Observation of Electron-antineutrino Disappearance at Daya Bay

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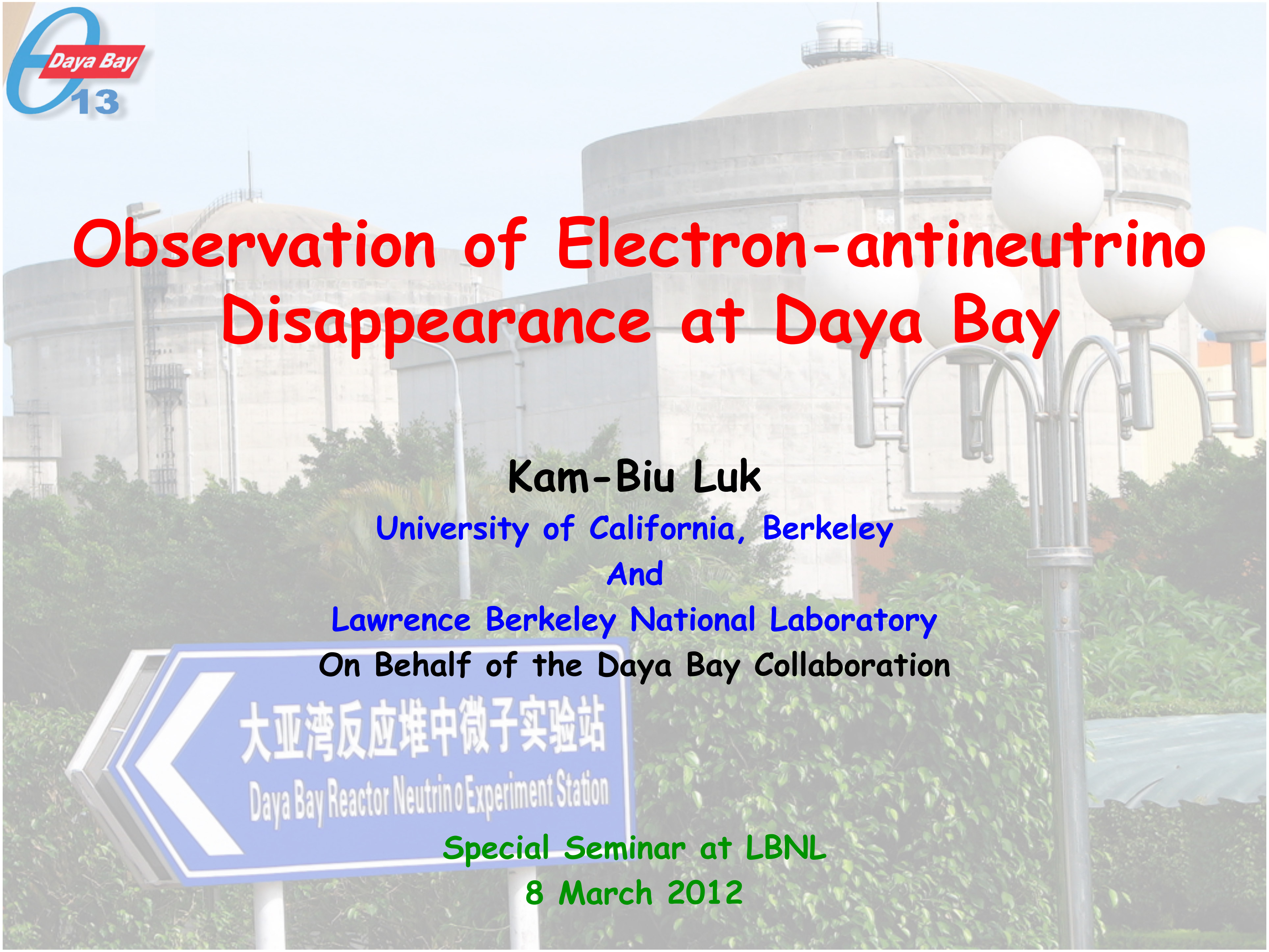
On Behalf of the Daya Bay Collaboration



Special Seminar at LBNL
8 March 2012

Neutrino Mixing

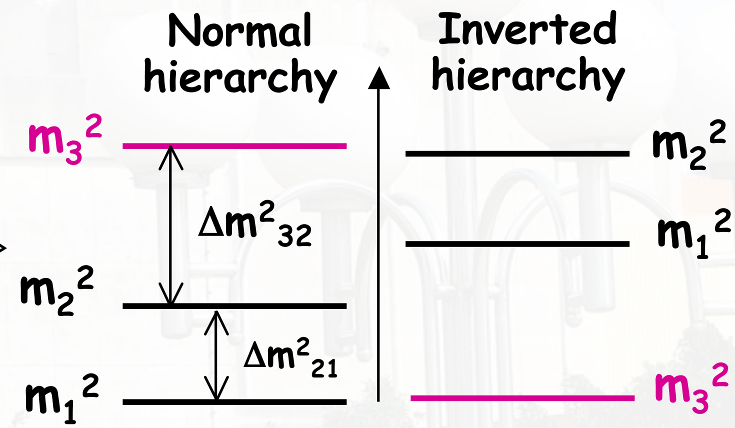
- Neutrino flavour eigenstates ≠ Mass eigenstates

$$\Downarrow$$

Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata Matrix



$$\Downarrow$$

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

$\theta_{12} = 33° \pm 1°$ θ_{13} and δ ? $\theta_{23} \approx 42° \pm 3°$

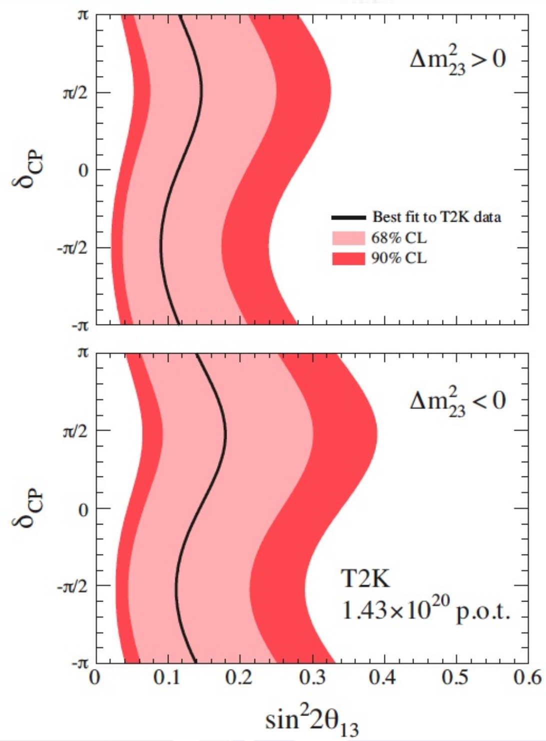
- Mass-squared differences: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}| \approx |\Delta m^2_{32}| = (2.45 \pm 0.09) \times 10^{-3}\, eV^2$

$\Downarrow$ $(7.6 \pm 0.2) \times 10^{-5}$ eV^2

New J. Phys. **13**(2011)063004

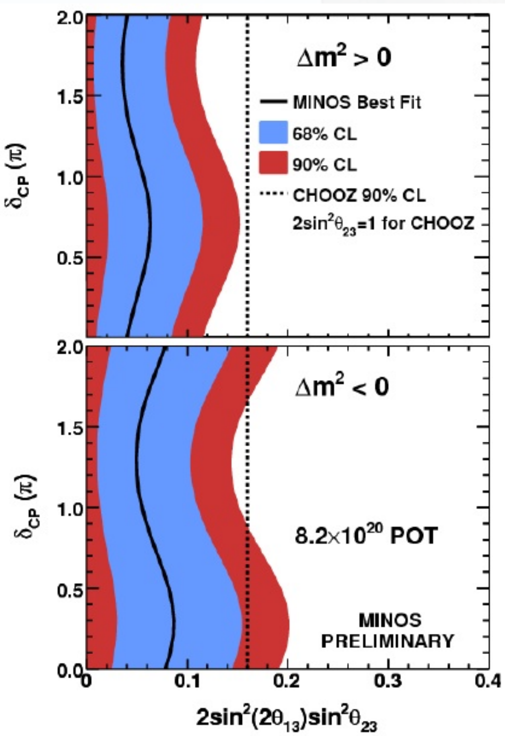
Current Knowledge of θ_{13}

T2K



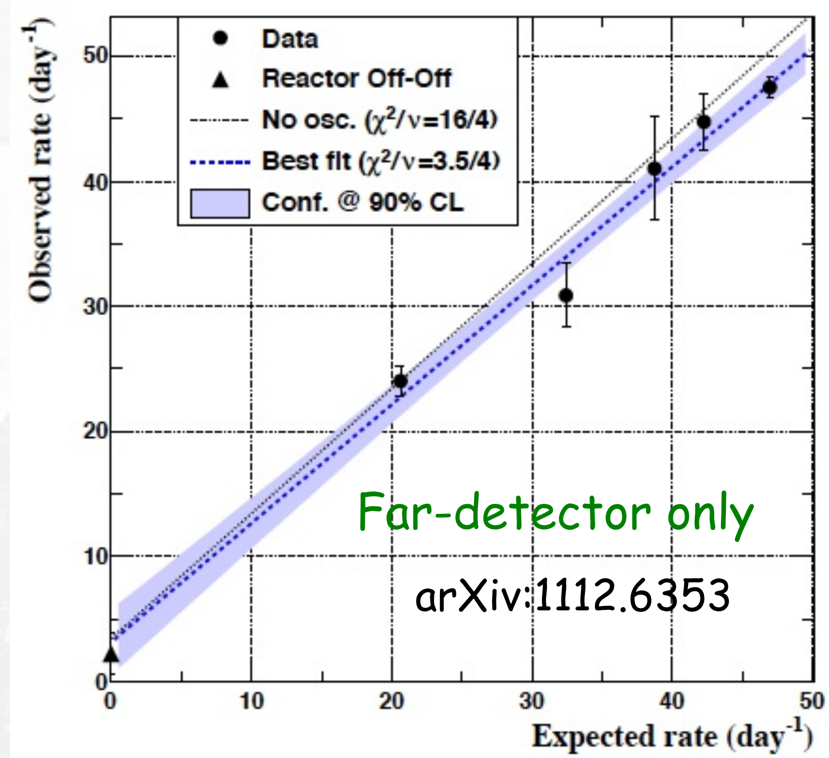
PRL **107**,041801 (2011)

MINOS



PRL **107**, 181802 (2011)

Double Chooz



$$\frac{N_{obs}}{N_{pre}} = 0.944 \pm 0.016 \pm 0.040$$

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041 \pm 0.030$$

Some hints of a non-zero θ_{13}

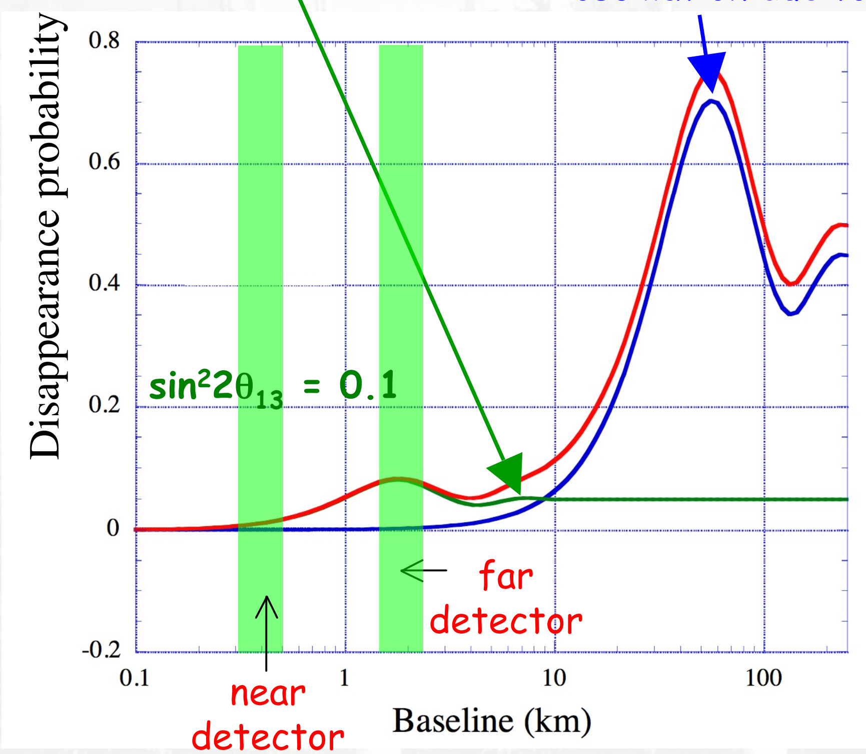
Determining θ_{13} With Reactor $\bar{\nu}_e$

- Look for disappearance of electron antineutrinos from reactors:

$$P(\bar{\nu}_e \to x) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}



- Perform a relative measurement:

$$\frac{R_{Far}}{R_{Near}} = \left(\frac{L_{Near}}{L_{Far}}\right)^2 \left(\frac{N_{Far}}{N_{Near}}\right) \left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right) \left(\frac{1-P_{Far}}{1-P_{Near}}\right)$$

$\bar{\nu}_e$ rate	$1/r^2$	number of protons	detection efficiency	yield $\sin^2 2\theta_{13}$

All correlated errors cancelled.

The Daya Bay Collaboration

Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

LBNL, BNL, Caltech, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary

Asia (20)

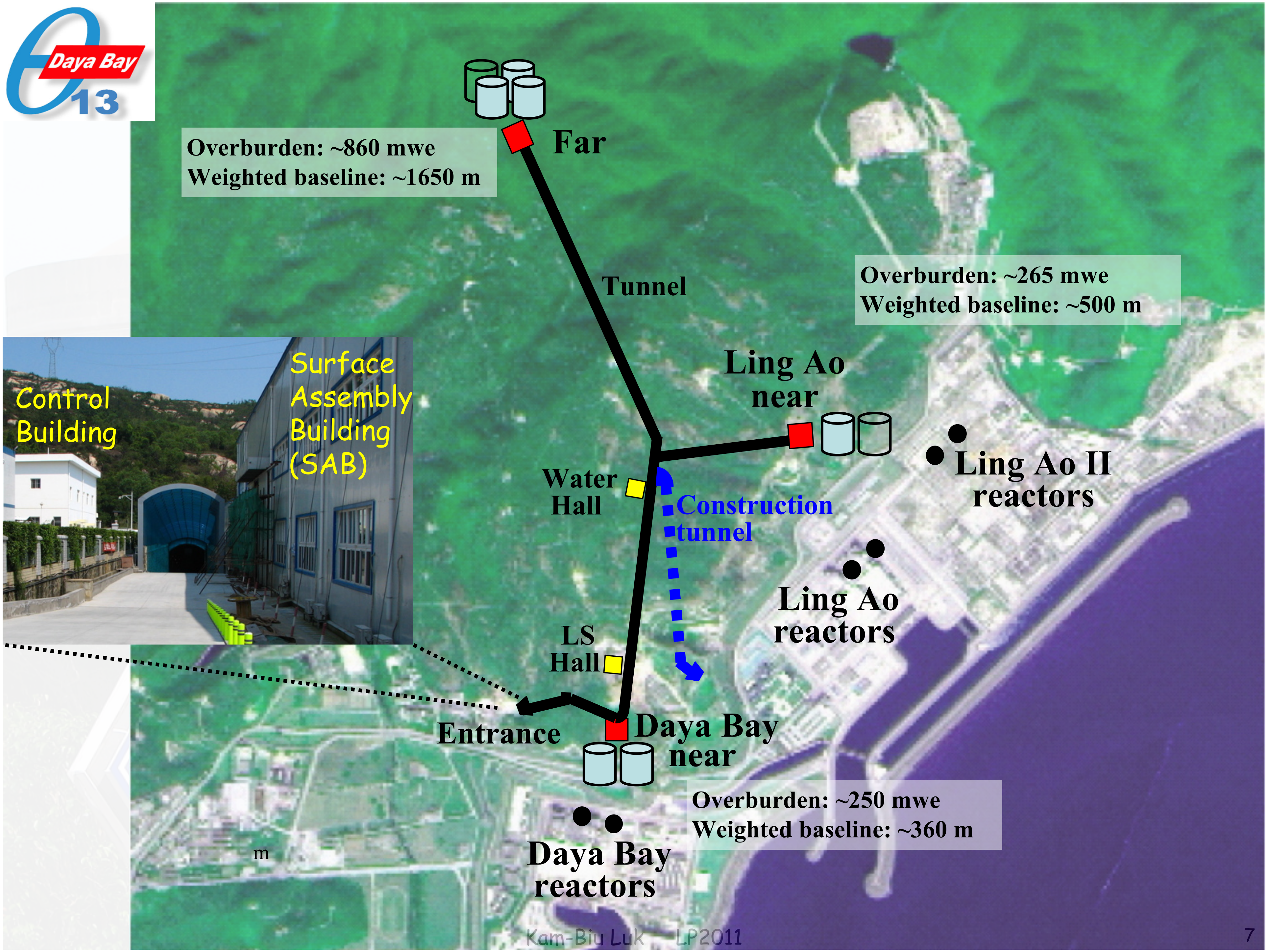
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Univ.Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National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

~230 Collaborators

Daya Bay Nuclear Power Complex

- ~55 km from Hong Kong central
- All 6 reactors are in commercial operation
- one of top 5 most powerful nuclear power plants in the world

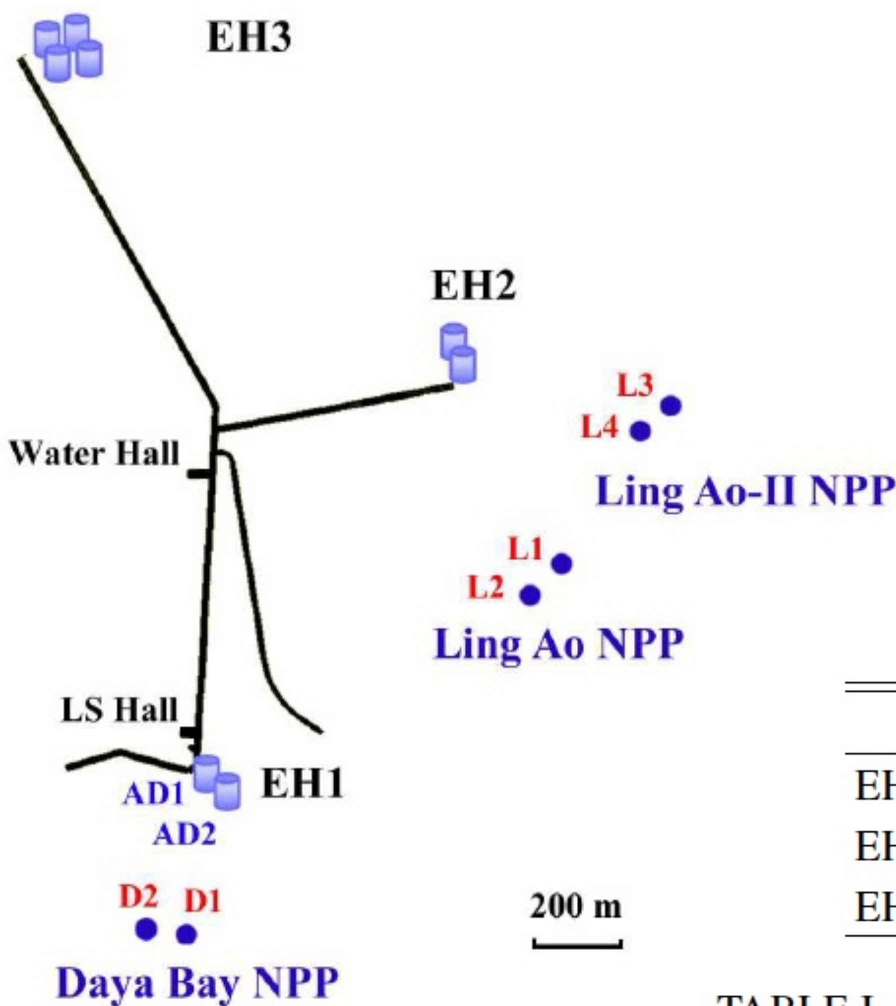
$6 \times 2.95\ GW_{th} = 17.7\ GW_{th}$


Far
Overburden: ~860 mwe
Weighted baseline: ~1650 m
Tunnel
Overburden: ~265 mwe
Weighted baseline: ~500 m
Ling Ao near
Ling Ao II reactors
Control Building
Surface Assembly Building (SAB)
Water Hall
Construction tunnel
Ling Ao reactors
LS Hall
Entrance
Daya Bay near
Overburden: ~250 mwe
Weighted baseline: ~360 m
Daya Bay reactors

Baselines

Detailed Survey:
- GPS above ground
- Total Station underground
- Final precision: 28mm

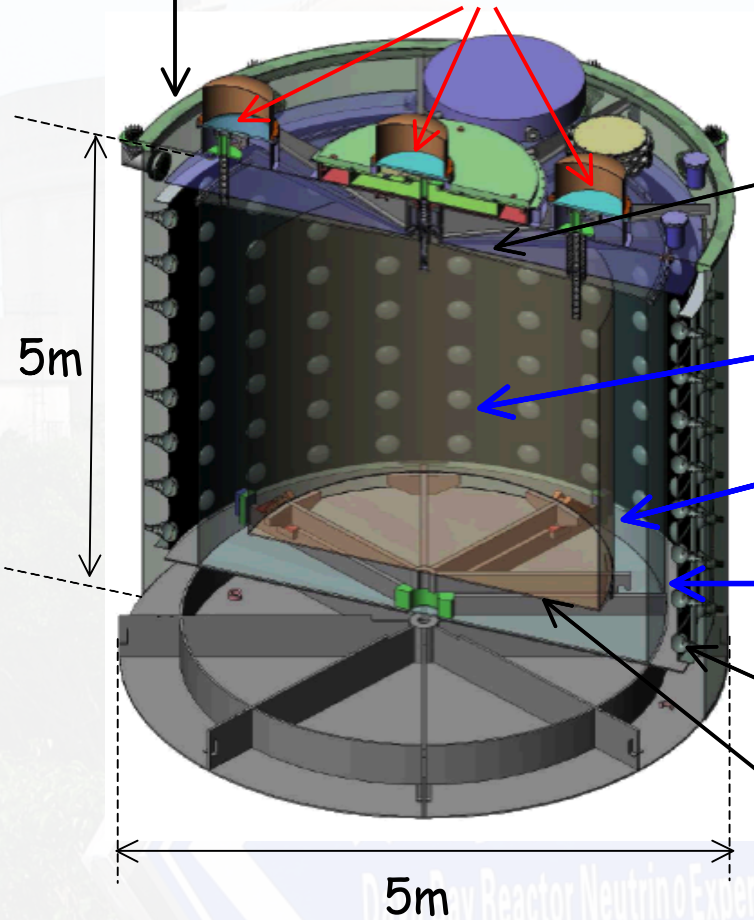
Validation:
- 3 independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans



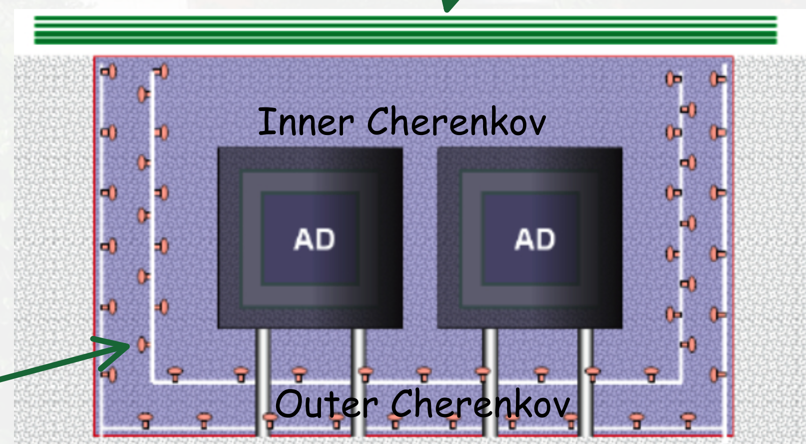
	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

Daya Bay Detector Design



Four layers of RPC's to tag muons



2.5m water:
- attenuates gamma rays & neutrons
- forms two optically decoupled Cherenkov counters

Detecting Reactor $\overline{\nu}_e$

- Use the inverse β-decay reaction in Gd-doped liquid scintillator:

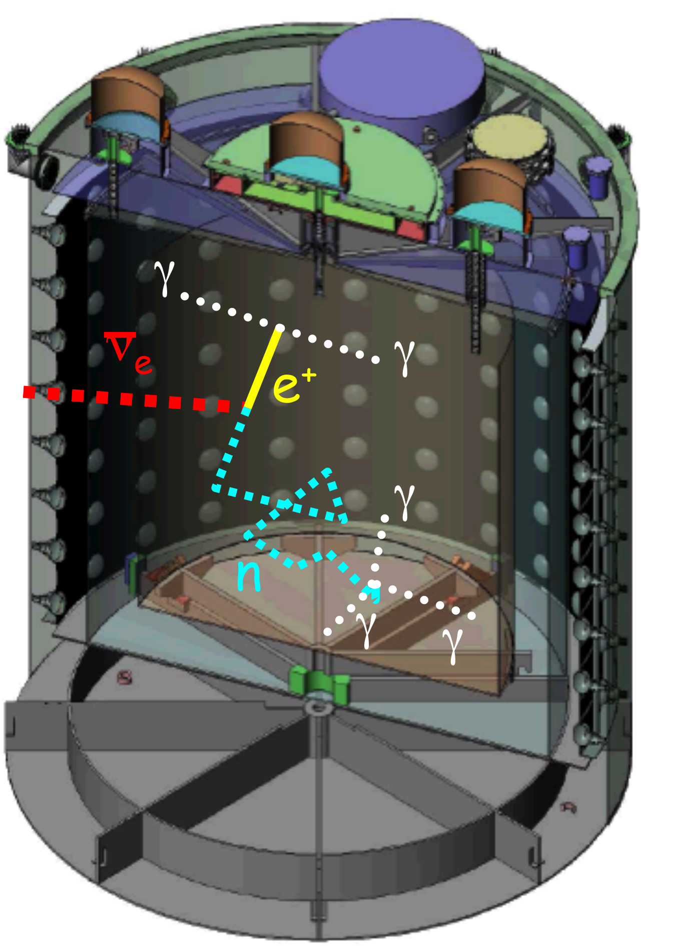
$$\overline{\nu}_e + p \rightarrow e^+ + n \quad \text{(prompt signal)}$$

~180μs → $+ p \rightarrow D + \gamma(2.2\ \text{MeV})$ (delayed signal)

→ $+ Gd \rightarrow Gd^*$

~30μs for 0.1% Gd

→ $Gd + \gamma\text{'s}(8\ \text{MeV})$ (delayed signal)



- Energy of $\overline{\nu}_e$ is given by:

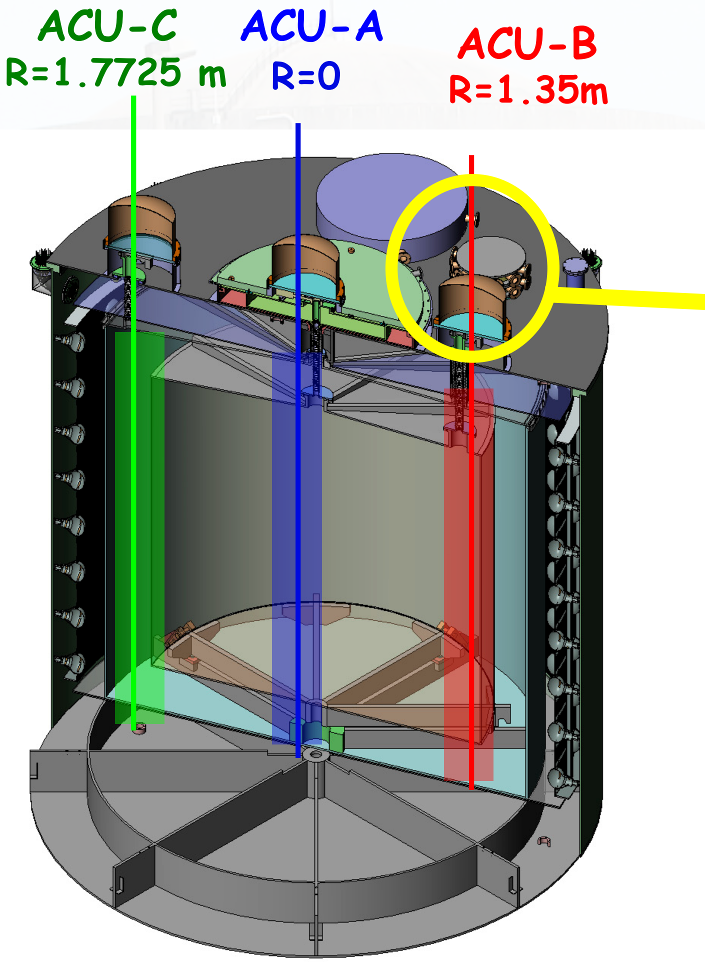
$$E_\nu \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$

10-40 keV

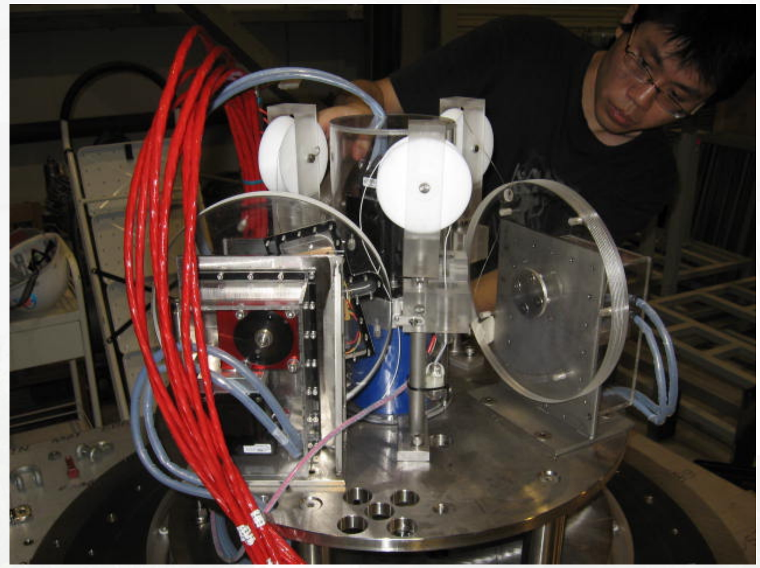
- Time- and energy-tagged signal is a good tool to suppress background events.

Calibration System of Antineutrino Detectors

3 Automatic calibration 'robots' (ACUs) on each detector



Three axes: center, edge of target, middle of gamma catcher

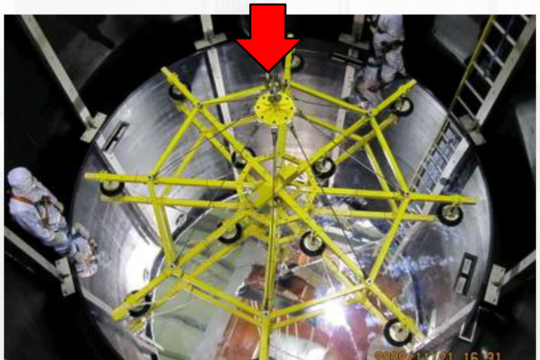


3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz ^{68}Ge (2×0.511 MeV γ's)
- 0.5 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for PMT gain and timing

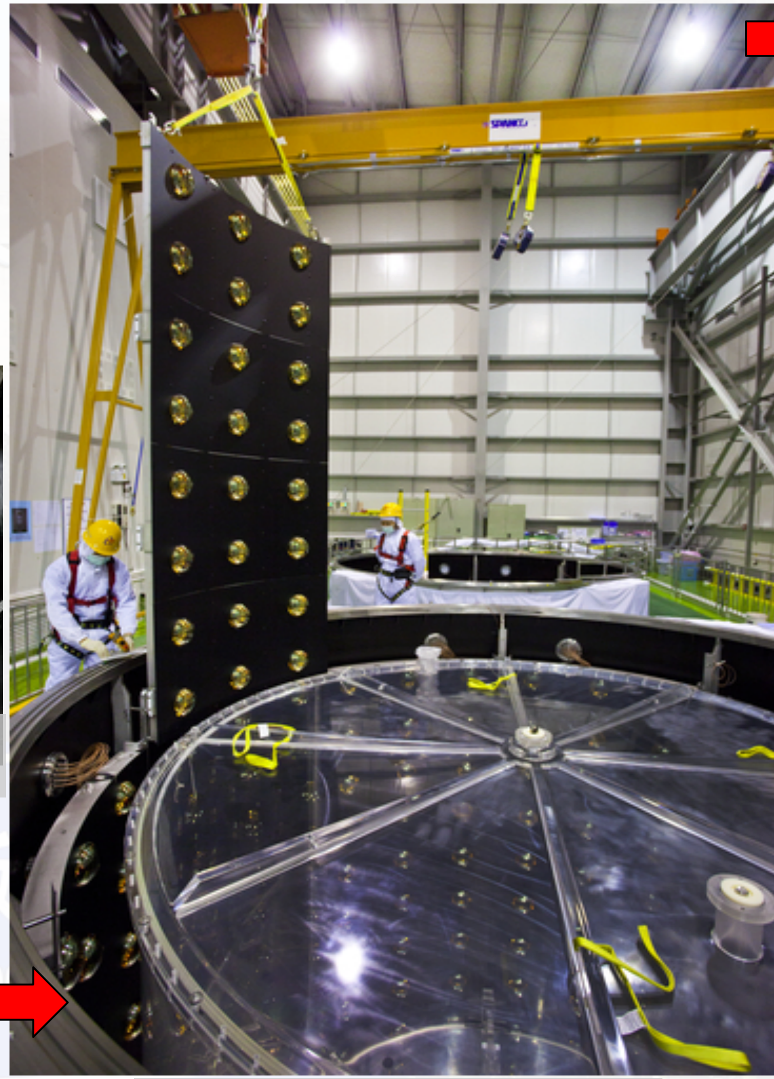
Assemble Antineutrino Detectors

Stainless Steel Vessel (SSV) in assembly pit



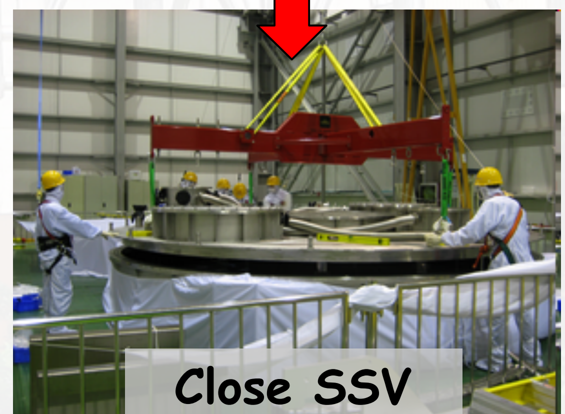
Install lower reflector

Install Acrylic Vessels

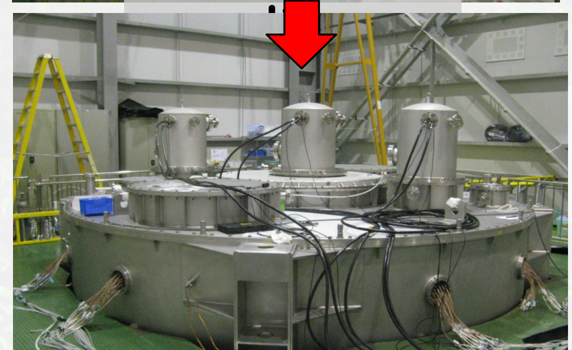


Install PMT ladders

Install top reflector



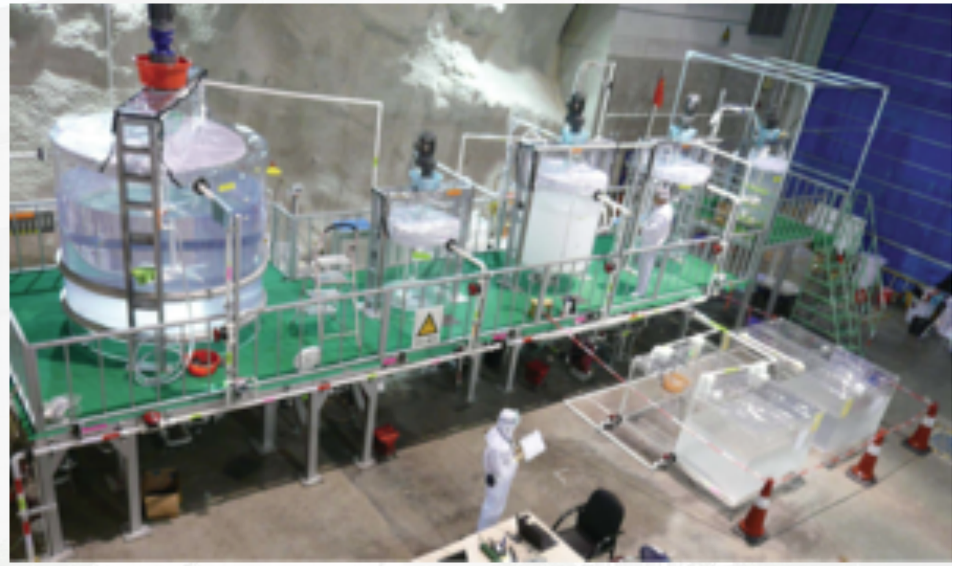
Close SSV

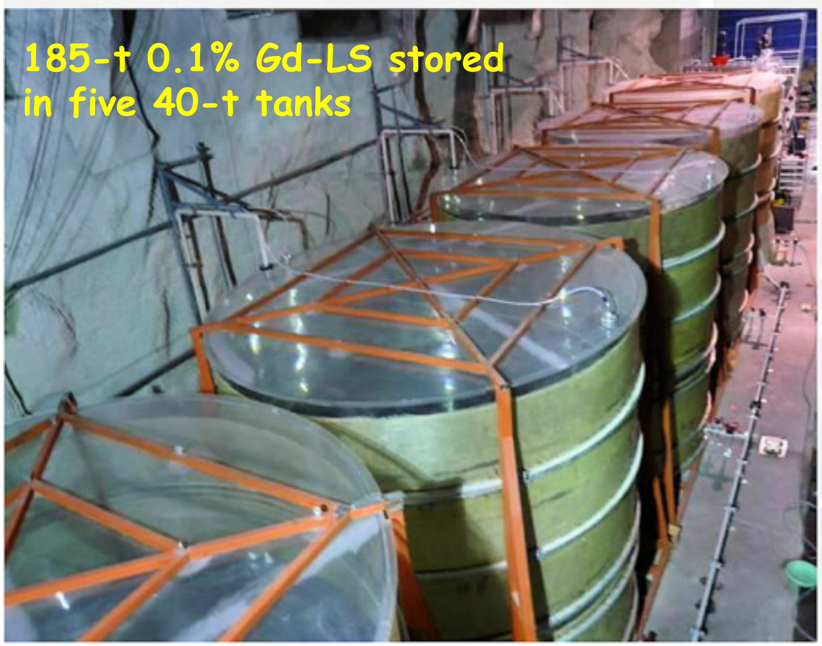


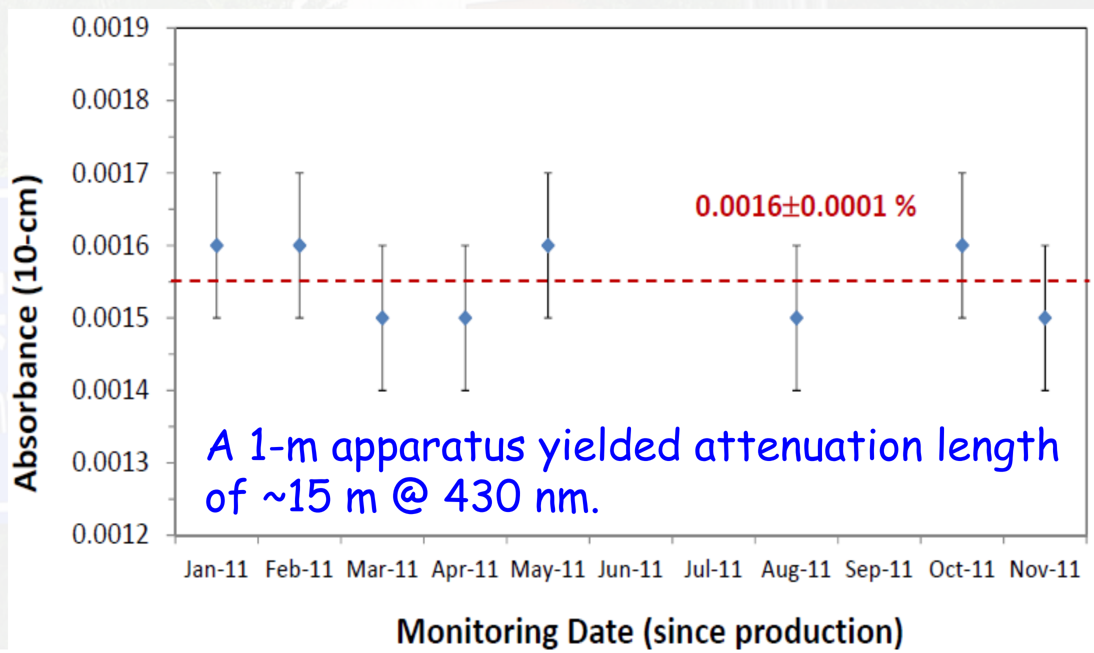
Install calibration units

Liquid Scintillators

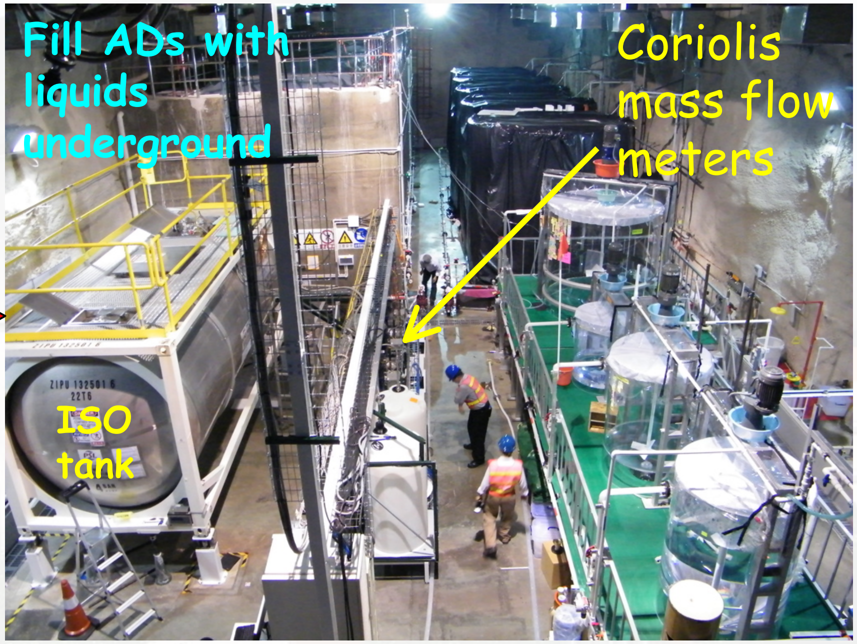
- Gd (0.1%) + PPO (3 g/L) + bis-MSB (15 mg/L) + LAB
- Number of proton: (7.169±0034) × 10^{25} p per kg
- 185-ton Gd-LS + 196-ton LS production







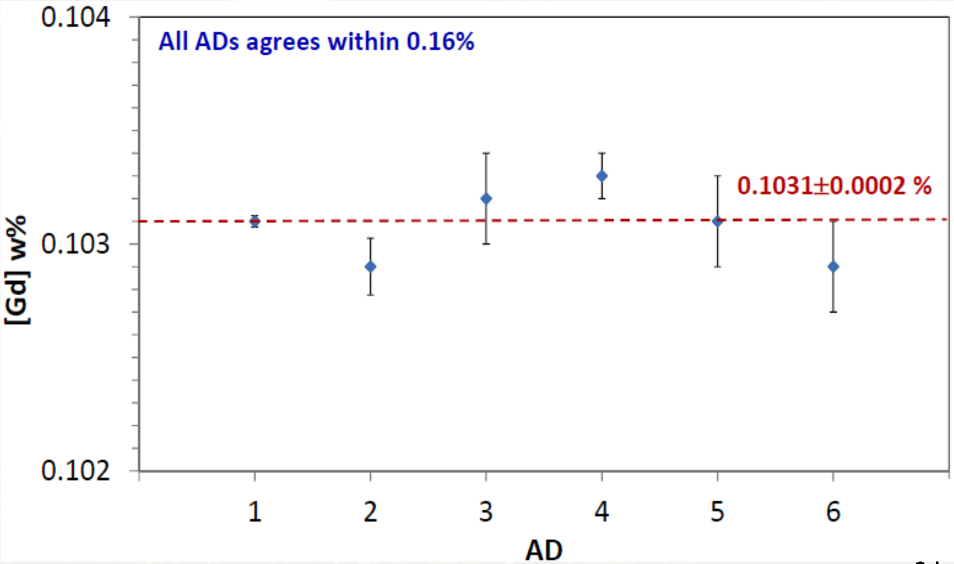
Fill Antineutrino Detectors (ADs)



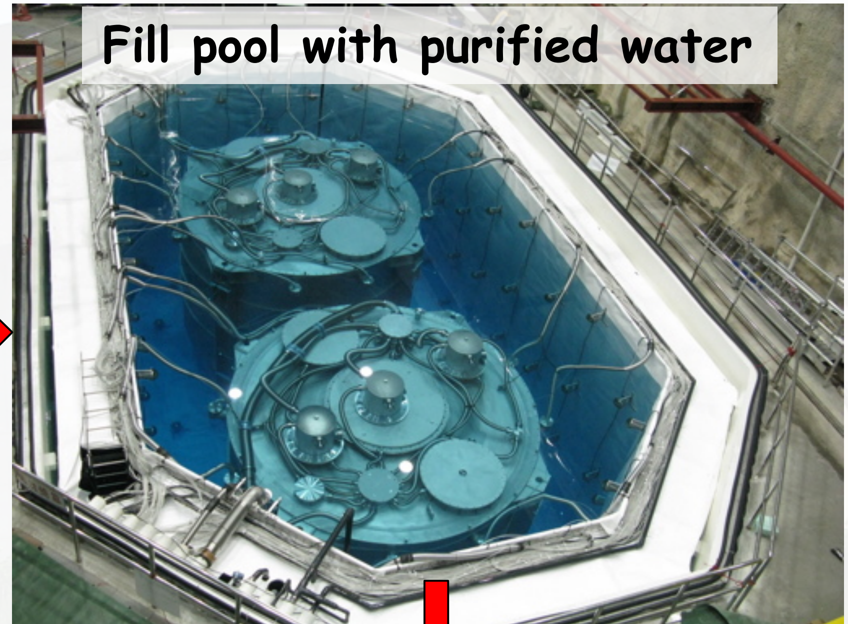
- Target mass is measured with:
  - (1) 4 load cells supporting the 20-t ISO tank
  - (2) Coriolis mass flow meters

  Absolute uncertainty: 0.02%

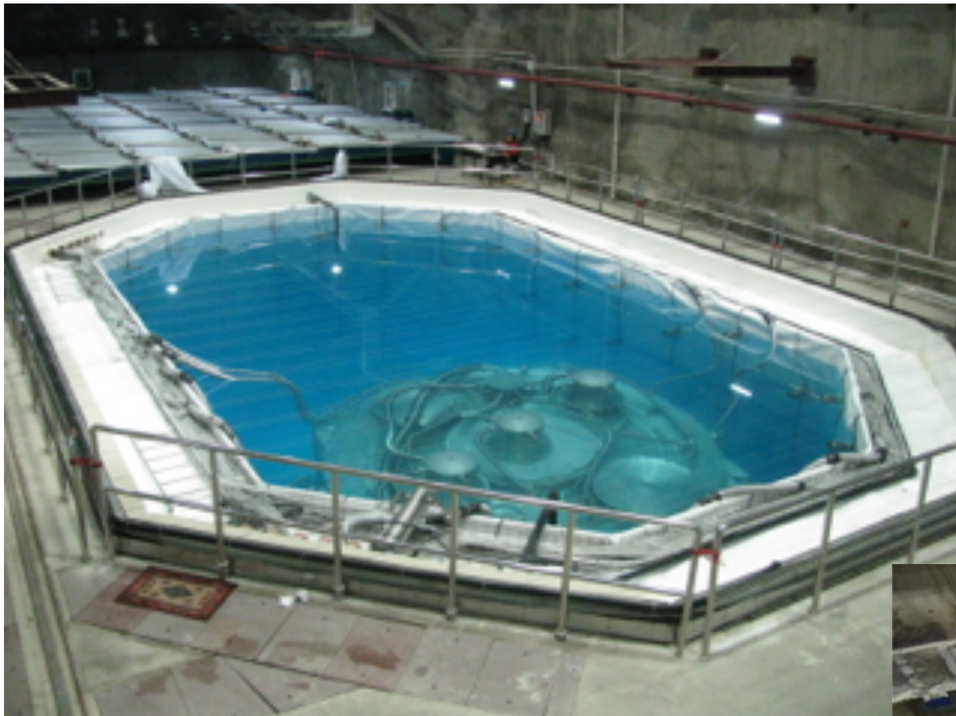
  Relative uncertainty: 0.02%
- Temperature is maintained constant
- Filling is monitored with in-situ sensors



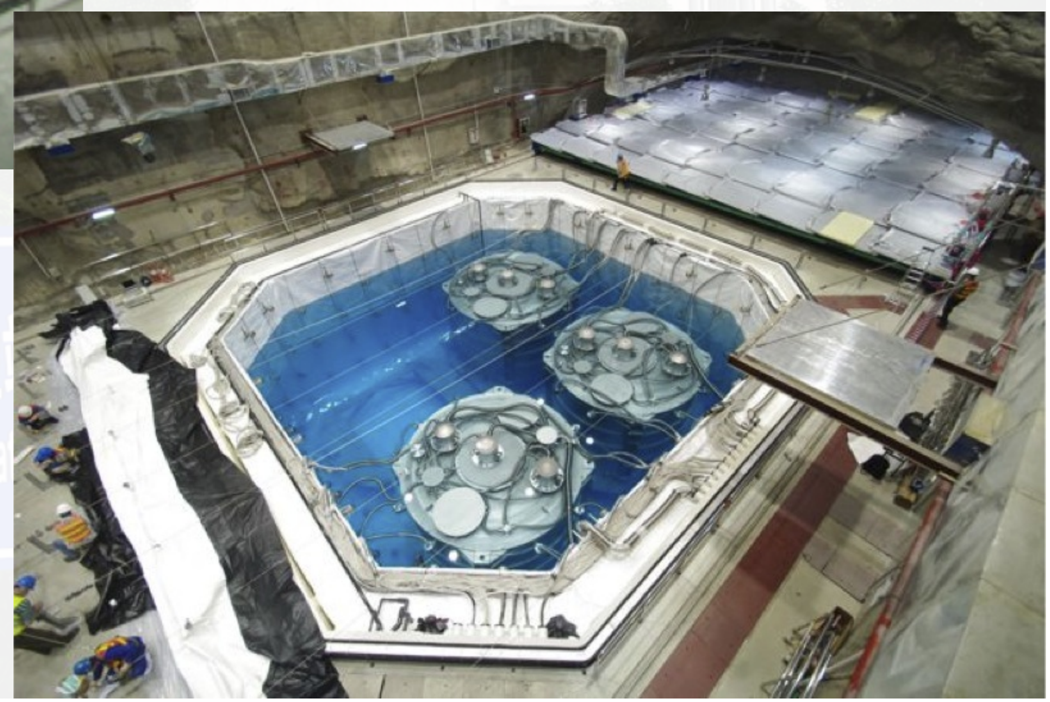
Daya Bay Near Hall (EH1)



Getting Ling Ao Near and Far Halls Ready



EH 2 (Ling Ao Near Hall):
Began operation on
5 Nov 2011



EH 3 (Far Hall):
Started data-taking on
24 Dec 2011

Data Taking

Comparison of two detectors in EH1 :
- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.
- Details presented in: F.P. An et al., arXiv:1202:6181 (2012)

Current oscillation analysis:
- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- DAQ uptime: >97%
- Antineutrino data: ~89%

Triggers & Their Performance

Discriminator threshold:

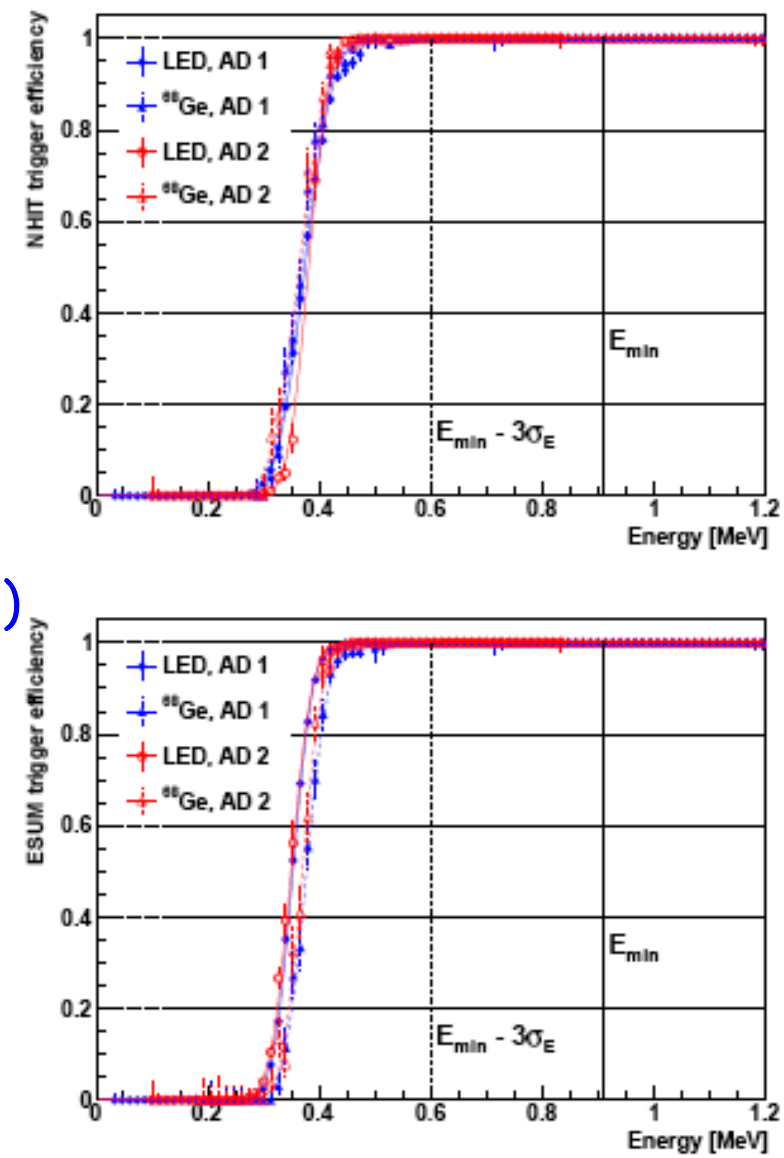
- ~0.25 p.e. for PMT signal

Triggers:

- AD: ≥ 45 PMTs (digital trigger)
  ≥ 0.4 MeV (analog trigger)
- Inner Water Cherenkov: ≥ 6 PMTs
- Outer Water Cherenkov: ≥ 7 PMTs (near)
  ≥ 8 PMTs (far)
- RPC: 3/4 layers in each module

Trigger rate:

- AD: < 280 Hz
- Inner Water Cherenkov: < 160 Hz
- Outer Water Cherenkov: < 200 Hz



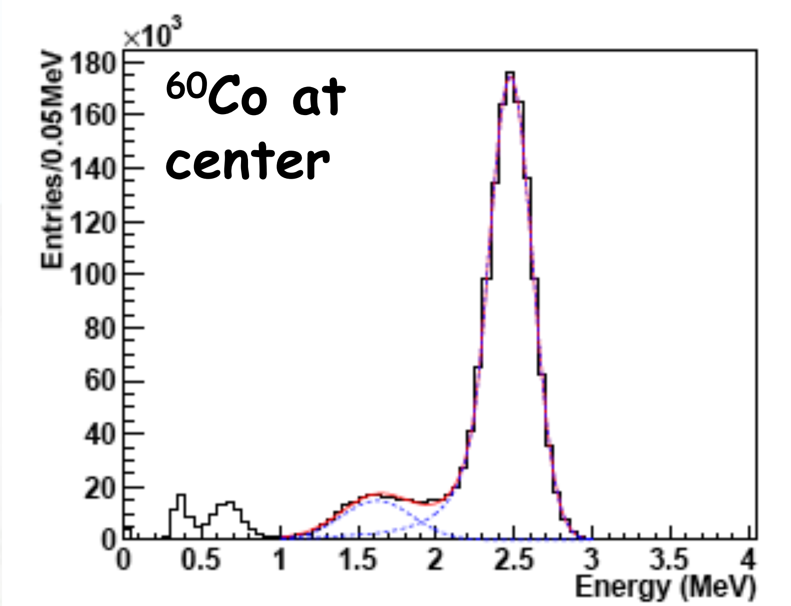
Multiple Independent Analyses

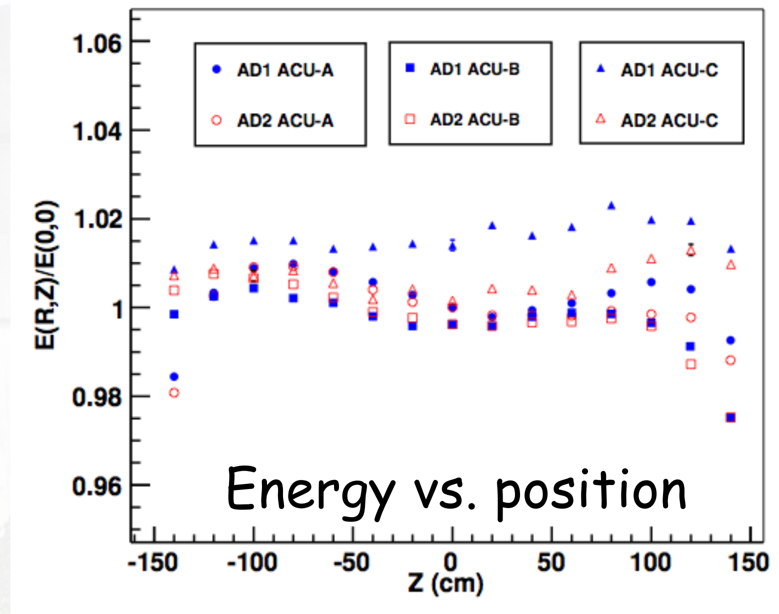
Multiple independent analyses to cross check results.

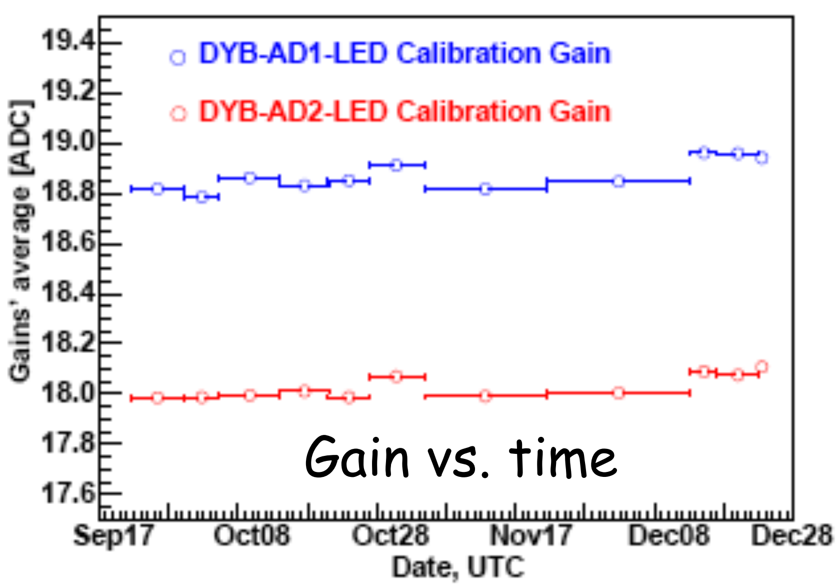
Highlights of differences between analyses:

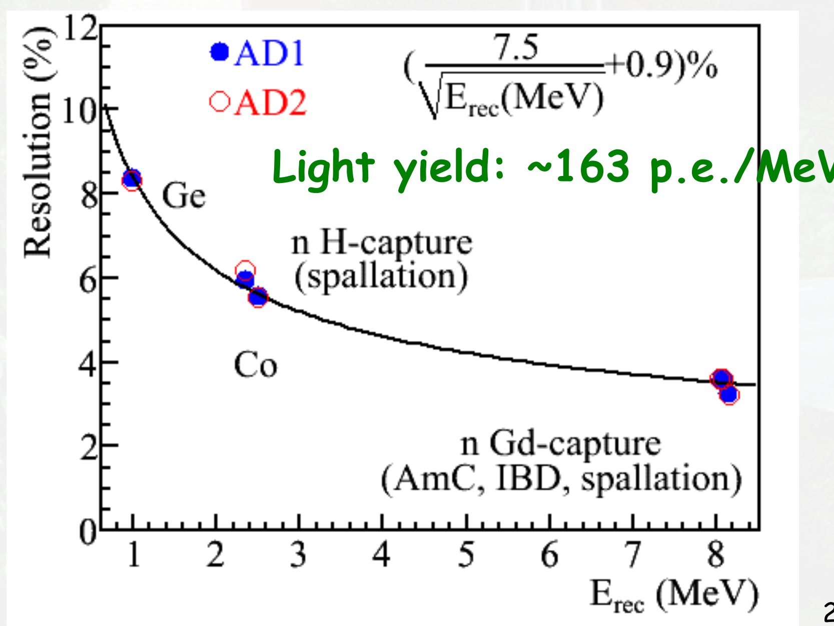
- Energy calibration/reconstruction
  - Calibration source (60Co, ‘point’ source)
  - Spallation neutron (full volume)
- Antineutrino candidate selection/efficiency
  - Muon veto
  - Multiplicity cut
- Background studies
- Rate-only θ_{13} analysis (perform blind analysis)

Energy Calibration







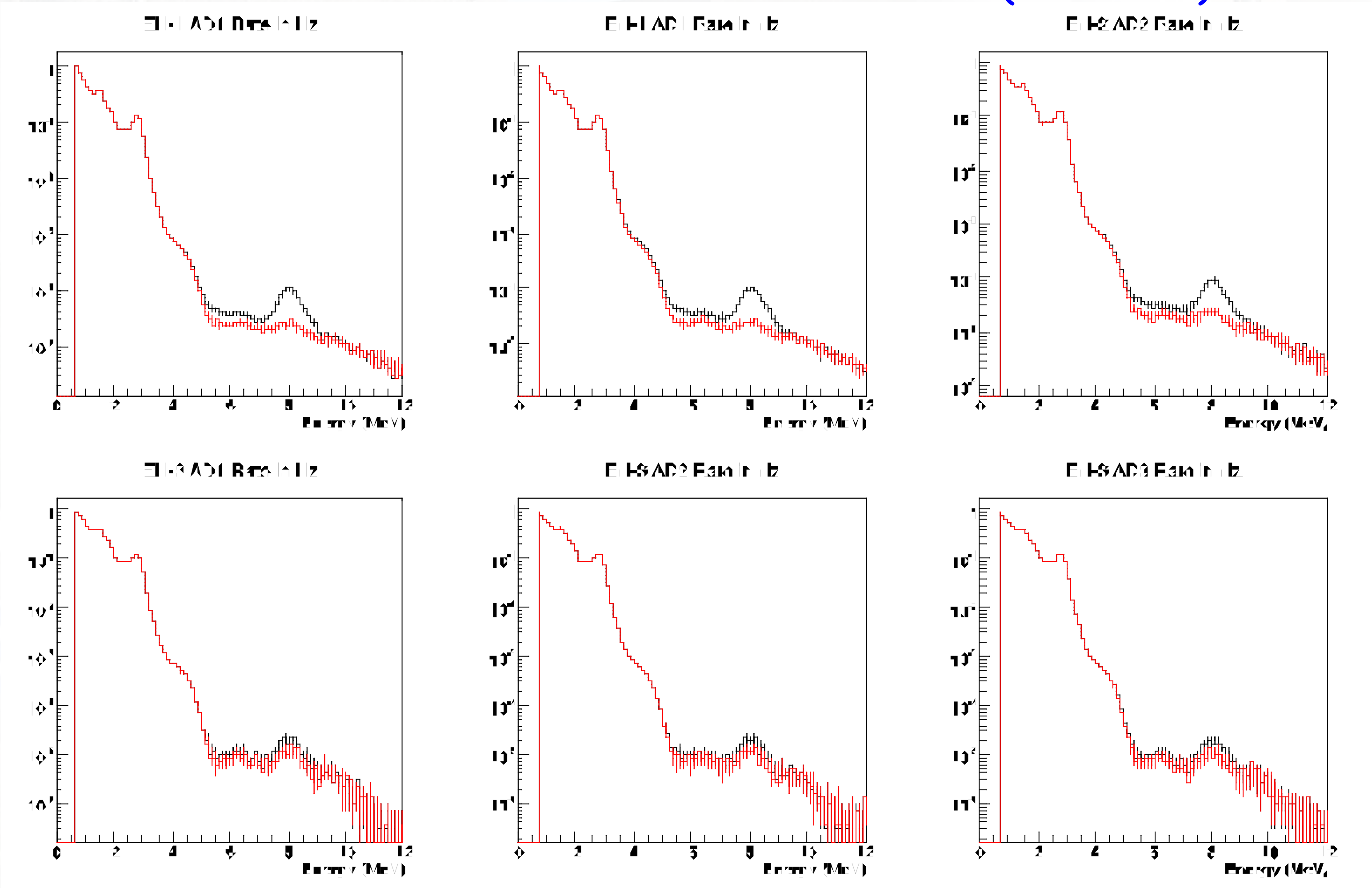


Singles Spectrum

Dominated by low-energy radioactivity

Sources: Stainless Steel (U/Th chains); PMTs (40K, U/Th chains)
Scintillator (Radon/U/Th chains)

Measured rates: ~65 Hz in each detector (>0.7 MeV)

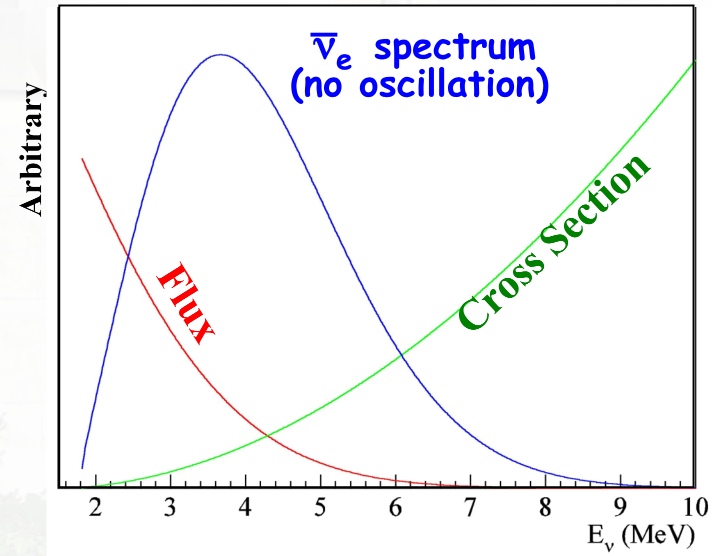


Selecting Antineutrino (IBD) Candidates

Use Prompt + Delayed correlated signal to select antineutrino candidates.

Selection:

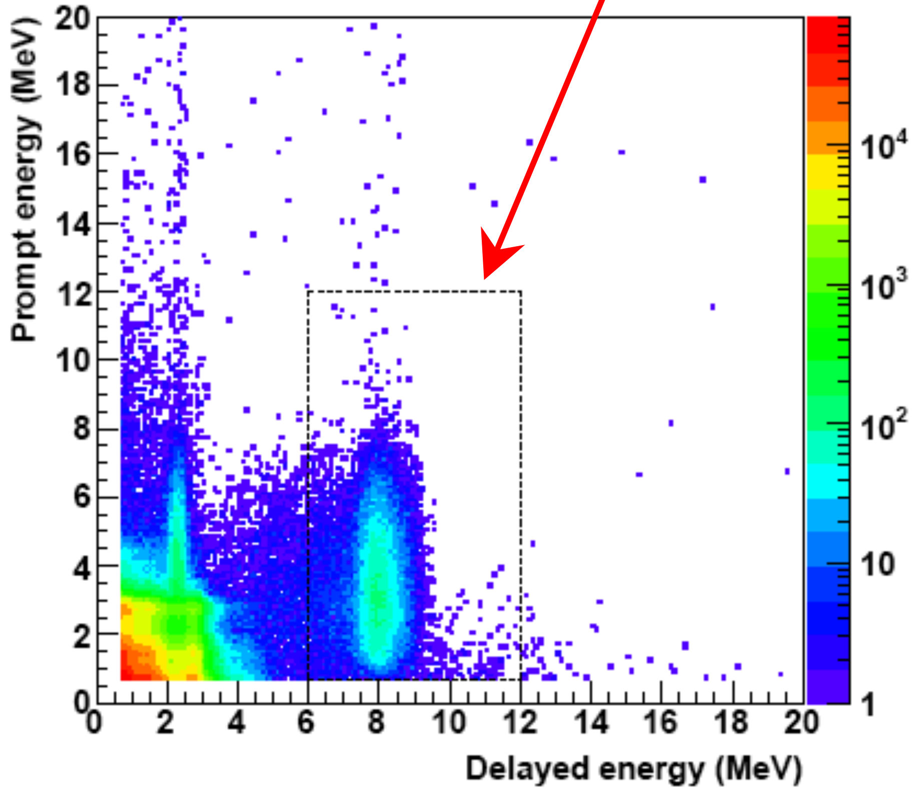
- -Prompt: 0.7 MeV < E_p < 12 MeV
- -Delayed: 6.0 MeV < E_d < 12 MeV
- -Capture time: 1 μs < Δt < 200 μs
- -Reject Flashers
- - Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- - Multiplicity:
  - No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.



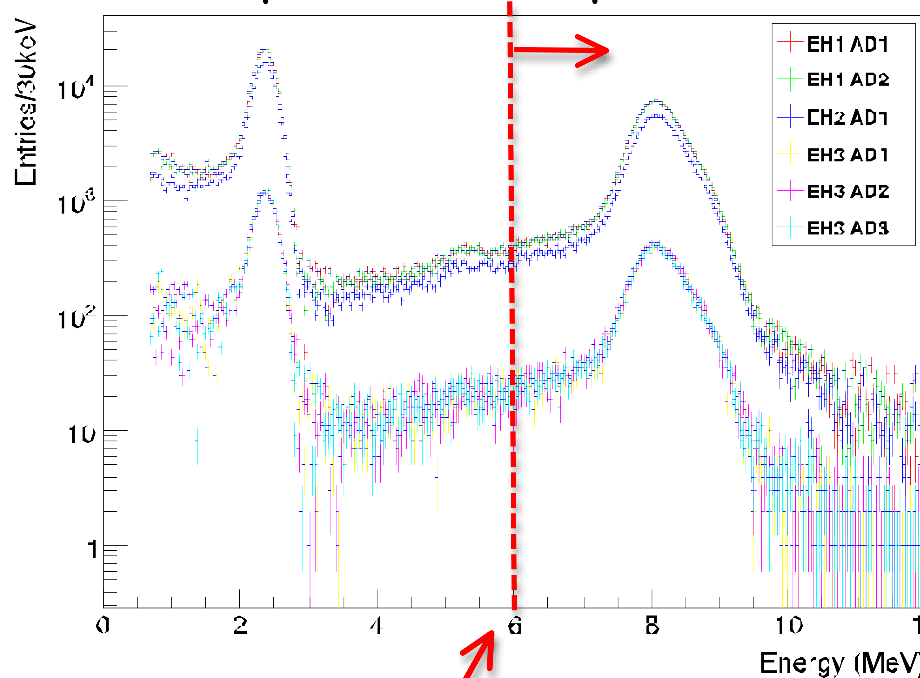
From Bemporad, Gratta and Vogel

Prompt/Delayed Energy

Clear separation of antineutrino events from most other signals

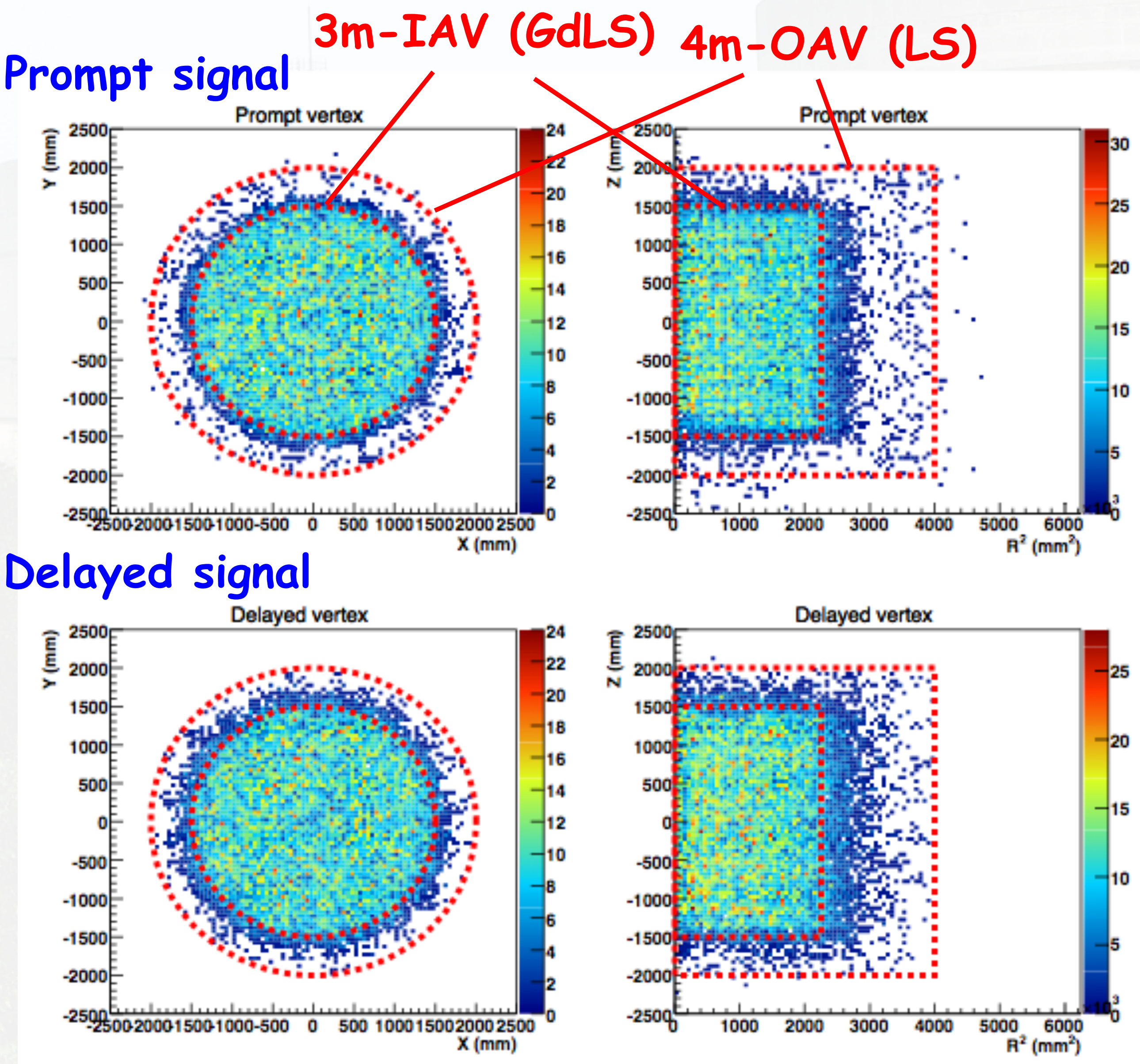


Spallation-n capture



Uncertainty in relative E_d efficiency (0.12%) between detectors.

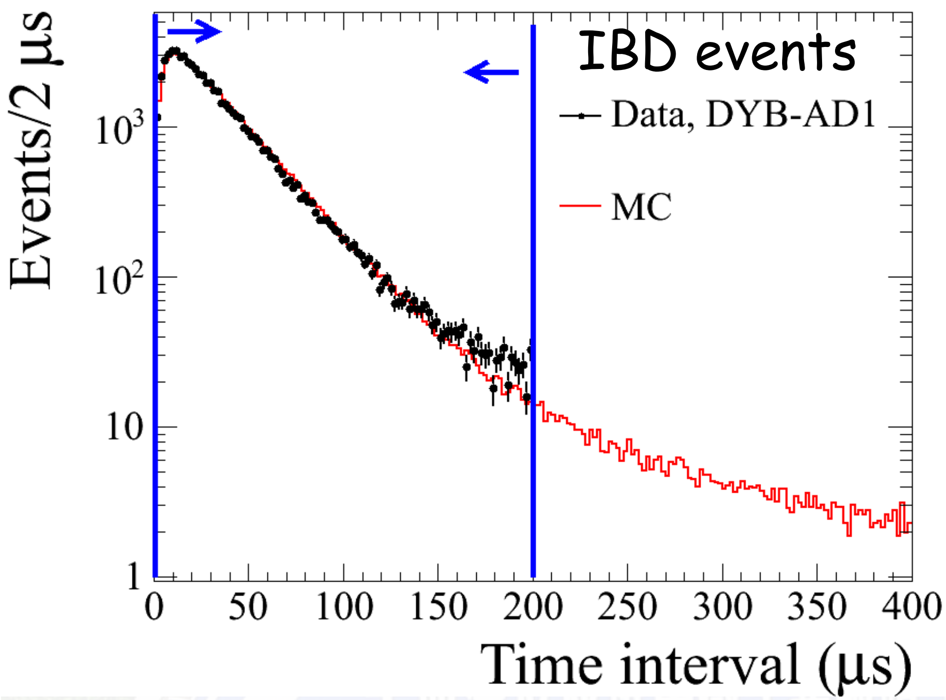
Spatial Distributions of IBD candidates



Real data
EH1-AD1

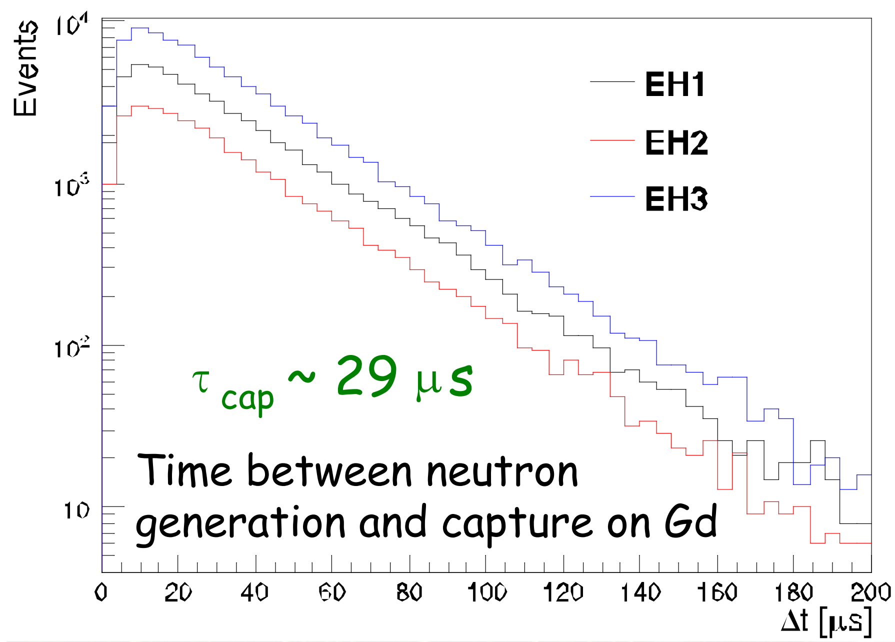
- After applying all IBD selection cuts.
- Vertices from IBD candidates are uniformly distributed within 3m-IAV.

Neutron Capture Time



Simulation contains no background
(deviates from data at >150 μ s)

Consistent capture time
measured in all detectors



Measured capture times
imply relative H/Gd
capture efficiency: <0.1% between
detectors.

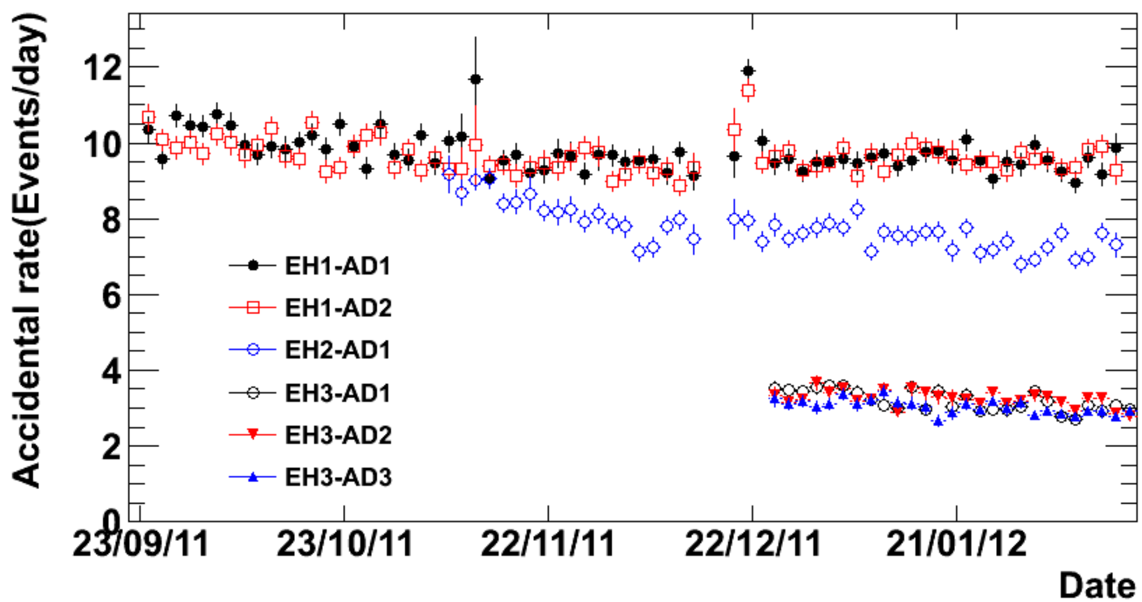
Remaining Background

- Uncorrelated background
  - Accidentals: two uncorrelated events 'accidentally' pass the cuts and mimic IBD event.
- Correlated background
  - Muon spallation products
    - 9Li/8He
    - Fast neutron
  - Correlated signals from ^{241}Am-^{13}C source
  - $^{13}C(\alpha,n)^{16}O$

Background: Accidentals

Two uncorrelated single signals mimic an antineutrino signal

Rate and spectrum can be accurately predicted from singles data.

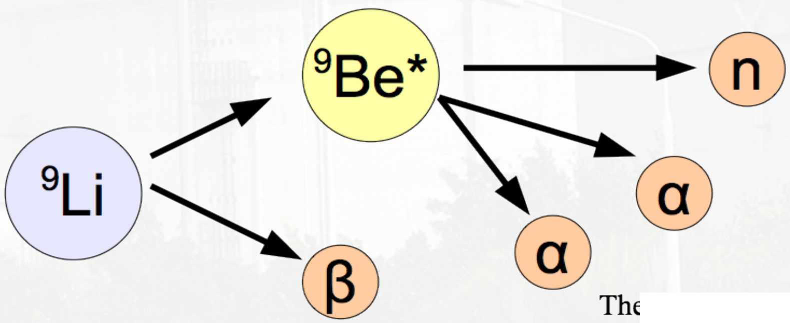


	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Accidental rate(/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29±0.03	3.33±0.03	3.12±0.03
B/S	1.37%	1.38%	1.44%	4.58%	4.77%	4.43%

Background: ^{9}Li/^{8}He β -n Decays

β-n decay:

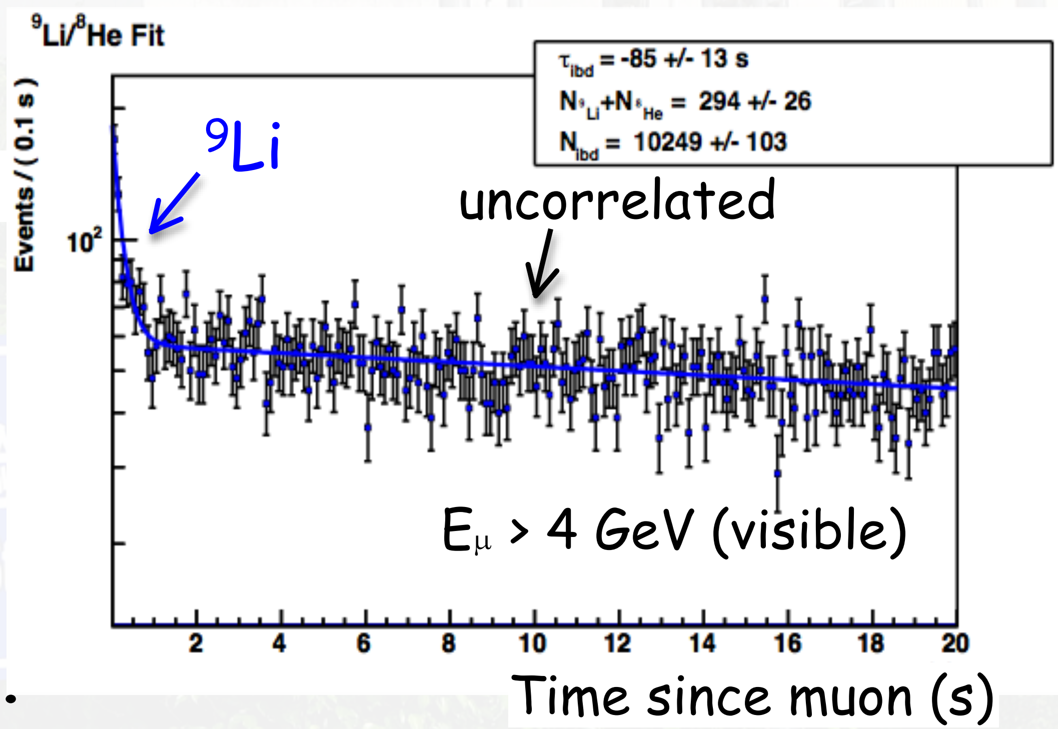
- Prompt: β-decay
- Delayed: neutron capture



^{9}Li: $\tau_{1/2}$ = 178 ms, Q = 13. 6 MeV
^{8}He: $\tau_{1/2}$ = 119 ms, Q = 10.6 MeV

Analysis muon veto cuts control B/S to ~0.4±0.2%.

- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal



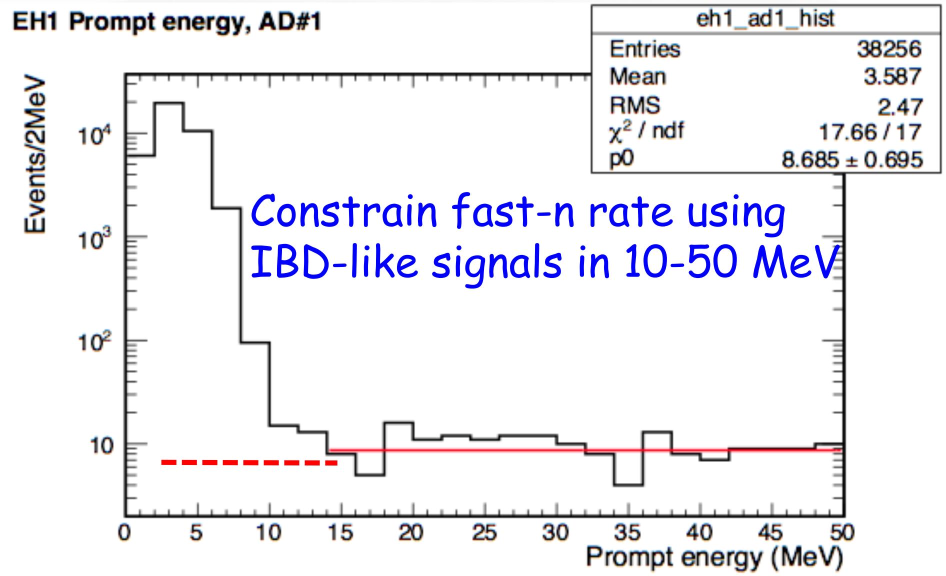
Background: Fast Neutrons

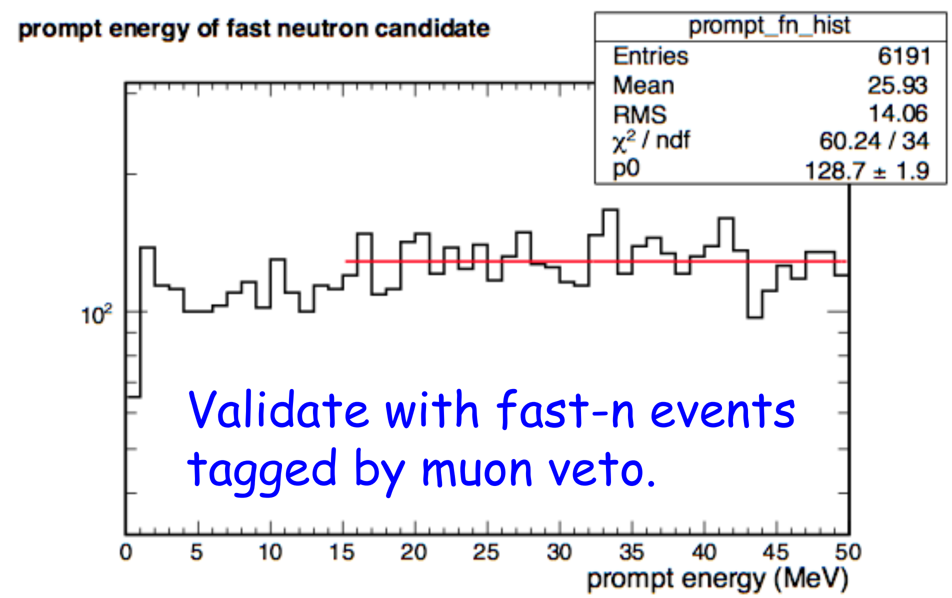
Fast neutrons:

Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

Mimics antineutrino (IBD) signal:

- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd

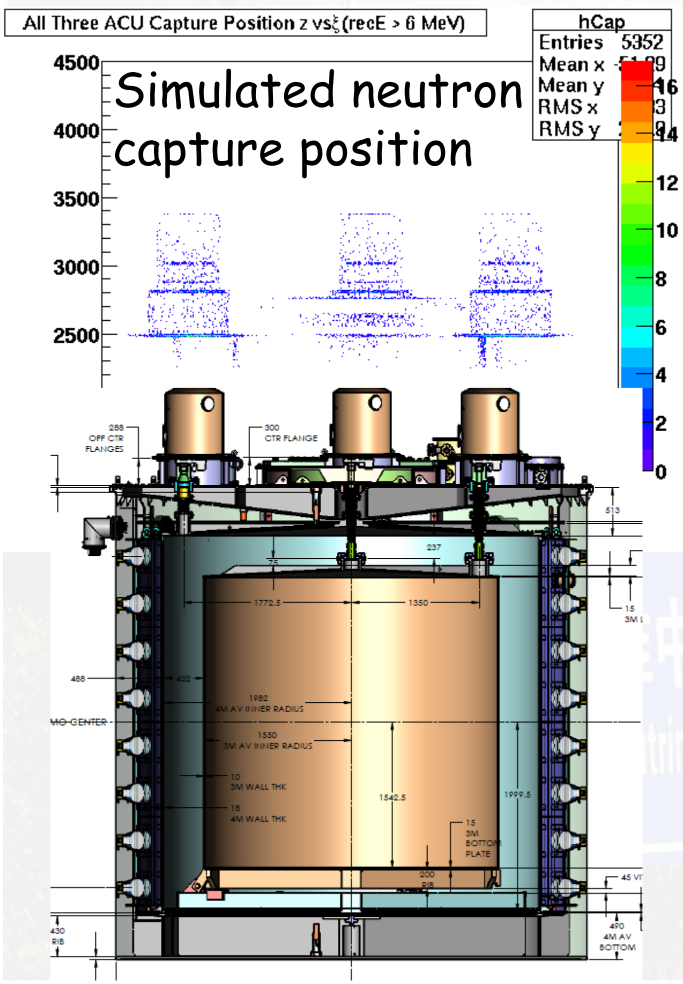


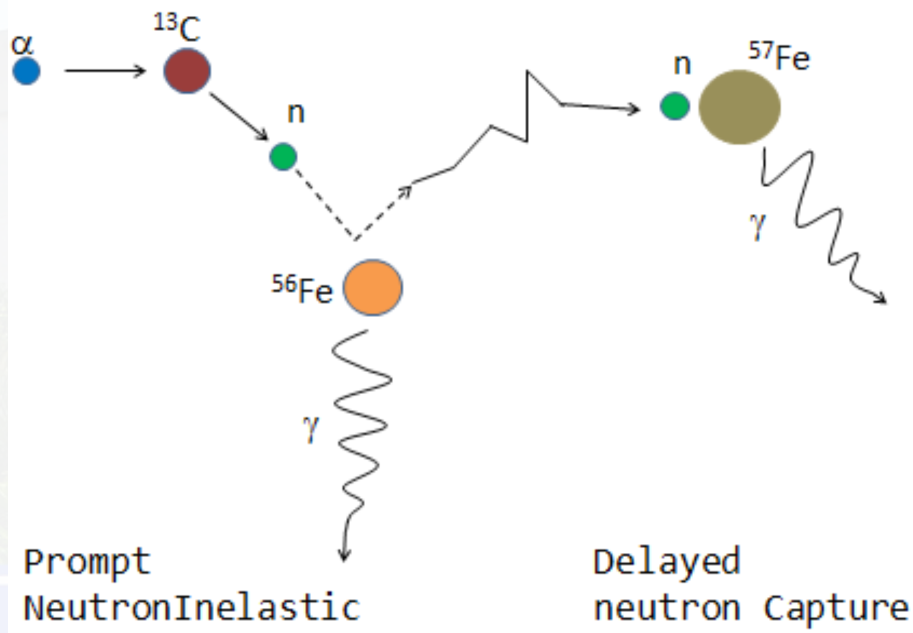


Analysis muon veto cuts control B/S to 0.06% (0.1%) of far (near) signal.

Background: ^{241}Am-^{13}C Source

Leakage (0.5Hz) of neutron source in ACU can mimic IBD via inelastic scattering and capture on elements in stainless steel.





Constrain far site B/S to 0.3 ± 0.3%:

- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation
- Assume 100% uncertainty from simulation

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

$^{13}C(\alpha, n)^{16}O$ — 1.1% natural abundance ^{13}C

- $\rightarrow n + p \longrightarrow n + p$ ①
- $\rightarrow n + {}^{12}C \longrightarrow n + {}^{12}C^{*}(4.4\ \text{MeV})$
  - $\rightarrow {}^{12}C + \gamma$ ②

$^{13}C(\alpha, n)^{16}O^{*}(6.05\ \text{MeV})$

- $\rightarrow {}^{16}O + \gamma$ ③

$^{13}C(\alpha, n)^{16}O^{*}(6.13\ \text{MeV})$

- $\rightarrow {}^{16}O + e^{+} + e^{-}$ ④

Example alpha rate in AD1	^{238}U	^{232}Th	^{235}U	^{210}Po
Bq	0.05	1.2	1.4	10

Potential alpha source:

^{238}U, ^{232}Th, ^{235}U, ^{210}Po

Each of them are measured in-situ:

U&Th: cascading decay of

Bi(or Rn) – Po – Pb

^{210}Po: spectrum fitting

Combining (α ,n) cross-section, correlated background rate is determined.

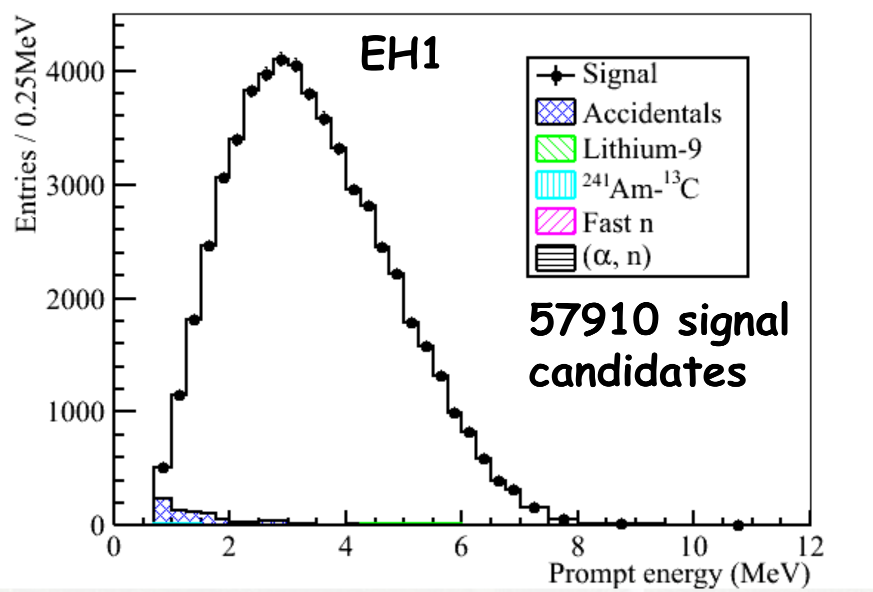
Near Site: 0.04±0.02 per day, B/S = (0.006±0.004)%

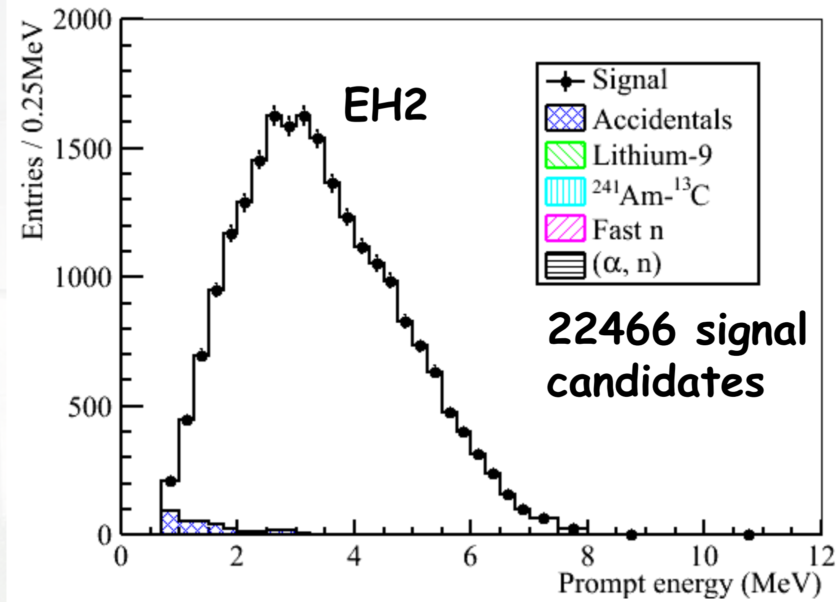
Far Site: 0.03±0.02 per day, B/S = (0.04±0.02)%

Data Summary

	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	28935	28975	22466	3528	3436	3452
DAQ live time (day)	49.5530		49.4971	48.9473		
Veto time (day)	8.7418	8.9109	7.0389	0.8785	0. 8800	0.8952
Efficiency	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
^{8}He/^{9}Li (/day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/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
Antineutrino 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**

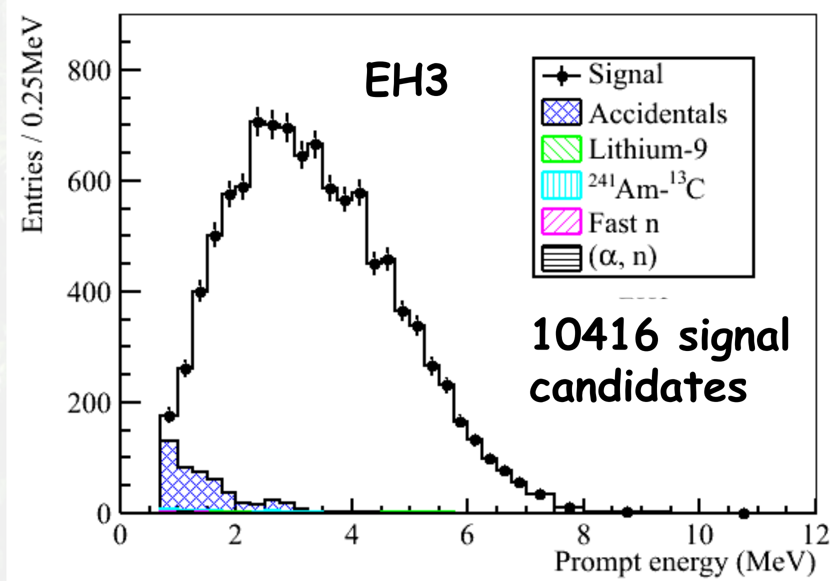
Prompt (Positron) Spectra





High-statistics reactor antineutrino spectra.

B/S ratio is 2% (5%) at near (far) sites.



Reactor Flux Calculation

Antineutrino flux is estimated for each reactor core

Flux estimated using:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Reactor operators provide:

- Thermal power data: W_{th}
- Relative isotope fission fractions: f_i

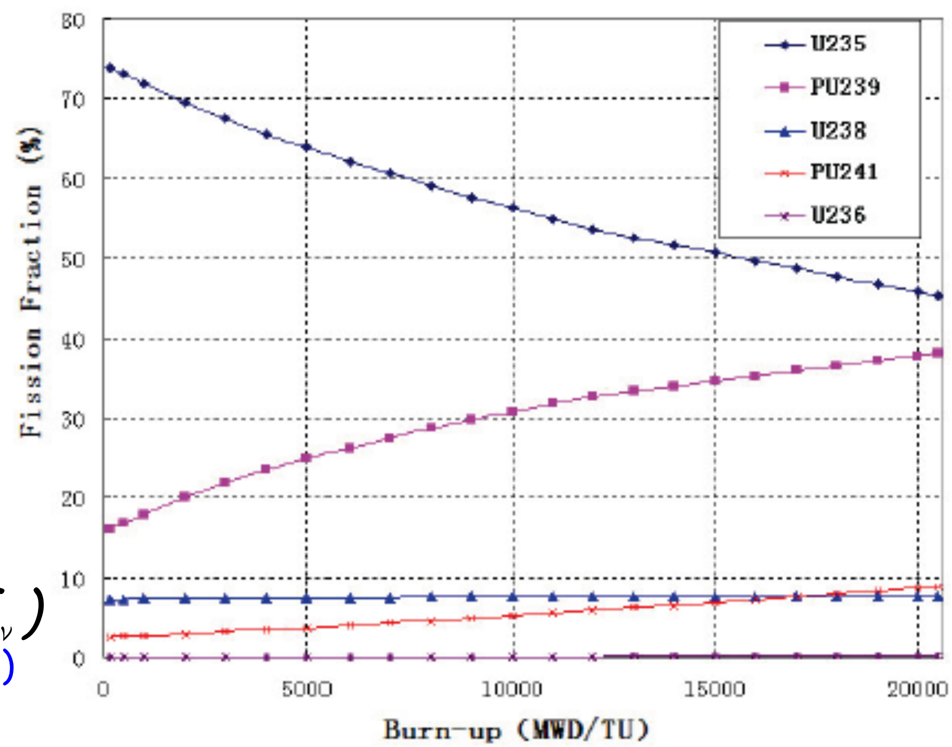
Energy released per fission: e_i

V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

Antineutrino spectra per fission: $S_i(E_\nu)$

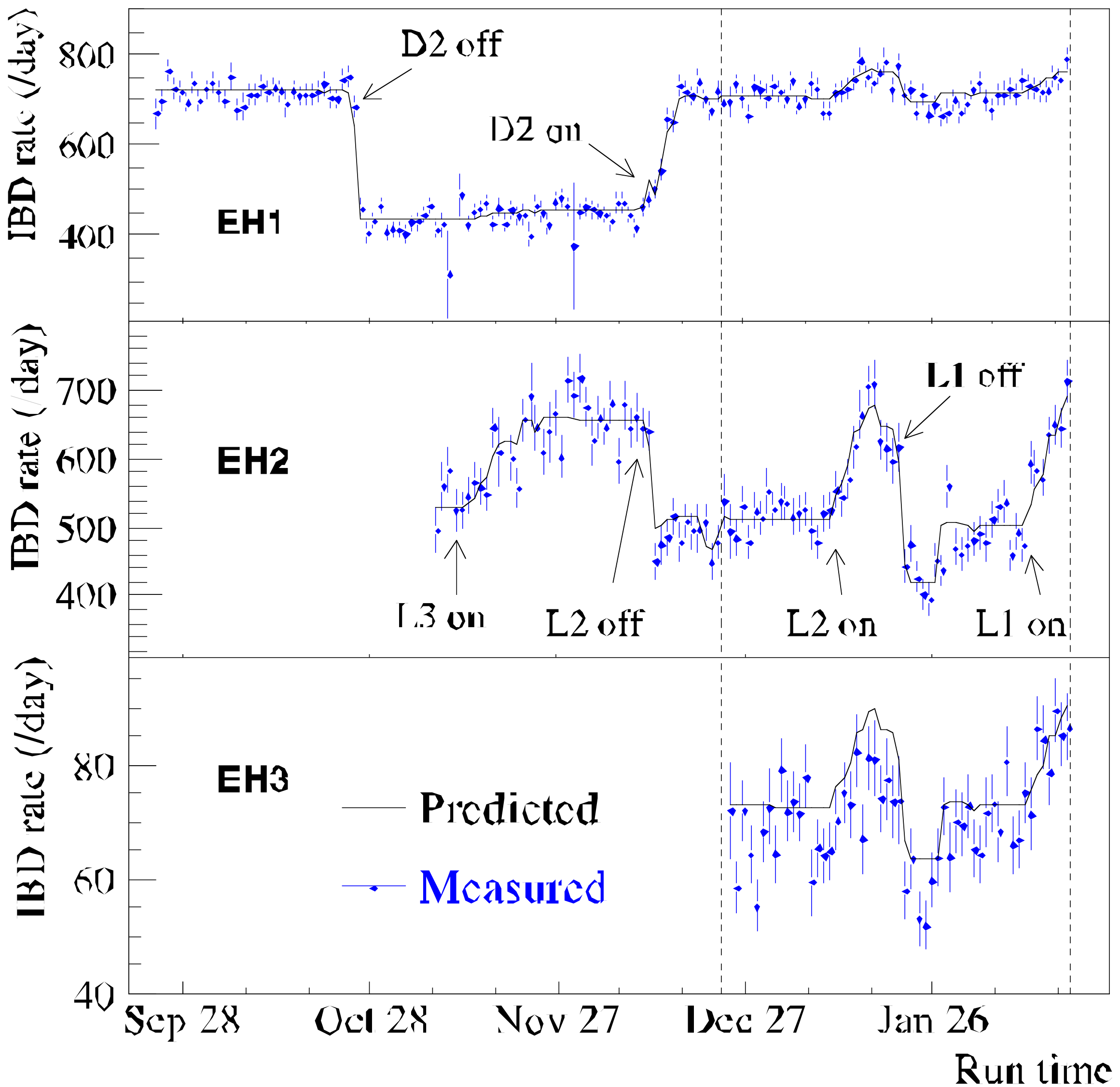
K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

Isotope fission rates vs. reactor burnup



Flux model has negligible impact on far vs. near oscillation measurement

Antineutrino Rate vs. Time



Detected rate strongly correlated with reactor flux expectations.

Predicted Rate:
- Assumes no oscillation.
- Normalization is determined by fit to near-hall data.
- Absolute normalization is within a few percent of expectations.

Summary of 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 near/far analysis, only uncorrelated uncertainties are used.

Far vs. Near Comparison : $\overline{\nu}_e$ Rate

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

M_n : measured rates in each detector.

Weights α_i, β_i : determined from baselines and reactor fluxes.

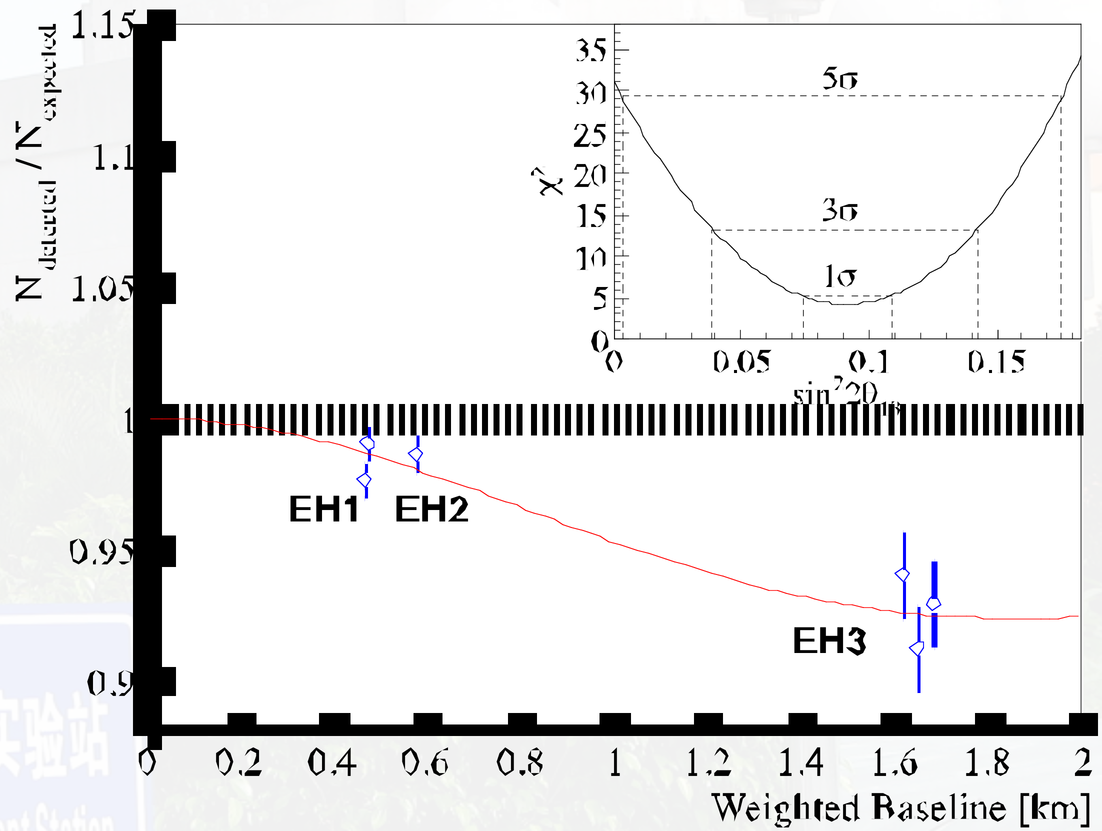
R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

Clear observation of $\overline{\nu}_e$ deficit at the far site.

Rate-only Analysis

Measure θ_{13} using measured rates in each detector.

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



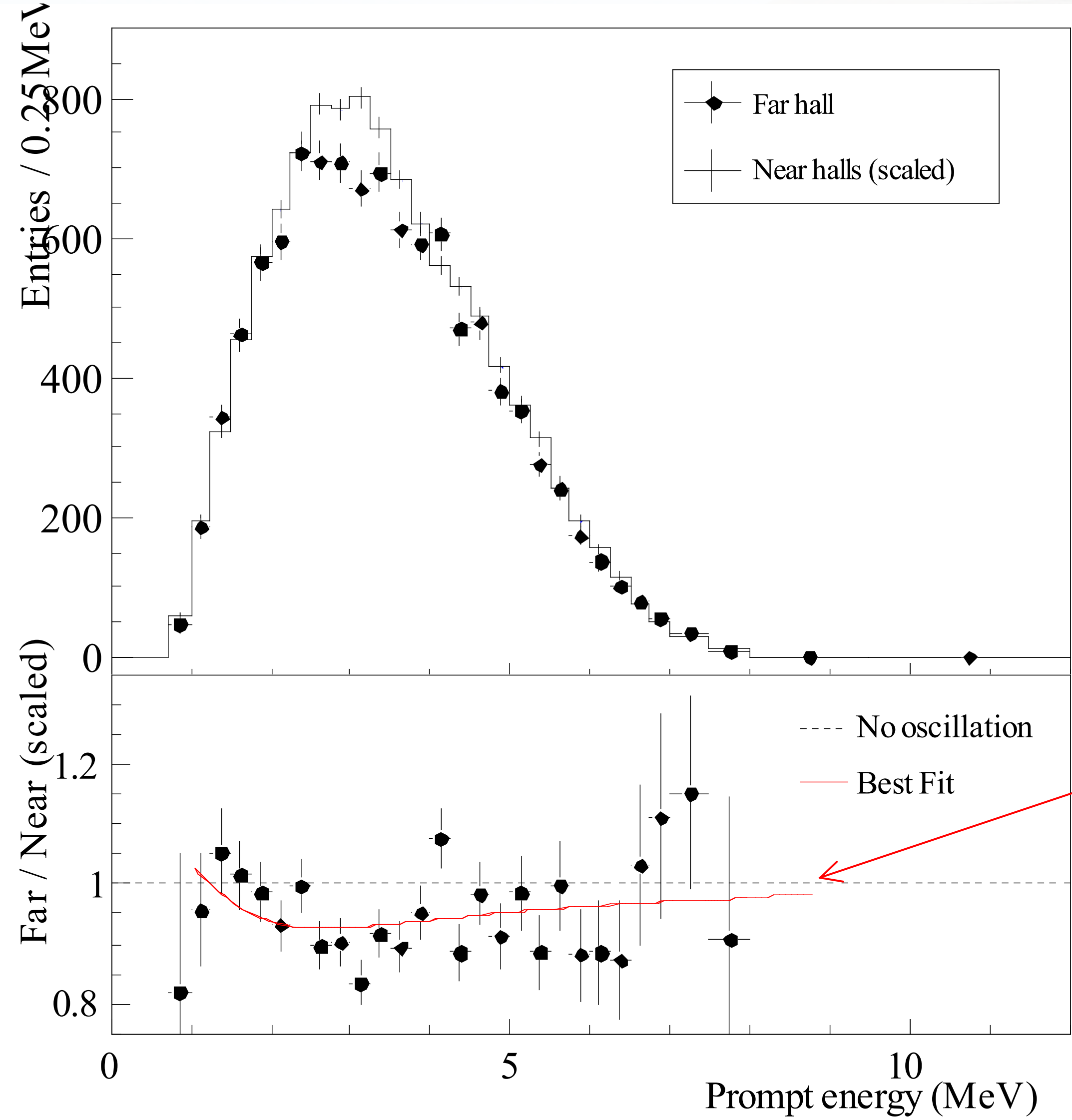
Far vs. near relative measurement.
[Absolute rate is not constrained.]

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

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

$\sin^2 2\theta_{13} = 0$ excluded at 5.2σ

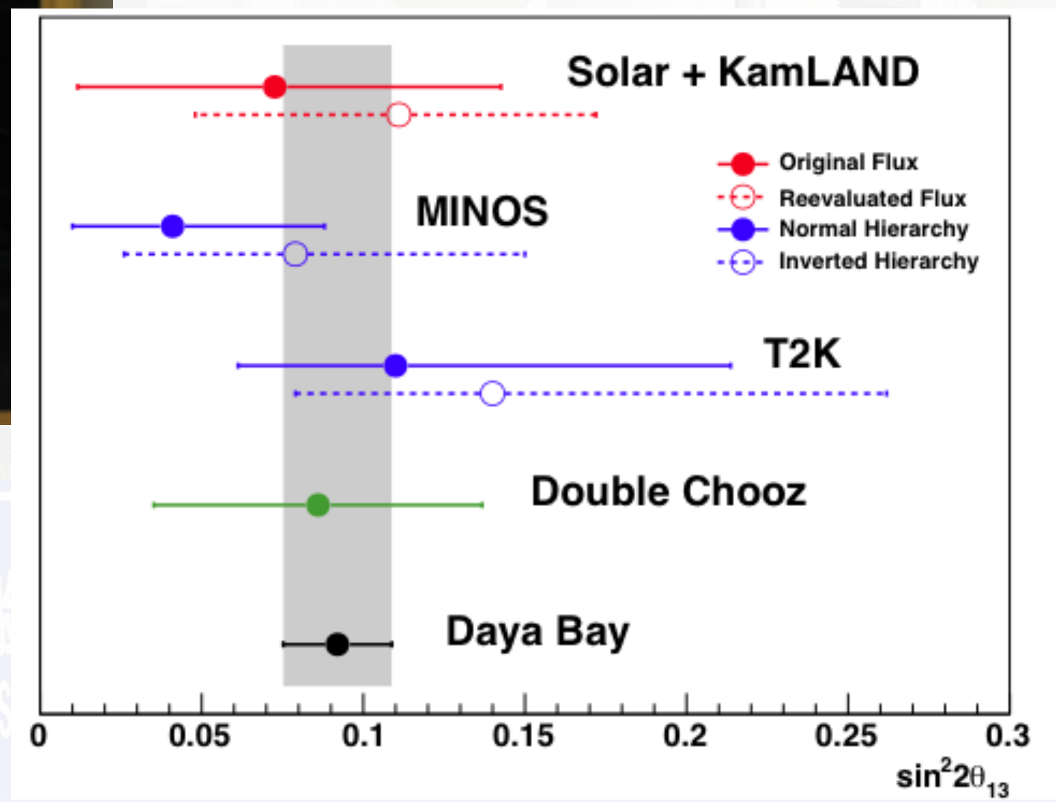
Far vs. Near Comparison : Spectrum



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

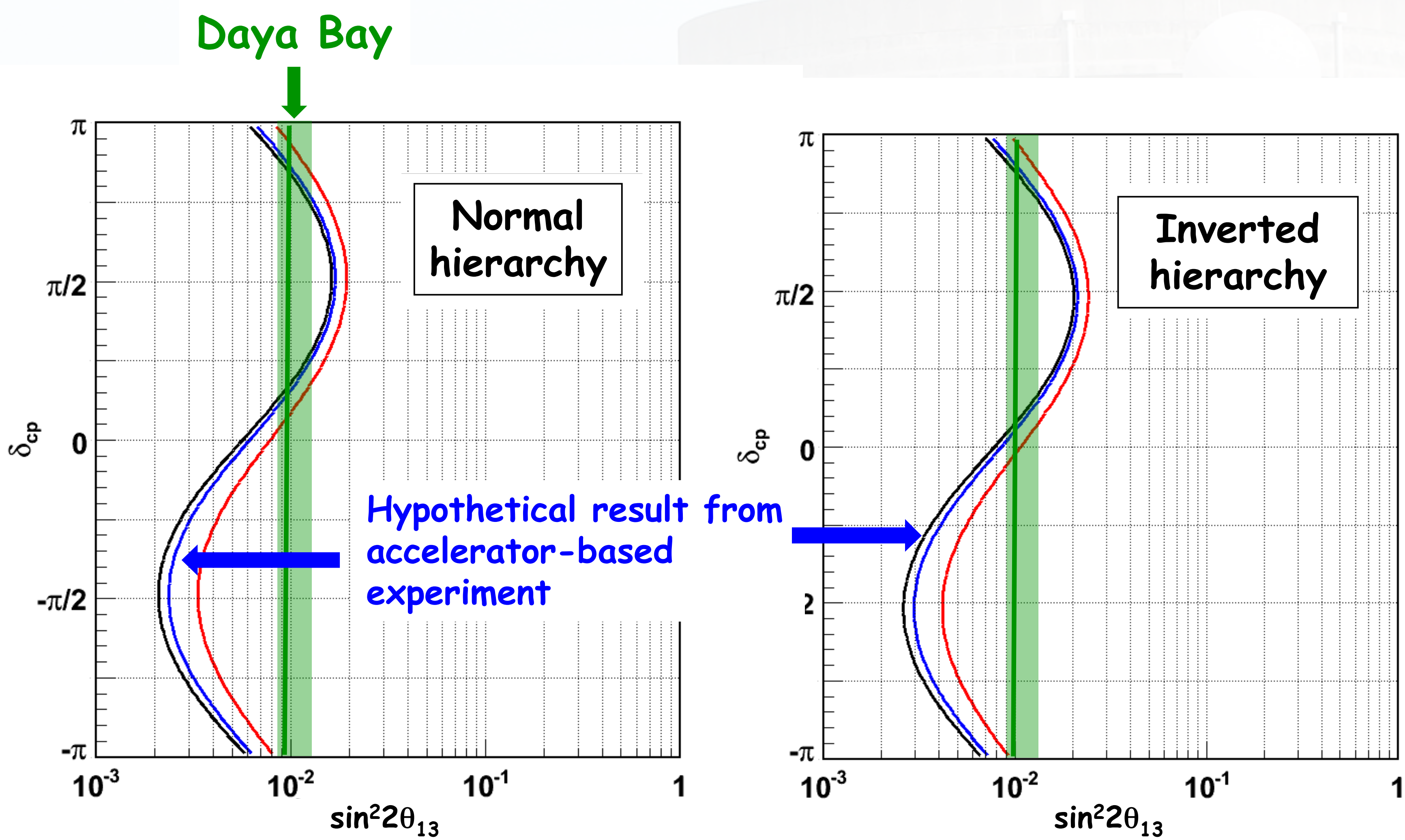
Spectral distortion consistent with oscillation.

Landscape of $\sin^2 2\theta_{13}$



Daya Bay surpasses all existing results

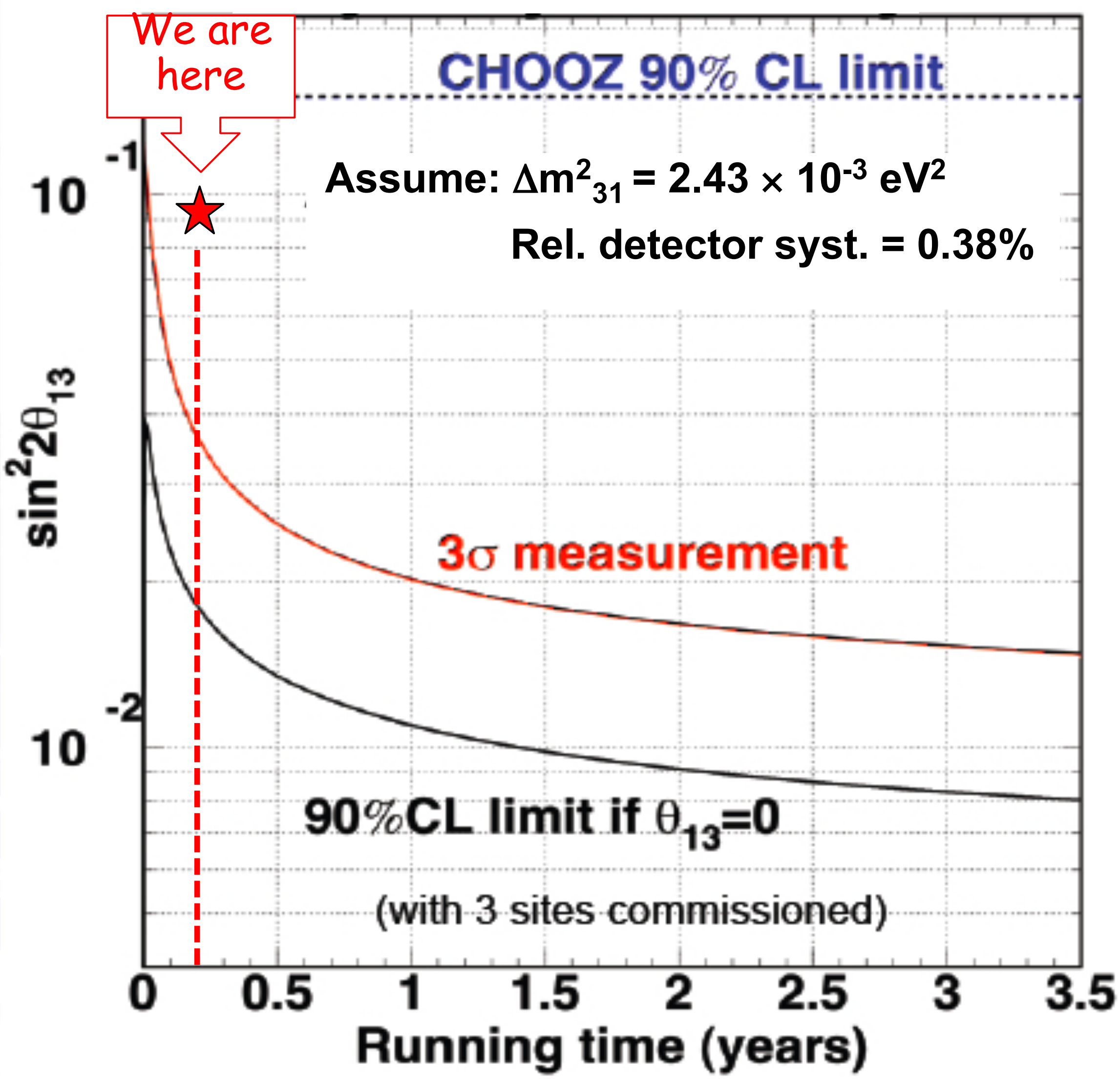
Complementarity



Combining results from accelerator- and reactor-based experiments could offer the first glimpse of δ_{CP}.

Prospects For Daya Bay

Install the last pair of antineutrino detectors in this summer.



Conclusions

- The Daya Bay reactor neutrino experiment has made an unambiguous observation of reactor electron-antineutrino disappearance at ~2 km:

  $R = 0.940 \pm 0.011 \text{ (stat)} \pm 0.004 \text{ (syst)}$

- Interpretation of disappearance as neutrino oscillation yields:

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

  ruling out zero at 5.2 standard deviations.

- Installation of last pair of antineutrino detectors this summer.

- Daya Bay now begins precision measurement of θ_{13}.

Thank you all for supporting Daya Bay