中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

DayaBay Experiment and its Future

Daya Bay θ_{13}

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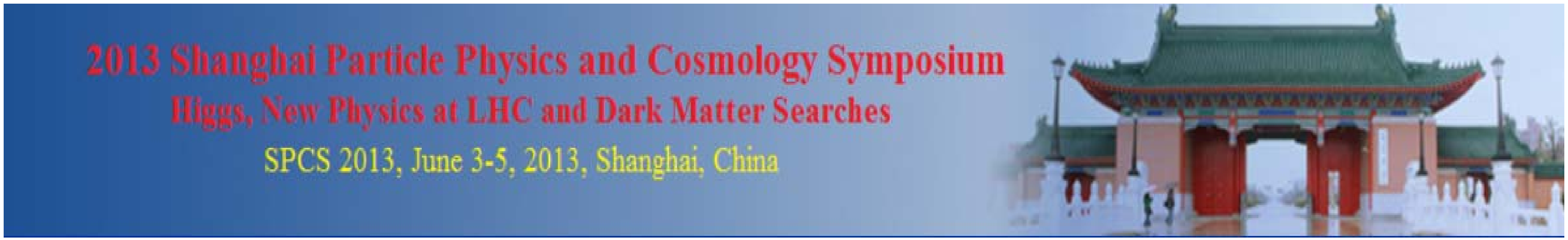
On behalf of the DayaBay collaboration

2013-June-3



Overview

- Θ_{13} review
- Introduction to Daya Bay Experiment
- Recent results of Daya Bay
- Near future of Daya Bay

Neutrino mixing

Neutrino **flavour eigenstates** ≠ **Mass eigenstates**

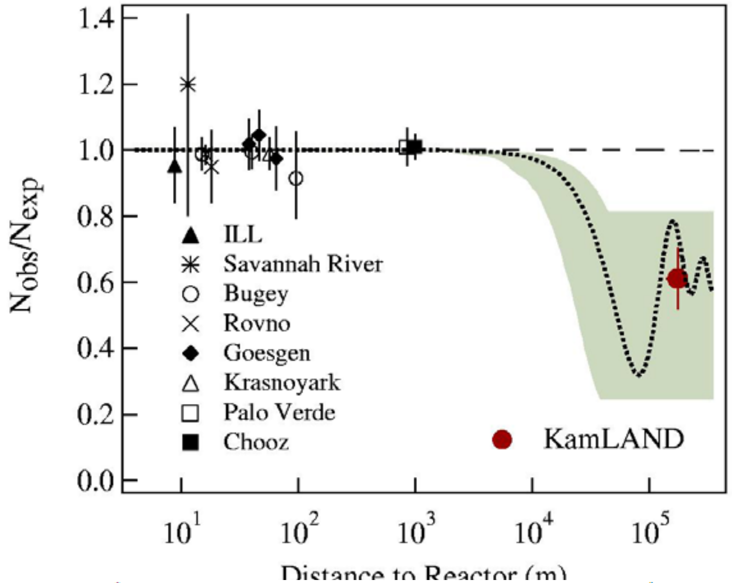
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-i\delta_1} & 0 & 0 \\ 0 & e^{-i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23}~45° by atmospheric neutrinos (1998)		θ_{12}~34° by solar neutrinos (2001)	neutrino-less double beta decay

Neutrino oscillation

If we focus on the reactor neutrino for disappearance experiments:



$$P_{\overline{\nu}_e \to \overline{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m_{31}^2 L / 4E\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\Delta m_{21}^2 L / 4E\right)$$

- **Why θ_{13} ?**
  - The last unknown mixing angle of neutrino before 2012.
  - Key input to future extensions, A non-zero θ_{13} could also open the door to answer many other questions:
    - Is there CP violation in the lepton sector?
    - Why is there more matter than anti-matter in our universe?
    - What is the mass hierarchy of neutrino sector?

Latest results of θ_{13}

Before March 2012

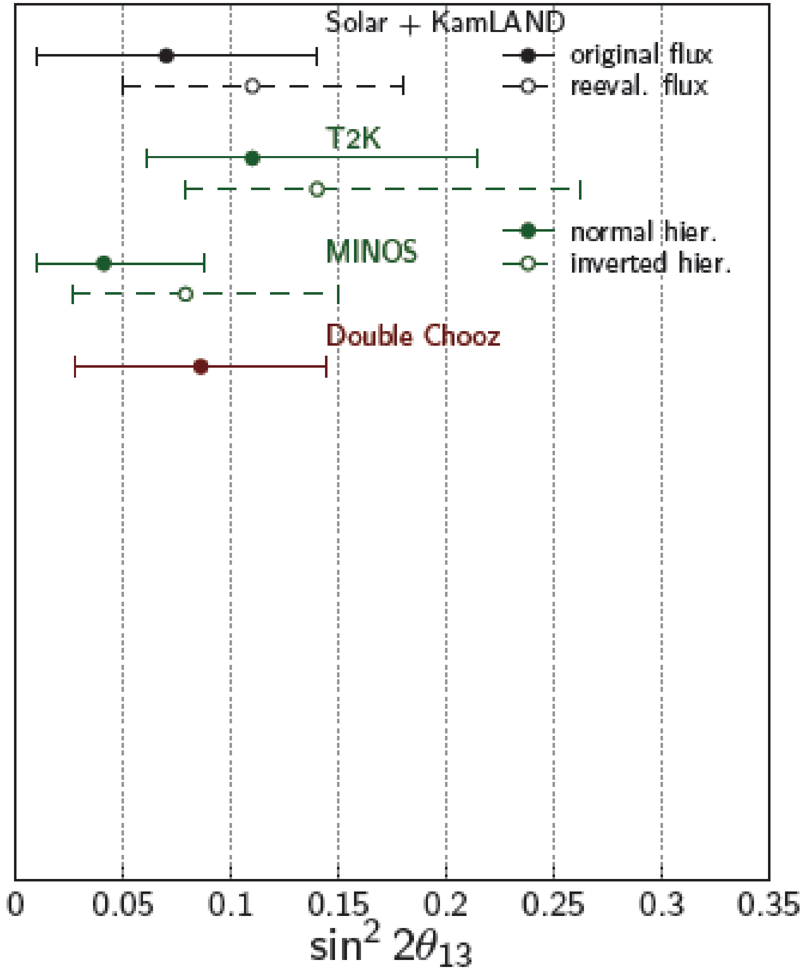
Only $\sigma < 2.5$ indication for non-zero θ_{13}

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

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



By Soeren

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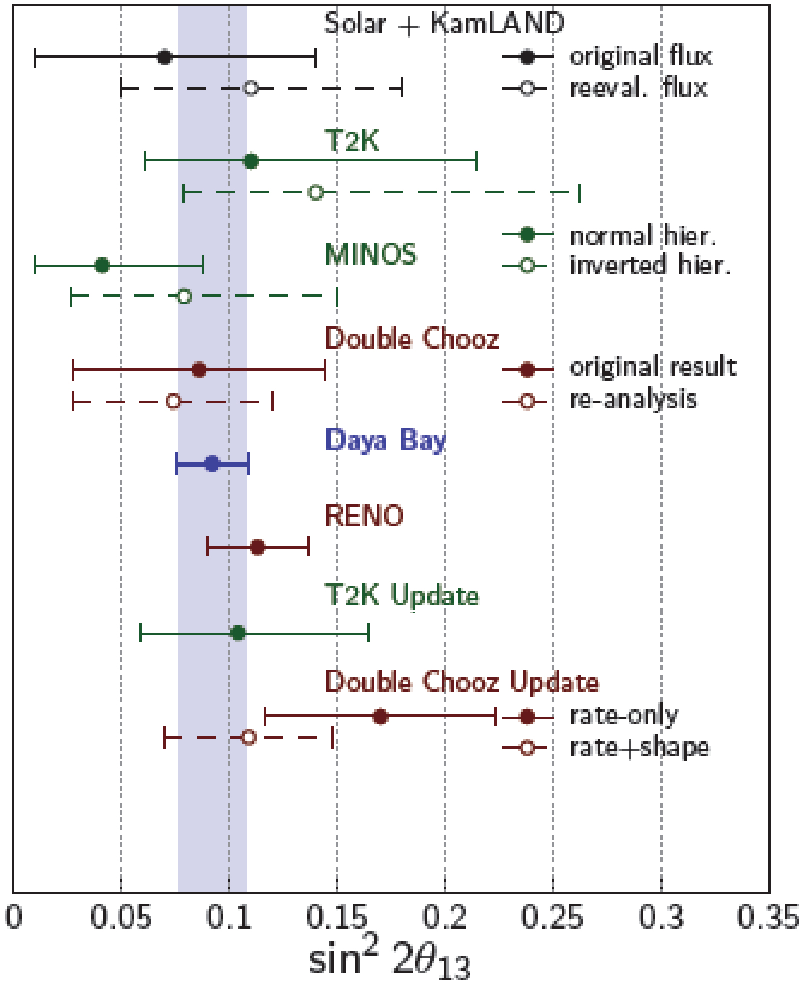

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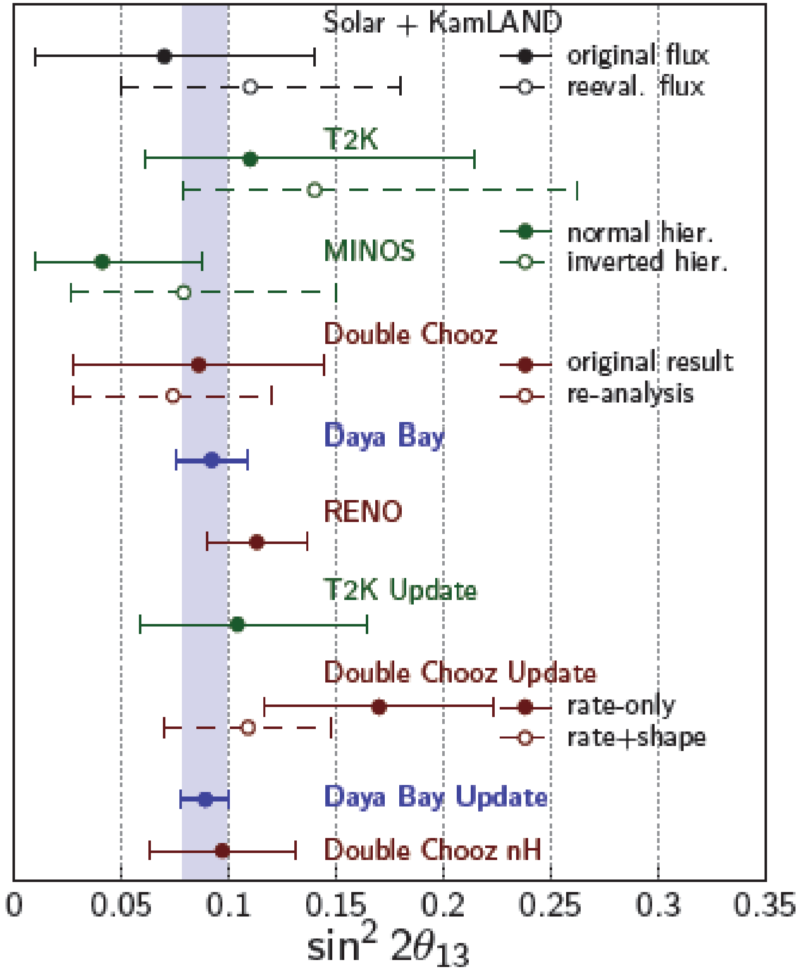
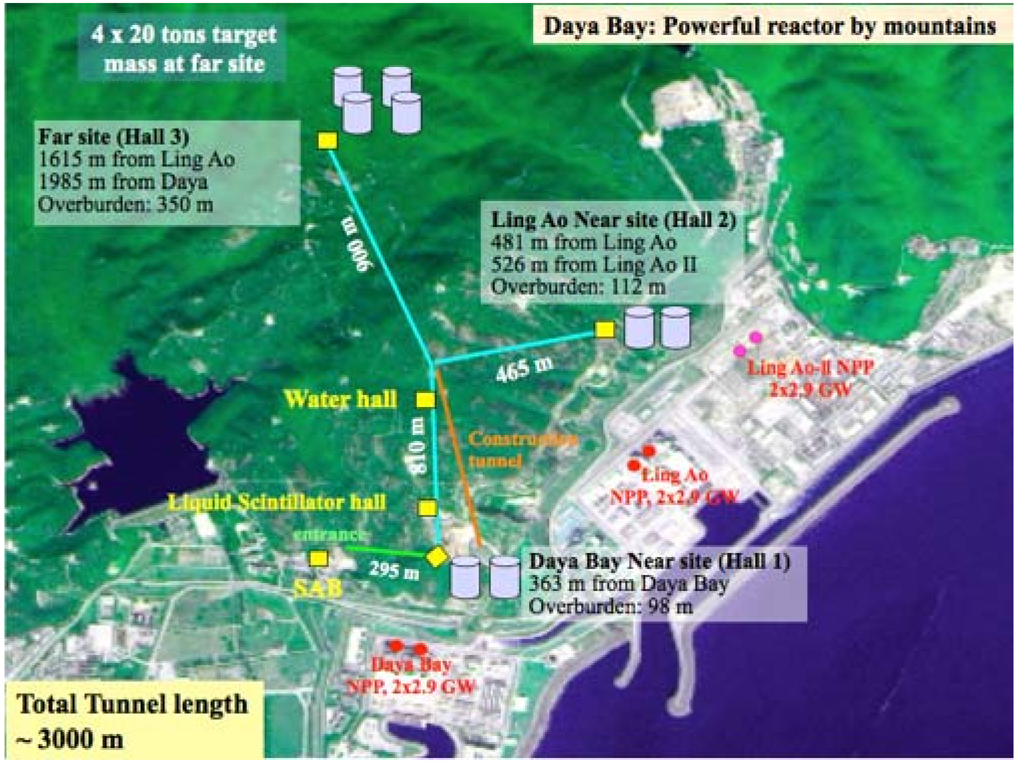
June,2012 ~7.7σ



By Soeren

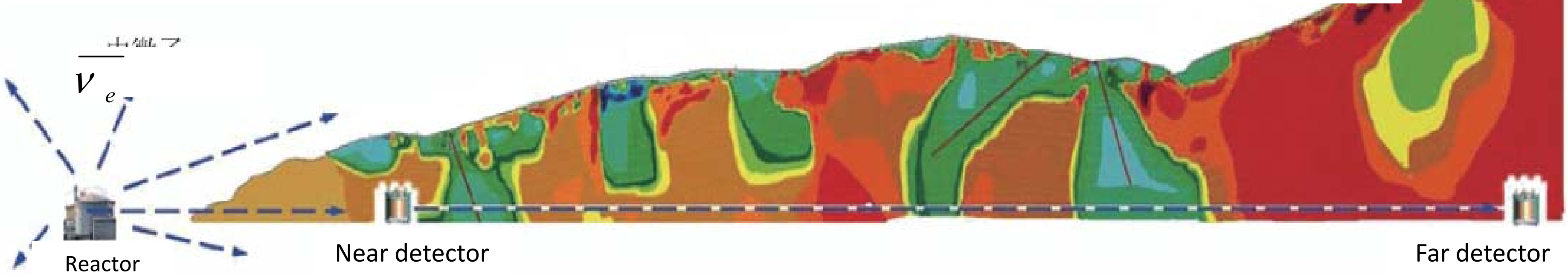
Daya Bay experiment

Location: Shenzhen, Guangdong province, China



- 6 reactor cores (one largest in the world)
  - 17.4 GW
- Good mountain shape for cosmic shielding
  - ~250 m.w.e@ near sites
  - ~860 m.w.e@ far site
- Relative measurement with Optimized location to cancel Corr. Syst. Err.
- Multiple detector modules per site to reduce Uncorr. Syst. Err.
- Multiple Muon detectors to reduce veto eff. uncertainties

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{31} L / 4E\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\Delta m^2_{21} L / 4E\right)$$



Daya Bay Collaboration

An International Effort

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.

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 Univ., Dubna

~230 collaborators

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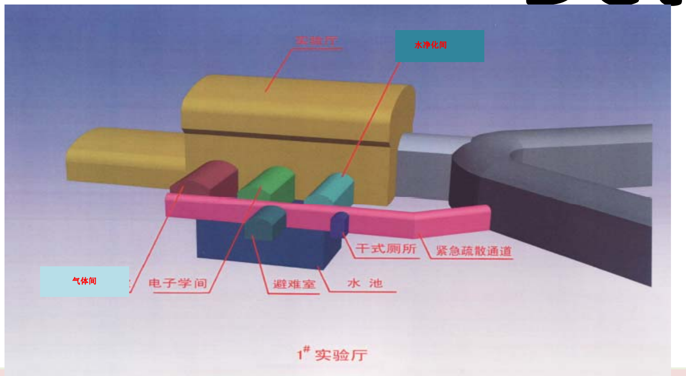
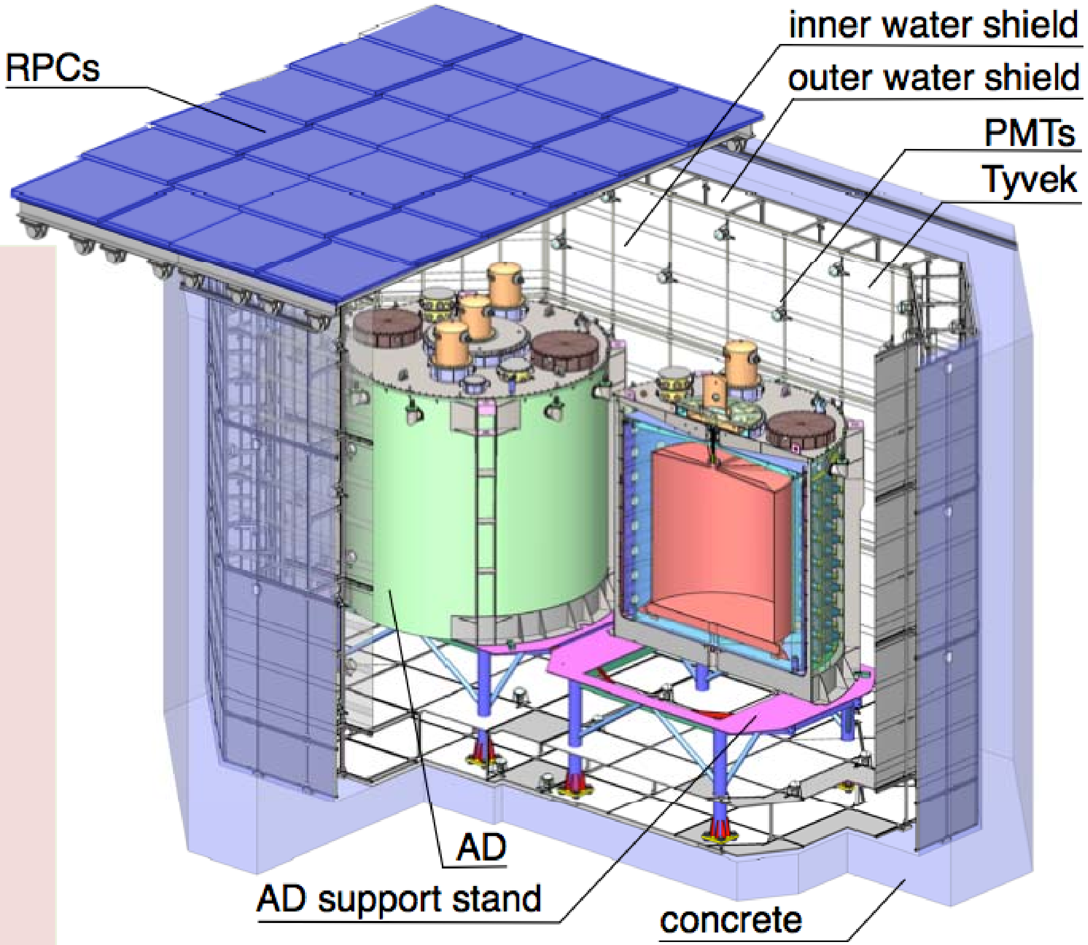
Detector system

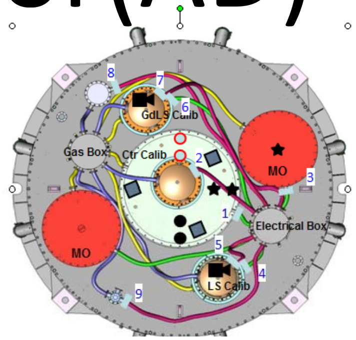


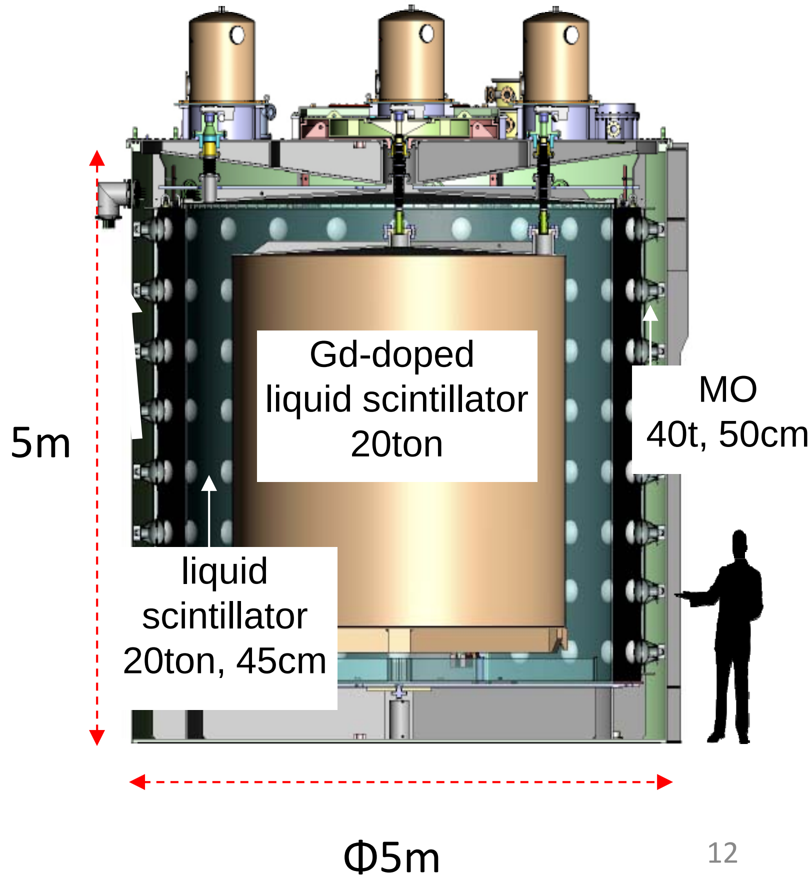
- Experiment pools：
  - Near site： 16m ×10m ×10m
  - Far site： 16m ×16m ×10m
- Detectors:
  - Multi identical Anti-neutrino Detector(AD)
    - Near 2 ADs total target mass 40t
    - Far site 4 ADs total target mass 80t
  - Muon Veto with 3 independent detectors
    - Two layer water Cerenkov(WP)
    - Top resistive plate chamber(RPC)



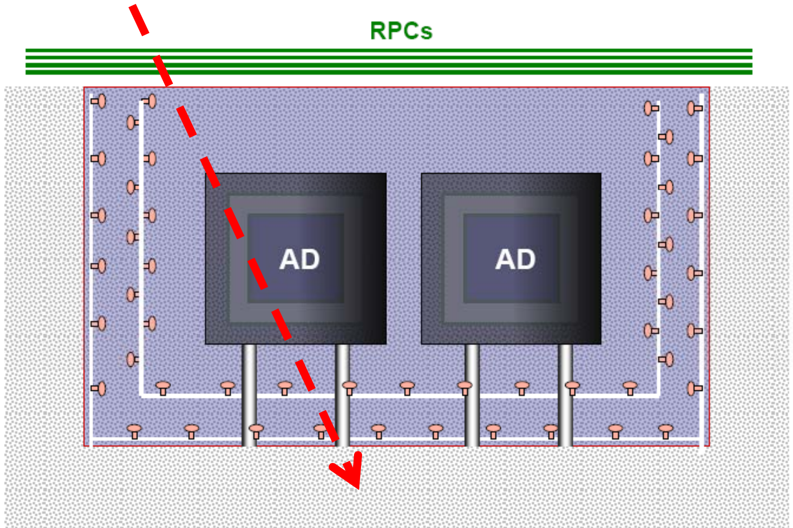
Anti-neutrino detector(AD)

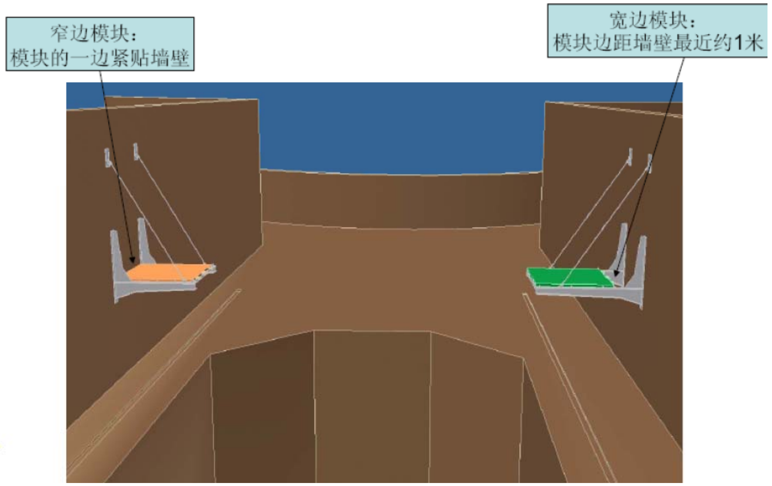
- 3 layers nestle cylinders per AD：
  - 20t GdLS, 20t LS, 40t MO, separated by Acrylic Vessels
    - Φ5m SSV(12mm), Φ4m OAV(18mm)，Φ3.1mIAV(10mm)
  - 192 8” PMTs in 8 rings with positive HV, top and bottom reflectors
  - 6 2” PMTs at top and bottom
  - 1 MO monitoring system
  - 3 vertical calibration units (ACU)
  - Other monitoring: temperature, camera etc.
- Basic physical requirements:
  - Precise target mass control
  - Low background
  - Low energy threshold
  - High precise calibration: auto scan and manual calibration
- No vertex cut, no fiducial volume cut





Daya Bay Muon detectors





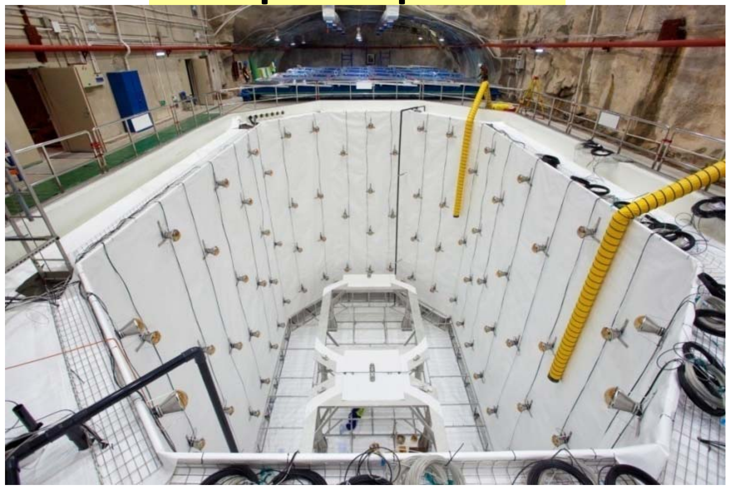
- Goals:
  - To shield the Antineutrino Detectors (AD) from natural and cosmogenic background
  - To serve as an active Muon detector to register the presence of a cosmic ray Muon and measure its time and position with respect to candidate events
- Redundant high efficiency to Muons ~ 99.5%
  - Water pool for passive shielding
  - Instrumented water pool with PMT: Cherenkov detector
  - Inner and outer pool optically separated by tyvek
  - 4-layer RPC (Resistive *Plate* Chamber) detectors covering the water pool: Independent of water Cherenkov, retractable “roof” above pool
  - Telescope RPCs for Muon track related background study
- The water also regulates the temperature of the antineutrino detectors


Stainless Steel Vessel
Bottom Reflector
3m/4m Acrylic Vessel
SSV Lid and ACU
Top Reflector
PMT Ladder
AD Transportation
AD Filling

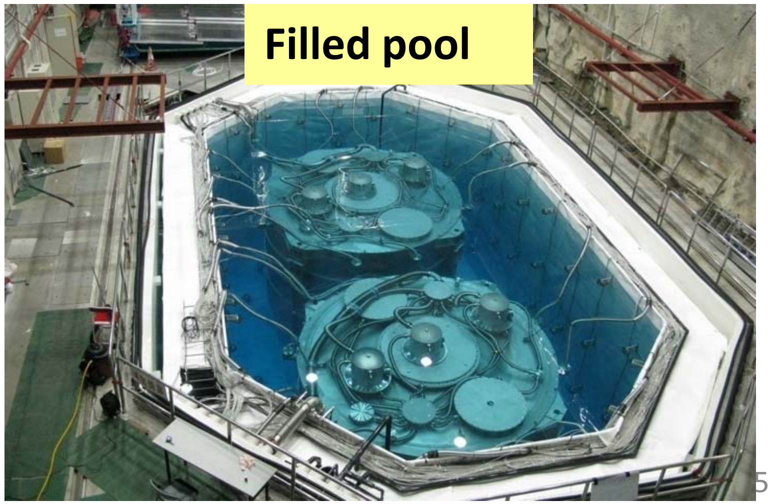
Installation of water Cerenkov detector

PMT supporting structure + tyvek+PMT

Completed pool

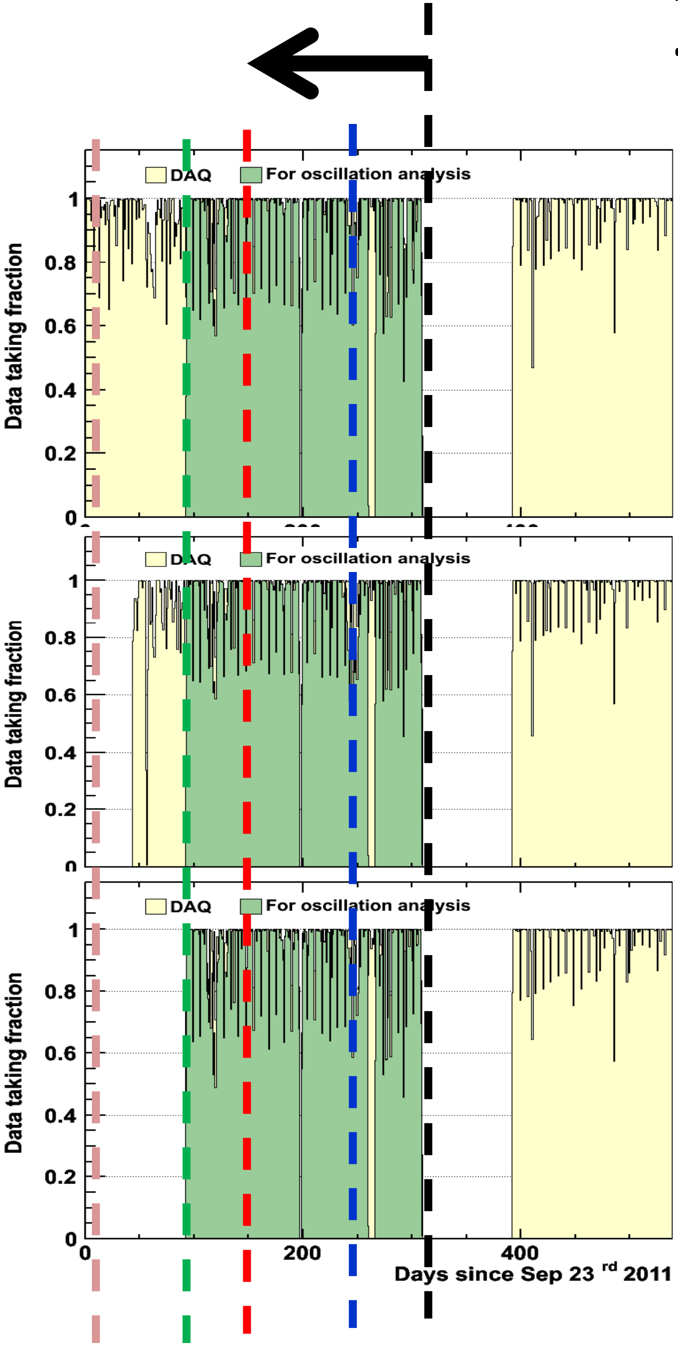


Filled pool

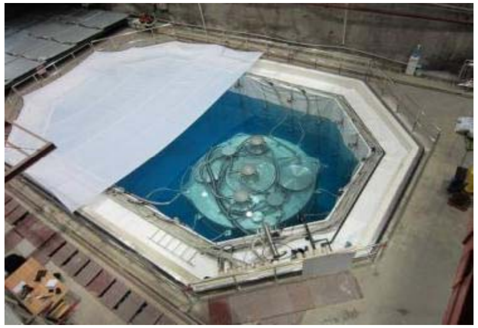


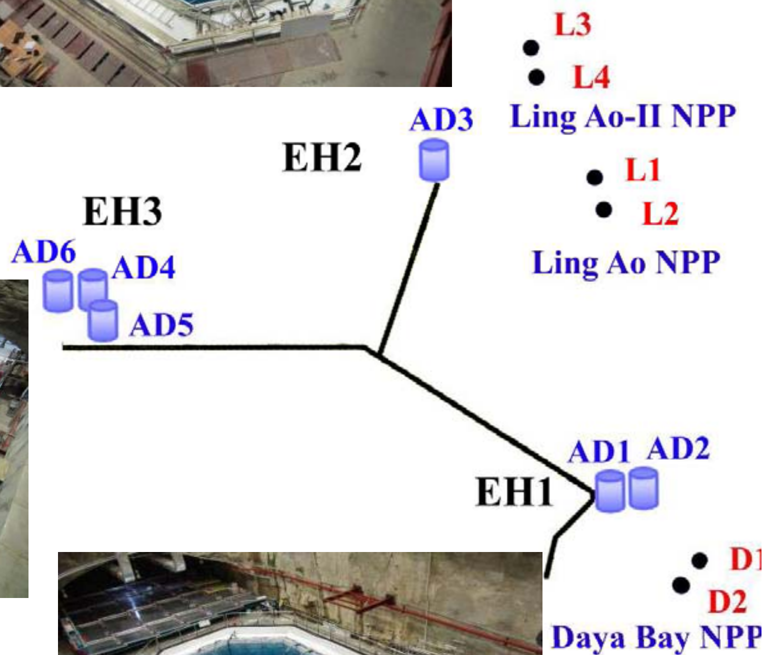
Pool cover installed

1st run stage



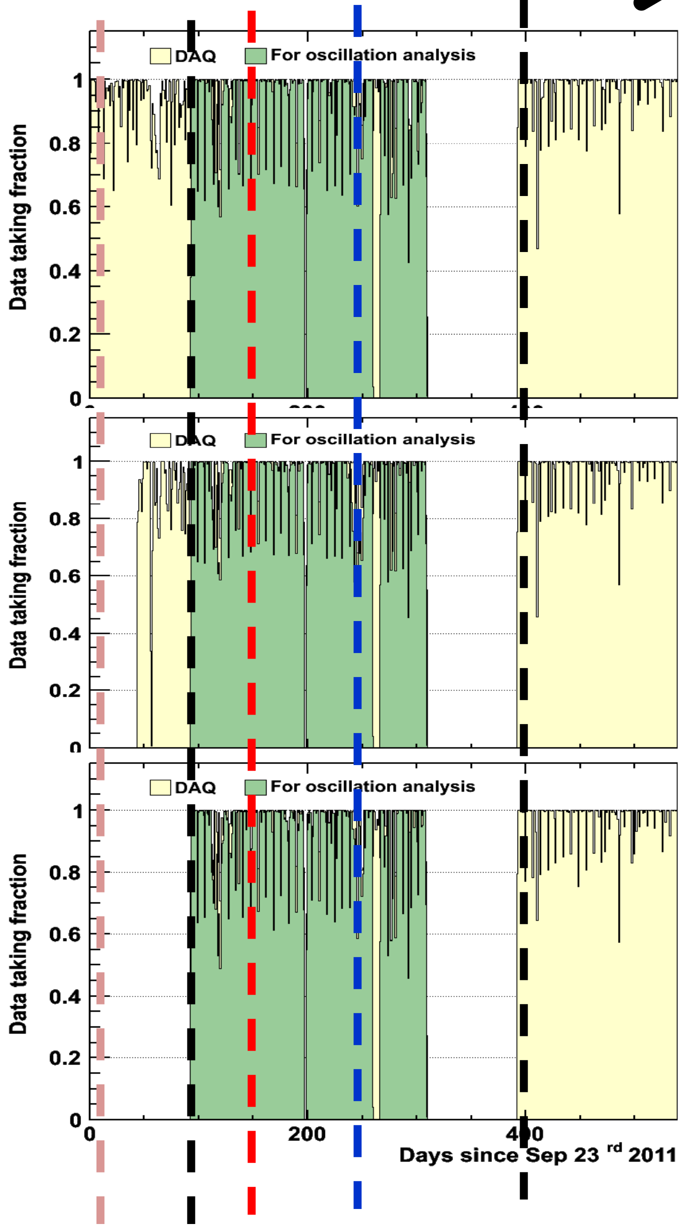
DYB: Aug.15,2011
3halls: Dec.24,2011

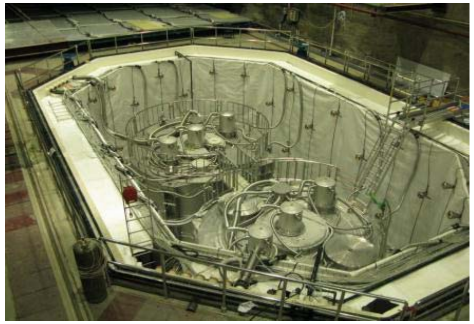


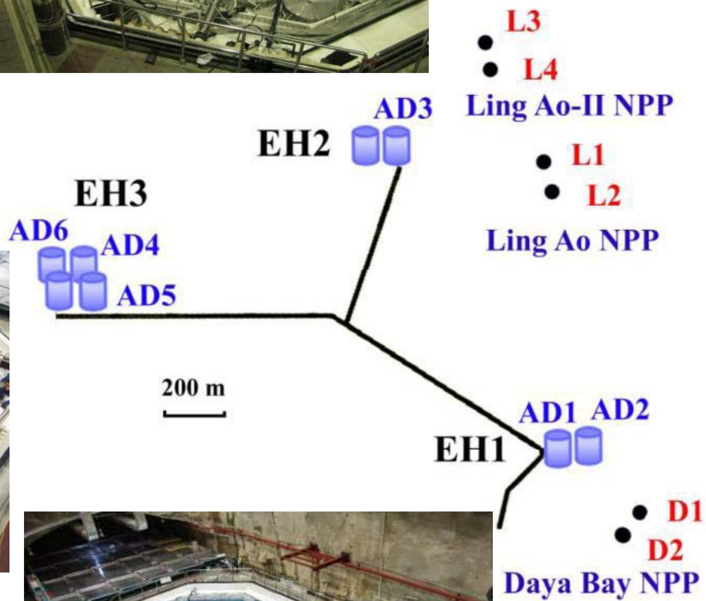


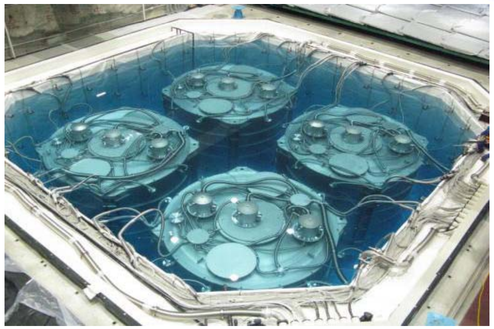
2^{nd} run stage

Oct.19,2012

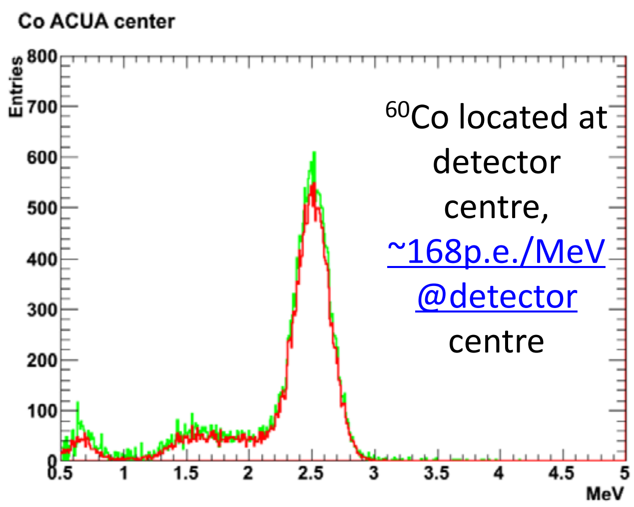


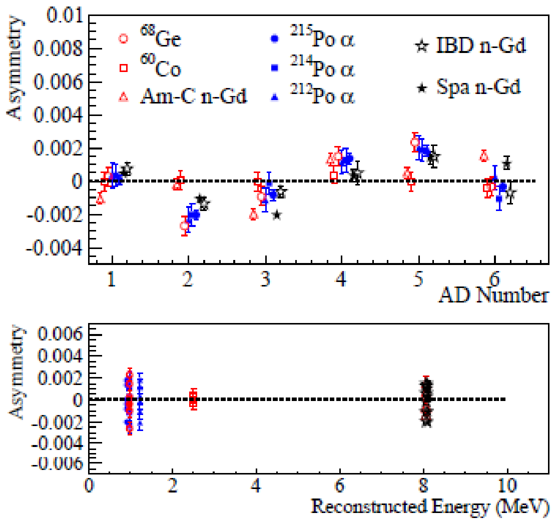




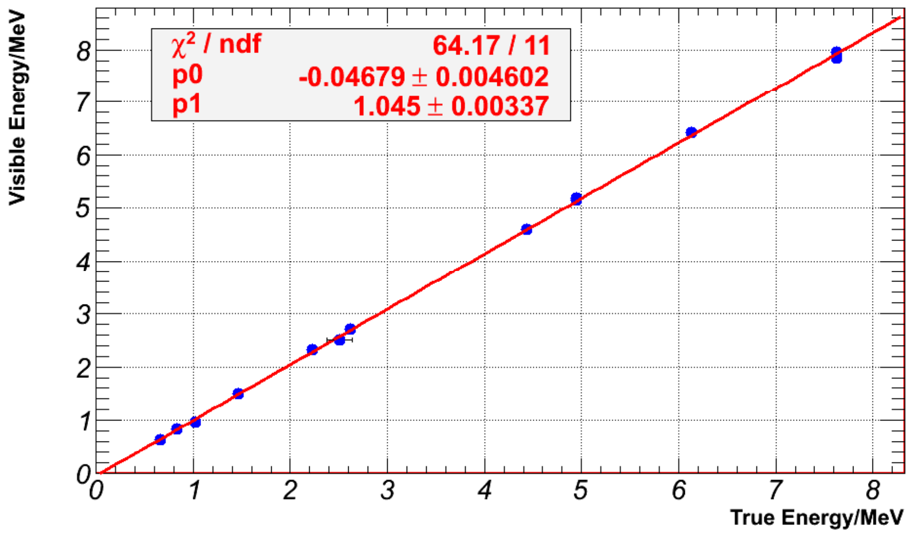


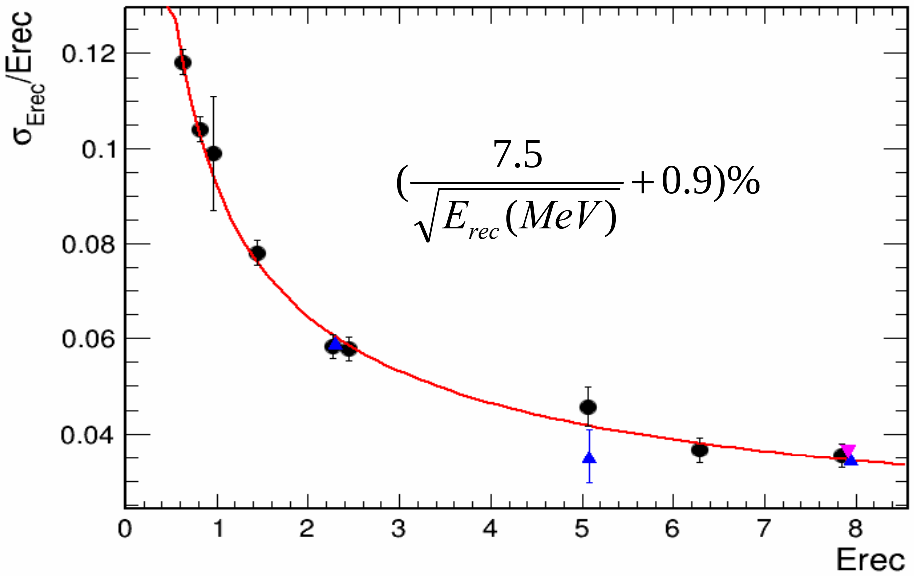
Detector response (AD)





Energy scale difference among ADs <0.5%





Neutrino detection

liquid scintillator based detector

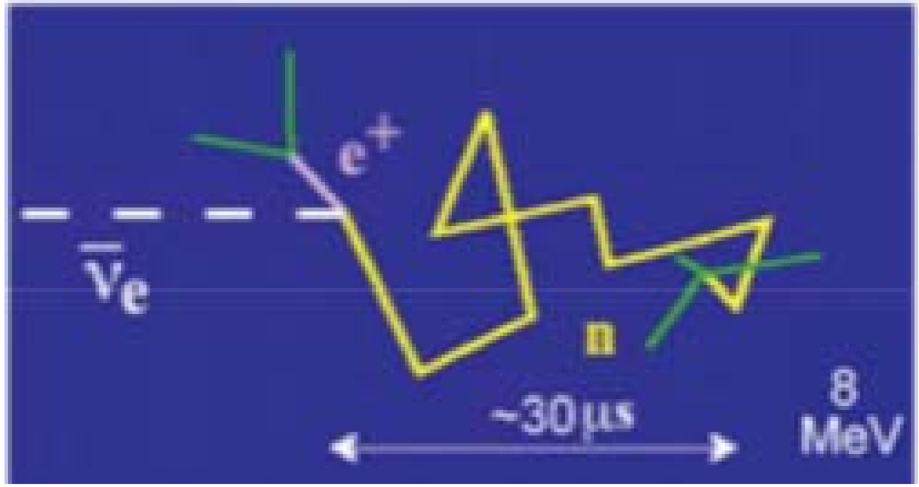
Inverse beta decay

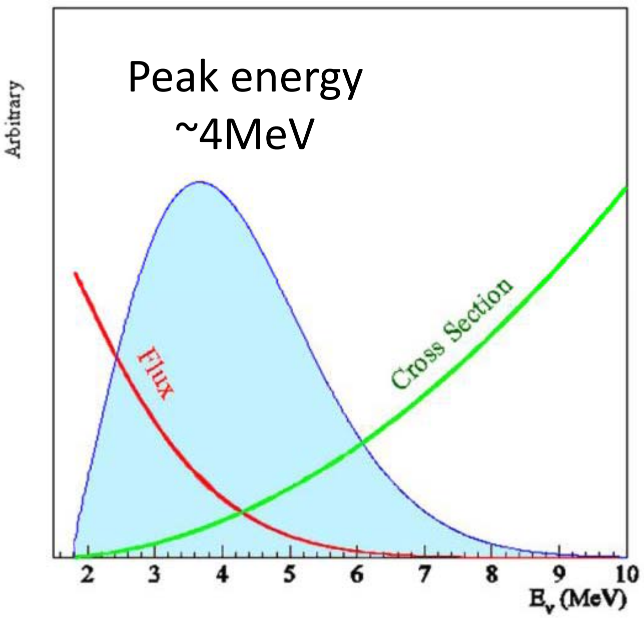
Prompt signal

$$e^{+} + e^{-} \rightarrow 2\gamma$$

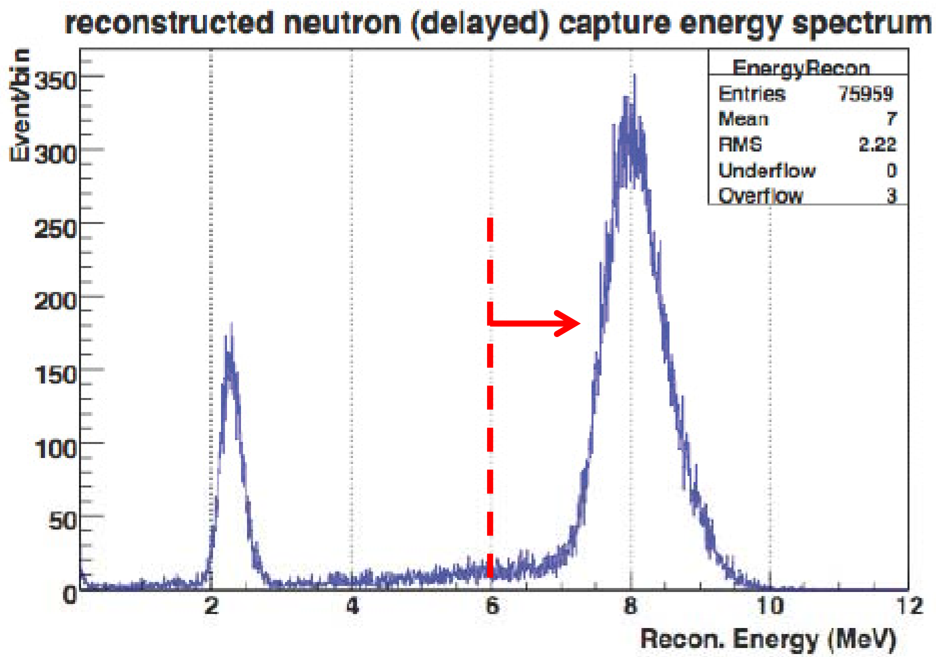
$$\bar{\nu}_e + p \rightarrow e^{+} + n$$

Delayed signal, Capture on H (2.2 MeV) or Gd (8 MeV), ~30μs



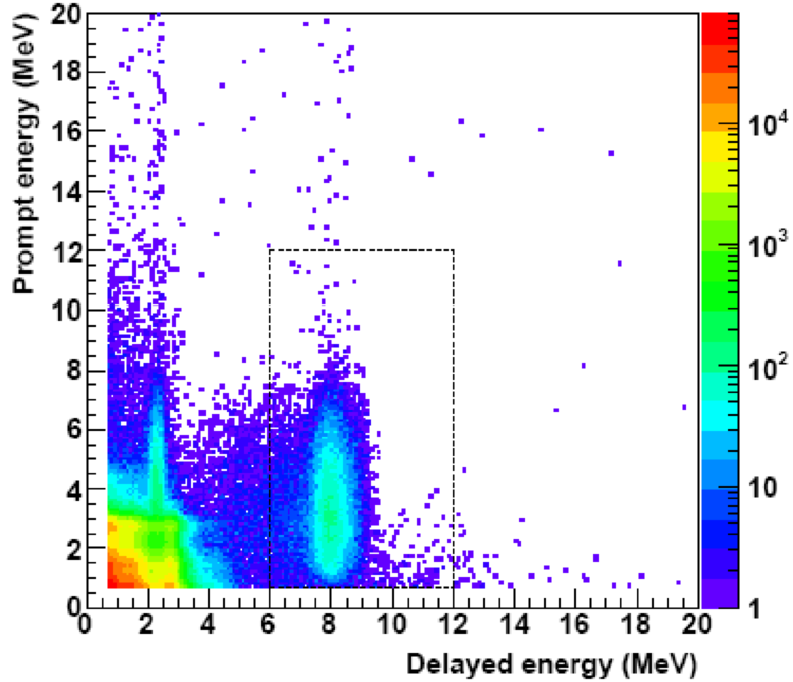


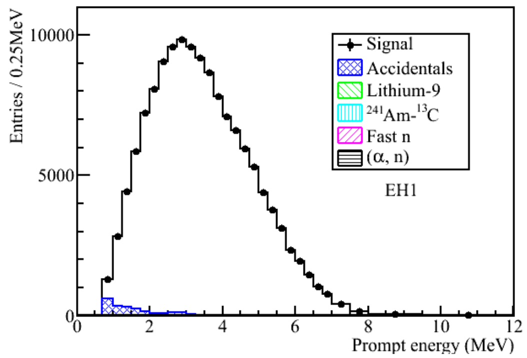
SPCS2(

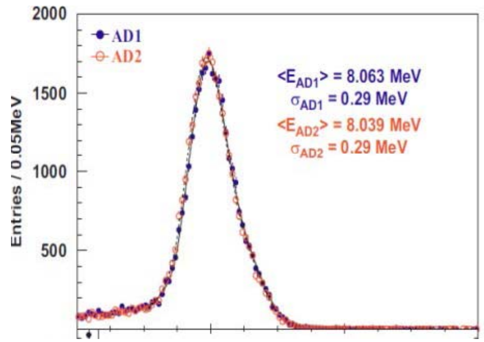


Neutrino event selection

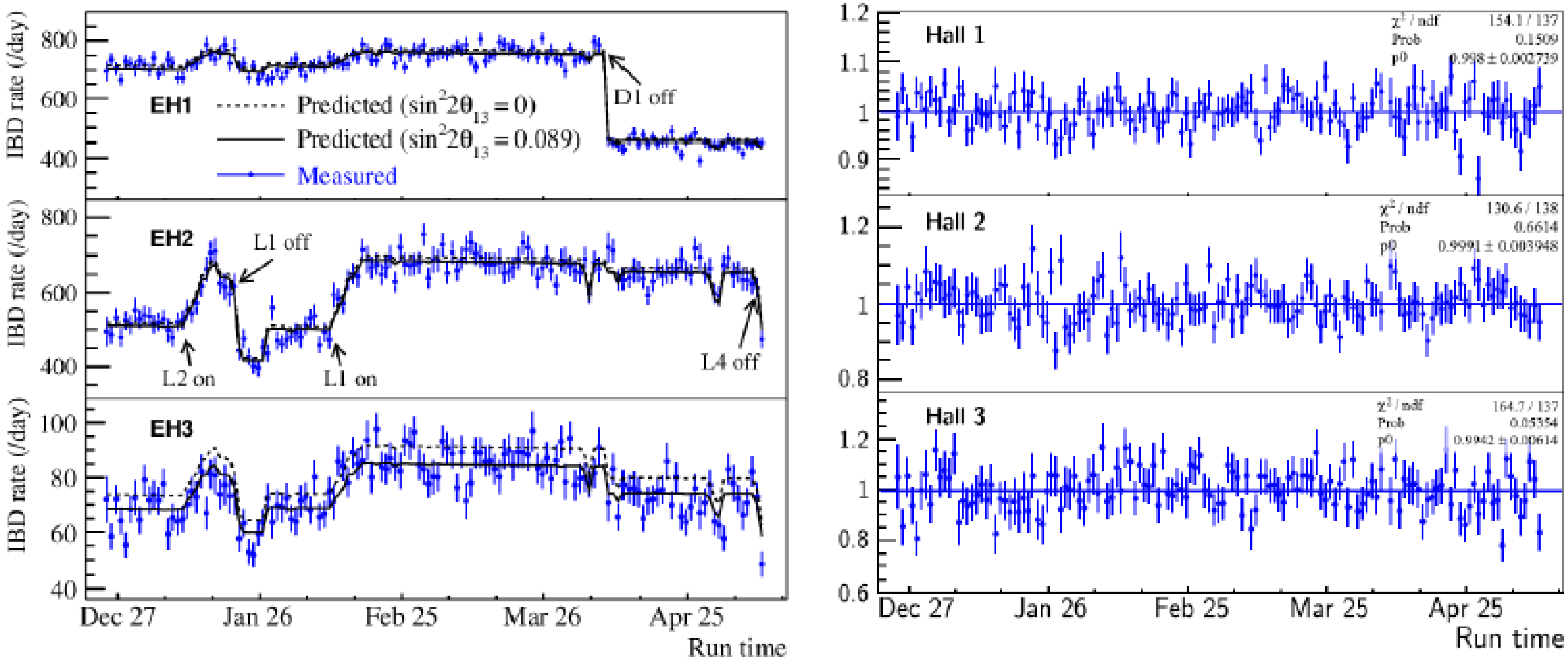
- **Anti-neutrino event selection**
  - **Remove spontaneous PMT light emission**
  - **0.7 MeV < Ep < 12.0 MeV**
  - **6.0 MeV < Ed < 12.0 MeV**
  - **1 μs < Δtp-d < 200 μs**
  - **Muon Veto:**
    - **0.6ms after a Pool Muon (reject fast neutron)**
    - **1ms after an AD Muon (reject double neutron)**
    - **1s after an AD shower Muon (reject 9Li/8He)**
  - **Multiplicity cut:**
    - **No other >0.7 MeV trigger in (tp-200 μs , td+200 μs)**





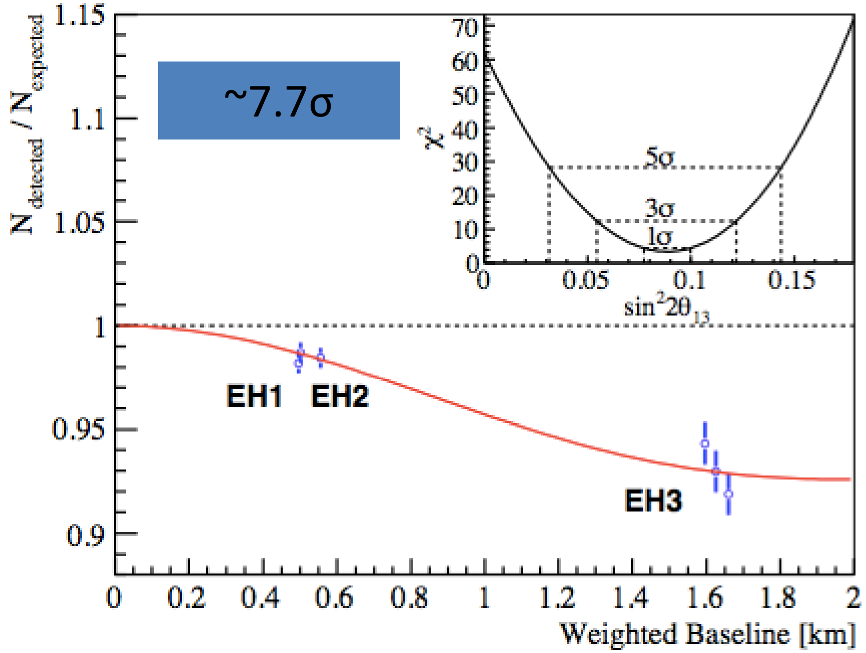


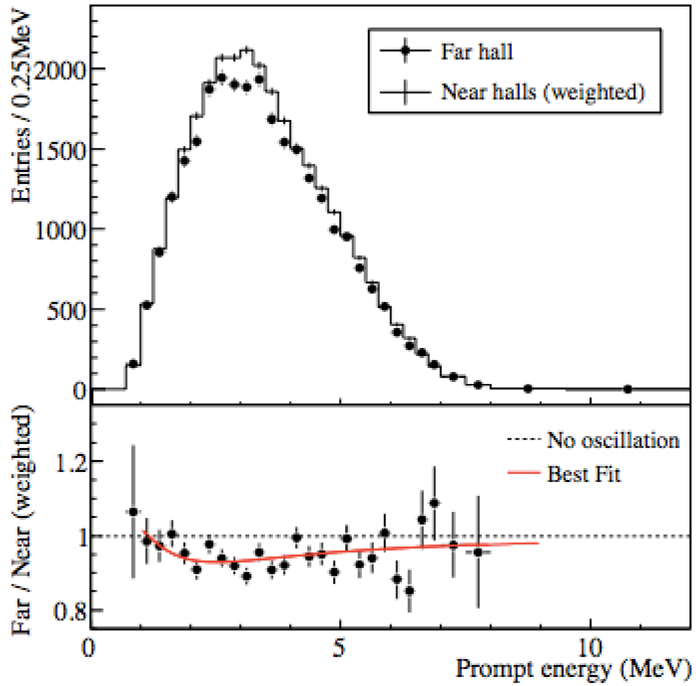
Measured reactor flux



- **Detected neutrino rates strongly correlated with reactor flux expectations.**
- **Predicted rate**
  - **Normalization is determined by fit to near/far data.**
  - **Absolute normalization is within a few percent of expectations.**

Recent results





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

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

Up to May 11,2012

Uncertainties

	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	69121	69714	66473	9788	9669	9452
Expected IBDs	68613	69595	66402	9922.9	9940.2	9837.7
DAQ livetime (days)	127.5470		127.3763		126.2646	
ϵ_μ	0.8231	0.8198	0.8576	0.9813	0.9813	0.9810
$\bar{\epsilon}_m$	0.9738	0.9742	0.9753	0.9737	0.9734	0.9732
Accidentals (per day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05 ±0.04	3.04 ± 0.04	2.93 ±0.03
Fast-neutron (per day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{9}Li/^{8}He (per AD per day)	2.9±1.5		2.0±1.1		0.22±0.12	
Am-C correlated (per AD per day)			0.2±0.2			
(α, n) background (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)	662.47±3.00	670.87±3.01	613.53±2.69	77.57±0.85	76.62±0.85	74.97±0.84

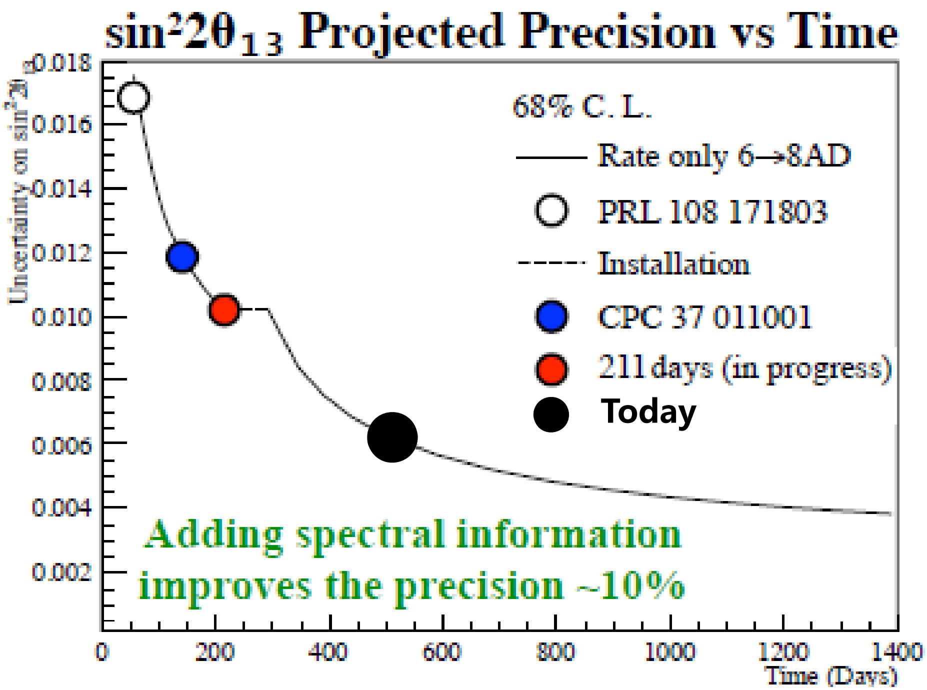
	Near Halls		Far Hall		
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %	ΔB/B
Accidentals	1.5	0.02	4.0	0.05	~1%
Fast neutrons	0.12	0.05	0.07	0.03	~40%
^{9}Li/^{8}He	0.4	0.2	0.3	0.2	~50%
^{241}Am-^{13}C	0.03	0.03	0.3	0.3	~100%
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03	~50%
Sum	2.1	0.21	4.7	0.37	~10%

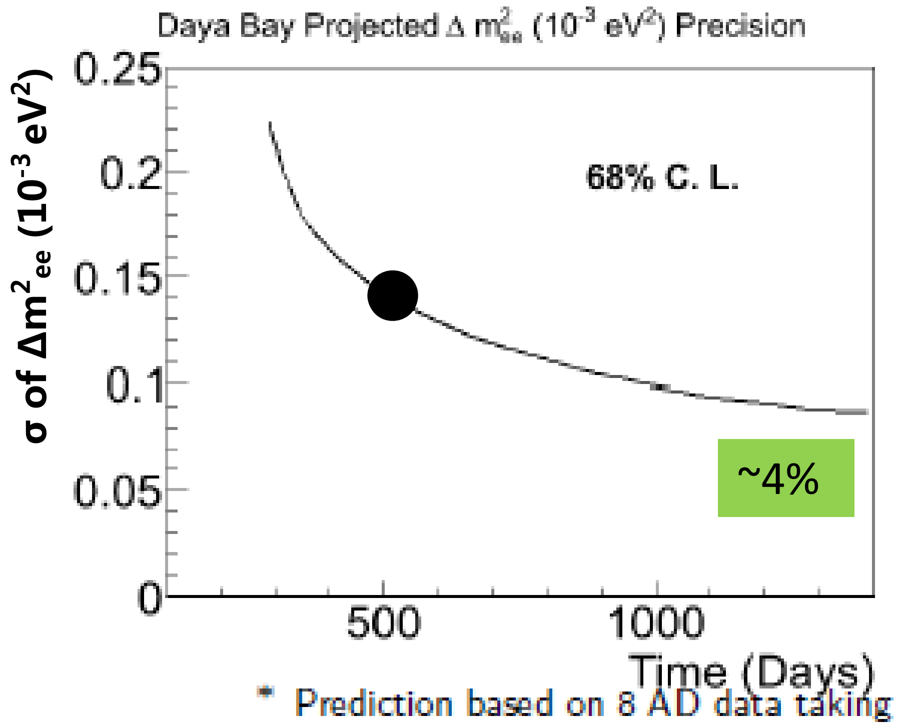
Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%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

Next goals: 1st

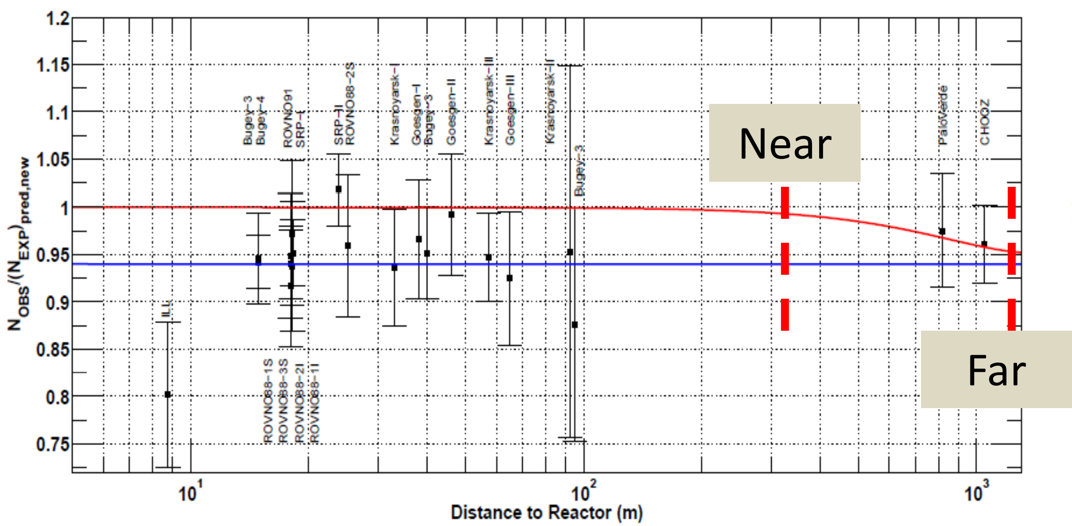
- Collect more data: current plan is to keep the experiment running in the next ~4year.
  - Complete shape analysis
    - Including energy scale analysis, further understanding 3D response
    - Will show up soon.
  - Beat down the systematic errors
  - Complete a definitive measurement of $\sin^2(2\theta_{13})$ (~0.004 or ~4%)
  - Measurements of Δm^2_{ee} (~4%)



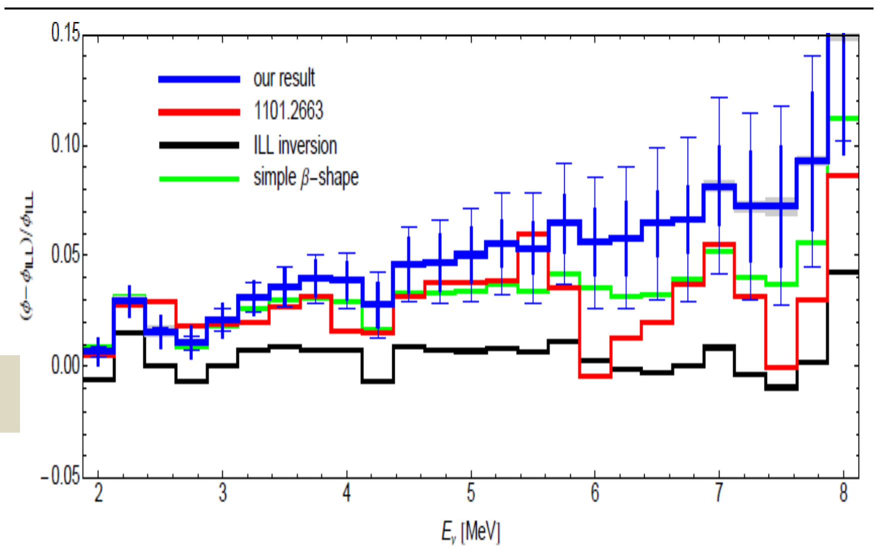


Next goals: 2nd

- Precise/Absolute reactor flux and spectra measurements
  - Tremendous rate at near sites
  - Achievable <1% statistical uncertainty over large range of energies
  - Study of reactor nuclear physics and non standard interactions
  - Search for new non-standard interactions



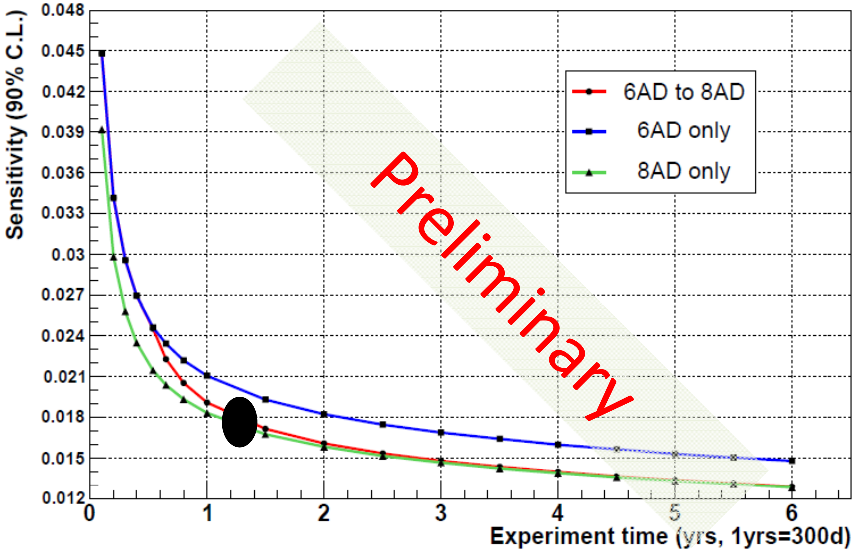
http://arxiv.org/abs/1101.2755

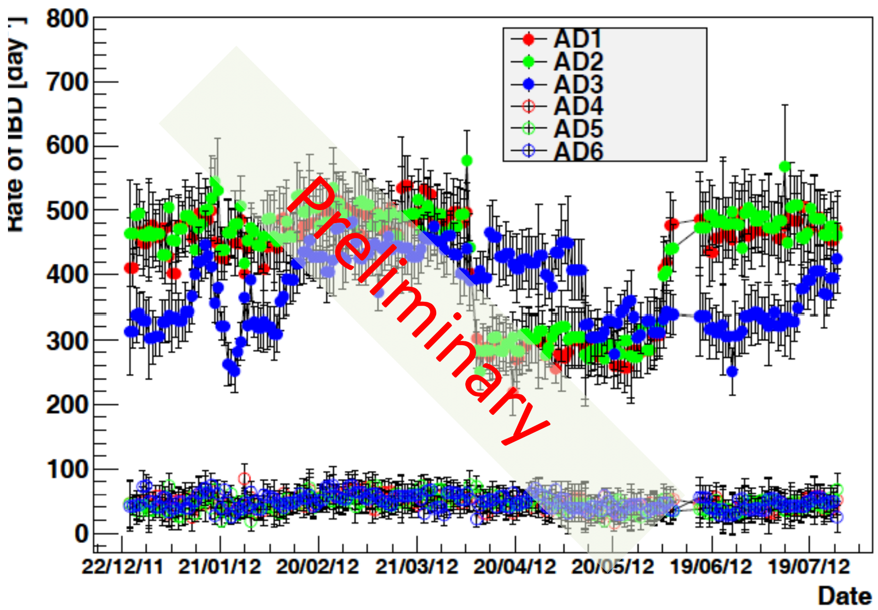


http://www.phys.hawaii.edu/~hanohano/post/AAP2012/Huber_AAP2012.pdf

Next goals: 3rd

- Neutrino analysis with nH capture (2.2MeV)
  - Background understanding/depressing
    - Near: B/S ratio ~1/7 (while nGd analysis is ~1/100)
    - Far: Bkg/Signal ratio ~1.5/1 (while nGd analysis is ~5/20)
  - Efficiency understanding precisely especially applied for background depressing





Next goals: 4th

- Measurements of cosmogenic neutrons and isotopes
  - Good Muon efficiency and track measurement
  - Distinct averaged Muon energy and flux
  - Cross check with different experiment halls

	Overburden (m.w.e)	R_μ (Hz/m^2)	$< E_\mu >$ (GeV)
EH1	250	1.27	57
EH2	265	0.95	58
EH3	860	0.056	137

RPC

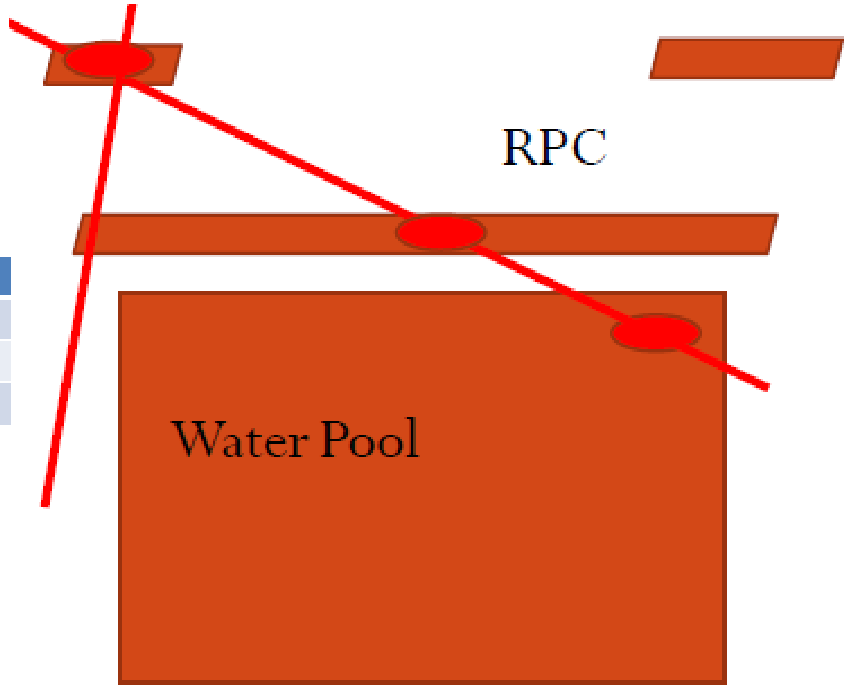
Site	DYB	LA	Far
DetRate(Hz/m²)	0.90±0.06	0.69±0.08	0.046±0.004
SimRate(Hz/m²)	0.88±0.09	0.69±0.07	0.039±0.004
Ratio=Sim/Det	0.98±0.12	1.00±0.15	0.85±0.13

WP

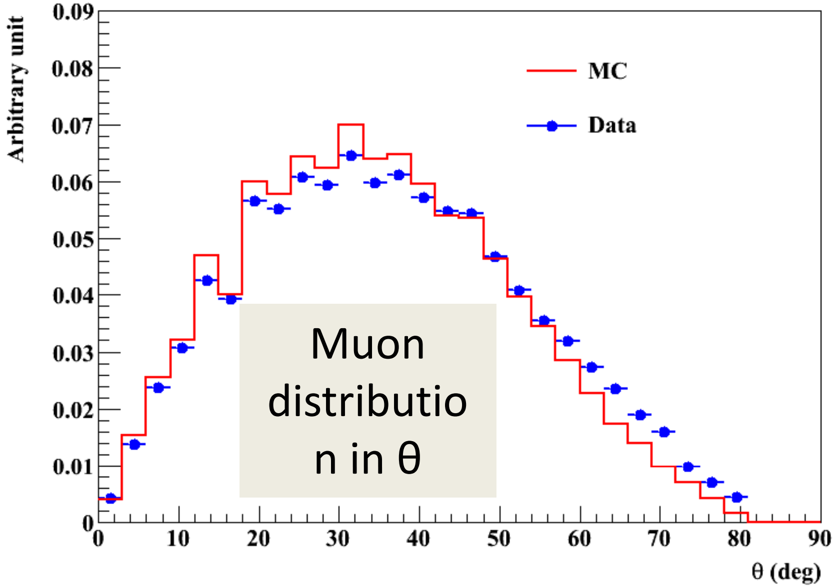
Sites	Measurement(Hz)	Simulation(Hz)	Ratio=Sim./Measur.
DYB	206±10	239.7±24	1.16±0.11
LingAo	154±8	179.5±18	1.17±0.11
Far	14.5±0.7	15.5±1.6	1.07±0.11

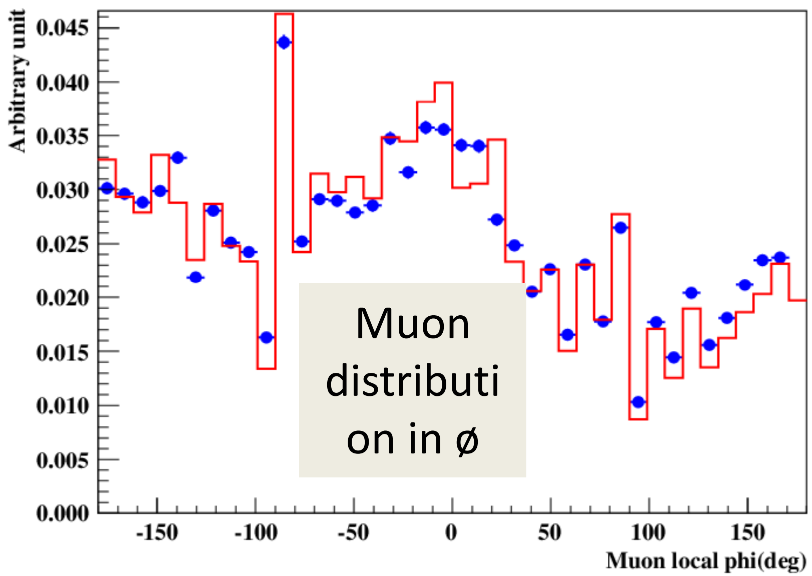
AD

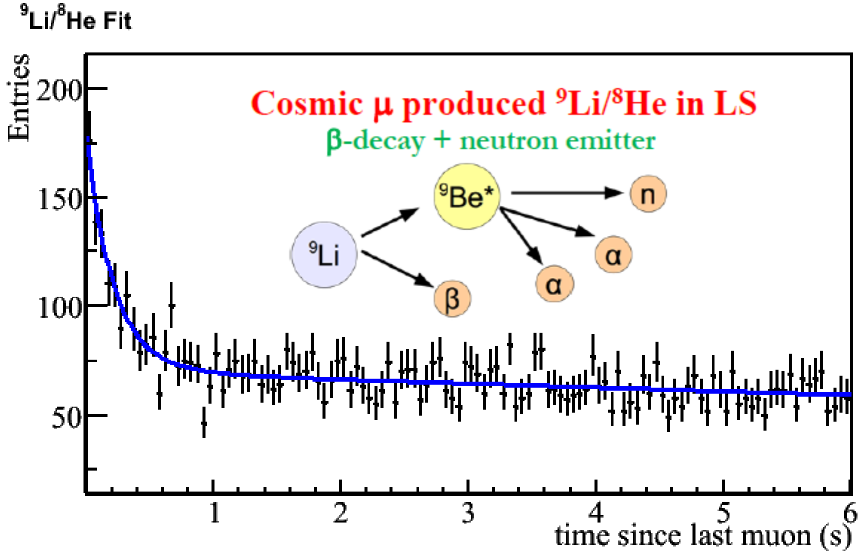
Sites	Measurement(Hz)	Simulation(Hz)	Ratio=Sim./Measur.
DYB	21.0±1.0	24.1±2.4	1.15±0.11
LingAo	15.7±0.8	18.0±1.8	1.15±0.11
Far	1.0±0.05	1.05±0.11	1.05±0.14

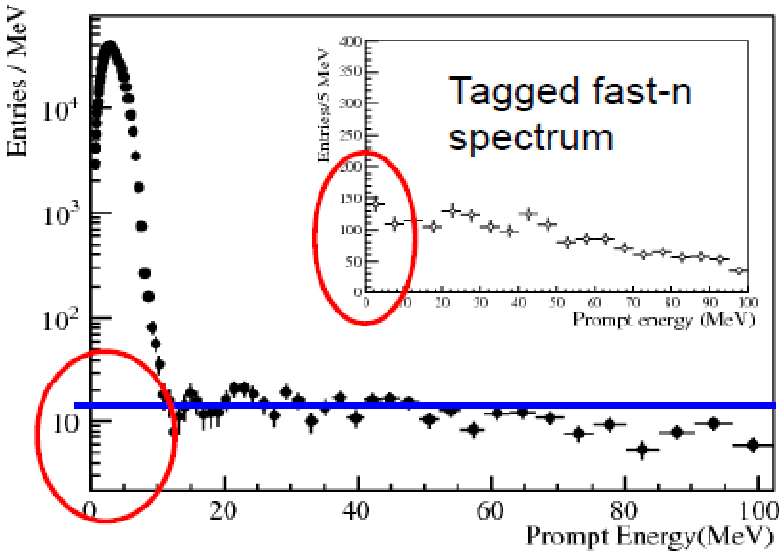


Some results



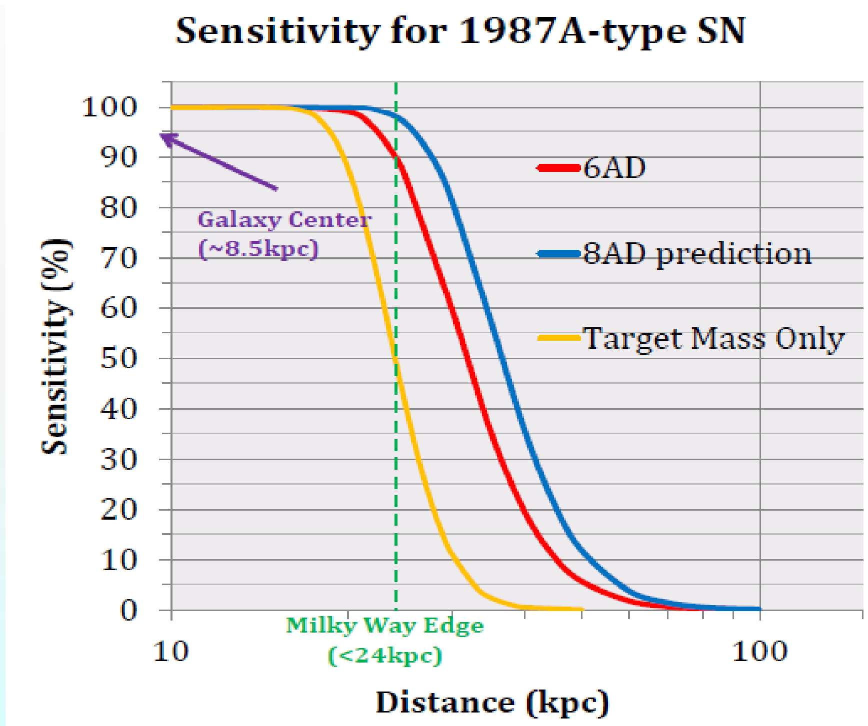


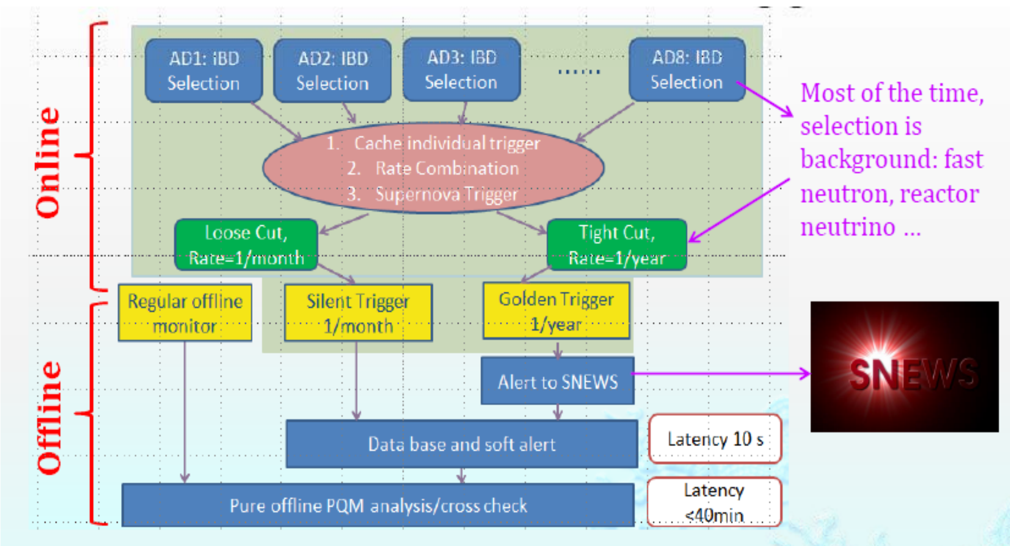




Next goals: 5th

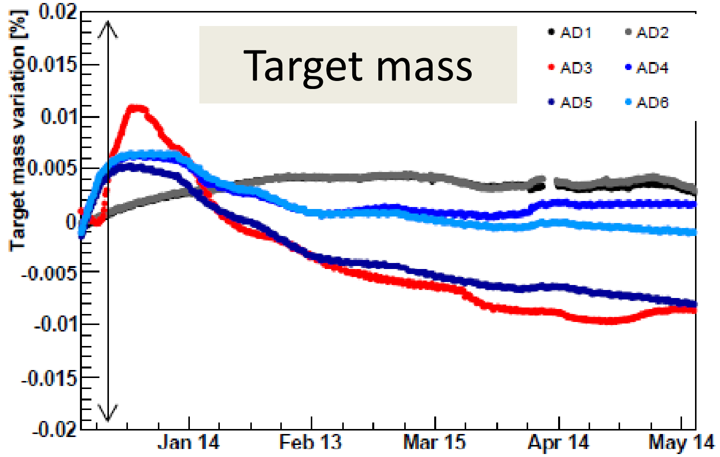
- Supernova monitoring:
  - 8AD deployment in 3 experiment sites 1km apart from each other
  - ~100% sensitivity to Galaxy center and ~98% to Milky Way edge with 8-AD data
  - Not far away the 'SNEWS' in Daya Bay officially established

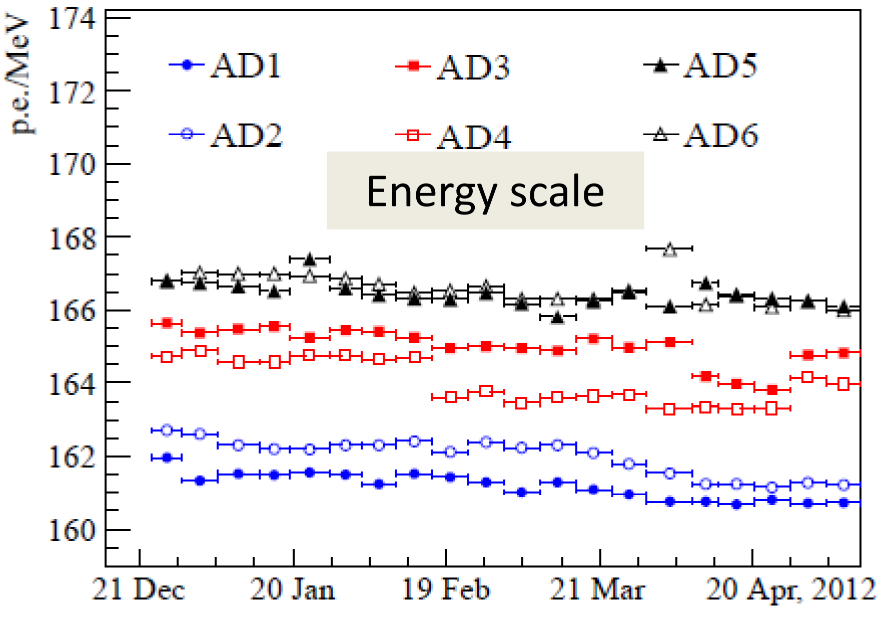


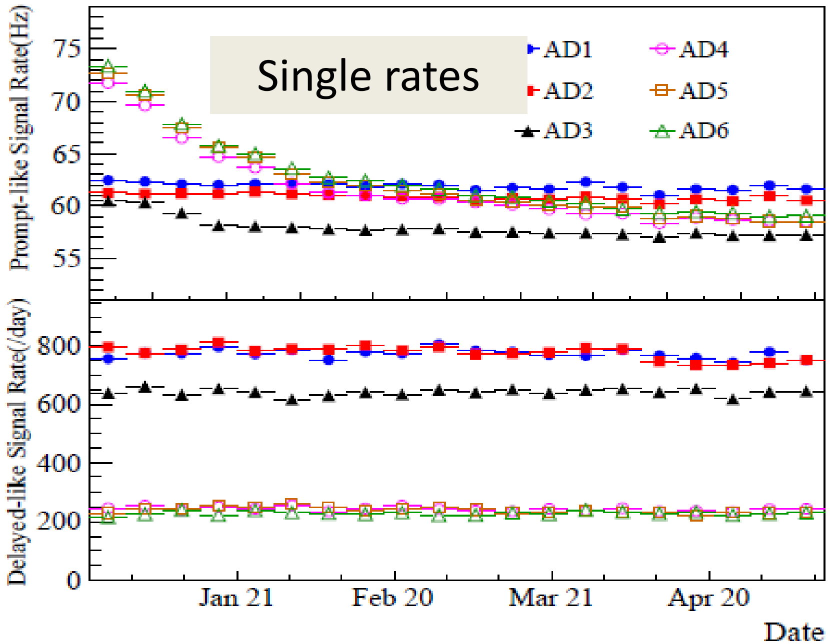


Next goals: 6^{th}

- Technical studies
  - Demonstrate multi-year operation of detectors
  - Verify Gd-LS long term stability
  - Swap detectors (optional)



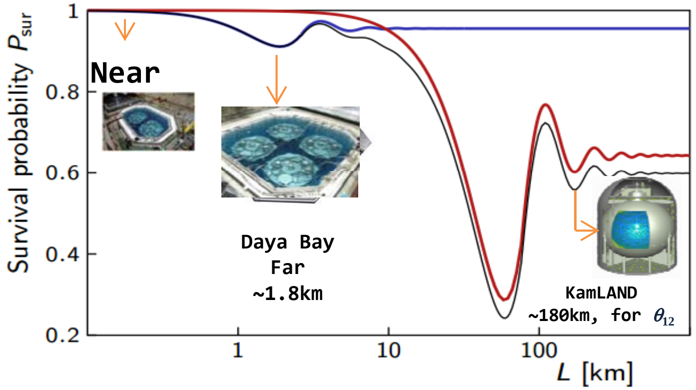




Others

- For Daya Bay
  - Further Background study
  - Underground laboratory monitoring
  - …
- Daya Bay experiment halls also are good candidate for underground experiments
  - Detector underground test
  - Radioactivity measurement
  - …
- After Daya Bay running
  - Further study for liquid scintillator
  - Detector response study
  - ….

Summary



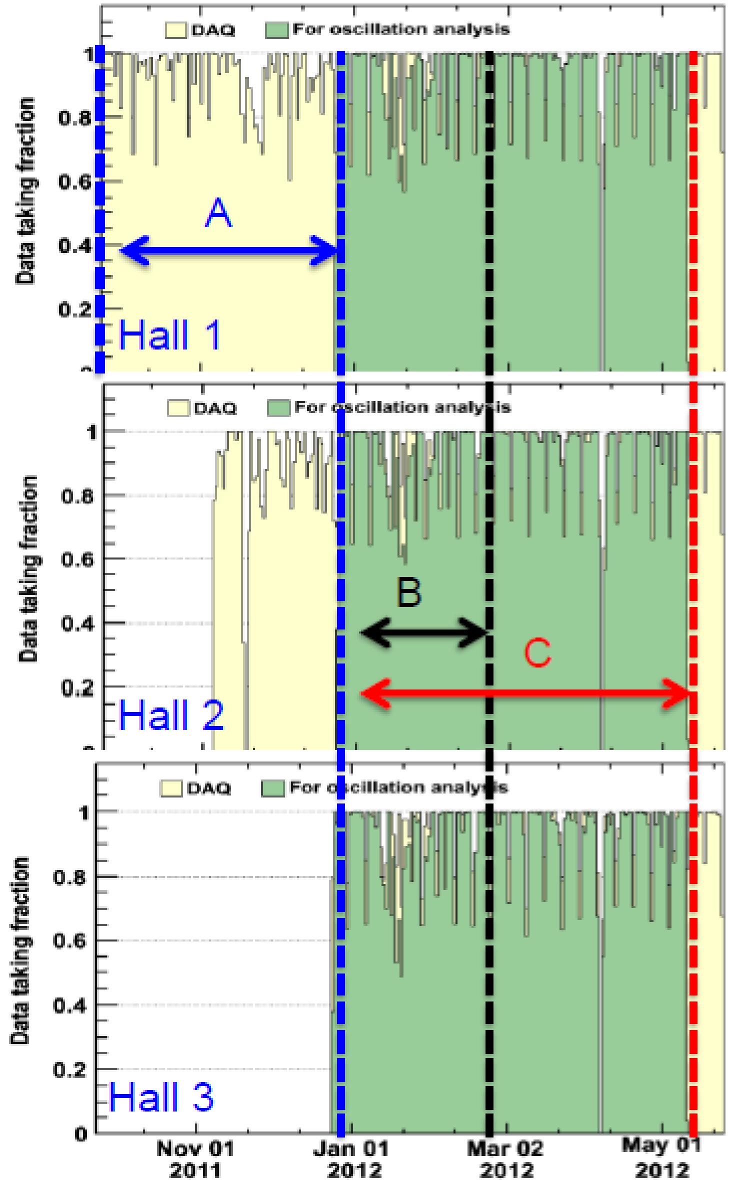
- Daya Bay has unambiguously observed reactor electron-antineutrino disappearance using 139 days of data
  - R = 0.944 $\pm$ 0.007 (stat.) $\pm$ 0.003 (syst.)
- In a 3-neutrino framework, the observed disappearance leads to a mixing angle
  - $\sin^2 2\theta_{13}$ = 0.089 $\pm$ 0.010 (stat.) $\pm$ 0.005 (syst.)
- All 8 antineutrino detectors are stable running.
- Full 6 AD data set with rate+shape analysis in preparation.
- In 3 years, Daya Bay will measure $\sin^2 2\theta_{13}$ to ~4% precision .
- Pursue other physics,
  - precise reactor neutrino flux and spectrum
  - measurement of Δm^2_{ee} (~ 4% precision)
  - Supernova
  - …

Thanks for your attention!

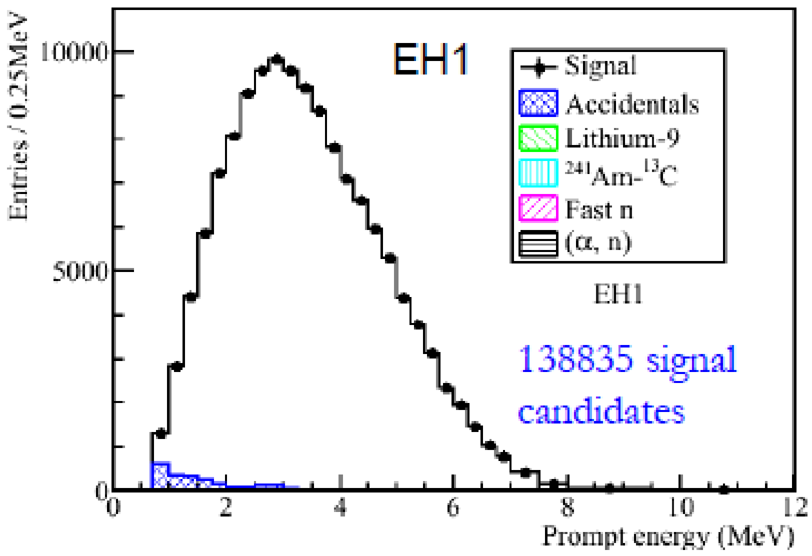
Backup

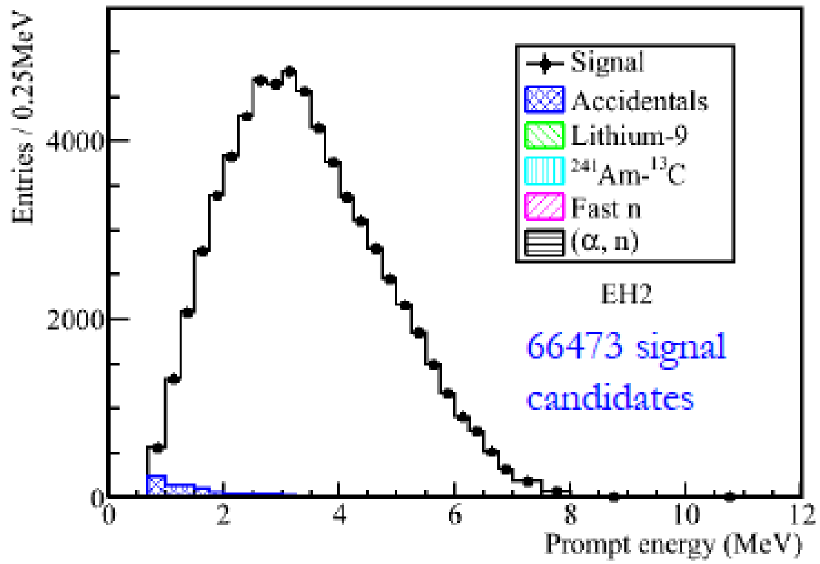
Data set

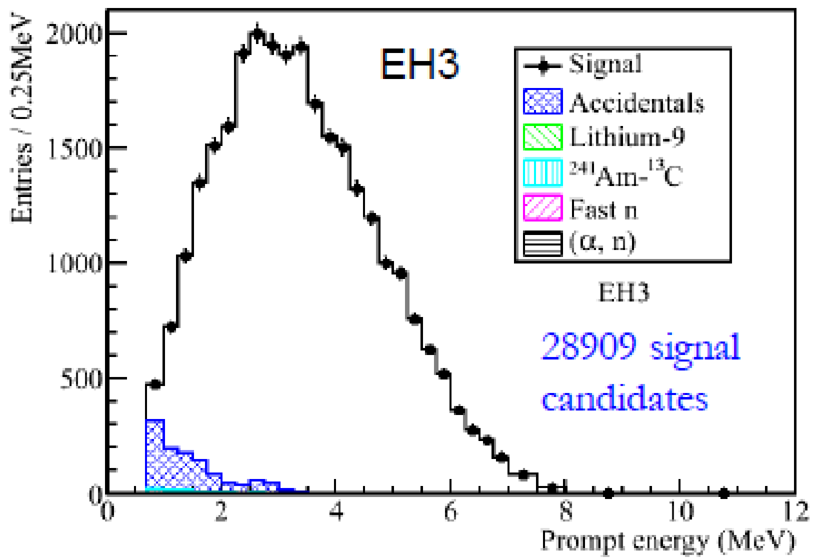
- **A→Two Detector Comparison:**
  Sep. 23, 2011 – Dec. 23, 2011
  Nucl. Inst. and Meth. A 685 (2012), pp. 78-97
- **B→First Oscillation Result:**
  Dec. 24, 2011 – Feb. 17, 2012
  Phys. Rev. Lett. 108, 171803 (2012)
- **C→Updated analysis:**
  Dec. 24, 2011 – May 11, 2012
  To be submitted to Chinese Physics C
  - **Data volume: 40TB**
  - **DAQ eff. ~96%**
  - **Eff. for physics: ~94%**



Signal+Backgound Spectrum



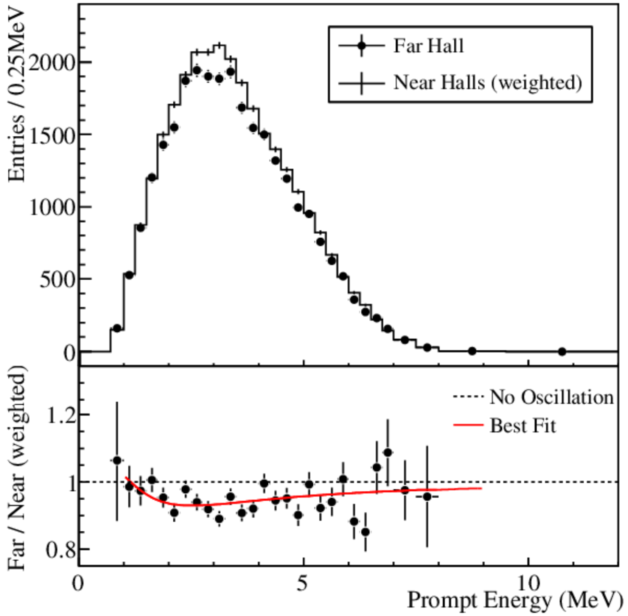




	Near Halls		Far Hall		
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %	ΔB/B
Accidentals	1.5	0.02	4.0	0.05	~1%
Fast neutrons	0.12	0.05	0.07	0.03	~40%
^{9}Li/^{8}He	0.4	0.2	0.3	0.2	~50%
^{241}Am-^{13}C	0.03	0.03	0.3	0.3	~100%
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03	~50%

Electron Anti-neutrino Disappearence: Latest results

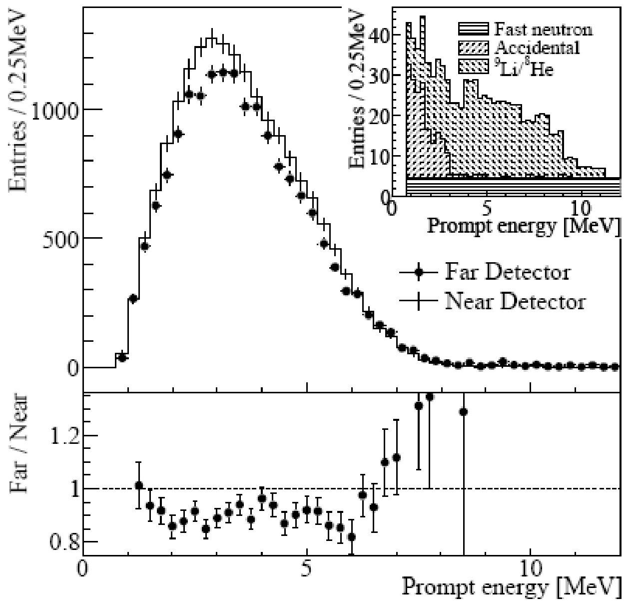
Daya Bay



R=0.944 ± 0.007 ± 0.003

$Sin^2 2\theta_{13}$=0.089±0.010±0.005
7.7 σ for non-zero θ_{13}

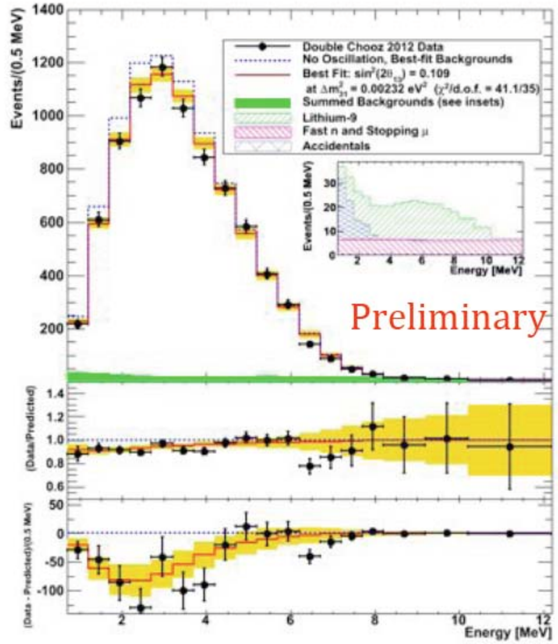
Reno



R= 0.920±0.009±0.014

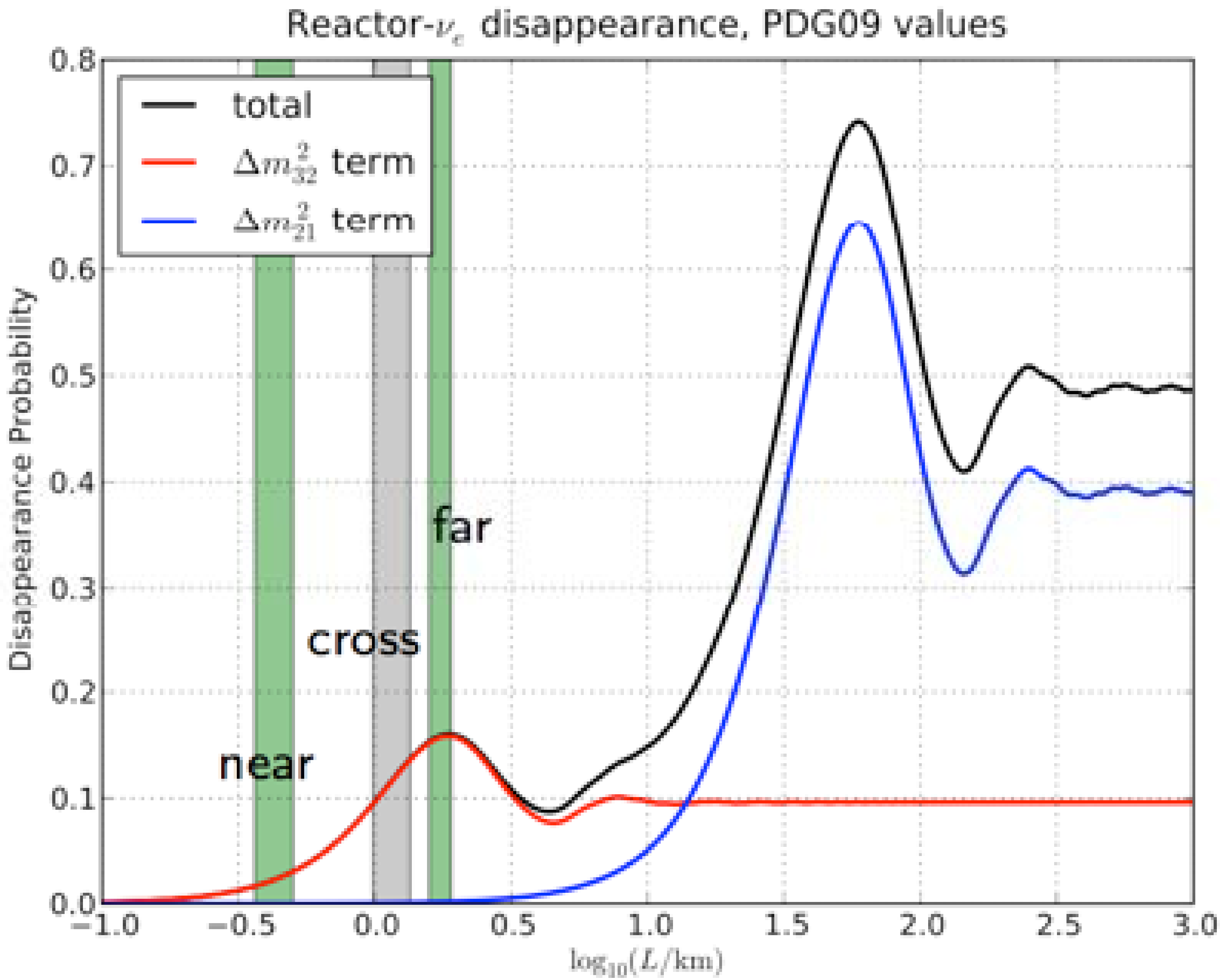
$Sin^2 2\theta_{13}$=0.113±0.013±0.019
4. 9σ for non-zero θ_{13}

Double Chooz



$Sin^2 2\theta_{13}$=0.170±0.035±0.040

$Sin^2 2\theta_{13}$=0.109±0.030±0.025
3.1 σ for non-zero θ_{13}



Reactor-ν_e disappearance, PDG09 values
total
Δm^2_{32} term
Δm^2_{21} term
Disappearance Probability
far
cross
near
$\log_{10}(L/\mathrm{km})$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0