Latest Results on Electron-antineutrino Disappearance at Daya Bay

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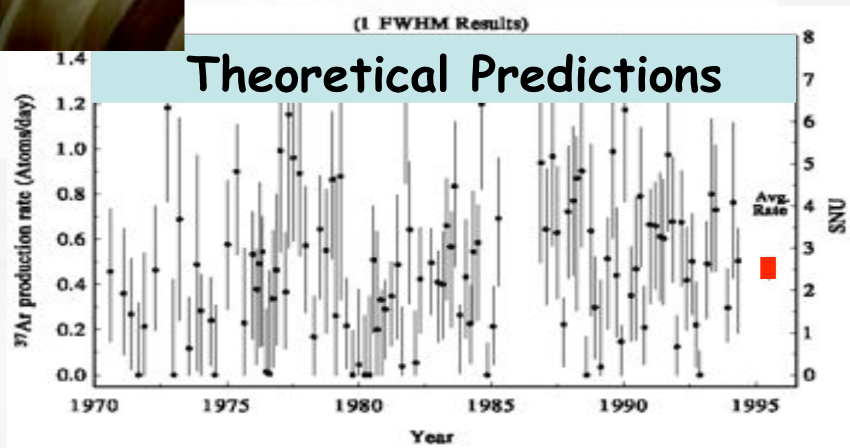
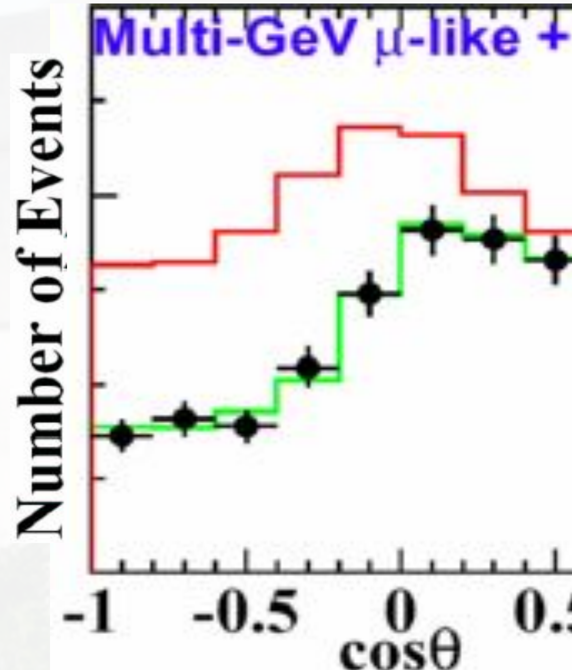
On Behalf of the Daya Bay Collaboration

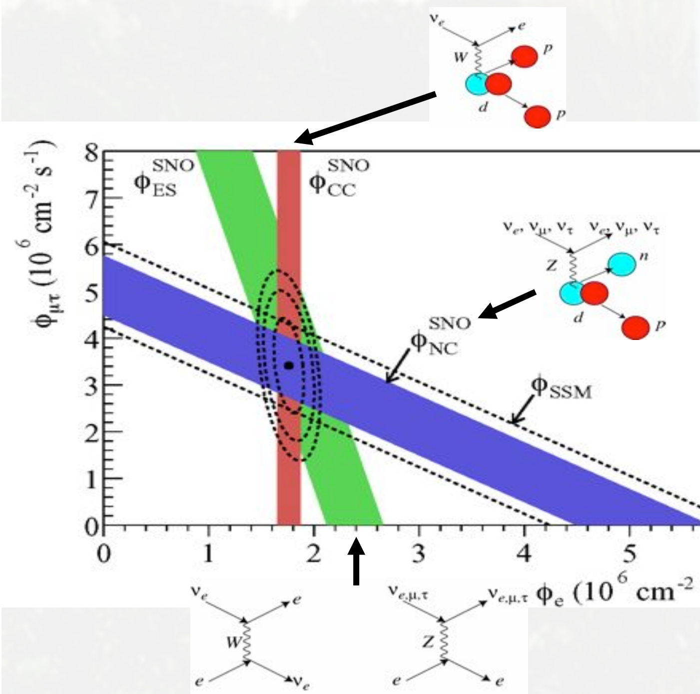
Seminar at Imperial College/UCL, 14 June 2012

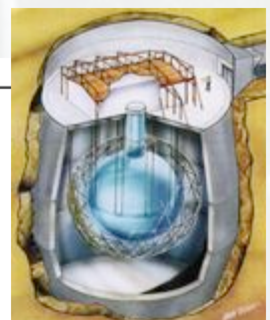
Discoveries of Neutrino Oscillation

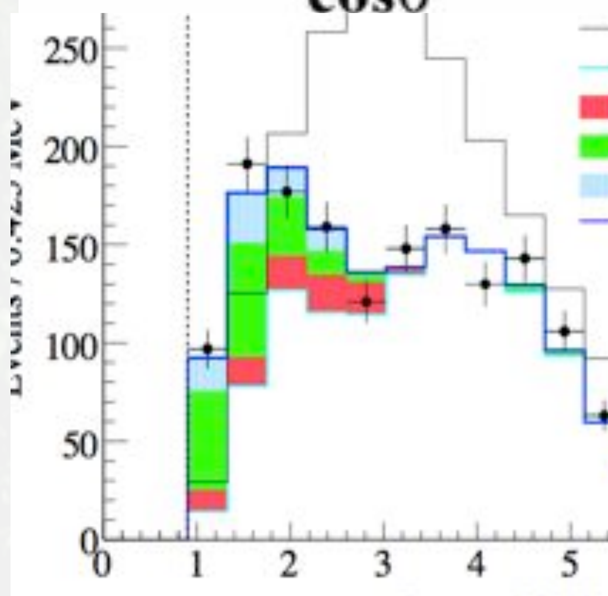


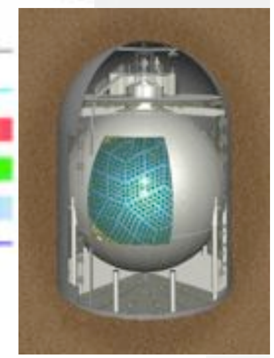
1 SNU = 10^{-36} interaction/atom/s











Neutrino Mixing

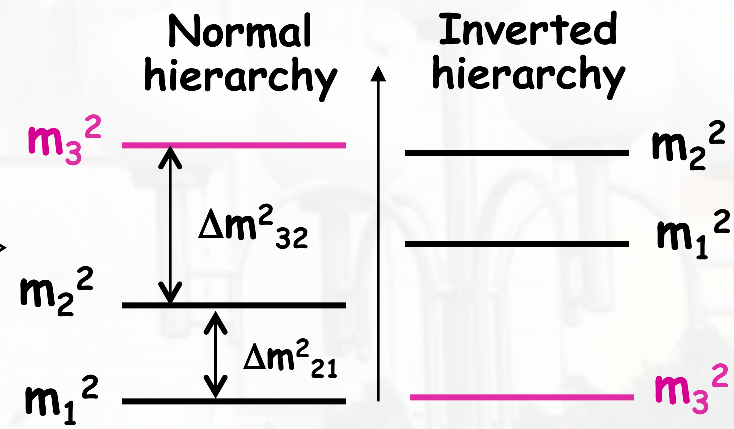
- Neutrino flavour eigenstates ≠ Mass eigenstates

$$\Downarrow$$

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



Which one ?

$$\Downarrow$$

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

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

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

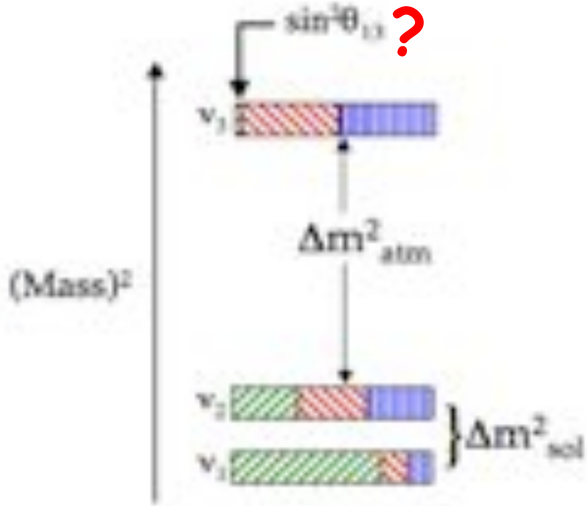
$\Downarrow$

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

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

Significance of Knowing θ_{13}

- Complete the determination of the mixing matrix
  - guide model-building
- Determine ν_e fraction of ν_3

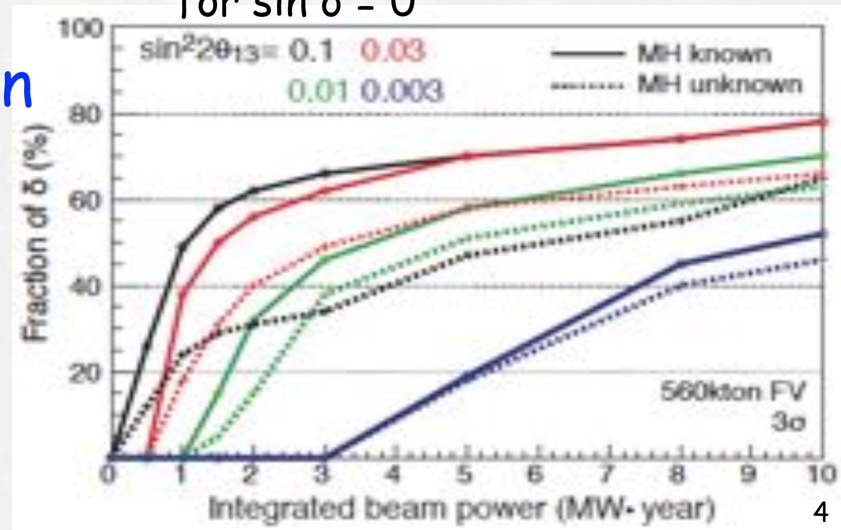


reduce theoretical uncertainties in predicting phenomena

- θ_{13} is the gateway to CP violation in the neutrino sector:

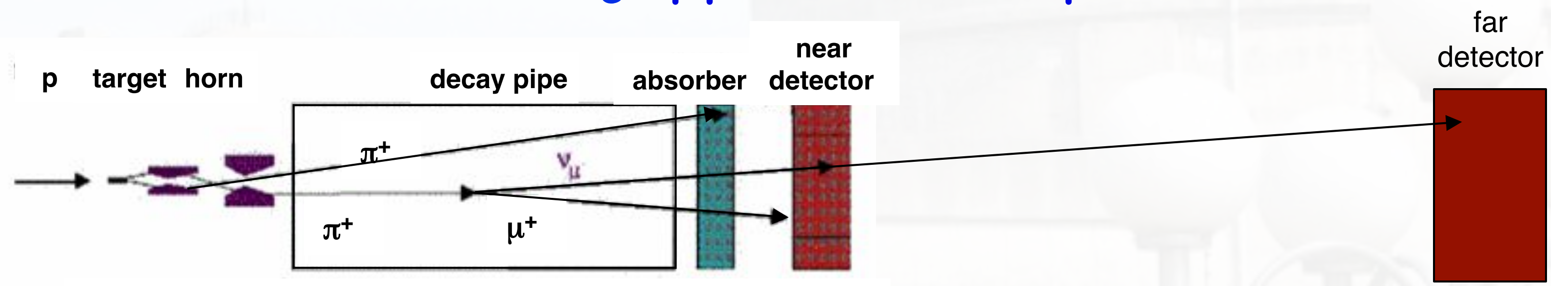
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$$
$$\propto \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Fraction of δ excluded at 3σ for sin δ = 0



Some Approaches For Measuring θ_{13}

- Accelerator-based ν_e appearance experiments



$$P_{\mu e} = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \text{terms}(\delta, \Delta\text{m}_{32}^2, \text{matter effect})$$

  - Baseline *O(100-1000 km)*, large detectors
  - Some ambiguities exist in extracting a value for θ_{13}
  - MINOS, NOvA, T2K, …

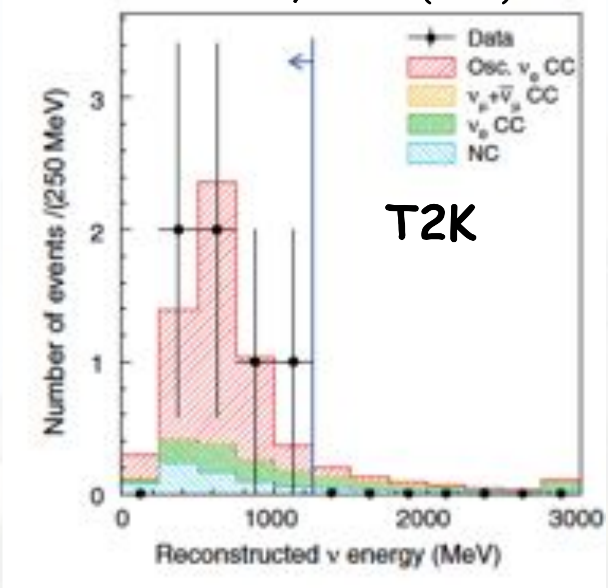
- Reactor-based $\bar{\nu}_e$ disappearance experiments

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

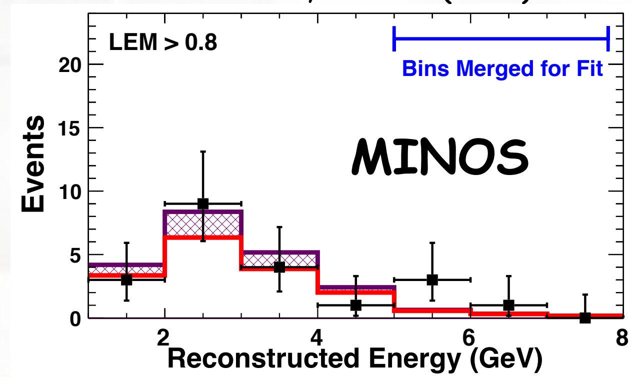
  - Baseline *O(1 km)*, no matter effect, small detectors
  - Daya Bay, Double Chooz, RENO

Knowledge of θ_{13} Circa March 2012

PRL**107**,041801 (2011)

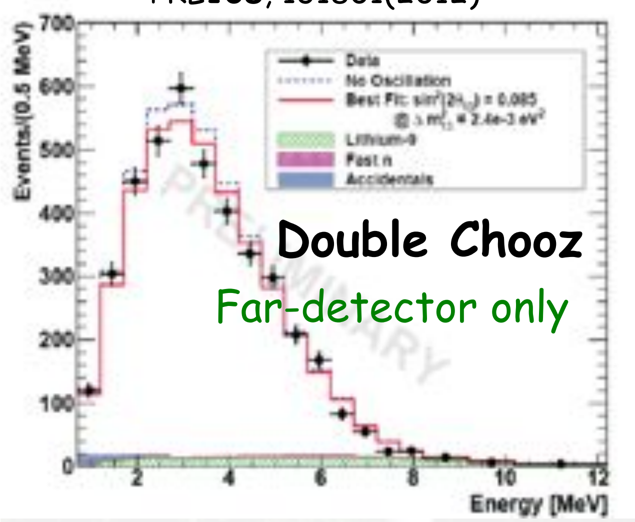


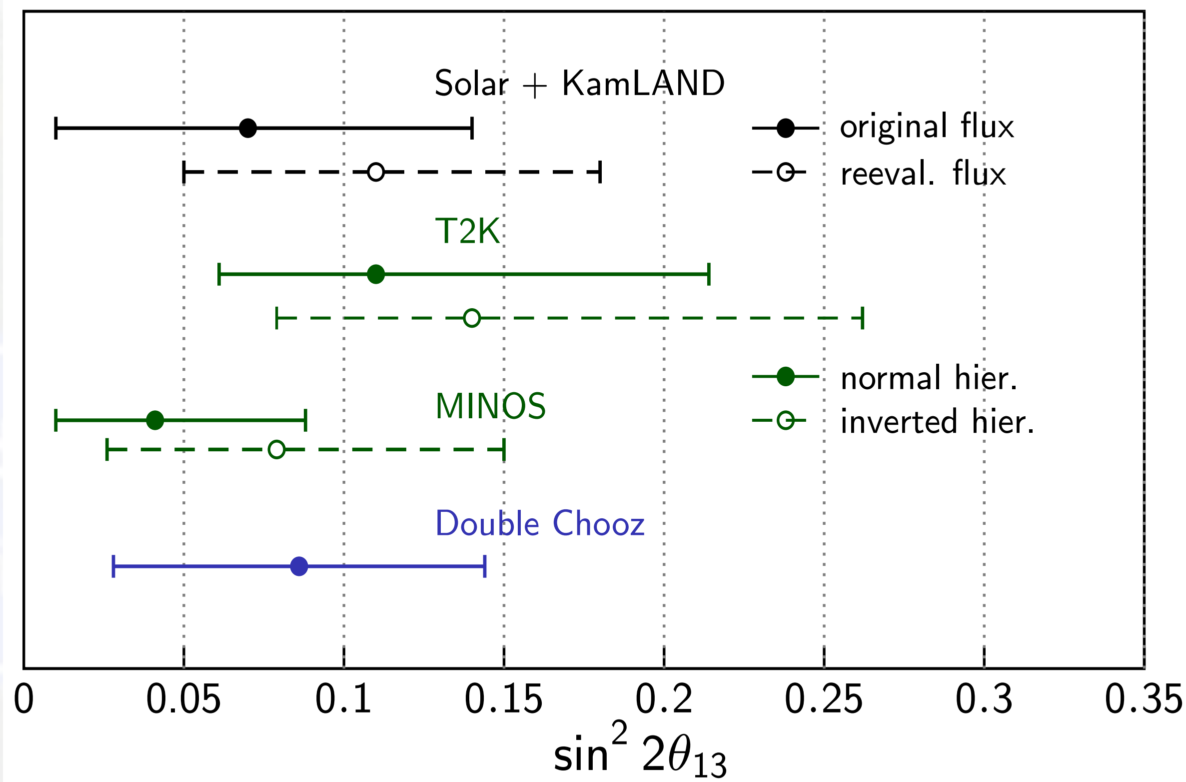
PRL**107**, 181802 (2011)



Some hints of a non-zero θ_{13}

PRL**108**, 131801(2012)





The Daya Bay Collaboration

Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

BNL, Caltech, Iowa State Univ., Illinois Inst. Tech., LBNL, 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)

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

~230 Collaborators

Daya Bay Nuclear Power Complex

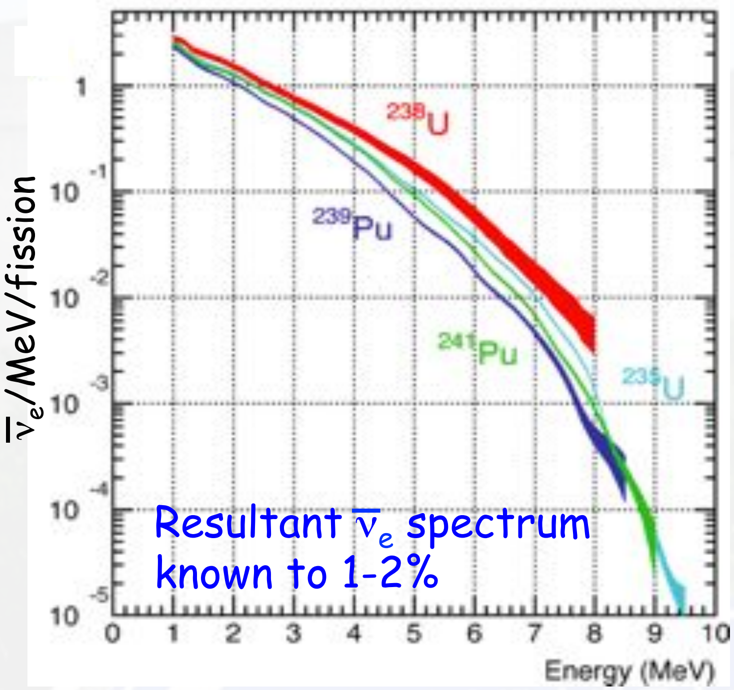
- ~55 km from Hong Kong central
- All 6 reactors are in commercial operation
- one of top 5 most powerful nuclear power plants in the world

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

Production of Reactor $\bar{\nu}_e$

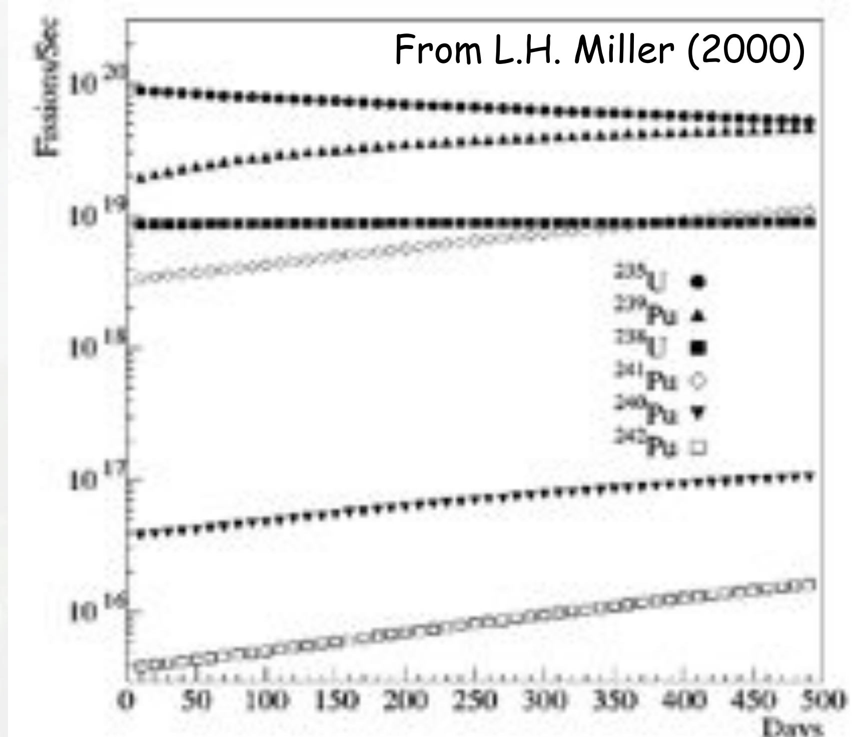
- Fission processes in a nuclear core produce radio-nuclides that decay rapidly to yield a huge number of low-energy $\bar{\nu}_e$:

3 GW_{th} generates 6×10^{20} $\bar{\nu}_e$ per sec



Resultant $\bar{\nu}_e$ spectrum known to 1-2%

From L.H. Miller (2000)



- $\bar{\nu}_e$ related to ^{235}U, ^{239}U, and ^{241}Pu :
  - measure β spectrum using thermal neutron induced fission on the isotope
  - convert β spectrum to $\bar{\nu}_e$ spectrum
- $\bar{\nu}_e$ related to ^{238}U :
  - $\bar{\nu}_e$ spectrum is based on calculation

- Uncertainty in $\bar{\nu}_e$ yield, ~2%, due to
  - Thermal power (<1%)
  - Sampling of fuel
  - Analysis of fractions of isotopes in samples

Detecting Reactor $\bar{\nu}_e$

- Use the inverse β-decay reaction in a liquid scintillator:

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

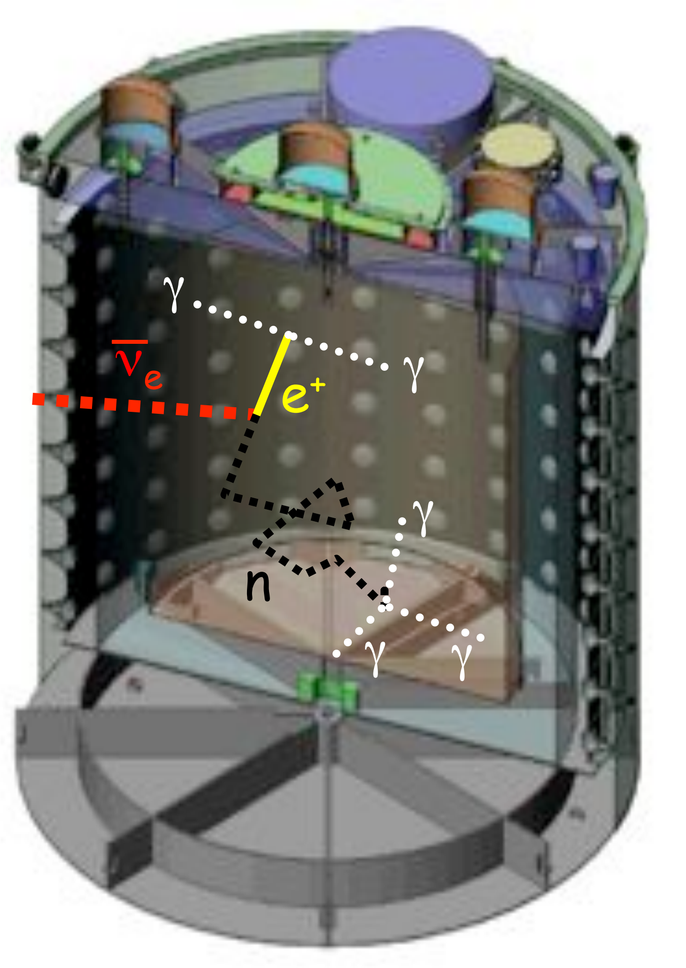
~180μs

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

$\rightarrow + Gd \rightarrow Gd^*$

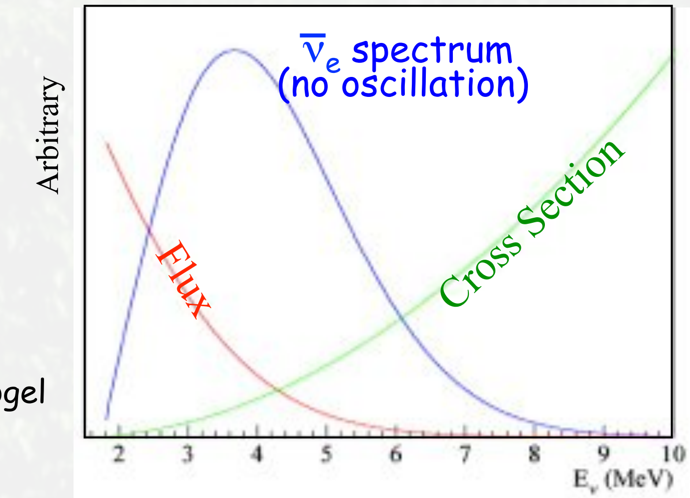
~30μs for 0.1% Gd

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



- Time- and energy-tagged signal is a good tool to suppress background events.
- Energy of $\bar{\nu}_e$ is given by:

$$E_\nu \approx \underbrace{T_{e+} + T_n}_{\text{10-40 keV}} + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$

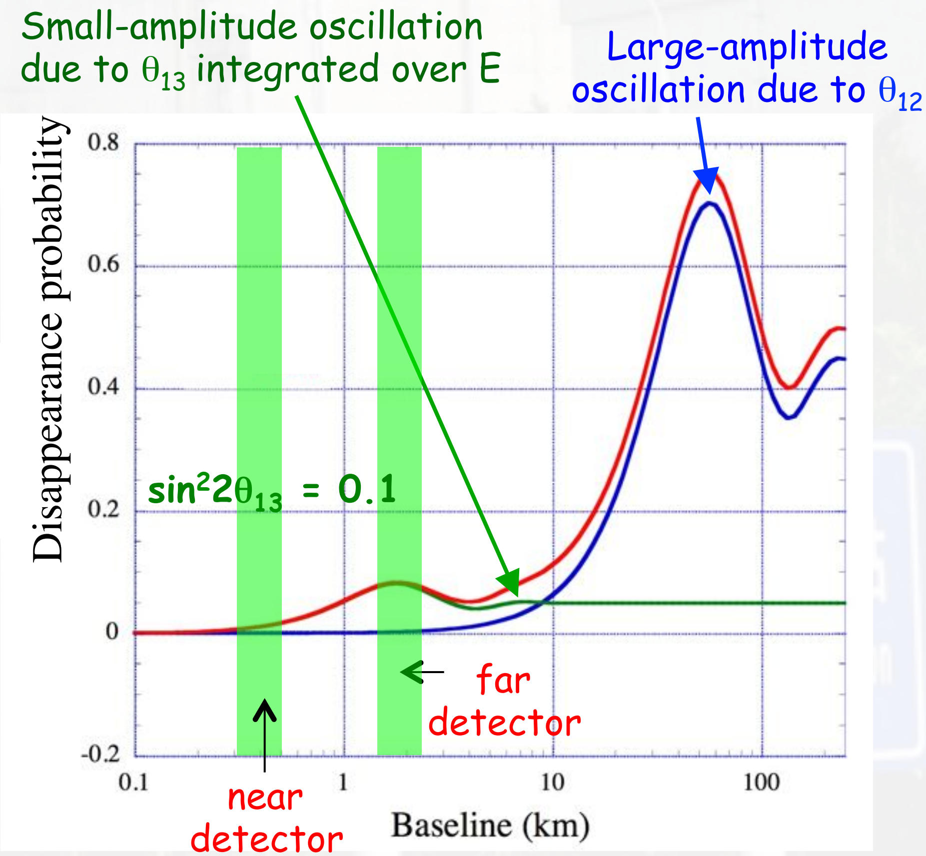


From Bemporad, Gratta and Vogel

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

- Look for disappearance of electron antineutrinos from reactors:

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

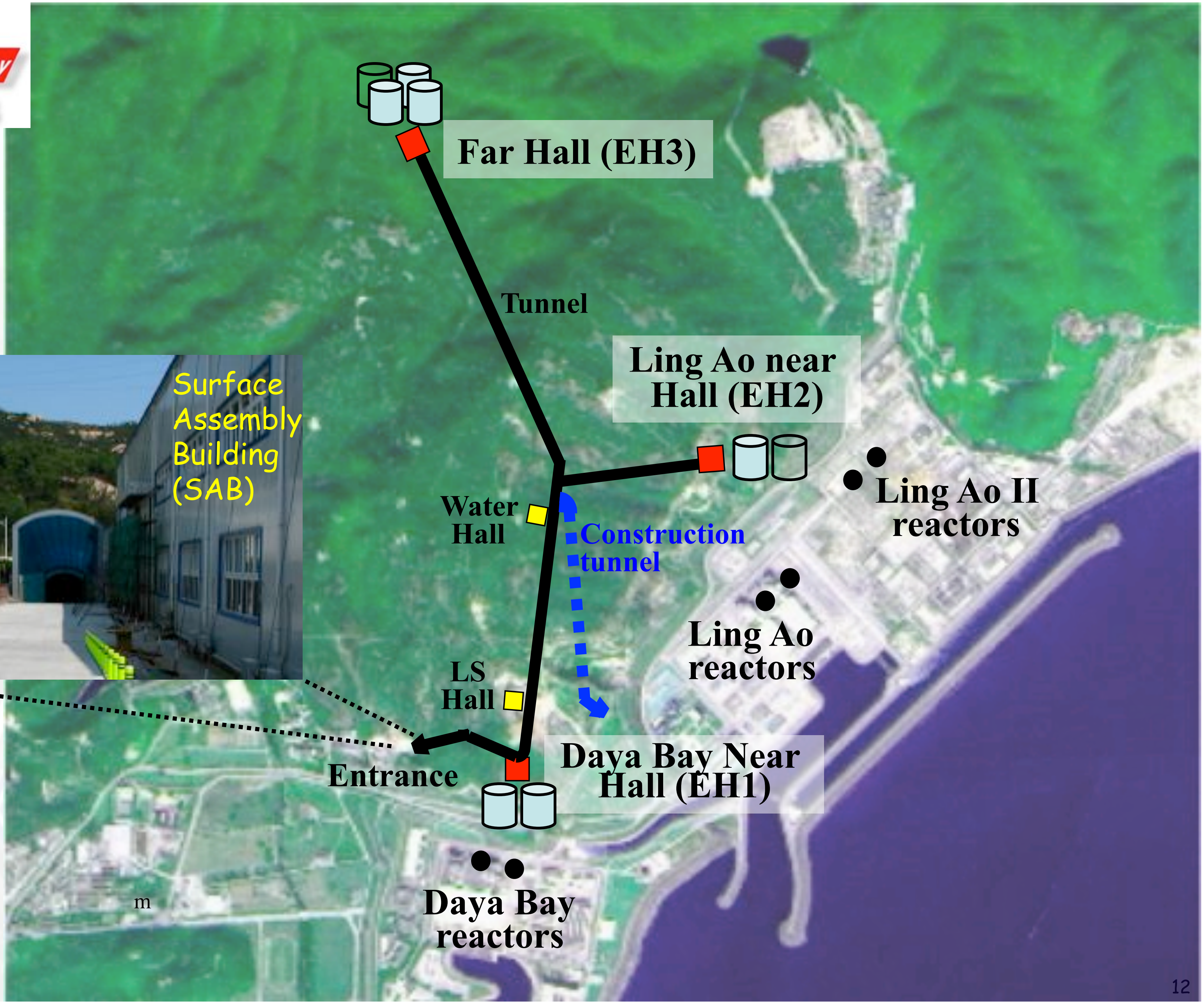


- Perform a relative measurement, for a given E :

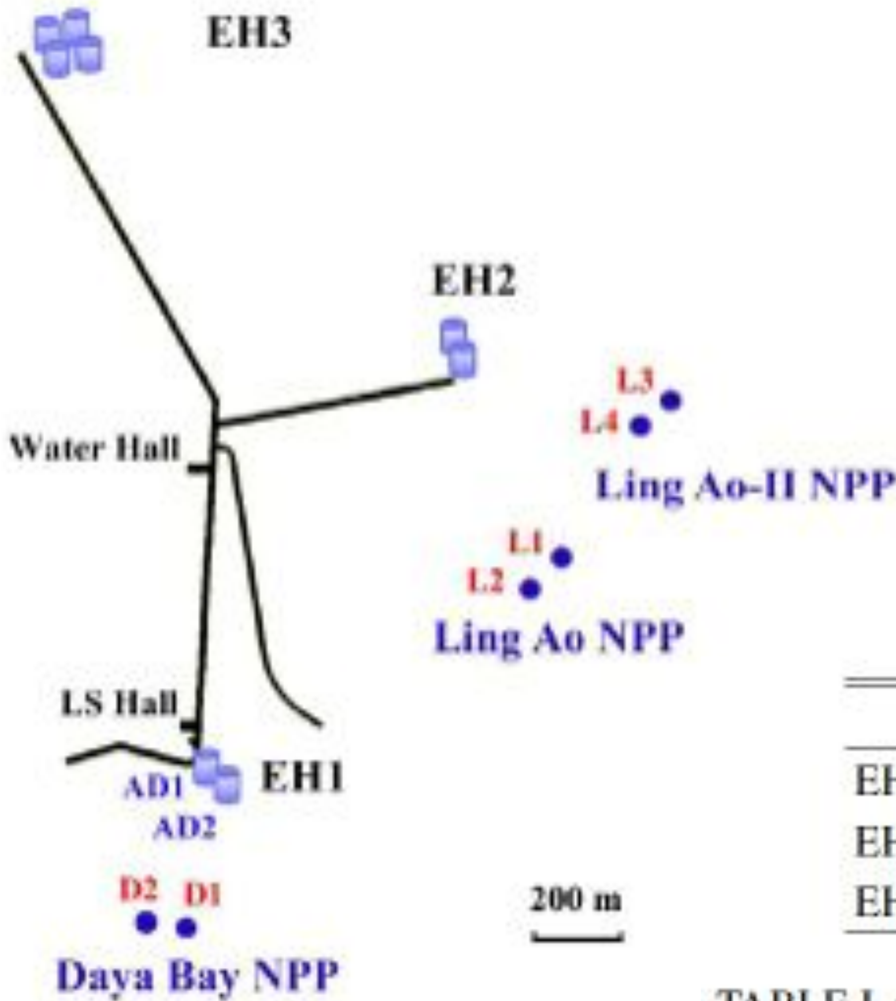
$$\frac{R_{Far}}{R_{Near}} = \left(\frac{L_{Near}}{L_{Far}}\right)^2 \left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{1-P_{Far}}{1-P_{Near}}\right)$$

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

All correlated errors cancelled.


Far Hall (EH3)
Tunnel
Ling Ao near Hall (EH2)
Control Building
Surface Assembly Building (SAB)
Water Hall
Construction tunnel
Ling Ao II reactors
Ling Ao reactors
LS Hall
Entrance
Daya Bay Near Hall (EH1)
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 power plant and design plans

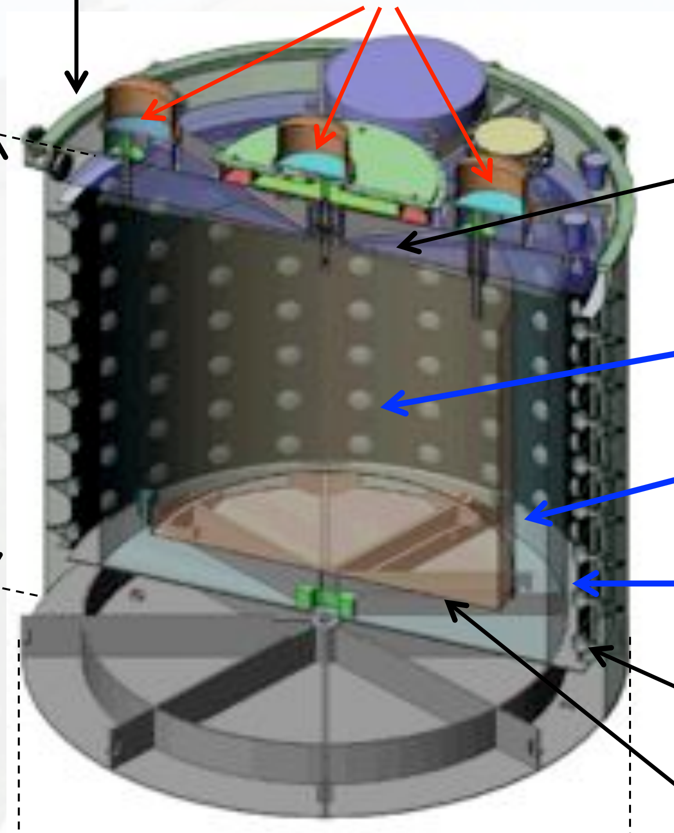
	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

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

Stainless steel tank

Calibration units (LED, ^{68}Ge, AmC-Co)



5m

5m

4m acrylic tank sandwiched between top and bottom reflectors

20t Gd-LS (target)

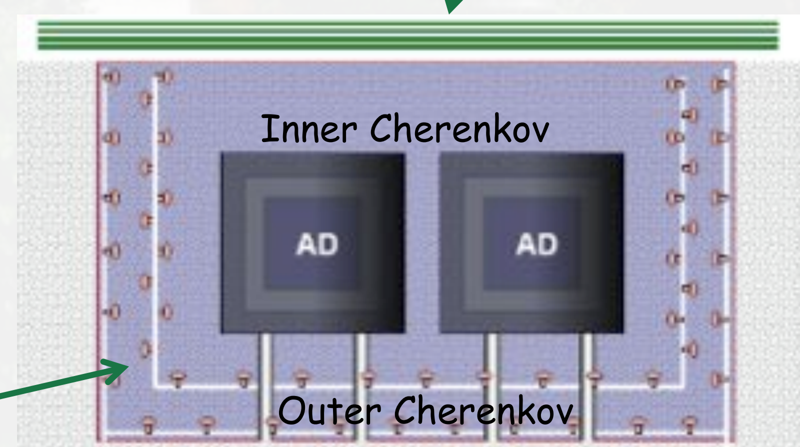
20t liquid scint. (gamma catcher)

37t mineral oil shield

192 PMTs

3m acrylic vessel

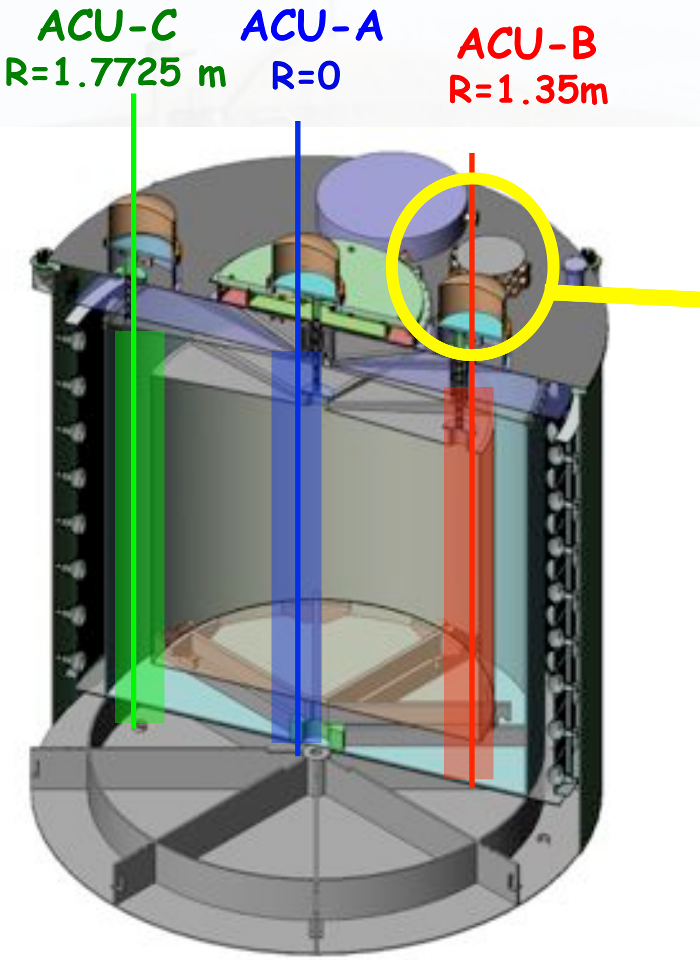
Four layers of RPC's to tag muons



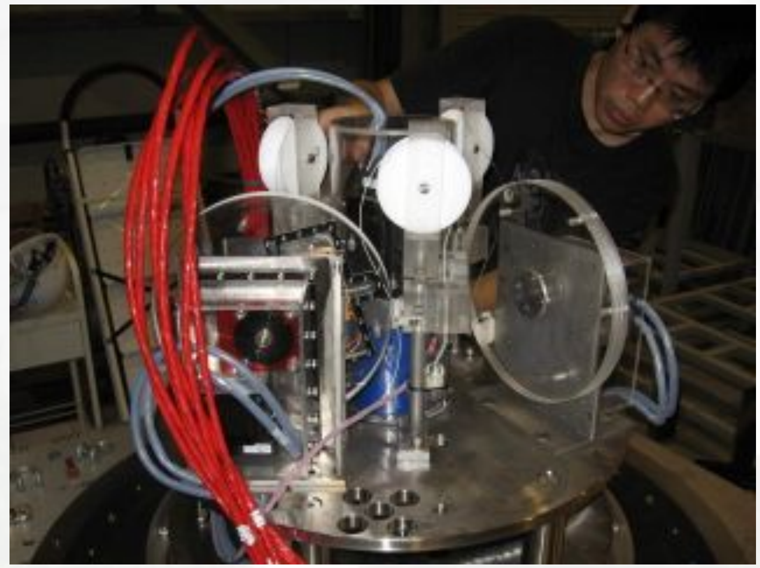
> 2.5m water:
- attenuates gamma rays & neutrons
- forms two optically decoupled Cherenkov counters

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):

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

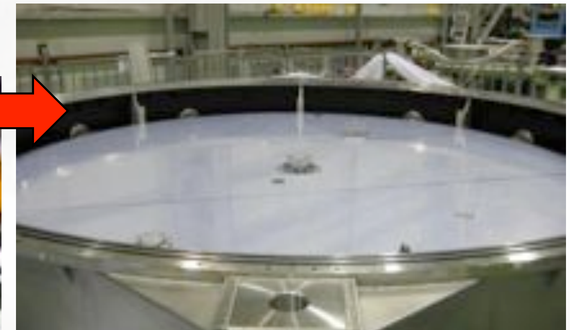
Assemble Antineutrino Detectors

Stainless Steel Vessel (SSV) in assembly pit

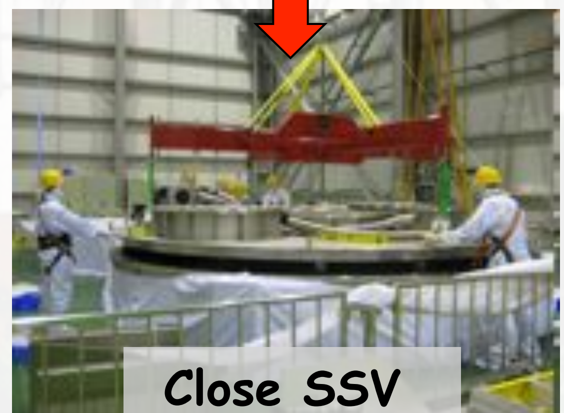
Install lower reflector

Install Acrylic Vessels

Install PMT ladders



Install top reflector

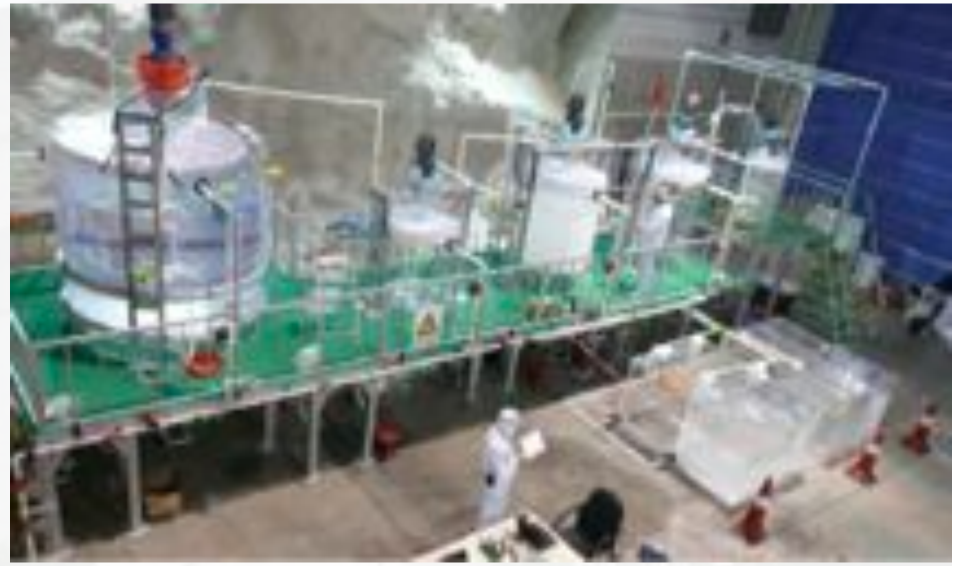


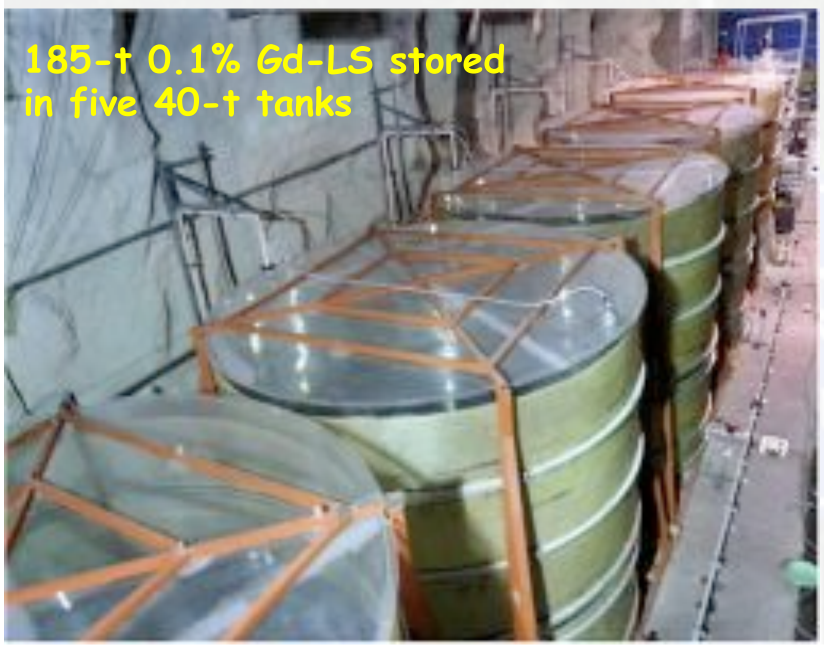
Close SSV

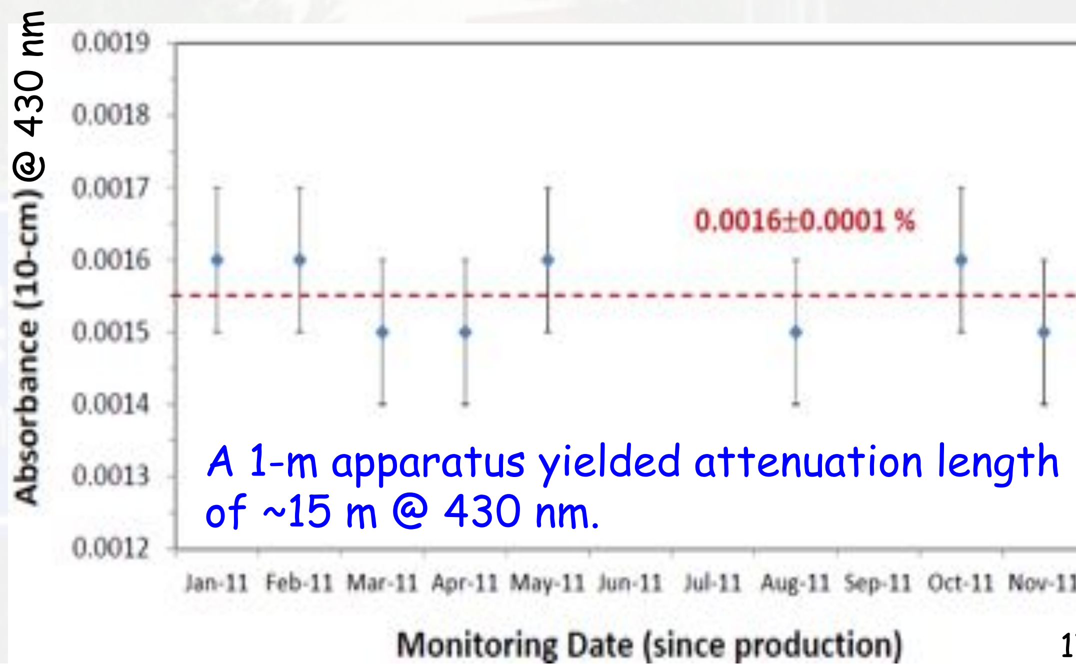
Install calibration units

Liquid Scintillators

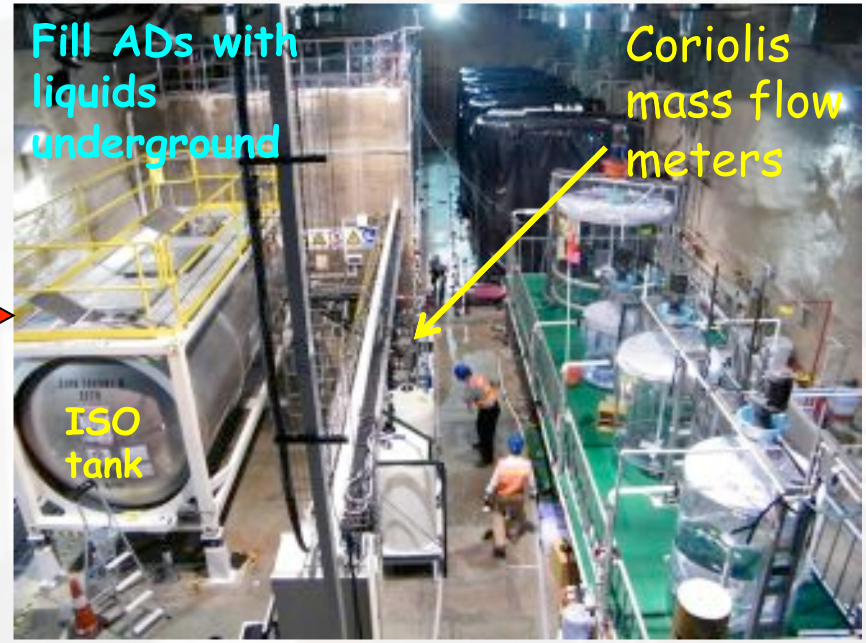
- Gd (0.1%) + PPO (3 g/L) + bis-MSB (15 mg/L) + LAB
- 185-ton Gd-LS + 196-ton LS production
- Number of protons:
  (7.169±0.034) × 10^{25} p per kg



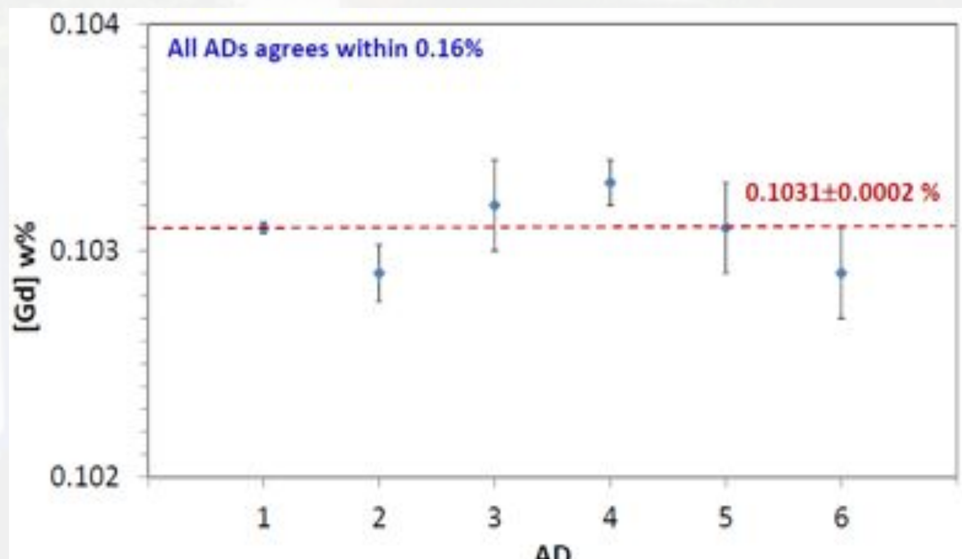




Fill Antineutrino Detectors (ADs)



- 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)

Install filled AD in pool

Fill pool with purified water

Place cover over pool

Data taking started on 15 Aug 2011

Roll RPC over cover

Getting Ling Ao Near and Far Halls Ready

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

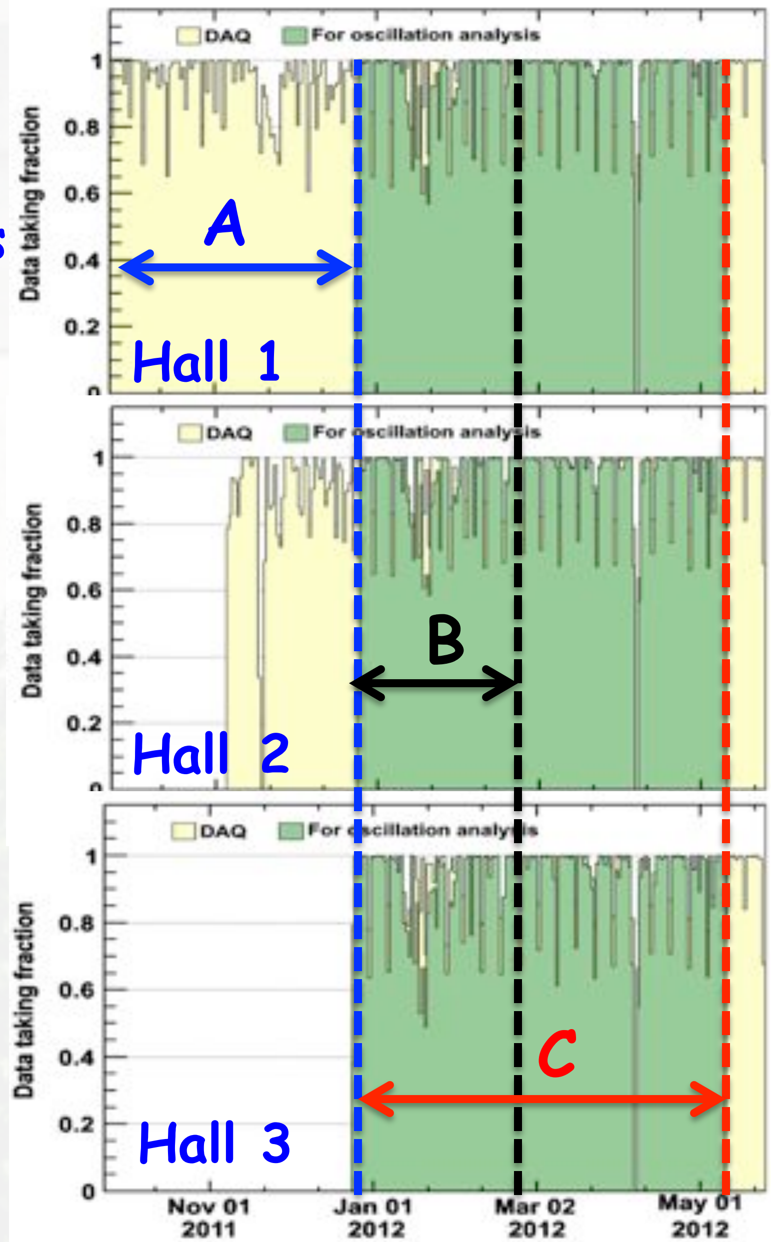
EH 3 (Far Hall):
Started data-taking on
24 Dec 2011

Data Taking

A. Comparison of two ADs :
- 23 Sept. 2011 – 23 Dec. 2011
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.
- Nucl. Instru. Meth. A685, 78 (2012)

B. First results on oscillation:
- 24 Dec. 2011 – 17 Feb. 2012
- All 3 halls with 6 ADs operating
- Observation of ν_e disappearance
- Phys. Rev. Lett. **108** (2012) 171803.

C. This updated analysis:
- 24 Dec. 2011 – 11 May 2012
- 2.5 times more data collected with the same configuration



Triggers & Their Performance

Discriminator threshold:

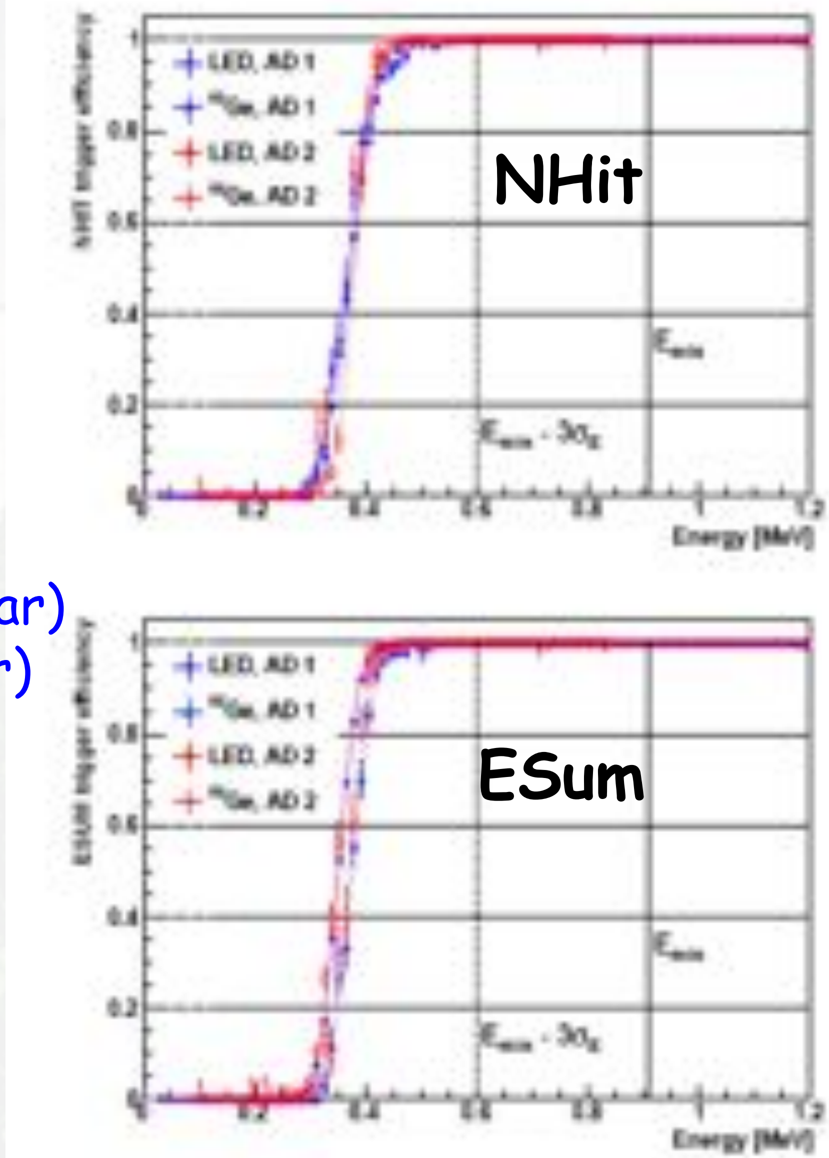
- ~0.25 p.e. for PMT signal

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:

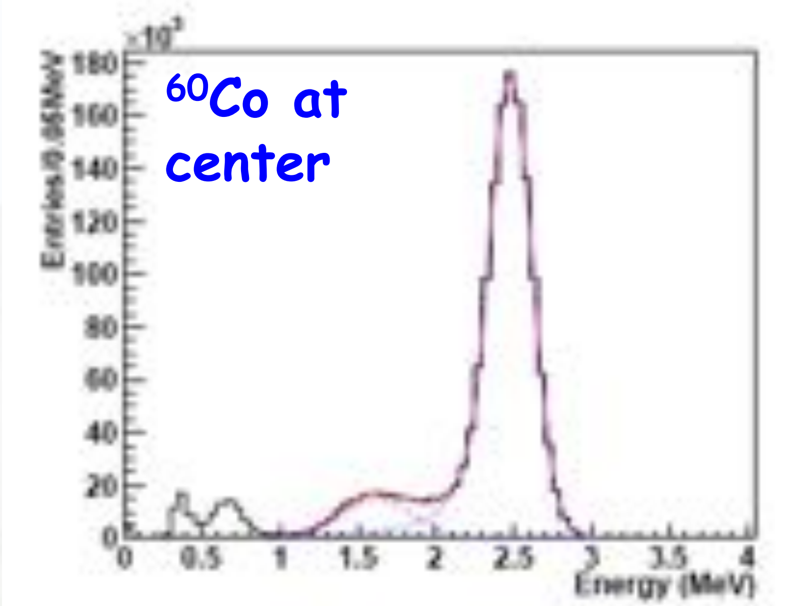
- AD: < 280 Hz
- Inner Water Cherenkov: < 160 Hz
- Outer Water Cherenkov: < 200 Hz

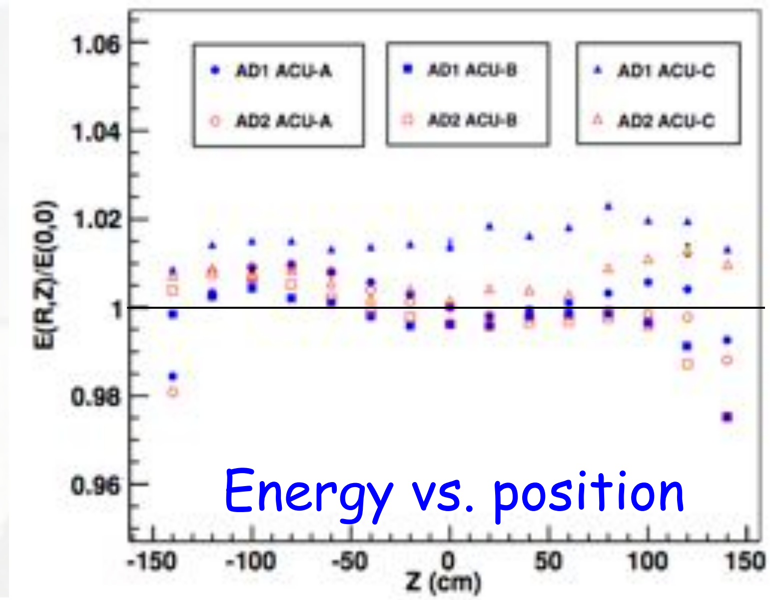


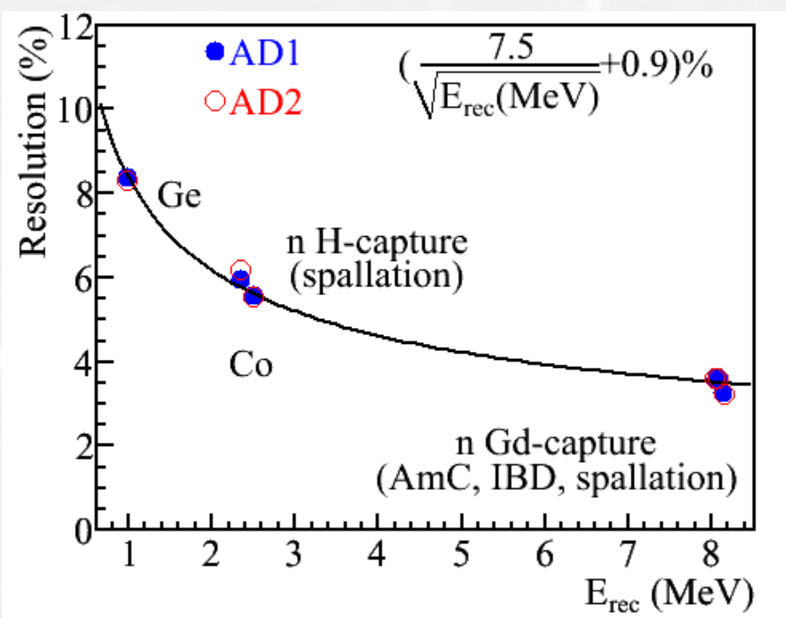
Analysis Approach

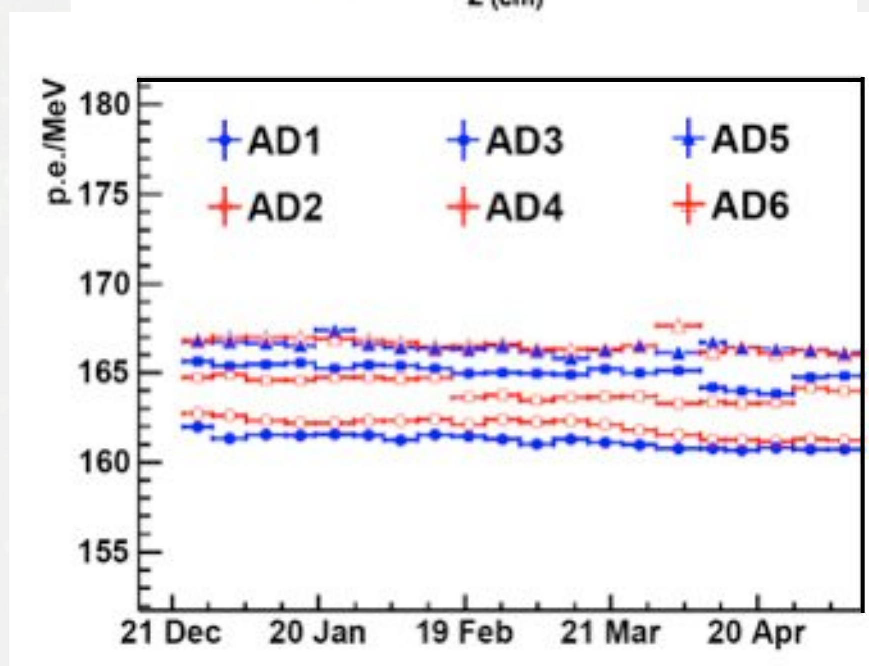
- Multiple independent analyses to cross check results.
- Highlights of differences between analyses:
  - Energy calibration and reconstruction
    - Calibration source (^{60}Co, 'point' source)
    - Spallation neutron (full volume)
  - Antineutrino candidate selection/efficiency
    - Muon veto
    - Multiplicity cut
  - Background studies
  - Extraction of θ_{13}
- Performed analyses with reactor flux blinded.
- All analyses yielded consistent results.

Energy Calibration







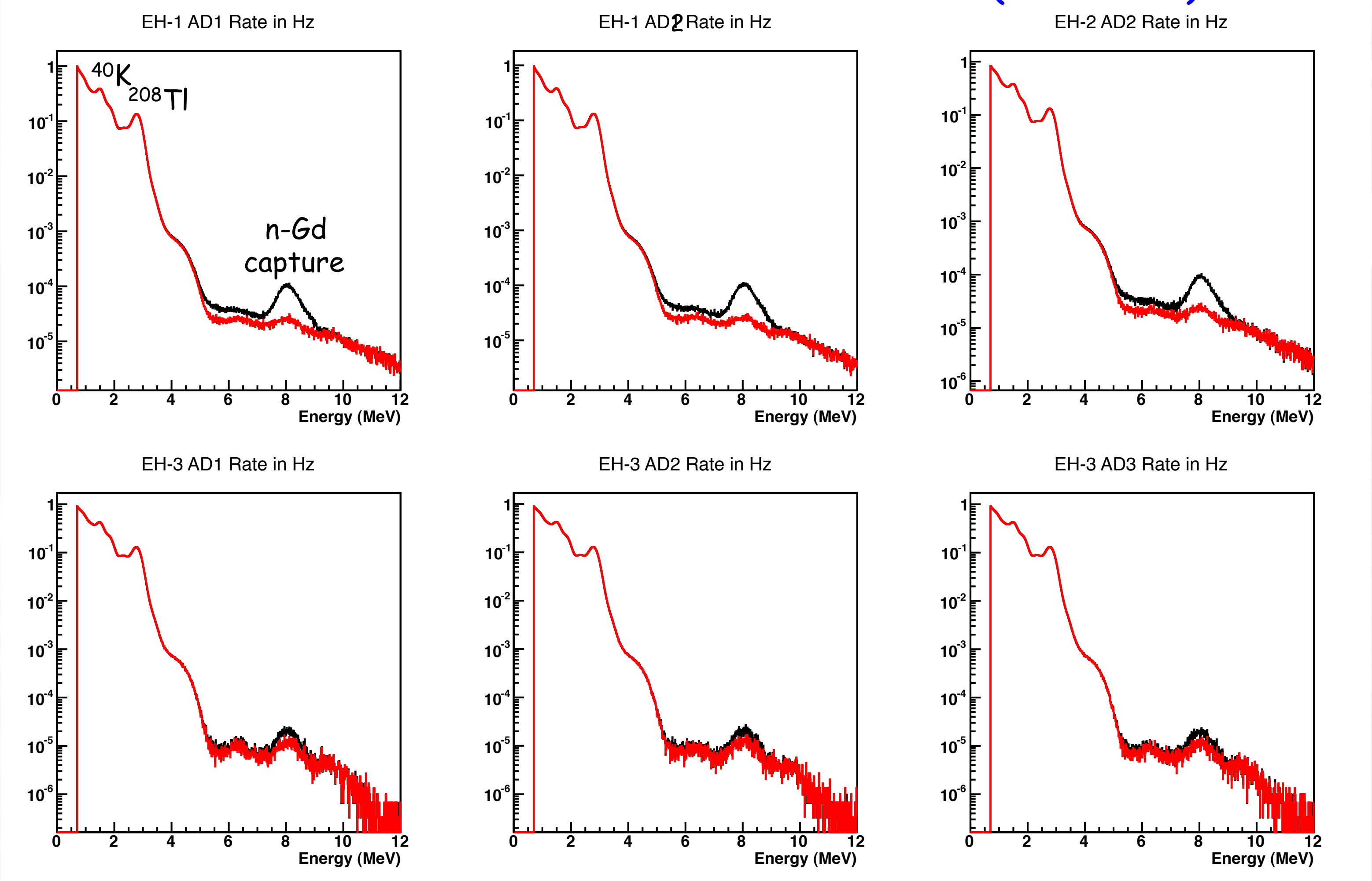


Singles Spectrum

Dominated by low-energy radioactivity

Sources: Stainless Steel (U/Th chains); PMTs (^{40}K, U/Th chains)
Liquid scintillators (Radon/U/Th chains)

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

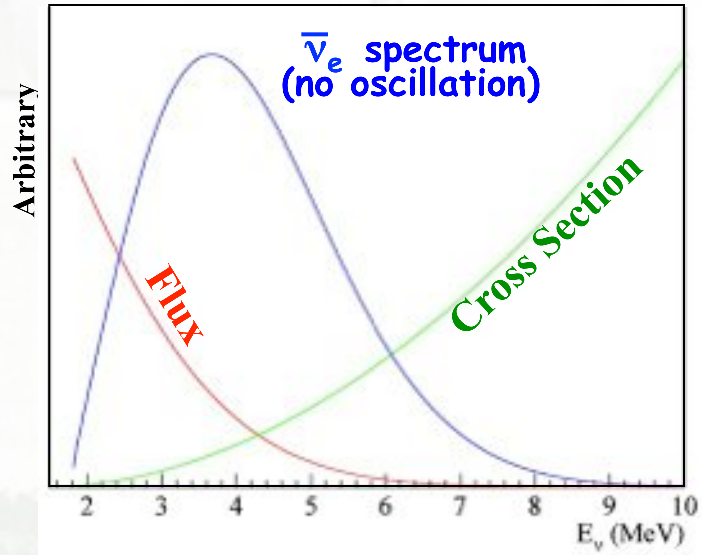


Selecting Antineutrino (IBD) Candidates

Use Prompt + Delayed correlated signal to select antineutrino candidates.

Selection:

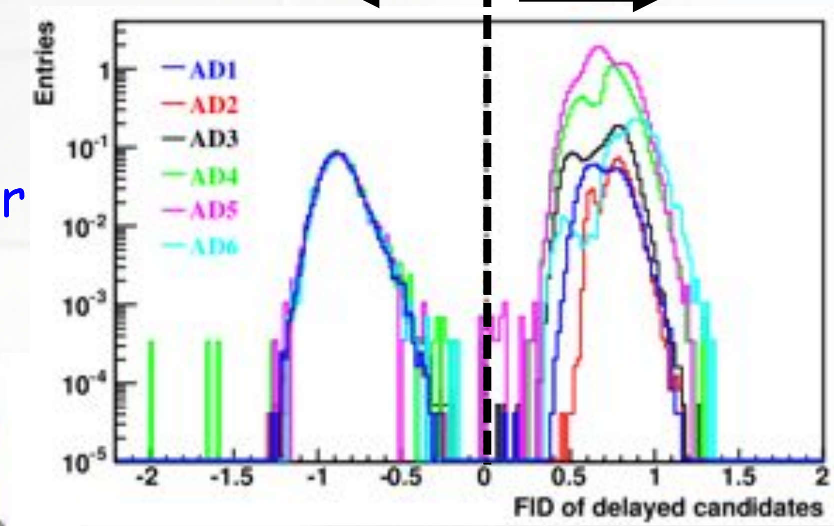
- Reject Flashers
- Prompt: 0.7 MeV < E_p < 12 MeV
- Delayed: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6 ms
  - AD Muon (>20 MeV): Reject 1 ms
  - AD Shower Muon (>2.5GeV): Reject 1 s
- Multiplicity:
  - No other signal > 0.7 MeV in -200 μs to 200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

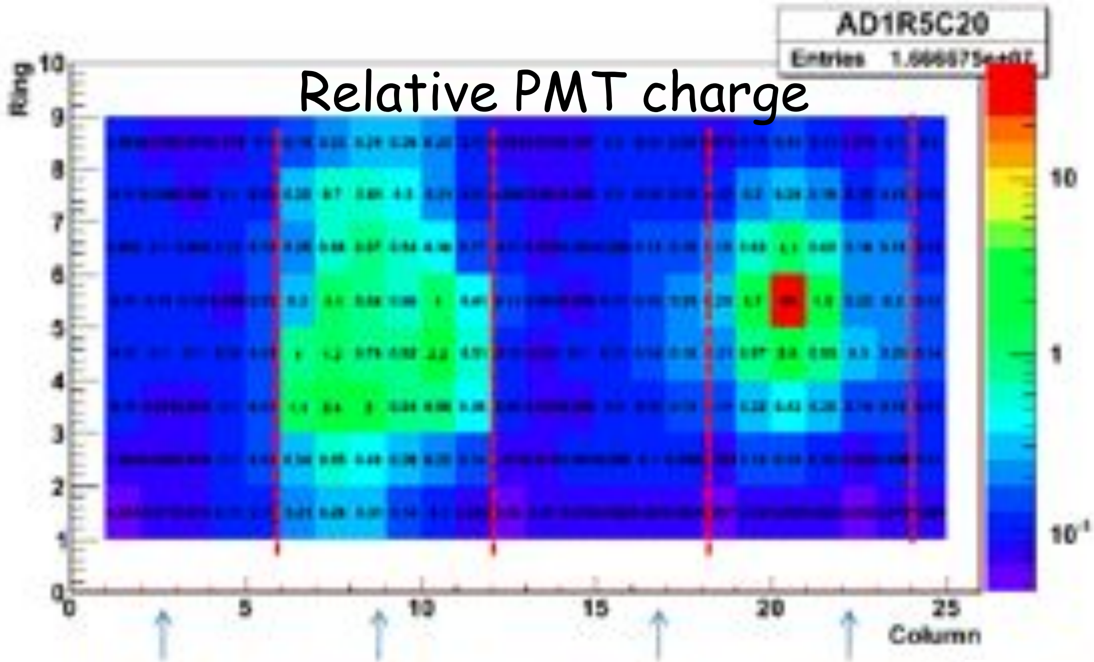


From Bemporad, Gratta and Vogel

PMT Light Emission ('Flasher')

Flashing PMTs:
- Instrumental background: ~5% of PMTS
- 'Shines' light to opposite side of detector
- Easily discriminated from normal signals



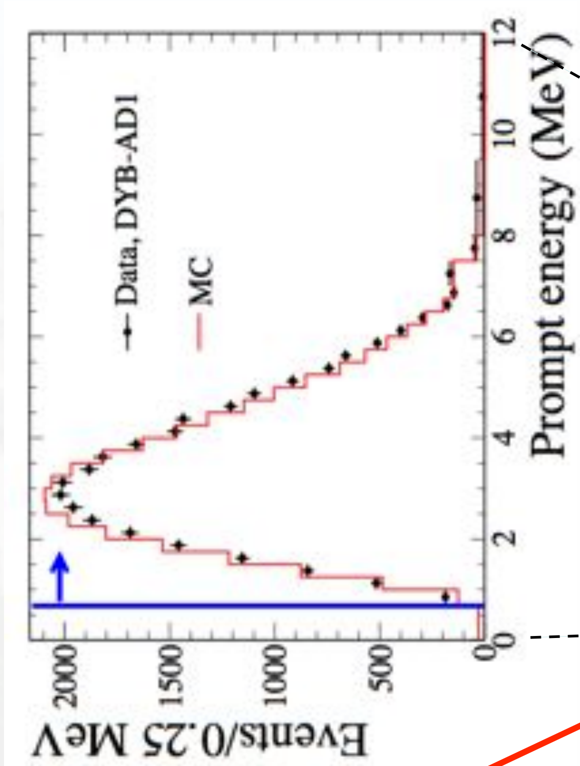


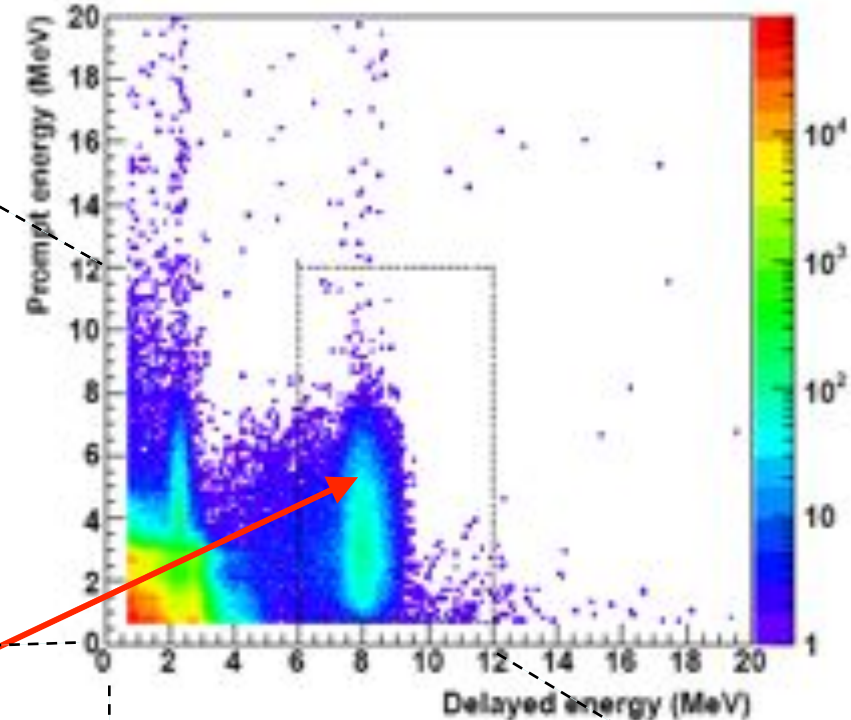
$$FID = \lg_{10}\left[\left(\frac{MaxQ}{0.45}\right)^2 + (Quad)^2\right]$$

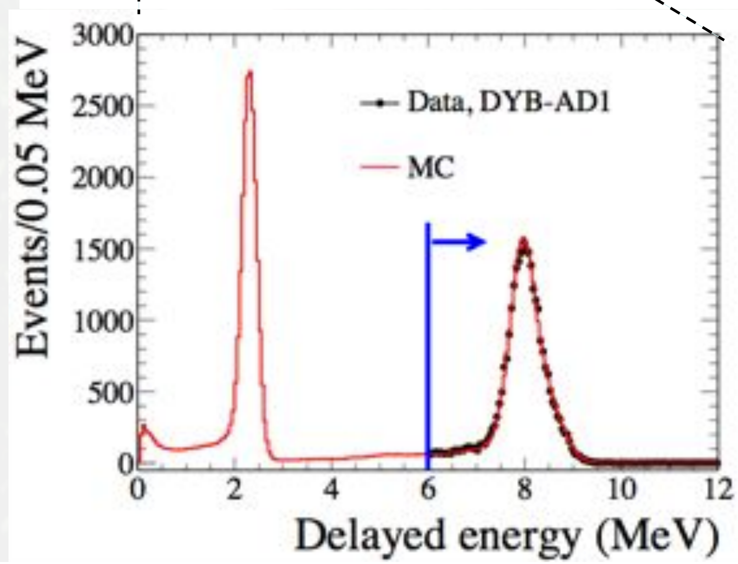
$$MaxQ = \frac{Q_{max}}{\sum_i Q_i}, \quad Quad = \frac{Q_3}{Q_2 + Q_4}$$

Inefficiency to antineutrinos signal:
0.024% ± 0.006%(stat)
Contamination: < 0.01%

Prompt/Delayed Energy

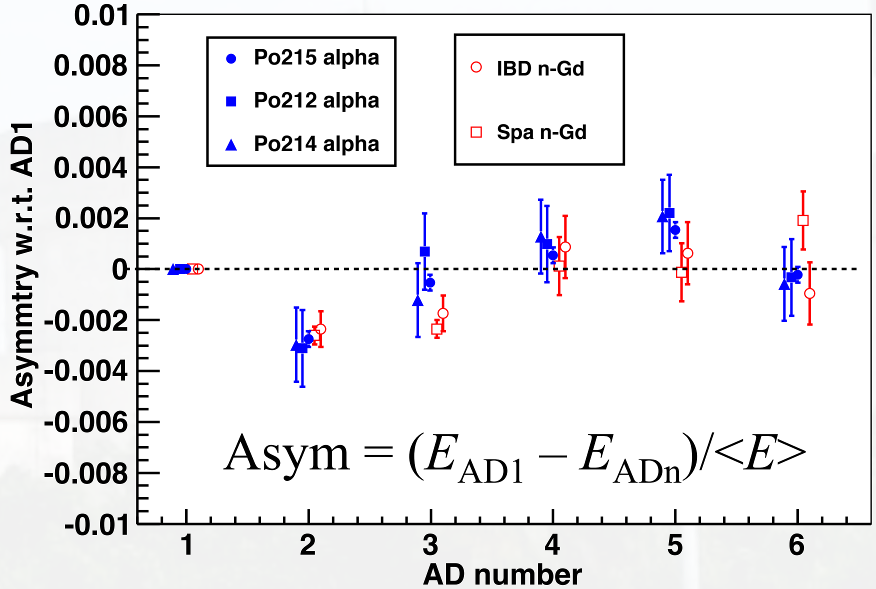






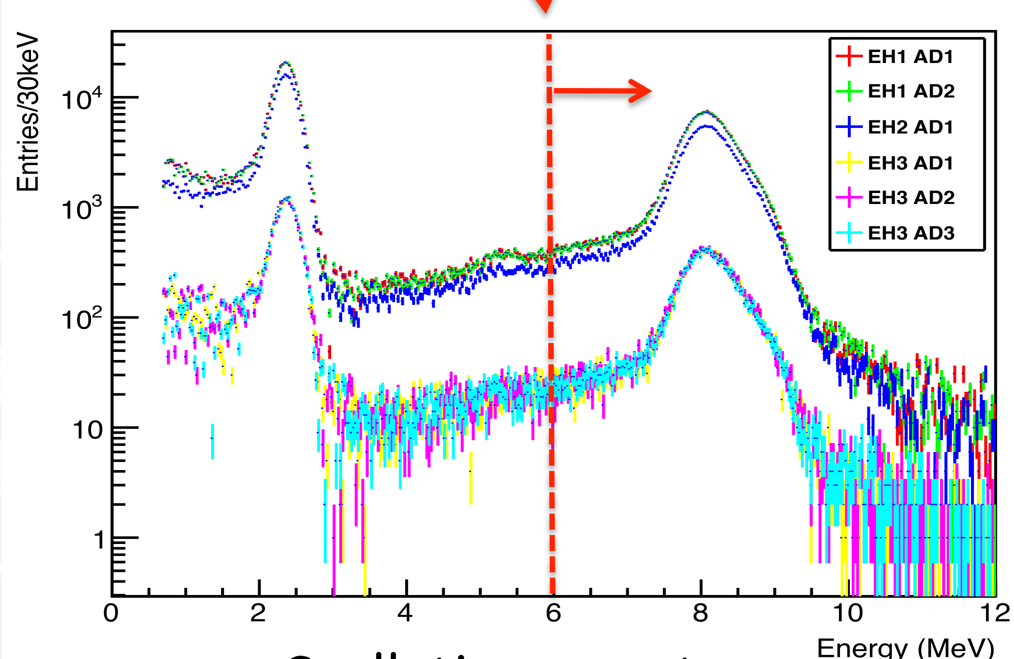
Clear separation of antineutrino events from most other signals

Relative Efficiency of Cut on Delayed Energy



Variation in n-capture peak-energy : ~0.3%

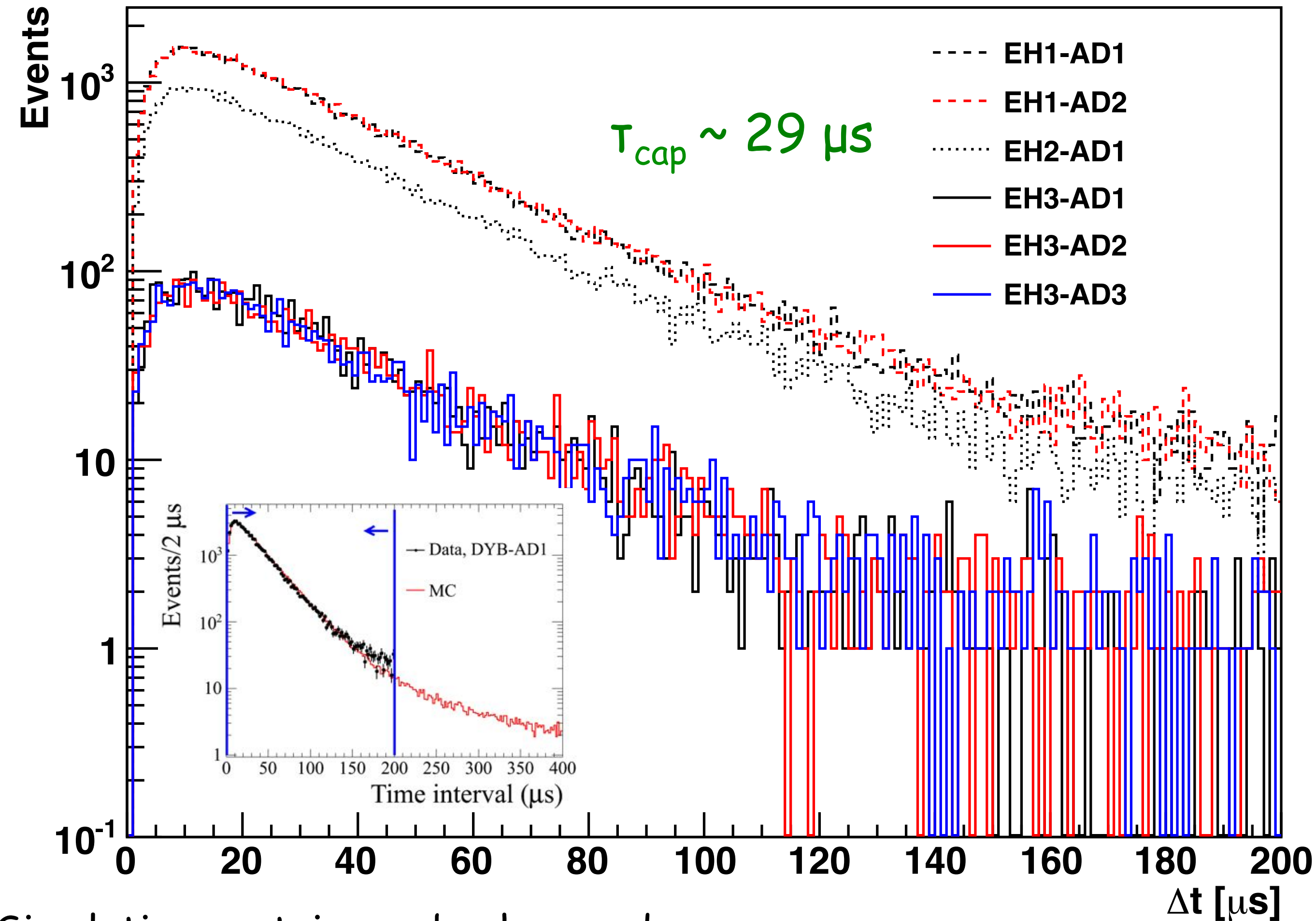
Uncertainty in relative E_d efficiency (0.12%) between detectors.



Spallation-n capture

Neutron Capture Time

Consistent capture time measured in all detectors



Time between neutron generation and capture on Gd

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

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

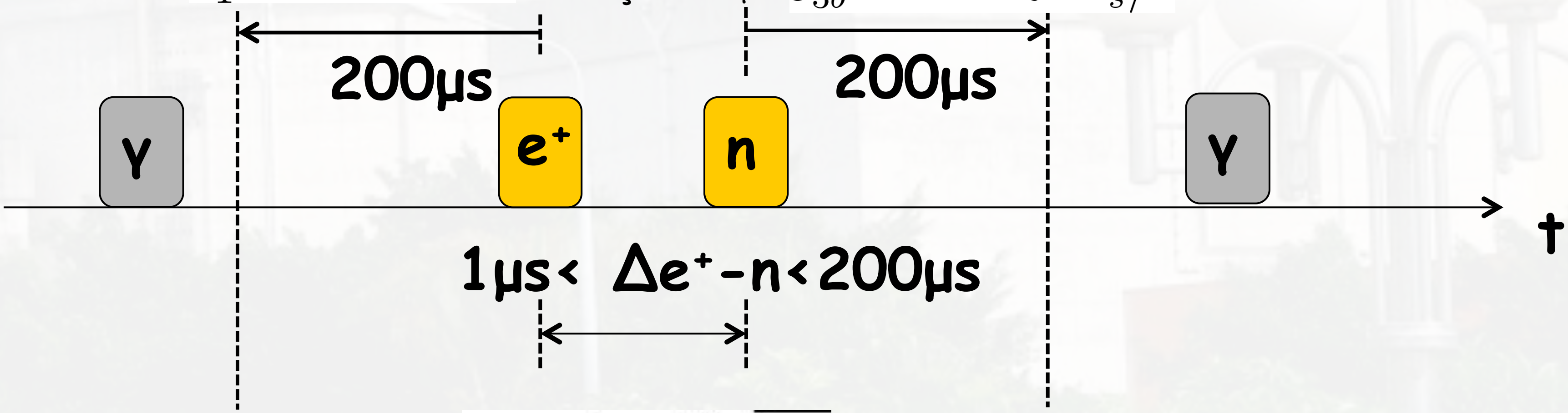
Multiplicity Cut

Ensure exactly one prompt-delayed coincidence

If T_s < 200 μs $\varepsilon_{3a} = 1 - R \cdot 200\mu s \cdot (1 - 100\mu s / \Delta T_s)$

If T_s > 200 μs $\varepsilon_{3b} = 1 - R \cdot T_s/2$

$\varepsilon_1 = e^{-R \cdot 200\mu s}$

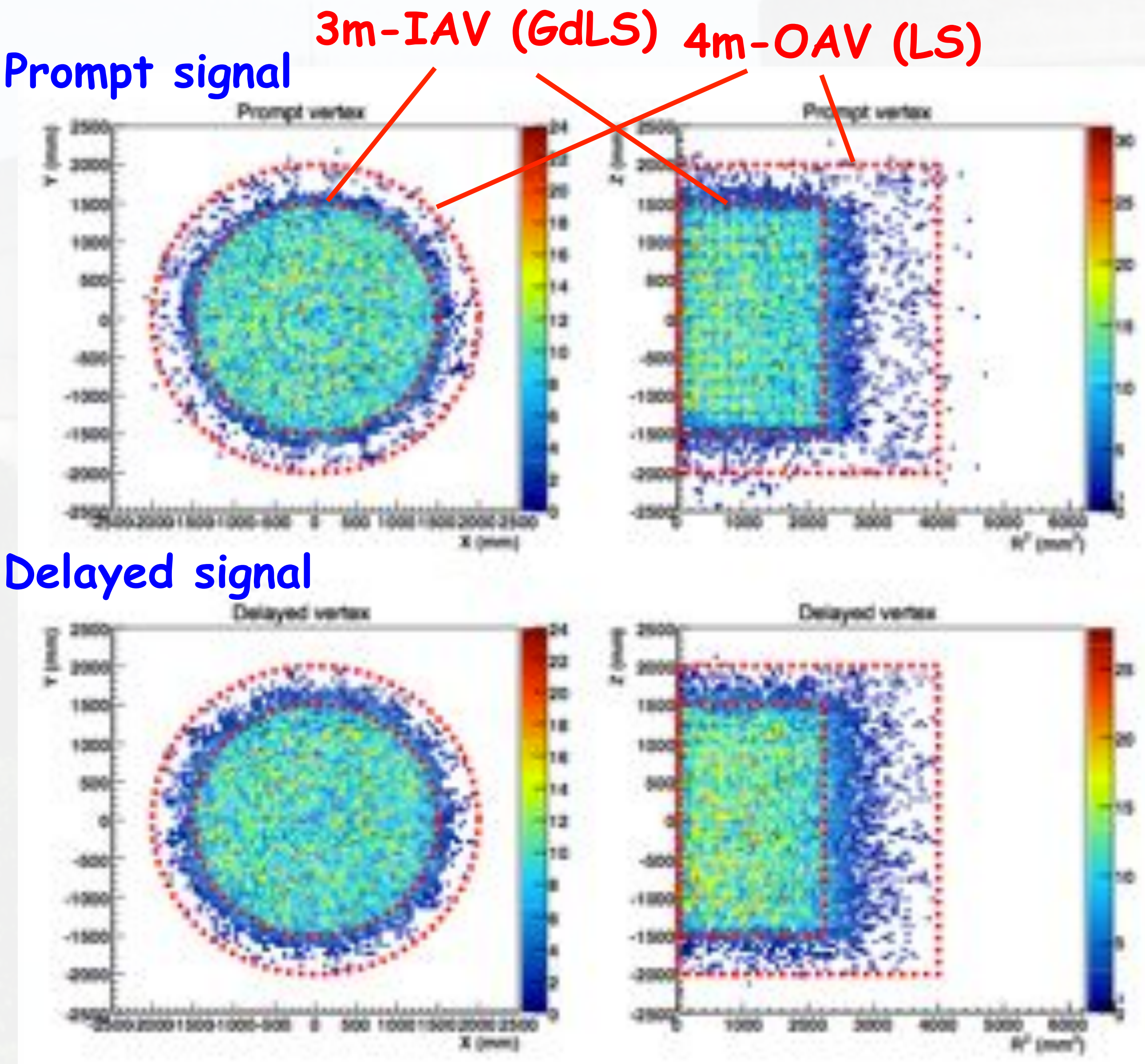


$\varepsilon_2 = 1 - R \cdot \overline{t_{cap}}$

Uncorrelated background and IBD signals result in ambiguous prompt-delayed signals.

➔ Reject all IBDs with >2 triggers above 0.7 MeV in -200μs to +200μs. Introduces ~2.5% IBD inefficiency, with negligible uncertainty.

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.

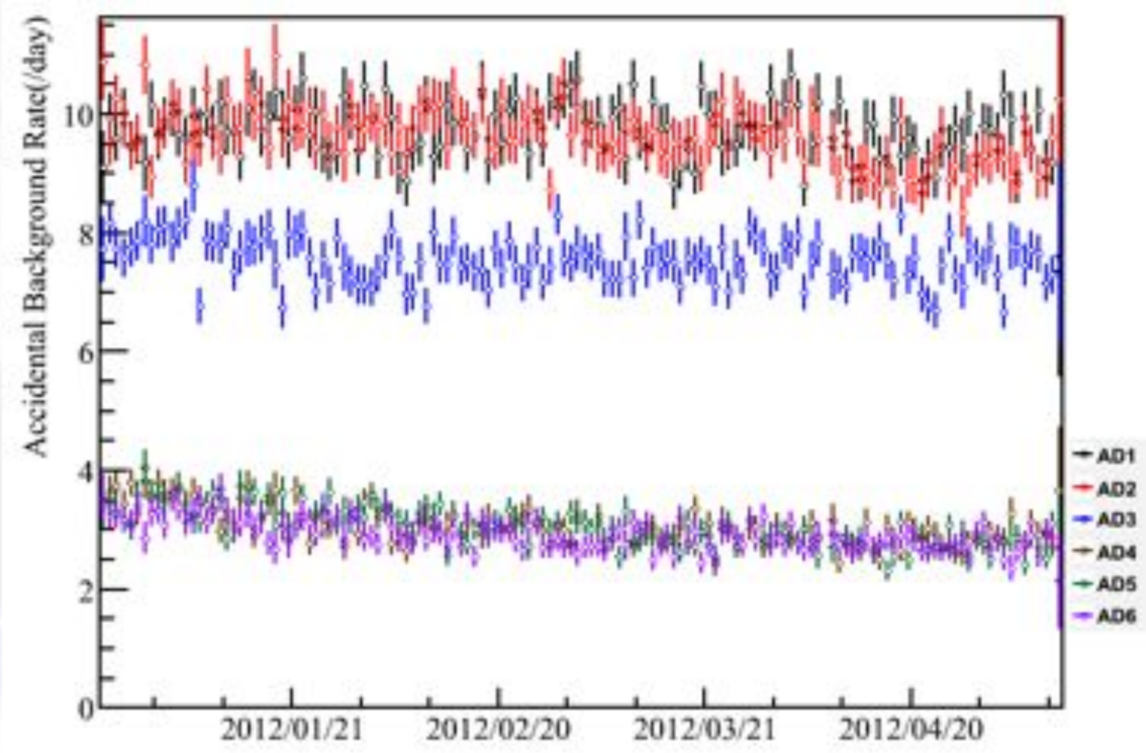
Remaining Background

- Uncorrelated background
  - Accidentals: two uncorrelated events 'accidentally' pass the cuts and mimic IBD event.
- Correlated background
  - Muon spallation products
    - $^{9}Li/^{8}He$
    - 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

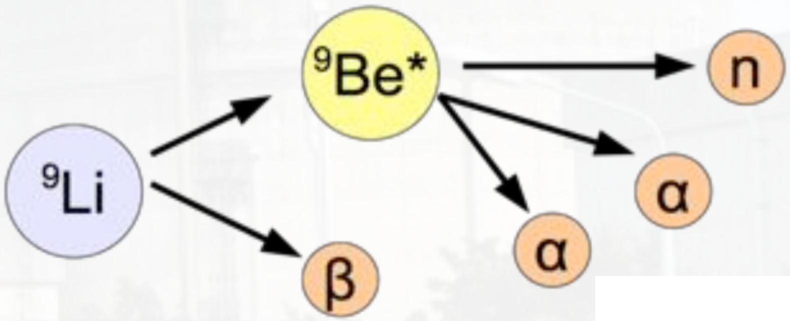
Rate and spectrum can be accurately predicted from singles data.



	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Accidental rate(/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
B/S	1.47%	1.43%	1.23%	3.93%	3.97%	3.91%

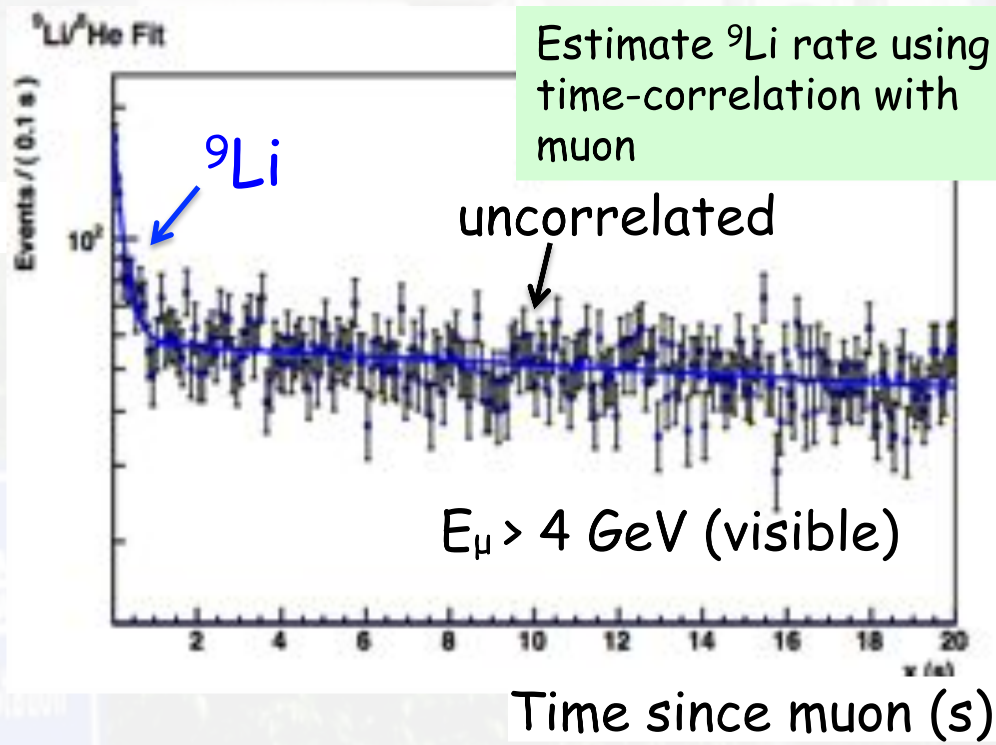
Background: $^{9}Li/^{8}He$ β-n Decays

β-n decay:
- Prompt: β-decay
- Delayed: neutron capture



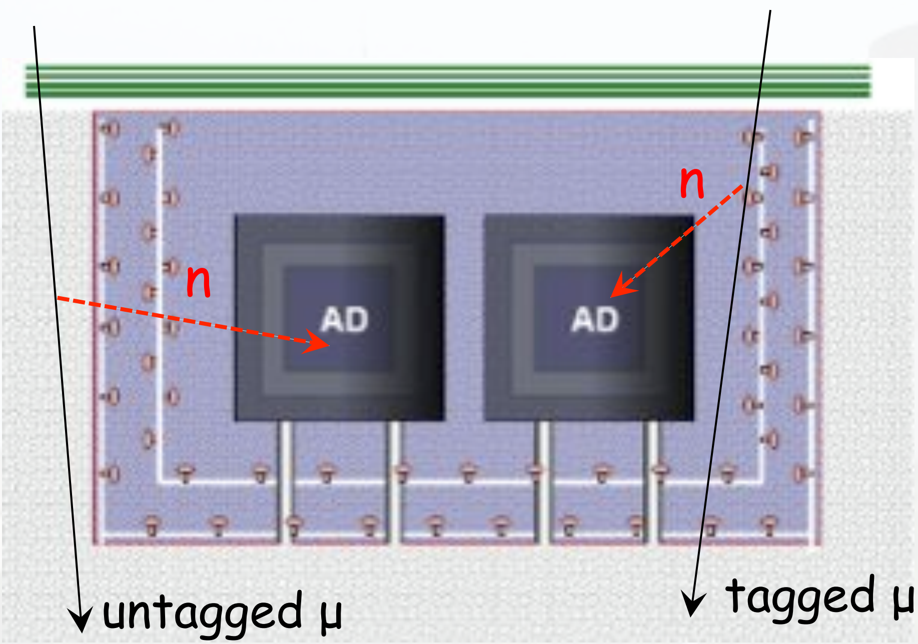
- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal

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



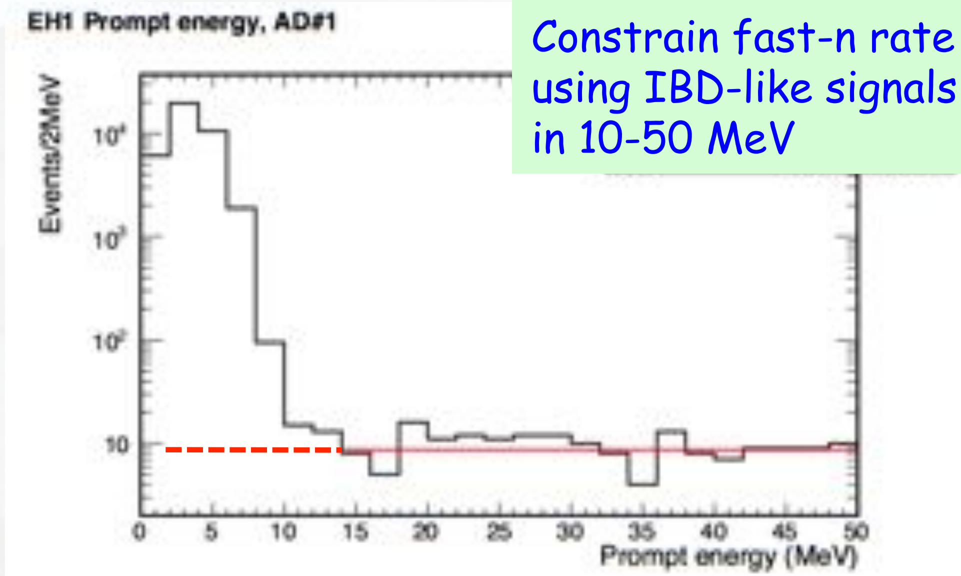
Muon veto software cuts control B/S to ~0.3% (0.4%) for the far (near) hall.

Background: Fast Neutrons

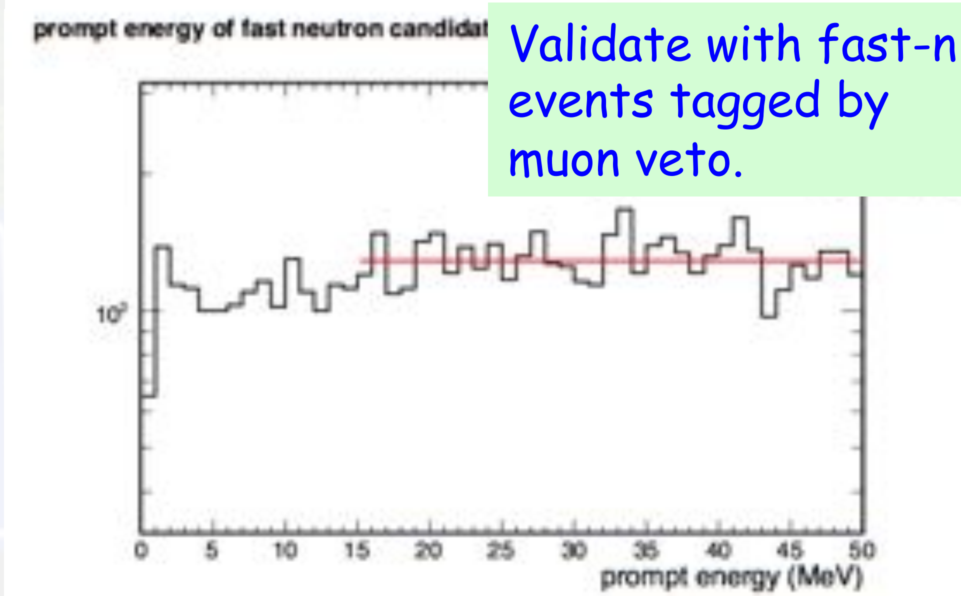


Can mimic the IBD signal:
- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd

Muon veto analysis-cuts control B/S to 0.07% (0.12%) of far (near) signal.



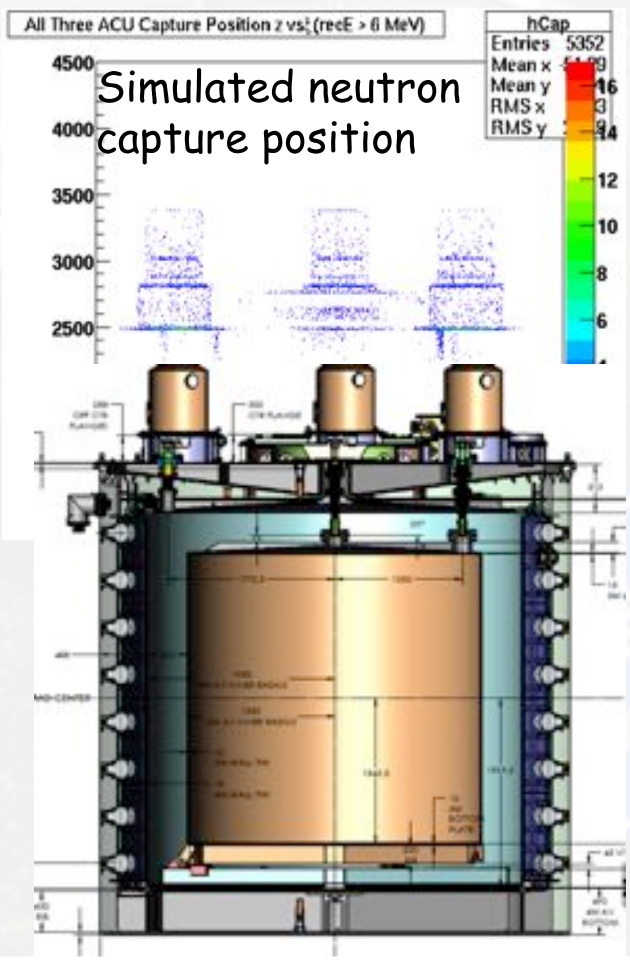
Constrain fast-n rate using IBD-like signals in 10-50 MeV

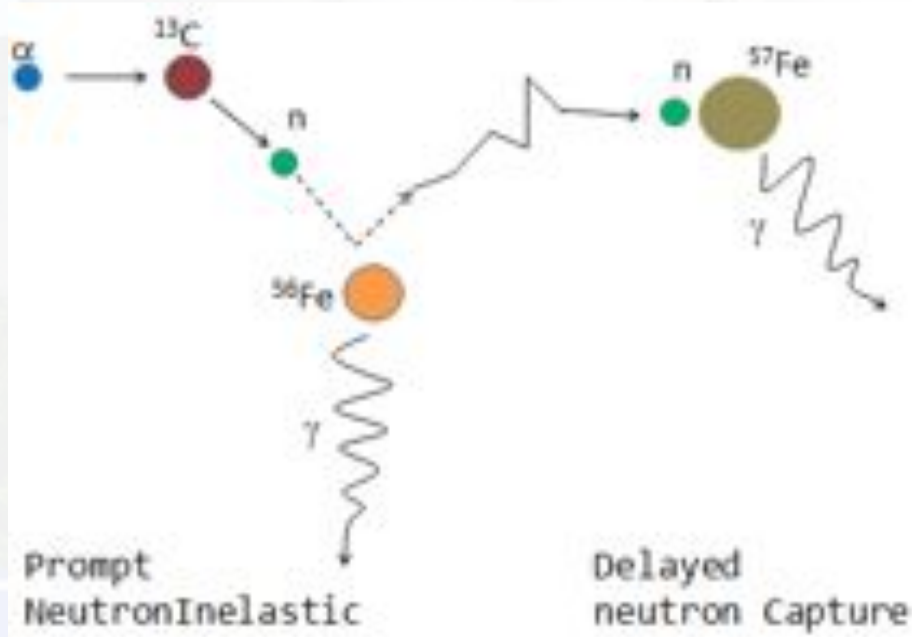


Validate with fast-n events tagged by muon veto.

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

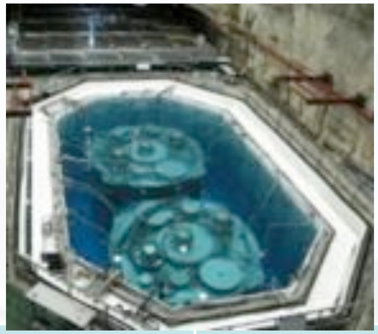
^{210}Po: spectrum fitting

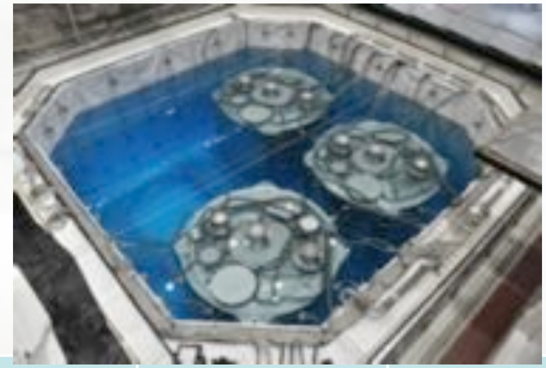
Combining (α,n) cross-section, correlated background rate is determined.

Near Site: ≤0.08±0.04 per day

Far Site: 0.04±0.02 per day

Data Summary





	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763		126.2646	
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{8}He/^{9}Li (/day)	2.9±1.5		2.0±1.1		0.22±0.12	
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

Total amount of background : ~5% (2%) in the far (near) hall

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

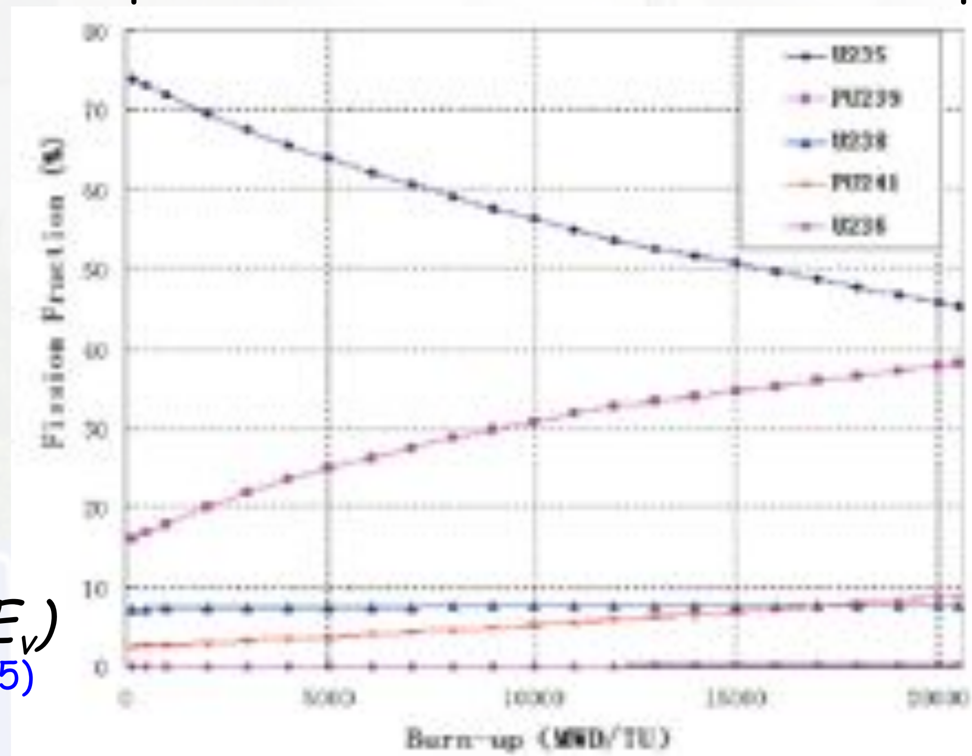
Energy released per fission: e_i

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

Summary of Uncertainties

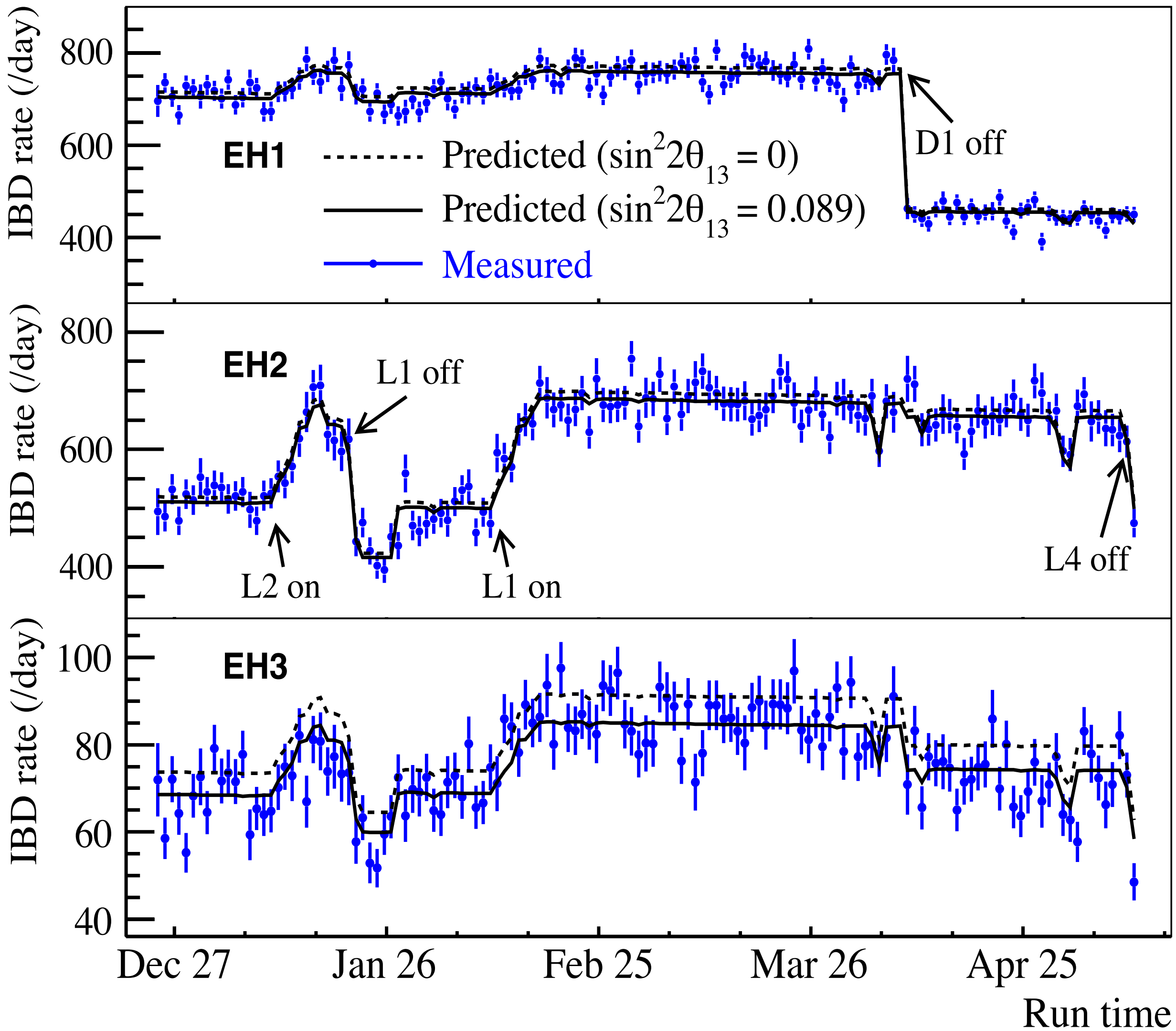
Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%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

Input to near/far analysis and is reduced in the far vs near measurement.

Antineutrino Rate vs. Time



Detected rate strongly correlated with reactor flux expectations.

Predicted Rate:

- Normalization is determined by fit to near-hall data.
- Absolute normalization is within a few percent of expectations.

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.

$\boxed{R = 0.944 \pm 0.007\ (\mathrm{stat}) \pm 0.003\ (\mathrm{syst})}$

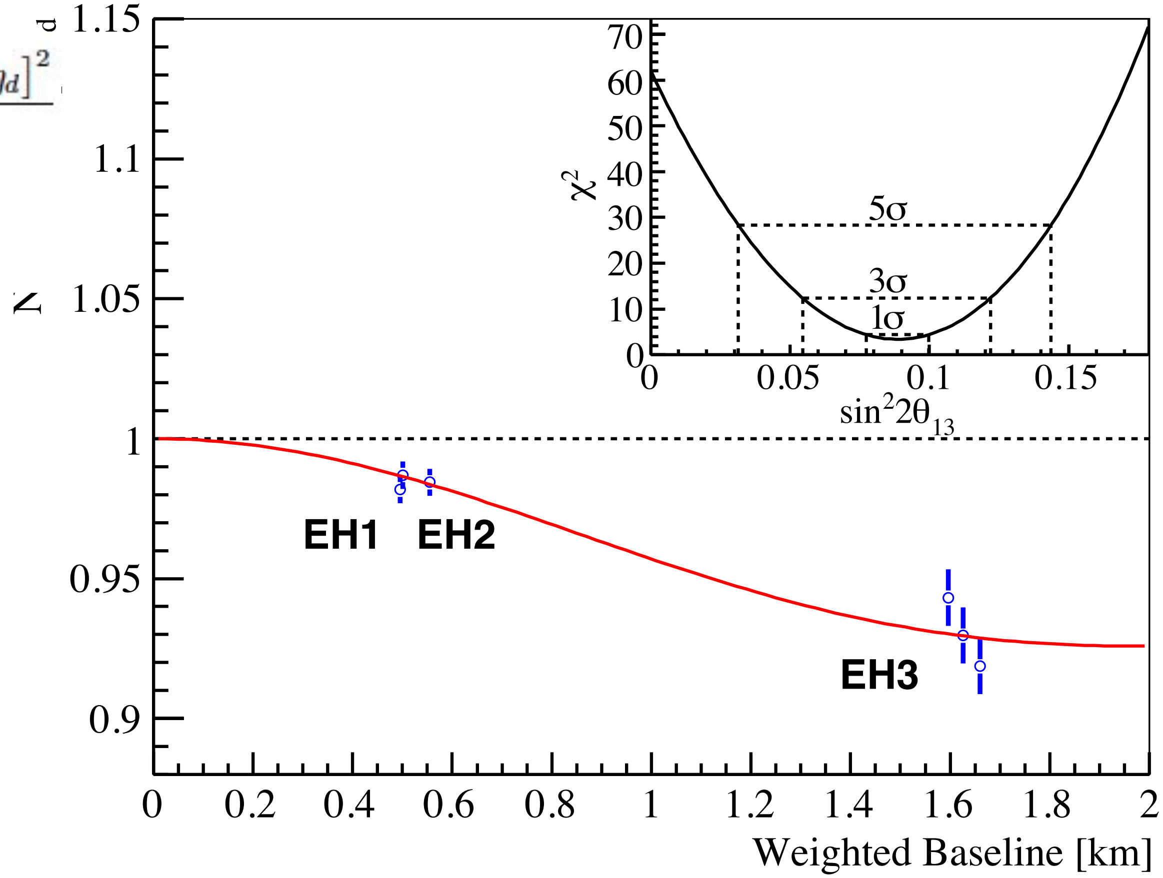
Clear observation of $\overline{\nu}_e$ deficit at the far site.

Rate-only Analysis

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

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

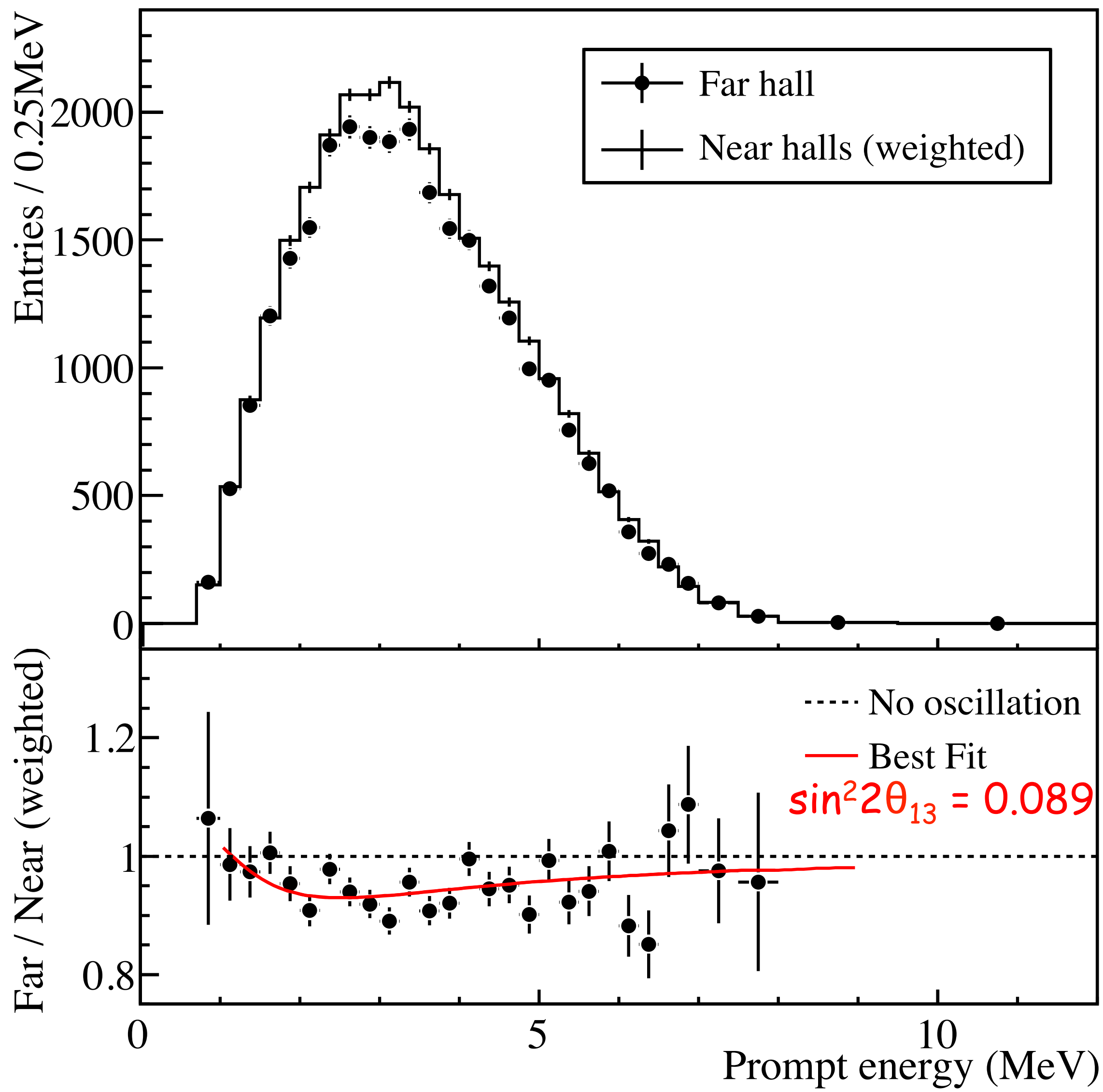
- Far vs. near relative measurement. [Absolute rate is not constrained.]
- Consistent results obtained by independent analyses, different reactor flux models.



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

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

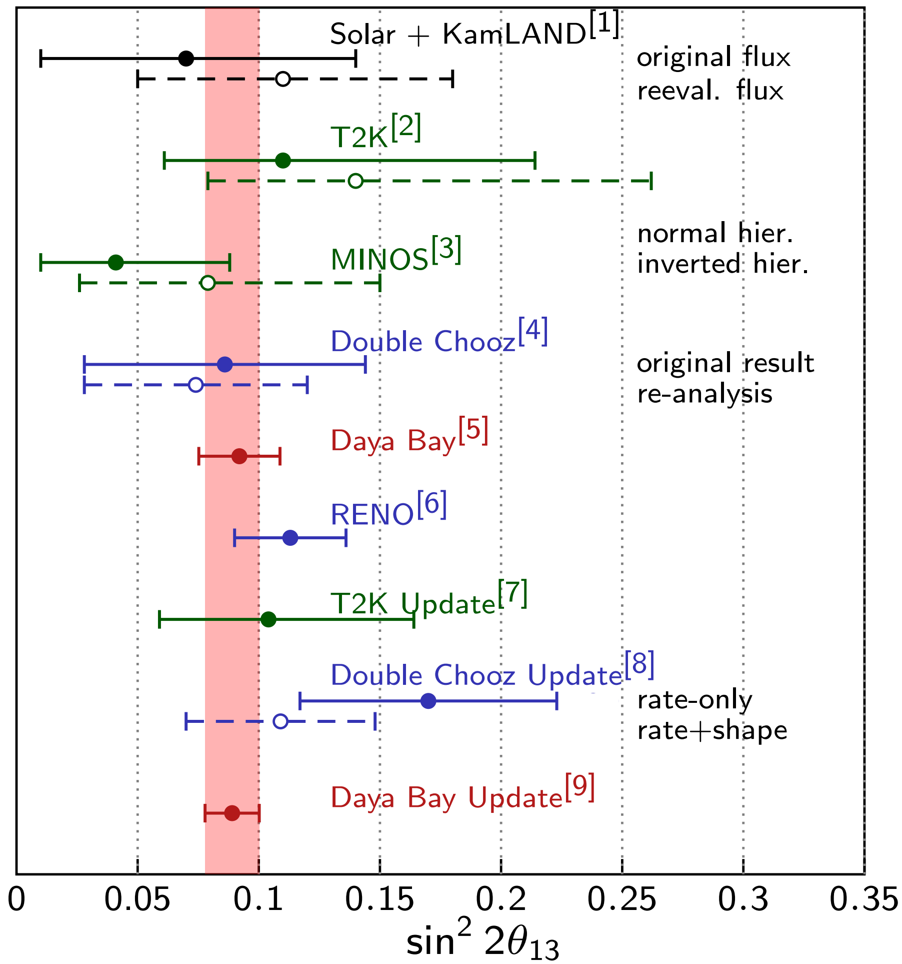
Far vs. Near Comparison : Spectrum



Spectral distortion is consistent with oscillation.

Caveat: spectral systematic issues are not fully settled, extracting θ_{13} from spectra is not recommended.

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



1. G.L. Fogli *et al.*, "Evidence of $\theta_{13} > 0$ from global neutrino data analysis," Phys. Rev. **D 84** (2011) 053007 arXiv:1106.6028
2. P. Adamson *et al.*, "Improved Search for Muon-Neutrino to Electron-Neutrino Oscillations in MINOS," Phys. Rev. Lett. **107** (2011) 181802, arXiv:1108.0015
3. K. Abe *et al.*, "Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam," Phys. Rev. Lett. **107** (2011) 041801, arXiv:1106.2822
4. Y. Abe *et al.*, "Indication of Reactor $\bar{\nu}_e$ Disappearance in the Double Chooz Experiment," Phys. Rev. Lett. **108**, 131801 (2012), arXiv:1112.6353
5. F. P. An *et al.* "Observation of electron-antineutrino disappearance at Daya Bay," Phys. Rev. Lett. **108** (2012), 171803, arXiv:1203.1669
6. J. K. Ahn *et al.* "Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment," Phys. Rev. Lett. **108** (2012) 191802, arXiv:1204.0626
7. T. Nakaya, "New Results from T2K," presented at Neutrino 2012 in Kyoto. Available at neu2012
8. Misaki Ishitsuka, "Double Chooz Results," presented at Neutrino 2012 in Kyoto. Available neu2012
9. D. Dwyer, "Improved Measurement of Electron-antineutrino Disappearance at Daya Bay, " presented at Neutrino 2012 in Kyoto. Available at neu2012

Conclusions & Outlook

- Daya Bay has made an unambiguous observation of reactor electron-antineutrino disappearance at ~2 km from the source:

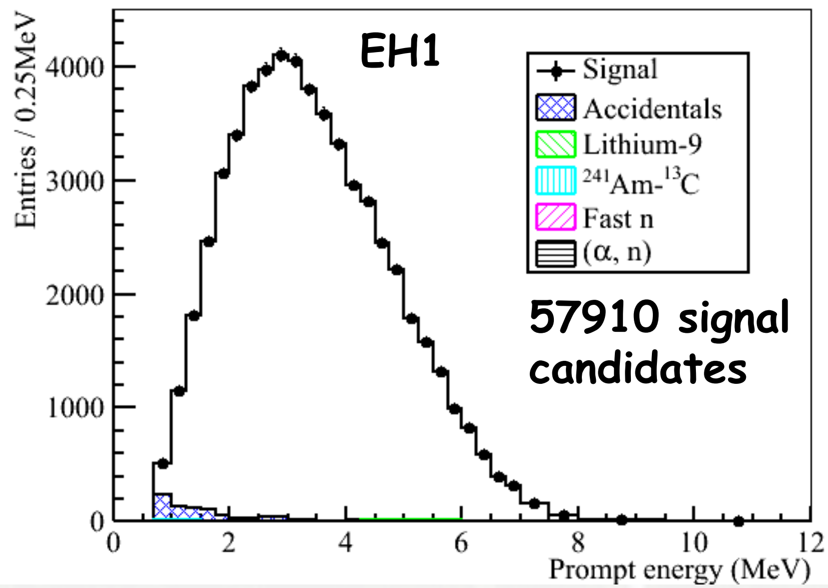
$$R = 0.944 \pm 0.007\ (\text{stat}) \pm 0.003\ (\text{syst})$$

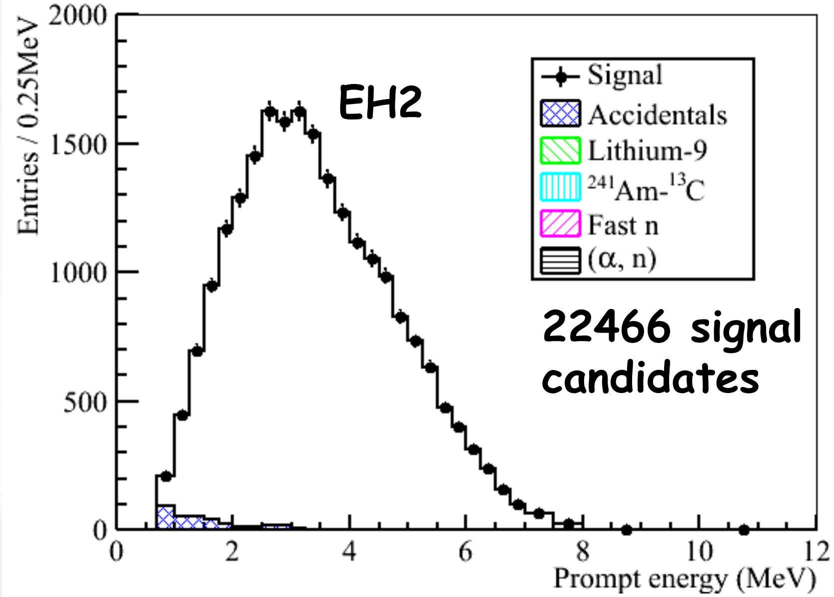
- Interpreting the disappearance as neutrino oscillation yields the most precise measurement of θ_{13}:

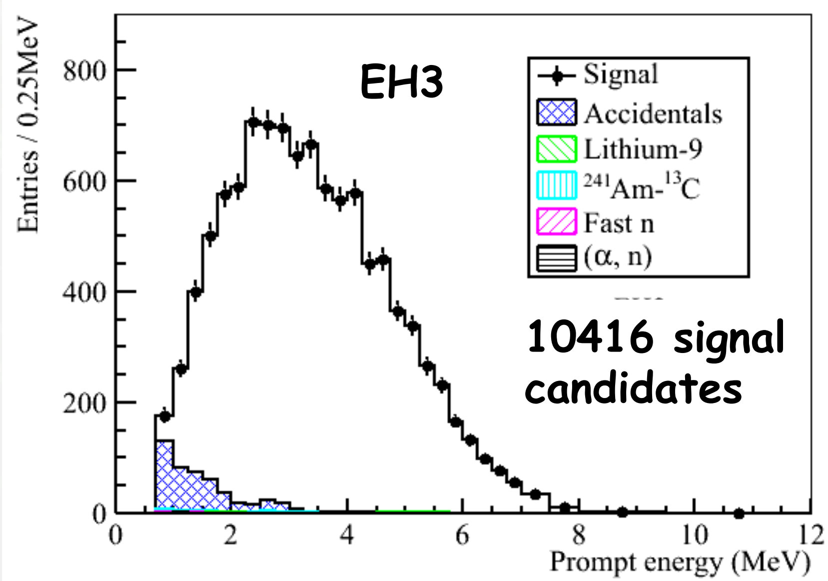
$$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$$

- Install the last pair of antineutrino detectors this year.
- Daya Bay will continue to provide the most precise measurement of θ_{13} in the world.
- Pursue other physics, such as precise reactor $\bar{\nu}_e$ flux and spectrum, and Δm^2_{31}.

Prompt (Positron) Spectra







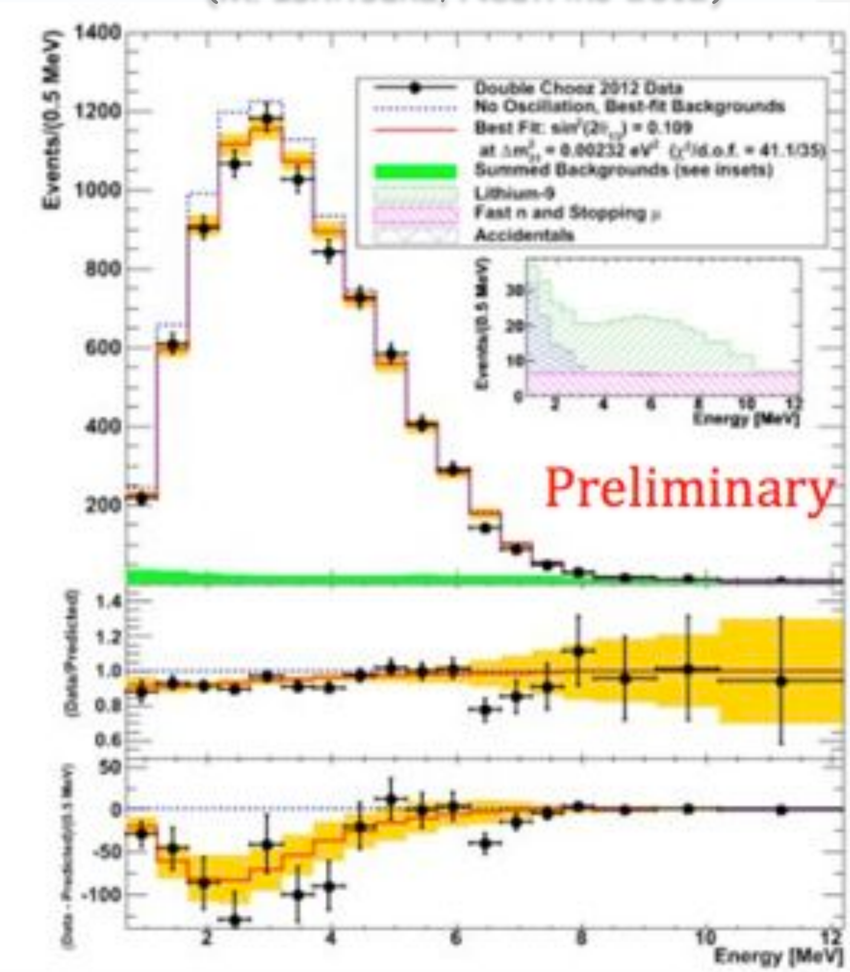
High-statistics reactor antineutrino spectra.

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

Consistency With Other Experiments

Double Chooz

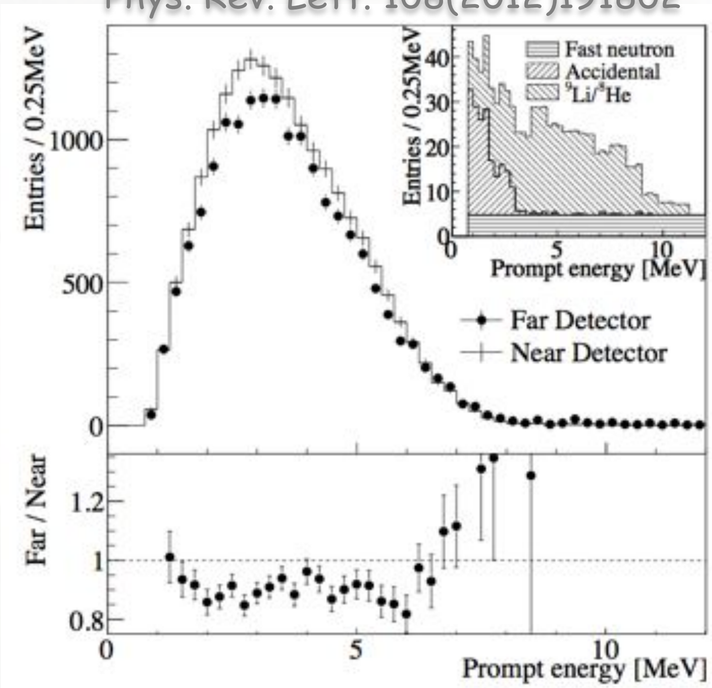
(M. Ishitsuka, Neutrino 2012)



Rate only: $\sin^2 2\theta_{13}$ = 0.170±0.035(stat)±0.040(syst)
Rate+shape: $\sin^2 2\theta_{13}$ = 0.109±0.030(stat)±0.025(syst)

RENO

Phys. Rev. Lett. 108(2012)191802



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

T2K

(T. Nakaya, Neutrino 2012)

Expected Bg.	Obs.
2.73±0.37 (syst)	10

$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$