Observation of Electron Anti-neutrino Disappearance at Daya Bay

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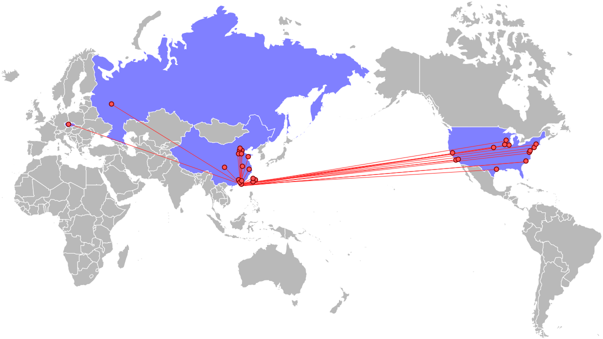
on behalf of the Daya Bay Experiment Collaboration

Charles University in Prague

Rencontres de Blois, May 28, 2013

Daya Bay: An International Effort, 229 Collaborators from 38 Institutions



North America (15)

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

Europe (2)

Charles Univ. in Prague, JINR Dubna

Asia (21)

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, Xian Jiao Tong Univ., Zhongshan Univ., Hong Kong Univ., Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

Introduction

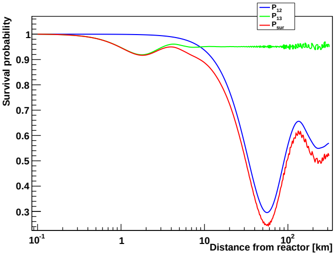
$$|\nu_\alpha\rangle = U_{PMNS}\,|\nu_i\rangle$$

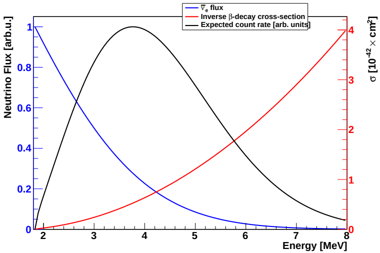
$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}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

$\theta_{23} \approx 45^\circ$	$\theta_{13} = (8.7 \pm 0.5)^\circ$	$\theta_{12} = (34 \pm 1)^\circ$
Atmospheric ν	Short-baseline Reactor ν	Solar ν
Accelerator ν	Accelerator ν	Long-baseline Reactor ν

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

Reactor $\overline{\nu}_e$

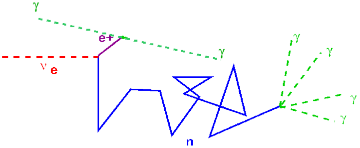




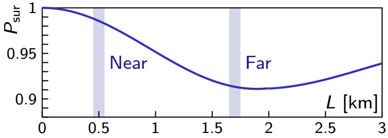
Measurement Strategy

- Search for reactor $\overline{\nu}_e$ disapearance

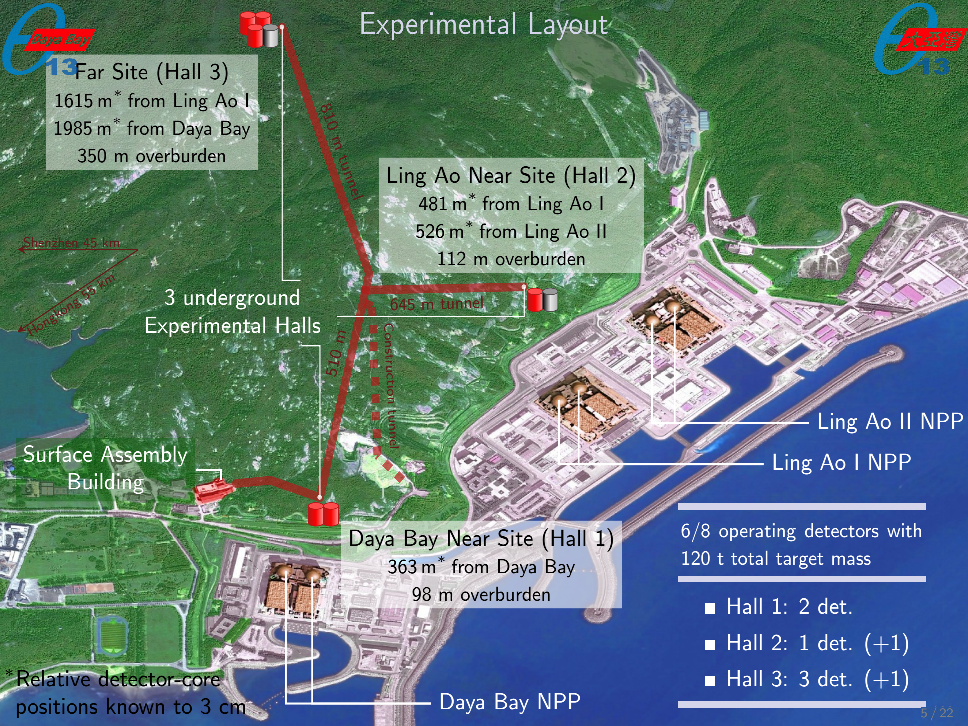
- Inverse β-decay: $\overline{\nu}_e + p \to e^+ + n$
- Trigger on 2-fold coincidence:
  - Prompt signal from e^+
  - Delayed signal from n capture
- Detector with Gd doped Liquid Scintillator (LS)
  - Rich in target protons
  - Neutron capture on Gadolinium
    - $\tau \sim 30\ \mu s$
    - 8 MeV
  - strong suppression of background



- Baseline optimisation + relative measurement

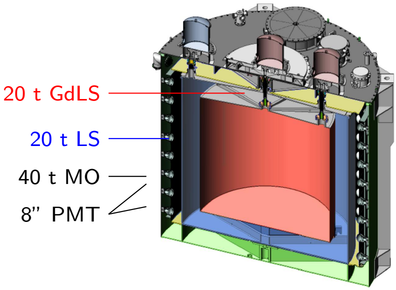


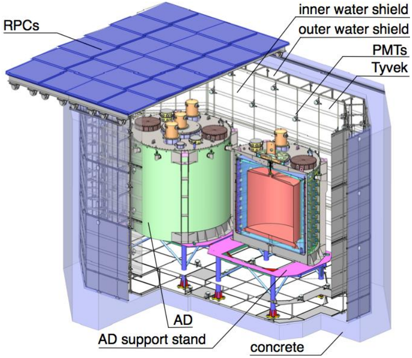
Experimental Layout



Detector Design

- Anti-neutrino Detector (AD)
  - 3 zones
  - Gd doped liquid scintillator (GdLS)
  - Liquid scintillator (LS)
  - Mineral oil (MO)
  - Instrumented with 8" PMTs
  - 5 m × 5 m
- Water Pool (WP)
  - Water Cherenkov counter
  - Provides at least 2.5 m shielding
  - inner, outer
  - instrumented with 8" PMTs
- Resistive Plate Chambers (RPC)
  - planar top cover
  - modular
  - 4 single gap layers per module

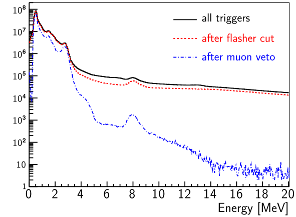


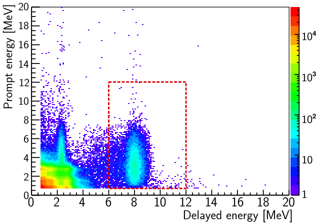


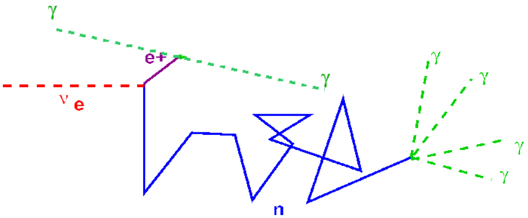
$\overline{\nu}_e$ Signal Selection

Cuts on Double Coincidence

- Remove flashing PMT events
- Energy
  - Prompt - 0.7 - 12 MeV - e^+
  - Delayed - 6 - 12 MeV - nGd capture
- Time separation of prompt and delayed signal
  - 1 $\mu s < \Delta T <$ 200 μs (neutron capture time $\sim 30 \mu s$)
- Muon Veto
  - Pool Muon ($>$ 12 PMTs) - 0.6 ms
  - AD Muon ($>$20 MeV) - 1 ms
  - AD Shower Muon ($>$2.5 GeV) - 1 s
- Multiplicity
  - No other signal $>$ 0.7 MeV in $\pm$200 μs of $\overline{\nu}_e$ candidate





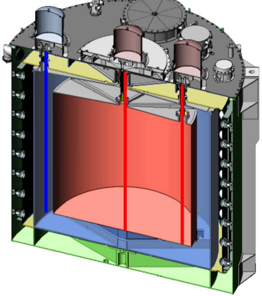


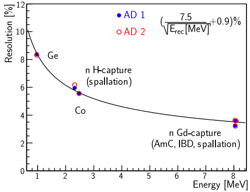
Calibration

Automated calibration system

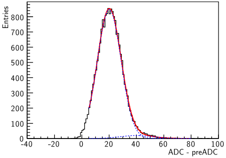
- 3 units
  - Center — energy scale, variation with time, linearity
  - Edge — Spatial response, efficiency
- Sources in each
  - ^{68}Ge — 2 × 511 MeV annihilation gammas
  - ^{60}Co — 1.17 + 1.33 MeV gammas
  - AmC — neutron source
  - LED diffuser ball
- PMT gains calibrated with low intensity LED runs
- Energy scale
  - ^{60}Co at center of AD, 1.5 MeV
  - Spallation neutrons captured on Gd, 8 MeV
- PMT gain and energy scale calibrations performed weekly

1.8 m 0 m1.35m

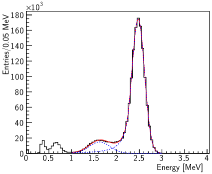




PMT Gain — 1 p.e. response



^{60}Co energy calibration



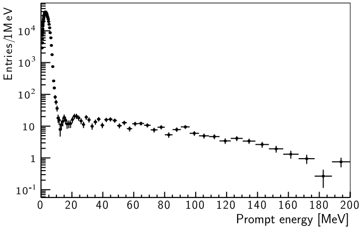
Backgrounds

- Accidentals
  - Suppressed by double coincidence time and energy cuts
- Correlated
  - ^{9}Li/^{8}He — β-decay with n emission
  - Fast n — produced by muons, can deposit prompt energy via recoils on protons and then capture

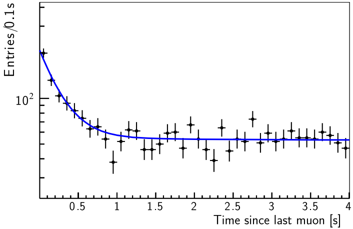
Major Contributors

	B/S (near halls)	B/S (far hall)
Accidentals	$\sim$ 1.4%	$\sim$ 4.5%
fast neutrons	$\sim$ 0.1%	$\sim$ 0.06%
^{9}Li/^{8}He	$\sim$ 0.4%	$\sim$ 0.2%
Am-C	$\sim$ 0.03%	$\sim$ 0.3%
α-n	$\sim$ 0.01%	$\sim$ 0.04%
Sum	$\sim$ 2.0%	$\sim$ 5.2%

Fast Neutron Estimation

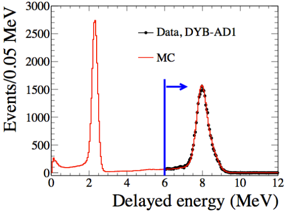


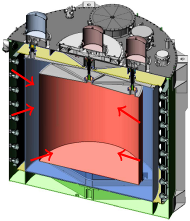
^{9}Li/^{8}He



Systematic Uncertainties

- Correlated among detectors and reactors cancels out due to near/far layout
- Uncertainty among reactor cores heavily cancels out due to near/far layout





Major Uncertainty Contributors

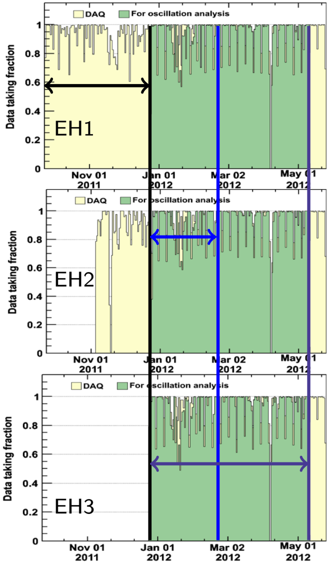
Detector Uncorrelated	
Target protons	0.03%
Delayed En. cut	0.12%
Spill-in	0.02%
Combined	0.2%

Reactor Uncorrelated	
Power	0.5%
Fission fraction	0.6%
Spent fuel	0.3%
Combined	0.8%

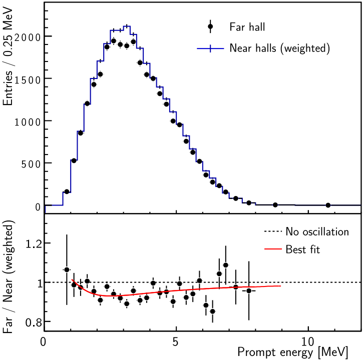
Backgrounds	EH1	EH2	EH3
^{9}Li/^{8}He	0.2%	0.2%	0.2%
Am-C	0.03%	0.03%	0.26%
Combined	0.2%	0.2%	0.3%

Collected Data

- Two Detector Comparison:
  - Sep.23 – Dec.23, 2011
  - Side–by–side comparison of 2 detectors in Hall 1
  - Demonstrated detector systematics better than requirements
  - *NIM A 685 (2012), pp.78–97*
- First Oscillation Result:
  - Dec.24, 2011 – Feb.17, 2012
  - All 3 halls (6 ADs) operating
  - First observation of $\overline{\nu}_e$ disappearance
  - *Phys.Rev.Lett. 108, 171803 (2012)*
- Updated oscillation analysis:
  - Dec.24, 2011 – May 11, 2012
  - More than 2.5x more data analyzed
  - *Chinese Phys. C 37, (2013) 011001*



Near vs. Far Comparison



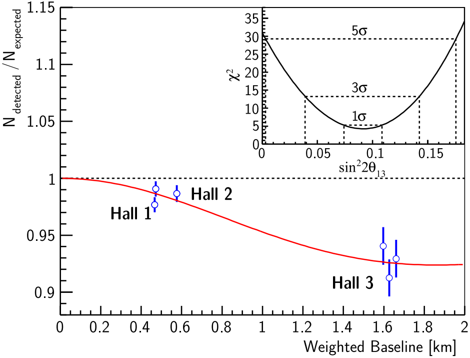
- $R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4+M_5+M_6}{\sum_{i=4}^{6} \alpha_i(M_1+M_2)+\beta_i M_3}$
- M_i are measured rates at i-th detector
- α_i and β_i weights to predict far from near detector rates — distances and reactor fluxes as input

$$R = 0.944 \pm 0.007 \pm 0.003$$

- Near/Far spectral distortion consistent with oscillation*

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

Rate-only θ_{13} analysis

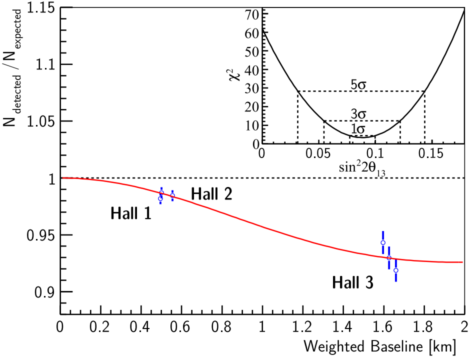


- Estimates θ_{13} using measured rates in each detector
- Uses standard χ^2 approach
- Far vs. near relative measurement, absolute rate is not constrained
- Consistent results obtained by independent analyses, different reactor flux models

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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- 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

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 $7.7\,\sigma$
- Details in *Chinese Phys. C 37, (2013) 011001*

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 127 day analysis, June 2012

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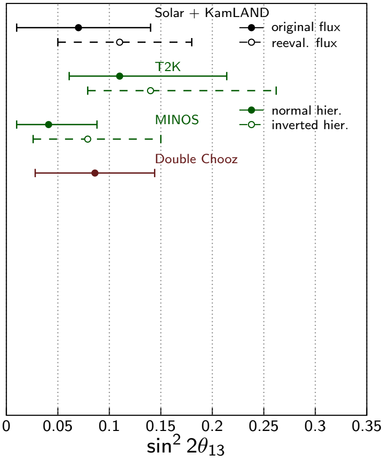

All experiments paint a consistent picture

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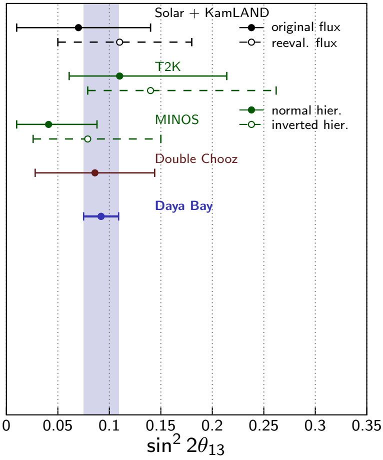

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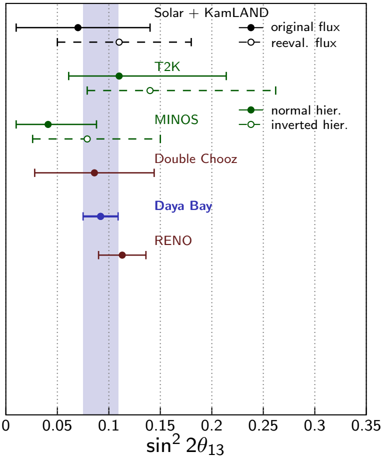

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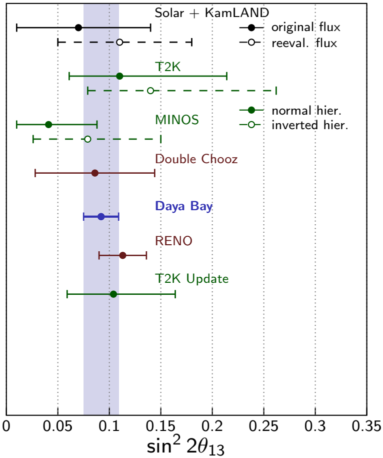

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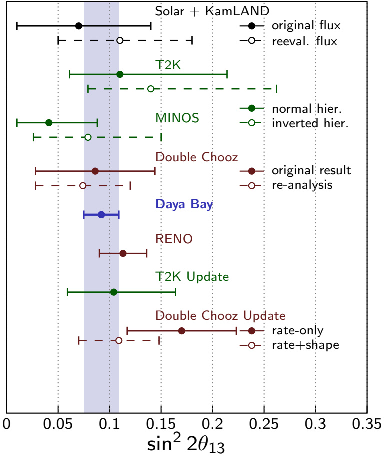

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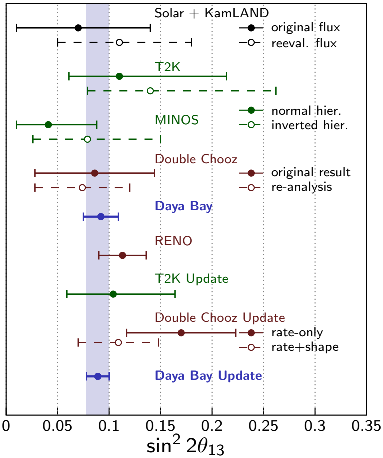

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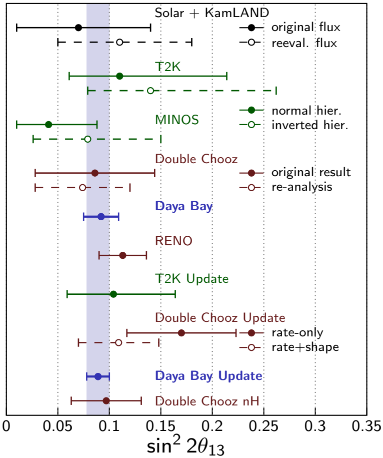
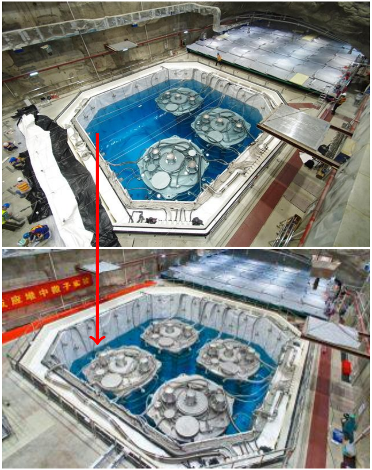


All experiments paint a consistent picture

Status

Full Setup

- Last 2 ADs installed last summer → 8 ADs taking data since October 19, 2012

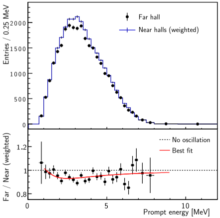


3-D Calibration

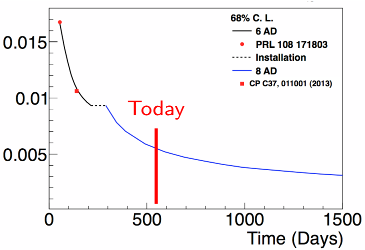
- 3-D Calibration campaign last summer
  - Analyzing data
  - Learning more about the detectors

Future

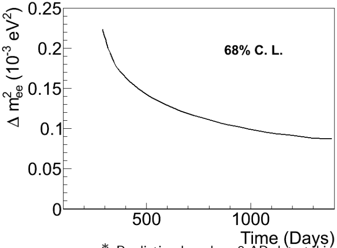
- Maintain most precise measurement of θ_{13}
  - We are still statistics dominated
  - Stay tuned for updates to come soon
- Energy spectrum shape analysis $\rightarrow \Delta m^2_{ee}$
  - Precision comparable to measurements using accelerator neutrinos
  - $\Delta m^2_A = [2.62^{-0.28}_{+0.31}(stat) \pm 0.09(syst)] \times 10^{-3}\ \mathrm{eV}^2$ [MINOS]
- Absolute flux and spectrum of reactor $\overline{\nu}_e$
  - Tremendous rate of $\overline{\nu}_e$ at near sites
  - Achievable $< 1\%$ statistical uncertainty over large range of energies
  - Study of reactor nuclear physics and non-standard interactions



$\sin^2 2\theta_{13}$ projected precision



Δm^2_{ee} expected precission



* Prediction based on 8 AD data taking

Summary

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
Door wide open to CP violation searches in the lepton sector

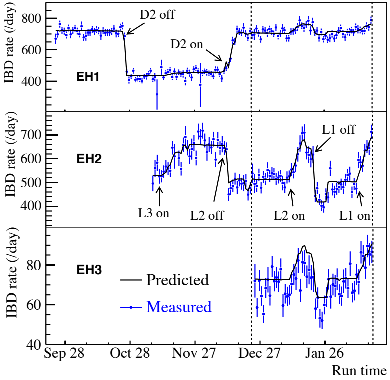
$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$$

Expect more from Daya Bay:

- Best sensitivity to θ_{13} among all experiments in operation or under construction
- More results to come soon: Δm^2 measurement, reactor flux and shape analysis

FIN

Reactor flux



Systematic Uncertainties — Complete Breakup

Detector Uncorrelated	
Target protons	0.03%
Flasher cut	0.01%
Delayed En. cut	0.12%
Prompt En. cut	0.01%
Multipl. cut	$< 0.01\%$
Capture t. cut	0.01%
Gd cap. ratio	$< 0.01\%$
Spill-in	0.02%
Livetime	$< 0.01\%$
Combined	0.03%

Reactor Uncorrelated	
Power	0.5%
Fission fraction	0.5%
Spent fuel	0.5%
Combined	0.8%

Backgrounds

	EH1	EH2	EH3
Accidentals	0.02%	0.01%	0.05%
Fast n	0.04%	0.05%	0.03%
^{9}Li/^{8}He	0.2%	0.2%	0.2%
Am-C	0.03%	0.03%	0.26%
C(α,n)O	0.006%	0.005%	0.026%
Combined	0.2%	0.2%	0.3%

Data analysis approach

Blind analysis

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right) \left(\frac{L_n}{L_f}\right)^2 \left(\frac{\epsilon_f}{\epsilon_n}\right) \left(\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right)$$

Nominal values for:

1. Reactor flux
2. Target mass
3. Reactor-detector baselines

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

Side-by-Side Detector Comparison

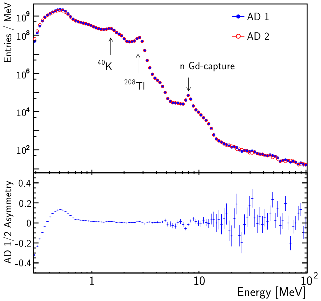


Figure: Side-by-side comparison of full spectrum after flasher and muon removal

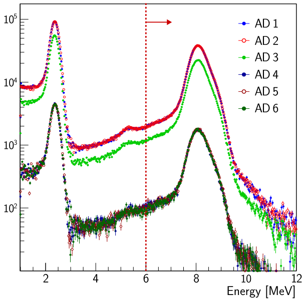


Figure: Energy spectrum of spallation neutrons for all six detectors

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