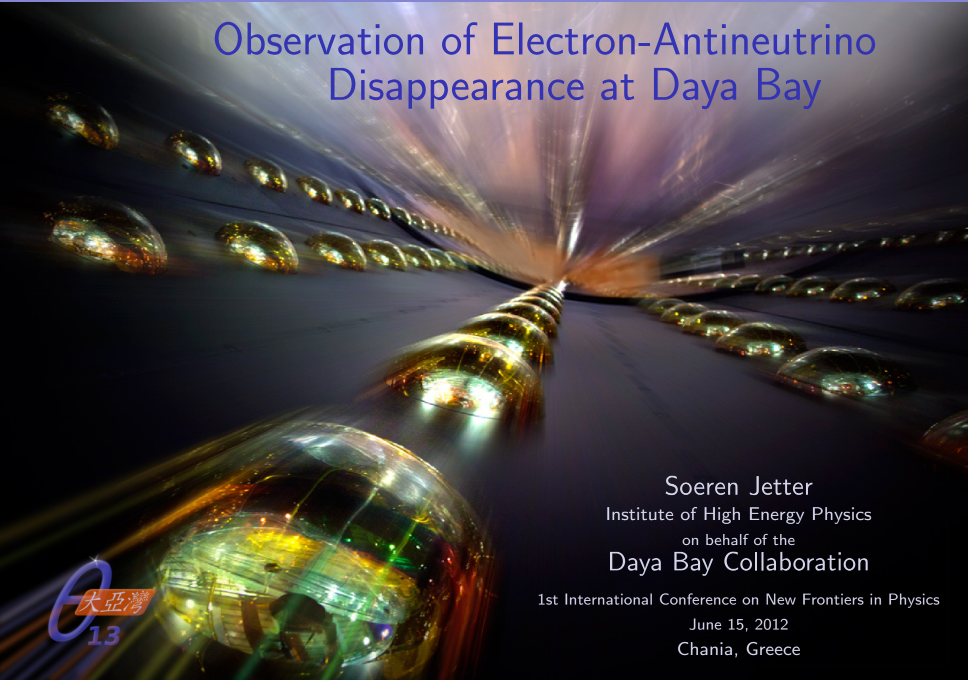
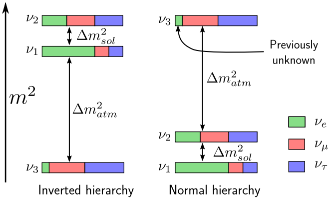


Observation of Electron-Antineutrino Disappearance at Daya Bay

Soeren Jetter
Institute of High Energy Physics
on behalf of the
Daya Bay Collaboration

1st International Conference on New Frontiers in Physics
June 15, 2012
Chania, Greece

Three Neutrino Oscillation: PMNS Matrix



Weak and mass eigenstates need not correspond:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i} \, |\nu_i\rangle$$

1. How they interact → $|\nu_\alpha\rangle$
2. How they propagate → $|\nu_i\rangle$

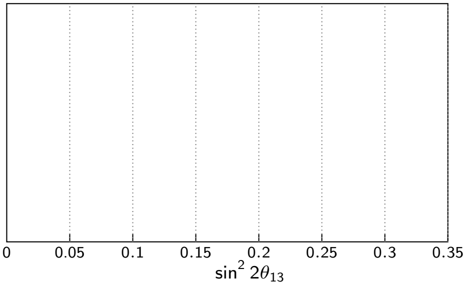
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12}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

- $\theta_{23} \sim 45^\circ$ established through atmosperic accelerators: possibly maximal
- $\theta_{12} \sim 34^\circ$ established through solar experiments and KamLAND: large but nor maximal

θ_{13} only mixing angle not previously well established: Small? Zero?

Recent Indication for a Non-Zero θ_{13}

- Tensions between solar, reactor oscillations suggest $\theta_{13} > 0$
- Appearance of ν_e in ν_μ accelerator beam
- Double Chooz reported improved single detector measurement



2011 has given many hints but no results $> 2.5\,\sigma$ from $\theta_{13} = 0$

- Solar + KamLAND: G.L. Fogli *et al.*, Phys. Rev. D 84, 053007 (2011)
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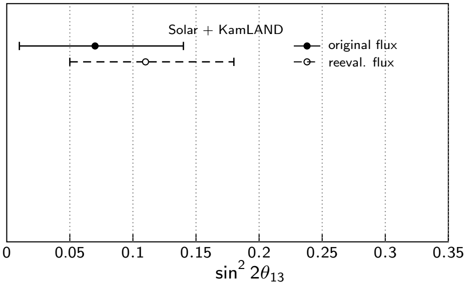

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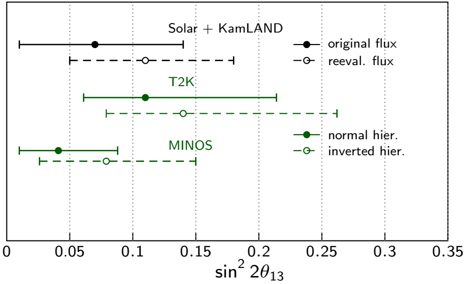

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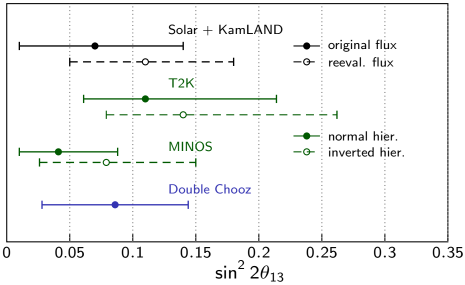

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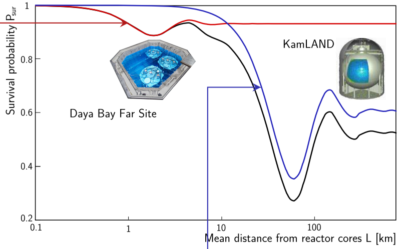
Reactor Neutrino Oscillation

Benefits of reactor neutrinos:

- Pure ν_e source
- Large statistics of antineutrinos
- Clean detection signal
- No cross-talk with δ phase and matter effects



$\Delta m^2_{32} \approx \Delta m^2_{31} \approx \Delta m^2_{atm}$

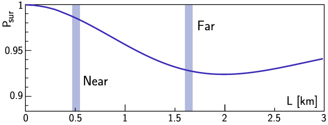
$$P_{sur} \approx 1 - \underbrace{\sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)}_{\text{Previously unknown}} + \underbrace{\sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)}_{\text{Measured by KamLAND}}$$

θ_{13} can be revealed by a deficit of reactor antineutrinos at $\sim$ 2 km.

The Daya Bay Strategy

Baseline optimization

- Optimized to known parameter space of Δm^2_{32}
- Far site maximizes term dependent on $\sin^2 2\theta_{13}$



Relative measurement with multiple detectors

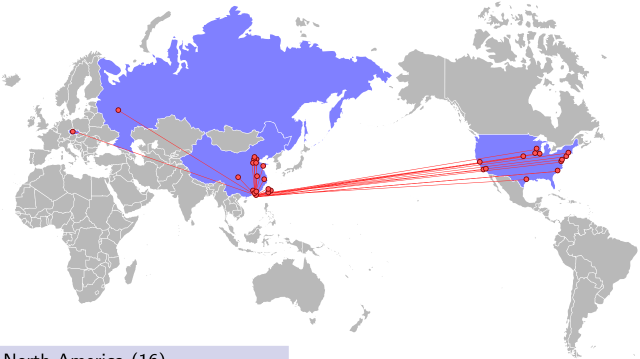
- Absolute reactor flux single largest uncertainty in previous measurements

Cancels in near/far ratio: $$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left(\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right)$$

- Reduction of systematic errors
  1. Detector target masses: Load cells measure masses to 0.015%
  2. Reactor-detector baselines: Negligible reactor flux uncertainty from precise survey (<0.02%)
  3. Detector efficiencies: 8 identically designed detectors, side-by-side comparison, calibration

Daya Bay: A Powerful Neutrino Source at an Ideal Location

An International Effort: 228 Collaborators from 28 Institutions



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

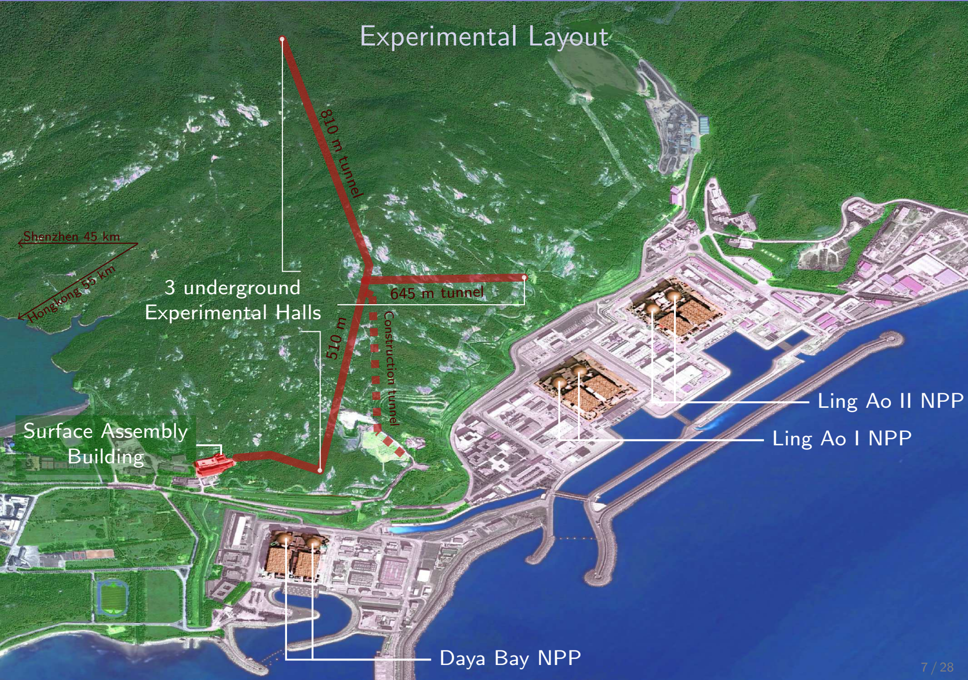
Europe (2)

Charles University, Dubna

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.

Experimental Layout



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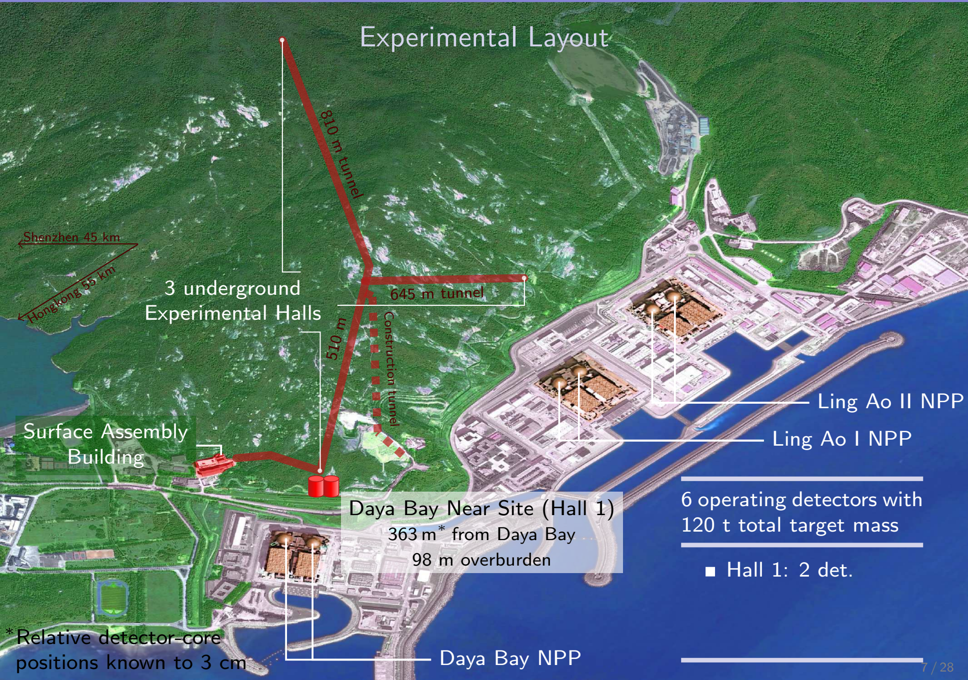
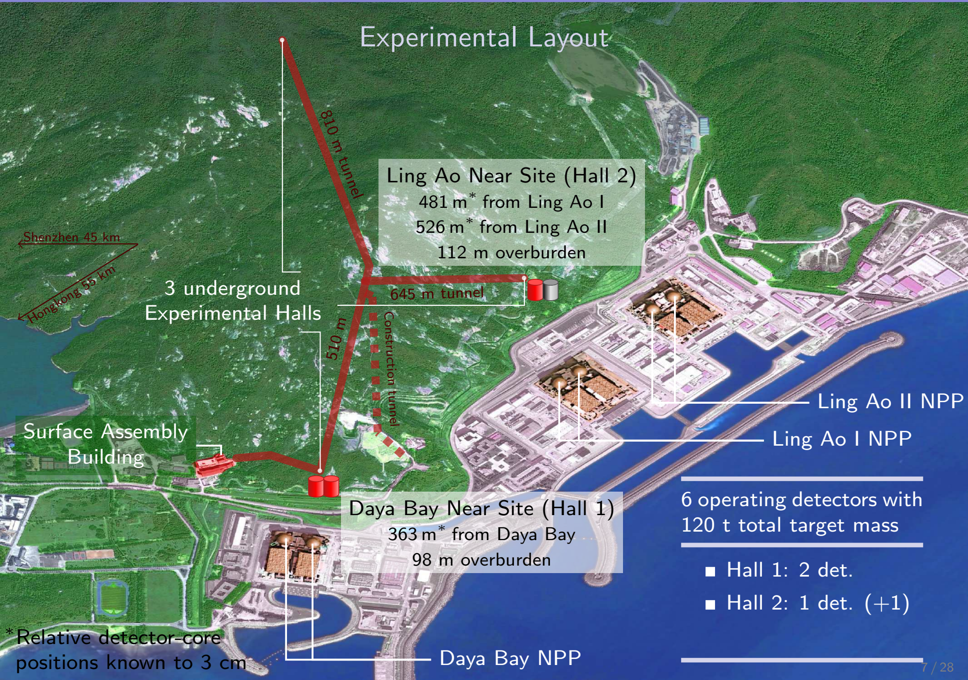


6 operating detectors with 120 t total target mass

- Hall 1: 2 det.

*Relative detector-core positions known to 3 cm

Experimental Layout



Ling Ao Near Site (Hall 2)
481 m* from Ling Ao I
526 m* from Ling Ao II
112 m overburden

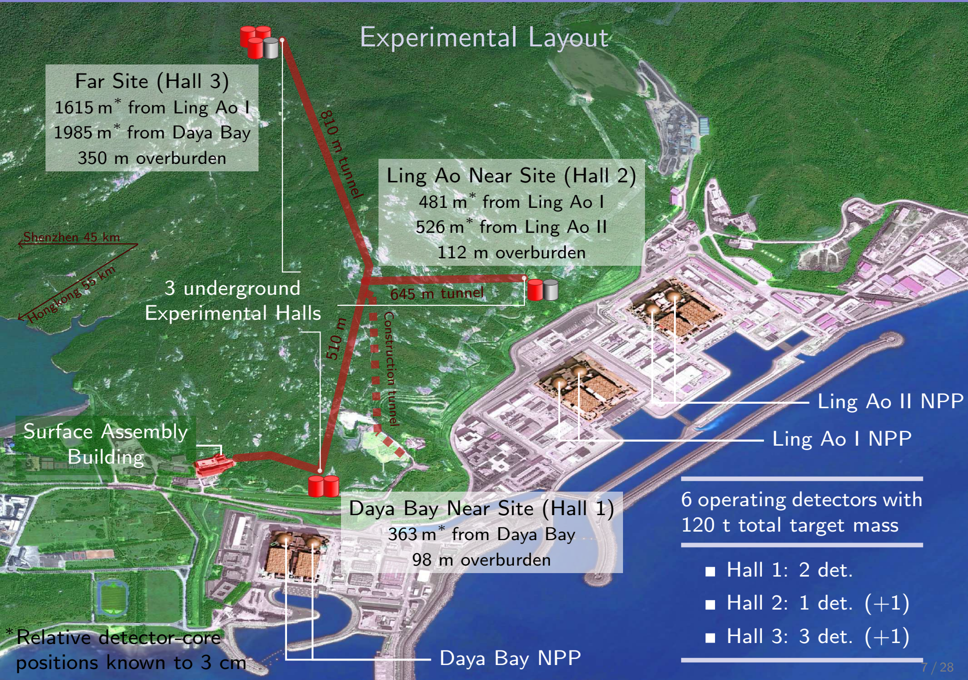
Daya Bay Near Site (Hall 1)
363 m* from Daya Bay
98 m overburden

6 operating detectors with 120 t total target mass

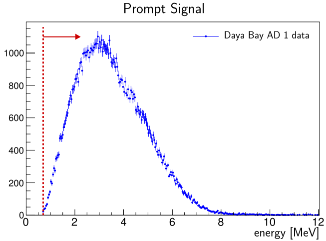
- Hall 1: 2 det.
- Hall 2: 1 det. (+1)

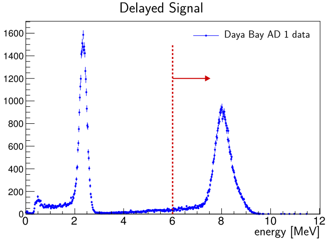
*Relative detector-core positions known to 3 cm

Experimental Layout



Antineutrino Detection via Inverse Beta Decay





Prompt+delayed coincidence provides distinctive signature

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

$\hookrightarrow + p \xrightarrow{\tau \approx 180\,\mu s} D + \gamma$ (2.2 MeV)

$\hookrightarrow + Gd \xrightarrow{\tau \approx 28\,\mu s} Gd^* \rightarrow Gd + n\gamma$ (8 MeV) *delayed*

- Neutrino energy: $E_{\bar{\nu}_e} \approx T_{e^+} + T_n + (m_n - m_p) + m_{e^+} \approx T_{e^+} + 1.8\,\text{MeV}$
- Higher energy and shorter capture time on Gd improve background rejection

Antineutrino Detector (AD) Design

6 functionally identical detectors
reduce systematic uncertainties

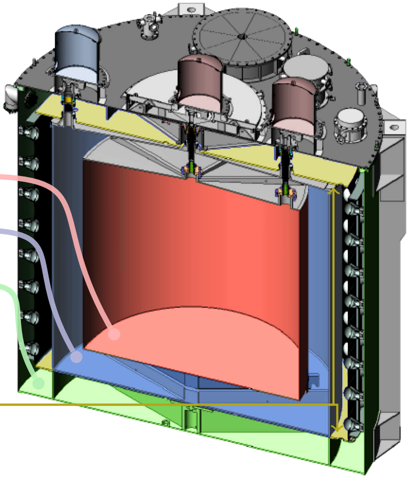
3 zone cylindrical vessels

	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

$(\frac{7.5}{\sqrt{E}} + 0.9)\%$ energy resolution



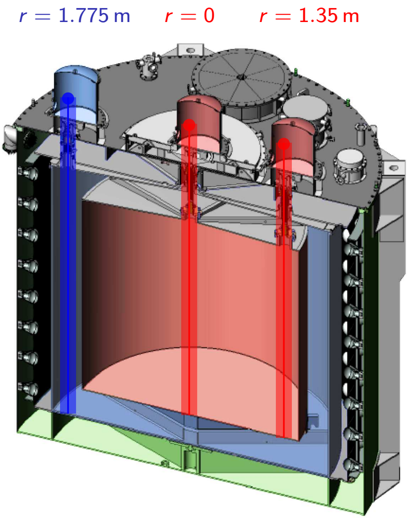
Calibration: Key to Reduction of Detector-Related Systematics

3 fully automated units per detector deploy sources along z-axis

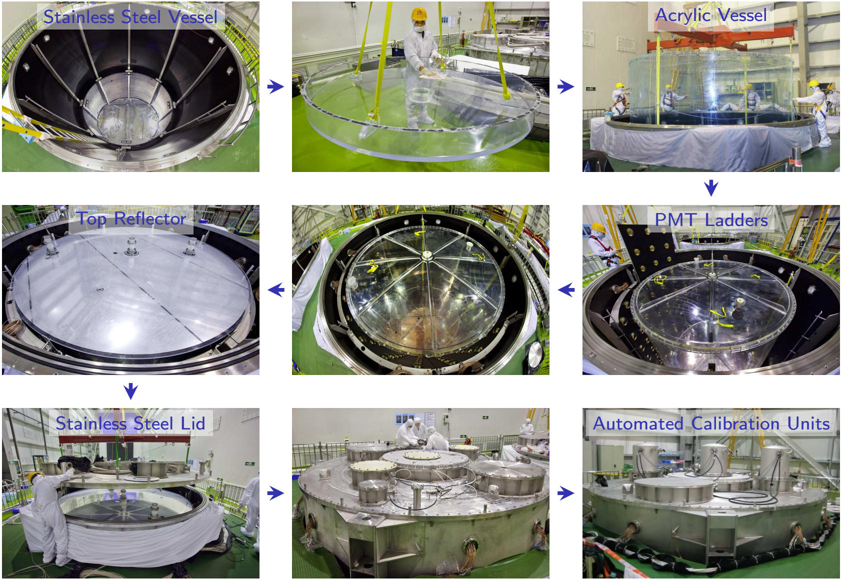
1. Center: time evol., energy scale, non-linearity
2. Edge: efficiency, space response
3. γ catcher: efficiency, space response

4 calibration sources in each unit

1. ^{68}Ge (2 × 511 keV γ source)
   positron threshold, non-linearity
2. ^{60}Co (1.17 + 1.33 MeV γ source)
   energy scale, response function
3. ^{241}Am^{13}C (neutron source)
   neutron capture time
4. LED diffuser ball
   PMT timing, gain and relative QE



Antineutrino Detector Assembly

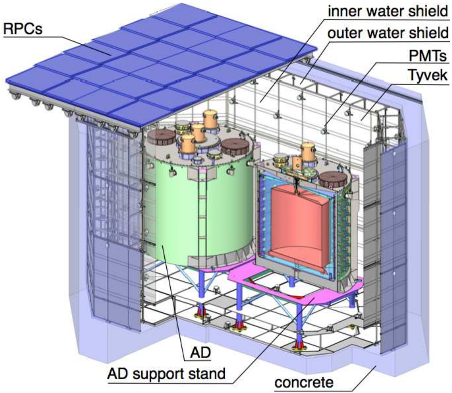


Interior of an Antineutrino Detector

Muon Tagging System

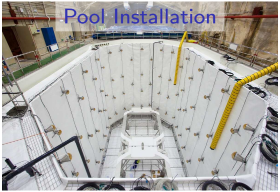
Complementary systems: 2.5 meter thick two-section water shield and RPC cover

1. Dual-purpose ultra pure water pool
   - Shields natural and cosmogenic background and attenuates rock radioactivity and fast neutrons
   - Serves as Cherenkov detector to observe the presence of cosmic ray muons
   - 1 m outer layer of water veto
   - >2.5 m inner layer of water veto
   - 288 8" PMTs in each near hall
   - 384 8" PMTs in the Far Hall
2. 4-layer RPC modules above pool
   - 54 modules in each near hall
   - 81 modules in Far Hall



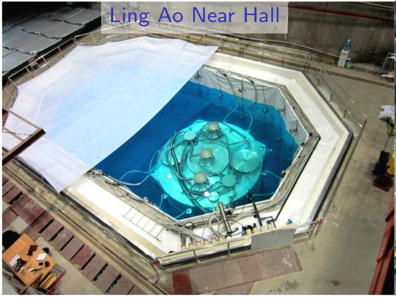
Goal efficiency: $\epsilon_\mu > 99.5\%$ with uncertainty $\sigma_\epsilon < 0.25\%$

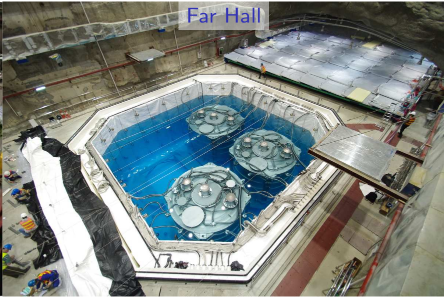
Daya Bay Experimental Hall 1 Installation



- Daya Bay Near Site began operation on 15 August 2011
- Stable data-taking started on 23 September 2011

Experimental Hall 2+3 Installation





Christmas Eve 2011: Start of simultaneous 3-site data-taking

- Ling Ao Near Hall began operation with 1 AD on 5 November 2011
- Far Hall started data-taking with 3 ADs on 24 December 2011
- Last remaining pair of ADs in assembly, will be installed in 2012

Analyzed Data Sets

Two detector comparison arXiv:1202.6181

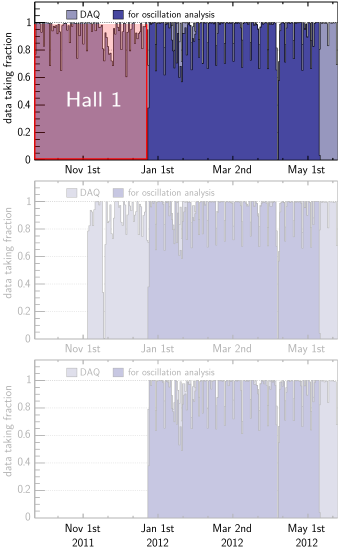
- Sep. 23–Dec. 23, 2011 (∼90 live days)
- Side-by-side comparison of two detectors
- Demonstrated detector systematics better than requirements
- Nucl. Inst. and Meth. **A 685** (2012), 78-97

First oscillation analysis arXiv:1203:1669

- Dec. 24, 2011–Feb. 23, 2012 (∼50 days)
- All 3 halls (6 ADs) operating
- DAQ uptime: >97 %, neutrino data: 89%
- Phys. Rev. Lett. **108** (2012), 171803

Improved osc. analysis: ∼ 2.5 as much data

- Dec. 24, 2011–May 11, 2012 (∼126 days)



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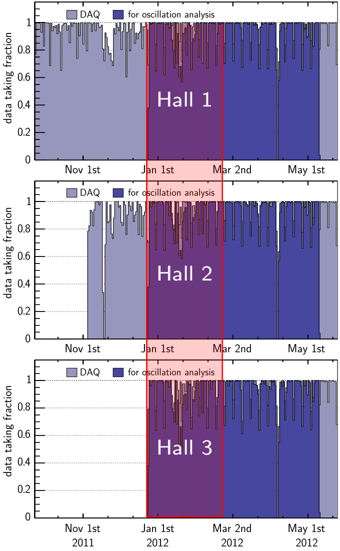

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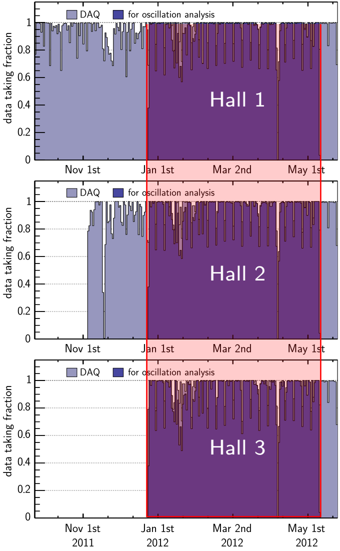


Data analysis approach

Blind analysis

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

Nominal values for:

1. Reactor flux
2. Target mass → $N_{p,\mathrm{f}}/N_{p,\mathrm{n}}$
3. Reactor-detector baselines → $L_\mathrm{n}/L_\mathrm{f}$

Multiple independent analyses

- Common data sets
- Redundant analyses use different approaches on:
  - Energy calibration and reconstruction
  - Antineutrino candidate selection
  - Background estimation
  - θ_{13} rate analysis
- Consistency checks of multiple analyses before unblinding

→ Results from one analysis shown in this talk

Side-by-Side Detector Comparison

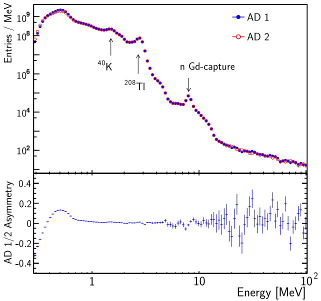


Figure: Side-by-side comparison of full spectrum after flasher and muon removal

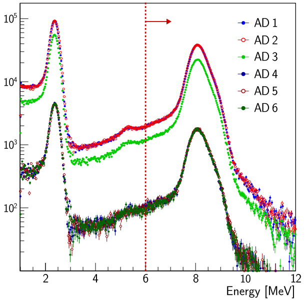


Figure: Energy spectrum of spallation neutrons for all six detectors

Multiple detectors allow detailed comparison and cross-checks

- Two ADs in Daya Bay Near Site Hall have functionally identical response
- Response of all detectors to neutrons constrains largest systematic uncertainty

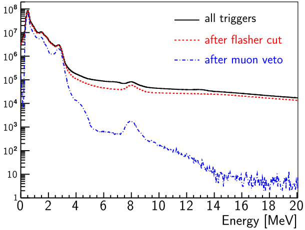
AD 1/2 Asymmetry $= 2(N_{\mathrm{AD1}} - N_{\mathrm{AD2}})/(N_{\mathrm{AD1}} + N_{\mathrm{AD2}})$

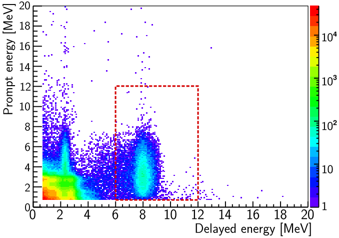
Antineutrino (IBD) Selection

Use IBD prompt+delayed coincidence signal to select antineutrinos

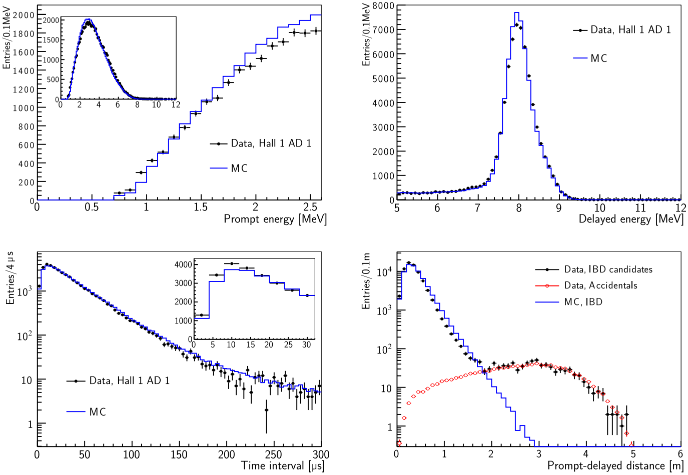
Selection steps:

1. Reject spontaneous PMT light emission (”flashers”)
2. Prompt positron: $0.7\,\text{MeV} < E_p < 12\,\text{MeV}$
3. Delayed neutron: $6.0\,\text{MeV} < E_d < 12\,\text{MeV}$
4. Neutron capture time: $1\,\mu\text{s} < \Delta t < 200\,\mu\text{s}$
5. Muon veto:
   - Water pool muon (>12 hit PMTs): Reject 0.6 ms
   - AD muon (>20 MeV): Reject 1 ms
   - AD shower muon (>2.5 GeV): Reject 1 s
6. Multiplicity: No other signal $> 0.7\,\text{MeV}$ in $-200\,\mu\text{s}$ to $200\,\mu\text{s}$ of IBD.



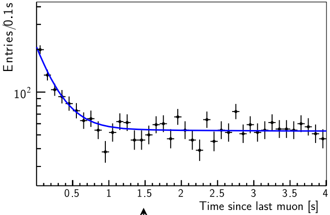


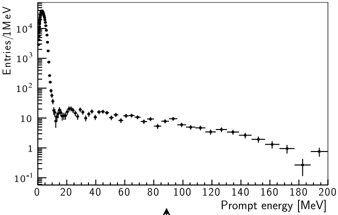
Spectra of Antineutrino Candidates



Except for prompt-delayed distance, all spectra are background-subtracted

Backgrounds





All backgrounds estimated using data-driven methods

- ^{9}Li rate evaluated using time-correlation with muon
- Fast neutron rate constrained using IBD-like signals in 10–50 MeV energy range

Low rates of total background

- $5\% \pm 0.3\%$ background/signal ratio for Far Hall, $2\% \pm 0.2\%$ for both near halls
- Accidental coincidences single largest contributor to total background rate
- ^{241}Am^{13}C source and ^{9}Li/^{8}He from muon spallation largest sources of uncertainty

Signal and Background Summary

	Near Sites			Far Site		
	AD 1	AD 2	AD 3	AD 4	AD 5	AD 6
IBD candidates	69121	69714	66473	9788	9669	9452
DAQ live time (days)	127.3763		127.3763	126.2646		
Muon veto time (days)	22.5656	22.9901	18.1426	2.3619	2.3638	2.4040
$\epsilon_\mu \cdot \epsilon_m$	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (per day)	9.73$\pm$0.10	9.61$\pm$0.10	7.55$\pm$0.08	3.05 $\pm$0.04	3.04 $\pm$0.04	2.93 $\pm$0.03
Fast-neutron (per day)	0.77$\pm$0.24	0.77$\pm$0.24	0.58$\pm$0.33	0.05$\pm$0.02	0.05$\pm$0.02	0.05$\pm$0.02
^{9}Li/^{8}He (per AD per day)	2.9$\pm$2.0		2.0$\pm$1.1	0.22$\pm$0.12		
Am-C corr. (per AD per day)	0.2$\pm$0.2					
^{13}C^{16}O backgr. (per day)	0.08$\pm$0.04	0.07$\pm$0.04	0.05$\pm$0.03	0.04$\pm$0.02	0.04$\pm$0.02	0.04$\pm$0.02
IBD rate (per day)	662.47$\pm$3.00	670.87$\pm$3.01	613.53$\pm$2.69	77.57$\pm$0.85	76.62$\pm$0.85	74.97$\pm$0.84

Table: The background and IBD rates were corrected for the $\epsilon_\mu \cdot \epsilon_m$ efficiency.

Collected more than 200k antineutrino interactions

- Consistent rates for side-by-side detectors
- Uncertainties dominated by statistics

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%**

- Only uncorrelated uncertainties relevant to near/far oscillation analysis
- Largest systematics smaller than far site statistics ($\sim$ 1%)

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	**Combined**	**0.8%**

- Impact of uncorrelated reactor systematics reduced by relative measurement

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Antineutrino Rate vs. Time

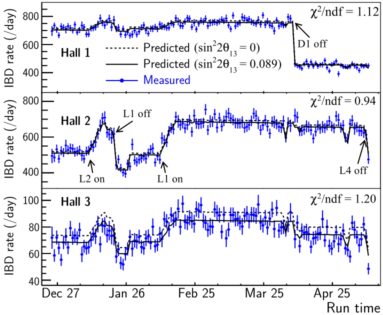


Figure: Expected vs. measured IBD rate

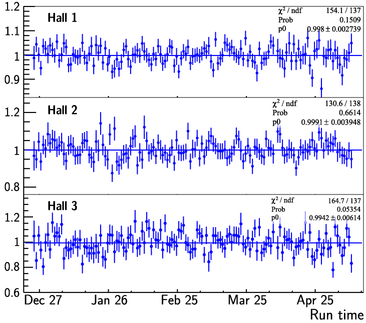
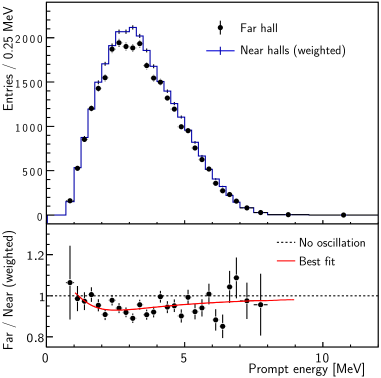


Figure: IBD rate normalized to expectation

Detected rate strongly correlated with reactor flux expectations

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

Antineutrino Near/Far Comparison



1. Near/Far rate comparison:

$$R = \frac{N_{\text{meas}}}{N_{\text{pred}}}$$
$$= \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6} \alpha_i (M_1 + M_2) + \beta_i M_3}$$
$$= 0.944 \pm 0.007(\text{stat}) \pm 0.003(\text{syst})$$

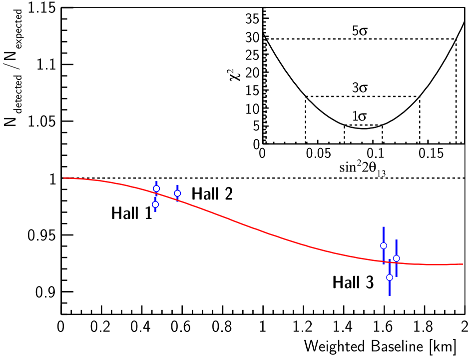
M_j: measured rates in each AD
α_i, β_i: weights determined from baselines and reactor fluxes

2. Near/Far spectral distortion consistent with oscillation*

* Spectral systematics not fully studied, θ_{13} shape analysis not recommended

Clear observation of an antineutrino deficit at the Far Site: $R = 0.944 \pm 0.008$

Rate-only θ_{13} analysis

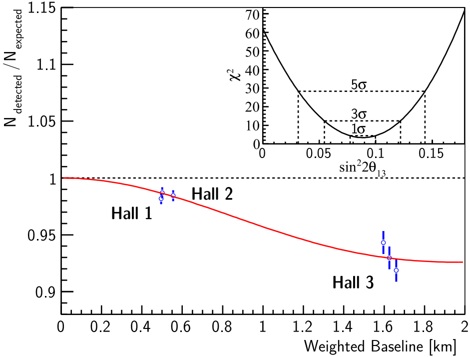


- Estimates θ_{13} using measured rates in each detector
- Uses standard χ^2 approach
- Far vs. near relative measurement, absolute rate is not constrained
- Consistent results obtained by independent analyses, different reactor flux models

First measurement of $\sin^2 2\theta_{13}$ in March 2012

- $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$
- Excludes $\sin^2 2\theta_{13} = 0$ at $5.2\,\sigma$
- Details in PRL **108**, 171803 (2012)

Rate-only θ_{13} analysis



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Improved result June 2012: Most precise measurement of $\sin^2 2\theta_{13}$ to date

- $\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$
- Excludes $\sin^2 2\theta_{13} = 0$ at $7.7\,\sigma$
- To be submitted to Chinese Physics C

Global Situation

Before March 2012

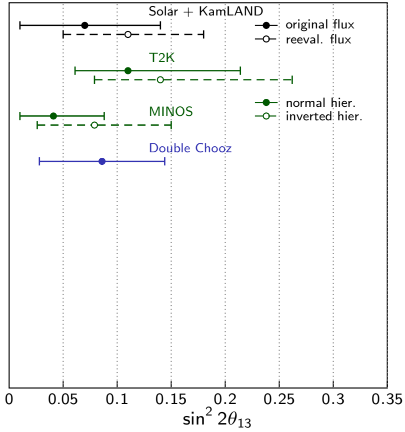
Only $\sigma < 2.5$ indication for non-zero θ_{13}

First Daya Bay result

- $R = 0.940 \pm 0.011(\text{stat}) \pm 0.004(\text{syst})$
- $\sin^2 2\theta_{13} = 0.092 \pm 0.017$

Updated 126 day analysis

- $R = 0.944 \pm 0.007(\text{stat}) \pm 0.003(\text{syst})$
- $\sin^2 2\theta_{13} = 0.089 \pm 0.011$



All experiments paint a consistent picture

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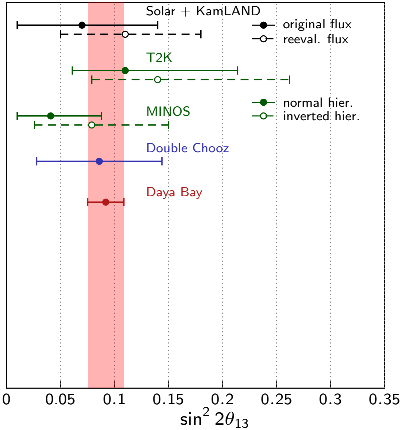

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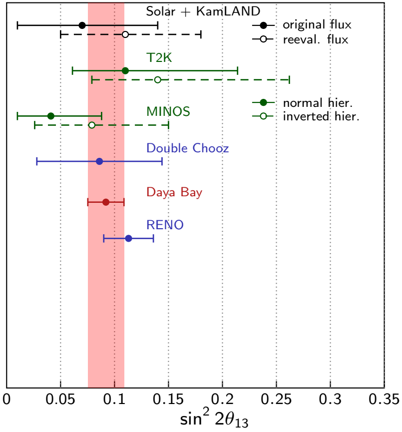

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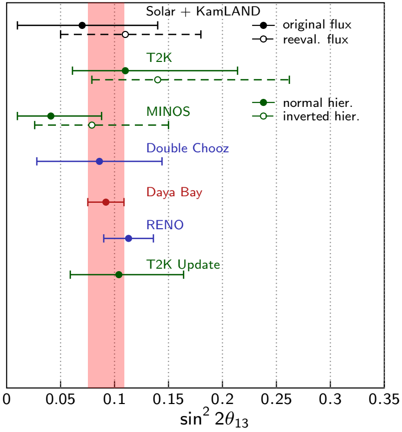

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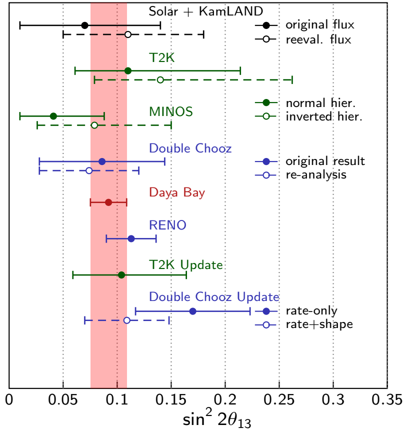

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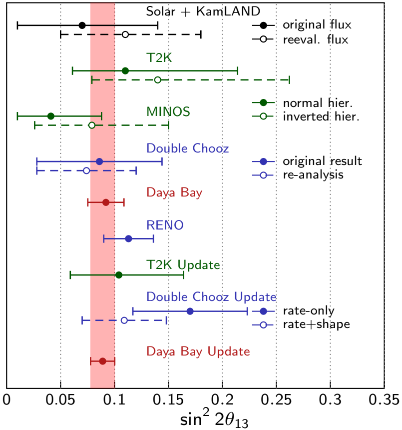


All experiments paint a consistent picture

Summary

First unambiguous observation of electron-antineutrino disappearance at $\sim 2\,\text{km}$

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

Interpretation in terms of neutrino oscillation excludes $\theta_{13} = 0$ at more than 7σ, shuts door wide open to CP violation searches in the neutrino sector

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

Expect more from Daya Bay:

- Last pair of detectors to be installed this year
- Best sensitivity to θ_{13} among all experiments in operation or under construction
- More results to come soon: reactor flux and shape analysis, Δm^2_{32} measurement

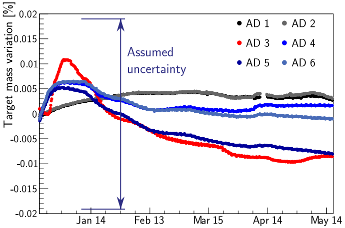
Backup

Gd-Doped Liquid Scintillator

Daya Bay liquid scintillator cocktail

- LAB + Gd (0.1%) + PPO (3 g/L) + bis-MSB (15mg/L)
- 185-ton Gd-LS production + 196-ton LS production
- 1-year 1-ton prototype monitoring on Gd-LS stability

Target mass measurement



- Load cells measure 20 ton target mass to 3kg (0.015%)
- Cross-checked by coriolis mass flow meters
- Target mass = total mass - overflow mass

Identicalness of Liquids

Control possible sources of non-identicalness

1. Batch-to-batch production variations	⟹	Storage tanks mix and hold 8 batches
2. Tank-to-tank variations	⟹	Fill each AD evenly from all 5 storage tanks
3. Storage tank vertical stratification	⟹	Recirculate storage tanks
4. Time-dependent optical properties	⟹	No evidence for this, but fill detectors in pairs anyway

Ensure identical properties between all detectors

1. H/C ratio
2. H/Gd ratio
3. Optical properties

View of the Scintillator Hall

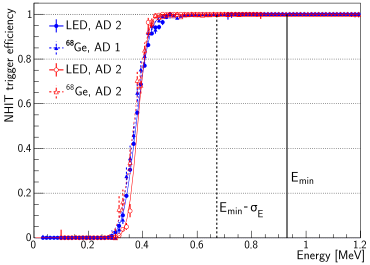
Trigger Performance

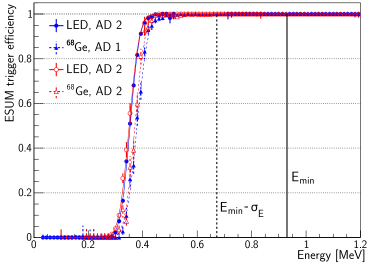
Trigger thresholds

- Antineutrino detecors:
  1. PMT multiplicity > 45 (digital trigger)
  2. Visible energy > 0.4 MeV (analog trigger)
- Inner waterpool veto: > 6 PMT
- Outer waterpool veto: > 7 PMT

Trigger efficiency

- Measurement from LED light and ^{68}Ge source
- No measureable inefficiency > 0.7 MeV
- Minimum expected energy for prompt neutrino signal $\sim$0.95 MeV





Calibration: PMT Gain

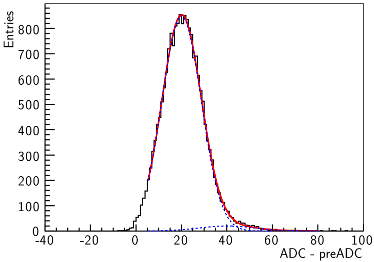


Figure: ADC charge from single photons

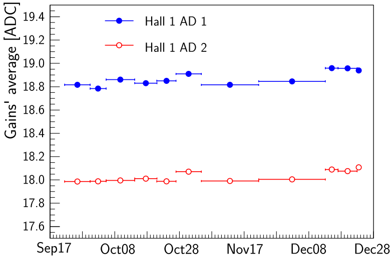
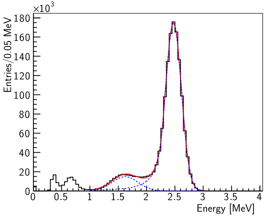


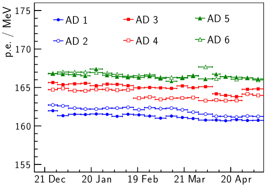
Figure: Variation of PMT gain with time

Weekly LED deployments measure charge due to single photons

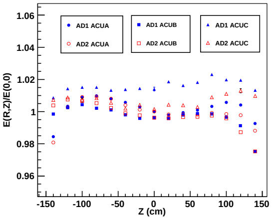
Calibration: Energy

Energy vs time

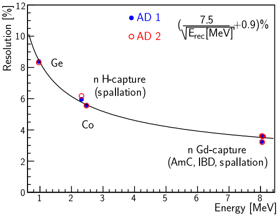




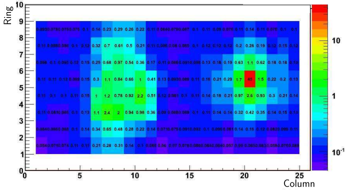
Energy vs position

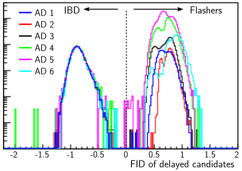


Energy resolution



Spontaneous PMT Light Emission (Flashing)





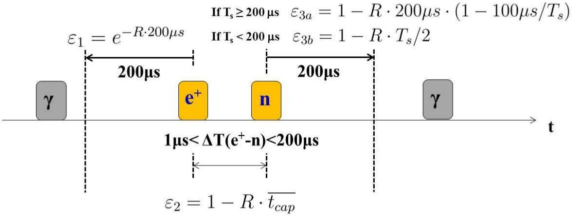
Two discriminators based on common features of AD flashers

- Flashing PMT has the largest charge: $d_{\text{max}} = \dfrac{Q_{\text{max}}}{Q_{\text{sum}}}$
- "Shines" light to opposite side of detector: $d_{\text{quad}} = \dfrac{Q_{\text{quad1}}}{Q_{\text{quad2}} + Q_{\text{quad4}}}$

Efficient rejection criterion

$$FID = \log\left(\left(\frac{d_{\text{max}}}{0.45}\right)^2 + \left(\frac{d_{\text{quad}}}{1}\right)^2\right) < 0$$

Multiplicity



Ensure exactly one prompt-delayed coincidence

- Uncorrelated backgrounds and IBD events results in ambiguous prompt-delayed signals
- Reject all IBD candidates with > 2 triggers above 7 MeV in in -200 μs to 200 μs window
- Introduces $\sim 2.5\%$ inefficiency, with negligible uncertainty

Delayed Energy Cut

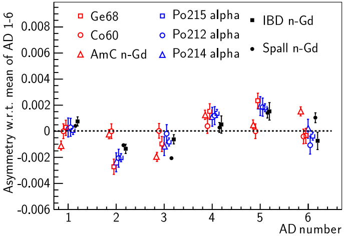
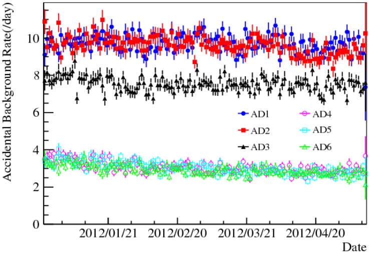


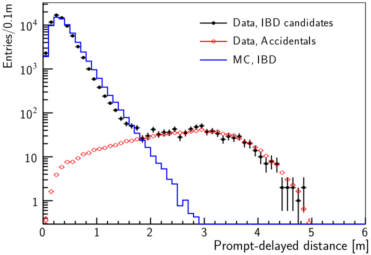
Figure: Intrinsic energy variation: all sources in all detectors are within a band of $\sim 0.5\%$

- Largest uncertainty between detectors: Some gammas escape scintillating volume, visible as tail of Gadolinium capture peak
- Use variations in energy peaks to constrain relative efficiency

Efficiency variations estimated at 0.12%

Background: Accidental





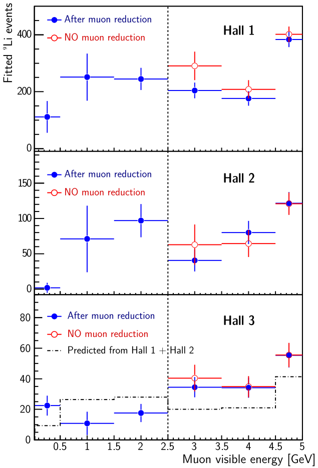
Two single signals can accidentally mimic an antineutrino (IBD) signal

- Rate and spectrum can be accurately calculated from singles data:

$$N_{acc} = \sum_i N^i_{n\text{-like singles}} \cdot (1 - e^{-R^i_{e^+\text{-like triggers}} \cdot 199\,\mu s}) \pm \frac{N_{acc}}{\sqrt{\sum_i N^i_{n\text{-like singles}}}}$$

- Complementary approaches estimate consistent rates:
  1. Prompt-delayed distance distribution
  2. Off-window coincidence

Background: $\beta - n$ Decay



Generated by cosmic rays

- Long-lived
  - ^{9}Li: $\tau = 178\,\mathrm{ms},\ Q = 13.6\,\mathrm{MeV}$
  - ^{8}He: $\tau = 119\,\mathrm{ms},\ Q = 10.6\,\mathrm{MeV}$
- Mimic antineutrino signal
  1. Prompt: β-decay
  2. Delayed: neutron capture

.

Measure rate and subtract statistically

- Rate evaluated from the distribution of the time since last muon based on the known decay times
- Compare results with and without requirement of detected co-production of neutrons to estimate uncertainty

Background: Fast Neutrons

Fast neutrons produced by cosmic muons external to the AD

May enter the AD
and mimic IBD signal:

1. Prompt: Recoil proton(s) produced by slowing neutron
2. Delayed: Capture of the neutron

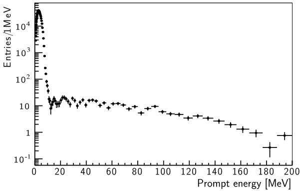


Figure: IBD spectrum with relaxed upper limit on prompt energy

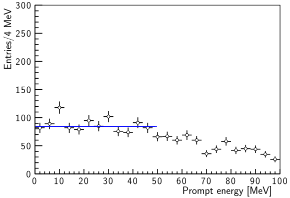


Figure: Spectrum of fast neutron tagged by water pool muons

Estimate contribution to selected IBD candidates

- Extrapolate from prompt energy distribution in 15-50 MeV range
- Check extrapolation by tagging fast neutrons using the water pool and RPCs

Background: ^{241}Am^{13}C neutron source

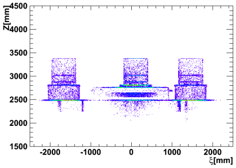


Figure: Position of neutron capture from simulation

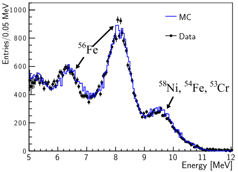


Figure: MC/data comparison of single delayed-type candidates from the source

Correlated background

- Neutrons emitted from the ~ 0.5 Hz ^{241}Am^{13}C neutron source parked on top of AD
- Produce fake prompt-delayed coincidence:
  1. γ via inelast. scattering with ^{56}Fe
  2. Neutron capture on Fe-Cr-Mn-Ni

Estimation based on MC

- Normalization in MC constrained by the measured rate of single delayed-type candidates from this source
- Simulation predicts a 0.2/day/detector correlated background

Reactor Flux Expectation

Antineutrino flux estimated for each core

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

- Provided by reactor operators:
  - Thermal power data: W_{th}
  - Relative isotope fission fractions: f_i
- Energy released per fission: e_i
  - V. Kopekin et al., Ph. Atom. Nucl. 67, 1892 (2004)
- Antineutrino spectra per fission: $S_i(E_\nu)$
  - K. Schreckenb. 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)

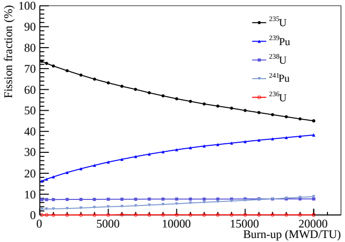


Figure: Fission fractions of reactor isotopes as a function of burn-up from a Monte Carlo simulation of reactor core D1

Impact of flux model on far vs. near oscillation measurement negligible

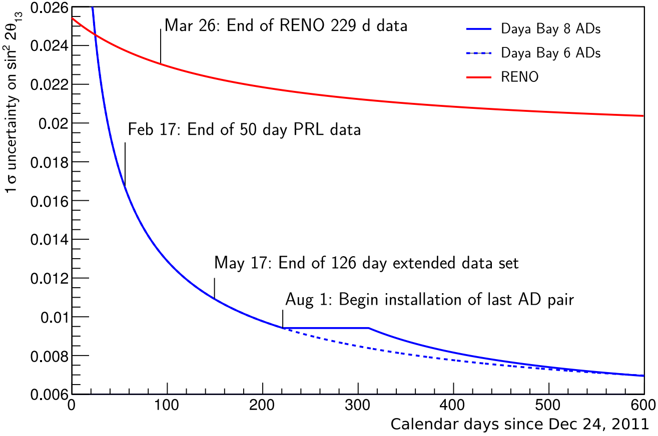
Full Definition of χ^2

The value of $\sin^2 2\theta_{13}$ was determined with a χ^2 constructed with pull terms accounting for the correlation of the systematic errors,

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

where M_d are the measured IBD events of the d-th AD with backgrounds subtracted, B_d is the correspoding backgrounds, T_d is the prediction from neutrino flux, MC, and neutrino oscillations, ω_r^d is the fraction of IBD contribution of the r-th reactor to the d-th AD determined by baselines and reactor fluxes.

Projected Sensitivity



Assuming no improvement on systematic uncertainties