Latest Results from the Daya Bay Reactor Neutrino Experiment

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on behalf of the Daya Bay Collaboration

Fourth International Workshop for the Design of the ANDES Underground Laboratory

Mexico city, Mexico – Jan. 2014

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- The Experiment
- Dataset for Oscillation Analysis
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- Summary & Conclusions

Disclaimer: as requested, the talk will focus significantly on the experiment's design and implementation; I will move quickly through the analysis.

Basic Concepts

Three-Neutrino Framework

- Very brief reminder on neutrino mixing:

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

How they interact

How they propagate

θ_{13} only recently well established by Daya Bay

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

θ_{23} ~ 45° established through atmospheric and accelerator experiments: possibly maximal

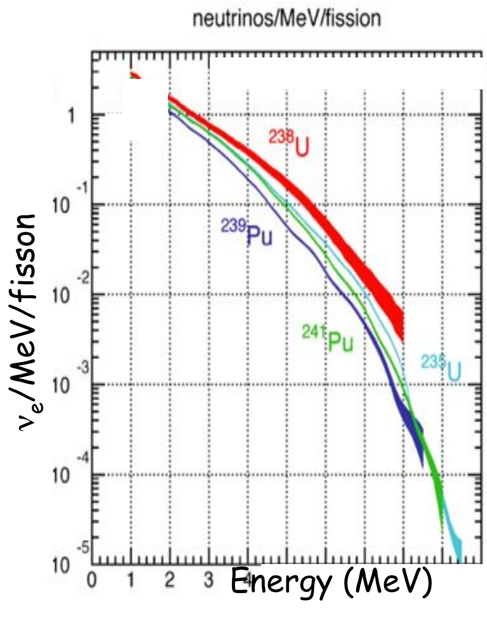
Gateway to CP violation and mass hierarchy

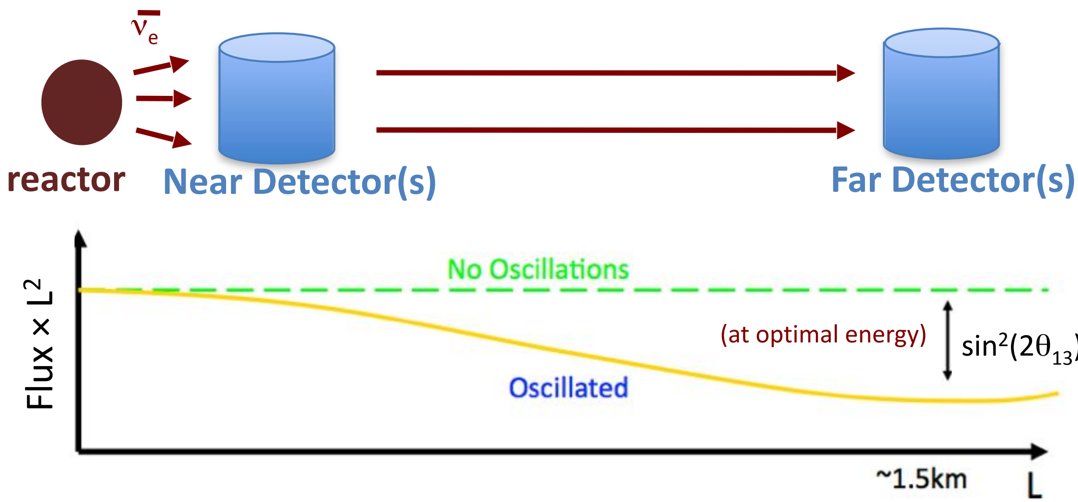
θ_{12} ~ 34° established through solar experiments and KamLAND: large but not maximal

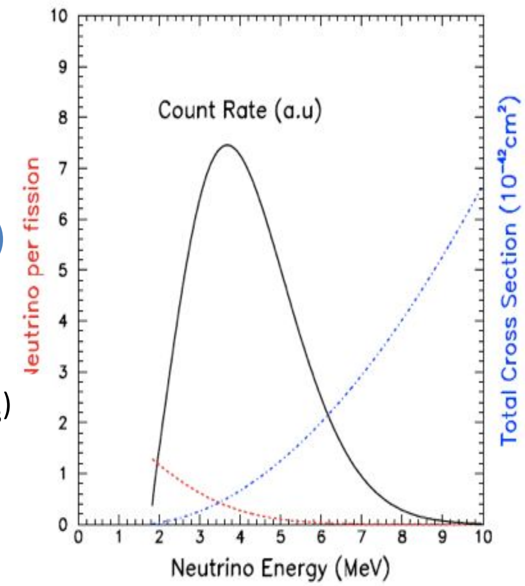
The primary goal of Daya Bay is to make a precision measurement of θ_{13}

Basic Principle

❖ Principle of the measurement:







➢ Benefits of reactor antineutrinos:

- Pure and very intense (>10^{20} ν's/s) antineutrino source
- Clean detection signal
- No effects from CP phase or matter interactions

➢ Looking for a small effect:

- **Key is to keep the systematics under control.**
- Use near and far detectors to cancel systematic errors

➢ Daya Bay is currently one of three experiments operating under this principle (together with Double CHOOZ, and RENO).

Keys to success

- Keys to a precise measurement of θ_{13}:

  1) **Baseline Optimization**

  2) **High statistics**: powerful nuclear reactors, big detectors, long run-time

  3) **Reduction of systematic errors**:

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

antineutrino flux — $1/r^2$ — number of protons — detection efficiency — yield $\sin^2 2\theta_{13}$

(i) **Detector-related**: identically designed detectors, calibration

(ii) **Reactor-related**: relative near-far measurements ← largest uncertainty in previous measurements

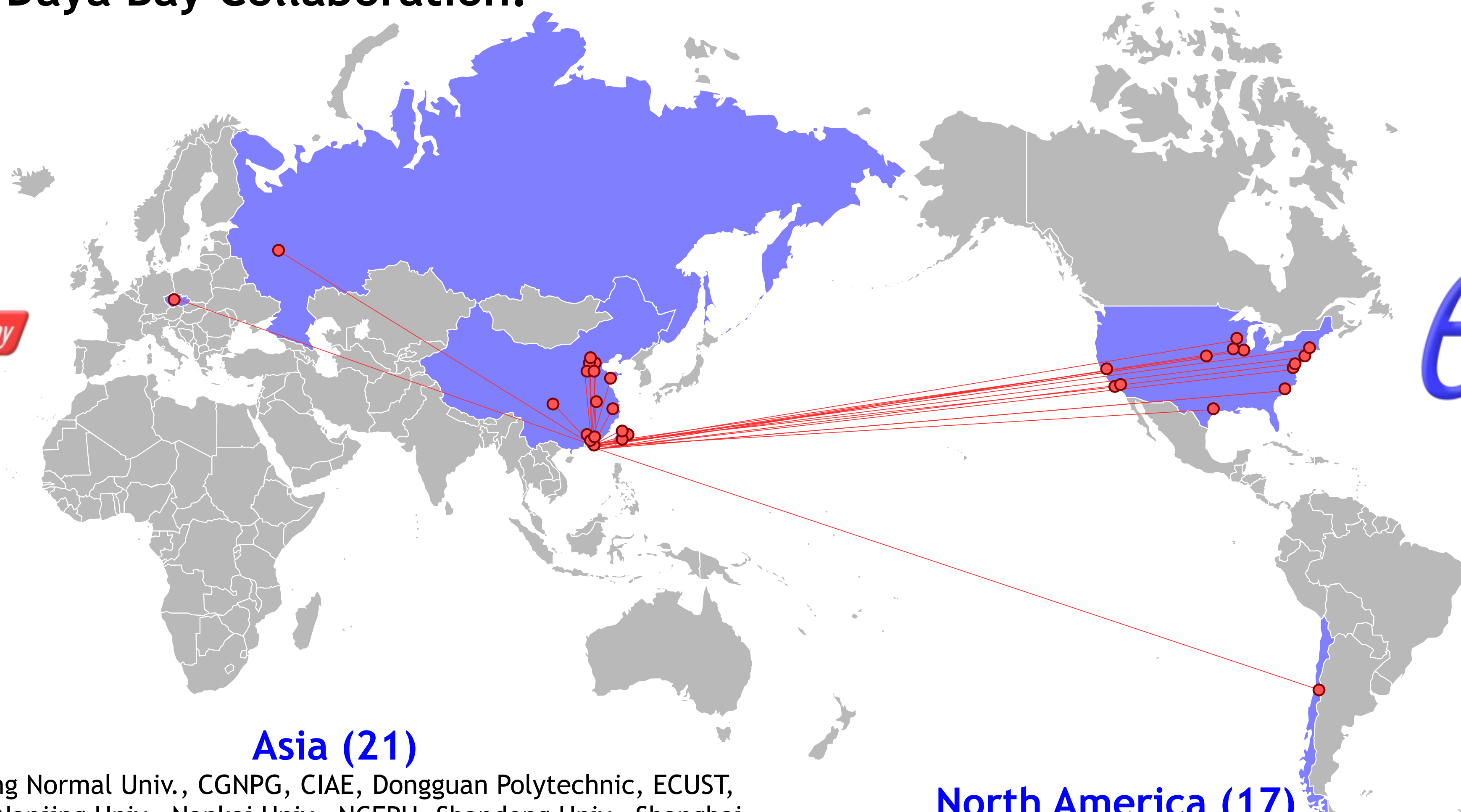
  4) **Background reduction**: use of water shield and veto

➢ **Will describe each of these (although not necessarily in this order) as we go along**

The Experiment

The Daya Bay Reactor Neutrino Experiment

❖ **The Daya Bay Collaboration:**



Asia (21)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ.,
Chinese Univ. of Hong Kong, Univ. of Hong Kong,
National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (17)

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

South America (1)

Catholic University of Chile

~230 Collaborators

Daya Bay Experimental Layout

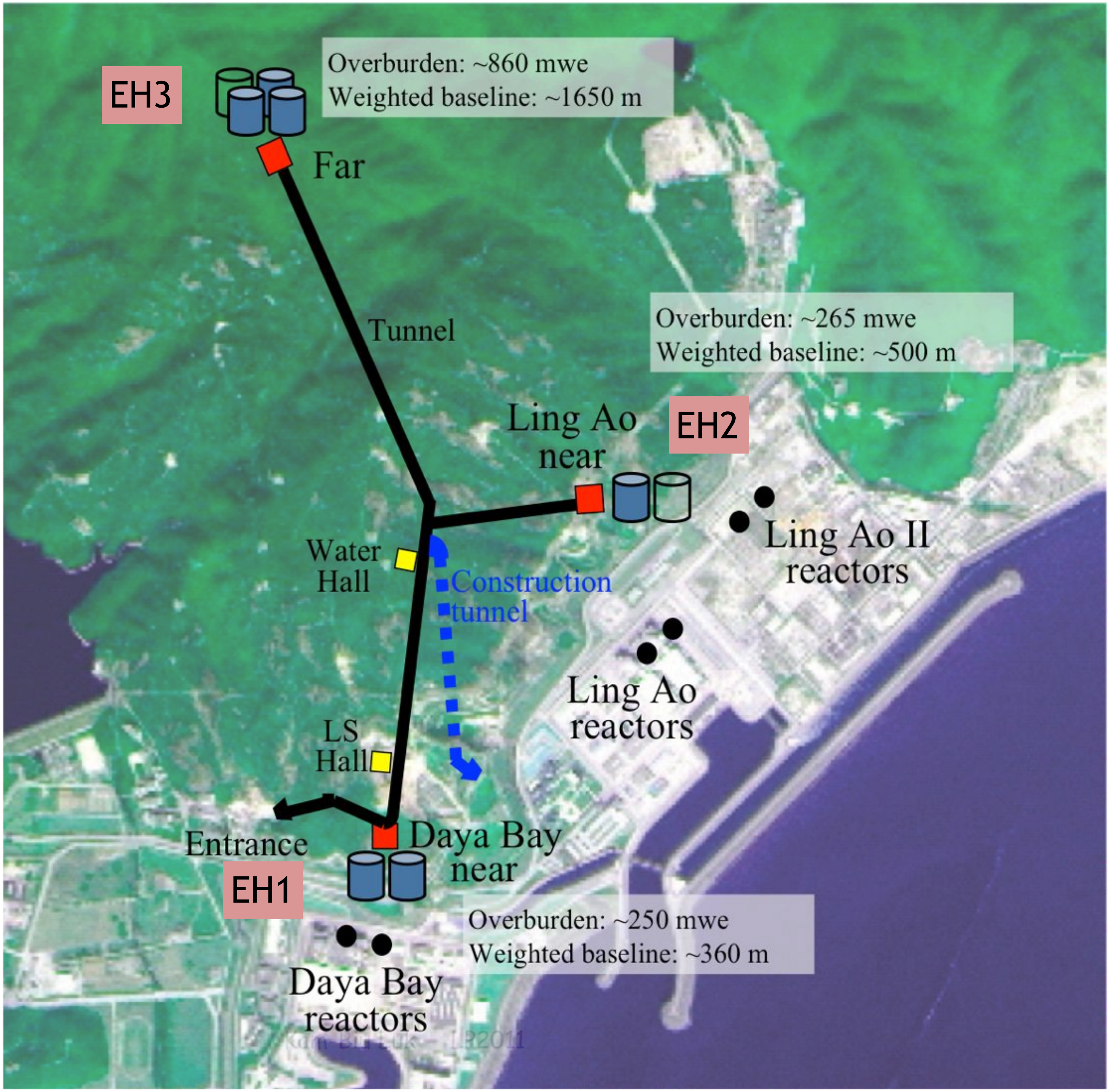
- A total of 8 identical detectors are placed around the Daya Bay & Ling Ao power plants in China

- **Main principle:**

  (i) sample the reactor anti-neutrino flux in the near and far locations, and

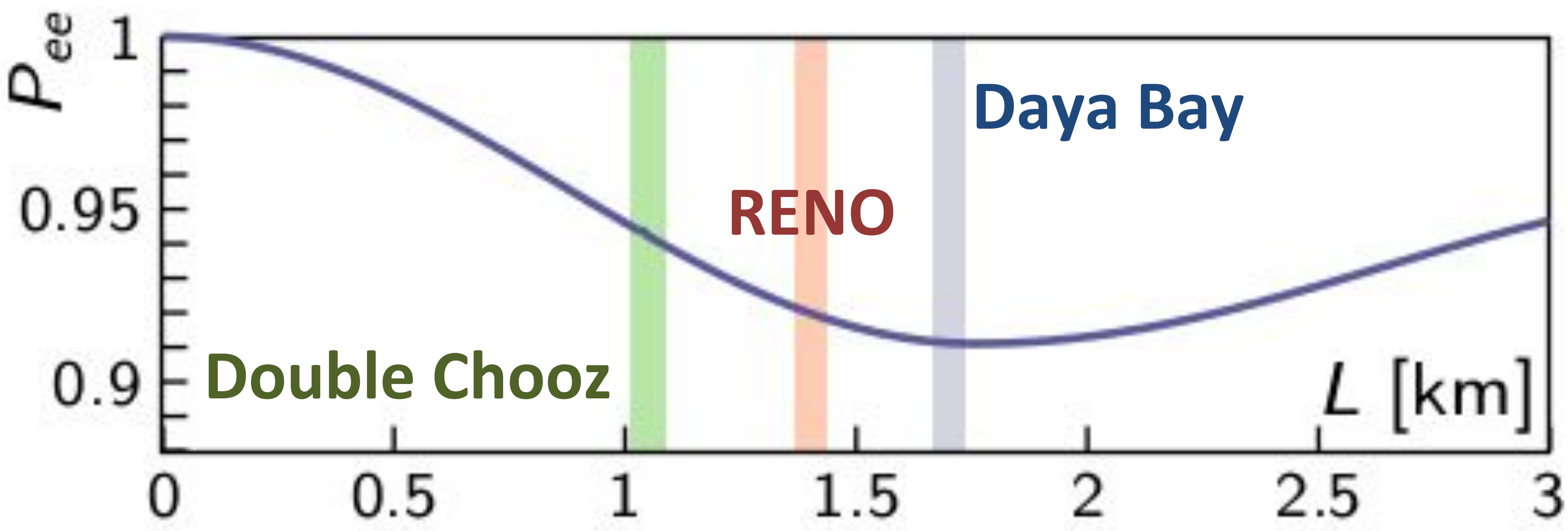
  (ii) look for evidence of disappearance

Note: results shown here use data collected with 6 / 8 detectors



Optimization

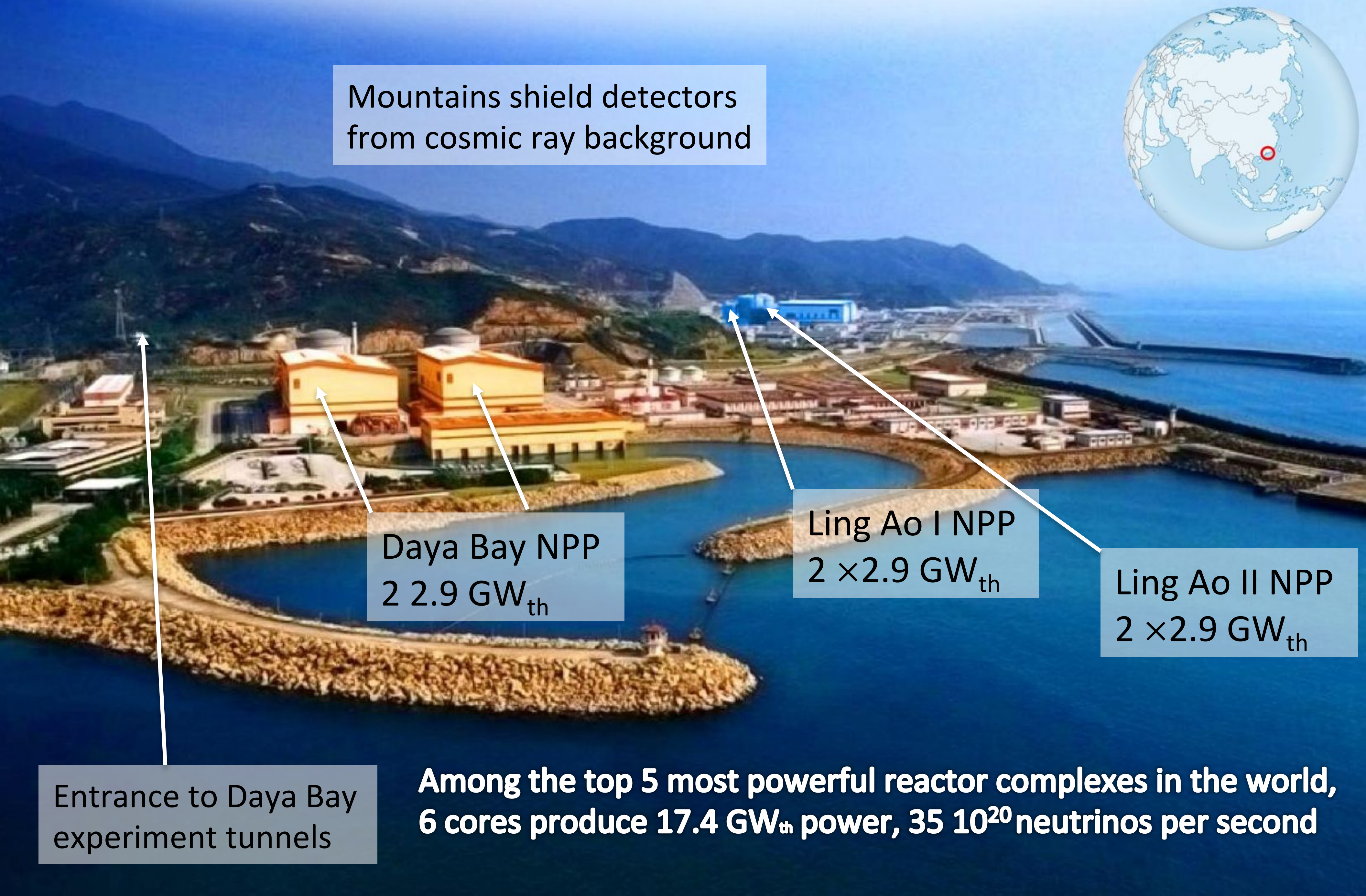
❖ Far site location maximizes term dependent on θ_{13}:



❖ **Strategy: Go strong, big, and deep!**

	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

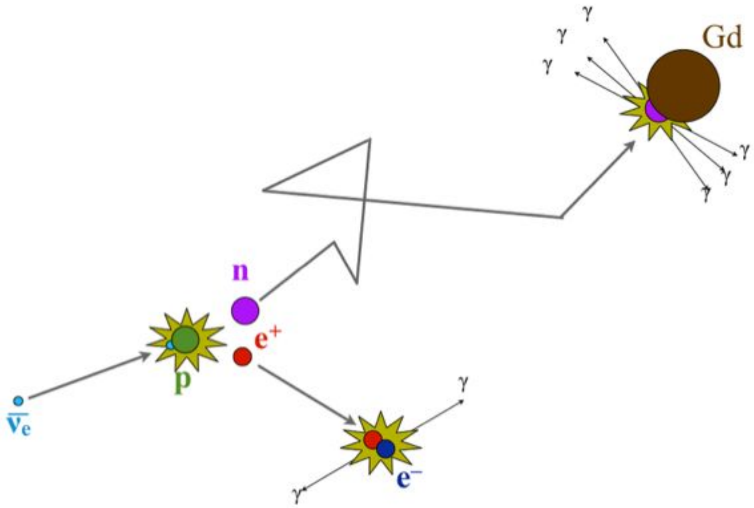
A Powerful Neutrino Source at an Ideal Location



Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW_{th} power, 35 10^{20} neutrinos per second

Antineutrino Detection

- **Anti-neutrinos are detected via the inverse beta-decay reaction:**



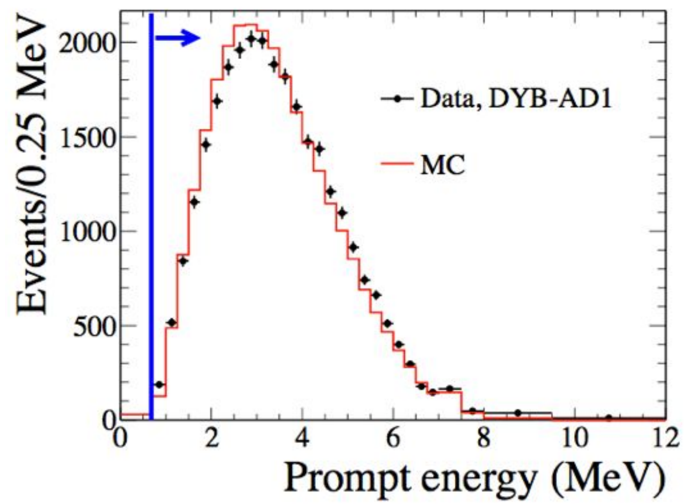
$\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

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

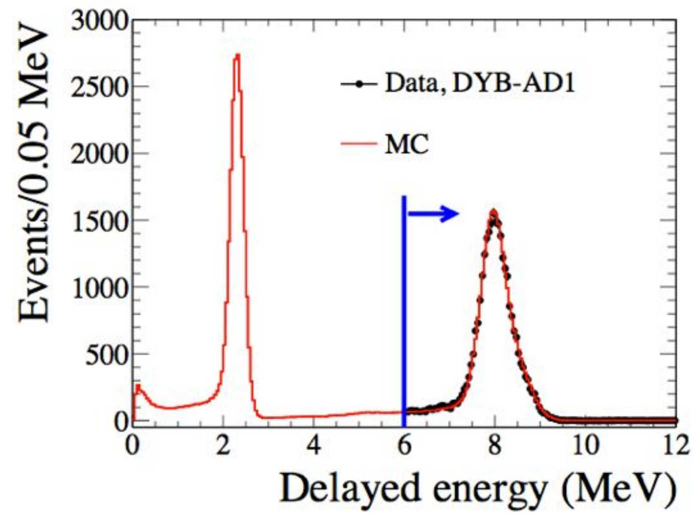
~30μs for 0.1% Gd $\rightarrow$ $+ Gd \rightarrow Gd^*$

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

Prompt Energy Signal



Delayed Energy Signal



- Powerful background rejection!
- Positron carries information of incoming neutrino:

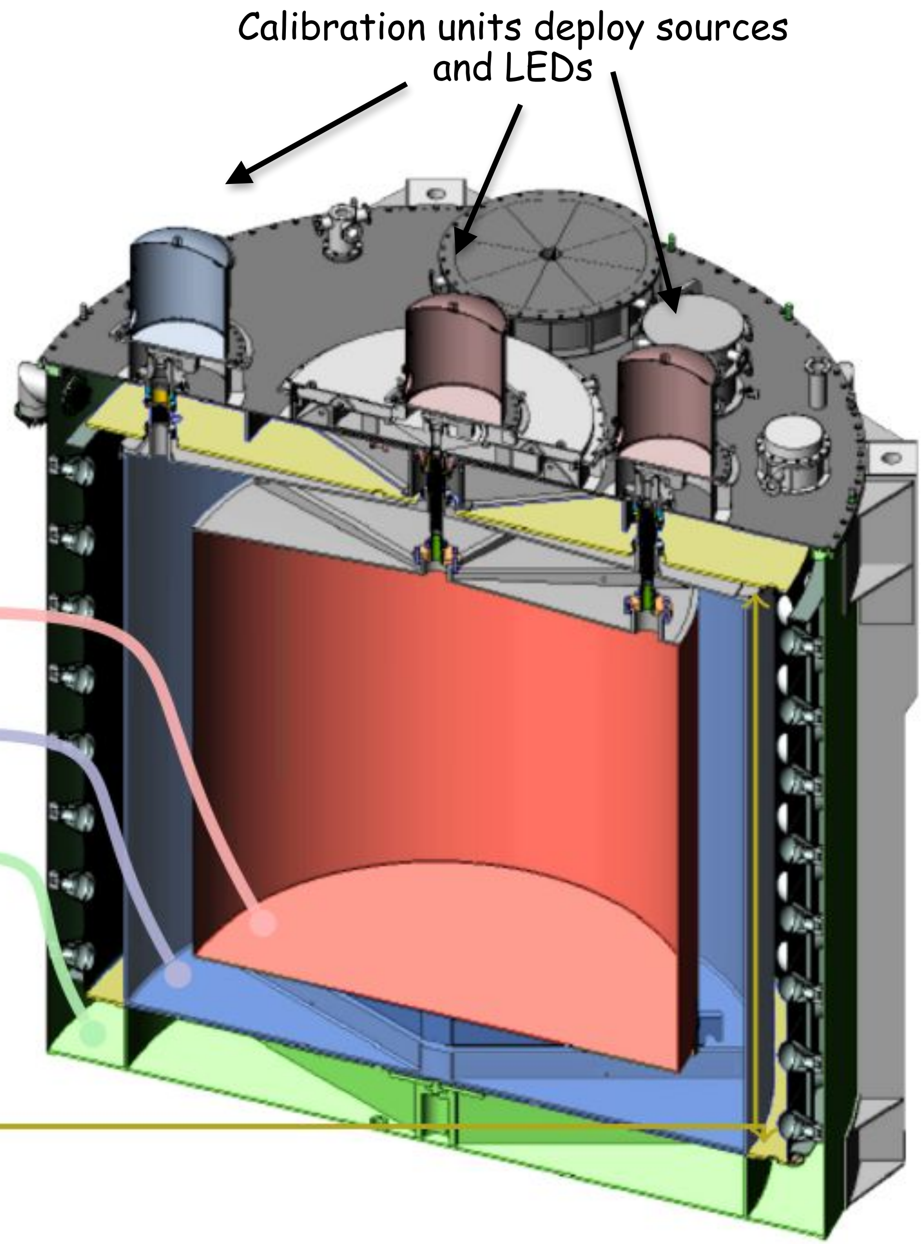
$$E_\nu \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$

(T_n ↓ 10-40 keV)

Antineutrino Detectors

❖ The Daya Bay anti-neutrino detectors (ADs) are "three-zone" cylindrical modules:

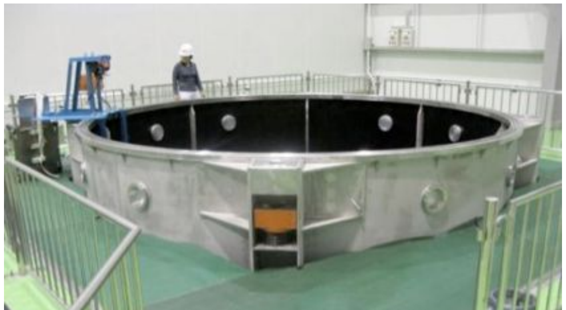
8 functionally identical detectors reduce systematic uncertainties			
	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding
192 8 inch PMTs in each detector			
Top and bottom reflectors increase light yield and flatten detector response			

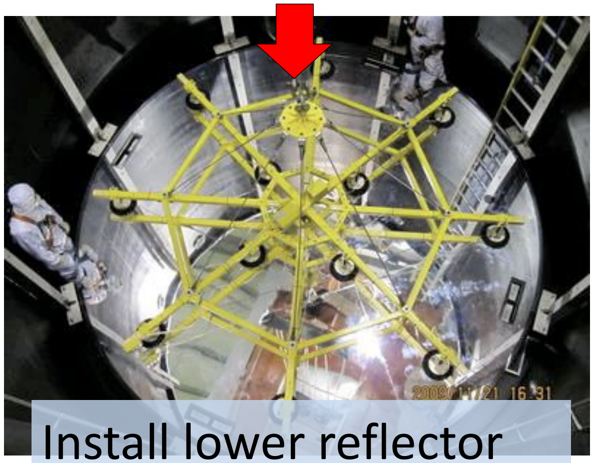


➢ Energy resolution: $\sigma_E/E = 7.5\%/\sqrt{E}$

Assembly of Antineutrino Detectors

ADs are assembled in clean-room in order to keep backgrounds under control


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

Liquid Scintillators

- **The Gd-LS was produced in 50 batches of 4 tons each and stored underground:**
  - Batches were mixed in storage tanks onsite to ensure identical detectors
  - Stability of liquids is continuously monitored
  - A 1-m apparatus yielded an attenuation length of ~15m @ 430nm (Gd-LS)

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Liquid Scintillators

❖ The detectors are filled in the Liquid Scintillator Hall:

➢ All Gd-LS storage tanks are equally sampled and mixed in same ISO tank →

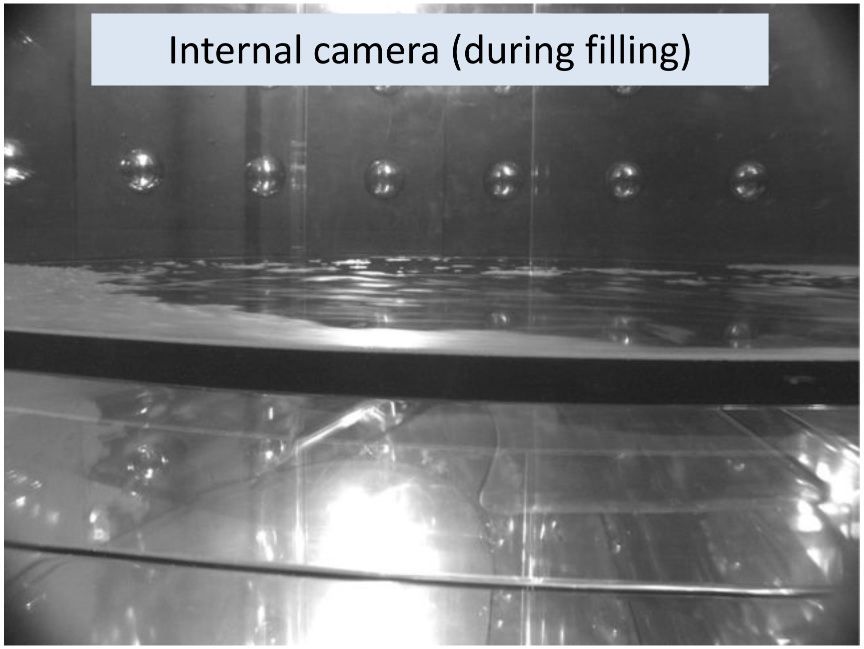
- Target mass is measured with:

  (1) 4 load cells supporting 20-ton ISO tank
  (2) Coriolis mass flow meters

  } uncertainty ~ 4kg in 20t (0.02%)

- Temperature is maintained constant
- Filling is monitored with in-situ sensors

Gd-LS ISO tank

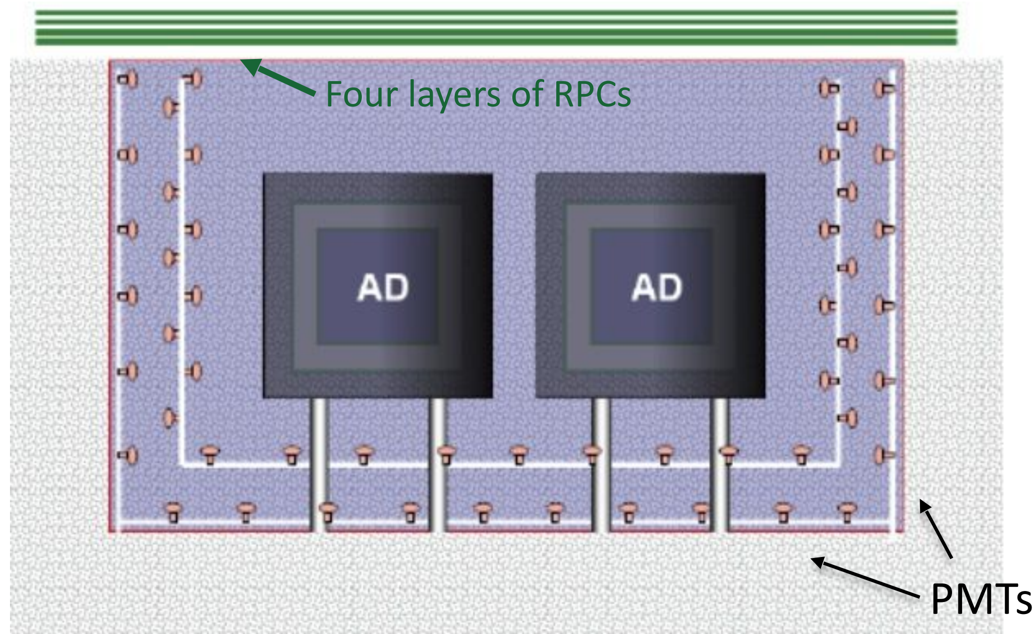


Internal camera (during filling)

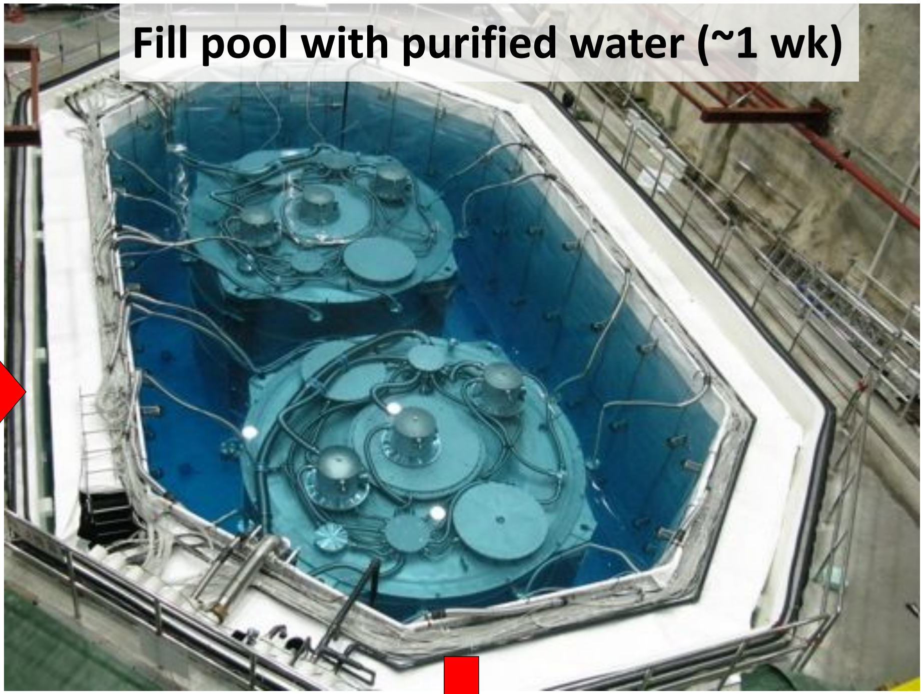
The Water Cerenkov Detectors

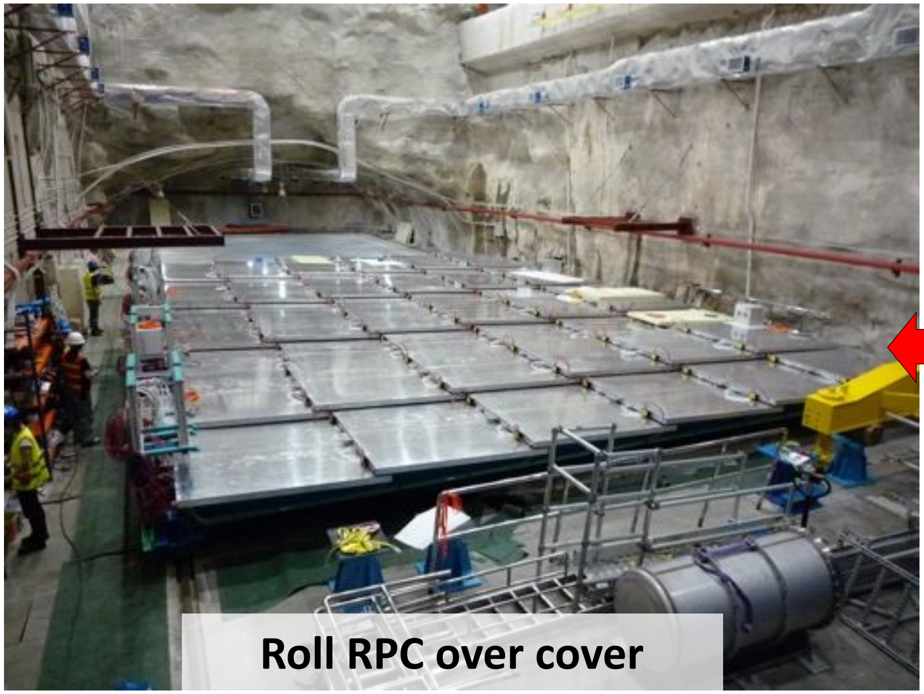
- The detectors are immersed in an instrumented water pool:
  - **Double purpose:**
    - ✓ Shields against gammas from ambient radioactivity and neutrons produced by cosmic rays
    - ✓ Serves as a Cerenkov detector to tag cosmic ray muons (thus reducing backgrounds)
- The water pool is divided into 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.

(not used for results shown in this talk)



Example: EH1 installation





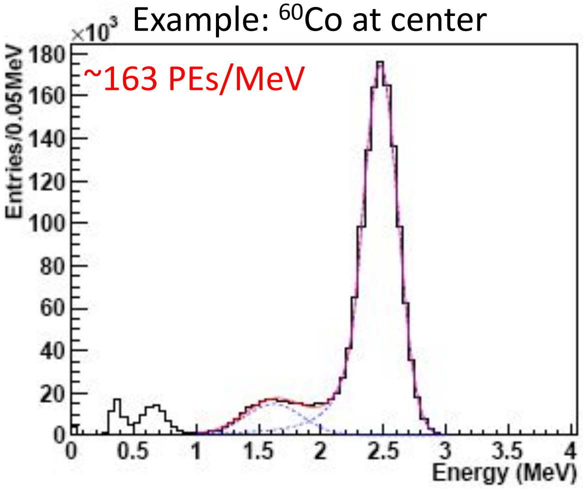
Calibration

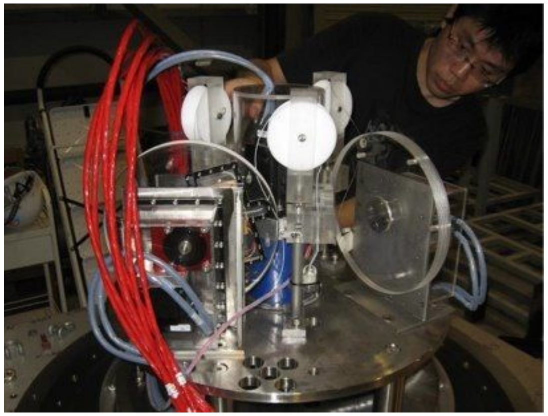
- Calibration is key to the reduction of the detector-related systematic errors:
  - Three sources + LED in each calibration unit, on a turn-table:
    - ^{68}Ge (1.02MeV)
    - ^{60}Co (2.5MeV)
    - ^{241}Am-^{13}C (8MeV)
    - LED

Energy calibration (linearity, detector response… etc)

LED → Timing, gain and relative QE

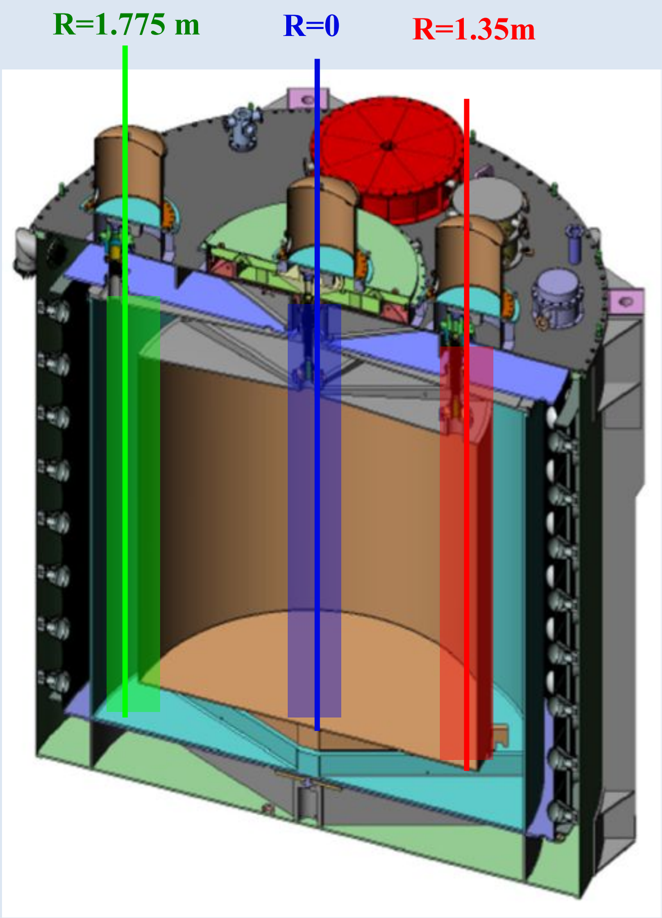
Example: ^{60}Co at center





  - Also have methods that allow us to calibrate gains and light-yield **in-situ**:
    - Gains: off-window hits
    - Spallation neutrons (see next slide)

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



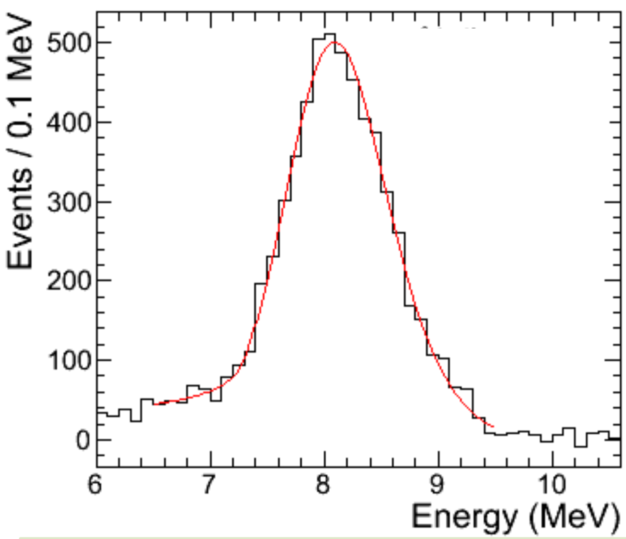
Three axes: center, edge of target, middle of gamma catcher

Energy Scale

❖ Can calibrate the energy scale (light-yield) in-situ with data-taking:

Calibrate charge (photoelectrons) collected per MeV in-situ using spallation nGd capture events. Also use weekly deployments of ^{60}Co source.

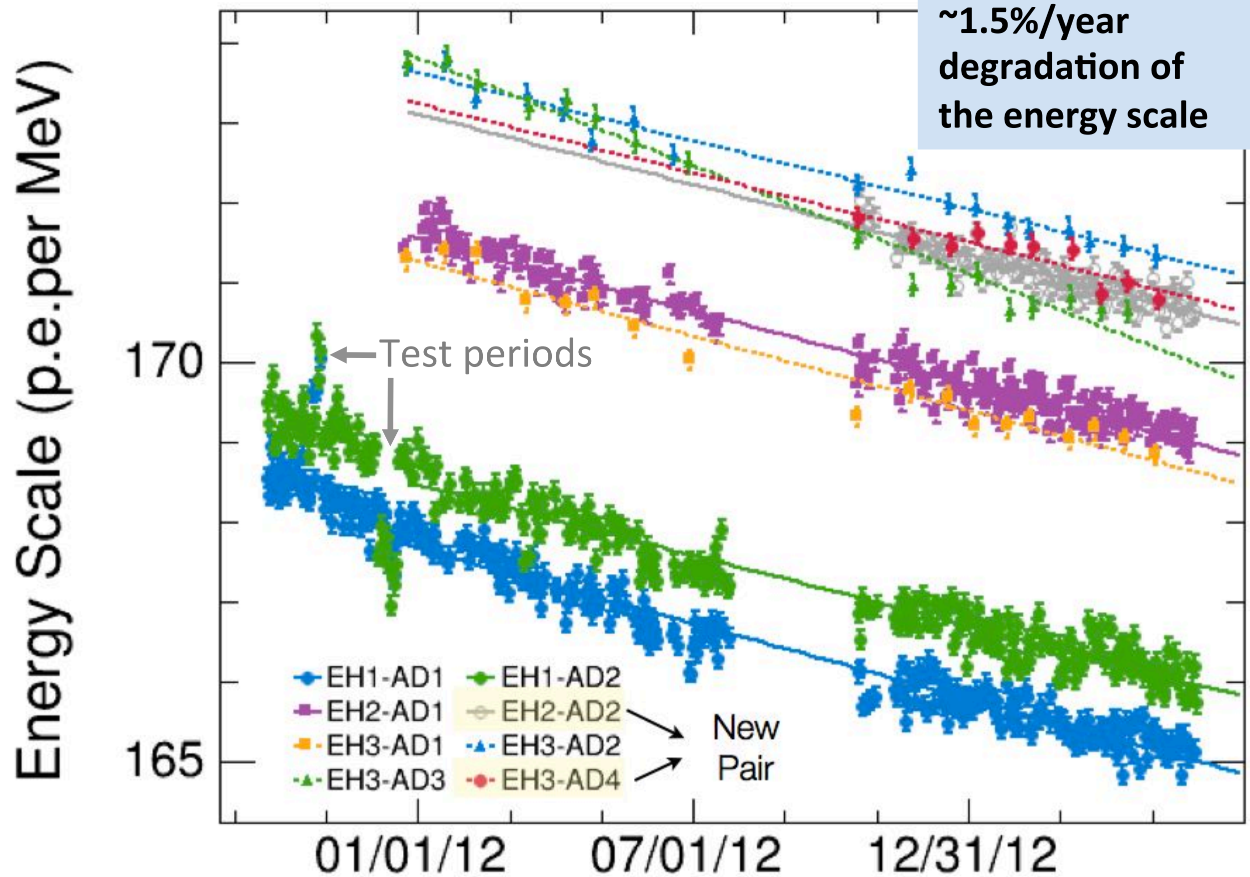
Spallation *n*Gd capture
(uniform throughout detector)



Energy Scale = Q / E

Measured charge of nGd peak

Average energy released in nGd



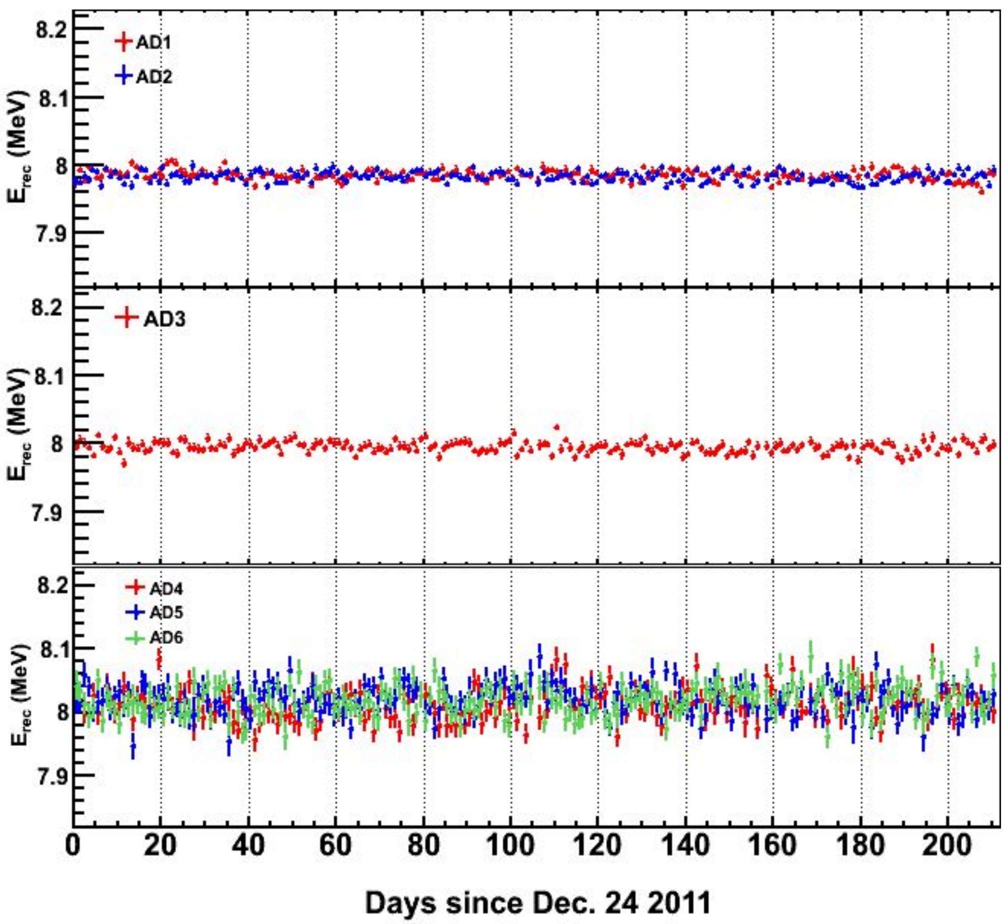
~1.5%/year degradation of the energy scale

Small degradation of energy scale is seen with nGd, ^{60}Co, and other event types. Its origin is still unknown, but do not anticipate any problems in experiment's lifetime.

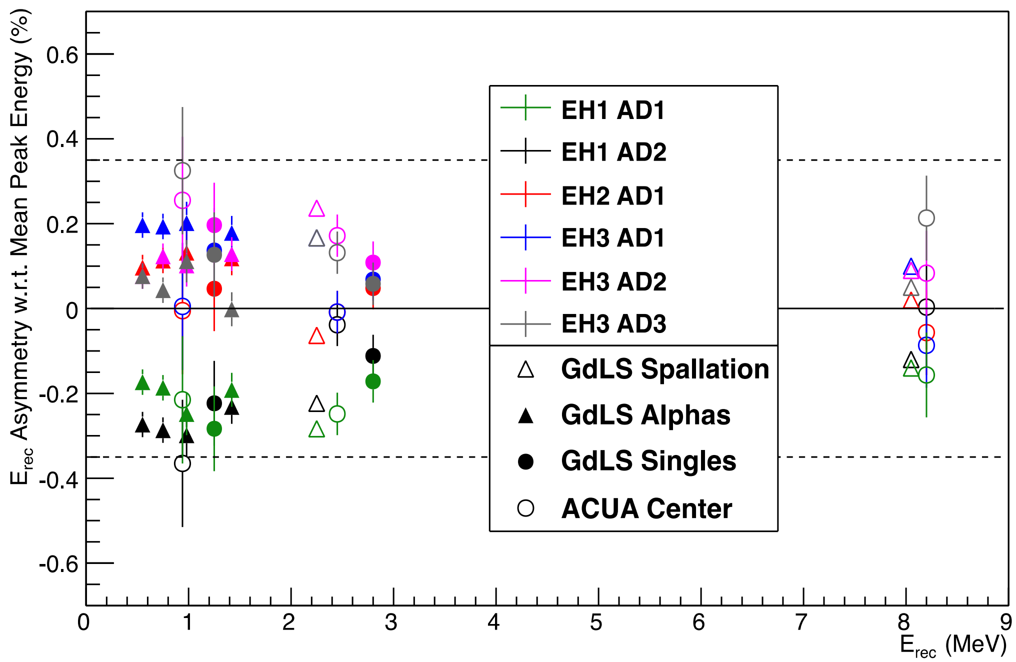
Calibration Performance

After calibration, achieve energy response that is **stable to ~0.1%** in all detectors, with a **total relative uncertainty of 0.35%** between detectors.

Spallation *n*Gd capture peak vs. time (after calibration)



Relative energy peaks in all detectors (after calibration)



After initial reconstruction, position non-uniformity is also corrected for

Dataset for Oscillation Analysis

Antineutrino Selection

① Reject spontaneous PMT light emission ("flashers")

② Prompt positron:
0.7 MeV < Ep < 12 MeV

③ Delayed neutron:
6.0 MeV < Ed < 12 MeV

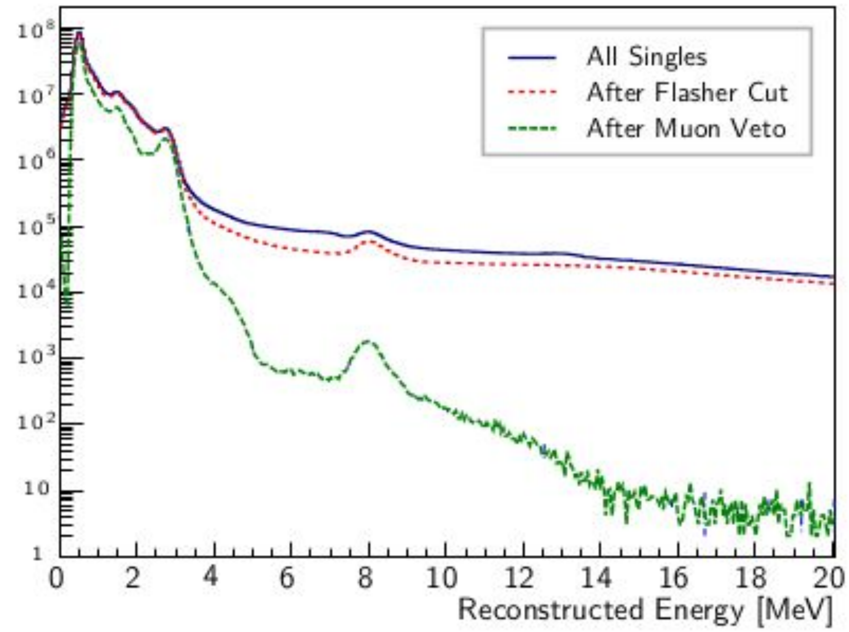
④ Neutron capture time:
1 μs < t < 200 μs

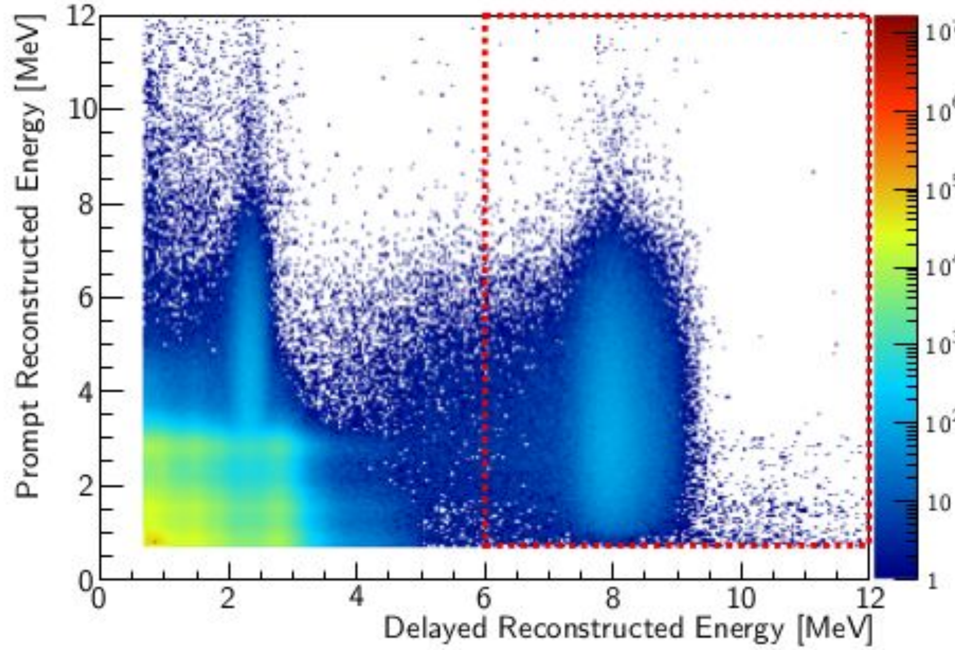
⑤ Muon veto:

- Water pool muon (>12 hit PMTs): Reject [-2μs; 600μs]
- AD muon (>3000 photoelectrons): Reject [-2 μs; 1400μs]
- AD shower muon (>3×10^5 p.e.): Reject [-2 μs; 0.4s]

⑥ Multiplicity:

- No additional prompt-like signal
  400μs before delayed neutron
- No additional delayed-like signal
  200μs after delayed neutron

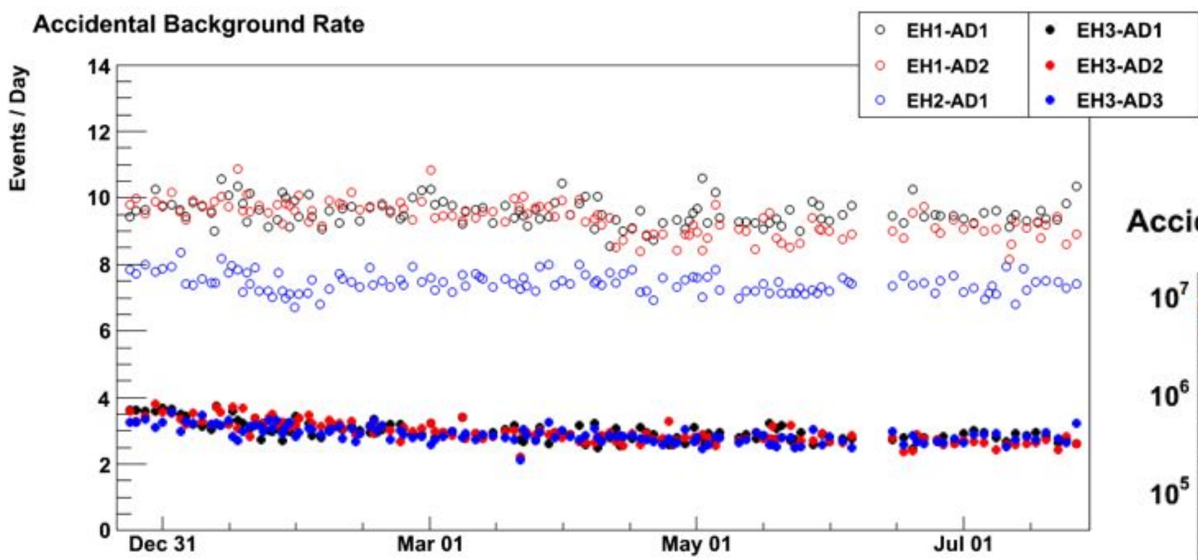


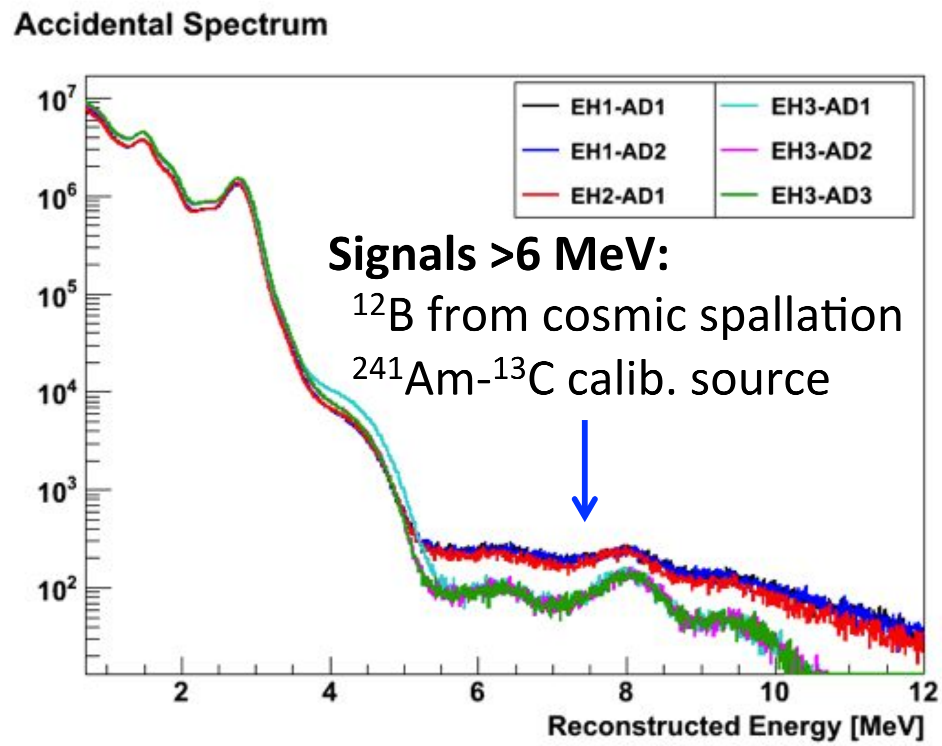


Backgrounds: accidentals

❖ Accidentals are the only source of uncorrelated background:

two uncorrelated events 'accidentally' pass the cuts and mimic an IBD event





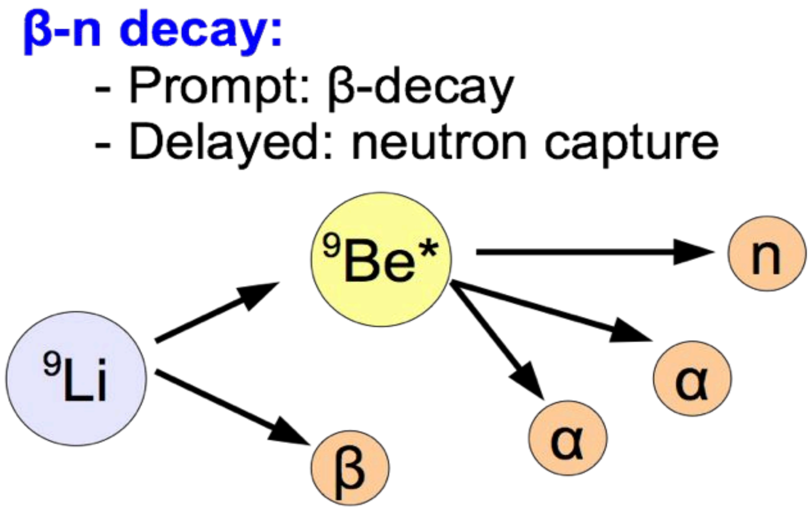
Signals >6 MeV:
^{12}B from cosmic spallation
^{241}Am-^{13}C calib. source

Accidental B/S is 4% (1.5%) of far (near) signal.

Accidental background be accurately modeled using uncorrelated signals in data.

➔ Negligible uncertainty in background rate or spectra.

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

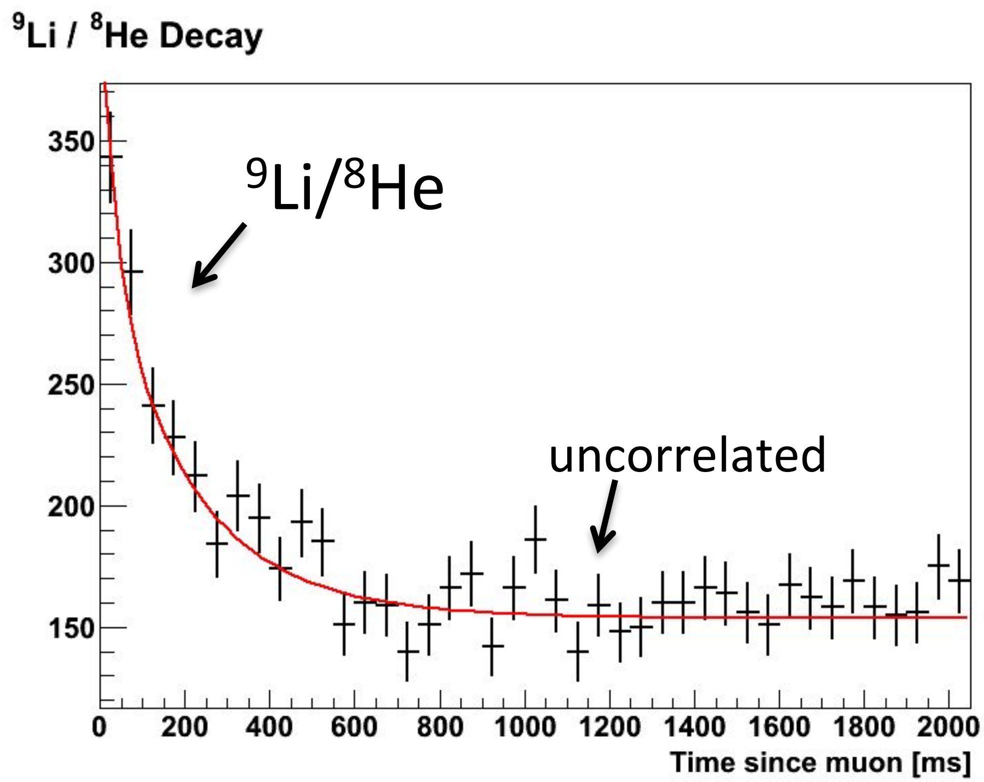


^{9}Li: $\tau_{1/2}$ = 178 ms, Q = 13. 6 MeV
^{8}He: $\tau_{1/2}$ = 119 ms, Q = 10.6 MeV

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

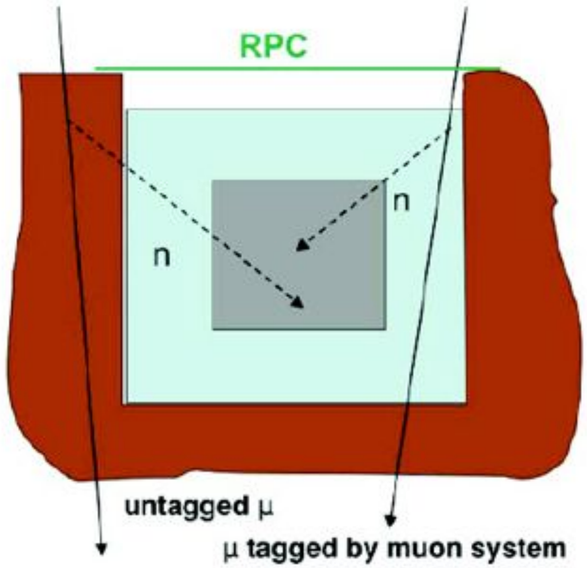
➢ Shape is determined from simulation benchmarked with external data and which accounts for all daughter particles

This background is directly measured by fitting the distribution of IBD candidates vs. time since last muon.



Analysis muon veto cuts control B/S to ~0.3±0.1%.

Backgrounds: Fast neutrons



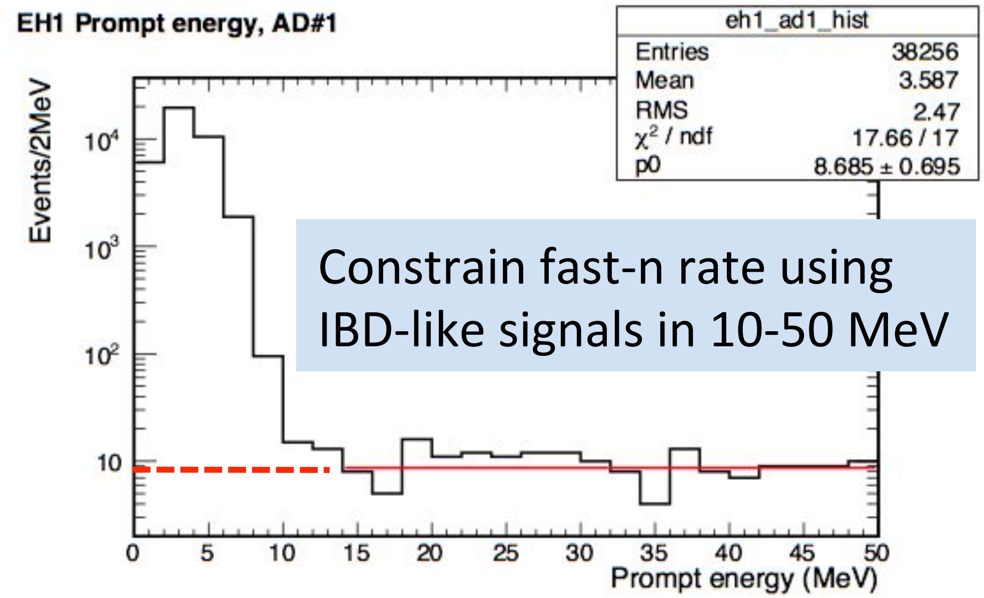
Fast Neutrons:

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

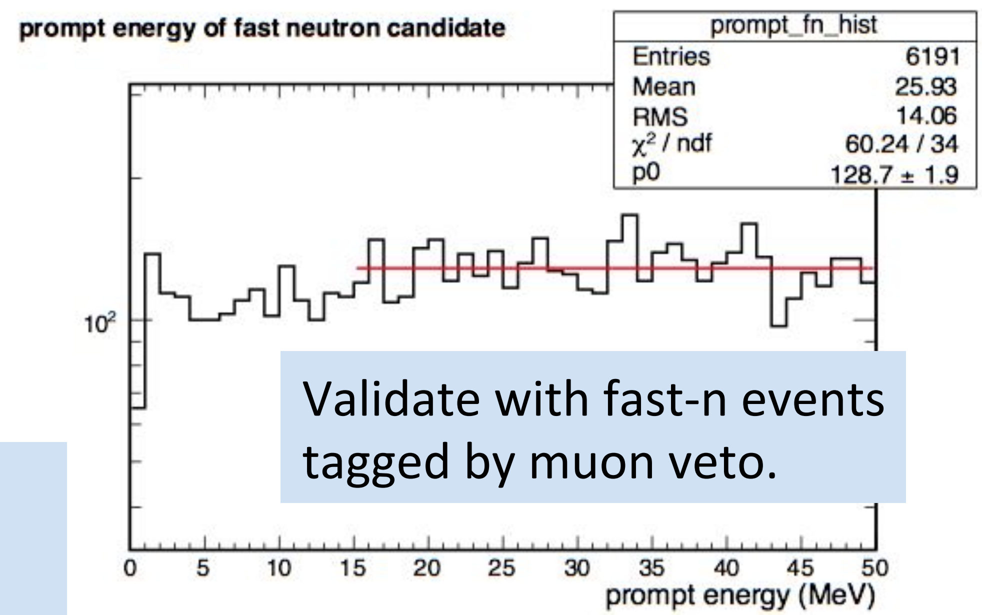
Mimics antineutrino (IBD) signal:

- 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.



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

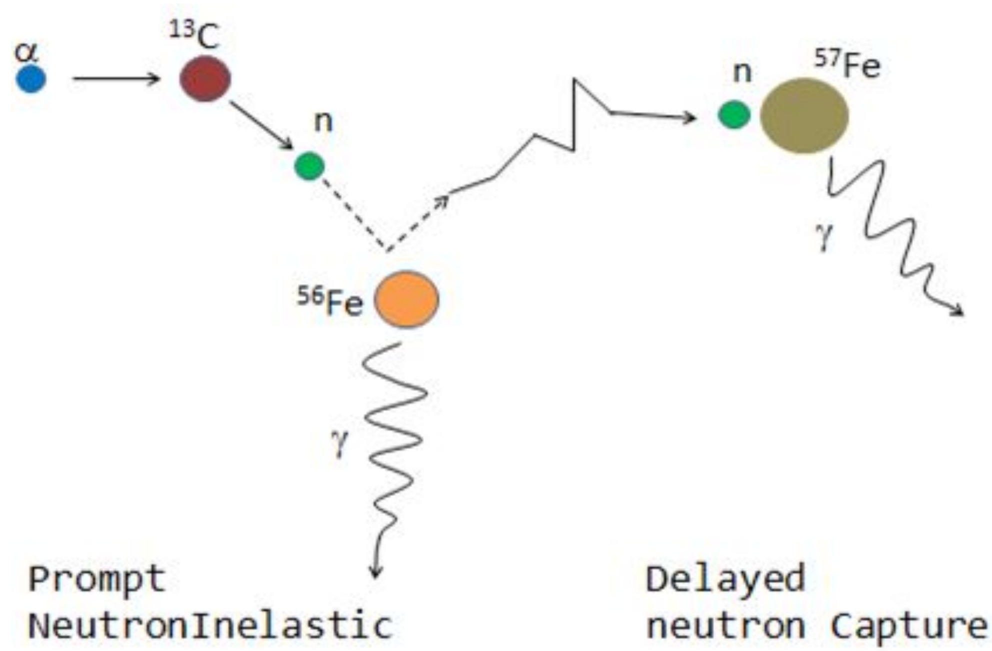


Validate with fast-n events tagged by muon veto.

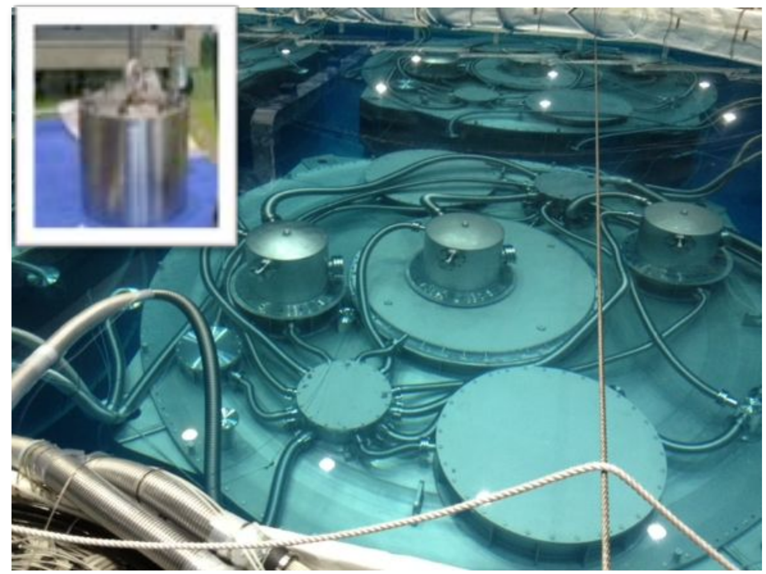
Backgrounds: ^{214}Am^{13}C source

❖ There is a subtle background from our calibration source:

- ❑ ^{241}Am-^{13}C source produces ~0.75 Hz neutrons via $^{13}C(\alpha,n)^{16}O$.
- ❑ Neutrons interact with steel to produce fake (prompt,delayed) pair

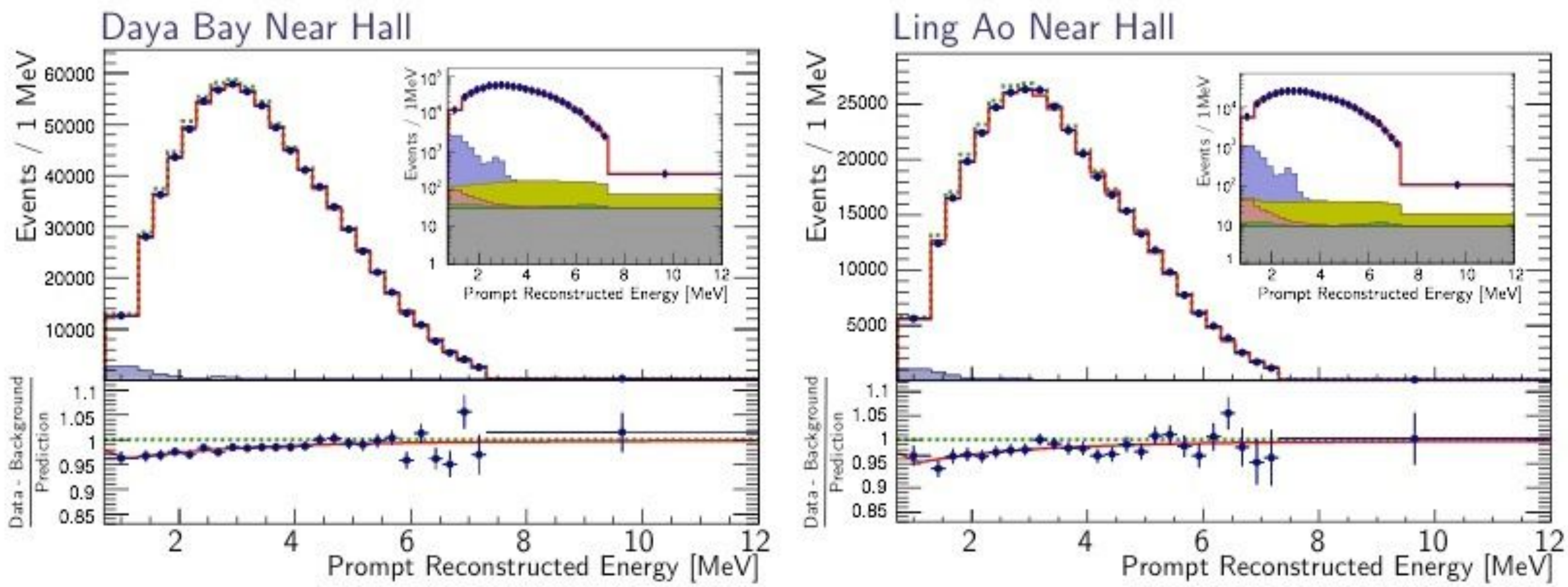


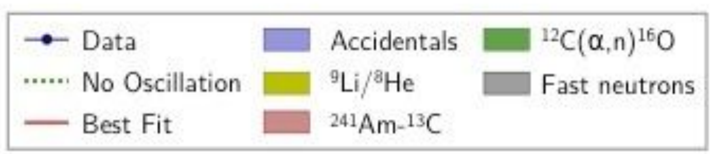
A special x80 stronger ^{241}Am-^{13}C source placed on the AD

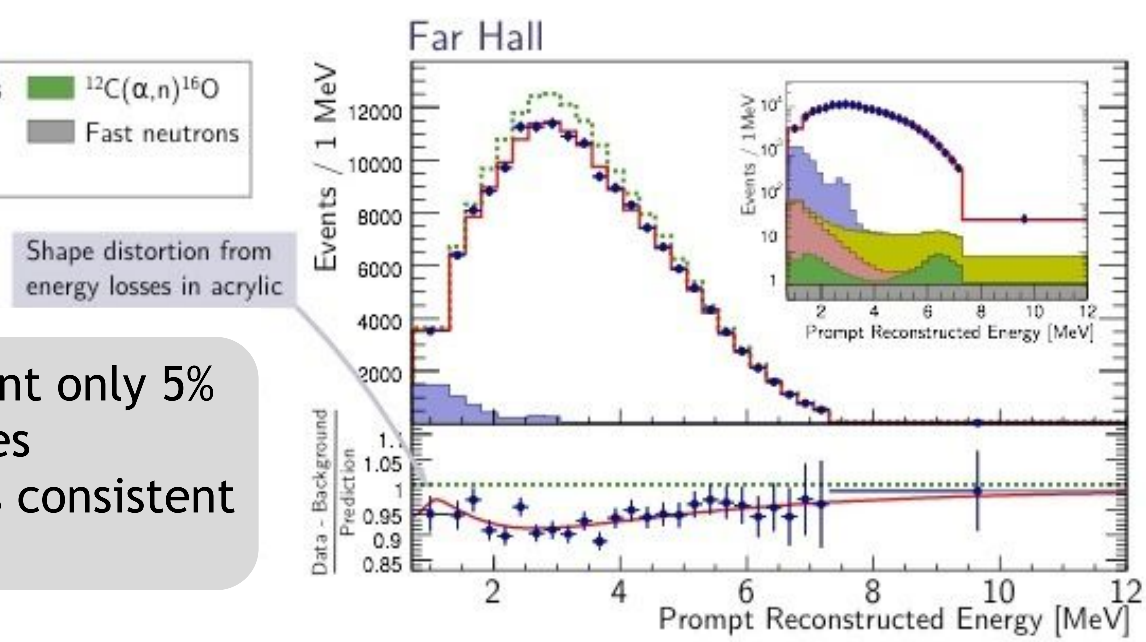


Correlated background in physics run =
measured single n-like due to AmC (normalization) x correlated/single ratio (MC benchmarked and corrected by strong AmC, spectrum)

Dataset for Oscillation Analysis







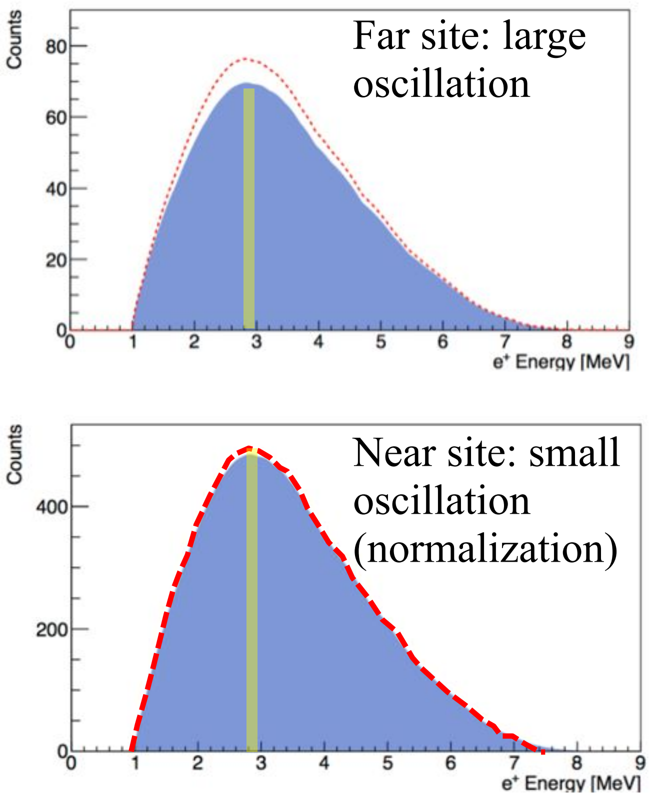
- Backgrounds represent only 5% (2%) in far (near) sites
- Spectral Distortion is consistent with oscillations

This analysis uses more than 300k antineutrino interactions

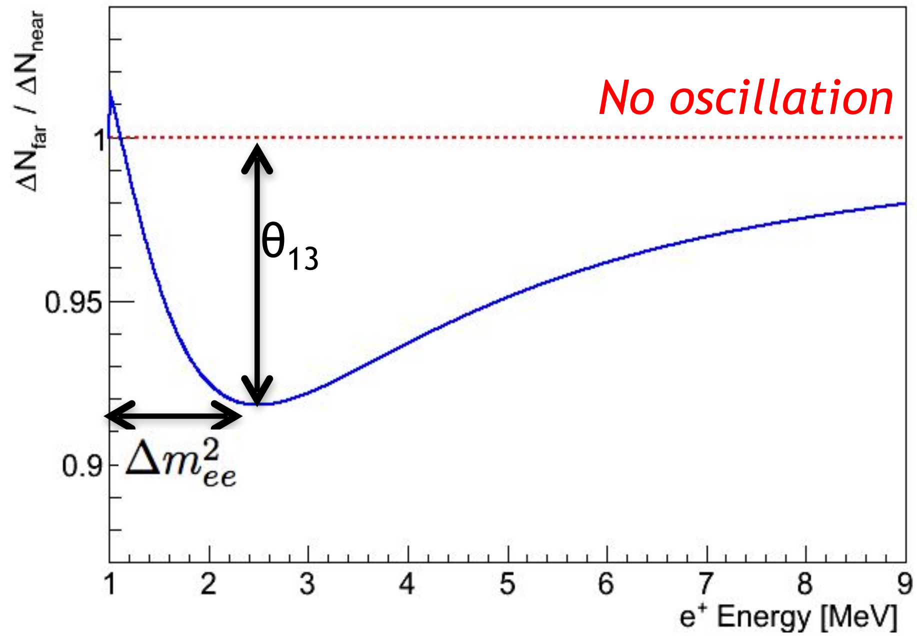
Latest Results

Doing a Spectral Measurement

- With a spectral measurement can measure the mass splitting:



Compare each energy



But require good understanding of the detectors' energy response!

- Which mass splitting do we measure? Define an effective mass splitting Δm^2_{ee}:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

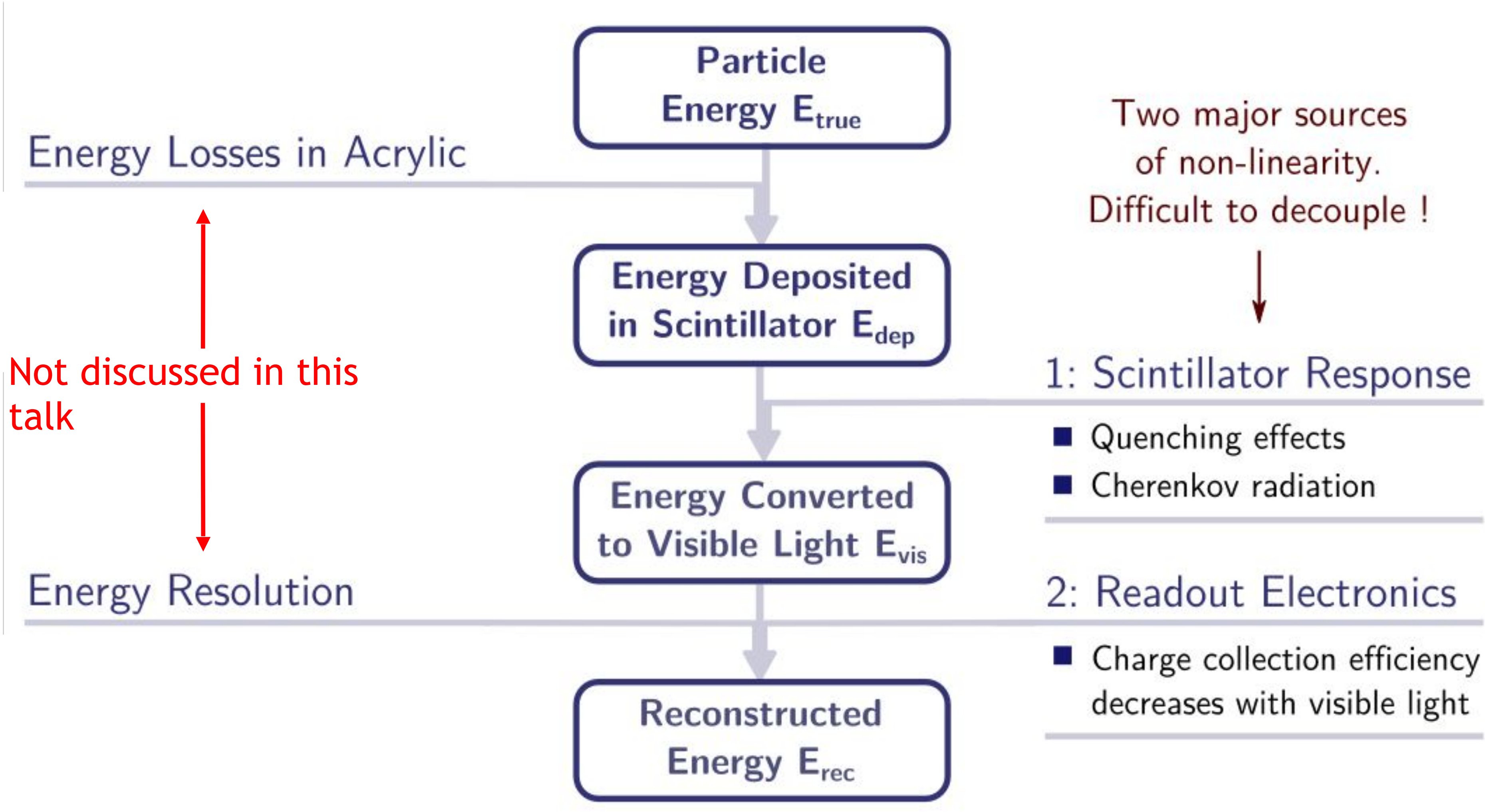
$$\sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) \equiv \cos^2\theta_{12} \sin^2\left(\Delta m^2_{31} \frac{L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

so that: $|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \mathrm{eV}^2$

+: Normal Hierarchy
–: Inverted Hierarchy

Energy Response Model

- Need to relate reconstructed kinetic energy E_{rec} to true energy E_{true}:



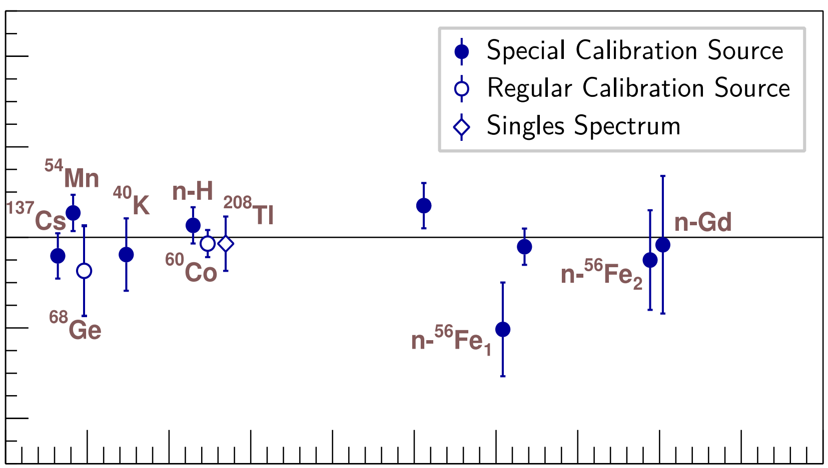
✓ **Minimal impact on oscillation measurement**

✓ **Crucial for measurement of reactor spectra (in progress)**

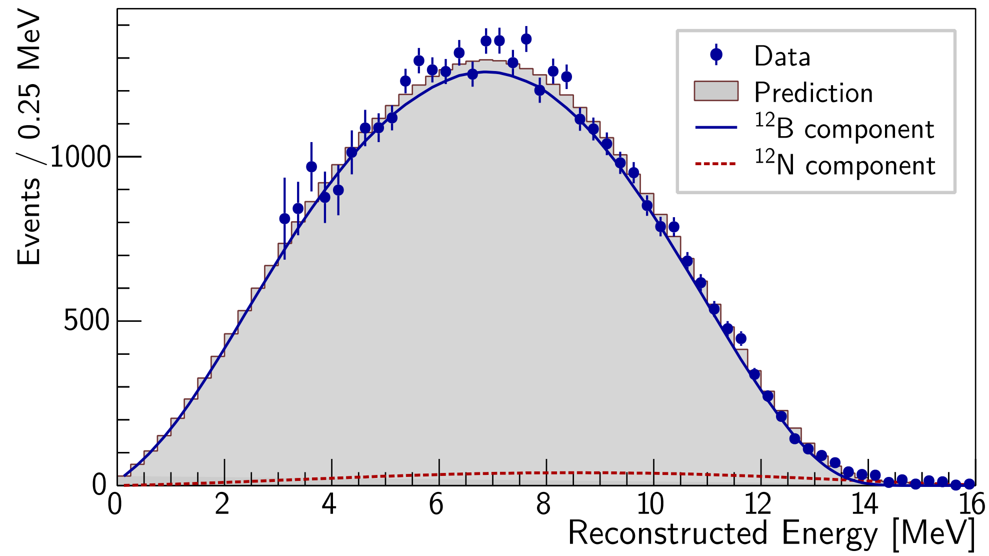
Non-Linearity Response Model

- Model is constrained using monoenergetic gamma lines from various sources and continuous spectrum from ^{12}B produced by muon spallation inside the scintillator:

Gamma Ray Energy Peaks

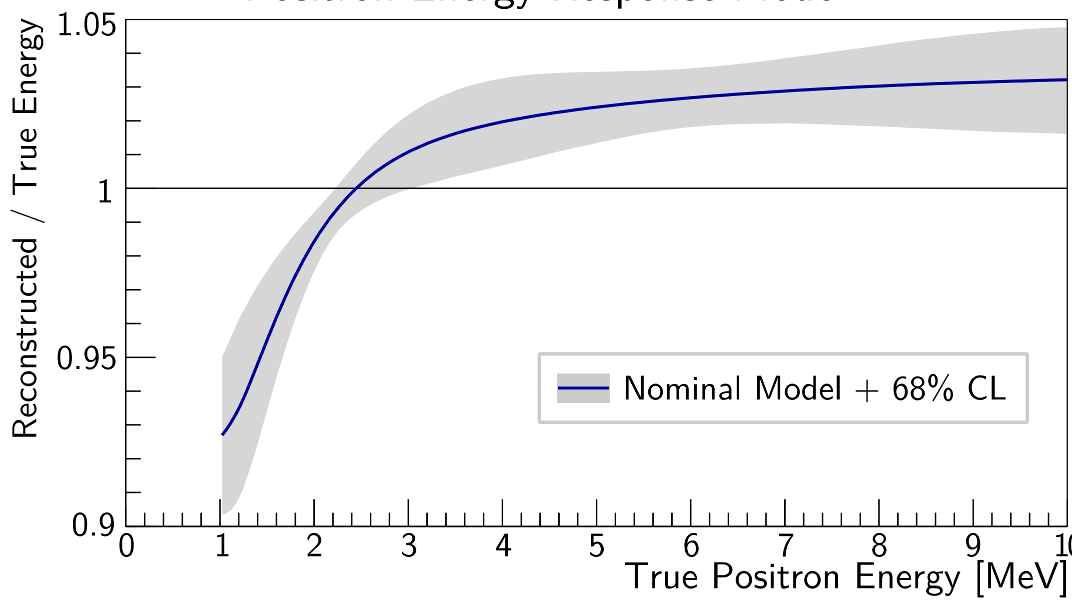


^{12}B Beta-Decay Spectrum



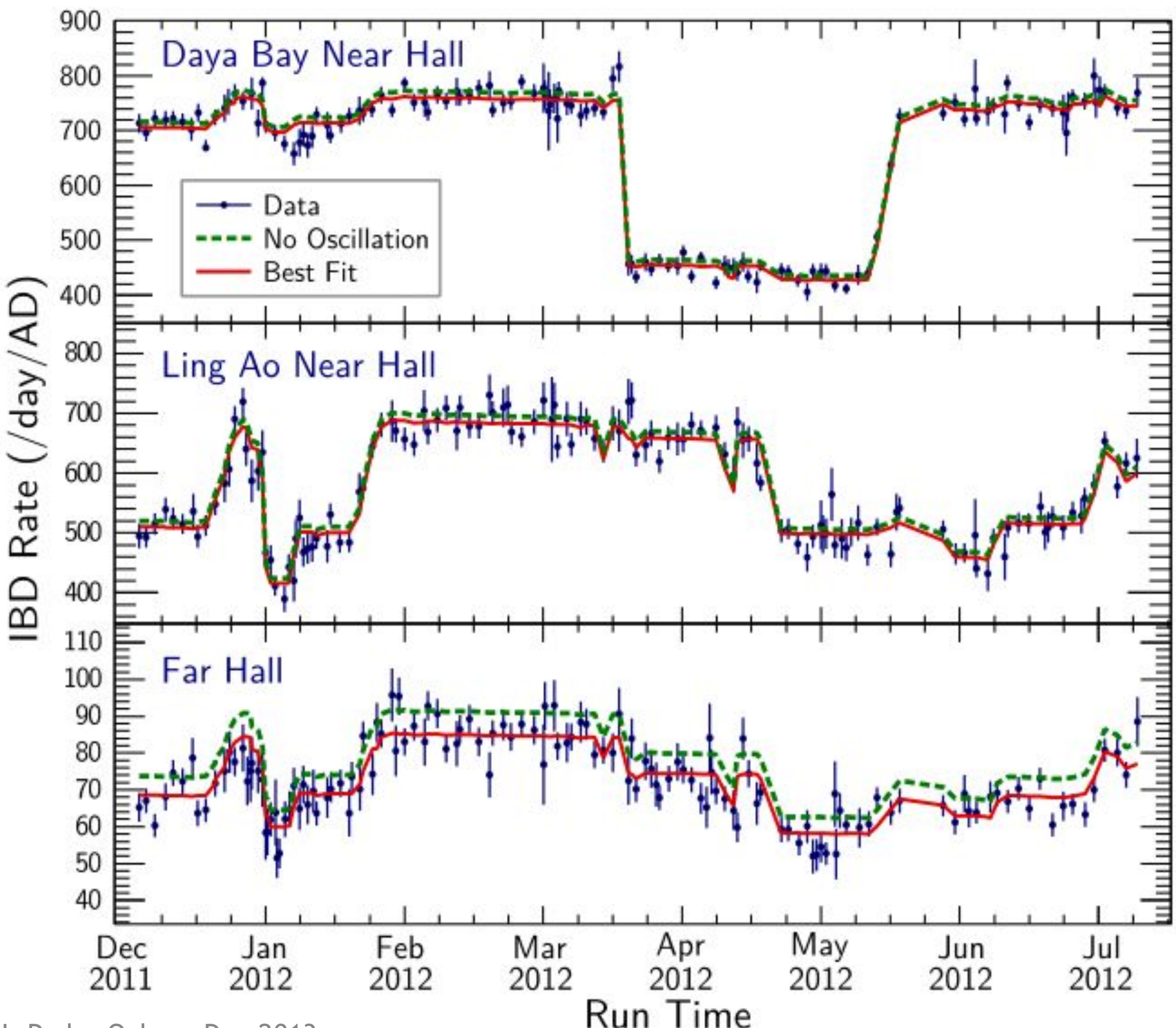
Final positron energy non-linearity response

Positron Energy Response Model



Antineutrino Rates vs. Time

- For main analysis we simultaneously fit all detectors using reactor model, with the absolute normalization as a free parameter:



Note:

- Normalization is determined by fit to data. It is within a few percent of expectations.
- Paper on absolute reactor neutrino flux and shape is in preparation

Detected rate strongly correlated with reactor flux expectations

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 near/far oscillation, only uncorrelated uncertainties play a significant role

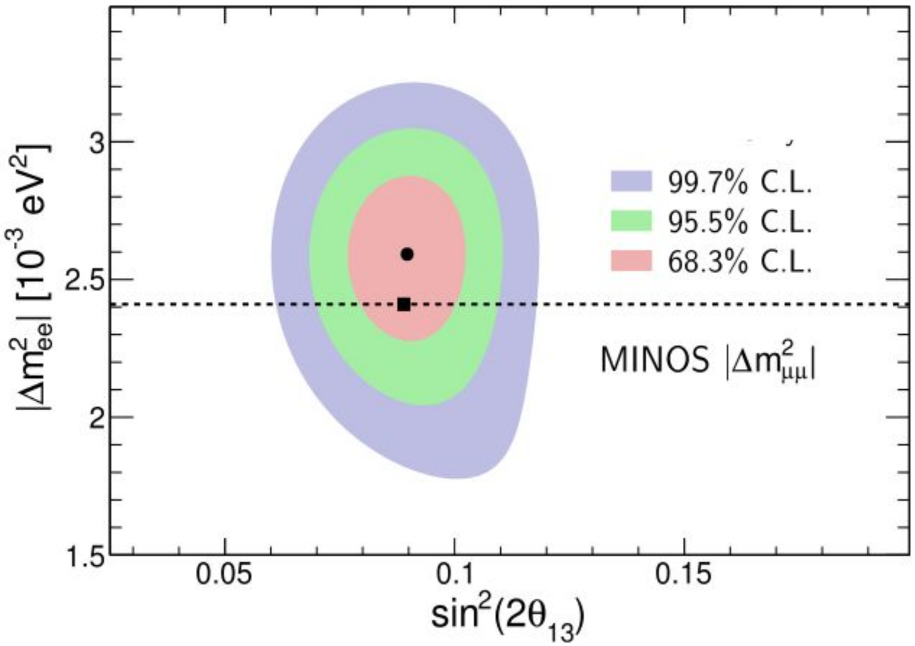
Largest systematics are smaller than far site statistics (~0.5%)

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
  - θ_{13}: Reactor model, relative + absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds

Results

❖ Rate + shape results are consistent with previous results:



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

$$\chi^2/N_{DoF} = 162.7/153$$

World's first measurement in this channel!

Strong confirmation of oscillation-interpretation of observed $\overline{\nu}_e$ deficit

	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

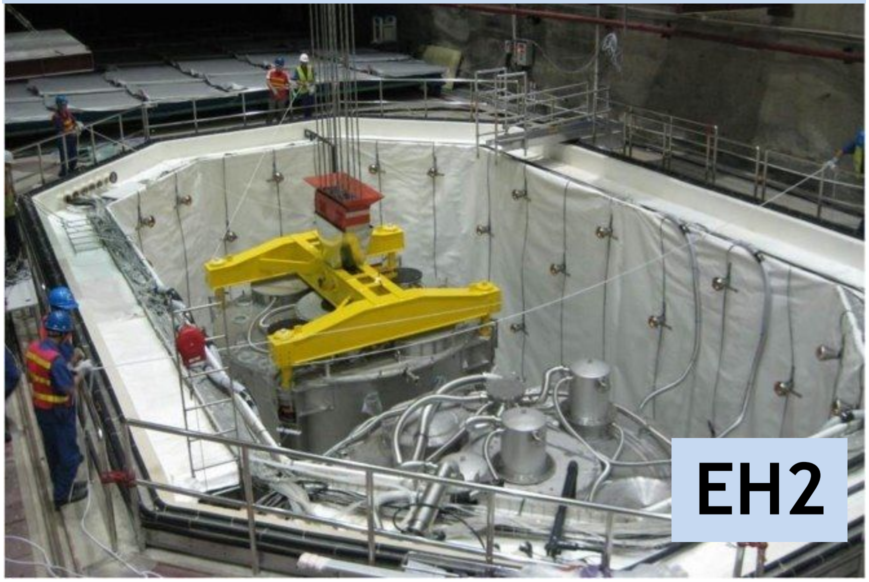
← A. Radovic, DPF2013

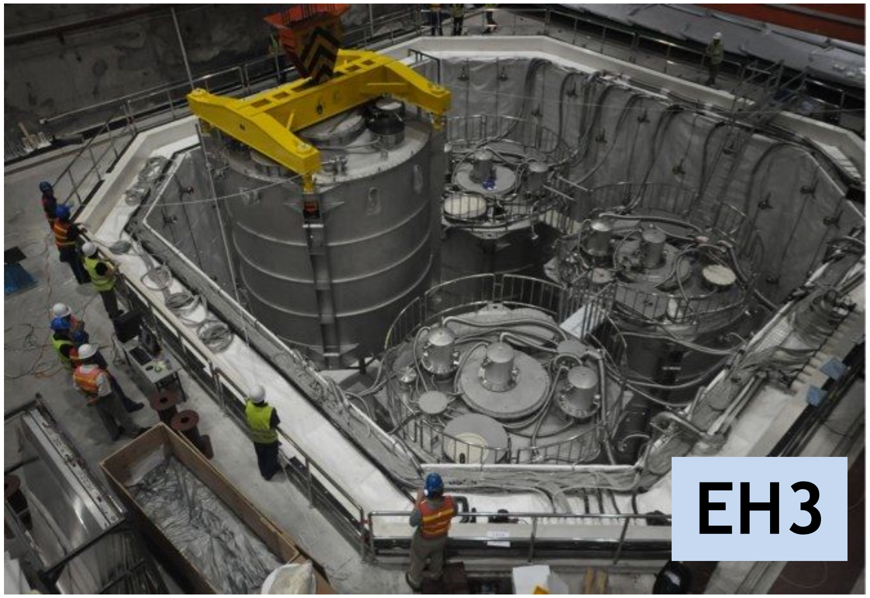
World's most precise measurement of θ_{13} to date.

The Future

Daya Bay Onsite Progress

Final two detectors installed, operating since Oct. 2012.

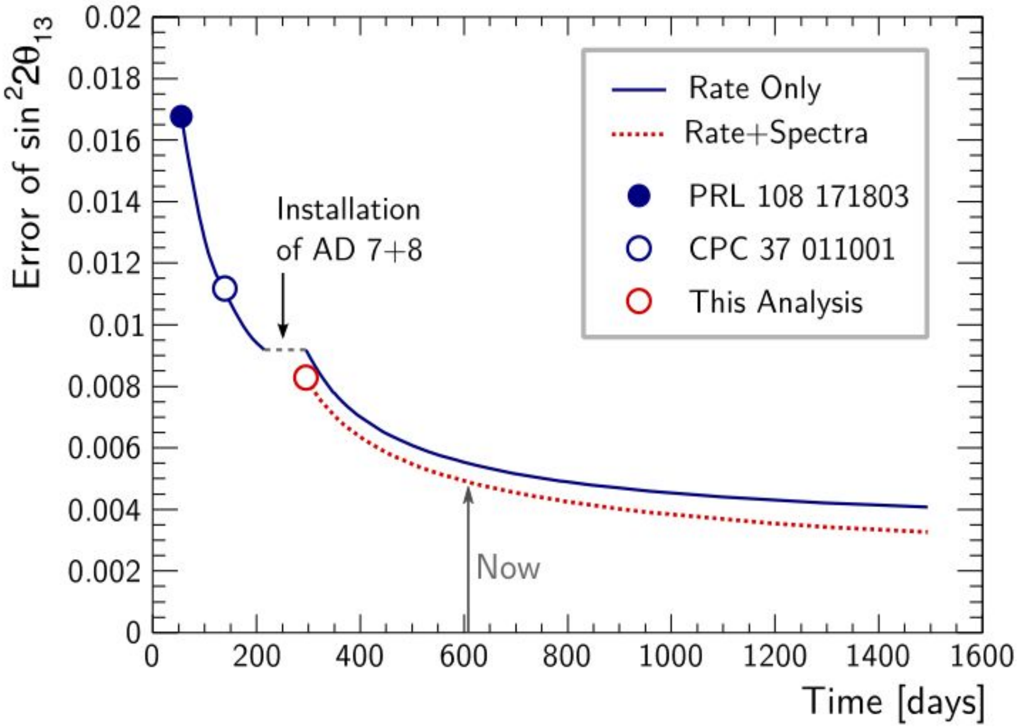


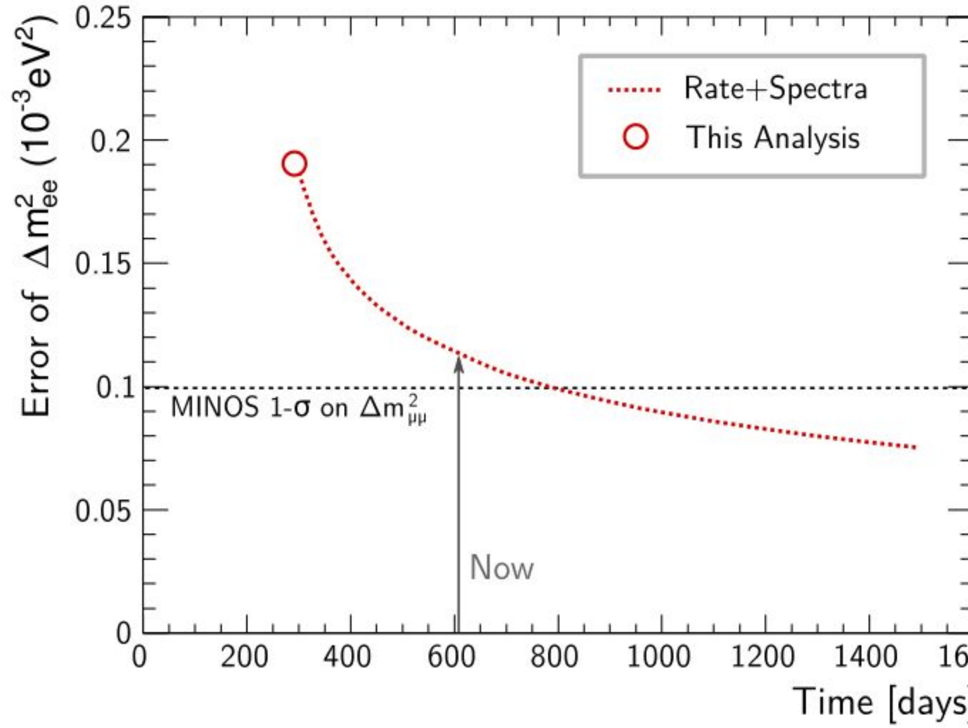


Full 4π detector calibration in Sep. 2012.

Daya Bay’s Future

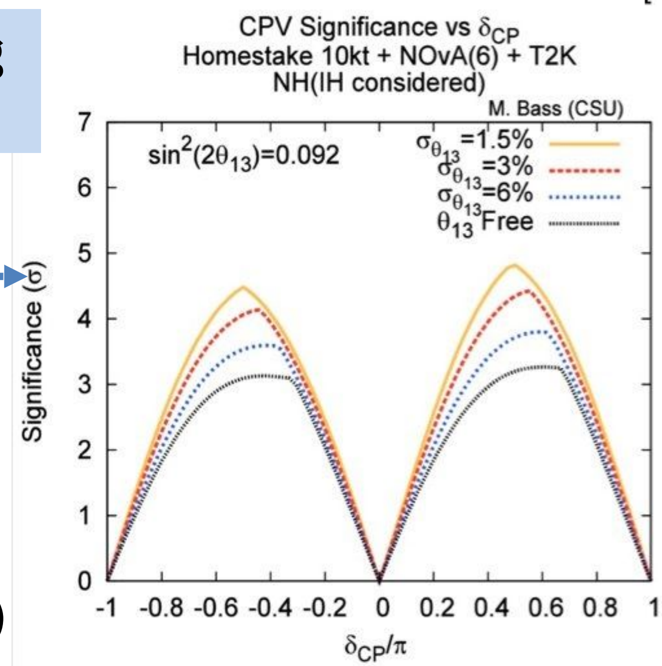
❖ Increased precision in oscillation parameters:





World’s most precise measurement of θ_{13} for a long time to come, and very precise estimate of Δm^2

- ✓ Constrains non-standard oscillation models
- ✓ Improves reach of next-generation experiments →



❖ Absolute reactor neutrino spectrum flux and shape measurement:

- ✓ Probe reactor models and explore reactor antineutrino ‘anomaly’

❖ Others (cosmogenic production, supernovae… etc)

Summary & Conclusions

- Daya Bay's careful design and its painstaking implementation have been key to its success
- Our latest results include the first direct measurement of the short-distance electron antineutrino oscillation frequency:

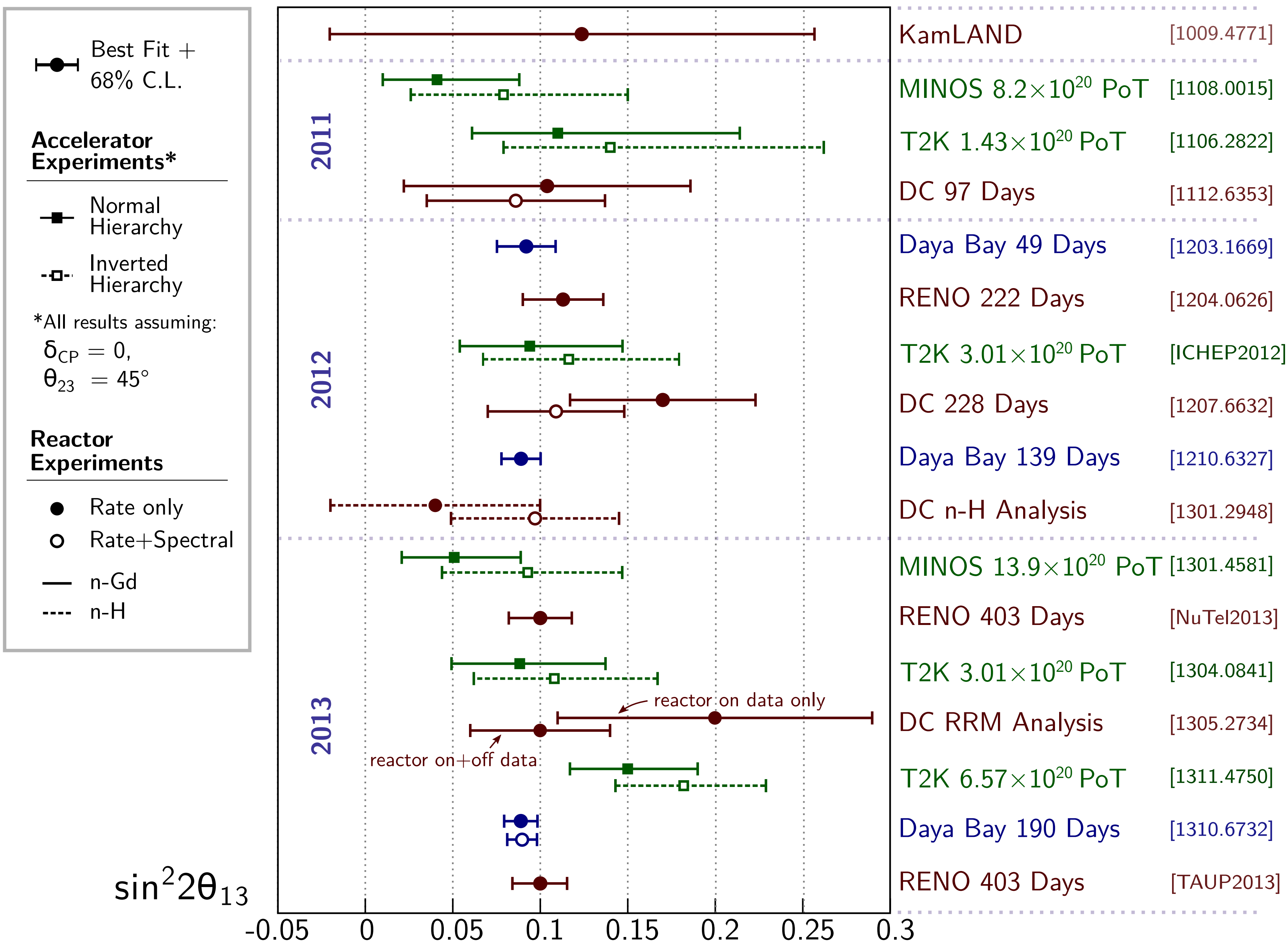
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\, eV^2$$

- They also include the most precise estimate of the θ_{13} mixing angle:

$$\sin^2(2\theta_{13}) = 0.090^{+0.008}_{-0.009}$$

- Stay tuned for more exciting results from Daya Bay!

Thank you for your attention!


Best Fit + 68% C.L.
Accelerator Experiments*
Normal Hierarchy
Inverted Hierarchy
*All results assuming:
$\delta_{CP} = 0$,
$\theta_{23} = 45°$
Reactor Experiments
Rate only
Rate+Spectral
n-Gd
n-H
2011
2012
2013
reactor on data only
reactor on+off data
$\sin^2 2\theta_{13}$
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
KamLAND [1009.4771]
MINOS 8.2×10^{20} PoT [1108.0015]
T2K 1.43×10^{20} PoT [1106.2822]
DC 97 Days [1112.6353]
Daya Bay 49 Days [1203.1669]
RENO 222 Days [1204.0626]
T2K 3.01×10^{20} PoT [ICHEP2012]
DC 228 Days [1207.6632]
Daya Bay 139 Days [1210.6327]
DC n-H Analysis [1301.2948]
MINOS 13.9×10^{20} PoT [1301.4581]
RENO 403 Days [NuTel2013]
T2K 3.01×10^{20} PoT [1304.0841]
DC RRM Analysis [1305.2734]
T2K 6.57×10^{20} PoT [1311.4750]
Daya Bay 190 Days [1310.6732]
RENO 403 Days [TAUP2013]

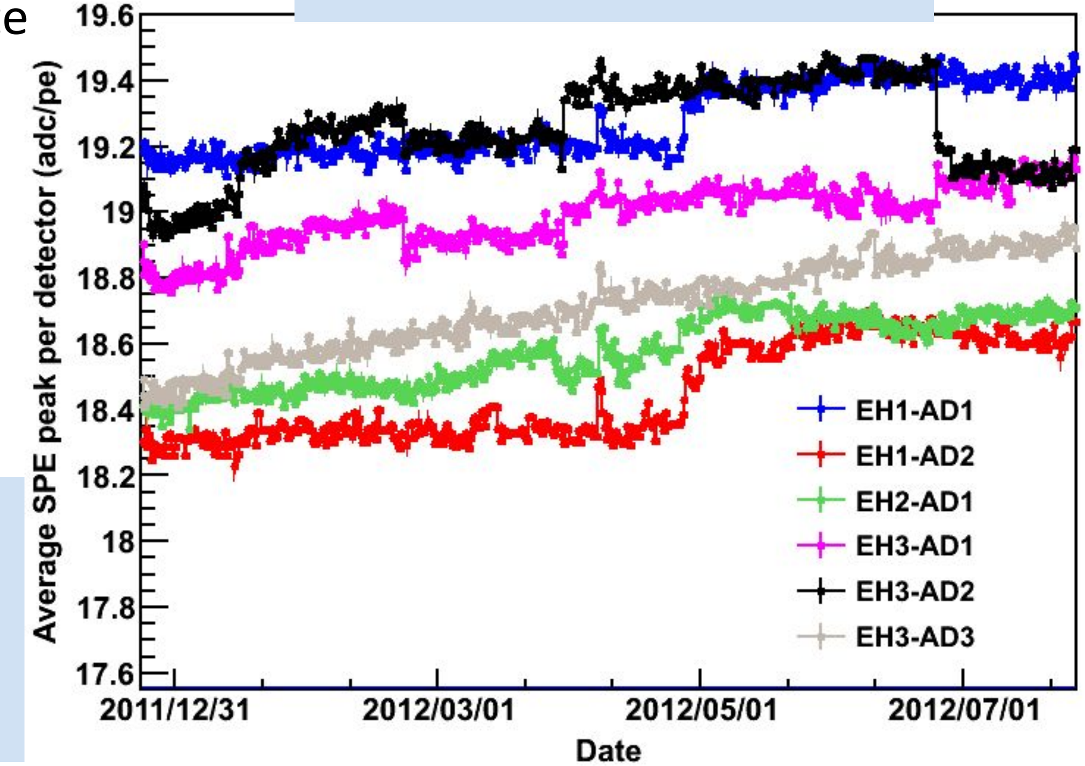
Calibration: PMT+Electronics Gain

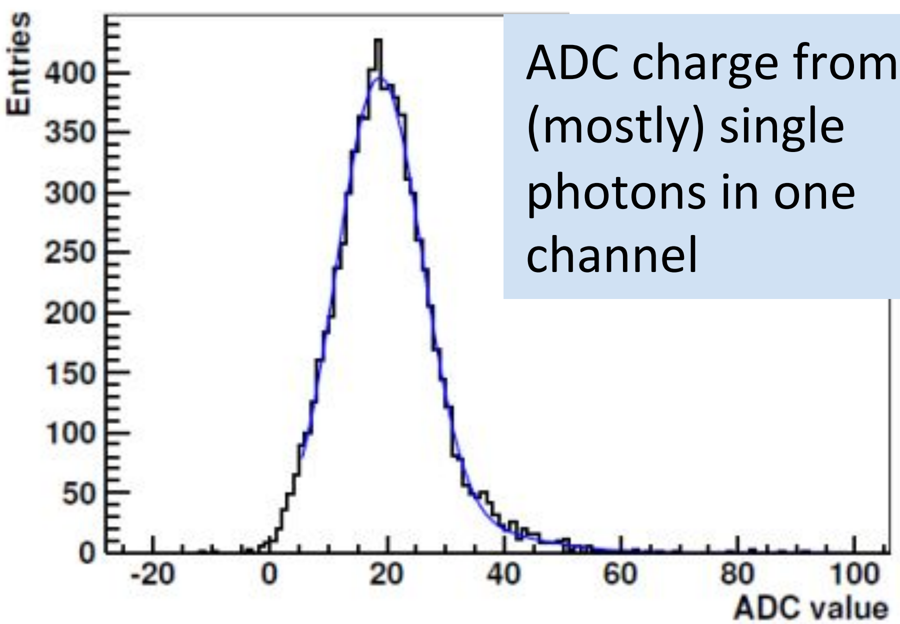
Measure charge from single photons in-situ with data

Use out-of-time PMT signals hits to calibrate the PMT + electronics response to single photons.

Cross-check with weekly LED deployments.

Gain variation with time





ADC charge from (mostly) single photons in one channel

Calibration driven by uncertainty in relative detector efficiency

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

Analyzed Datasets

Two detector comparison [1202.6181]

- 90 days of data, Daya Bay near only
- NIM A **685** (2012), 78-97

First oscillation analysis [1203:1669]

- 55 days of data, 6 ADs near+far
- PRL **108** (2012), 171803
- **Top 10 breakthrough of 2012 by Science Magazine**

Improved oscillation analysis [1210.6327]

- 139 days of data, 6 ADs near+far
- CP C **37** (2013), 011001

Spectral Analysis [1310.6732]

- 217 days complete 6 AD period
- 55% more statistics than CPC result