Observation of electron-antineutrino disappearance at Daya Bay

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Neutrino flavor eigenstates $|\nu_f\rangle,\ f = e/\mu/\tau$ produced in weak Interactions are different from mass eigenstates $|\nu_i\rangle,\ i = 1/2/3$

➔non-diagonal Unitary mixing matrix: $U_{fi} \equiv \langle \nu_f | \nu_i \rangle \Rightarrow |\nu_f\rangle = U^*_{fi} |\nu_i\rangle$

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

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

$\theta_{23} \cong 45^o$

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

$\theta_{12} \cong 34^o$

Majorana phases α are irrelevant for oscillations.

If masses of mass eigenstates are different then probabilities oscillate:

$$P_{\nu_f \to \nu_g}(L) = \delta_{fg} - 4\sum_{i<j} \Re\left(U_{gi}U_{fi}^{*}U_{fj}U_{gj}^{*}\right)\sin^2\left(\frac{m_j^2 - m_i^2}{4\hbar c}\frac{L}{E}\right) + 2\sum_{i<j} \Im\left(U_{gi}U_{fi}^{*}U_{fj}U_{gj}^{*}\right)\sin\left(\frac{m_j^2 - m_i^2}{2\hbar c}\frac{L}{E}\right)$$

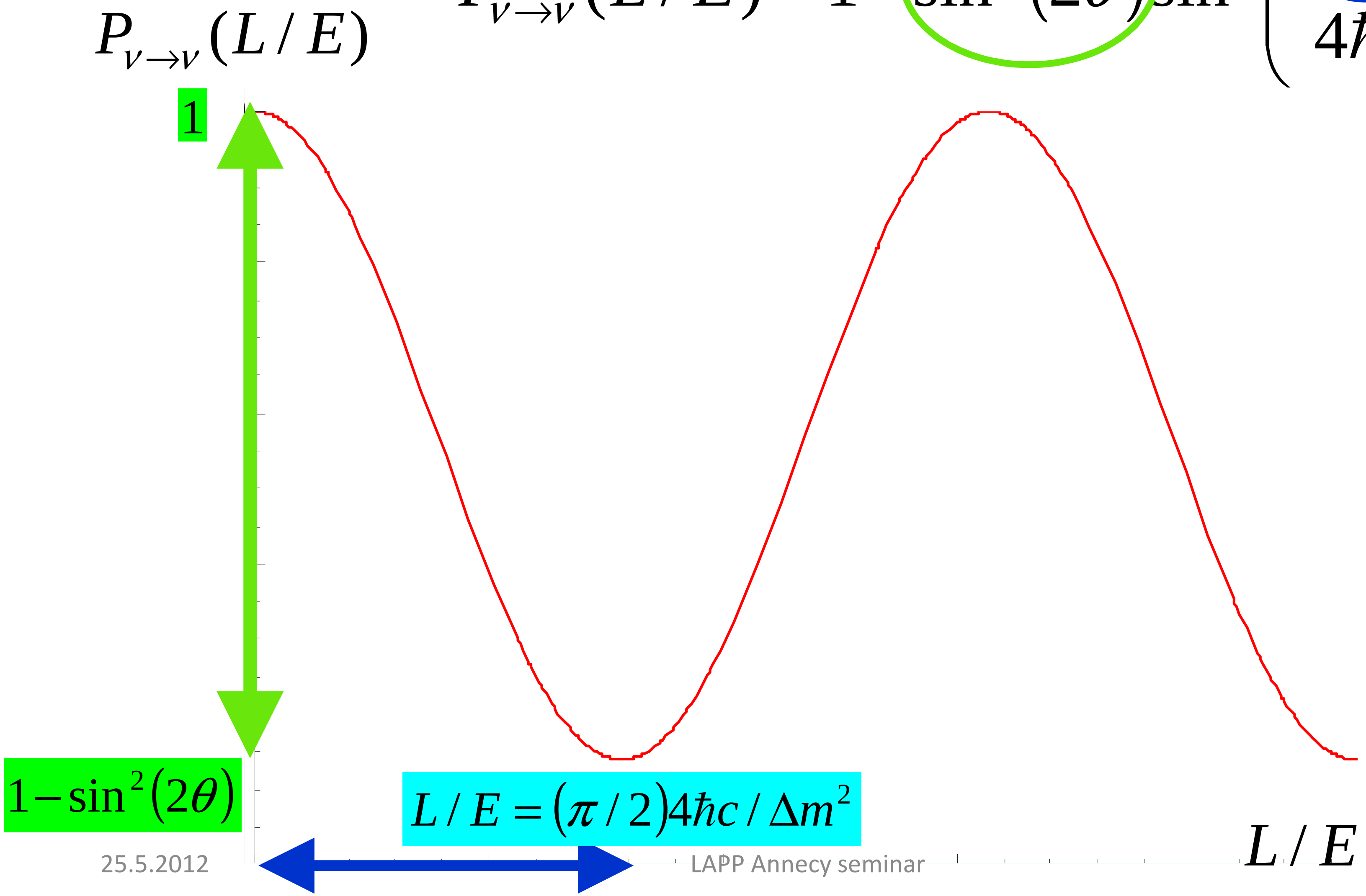
Last term is CP and T odd and it is ≠0 only if:

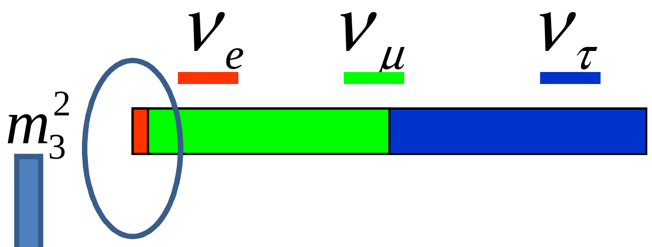
- all three mixing angles ≠0 and
- Sin(δ) ≠0 (imaginary part of exp(i δ) ≠0)

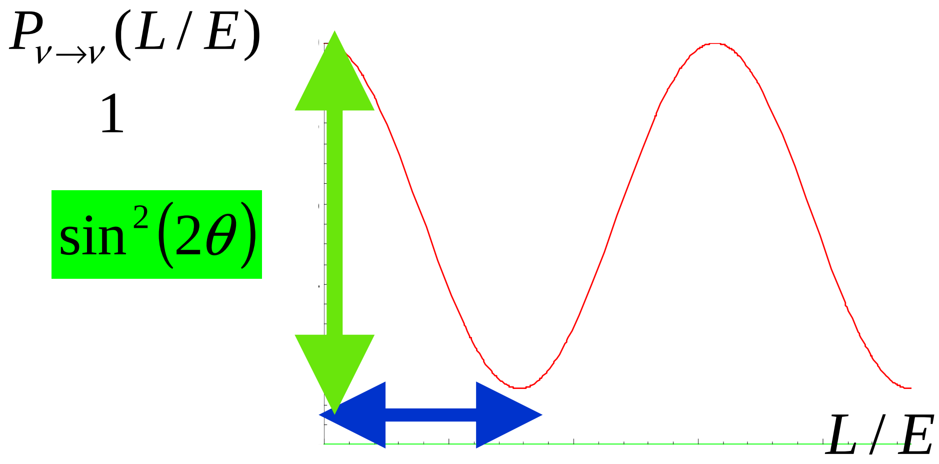
Amplitude of oscillations = sin²(2θ),

oscillation length is inversely proportional to Δm²

$$P_{\nu\to\nu}(L/E) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4\hbar c}\frac{L}{E}\right)$$



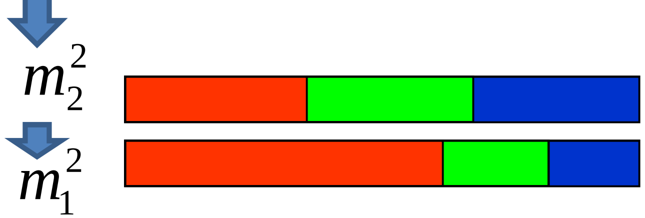




$$(L/E)_{1stMINIMUM} = (\pi/2)4\hbar c/\Delta m^2$$
$$\approx 0.5\, km/MeV = 500\, km/GeV$$
$$\approx 15\, km/MeV = 15000\, km/GeV$$

Two Δm² differs app. by a factor of 30
➔ two very different oscillation lengths

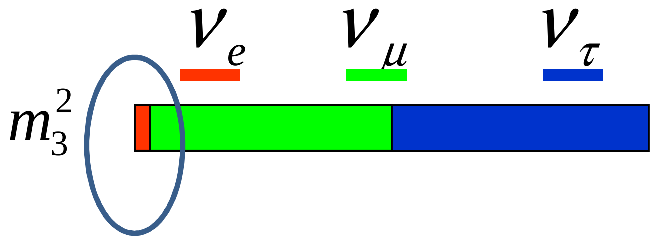
$$\left|m_3^2 - m_1^2\right| \cong 2.3\times10^{-3} eV^2$$
$$m_2^2 - m_1^2 \cong 7.6\times10^{-5} eV^2$$



	0.5 km/MeV 500 km/GeV	15 km/MeV 15000 km/GeV
$\nu_e \to \nu_e$	Daya Bay Double Chooz/RENO	reactor KAMLAND Sun ν_e (+matter efffect)
$\nu_\mu \to \nu_\mu / \nu_e / \nu_\tau$	atmospheric accelerator	

Mixing angle θ13

$\sin^2(\theta_{13})$ is the fraction of electron neutrino in mass eigenstate m3

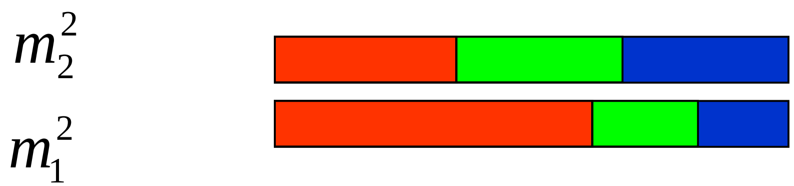


Two ways to measure θ13

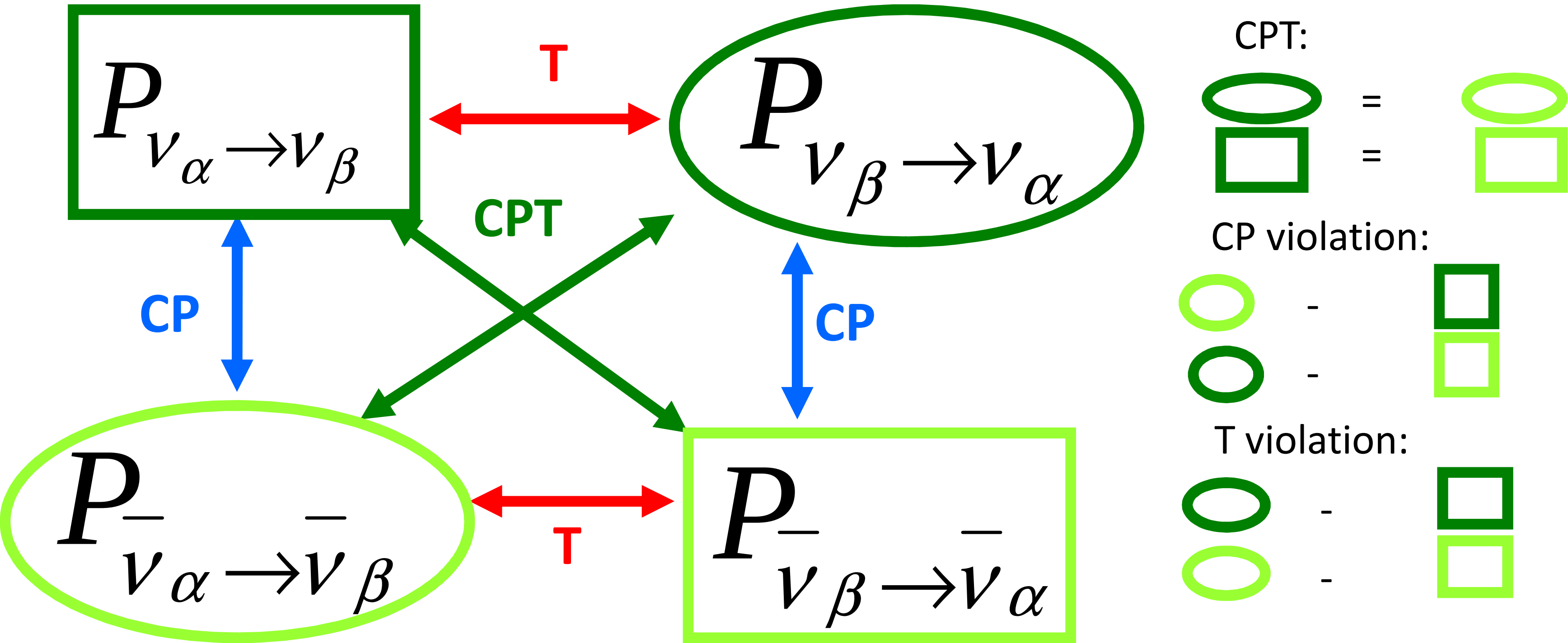
-To measure electron (anti)neutrino disappearance

-To measure electron (anti)neutrino appearance in muon (anti)neutrino beam

both measurements done at small values of L/E~0.5km/MeV = 500 km/GeV:



If $\theta_{13} \neq 0$ then CP and T violation in lepton sector could be investigated with neutrino oscillations



$$P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e} = -2\sin(\delta)\cos(\theta_{13})\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})$$

$$\times \sin\left(\frac{\Delta m_{12}^2}{4\hbar c}\frac{L}{E}\right)\sin\left(\frac{\Delta m_{31}^2}{4\hbar c}\frac{L}{E}\right)\sin\left(\frac{\Delta m_{23}^2}{4\hbar c}\frac{L}{E}\right)$$

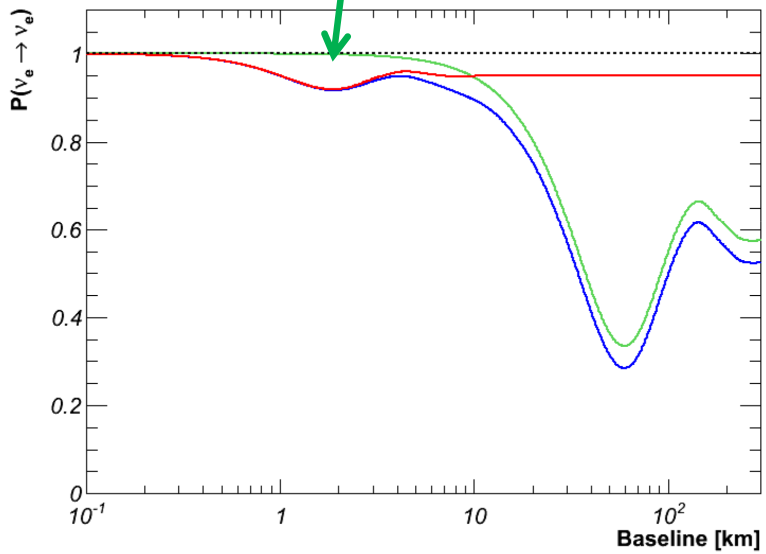
Disappearance probabilty

$$P_{\nu_f \to \nu_f}(x) = 1 - \sum_{i<j} 4 \left|U_{fi}\right|^2 \left|U_{fj}\right|^2 \sin^2\left(1.267 \Delta m_{ij}^2 \left[eV^2\right] \frac{x[m]}{E[MeV]}\right)$$

Disappearance probabilty for electron (anti)neutrinos:

$$P_{\nu_e \to \nu_e}(x) \xrightarrow[\Delta m_{31}^2 \cong \Delta m_{32}^2]{} 1 - \sin^2(2\theta_{13}) \sin^2\left(1.267 \Delta m_{31}^2 \left[eV^2\right] \frac{x[m]}{E[MeV]}\right) - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(1.267 \Delta m_{21}^2 \left[eV^2\right] \frac{x[m]}{E[MeV]}\right)$$

For Daya Bay the last term is <0.1%:



$$P_{\nu_e \to \nu_e}(x) \cong 1 - \sin^2(2\theta_{13}) \sin^2\left(1.267 \Delta m_{31}^2 \left[eV^2\right] \frac{x[m]}{E[MeV]}\right)$$

Daya Bay is one of three competing experiments

Daya Bay Site Guangdong, China

Entrance to Daya Bay experiment tunnels

Daya Bay NPP
2x2.9GW

Ling Ao NPP
2x2.9GW

Ling Ao II NPP
2x2.9GW

Mountains shield detectors from cosmic ray backgrounds

6 reactors:
17.4 GW total (thermal) power

Experimental Layout

A total of eight functionally identical and moveable detectors in three detector halls.

6 of the 8 detectors have been taking physics data since Dec. 2012

The remaining two detectors will be installed and commissioned later this year.

Daya Bay Collaboration ~240 members

Asia (20)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci and Tech, CGNPG, CIAE, Dongguan Polytech, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

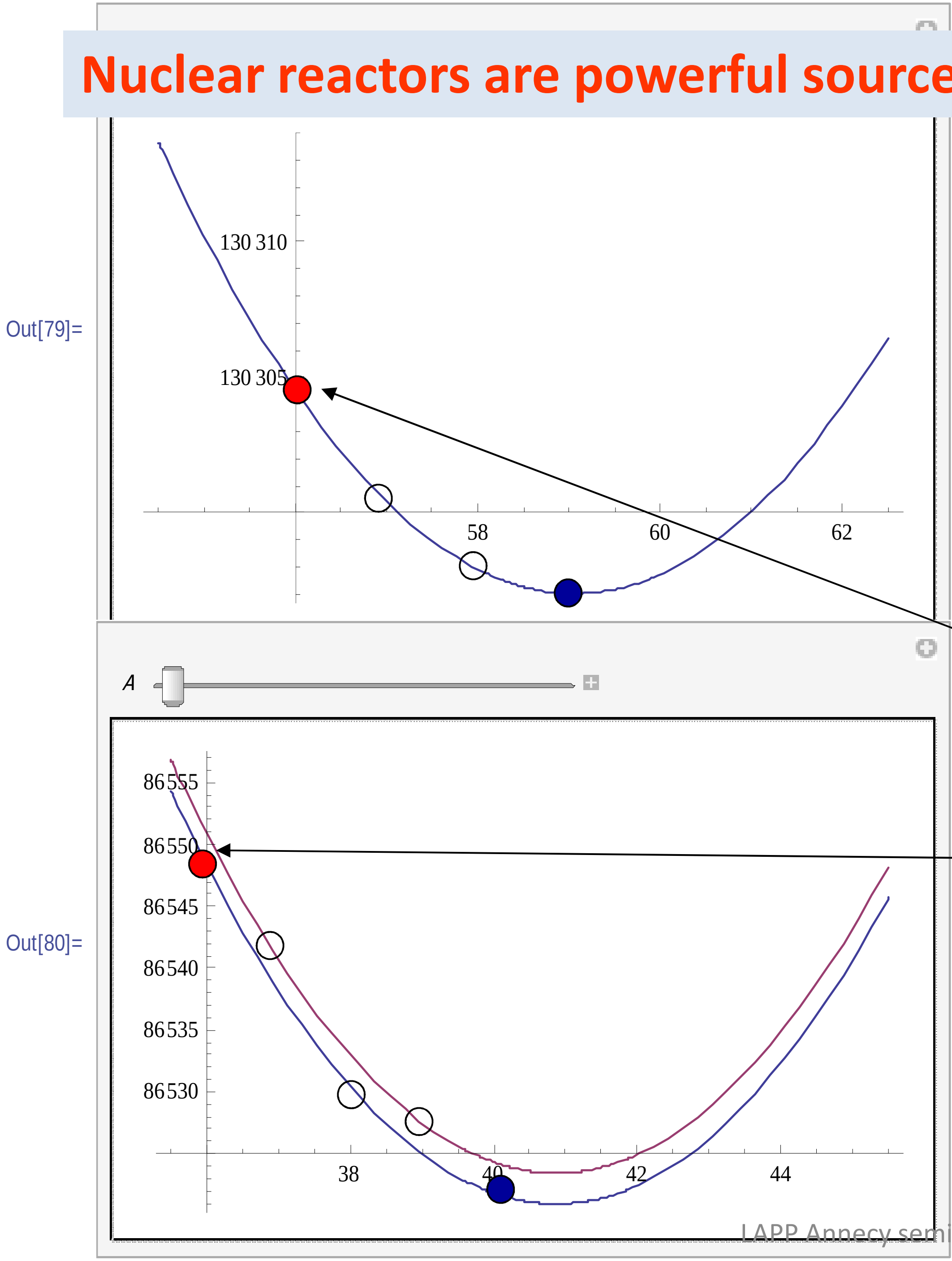
North America (16)

Brookhaven Natl' Lab, Cal Tech, Cincinnati, Houston, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl' Lab, Princeton, Rensselaer Polytech, UC Berkeley, UCLA, Wisconsin, William & Mary, Virginia Tech, Illinois, Siena College

Europe (2)

Charles Univ., Dubna

Nuclear reactors are powerful sources of electron antineutrinos



Fission products are neutron rich. The valley of stability is reached by series of beta- decays.
In average app. **6 electron antineutrinos** are produced in each fission.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{139}_{56}Ba + ^{94}_{36}Kr + 3^{1}_{0}n$$

$$2 \cdot 10^{20} \bar{\nu}_e / s / GW_{th}$$

Detection of antineutrinos: interactions with protons via so called Inverse Beta Decay (IBD)

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

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

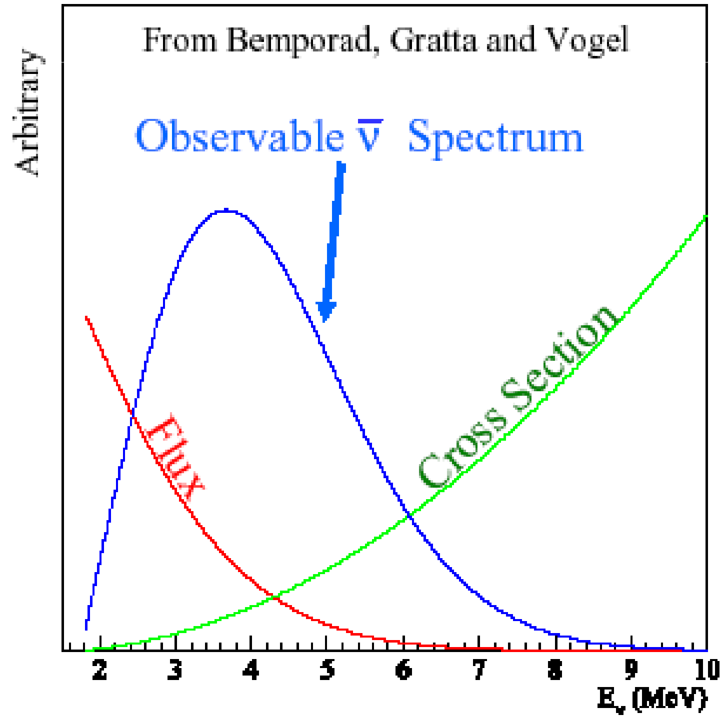
$$(E_{\nu,THR} + m_p)^2 - E_{\nu,THR}^2 = (m_n + m_e)^2$$

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

$$= 1.00096(m_n - m_p + m_e) = 1.83 MeV$$

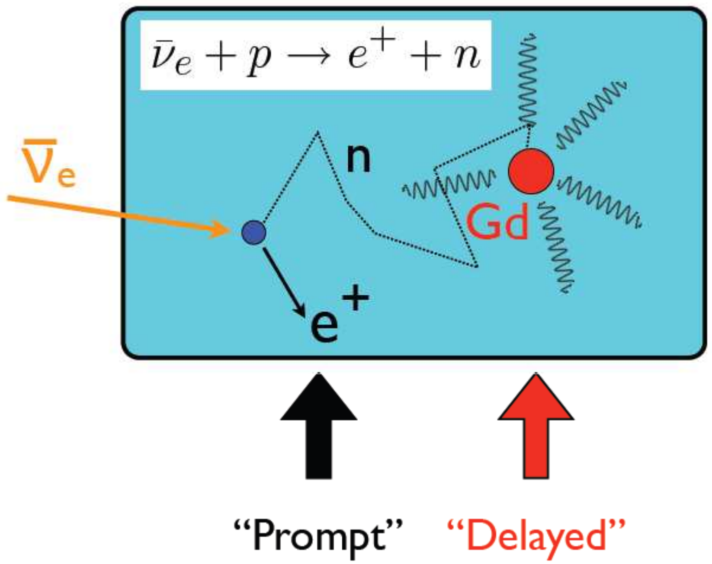
Only antineutrinos with energies larger than 1.8 MeV interact.

Detected energy spectrum is the product of original energy spectrum 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 positron and neutron is done using Gd-doped Liquid scintillator

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



$\tau \approx 28\ \mu s$(0.1% Gd)

n + Gd → Gd* + γ (8 MeV)

(n + p → d + γ (2.2 MeV))

Neutrino Event: coincidence in time, space and energy

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

$$E_\nu = E_{prompt} + (m_n - m_p - m_e) + T_{k,n} \cong E_{prompt} + 0.8 MeV$$

Neutrino energy:

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV: Threshold}}$$

Neutron capture on Gadollinium

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

${}^{A}_{64}Gd$	$\sigma_{n+{}^{A}_{64}Gd\rightarrow{}^{A+1}_{64}Gd^{*}}$ [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

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

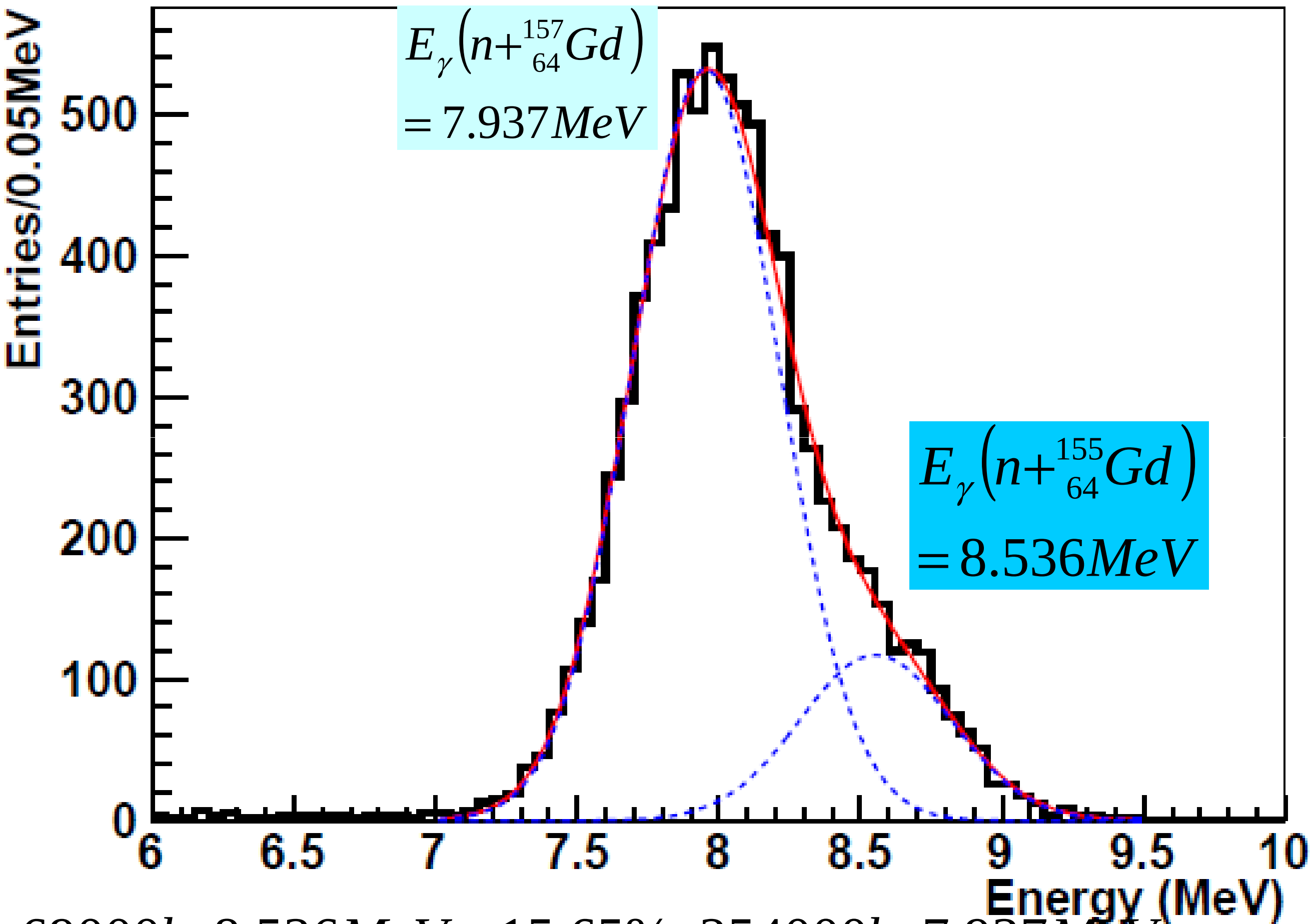
$$\sum E_{\gamma}\left(n+{}^{157}_{64}Gd\right)=7.937MeV$$

$$\left\langle E_{\gamma}\right\rangle = 8.048MeV$$

^{241}Am-^{13}C

$$^{241}_{95}Am \xrightarrow{432 mil.years} \alpha + ^{237}_{93}Np$$

$$\alpha + ^{13}_{6}C \rightarrow ^{16}_{8}O + n$$



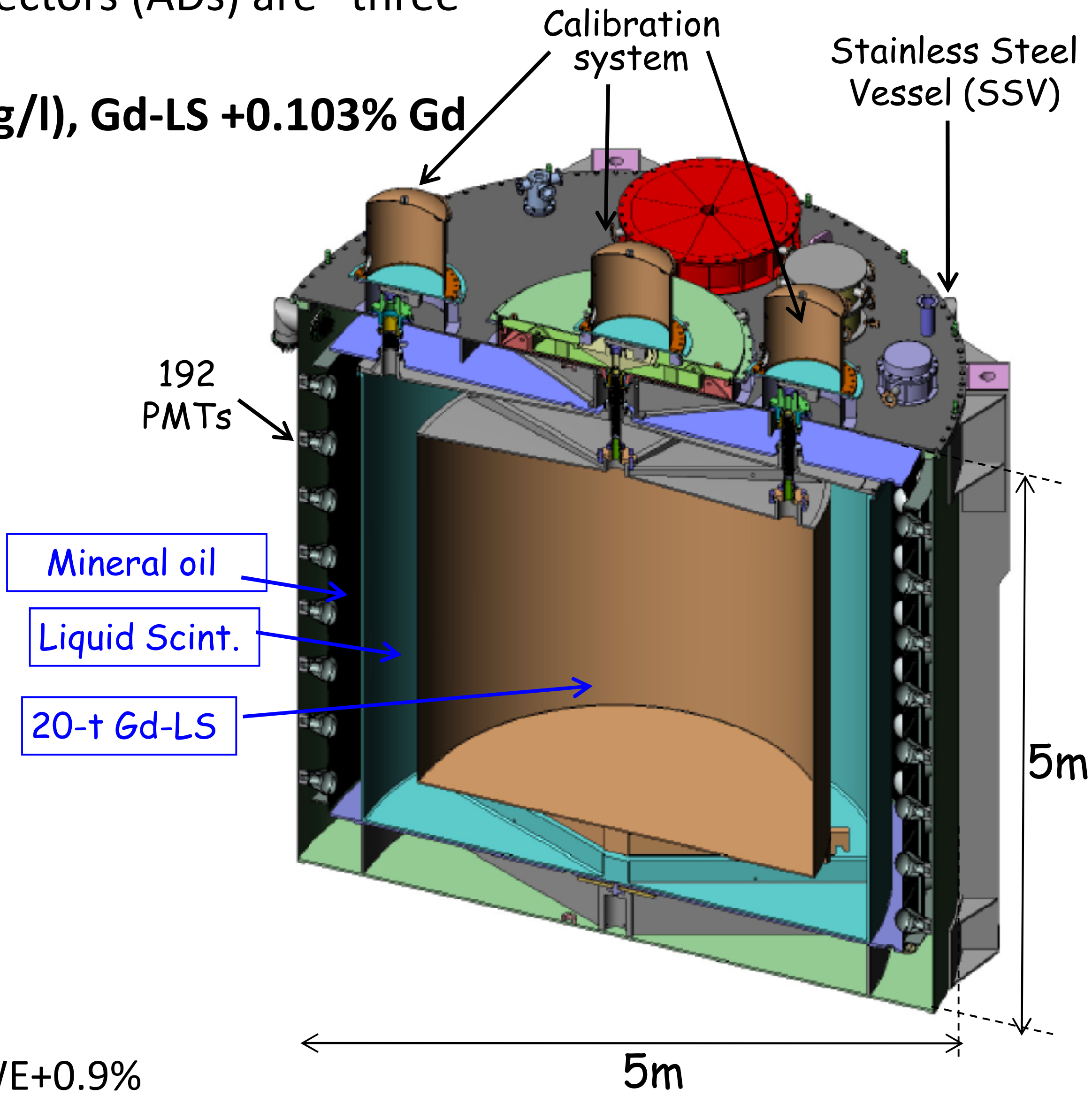
$$\left\langle E_\gamma \right\rangle = \frac{14.80\% \cdot 69000b \cdot 8.536MeV + 15.65\% \cdot 254000b \cdot 7.937MeV}{14.80\% \cdot 69000b + 15.65\% \cdot 254000b} = 8.048MeV$$

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 +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	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

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

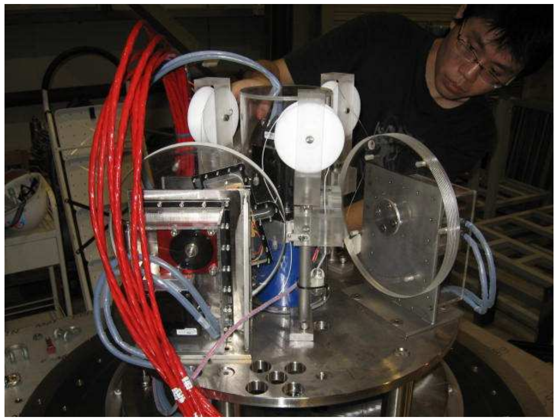


Detector calibration

- ❖ Calibration is key to the reduction of the detector-related systematic errors:
  - Three sources + LED in each calibration unit, on a turn-table:
    - o ^{68}Ge (1.02MeV)
    - o ^{60}Co (2.5MeV)
    - o ^{241}Am-^{13}C (8MeV)

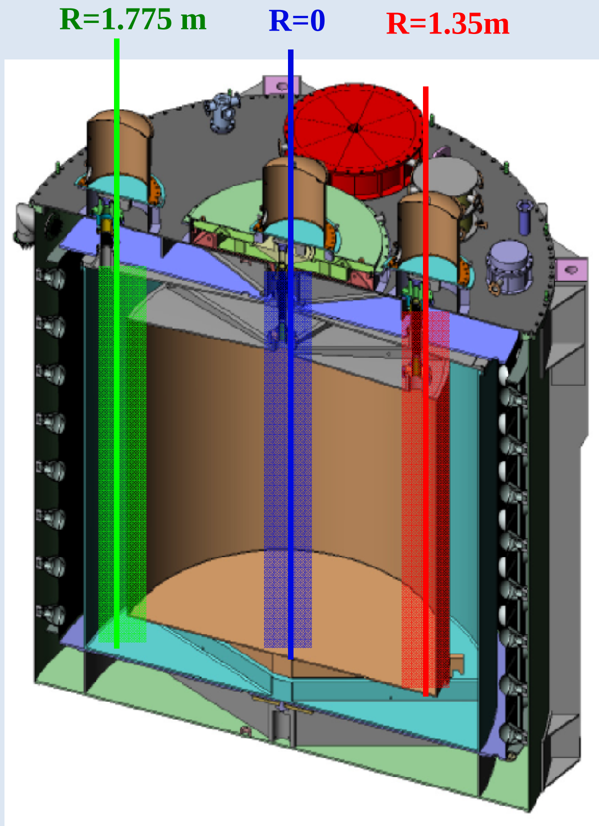
    Energy calibration (linearity, detector response… etc)

    - o LED → Timing, gain and relative QE



  - Can also use spallation neutrons (uniformity, stability, calibration, etc).

Three calibration units per detector that deploy sources along z-axis

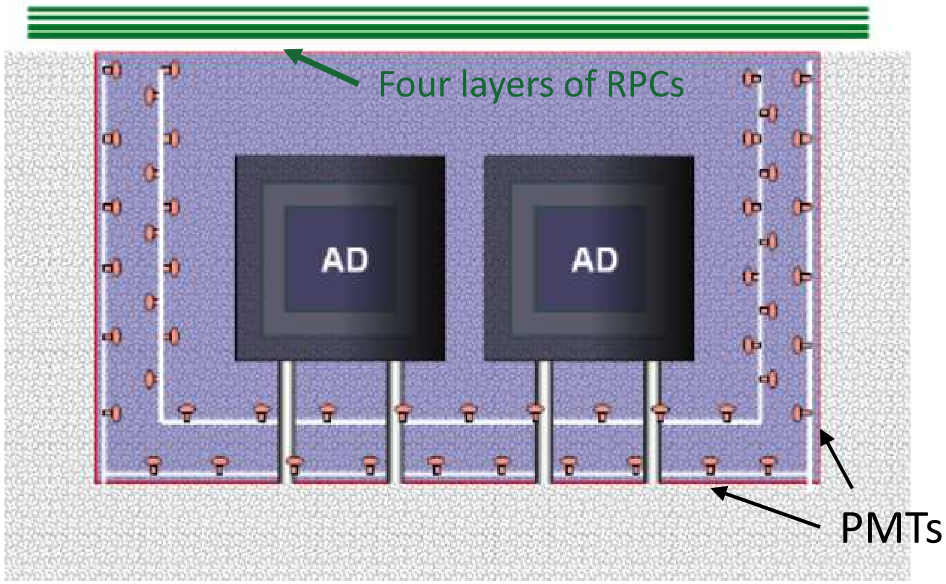


Automated Calibration Units

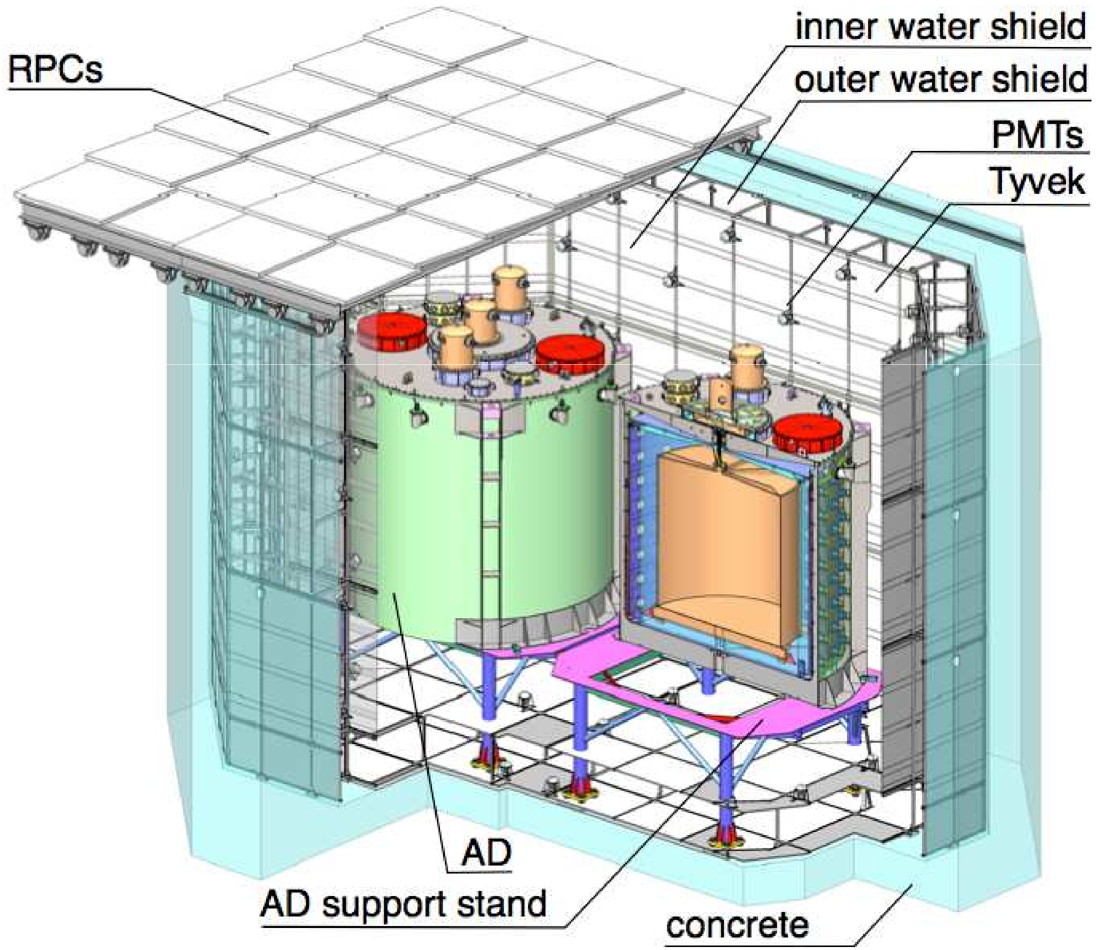
The water Čerenkov detectors

- The detectors are immersed in an instrumented water pool:
  - Double purpose:
    - ✓ Attenuates ambient neutrons as well as gammas
    - ✓ Serves as a Cerenkov detector to tag cosmic ray muons.
- The water pool is divided into two optically decoupled detectors:
    - ✓ Allows for increased redundancy and thus better tagging efficiency
- The pools are covered with a retractable RPC roof for further cosmic ray tagging.

  (in commissioning; not used for first analysis)



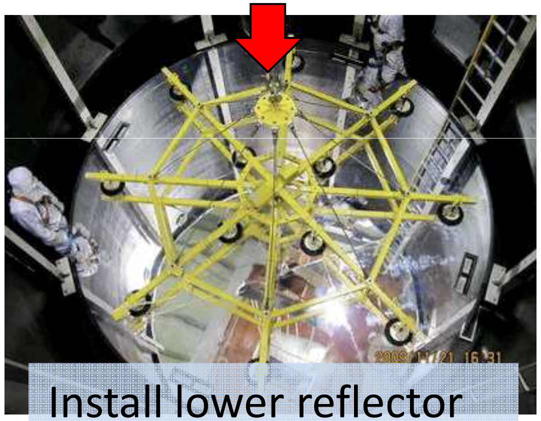
- Outer layer of water Čerenkov detector (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall



Assembly of Anti-neutrino detectors

ADs are assembled in clean-room

Stainless Steel Vessel (SSV) in assembly pit

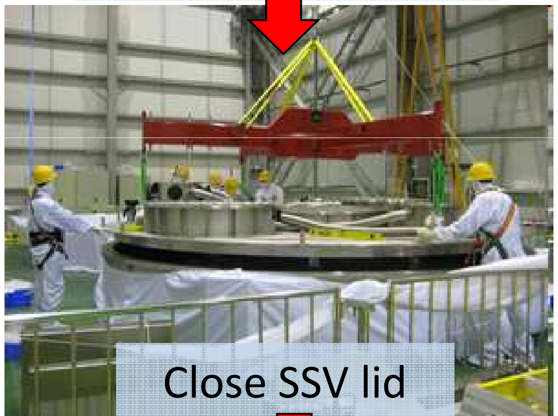


Install lower reflector

Install Acrylic Vessels

Install PMT ladders

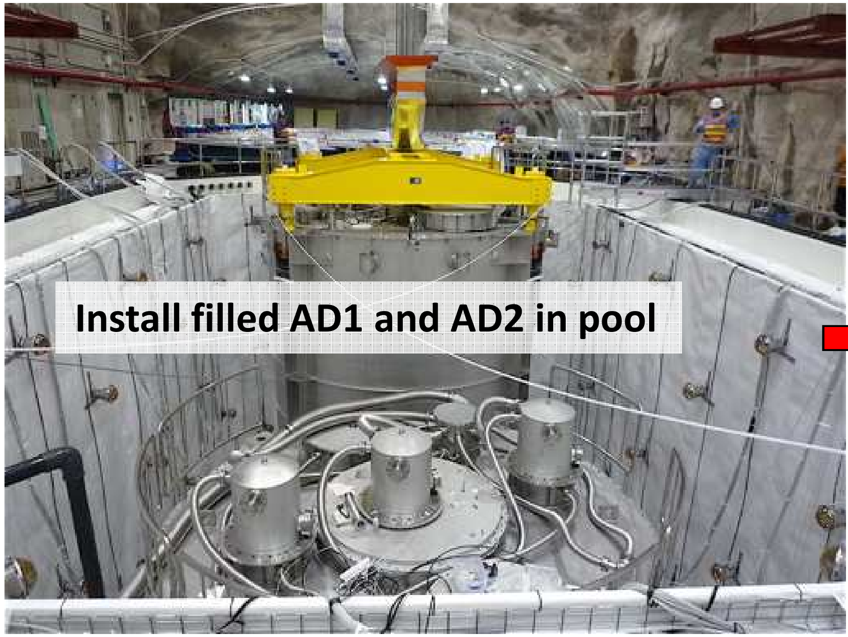
Install top reflector

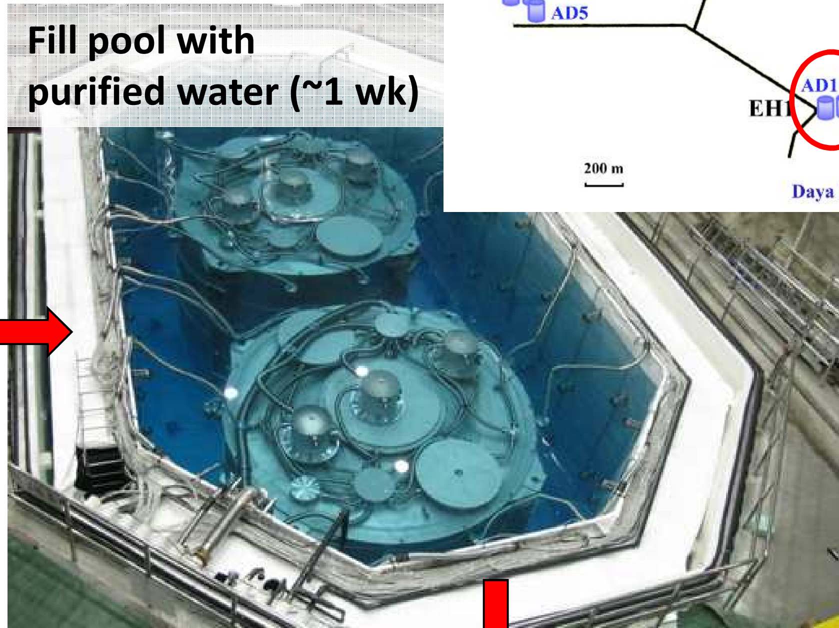


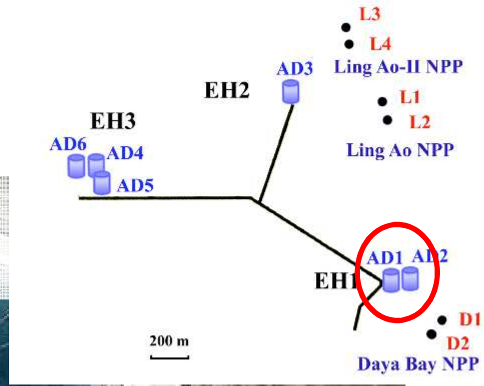
Close SSV lid

Install calibration units

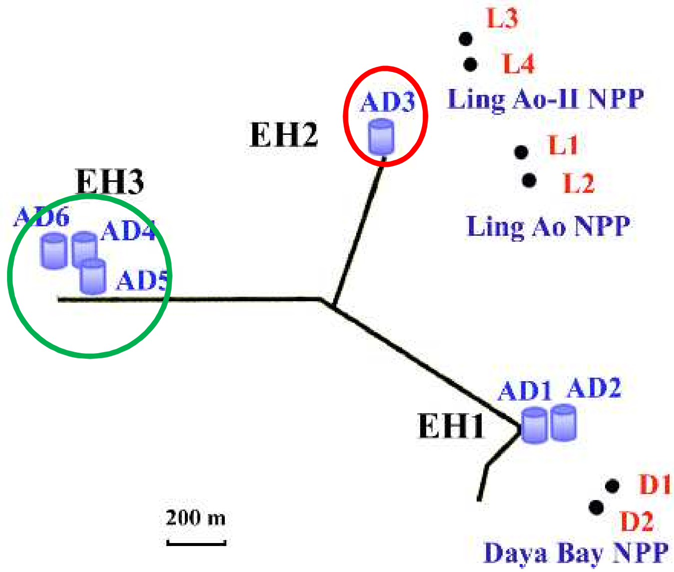
Near Hall (EH1) Installation







Ling Ao (EH2) and Far (EH3) Halls



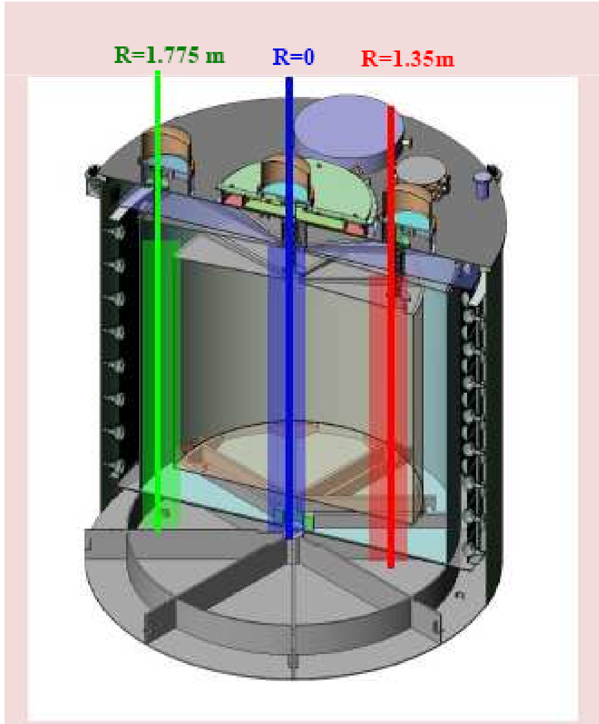
EH2 (Ling Ao Near Hall):
Began operation on 5 Nov 2011

EH3 (Far Hall):
Started data-taking on 24 Dec 2011

- Remaining two ADs will be installed in 2012

Automatic Calibration system

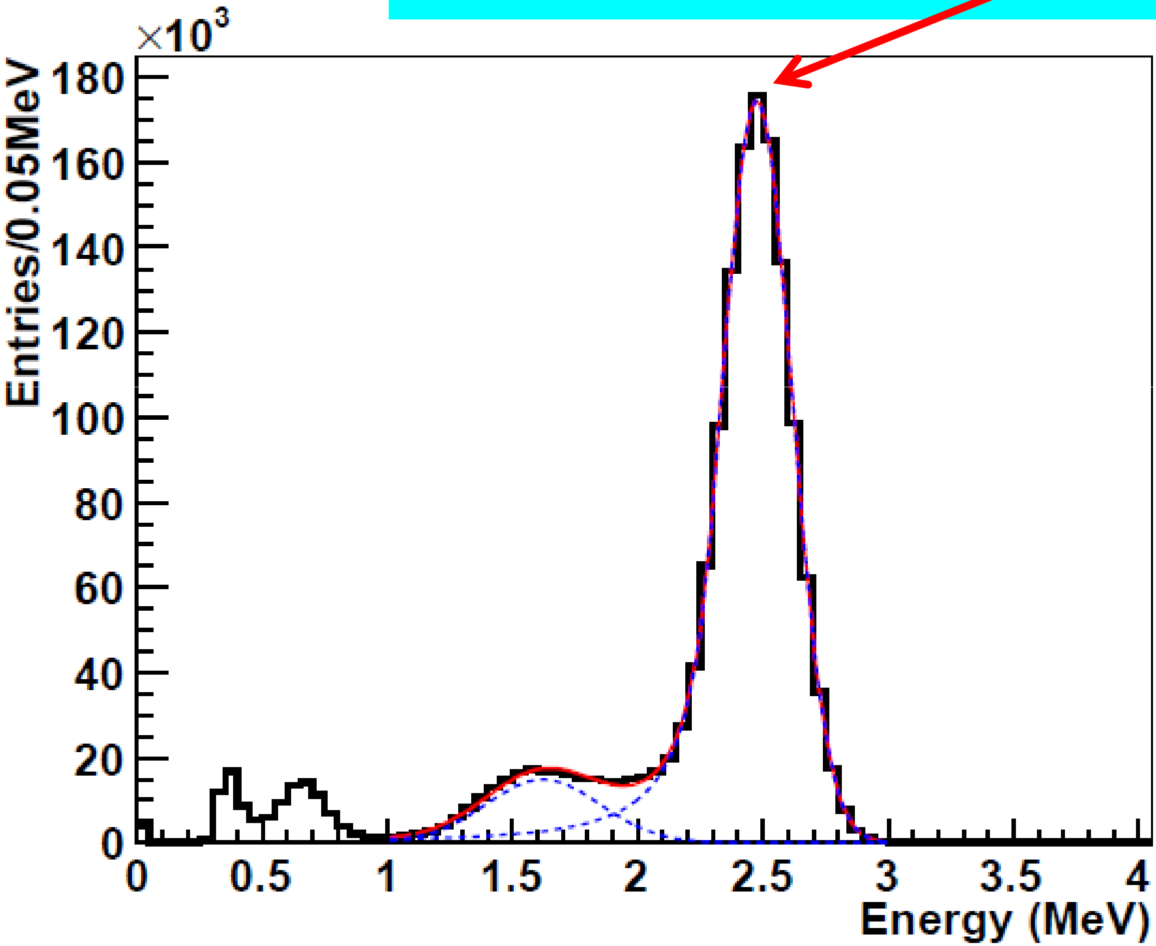
- Three Z axis:
  - **One at the center**
    - **For time evolution, energy scale, non-linearity…**
  - **One at the edge**
    - **For efficiency, space response**
  - **One in the γ-catcher**
    - **For efficiency, space response**
- 3 sources for each z axis:
  - **LED**
    - **for T_0, gain and relative QE**
  - **^{68}Ge (2$\times$0.511 MeV γ's)**
    - **for positron threshold & non-linearity…**
  - **^{241}Am-^{13}C + ^{60}Co (1.17+1.33 MeV γ's)**
    - **For neutron capture time, …**
    - **For energy scale, response function, …**
- Once every week:
  - **3 axis, 5 points in Z, 3 sources**



Automated Calibration

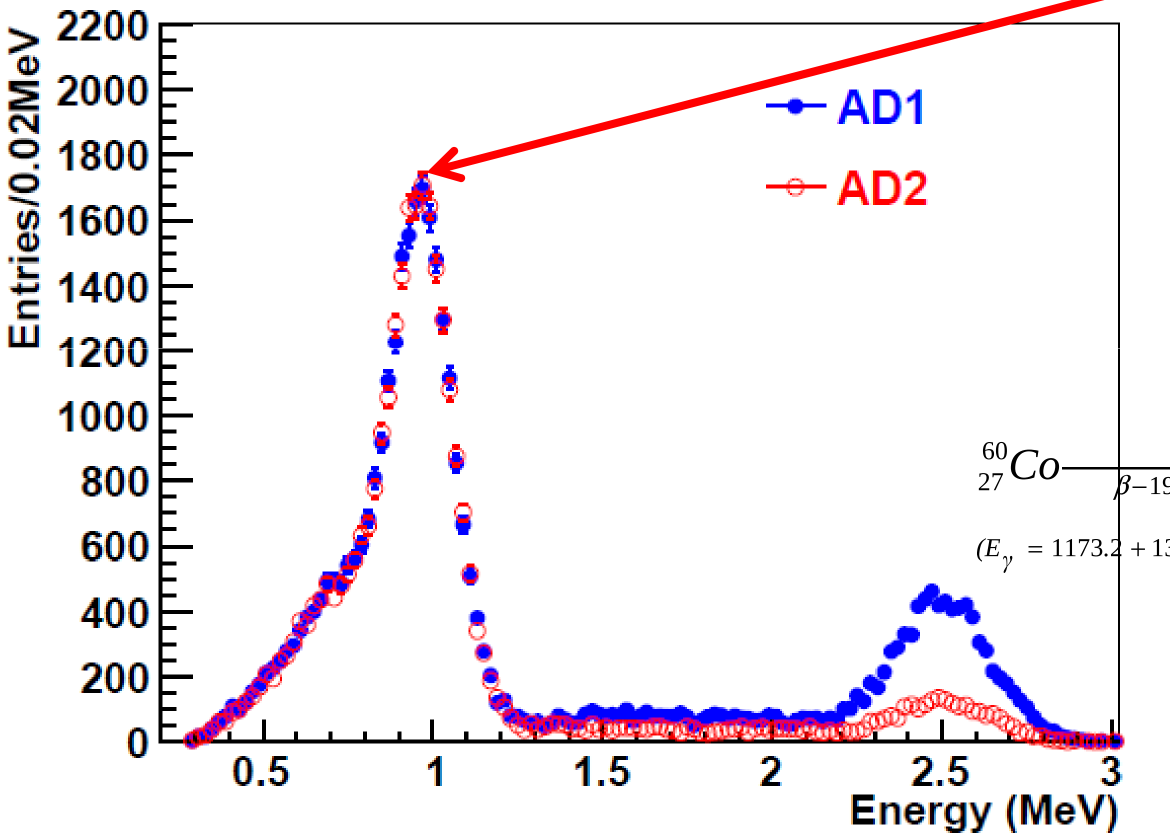
$$^{60}_{27}Co \xrightarrow[\beta - 1925d]{} {}^{60}_{28}Ni^{*} \longrightarrow {}^{60}_{28}Ni$$

$$(E_{\gamma} = 1173.2 + 1332.5 = 2505.7\,MeV)$$



$$^{68}_{32}Ge \xrightarrow[E.C.\,276d]{} {}^{68}_{31}Ga \xrightarrow[\beta+\,68m]{} {}^{68}_{30}Zn$$

$$e^{+} + e^{-} \rightarrow 2\times 511 keV\ \gamma$$



$$^{60}_{27}Co \xrightarrow[\beta-1925d]{} {}^{60}_{28}Ni^{*} \longrightarrow {}^{60}_{28}Ni$$

$(E_{\gamma} = 1173.2 + 1332.5 = 2505.7\, MeV)$

Figure 15: The energy spectrum of the ^{68}Ge source.

ENERGY RESOLUTION

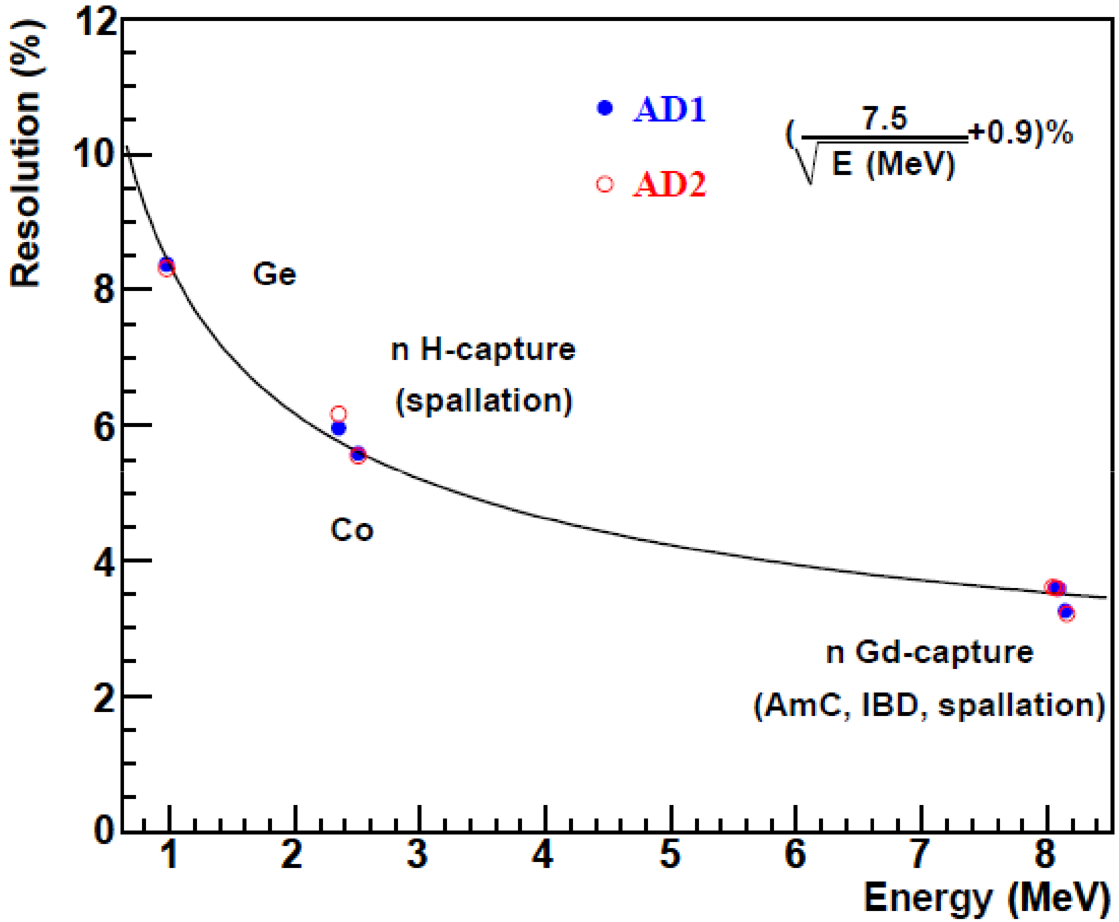
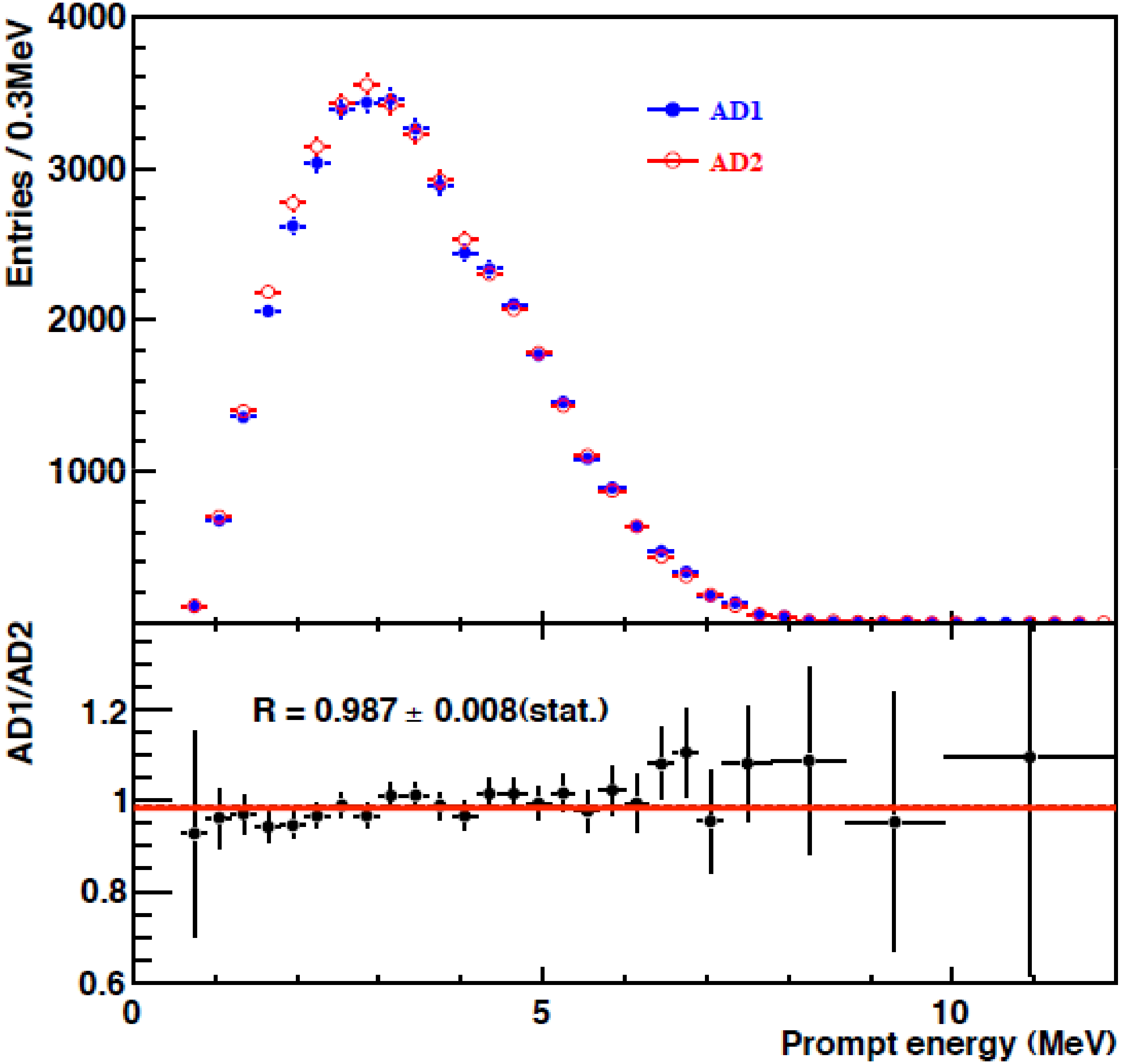


Figure 25: Resolution of reconstructed energy.

Detailed comparison of AD1 and AD2

arXiv:1202.6181

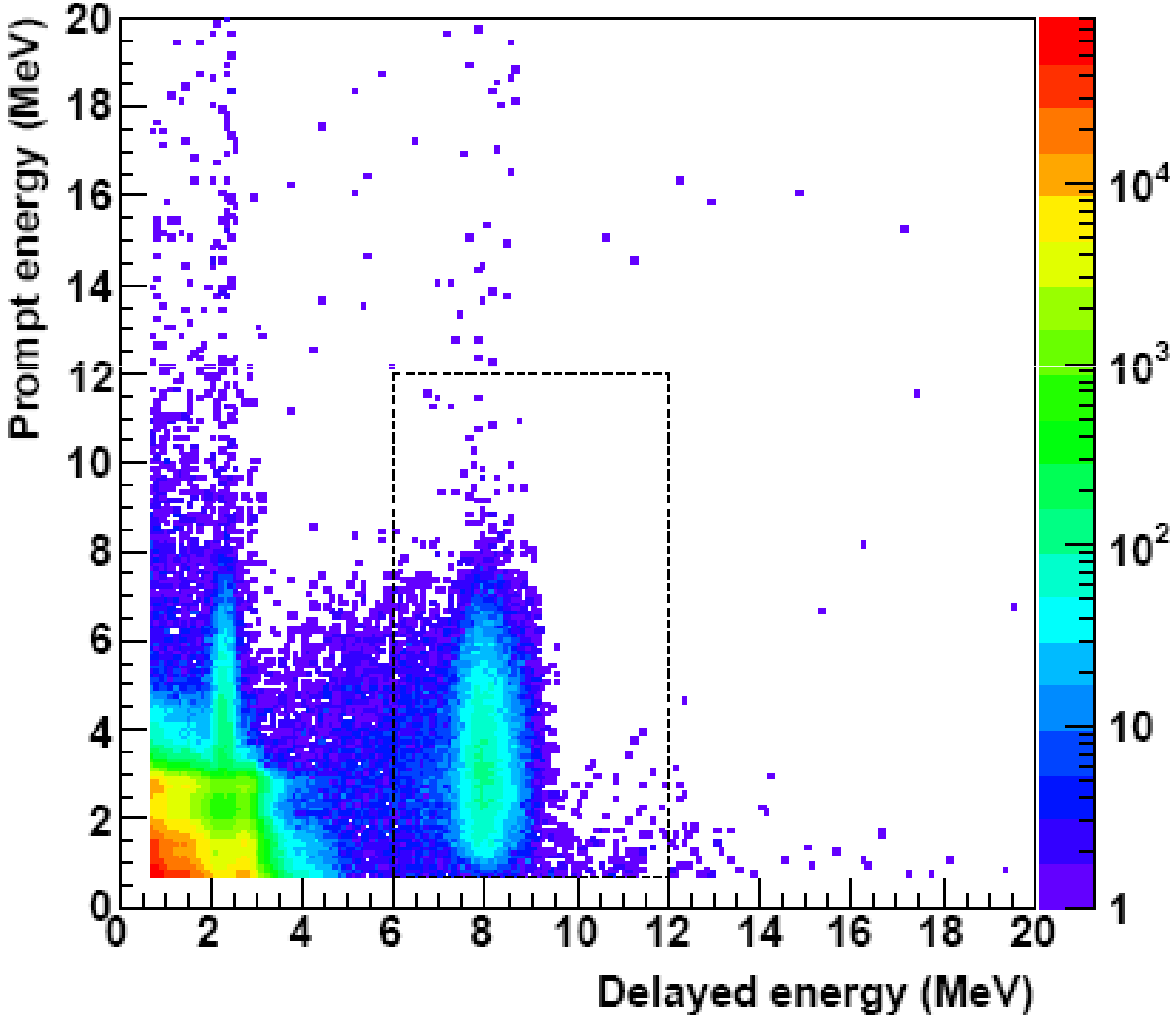


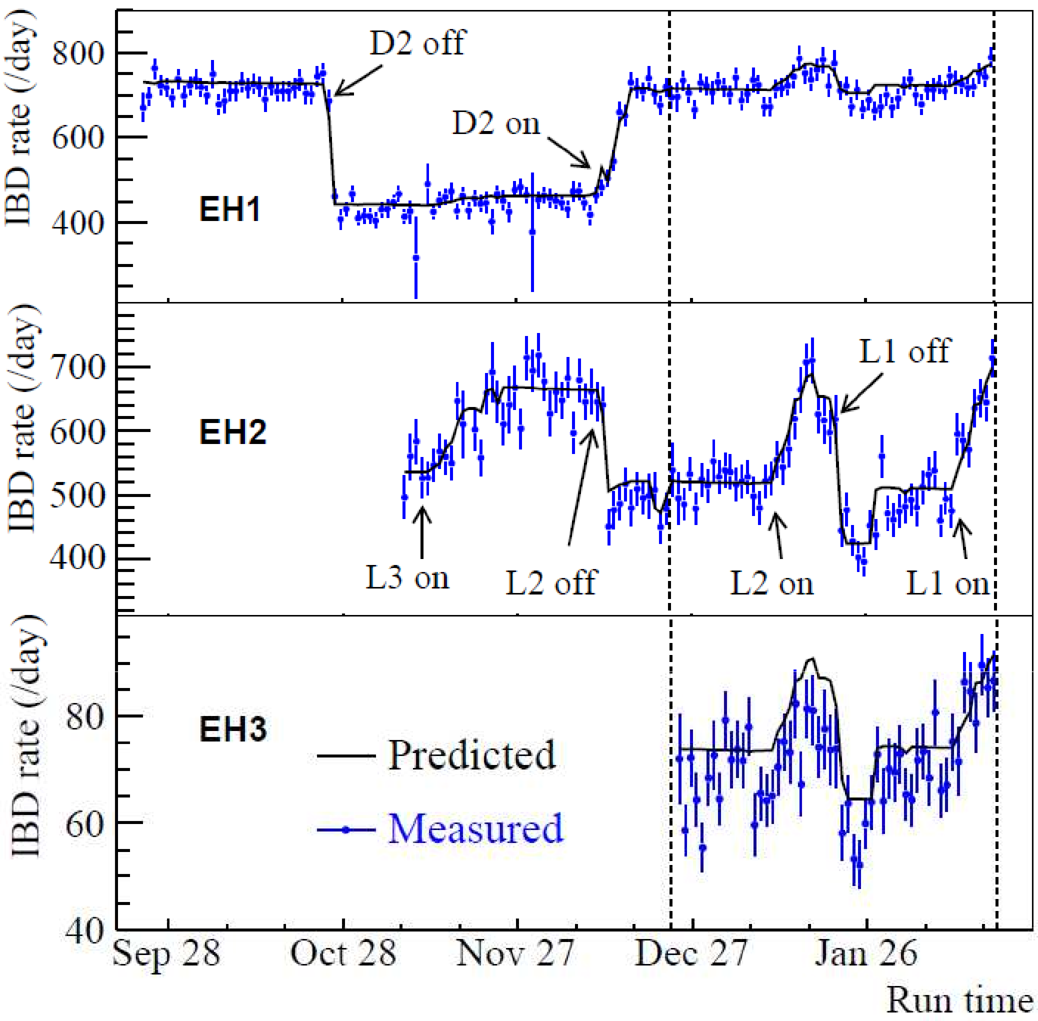
Antineutrino (IBD) Event Selection

- IBD Selection
  - Prompt positron: 0.7 MeV < E_p < 12 MeV
  - Delayed neutron: 6.0 MeV < E_d < 12 MeV
  - Capture Time: 1 μs < $\Delta t = t_{delayed} - t_{prompt}$ < 200 μs
- Muon Veto
  - Pool muon: veto following 0.6 ms
  - AD muon (> 20 MeV): veto following 1 ms
  - AD shower muon (>2.5 GeV): veto following 1 s
- Multiplicity
  - No other signal > 0.7 MeV within ±200 μs of IBD

Prompt positron + delayed neutron correlated signal is signature for IBD events

- **IBD Selection**
  - 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





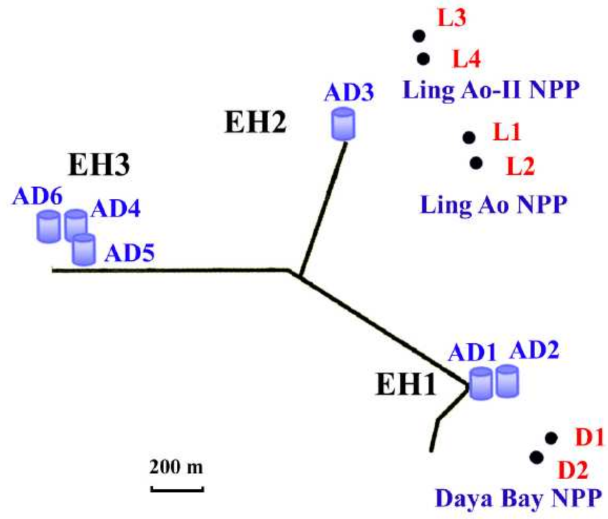
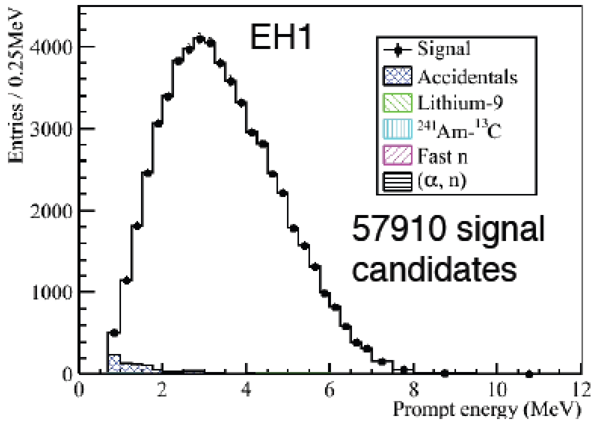


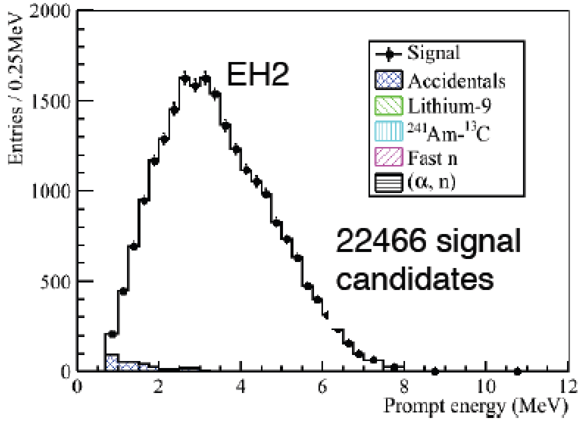
FIG. 3. Daily average measured IBD rates per AD in the three experimental halls as a function of time. Data between the two vertical dashed lines are used in this analysis. The black curves are no-oscillation predictions based on reactor flux analyses and detector simulation for comparison. The predictions have been corrected with the best-fit normalization parameters in determining $\sin^2 2\theta_{13}$.

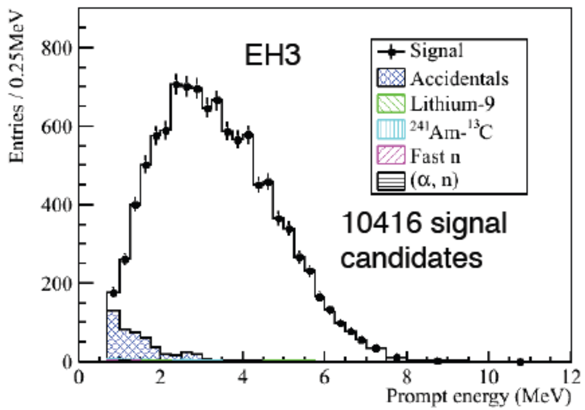
Backgrounds

	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	28935	28975	22466	3528	3436	3452
DAQ live time (day)	49.5530		49.4971	48.9473		
Muon veto time (day)	8.7418	8.9109	7.0389	0.8785	0.8800	0.8952
$\epsilon_\mu \cdot \epsilon_m$	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29 ±0.03	3.33 ± 0.03	3.12 ±0.03
Fast neutron (/day)	0.84±0.28	0.84±0.28	0.74±0.44	0.04±0.04	0.04±0.04	0.04±0.04
^{9}Li/^{8}He (/day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C correlated (/day)	0.2±0.2					
^{13}C(α, n)^{16}O background (/day)	0.04±0.02	0.04±0.02	0.035±0.02	0.03±0.02	0.03±0.02	0.03±0.02
IBD rate (/day)	714.17±4.58	717.86± 4.60	532.29±3.82	71.78 ± 1.29	69.80±1.28	70.39±1.28

TABLE II. Signal and backgrounds summary. The background and IBD rates are corrected for the $\epsilon_\mu \cdot \epsilon_m$ efficiency.







Li9 and He8 background

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

$$^{8}_{2}He \xrightarrow{119ms\,16\%} {}^{7}_{3}Li + e^{-} + \bar{\nu}_e + n$$

$$^{8}_{2}He \xrightarrow{84\%} {}^{8}_{3}Li^{*} + e^{-} + \bar{\nu}_e$$

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

$$^{8}_{3}Li \xrightarrow{840ms} {}^{8}_{4}Be + e^{-} + \bar{\nu}_e$$

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

$$^{9}_{3}Li \xrightarrow{178ms\,50\%} {}^{8}_{4}Be + e^{-} + \bar{\nu}_e + n$$

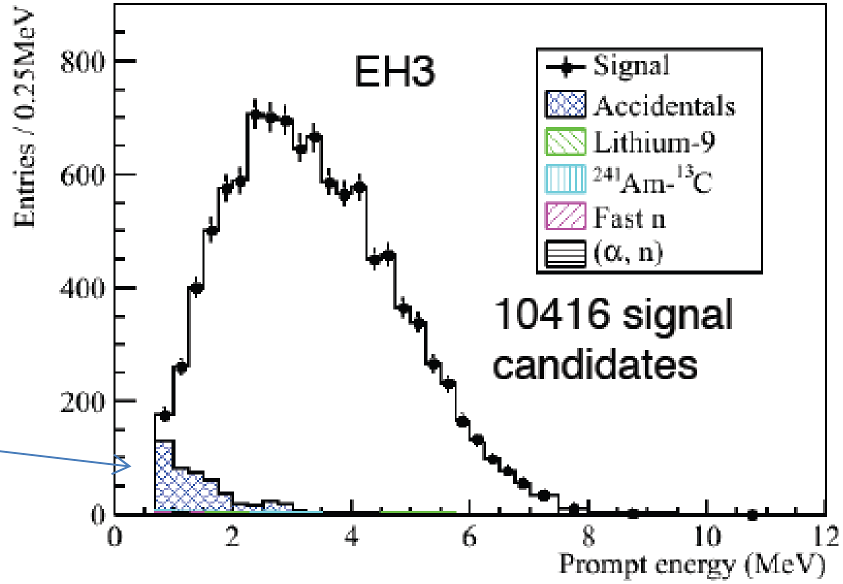
$$^{8}_{4}Be \rightarrow \alpha + \alpha$$

$$^{9}_{3}Li \xrightarrow{178ms\,50\%} {}^{9}_{4}Be + e^{-} + \bar{\nu}_e$$

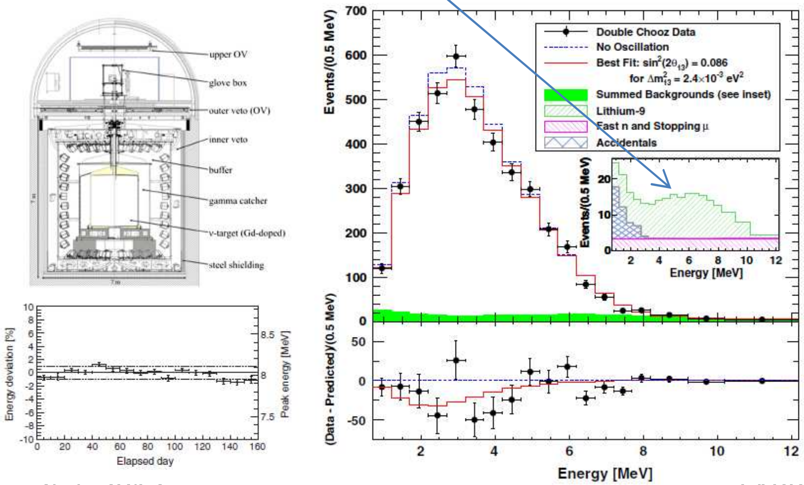
Muon VETO:

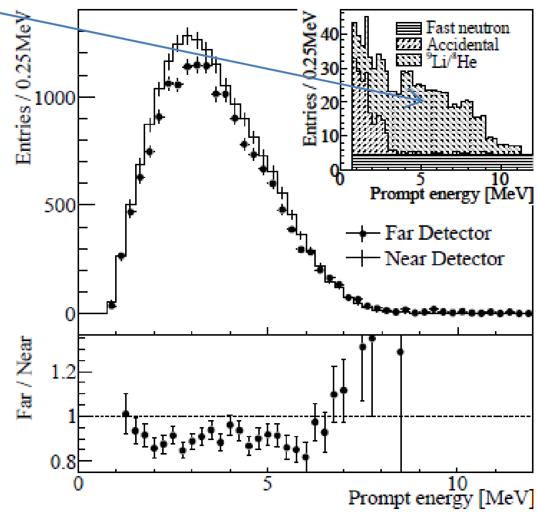
***1s* after an AD shower muon**

Results of large overburden and strict showering muons veto cut is that Daya Bay Li/He background is suppressed and the background is dominated by accidental coincidencies and is concentrated at low neutrino energies.



In Double Chooz and RENO the background is still dominated by decays of Li/He isotopes and spans the whole range of neutrino energies.





Systematic Uncertainties

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

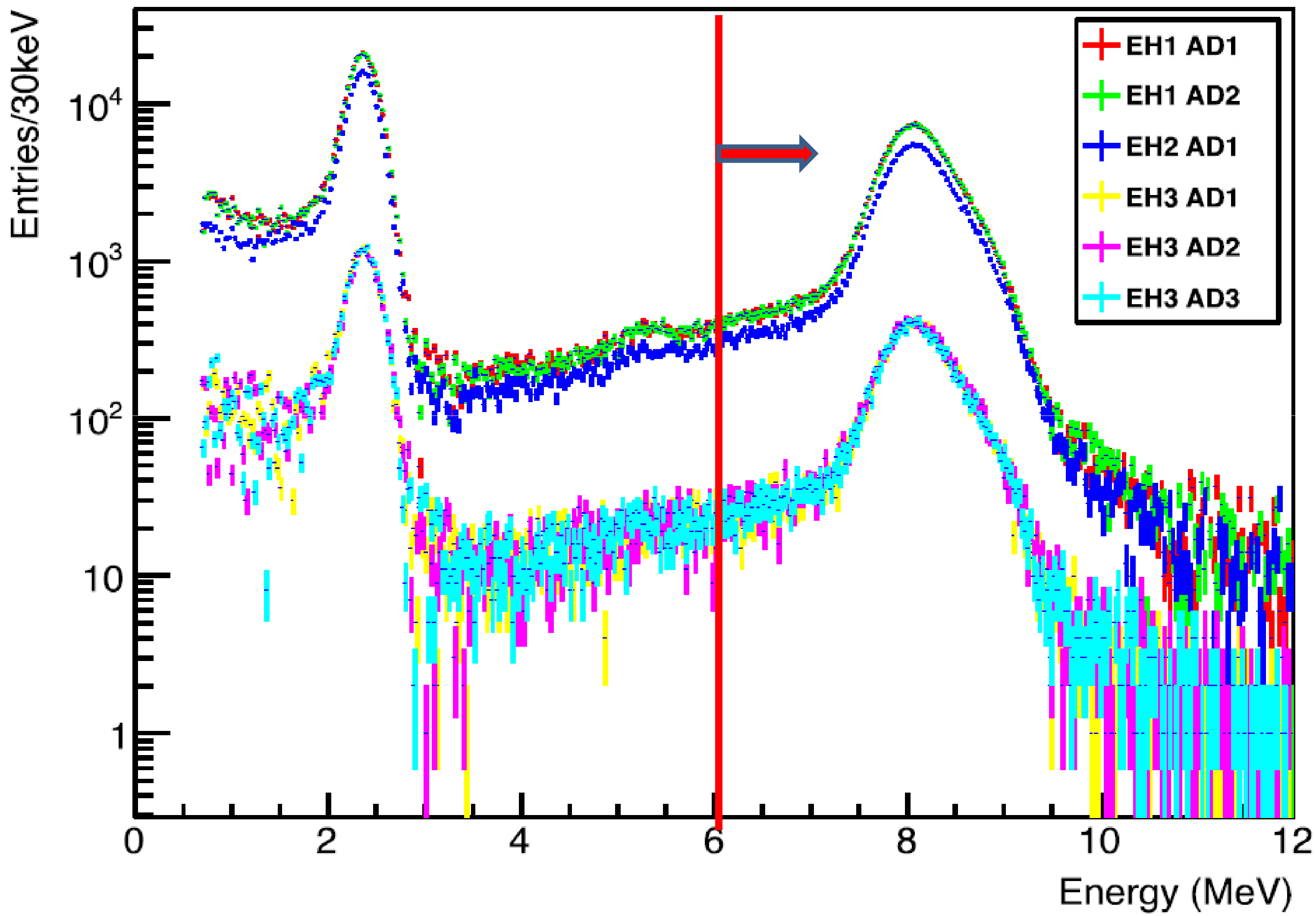
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

For oscillation analysis, only **uncorrelated** uncertainties are used.

Largest systematic uncertainties:
- Delayed energy cut
- Gd capture ratio
- Smaller than far site statistical uncertainty (1%)

Influence of uncorrelated reactor systematics (0.8%) is only **0.04%** on oscillation analysis.

DELAYED ENERGY CUT



Gd content is monitored by measurement of the time of neutron capture on Gd

$$\langle \tau \rangle = \frac{1}{\langle v_n \cdot \sigma \rangle \cdot N_{Gd}}$$

Very simplified estimation using Maxwell Boltzmann distribution of neutron velocities, app. cross section and Gd concentration gives:

$$\frac{dP}{dv} = \sqrt{\frac{2}{\pi}\left(\frac{m}{kT}\right)^3} v^2 e^{-\frac{mv^2}{2kT}} \Rightarrow m.p.\ \ v = \sqrt{\frac{2kT}{m_n}} \xrightarrow[T=20^o C]{} 2200 m/s$$

$$N_{Gd} = 0.103\% \cdot \rho \cdot \frac{N_A}{\langle A_{Gd} \rangle} = 0.00103 \cdot 0.86 g/cm^3 \cdot \frac{6.022/mol}{157.25 g/mol} = 3.29 \cdot 10^{18}/cm^3$$

$$\langle \sigma \rangle = (0.148 \cdot 60900 + 0.1565 \cdot 254000) \cdot 10^{-24} cm^2 = 4.876 \cdot 10^{-20} cm^2$$

$$\langle \tau \rangle = \frac{1}{v \cdot \langle \sigma \rangle \cdot N_{Gd}} = 28.3 \mu s$$

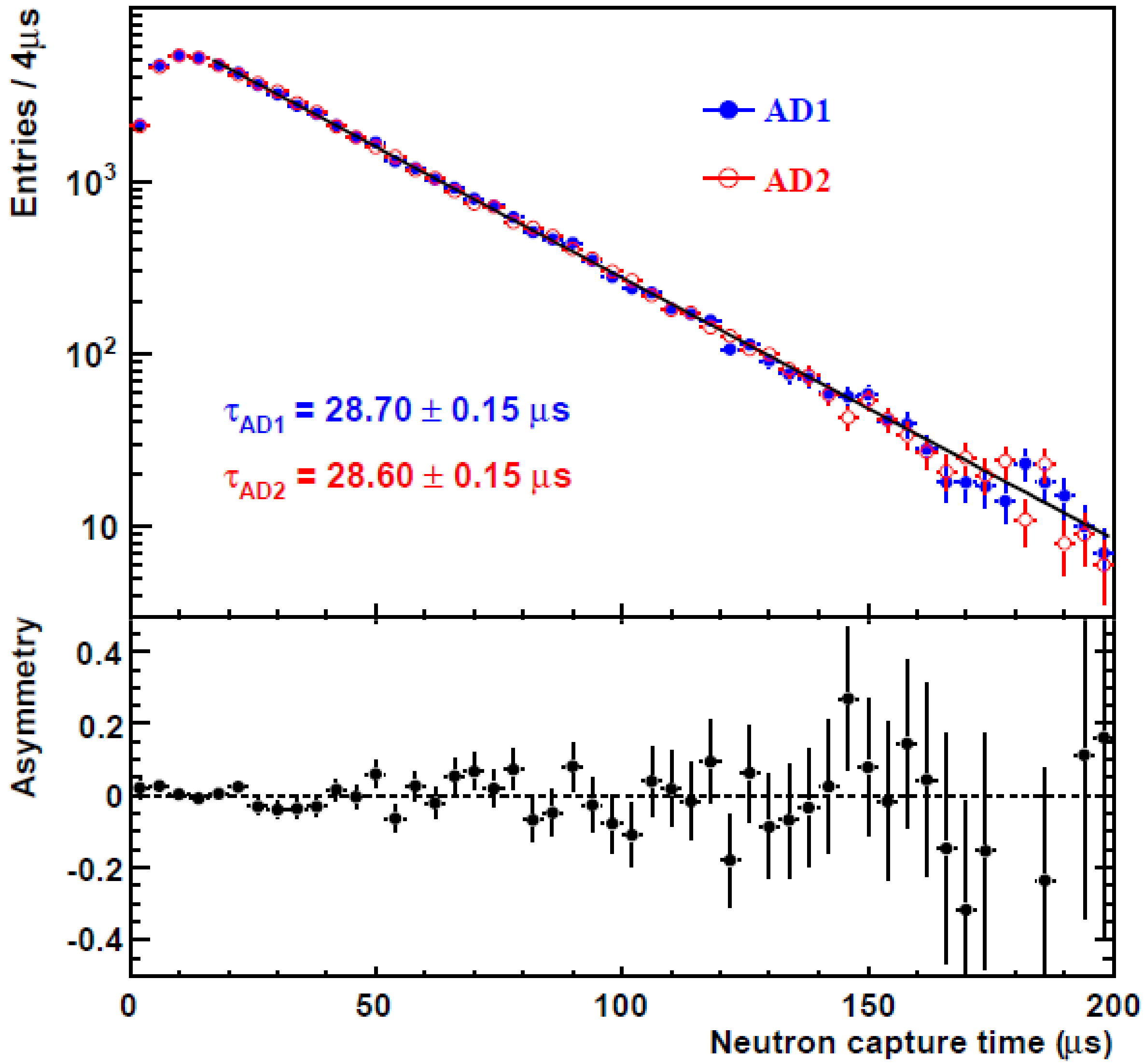
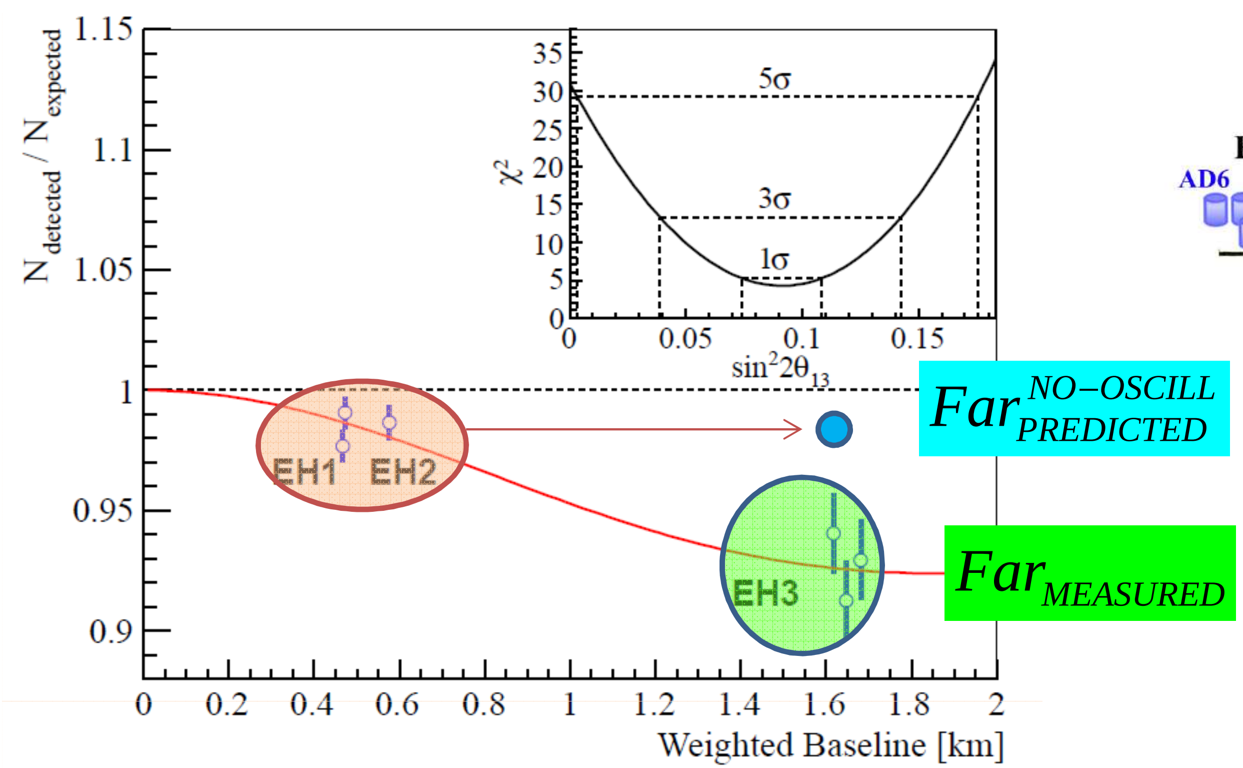
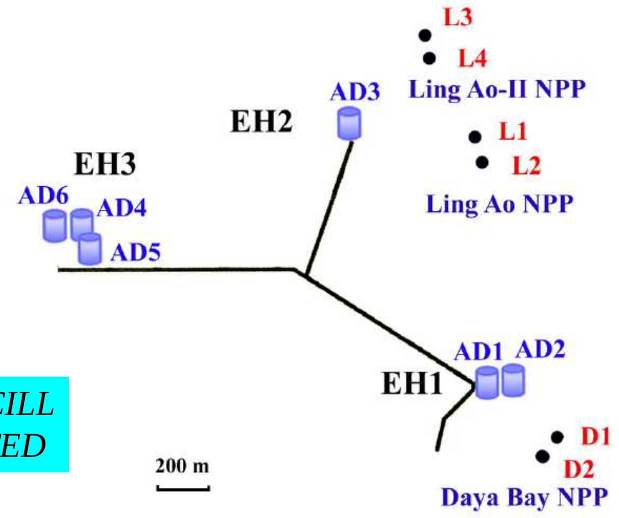


Figure 14: The neutron capture time on Gd from the Am-^{13}C source at the detector center.





$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n : measured rates in each detector.

Weights α_i,β_i : determined from baselines and reactor fluxes, no oscillations assumed.

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

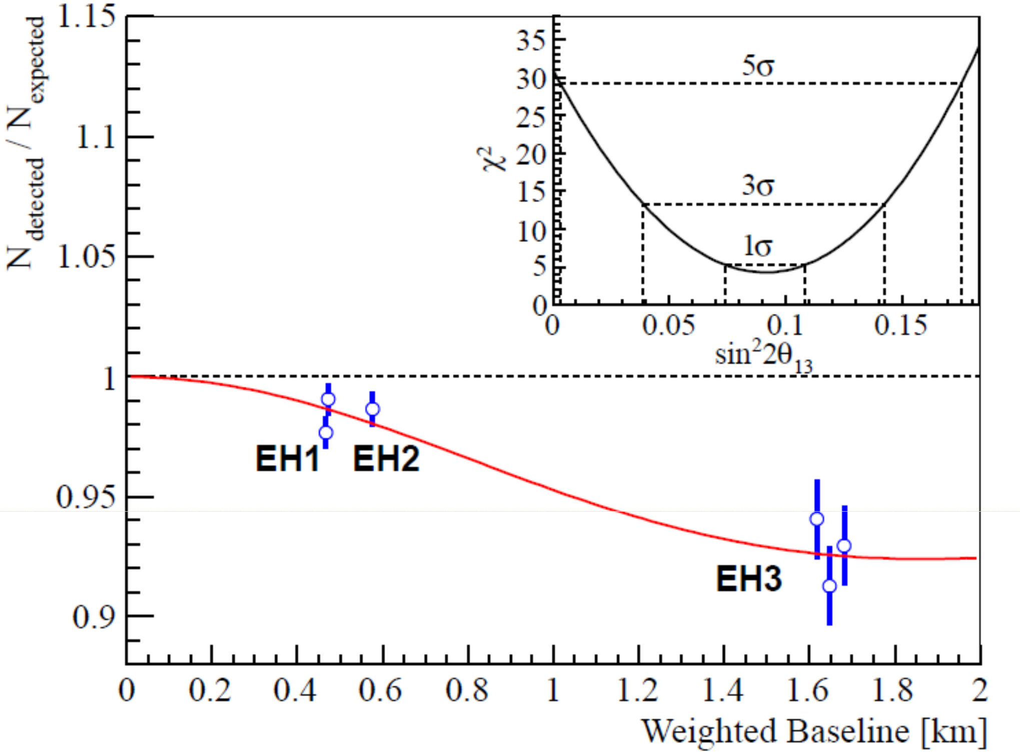
- Unambiguous observation of antineutrino deficit at the far site!

Rate-only analysis

❖ Determine θ_{13} using measured rates in each detector:

Uses standard χ^2 approach:
(χ^2/NDF=4.26/4)

$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1+\varepsilon+\sum_r \omega_r^d \alpha_r + \varepsilon_d\right) + \eta_d\right]^2}{M_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right),$$



Far vs. near relative measurement.
[Absolute rate is not constrained.]

Consistent results obtained by independent analyses, different reactor flux models.

$\sin^2 2\theta_{13}$ = 0.092 ± 0.016 (stat) ± 0.005 (syst)
$\sin^2 2\theta_{13}$ = 0 excluded at 5.2σ

$$\theta_{13} \cong 8.8^o$$

The smallest lepton mixing angle is comparable to largest (Cabibbo) quark mixing angle.

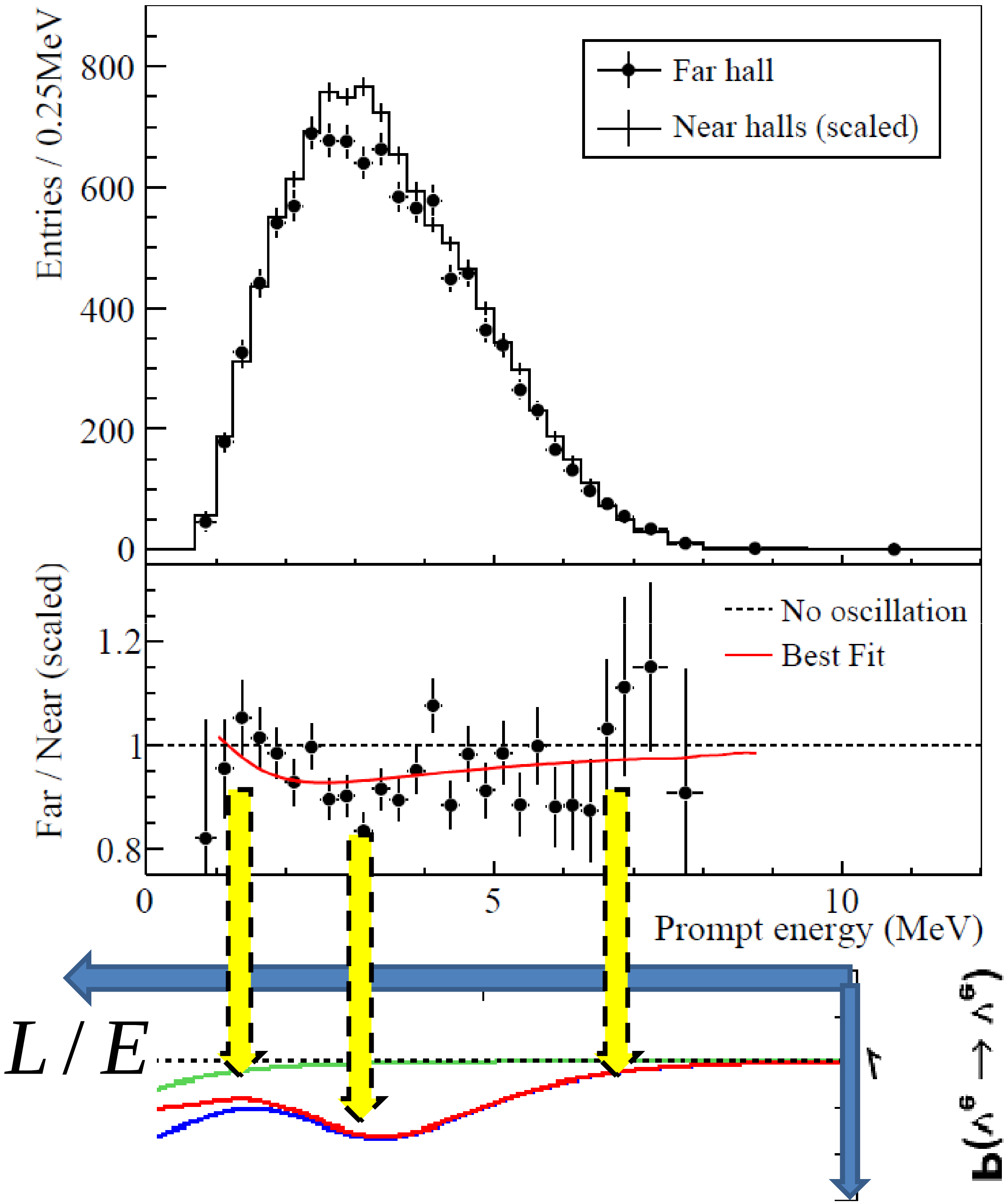
The disagreement of the spectra in far and near hall provides further evidence of neutrino oscillation.

The ratio of the spectra is consistent with the best-fit oscillation solution of

$\sin^2 2\theta_{13} = 0.092$

obtained from the rate-only analysis.

Currently the result is only from rate analysis!



Global situation of θ_{13}

Daya Bay

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

Phys.Rev.Lett. 108 (2012) 171803

Previous results suggest a non-zero θ_{13}

T2K

$$0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$$

PRL 107, 041801 (2011)

MINOS

$$2\sin^2(\theta_{23})\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$$

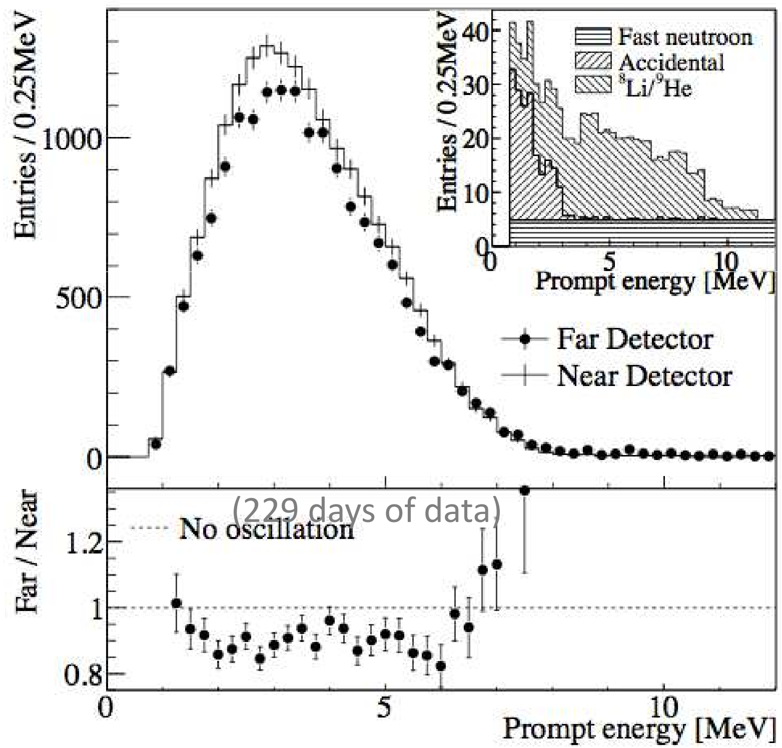
PRL. 107, 181802 (2011)

Double Chooz

$\sin^2(2\theta_{13}) = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$

Y. Abe et al. PRL 108 131801 (2012)

Recent results from RENO



(229 days of data)

$\sin^2 2\theta_{13} = 0.113 \pm 0.013\ (\text{stat}) \pm 0.019\ (\text{syst})$

(http://arxiv.org/pdf/1204.0626v2.pdf)

CONCLUSIONS

-Daya Bay experiment has started to take data with 3 far and 3 near detectors on December 24, 2011

-Daya Bay has the highest sensitivity to θ_{13} among all the other experiments that are currently in operation or under construction

-With 43 ktons x GW x day exposure in 55 days, the (6.0 +- 1.1(stat) +- 0.4(syst)) % deficit of neutrino flux in far detectors has been measured

-This result implies the value of

$\sin^2 2\theta_{13}$ =0.092 +- 0.016(stat) +- 0.005(syst)

with a significance of 5.2 σ