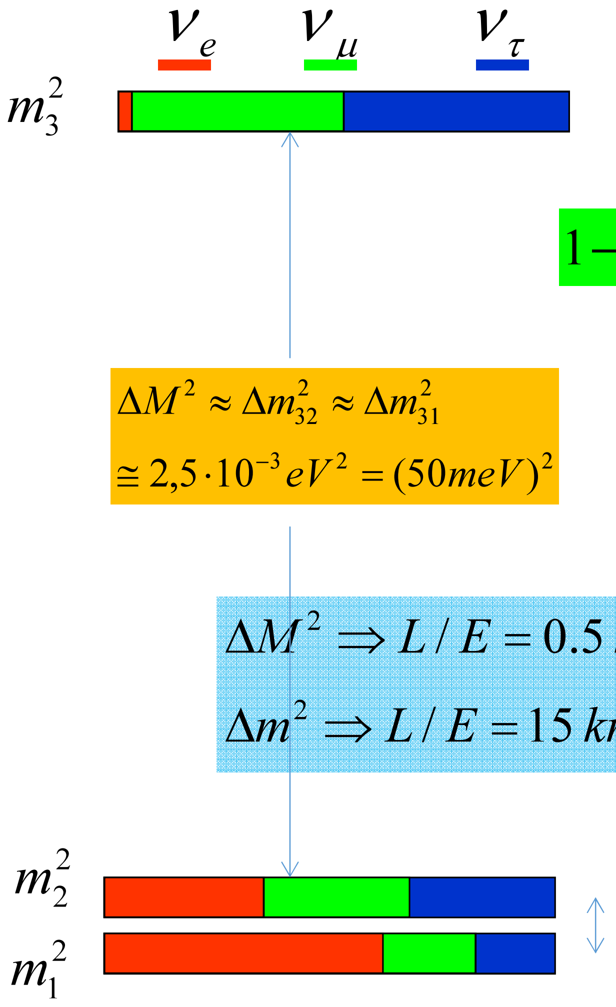
Neutrino mixing - 3 flavors x 3 mass case:

Canonical representation of Pontecorvo-Magi-Nakagawa-Sakata mixing matrix is done by ordered product of 12, 13 and 23 rotations, one Dirac CP violating phase δ connected to the smallest mixing angle θ_{13} and two Majorana phases $\alpha_{1,2}$:

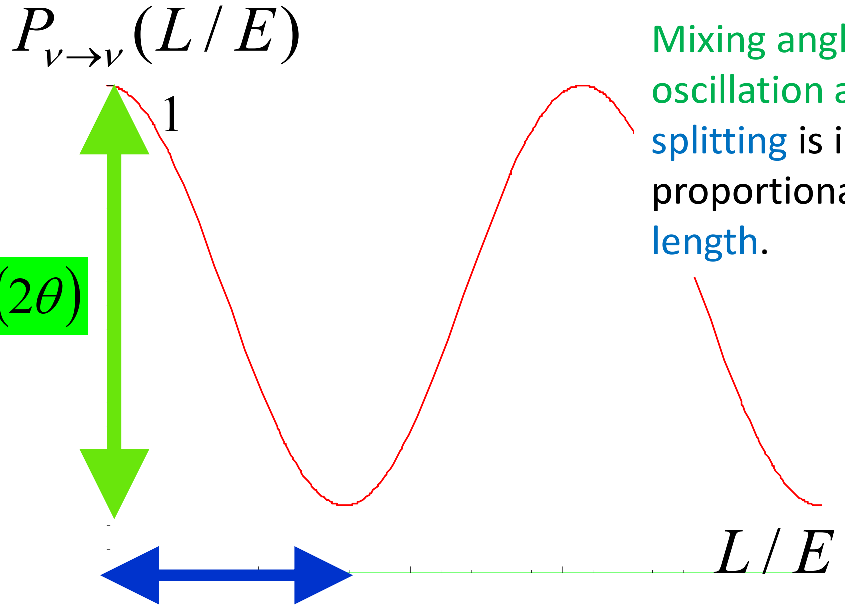
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \cdot \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13}) \cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13}) \cdot e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \cdot$$

$$\begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Majorana phases α are irrelevant for oscillations.



$$\Delta M^2 \approx \Delta m_{32}^2 \approx \Delta m_{31}^2$$
$$\cong 2{,}5 \cdot 10^{-3} eV^2 = (50 meV)^2$$



$1 - \sin^2(2\theta)$

Mixing angles determines the oscillation amplitude, mass splitting is inversely proportional to the oscillation length.

$\Delta M^2 \Rightarrow L/E = 0.5\, km/MeV = 500\, km/GeV$ **Atmospheric, Accelerator, Reactor**

$\Delta m^2 \Rightarrow L/E = 15\, km/MeV = 15000\, km/GeV$ **Sun, Reactor**

$$\Delta m^2 \approx \Delta m_{21}^2 \cong 7.5 \cdot 10^{-5} eV^2 \approx (8.7\, meV)^2$$

Only reactor neutrino experiments can measure oscillations governed by both large and small mass splitting.

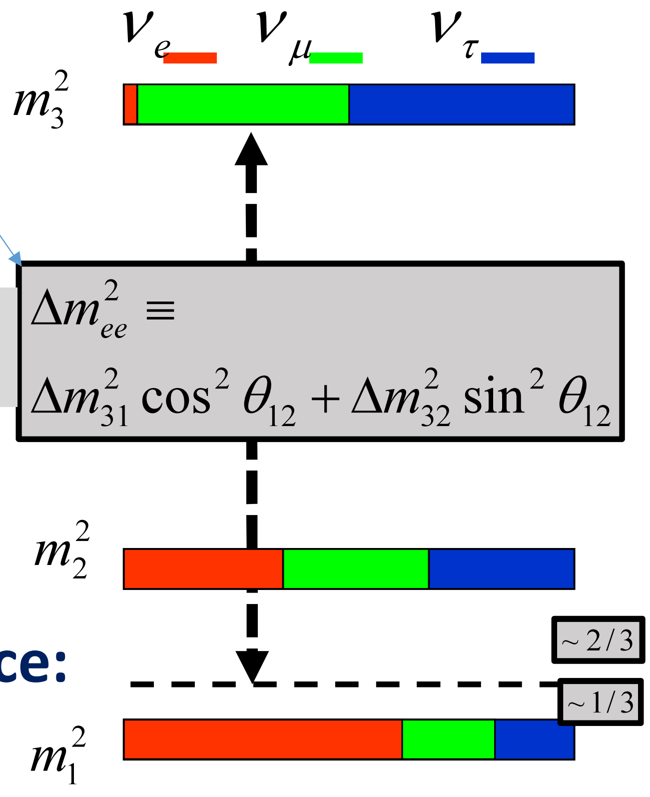
Electron (anti)neutrino disappearance does not depend on CP violating phase δ, nor mixing angle θ_{23} , matter effect is negligible:

$$P^{3x3}_{\bar{\nu}e\to\bar{\nu}e} = 1-\cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4\hbar c}\frac{L}{E}\right)-\sin^2(2\theta_{13})\left(\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}}{4\hbar c}\frac{L}{E}\right)+\sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}}{4\hbar c}\frac{L}{E}\right)\right)$$

$$\cong 1-\boxed{\cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4\hbar c}\frac{L}{E}\right)}-\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee}}{4\hbar c}\frac{L}{E}\right)$$

Sub-percent contribution at the first local minimum.

Only one unknown parameter

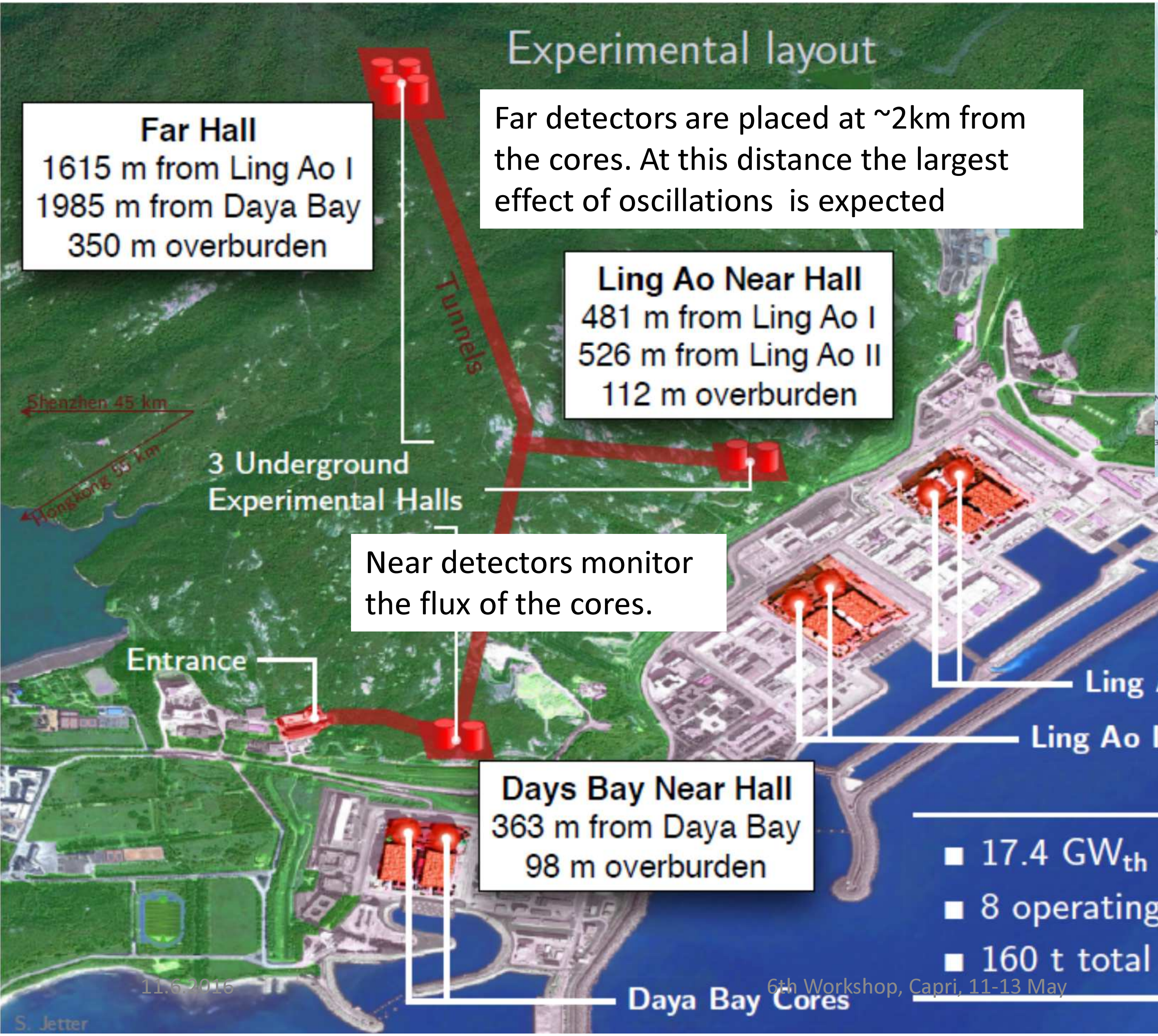


Daya Bay can also measure the effective mass splitting

$$\Delta m^2_{ee} \equiv \Delta m^2_{31}\cos^2\theta_{12}+\Delta m^2_{32}\sin^2\theta_{12}$$

Electron (anti)neutrino disappearance experiment at the distance of 2 km is pure measurement of the mixing angle θ_{13}.

There are 3 reactor neutrino experiments at km distance: Daya Bay, Double Chooz in France and RENO in Korea



Experimental layout

Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden

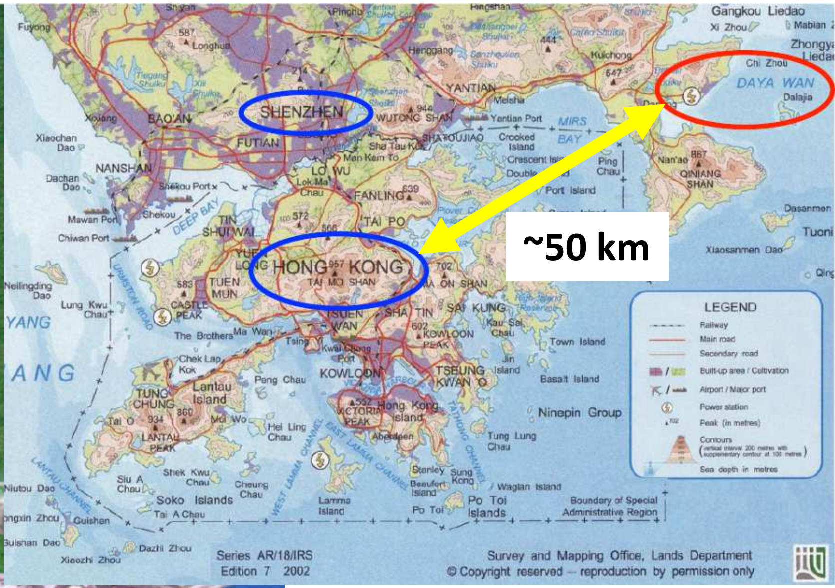
Far detectors are placed at ~2km from the cores. At this distance the largest effect of oscillations is expected

Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden

Near detectors monitor the flux of the cores.

Days Bay Near Hall
363 m from Daya Bay
98 m overburden

- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass



Daya Bay experiment is located in southern China.

Nuclear cores with total thermal power of 17.4 GW emit ~3.5 10^{21} electron antineutrinos per second.

Neutrinos are detected by 8 identical detectors placed in two near halls (2 in EH1, 2 in EH2) and in one far (4 in EH3).

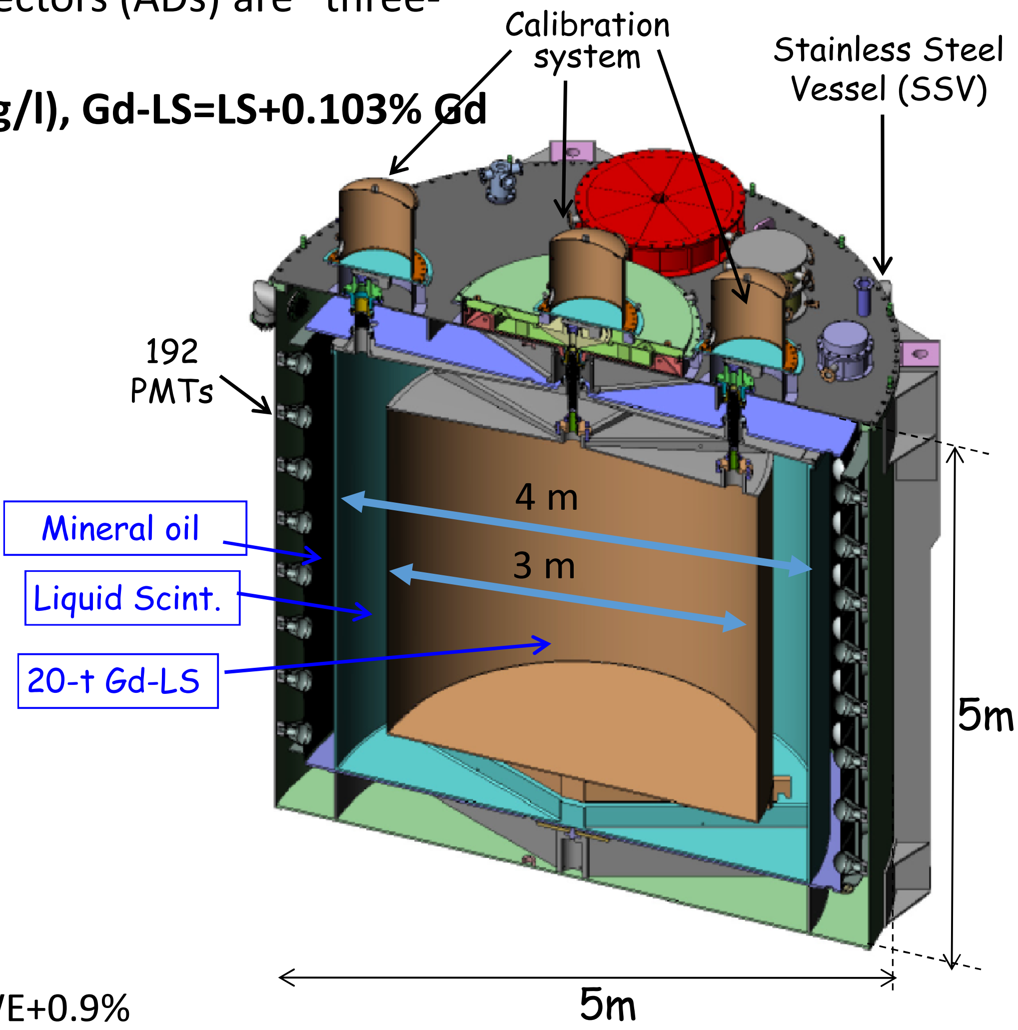
Anti-neutrino detectors

- The Daya Bay anti-neutrino detectors (ADs) are "three-zone" cylindrical modules.
- **LS=LAB+PPO(3 g/l)+MSB(15 mg/l), Gd-LS=LS+0.103% Gd**

   - Zones are separated by acrylic vessels:

Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	**Anti-neutrino target**
Outer acrylic vessel	22 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	43 t	Mineral Oil	Radiation shielding

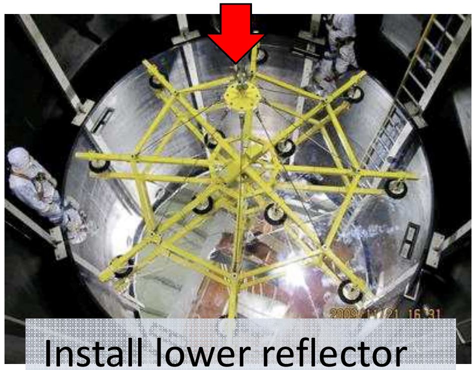
   - Top and bottom reflectors are used to increase light yield
   - Energy resolution: $\sigma_E/E = 7.5\%/\sqrt{E}+0.9\%$



Assembly of Anti-neutrino detectors

ADs are assembled in clean-room

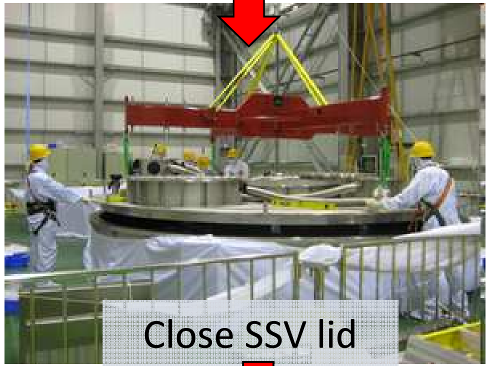

Stainless Steel Vessel (SSV) in assembly pit


Install lower reflector


Install Acrylic Vessels


Install PMT ladders

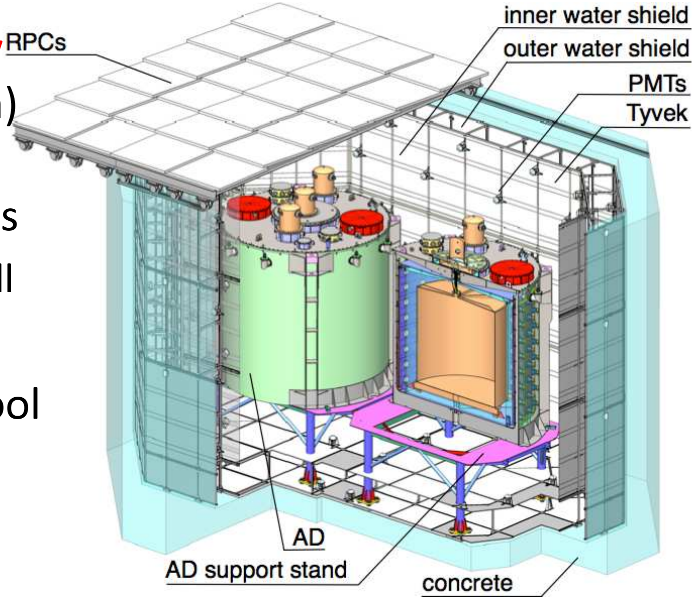

Install top reflector

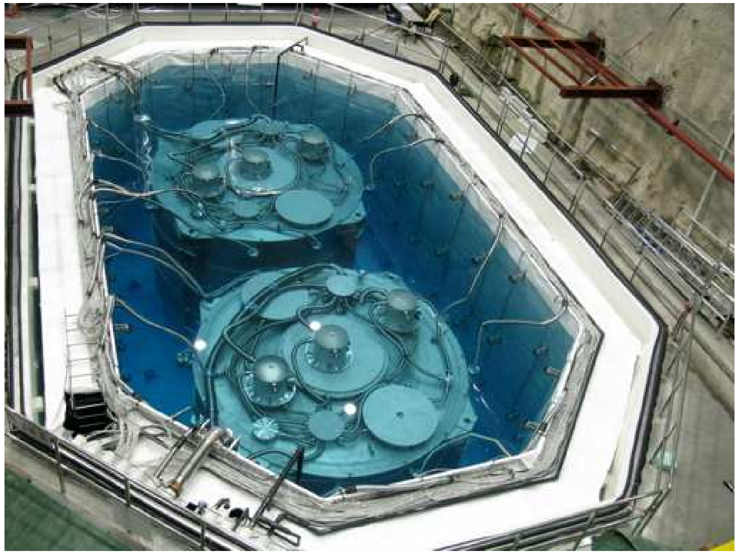

Close SSV lid


Install calibration units

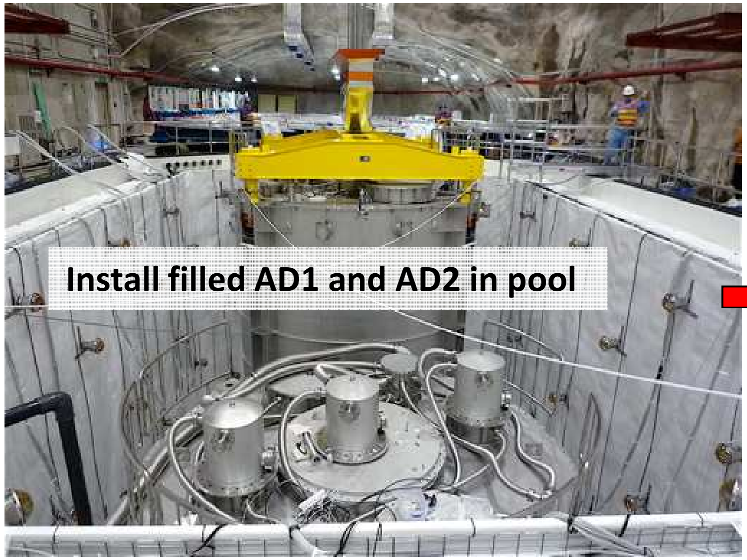
Antineutrino detectors are immersed in instrumented water pools and covered by RPC detectors from the top

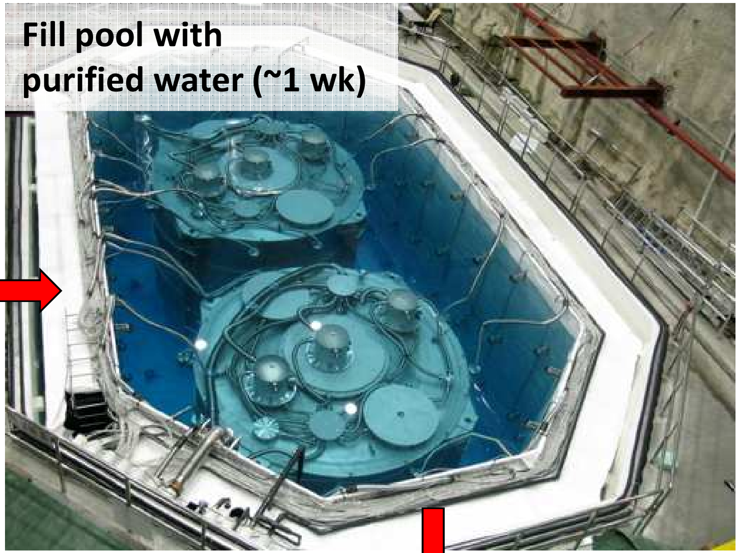
- Outer layer of **water Čerenkov detector** (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer **RPC modules** above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall





Near Hall (EH1) Installation


Install filled AD1 and AD2 in pool


Fill pool with purified water (~1 wk)


Place cover over pool


Data taking started on 15 Aug 2011

Roll RPC over cover

Detection of antineutrinos: Inverse Beta Decay (IBD)

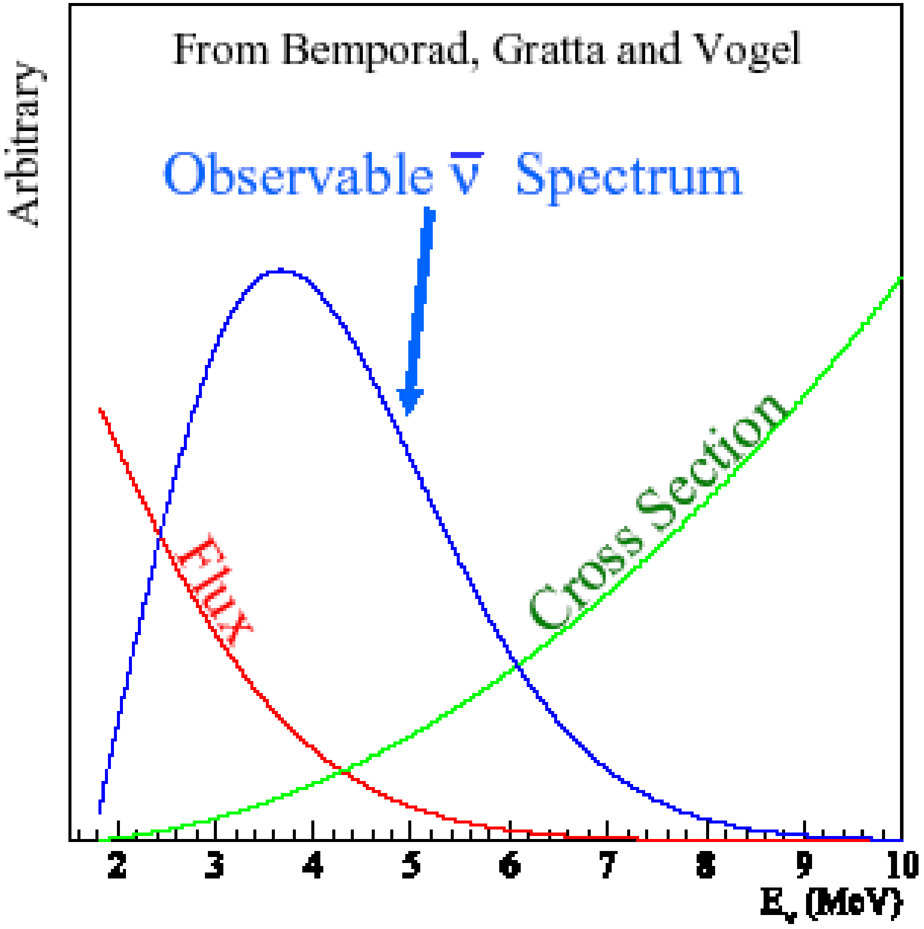
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$E_{\nu,THR} = \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = \frac{m_n + m_p + m_e}{2m_p}(m_n - m_p + m_e)$$

$$\approx m_n - m_p + m_e = 1.83 MeV$$

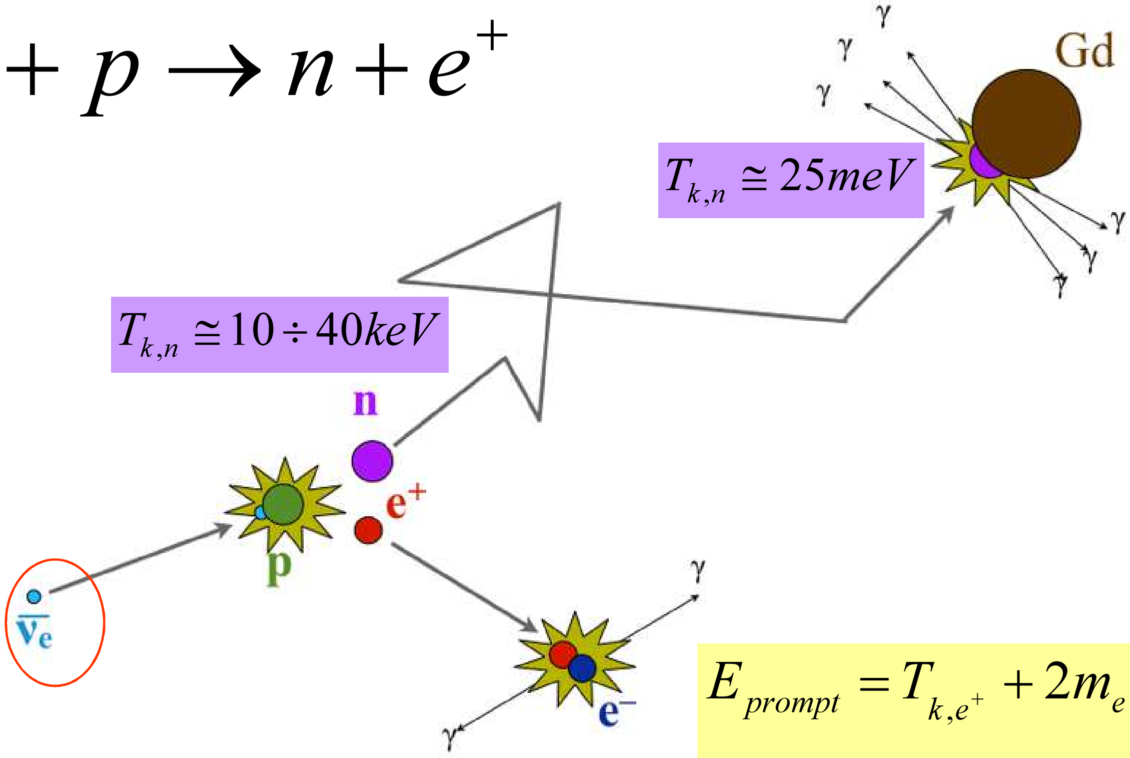
Only antineutrinos with energies larger than 1.8 MeV interact.

Detected energy spectrum is the product of reactor neutrino Flux and IBD cross section and it reaches the maximum around 4 MeV → the first oscillation minimum is at 0.5 km/MeV→2 km for 4MeV



Detection of antineutrinos via Inverse Beta Decay (IBD) is performed by the coincidence of prompt signal from positron and delayed signal of neutron capture on Gd (or H).

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



$$T_{k,n} \cong 25meV$$

$$T_{k,n} \cong 10 \div 40keV$$

Capture on Gd

$$\left\langle \sum E_\gamma \right\rangle = 8.05MeV$$

$$0.1\%Gd \Rightarrow \left\langle \tau_{capture} \right\rangle \cong 29\mu s$$

Capture on H

$$nH \rightarrow D + \gamma\left(E_\gamma = 2.2MeV\right)$$

$$\tau^H_{capture} = 200\mu s$$

$$E_{prompt} = T_{k,e^+} + 2m_e$$

$$E_\nu \cong E_{prompt} + 0.8MeV$$

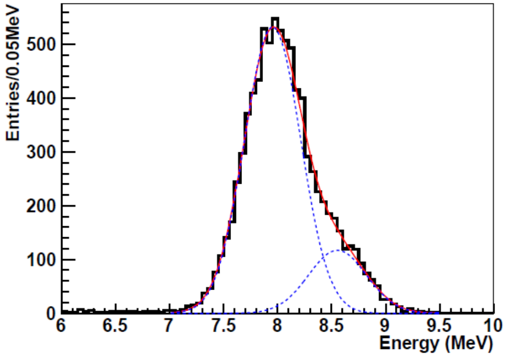
Neutron capture on Gadollinium

$$n+{}^{A}_{64}Gd\rightarrow{}^{A+1}_{64}Gd^{*}\rightarrow{}^{A+1}_{64}Gd+E_{\gamma}$$

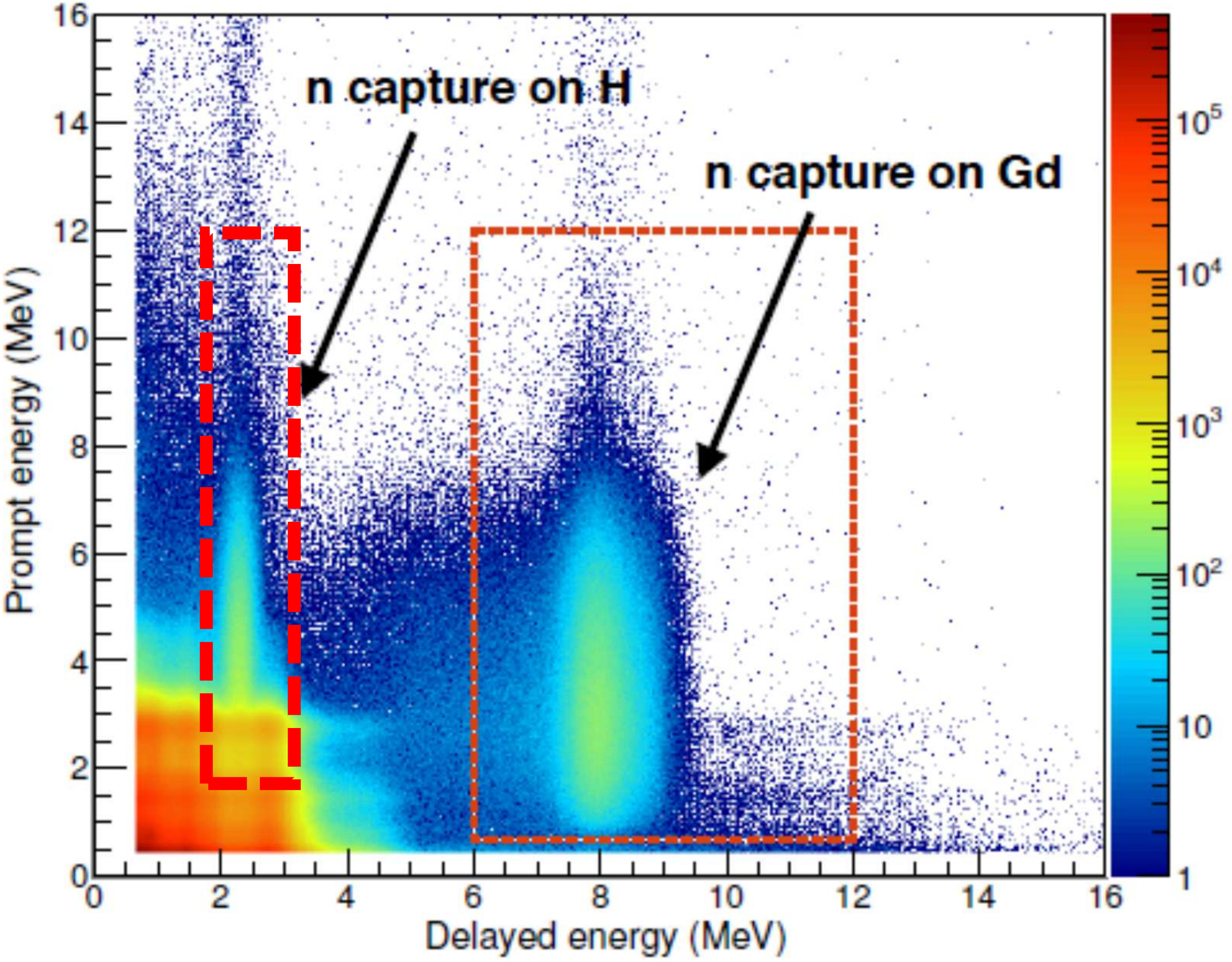
${}^{A}_{64}\mathrm{Gd}$	$\sigma_{n+{}^{A}_{64}Gd\rightarrow{}^{A+1}_{64}Gd^{*}}$ [b]	Abund.[%]	B[MeV/A]
$A=152\ \left(\xrightarrow{\alpha}{}^{148}_{62}Sm\right)$	735	0.20	8.233399
$A=154$	85	2.18	8.224794
$A=155$	60900	14.80	8.213248
$A=156$	1.8	20.47	8.215320
$A=157$	254000	15.65	8.203501
$A=158$	2.2	24.84	8.201817
$A=160\ \left(\xrightarrow{2\beta}{}^{160}_{66}Dy\right)$	1.4	21.86	8.183010

$$\sum E_{\gamma}\left(n+{}^{155}_{64}Gd\right)=8.536\,MeV$$

$$\sum E_{\gamma}\left(n+{}^{157}_{64}Gd\right)=7.937\,MeV$$

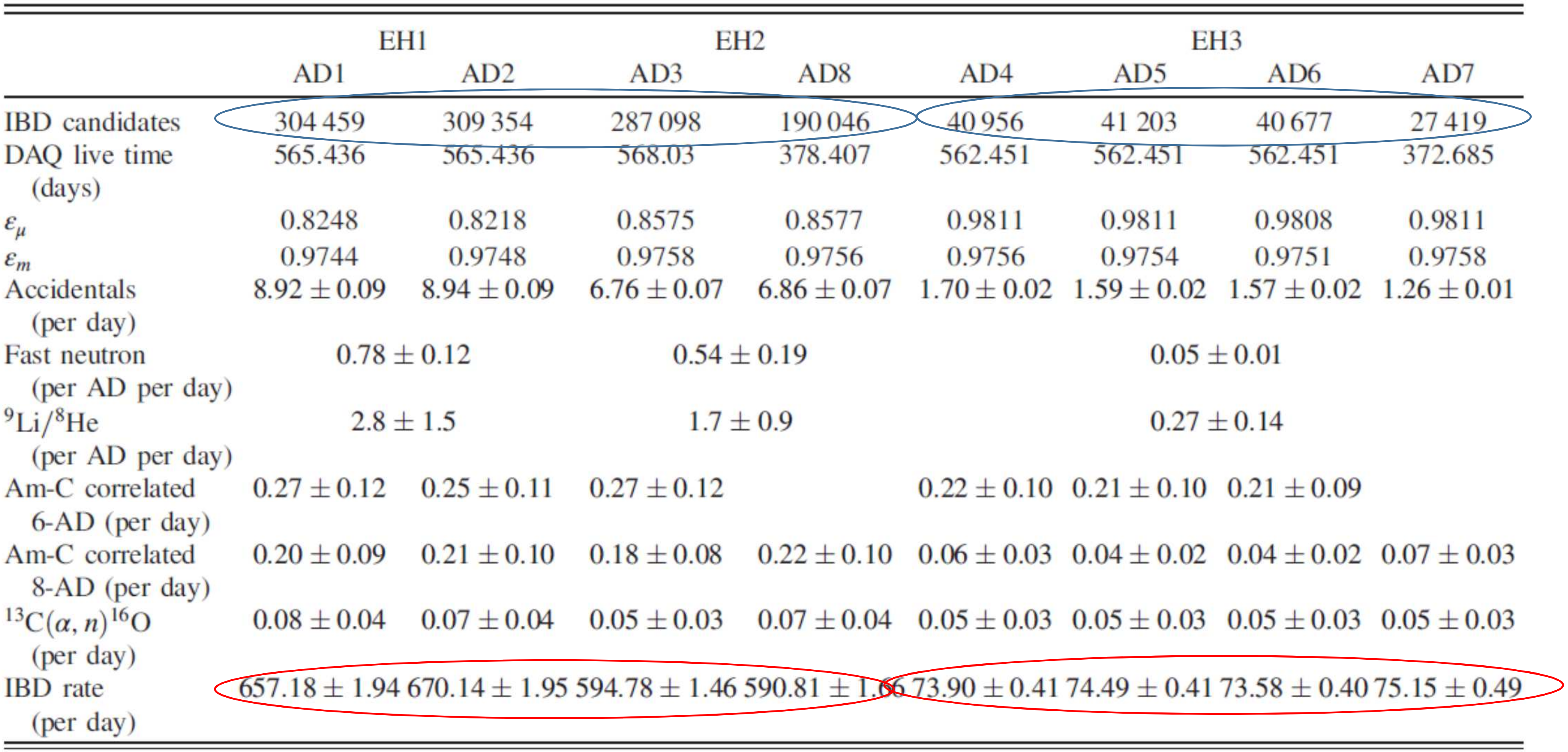


Prompt .vs. Delayed Signal



In presented nGd analysis more than 1 milion inverse beta decays have been detected in near halls

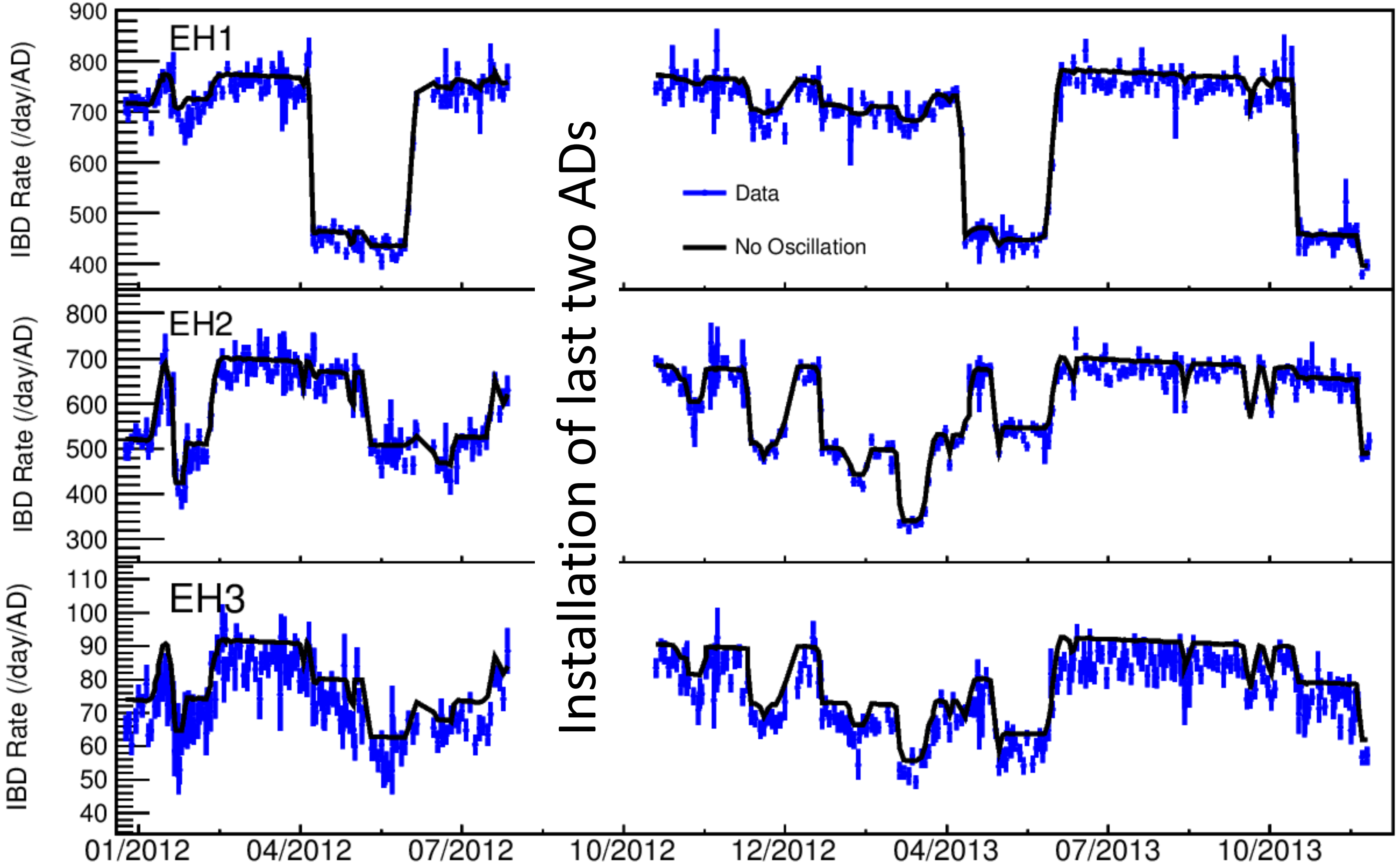
and more than 150 thousands inverse beta decays have been detected in far hall



	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	304 459	309 354	287 098	190 046	40 956	41 203	40 677	27 419
DAQ live time (days)	565.436	565.436	568.03	378.407	562.451	562.451	562.451	372.685
ε_μ	0.8248	0.8218	0.8575	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9744	0.9748	0.9758	0.9756	0.9756	0.9754	0.9751	0.9758
Accidentals (per day)	8.92 ± 0.09	8.94 ± 0.09	6.76 ± 0.07	6.86 ± 0.07	1.70 ± 0.02	1.59 ± 0.02	1.57 ± 0.02	1.26 ± 0.01
Fast neutron (per AD per day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
^{9}Li/^{8}He (per AD per day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
Am-C correlated 6-AD (per day)	0.27 ± 0.12	0.25 ± 0.11	0.27 ± 0.12		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.09	
Am-C correlated 8-AD (per day)	0.20 ± 0.09	0.21 ± 0.10	0.18 ± 0.08	0.22 ± 0.10	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.07 ± 0.03
$^{13}C(\alpha, n)^{16}O$ (per day)	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
IBD rate (per day)	657.18 ± 1.94	670.14 ± 1.95	594.78 ± 1.46	590.81 ± 1.66	73.90 ± 0.41	74.49 ± 0.41	73.58 ± 0.40	75.15 ± 0.49

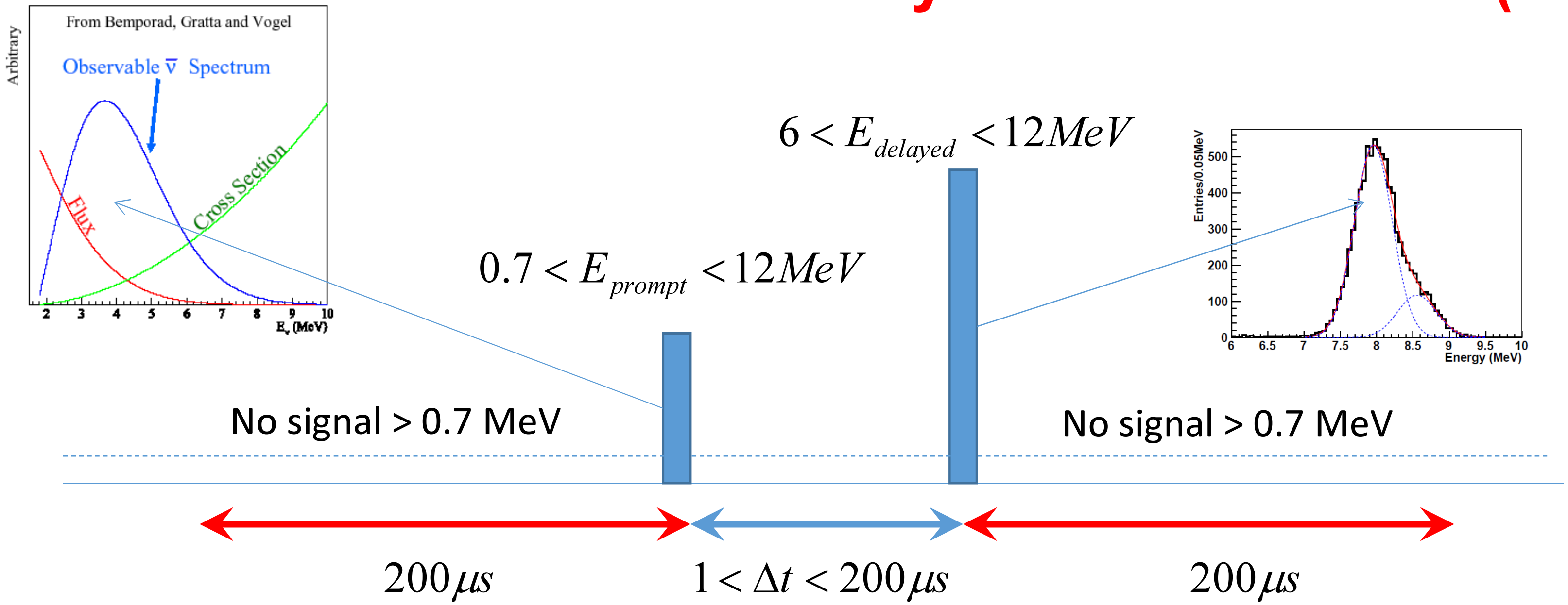
Daily rate is ~2500 IBD events in near halls and ~300 IBD events in far hall.

IBD event rates follow reactor powers.



Due to oscillations **measured rates** in the FAR hall (EH3) are lower than **expected**.

Inverse Beta Decay Events Selection (nGd)



$6 < E_{delayed} < 12 MeV$

$0.7 < E_{prompt} < 12 MeV$

No signal > 0.7 MeV

No signal > 0.7 MeV

$200 \mu s$ $1 < \Delta t < 200 \mu s$ $200 \mu s$

Prompt-delayed coincidence:

- Prompt positron: 0.7 MeV < E_p < 12 MeV Delayed neutron: 6.0 MeV < E_d < 12 MeV
- Capture Time: 1 μs < Δt< 200 μs

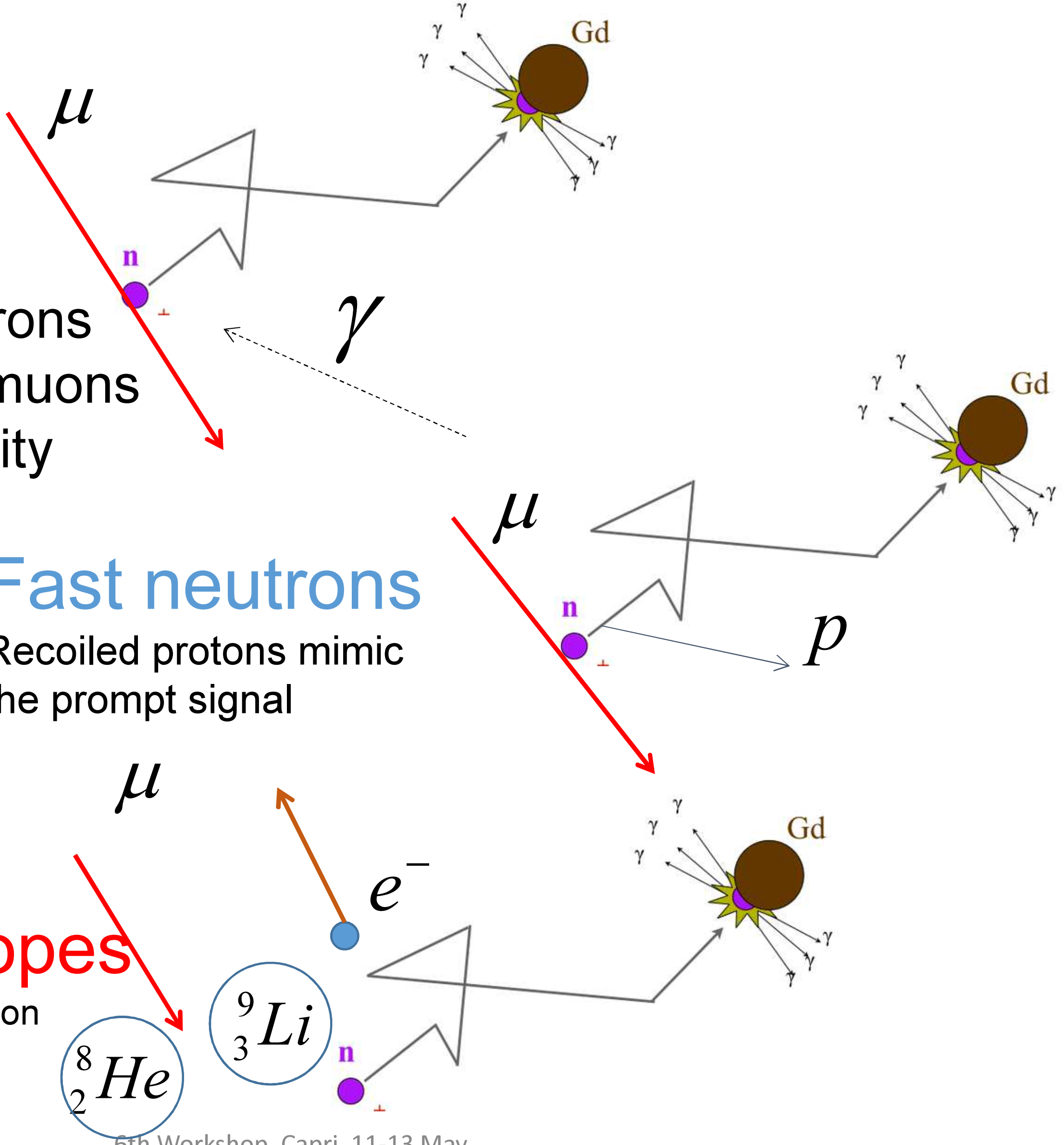
Multiplicity:

- No signal 200 μs around IBD

Muon Veto:

Pool muon (muon detected in water pool): veto following 0.6 ms
Muon signal (> 20 MeV) detected in AD: veto following 1 ms
High energy muon signal (AD shower muon >2.5 GeV): veto following 1 s (that is >5 $T_{1/2}$ of ^{9}Li / ^{8}He isotopes)

Backgrounds



-Accidental

coincidencies of neutrons produced by cosmic muons and natural radioactivity

Fast neutrons

Recoiled protons mimic the prompt signal

^{9}Li and ^{8}He isotopes

Beta decays with neutron emission

^{9}Li and ^{8}He isotopes background

These isotopes are products of photonuclear interactions of cosmic muons on C nuclei

$$
{}^{9}_{3}Li \xrightarrow{T_{1/2}=178ms\ 50\%} {}^{8}_{4}Be + \enclose{circle}{e^{-}} + \bar{\nu}_{e} \enclose{circle}{+ n}
$$

$$
{}^{8}_{4}Be \rightarrow \alpha + \alpha
$$

$$
{}^{9}_{3}Li \xrightarrow{T_{1/2}=178ms\ 50\%} {}^{9}_{4}Be + e^{-} + \bar{\nu}_{e}
$$

$$Q = 13.607\ MeV$$

Electron produces prompt signal. Due to lare Q value it spans whole spectrum. Together with released neutron it fully mimic the signature of antineutrino signal.

$$
{}^{8}_{2}He \xrightarrow{T_{1/2}=119ms\ 16\%} {}^{7}_{3}Li + \enclose{circle}{e^{-}} + \bar{\nu}_{e} \enclose{circle}{+ n}
$$

$$Q = 10.651\ MeV$$

$$
{}^{8}_{2}He \xrightarrow{T_{1/2}=119ms\ 84\%} {}^{8}_{3}Li^{*} + e^{-} + \bar{\nu}_{e}
$$

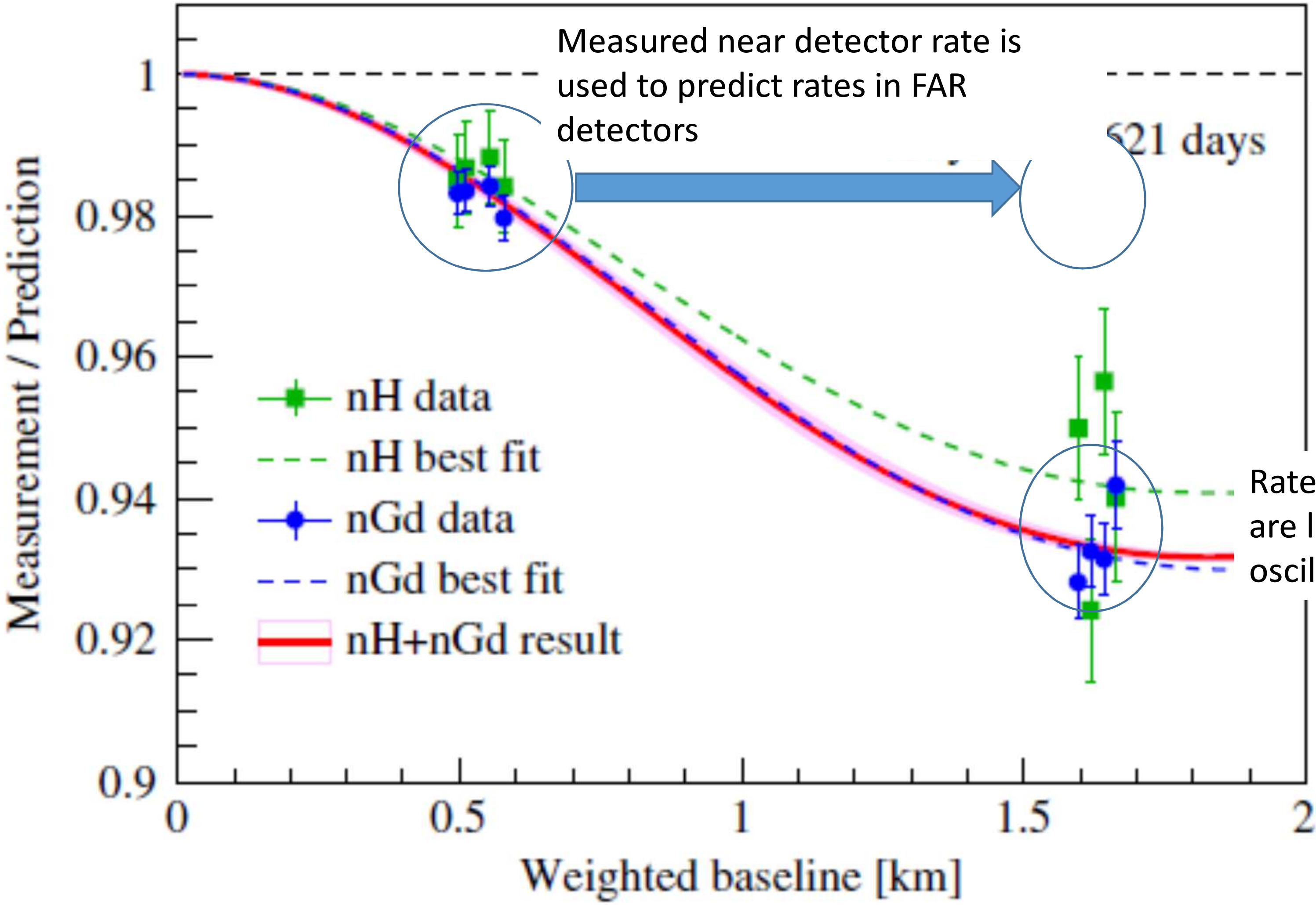
$$
{}^{8}_{3}Li^{*} \rightarrow {}^{8}_{3}Li \ + 0.98 MeV\gamma
$$

$$
{}^{8}_{3}Li \xrightarrow{T_{1/2}=840ms} {}^{8}_{4}Be + e^{-} + \bar{\nu}_{e}
$$

$$
{}^{8}_{4}Be \rightarrow \alpha + \alpha
$$

RATE ANALYSIS

Rate analysis measures only θ13



Measured near detector rate is used to predict rates in FAR detectors

Predicted rate in FAR hall:

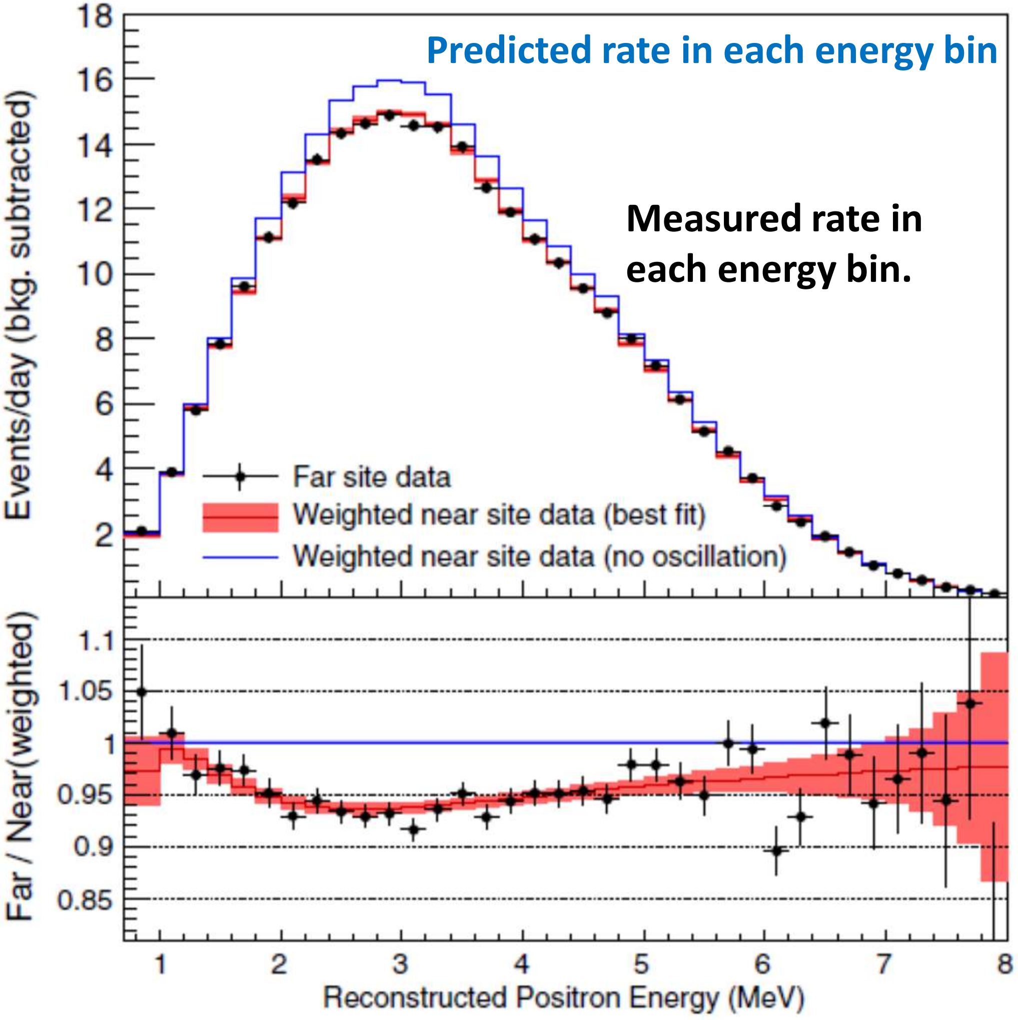
$$\bar{N}_{\mathrm{EH3}} \equiv \alpha N_{\mathrm{EH1}} + \beta N_{\mathrm{EH2}}$$

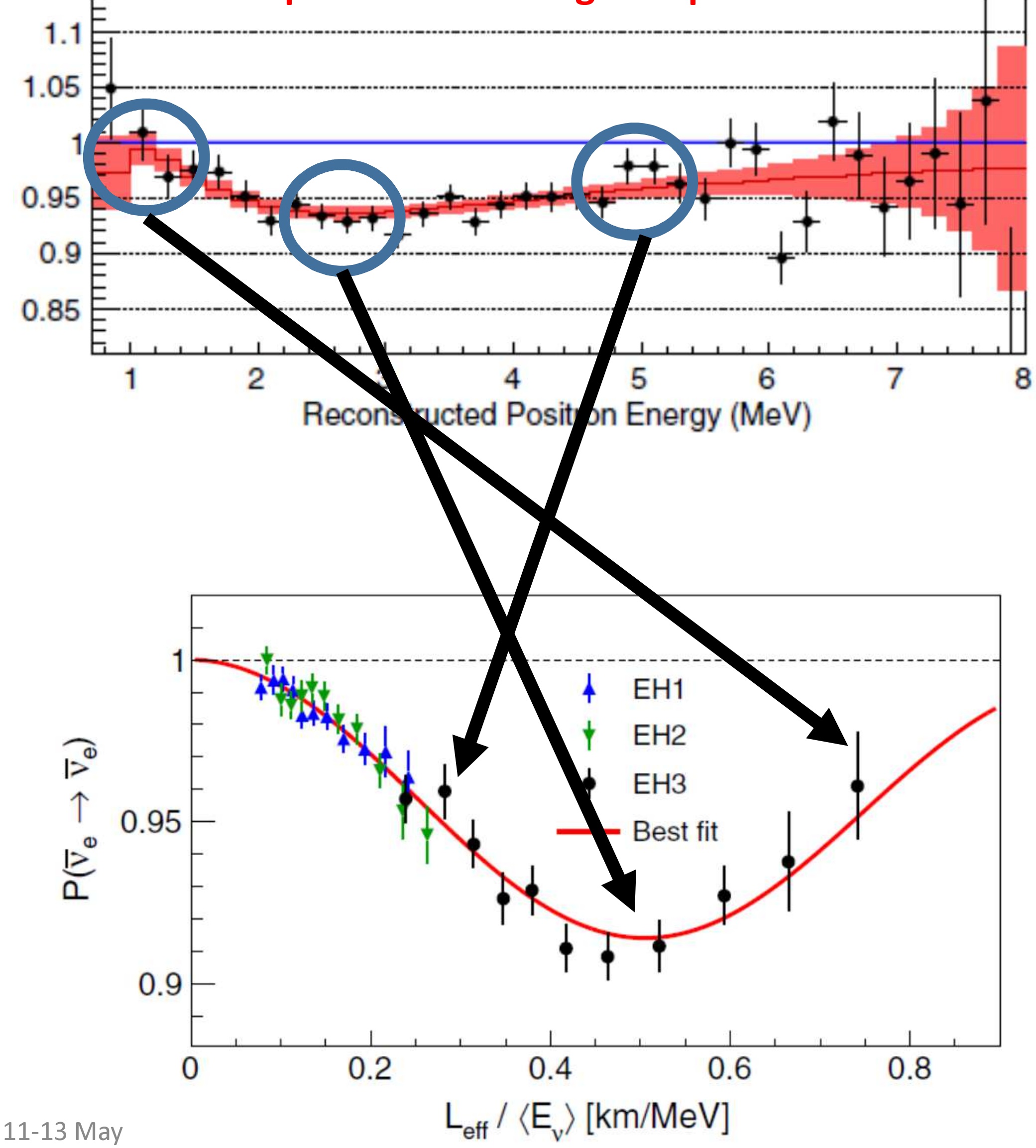
$$R \equiv \frac{N_{\mathrm{EH3}}}{\bar{N}_{\mathrm{EH3}}}$$

Rates measured in FAR detectors are lower than predicted due to oscillations

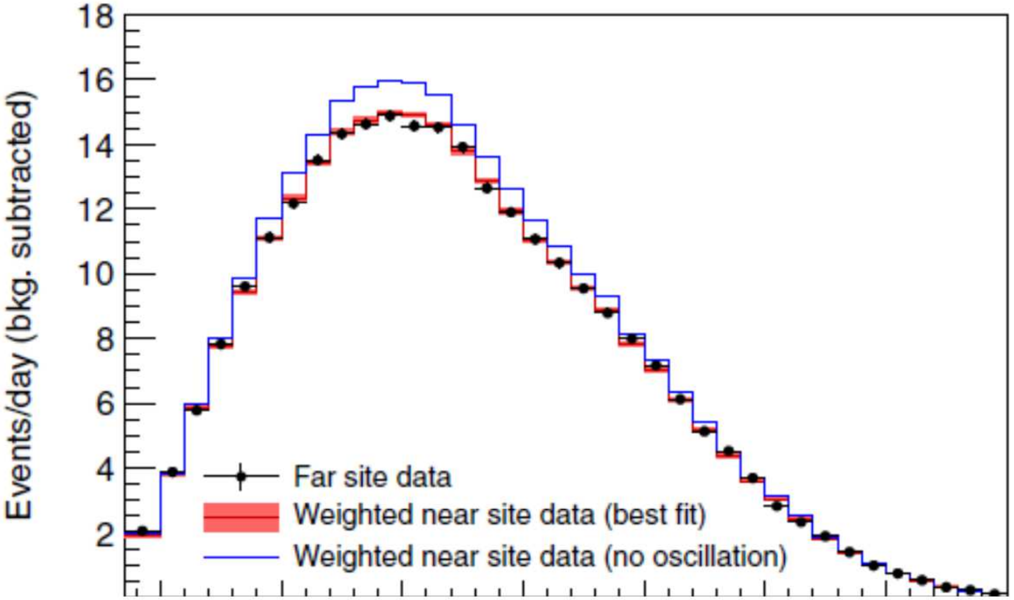
SPECTRAL ANALYSIS

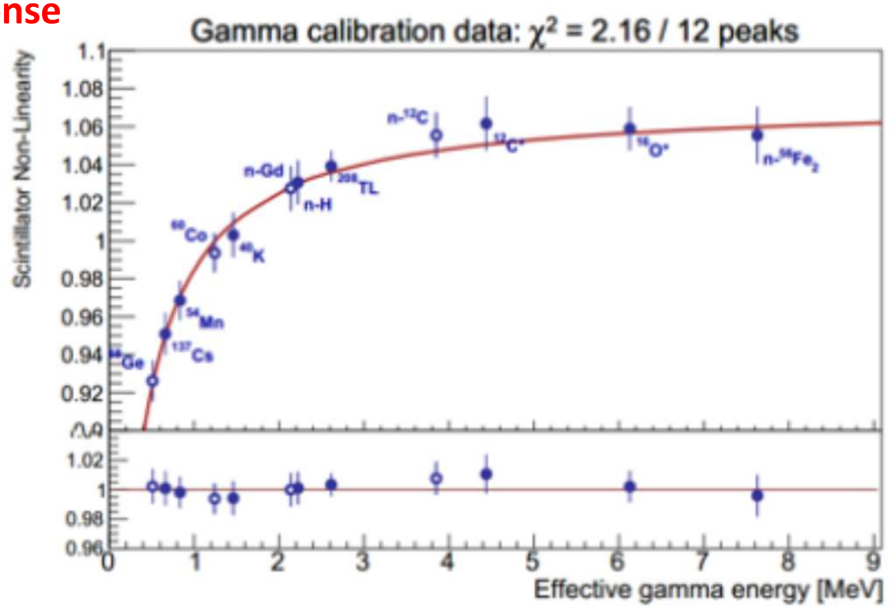
Spectral analysis measures θ13 and Δm_{ee}^2 and **provides unambiguous proof of oscillations**

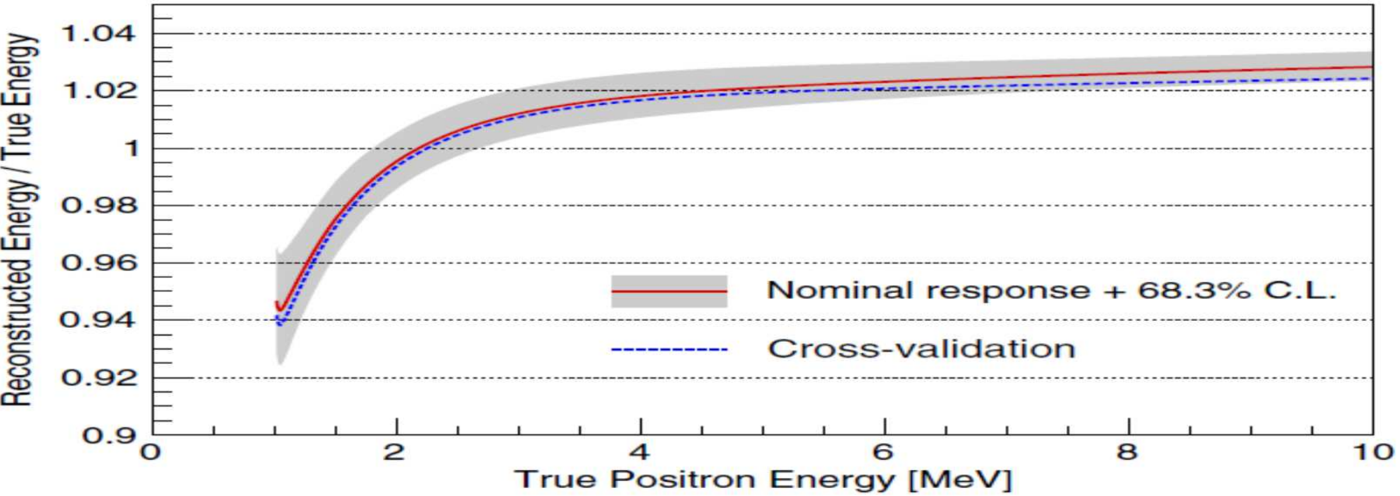


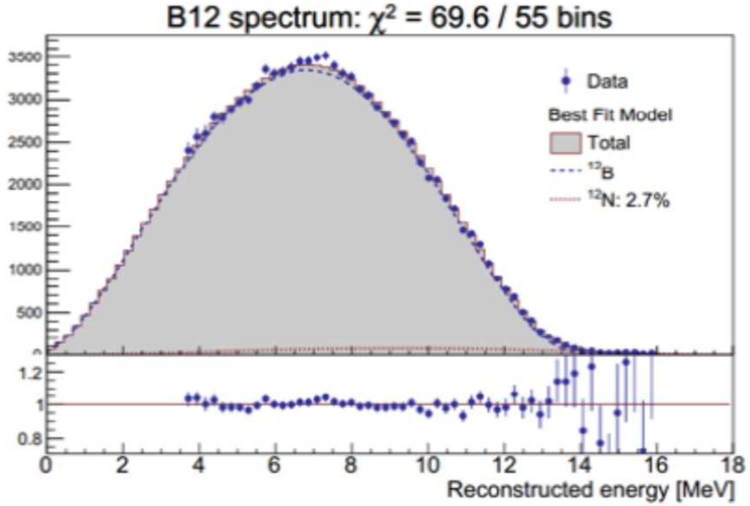


Spectral analysis requires detailed knowledge of detecor energy response



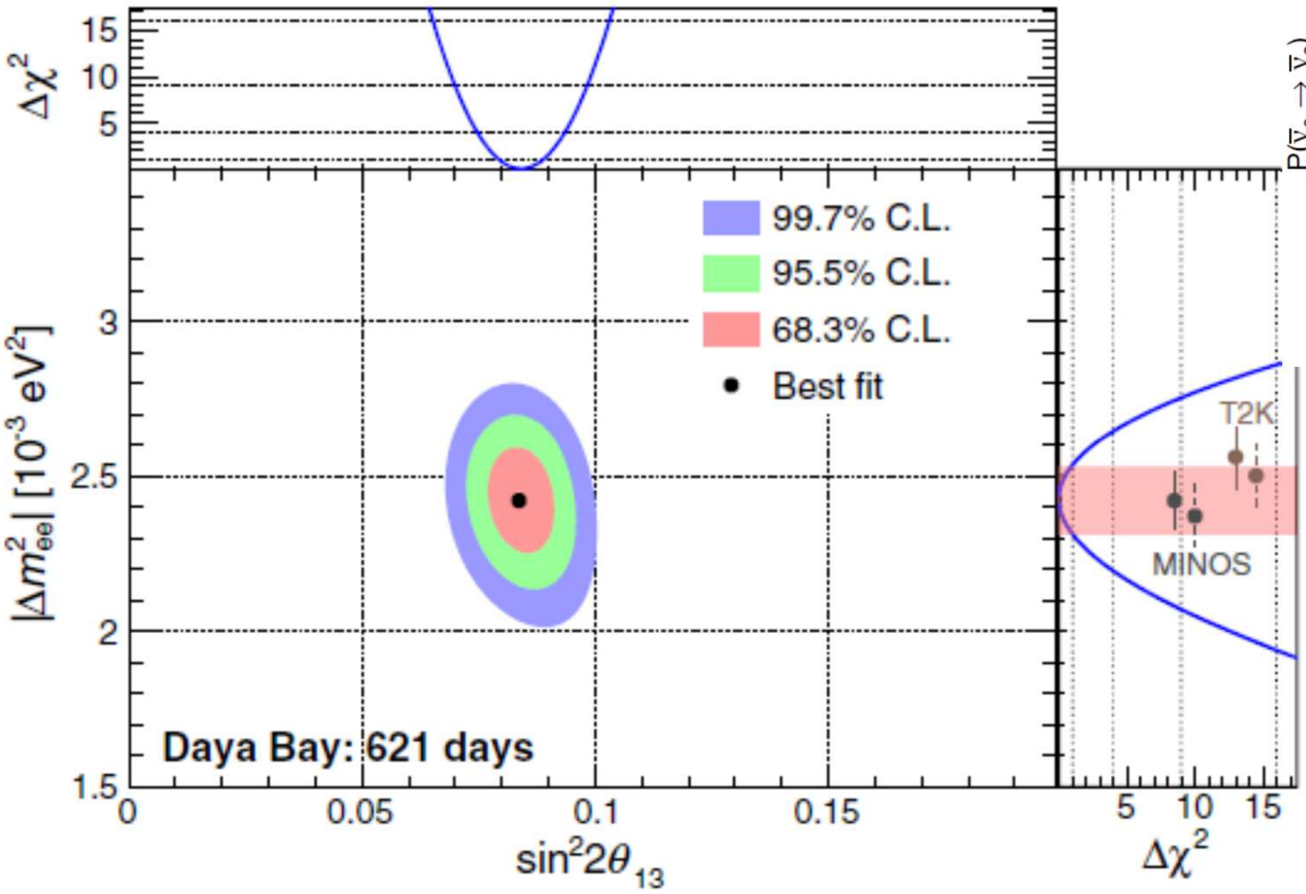


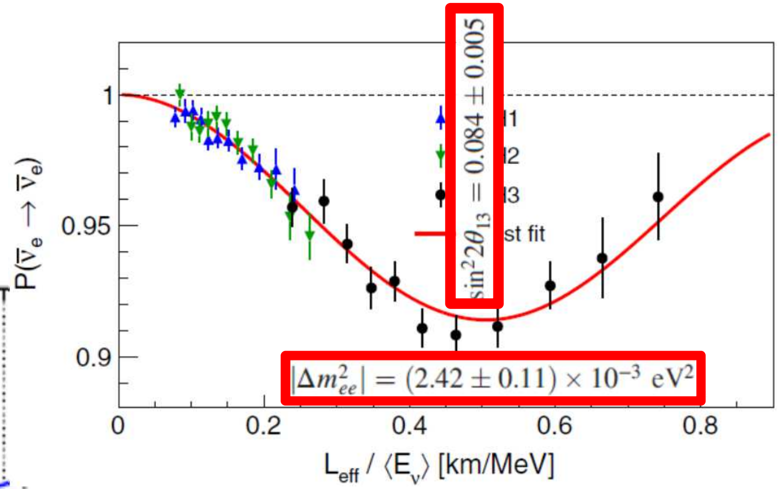




Result of spectral analyses is simultaneous fit of (almost uncorrelated) values of θ13 and mass splitting Δm²ee

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$





$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\ \text{eV}^2$$

Major milestones of the Daya Bay experiment

Proposal Dec 2006

Aug 2011 Data taking with NEAR det.

Dec 2011 Start of the data taking with NEAR+FAR

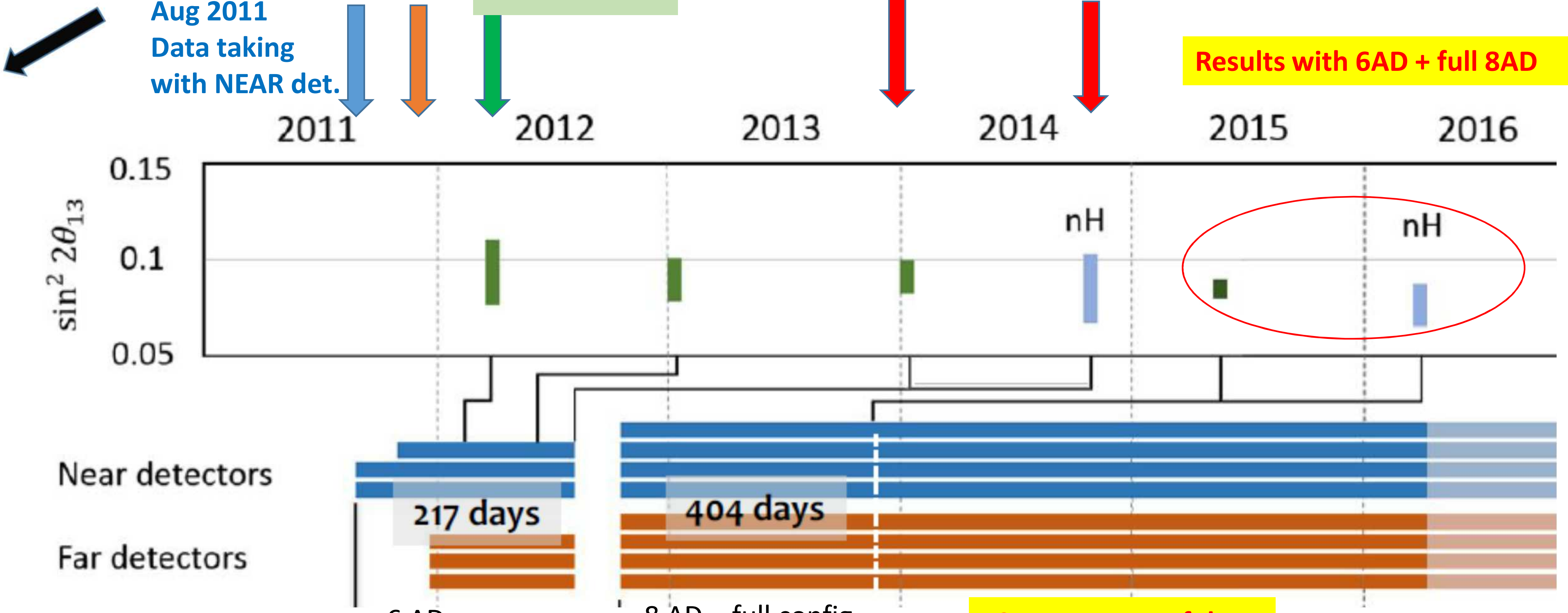
March 2012 observation of theta13≠0

Summary results with 6AD

First meas of Δmee

First meas of θ13 in nH capture

Results with 6AD + full 8AD

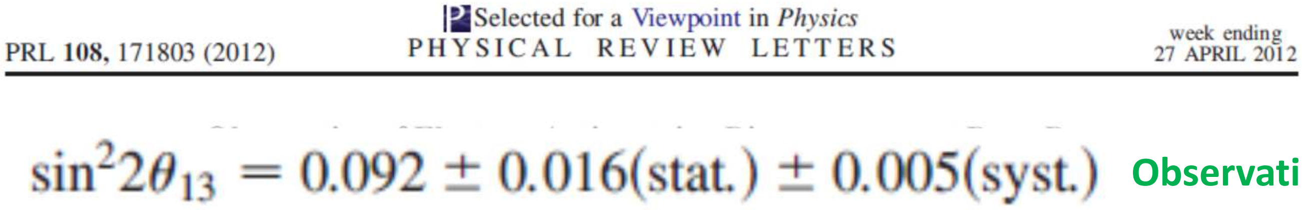


6 AD
3 NEAR + 3 FAR

8 AD – full config.
4 NEAR + 4 FAR

>2 more years of data not yet published

DAYA BAY nGd RESULTS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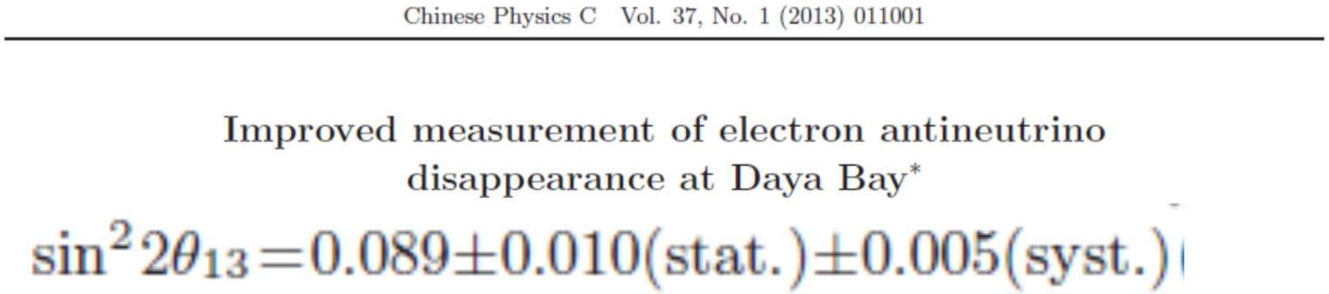
PRL **108,** 171803 (2012) PHYSICAL REVIEW LETTERS week ending 27 APRIL 2012

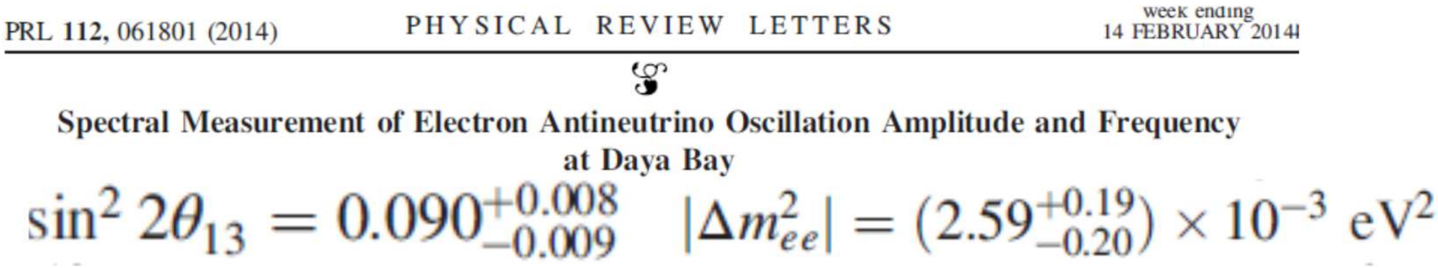
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

Observation - 18% precision


Chinese Physics C Vol. 37, No. 1 (2013) 011001

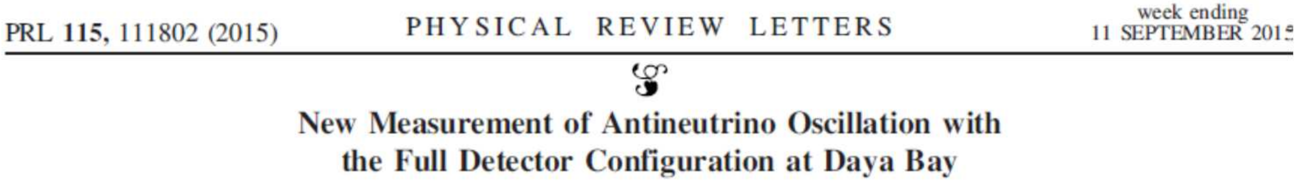
Improved measurement of electron antineutrino disappearance at Daya Bay*

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.})$$


PRL **112,** 061801 (2014) PHYSICAL REVIEW LETTERS week ending 14 FEBRUARY 2014

Spectral Measurement of Electron Antineutrino Oscillation Amplitude and Frequency at Daya Bay

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009} \quad |\Delta m^2_{ee}| = (2.59^{+0.19}_{-0.20}) \times 10^{-3}\ \text{eV}^2$$


PRL **115,** 111802 (2015) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 201

New Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay

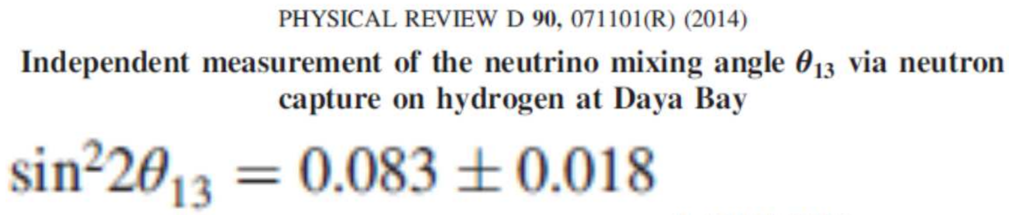
$$\boxed{\sin^2 2\theta_{13} = 0.084 \pm 0.005}$$

6% precision

$$\boxed{|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\ \text{eV}^2}$$

4.5% precision

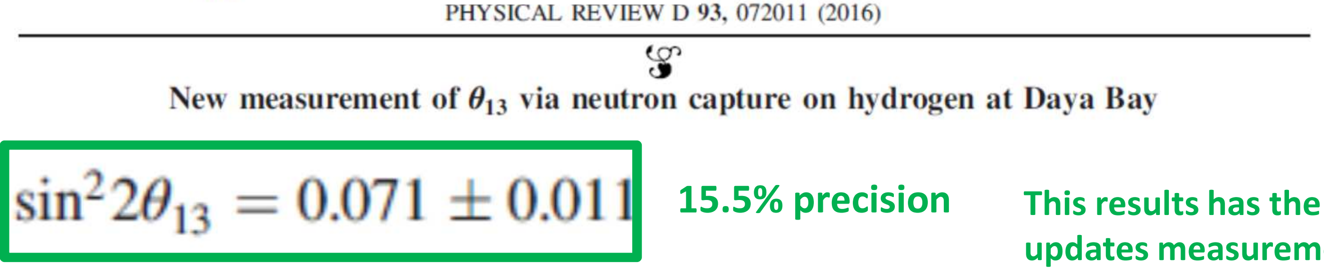
DAYA BAY nH RESULTS



PHYSICAL REVIEW D 90, 071101(R) (2014)

Independent measurement of the neutrino mixing angle θ_{13} via neutron capture on hydrogen at Daya Bay

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



PHYSICAL REVIEW D 93, 072011 (2016)

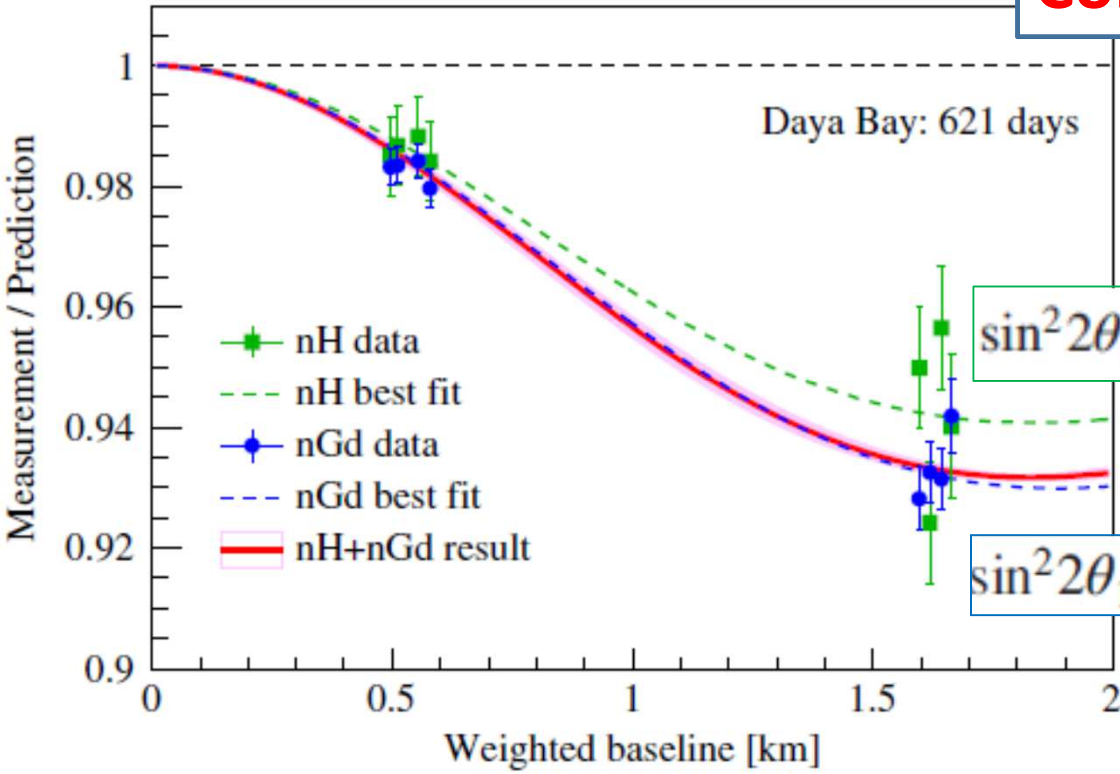
New measurement of θ_{13} via neutron capture on hydrogen at Daya Bay

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

15.5% precision

This results has the same precision as recently published updates measurement of RENO Experiment.

Combination of nGd and nH results



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

4.9% precision

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

$\sin^2 2\theta_{13} = 0.084 \pm 0.005$

nGd result

4.5% precision

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\ \mathrm{eV}^2$$

Importance of precise measurement of θ13

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

1. We know precisely the electron neutrino content in the m3 mass eigenstate:

$$|U_{e3}|^2 \equiv \sin^2\theta_{13} = (2.09 \pm 0.10)\%$$

2. θ13 is also measured via an appearance of electron (anti)neutrinos in muon (anti)neutrino beams in T2K, MINOS and NOvA. Measured appearance probability in these experiments is the function of θ13 but also of yet unknown CP violating phase, neutrino mass hierarchy and the octant of θ23. Comparison of reactor and accelerator measurements will shed a light on yet unknown variables of neutrino mixing.

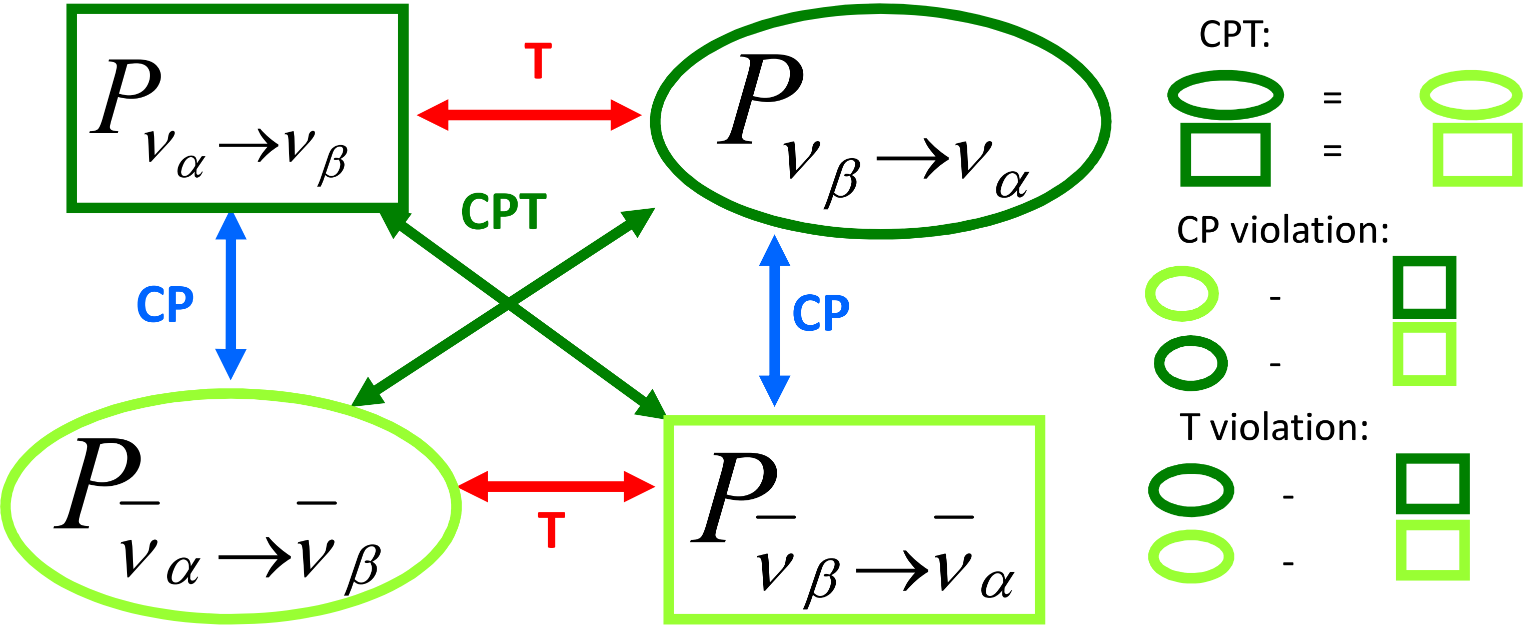
$$\sin^2 2\theta_{13}^{REACTOR} \qquad \sin^2 2\theta_{13}^{ACC}\left(\delta,\ NH/IH,\ \theta_{23} < 45^o / \theta_{23} > 45^o\right)$$

3. The effect of CP violation in neutrino oscillations is proportional to θ13: $\cos(\theta_{13})\sin(2\theta_{13}) \cong 0.28$

$$P_{\bar{\nu}\mu \to \bar{\nu}e}(L/E) - P_{\nu\mu \to \nu e}(L/E) = 2\sin(\delta)\cos(\theta_{13})\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})$$

$$\times \sin\left(\frac{\Delta m_{21}^2}{4\hbar c}\frac{L}{E}\right)\sin\left(\frac{\Delta m_{31}^2}{4\hbar c}\frac{L}{E}\right)\sin\left(\frac{\Delta m_{32}^2}{4\hbar c}\frac{L}{E}\right)$$

CP and T violation in lepton sector can be investigated with neutrino oscillations



With current experiments we can probe CP symmetry:

$$P_{\bar{\nu\mu} \to \bar{\nu e}}(L/E) - P_{\nu\mu \to \nu e}(L/E)$$

To measure T violation, sources of electron neutrinos with GeV energies will be needed.

$$P_{\nu\mu \to \nu e}(L/E) - P_{\nu e \to \nu\mu}(L/E)$$

Importance of Δm^2_{ee} measurement

$$\Delta m^2_{32}(NH) = (2.37 \pm 0.11)\cdot 10^{-3}\, eV^2$$

$$\boxed{|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\ \mathrm{eV}^2}$$

$$\Delta m^2_{32}(IH) = -(2.47 \pm 0.11)\cdot 10^{-3}\, eV^2$$

Uncertainties are compatible to those measured by muon neutrinos disappearance experiments MINOS and T2K.

This year we will celebrate 60 years from the discovery of neutrino. Even after 60 years we still do not know absolute values of neutrino masses. **Results of neutrino oscillation experiments provide lower limits of neutrino masses.**

Normal hierarchy:
m1≥0, m2 ≥~8.7 meV, m3 ≥~50 meV → mve ≥~3 meV; Σmi ≥~60meV

Inverse hierarchy:
m3≥0, m1,m3 ≥~50 meV → mve ≥~50 meV; Σmi ≥~100meV

Searches for light sterile neutrinos.

Fourth neutrino mass eigenstate imply **three additional mixing angles** θ$_{14}$, θ$_{24}$ and θ$_{34}$ (cij = Cos(θ ij), sij = Sin(θ ij)) and **two additional CP violating Dirac phases**:

$$U^{4x4} = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & c34 & s34\cdot e^{-i\delta 34} \\ & & -s34\cdot e^{+i\delta 34} & c34 \end{pmatrix} \begin{pmatrix} 1 & & & \\ & c24 & & s24\cdot e^{-i\delta 24} \\ & & 1 & \\ & -s34\cdot e^{+i\delta 34} & & c24 \end{pmatrix} \begin{pmatrix} c14 & & & s14 \\ & 1 & & \\ & & 1 & \\ -s14 & & & c14 \end{pmatrix} \begin{pmatrix} U_{e1}^{3x3} & U_{e2}^{3x3} & U_{e3}^{3x3} & \\ U_{\mu 1}^{3x3} & U_{\mu 2}^{3x3} & U_{\mu 3}^{3x3} & \\ U_{\tau 1}^{3x3} & U_{\tau 2}^{3x3} & U_{\tau 3}^{3x3} & \\ & & & 1 \end{pmatrix}$$

Electron (anti) neutrino disappearance measurement is described by the Uei terms of the mixing matrix and **is sensitive only to 1-4 mixing**

$$U_{e1}^{4x4} = c14 \cdot U_{e1}^{3x3}$$

$$U_{e2}^{4x4} = c14 \cdot U_{e2}^{3x3}$$

$$U_{e3}^{4x4} = c14 \cdot U_{e3}^{3x3}$$

$$U_{e4}^{4x4} = s14$$

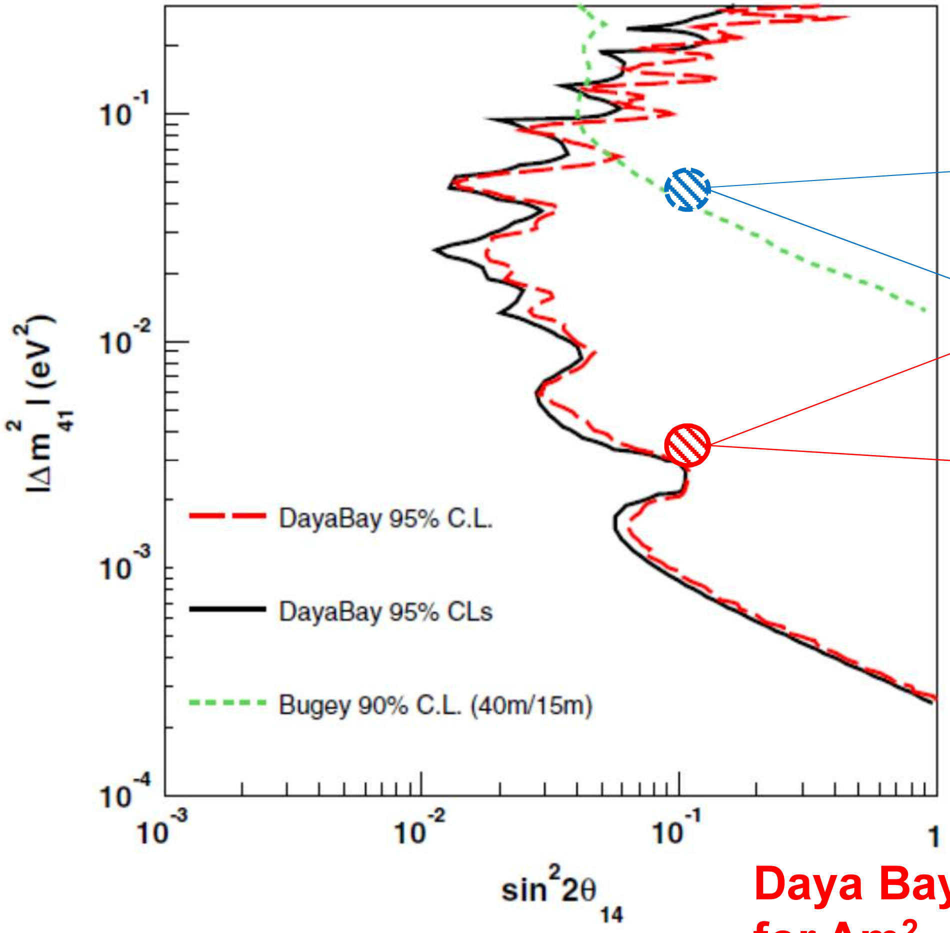
$$\Rightarrow 1 - P_{ee}^{4x4} \cong \cos^2(\theta_{14})\left(1 - P_{ee}^{3x3}\right) + \boxed{\sin^2(2\theta_{14})}\sin^2\left(\frac{\boxed{\Delta m_{4e}^2}}{4\hbar c}\frac{L}{E}\right)$$

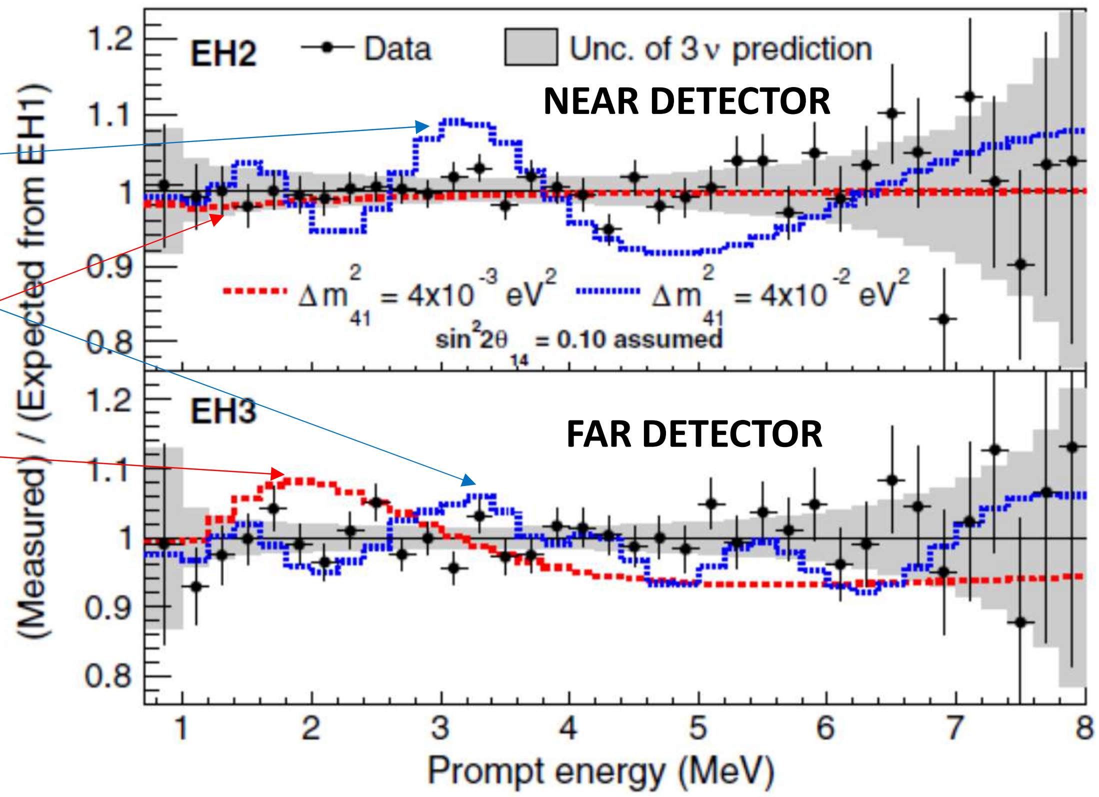
$$\Delta m_{4e}^2 \equiv \frac{\left|U_{e1}^{3x3}\right|^2 \Delta m_{41}^2 + \left|U_{e2}^{3x3}\right|^2 \Delta m_{42}^2 + \left|U_{e3}^{3x3}\right|^2 \Delta m_{43}^2}{\left|U_{e1}^{3x3}\right|^2 + \left|U_{e2}^{3x3}\right|^2 + \left|U_{e3}^{3x3}\right|^2} \cong \Delta m_{41}^2$$

PRL **113,** 141802 (2014) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2014

Search for a Light Sterile Neutrino at Daya Bay

Effect on measured spectra:



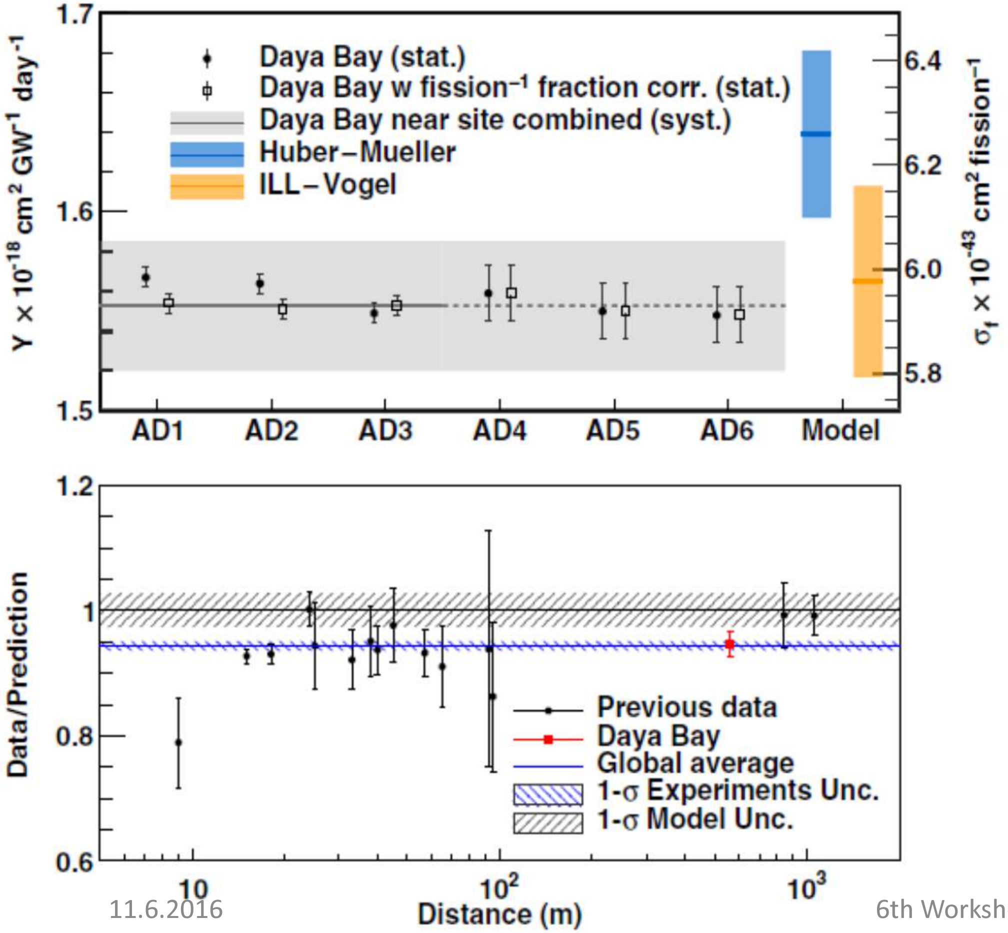


Daya Bay result yields world most stringent limits on θ14 for Δm^2_{41} below 0.1 eV^2.

Precise measurement of the reactor neutrino flux

PRL 116, 061801 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay

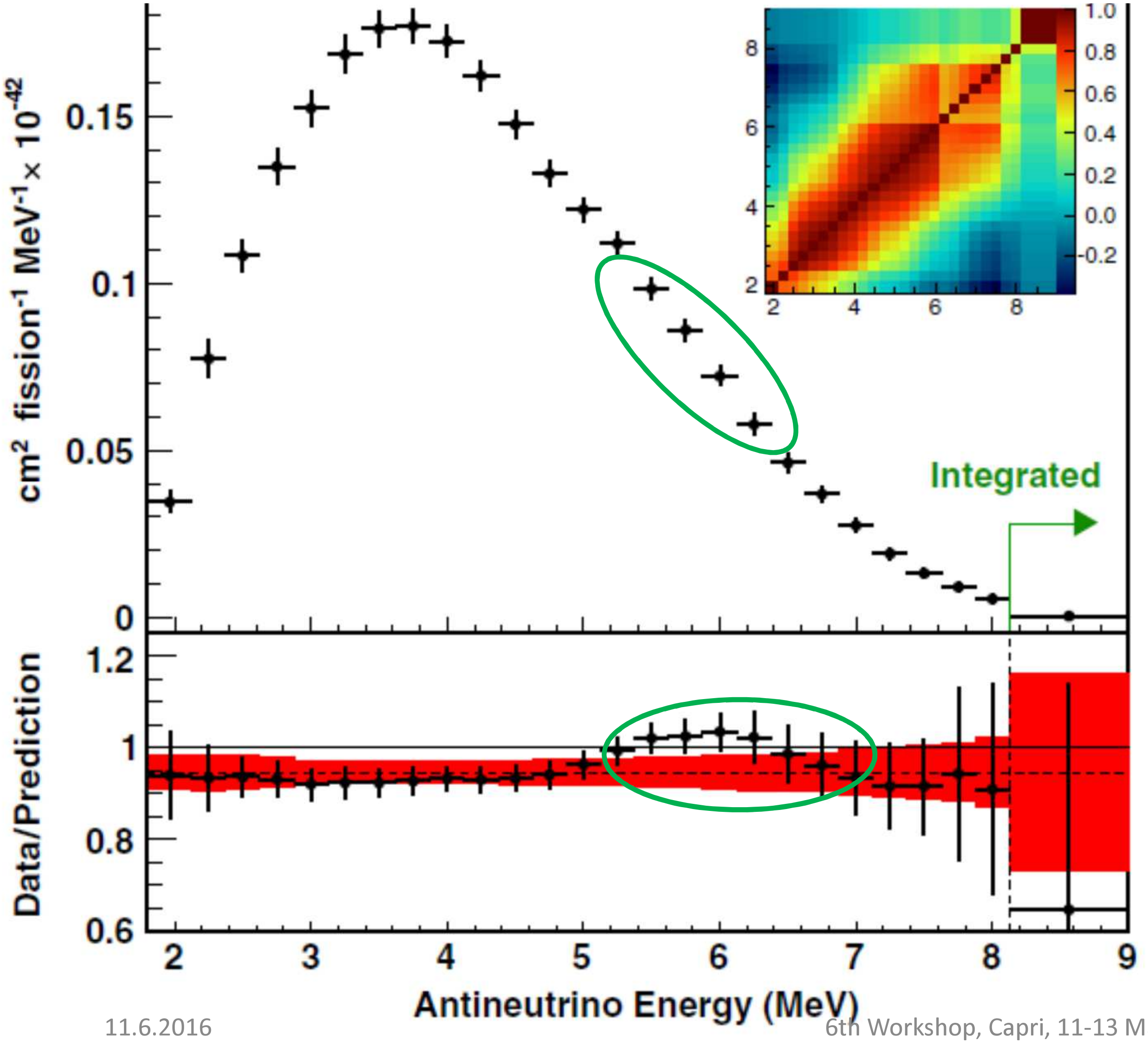


IBD yield and total neutrino flux:

IBD Yield	
Y (cm^2 GW^{-1} day^{-1})	$(1.55 \pm 0.04) \times 10^{-18}$
σ_f (cm^2 fission^{-1})	$(5.92 \pm 0.14) \times 10^{-43}$
Data/Prediction	
R (Huber-Mueller)	0.946 ± 0.022
R (ILL-Vogel)	0.991 ± 0.023

Daya Bay measurement confirm ~5% deficit of reactor neutrino flux wrt contemporary models.

Unfolded antineutrino spectrum



App 4 sigma discrepancy around antineutrino energies of 6 MeV is observed.
That is consistent with RENO and Double Chooz observation.

Ratio of antineutrino spectrum to Huber-Mueller model

Summary

- The Daya Bay reactor neutrino oscillation experiment measures the value of $\sin^2 2\theta_{13}$ with 6% precision (via nGd). Measurement via nH capture provide an independent measurement with 15.5% precision. The combined result has 5% precision.

- The precision of $|\Delta m^2_{ee}|$ is 4.5 % and it is comparable to the results from accelerator experiments T2K & MINOS.

- Daya Bay provides the most stringent constraints on the content of electron neutrino in hypothetical fourth neutrino mass eigenstate in the region of mass splitting:
$$10^{-3}\ eV^2 < \left|\Delta m^2_{41}\right| < 0.1\ eV^2$$

- Measured total flux of reactor neutrinos confirmed the reactor neutrino anomaly. Spectrum of neutrinos exhibit an excess up to 4σ around neutrino energies of 6 MeV.

- Further improvement of the results is expected.