Recent results from Daya Bay

Viktor Pěč
Charles University in Prague
on behalf of
the Daya Bay Experiment Collaboration

La Thuile, Feb 24, 2014

Outline

Neutrino oscillation and θ_{13}

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

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

$\theta_{23} \approx 45^\circ$
Atmospheric ν
Accelerator ν

$\theta_{13} \approx 9^\circ$
Short-baseline Reactor ν
Accelerator ν

$\theta_{12} \approx 34^\circ$
Solar ν
Long-baseline Reactor ν

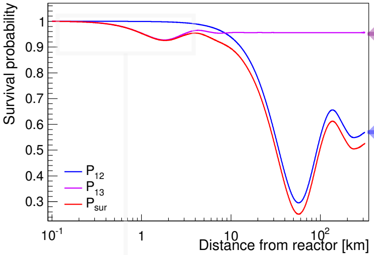
$$\delta \approx ?$$

Measurement Strategy – Reactor $\bar{\nu}_e$

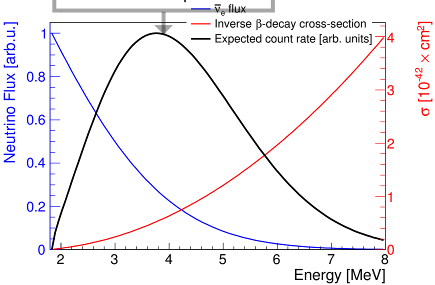
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

Reactor $\bar{\nu}_e$

Integrated over energy spectrum

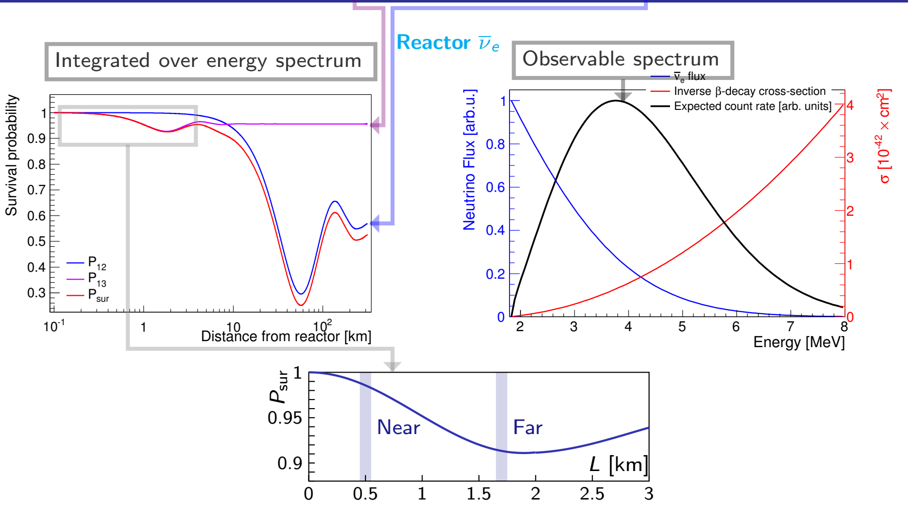


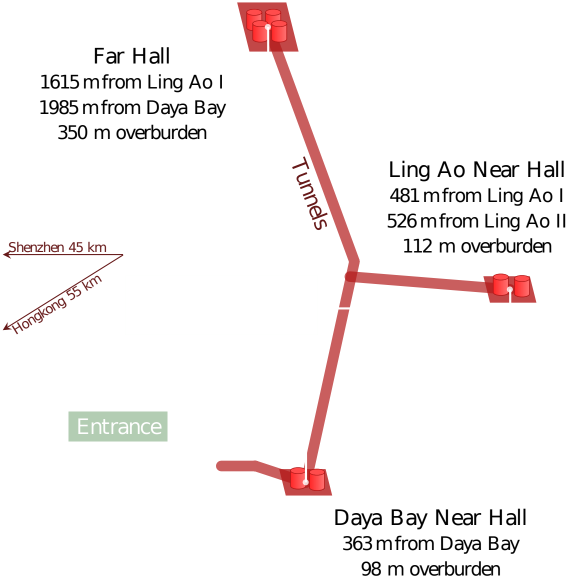
Observable spectrum



Measurement Strategy – Reactor $\bar{\nu}_e$

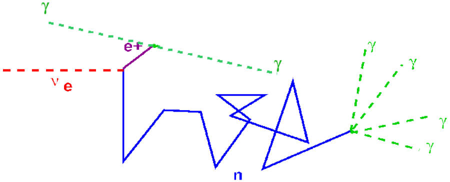
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$




Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden
Tunnels
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
Shenzhen 45 km
Hongkong 55 km
Entrance
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden

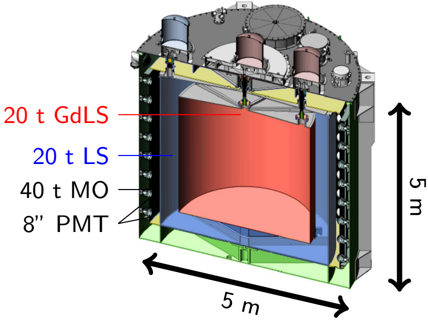
Detection Method

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



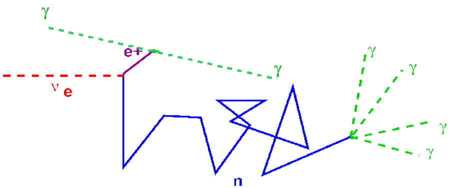
- Prompt
  - continuous energy spectrum
  - e^+ kinetic energy $+ 2 \times 511$ keV γ
  - $E_P = E_{\bar{\nu}_e} - Q + 2m_e$
- Delayed
  - neutron capture on Gd
  - 30 μs
  - γ cascade, total energy ~ 8 MeV

Anti-neutrino Detector

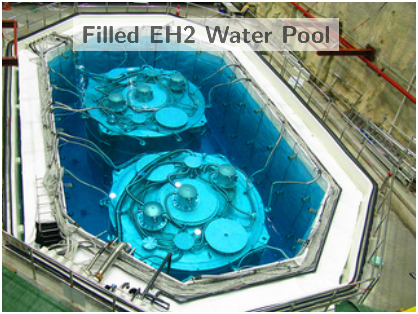


Detection Method

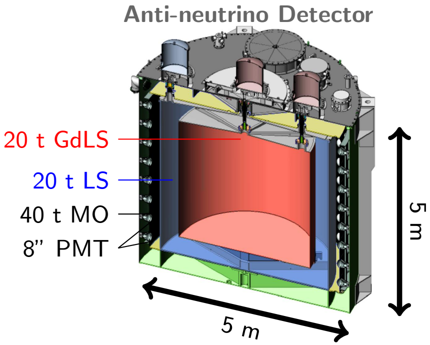
$$\overline{\nu}_e + p \rightarrow e^+ + n$$



- Prompt
  - continuous energy spectrum
  - e^+ kinetic energy $+ 2 \times 511$ keV γ
  - $E_P = E_{\bar{\nu}_e} - Q + 2m_e$
- Delayed
  - neutron capture on Gd
  - 30 μs
  - γ cascade, total energy ~ 8 MeV

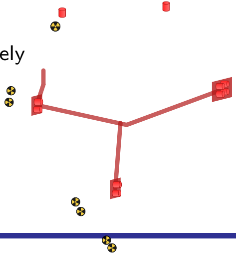


- Water Čerenkov detector
- Inner/Outer layer

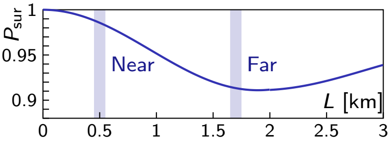


θ_{13} extraction

- Observation of deficit of $\bar{\nu}_e$ interactions in far detector
- Compare rates in far detector to prediction based on near detector measurement
  - Relative measurement cancels large uncertainties in reactor flux prediction as well as detector related
- Ideal case:
  - 1 source, 2 identical detectors – near and far
  - Reactor related uncertainties cancel completely
  - Uncertainties correlated between detectors cancel completely
- Reality:
  - Multiple sources, multiple "identical" detectors
  - Standard χ^2 method employed
  - All reactor related uncertainties are vastly suppressed
  - Uncertainties of individual detectors dominate

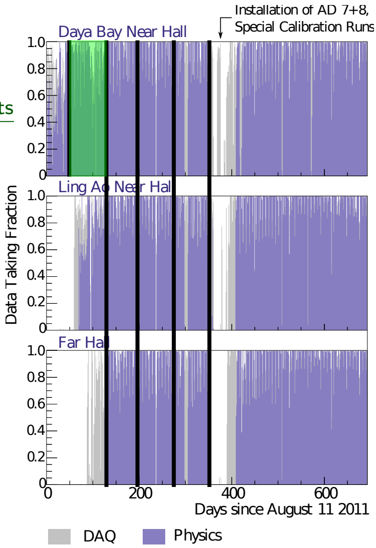


$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$



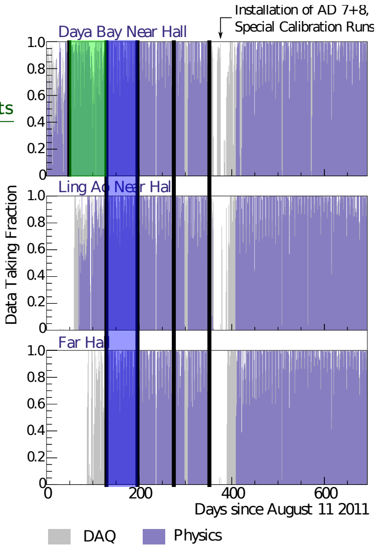
History

- Two Detector Comparison:
  - Sep23 – Dec23, 2011: 90 days
  - Side–by–side comparison of 2 detectors in Hall 1
  - Demonstrated detectors **operationally identical**, surpassing deisng requirements
  - NIM A **685**, (2012), pp.78–97
- First Oscillation Result:
  - Dec24, 2011 – Feb17, 2012: 55 days
  - All 3 halls (6 ADs) operating
  - First observation of $\overline{\nu}_e$ disappearance
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.017$
  - PRL **108**, (2012), 171803
- Updated oscillation analysis:
  - Dec24, 2011 – May11, 2012: 139 days
  - More than 2.5x more data analyzed
  - $\sin^2 2\theta_{13} = 0.089 \pm 0.011$
  - CPC **37**, (2013), 011001
- Latest Rate+Shape analysis:
  - Dec24, 2011 – Jul28, 2012: 217 days
  - Complete 6 AD data period
  - Δm^2_{ee} measurement
  - PRL **112**, (2014), 061801



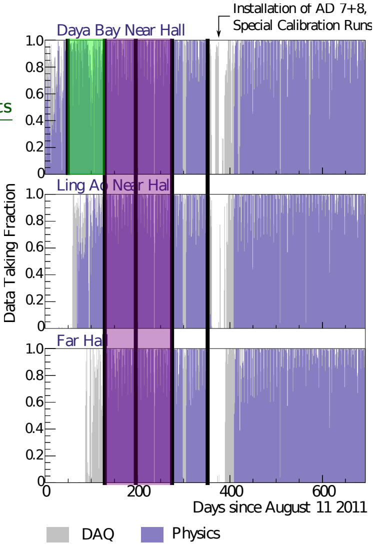
History

- Two Detector Comparison:
  - Sep23 – Dec23, 2011: 90 days
  - Side–by–side comparison of 2 detectors in Hall 1
  - Demonstrated detectors **operationally identical**, surpassing deisng requirements
  - NIM A **685**, (2012), pp.78–97
- First Oscillation Result:
  - Dec24, 2011 – Feb17, 2012: 55 days
  - All 3 halls (6 ADs) operating
  - First observation of $\overline{\nu}_e$ disappearance
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.017$
  - PRL **108**, (2012), 171803
- Updated oscillation analysis:
  - Dec24, 2011 – May11, 2012: 139 days
  - More than 2.5x more data analyzed
  - $\sin^2 2\theta_{13} = 0.089 \pm 0.011$
  - CPC **37**, (2013), 011001
- Latest Rate+Shape analysis:
  - Dec24, 2011 – Jul28, 2012: 217 days
  - Complete 6 AD data period
  - Δm^2_{ee} measurement
  - PRL **112**, (2014), 061801



History

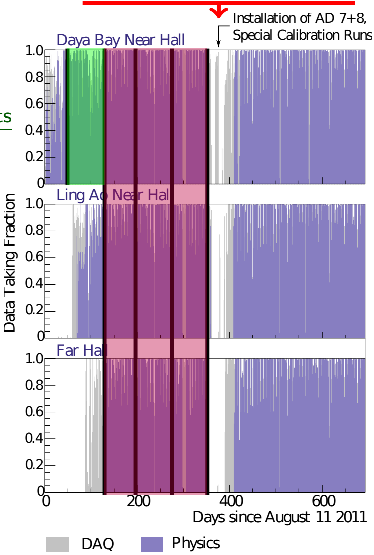
- Two Detector Comparison:
  - Sep23 – Dec23, 2011: 90 days
  - Side–by–side comparison of 2 detectors in Hall 1
  - Demonstrated detectors **operationally identical**, surpassing deisng requirements
  - NIM A **685**, (2012), pp.78–97
- First Oscillation Result:
  - Dec24, 2011 – Feb17, 2012: 55 days
  - All 3 halls (6 ADs) operating
  - First observation of $\overline{\nu}_e$ disappearance
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.017$
  - PRL **108**, (2012), 171803
- Updated oscillation analysis:
  - Dec24, 2011 – May11, 2012: 139 days
  - More than 2.5x more data analyzed
  - $\sin^2 2\theta_{13} = 0.089 \pm 0.011$
  - CPC **37**, (2013), 011001
- Latest Rate+Shape analysis:
  - Dec24, 2011 – Jul28, 2012: 217 days
  - Complete 6 AD data period
  - Δm^2_{ee} measurement
  - PRL **112**, (2014), 061801



History

- Two Detector Comparison:
  - Sep23 – Dec23, 2011: 90 days
  - Side–by–side comparison of 2 detectors in Hall 1
  - Demonstrated detectors **operationally identical**, surpassing deisng requirements
  - NIM A **685**, (2012), pp.78–97
- First Oscillation Result:
  - Dec24, 2011 – Feb17, 2012: 55 days
  - All 3 halls (6 ADs) operating
  - First observation of $\overline{\nu}_e$ disappearance
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.017$
  - PRL **108**, (2012), 171803
- Updated oscillation analysis:
  - Dec24, 2011 – May11, 2012: 139 days
  - More than 2.5x more data analyzed
  - $\sin^2 2\theta_{13} = 0.089 \pm 0.011$
  - CPC **37**, (2013), 011001
- Latest Rate+Shape analysis:
  - Dec24, 2011 – Jul28, 2012: 217 days
  - Complete 6 AD data period
  - Δm^2_{ee} measurement
  - PRL **112**, (2014), 061801

Summer 2 AD deployment
3D calibration campaign

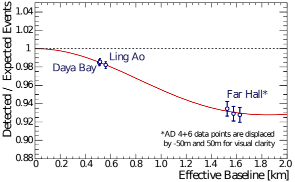


Rate → Rate+Shape

Rate

$$\frac{N_f}{N_n} = \frac{N_{p,f}}{N_{p,n}} \frac{L_n^2}{L_f^2} \frac{\epsilon_f}{\epsilon_n} \frac{\int_{E_{min}}^{E_{max}} dE \;\; P_{sur}(E, L_f)\sigma(E)\Phi(E)}{\int_{E_{min}}^{E_{max}} dE \;\; P_{sur}(E, L_n)\sigma(E)\Phi(E)}$$

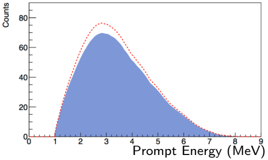
- Fewer systematic uncertainties
- Weak sensitivity to Δm_{ee}^2

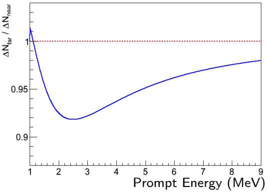


Rate + Shape

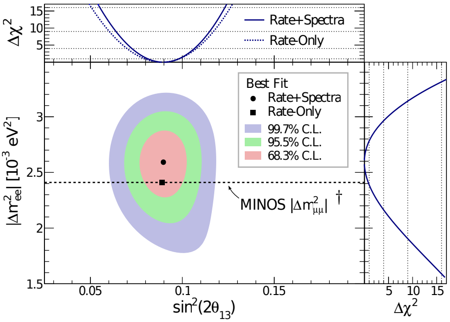
$$\frac{dN_f/dE}{dN_n/dE} = \frac{N_{p,f}}{N_{p,n}} \frac{L_n^2}{L_f^2} \frac{\epsilon_f}{\epsilon_n} \frac{P_{sur}(E, L_f)\sigma(E)\Phi(E)}{P_{sur}(E, L_n)\sigma(E)\Phi(E)}$$

- Measurement of Δm_{ee}^2 possible
- Gives nearly full oscillation cycle
- Requires good knowledge of detector energy response





Rate+Shape Oscillation Results



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

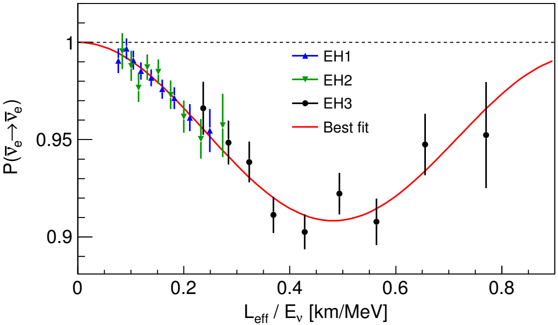
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20}\Delta 10^{-3} eV^2$$

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

† $\Delta m^2_{32} = 2.37^{+0.09}_{-0.09} \times 10^{-3}$ eV^2 (NH) / $2.41^{+0.12}_{-0.09} \times 10^{-3}$ (IH) [J.A.B.Coelho, NuFact2013]

Oscillation Curve

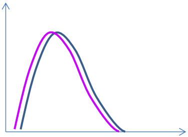
- Evidence of oscillation characteristic of reactor $\bar{\nu}_e$ deficit in far hall



- Rates in energy bins over prediction with no oscillation
- L_{eff} is effective distance to one virtual source – transformed from multi-source case

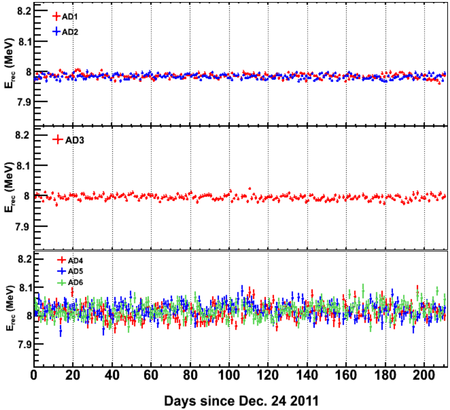
Some Essentials

- Reactor flux model
  - large systematic uncertainties supressed in relative measurement
  - follows treatment of previoius publications, not covered here
- Detector energy scale
  - ensure all detectors have the same energy response
- Background subtraction
- Energy response model



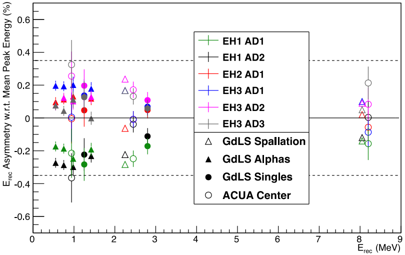
Detector Energy Scale

Energy scale stability over time



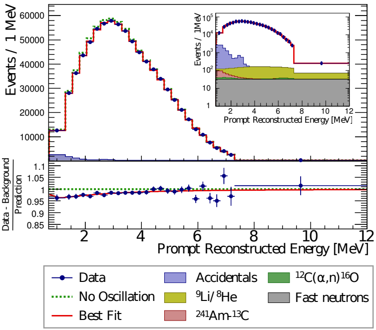
- Stability of nGd capture peak
- Stable to $\sim 0.1\%$

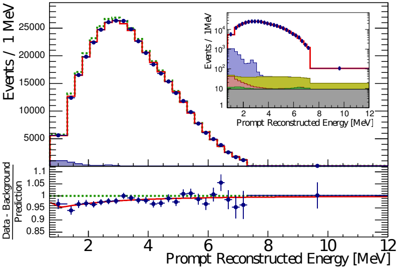
Relative detector energy scale

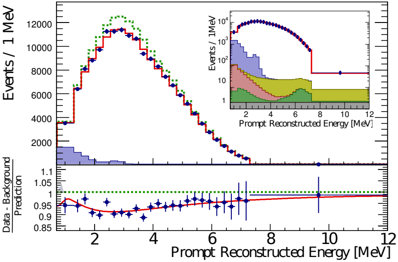


- Relative energy reconstruction
- Differences within 0.35% $\rightarrow$ relative uncertainty on energy scale

Background Subtraction

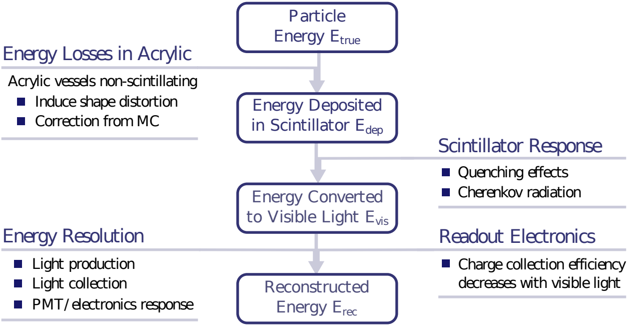






- Accidentals
  - Predicted based on uncorrelated signals $\rightarrow$ "unlimited" statistics $\approx$ negligible uncertainty
- ^{9}Li/^{8}He
  - Cosmogenic
  - Measured using time correlation with muons

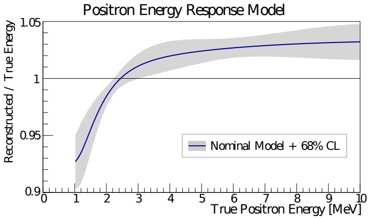
Energy Response



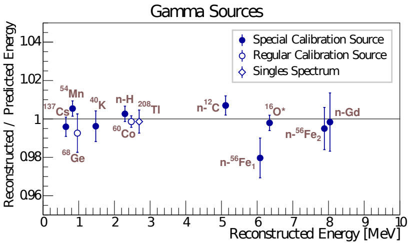
- Multiple models considered
- Nominal model is purely empirical
- Other models semi-empirical
- Differences used as estimated model related uncertainty

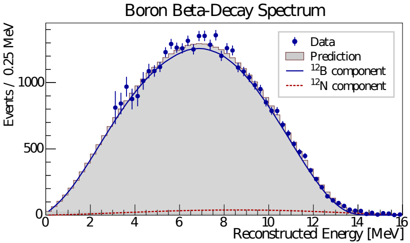
$$f = \frac{E_{rec}}{E_{true}} = \frac{E_{vis}}{Etrue} \times \frac{E_{rec}}{E_{vis}} = f_{scint}(E_{true}) \times f_{elec}(E_{vis})$$

Non-linearity model



- model constrained by in-situ measurements and separate measurements with neutron beams and Compton-scatered electrons
  - γ peaks from calibration sources
  - ^{208}Tl from natural radioactivity
  - Continuous β–γ spectrum of ^{12}B
  - Cosmogenic isotope



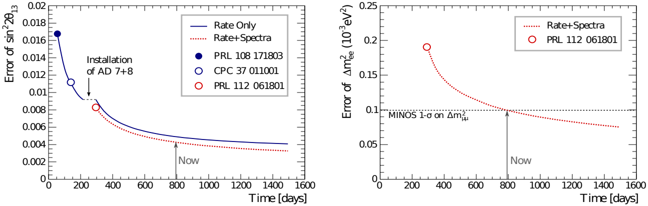


Future

- 8 detectors running in 3 halls since October 19, 2012
- As of today, 493 days of 8 AD and 217 days of 6 AD data collected, and still counting
- Aproaching limitation by systematic uncertainties

Sensitivity Projection

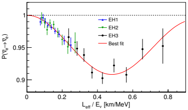
$\sin^2 2\theta_{13}$



Δm^2_{ee}

- Largely independent measurement using events with delayed neutron capture on hydrogen under internal review
- Further improvement on current understanding of detector response, energy and absolute efficiency, allows us to report absolute reactor anti-neutrino flux and sterile neutrino analysis – in preparation

Summary

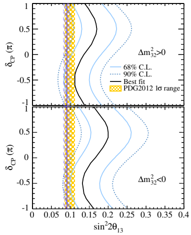


- With large statistics collected with 6 ADs, over 330k $\bar{\nu}_e$, we have:
  - evidenced oscillation characteristic of $\bar{\nu}_e$ disapprearance
  - measured θ_{13} with best precision
  - provided first measurement of Δm^2_{ee}

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}, \ \left|\Delta m^2_{ee}\right| = 2.59^{+0.19}_{-0.20} \times 10^{-3} \text{ eV}$$

- Precise measurement of θ_{13} will aid searches for CP violation by accelerator experiments – T2K, NOνA
- We have been improving statistics with 8 ADs deployed
  - Will bring more precise θ_{13} and Δm^2_{ee}
- Unique statistics allows more analyses
  - nH analysis and absolute reactor flux in preparation

T2K† with DB latest

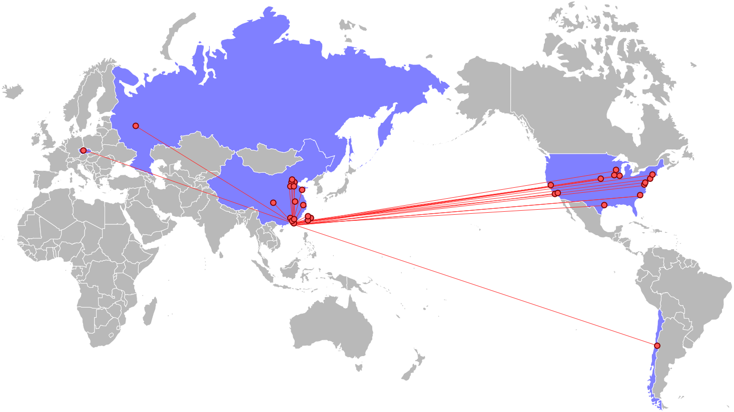


---

† PRL 112, 061802 (2014)

The Daya Bay Experiment Collaboration

- Collaborative Effort of 41 institutions, ∼230 members



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)

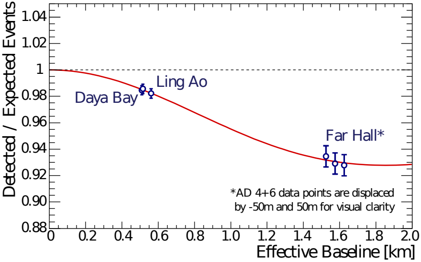
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

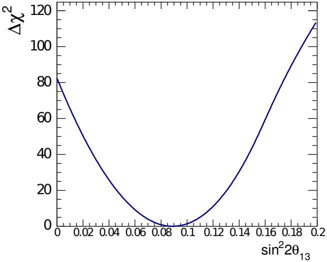
South America (1)

Catholic University of Chile

Backup

Rate-Only Oscillation Results

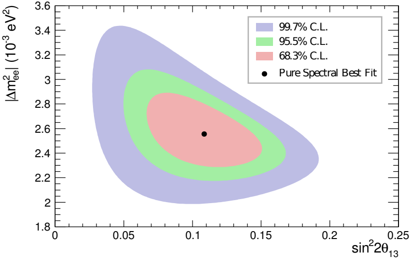




$$\sin^2 2\theta_{13} = 0.089 \pm 0.009$$

- Uncertainty reduced by statistics of complete 6 AD data period
- Standard χ^2 approach: $\chi^2/N_{DoF} = 0.48/4$
- $|\Delta m^2_{ee}|$ constrained by MINOS: $|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \cdot 10^{-3}\,\mathrm{eV}^2$ [PRL 110, 251801 (2013)]
- Far vs. near relative measurement: absolute rate not constrained
- Consistent results from independent analyses, different reactor flux models

Pure Spectral Analysis



$\sin^2 2\theta_{13} = 0.108 \pm 0.028$

$|\Delta m^2_{ee}| = 2.55^{+0.21}_{-0.18} \cdot 10^{-3} eV^2$

$\chi^2 / N_{DoF} = 161.2/148$

$\theta_{13} = 0$ can be excluded at $> 3\sigma$ from spectral information alone

For each AD, total event prediction fixed to observed data:

1. θ_{13} free-floating: $\chi^2 / N_{DoF} = 161.2/148$
2. $\theta_{13} = 0$: $\chi^2 / N_{DoF} = 178.5/146$

$\Rightarrow$ $\Delta\chi^2 / N_{DoF} = 17.3/2$, corresponding to $p = 1.75 \cdot 10^{-4}$

A Comment on the Mass Splitting

Short-baseline reactor experiments insensitive to mass hierarchy

Cannot discriminate 2 frequencies contributing to oscillation: Δm^2_{31}, Δm^2_{32}

One effective oscillation frequency Δm^2_{ee} is measured:

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

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

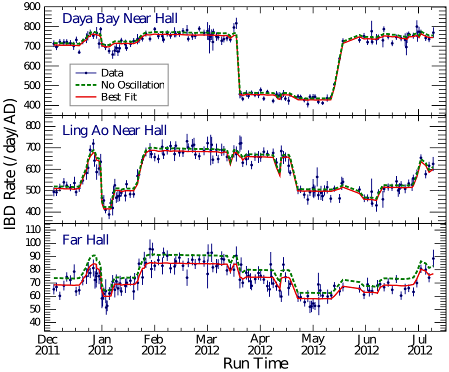
Result easily related to actual mass splitting

Normal hierarchy (+), inverted hierarchy (−):

$$|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 5.21 \times 10^{-3} \mathrm{eV}^2$$

Hierarchy discrimination requires ~ 2% precision on both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$

Reactor flux



- Strong correlation of detected rates with reactor flux expectations
- Fitted normalization within a few percent of expectations

Summary of Uncertainties

	Detector		
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	$<0.01\%$
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	$<0.1\%$
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	$<0.01\%$
Combined	78.8%	1.9%	0.2%

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

Signal and Background Summary

	Near Halls			Far Hall		
	AD 1	AD 2	AD 3	AD 4	AD 5	AD 6
IBD candidates	101290	102519	92912	13964	13894	13731
DAQ live time (days)	191.001		189.645		189.779	
Efficiency $\mu \cdot m$	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (per day)*	9.54± 0.03	9.36± 0.03	7.44± 0.02	2.96± 0.01	2.92± 0.01	2.87± 0.01
Fast-neutron (per day)*	0.92± 0.46		0.62± 0.31		0.04± 0.02	
^{9}Li/ ^{8}He (per day)*	2.40± 0.86		1.2± 0.63		0.22± 0.06	
Am-C corr. (per day)*			0.26± 0.12			
^{13}C^{16}O backgr. (per 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
IBD rate (per day)*	653.30± 2.31	664.15± 2.33	581.97± 2.07	73.31± 0.66	73.03± 0.66	72.20± 0.66

*Background and IBD rates were corrected for the efficiency of the muon veto and multiplicity cuts $\mu \cdot m$