Daya Bay Reactor Neutrino Experiment
— A Precise Measurement of θ_{13} in Near Future

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C2CR07 Conference, Lake Tahoe, Feb. 28, 2007

Physics Motivation

Weak eigenstate ≠ mass eigenstate ⇒
Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Parametrize the PMNS matrix as:

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

Solar, reactor | reactor and accelerator | Atmospheric, accelerator | $0\nu\beta\beta$

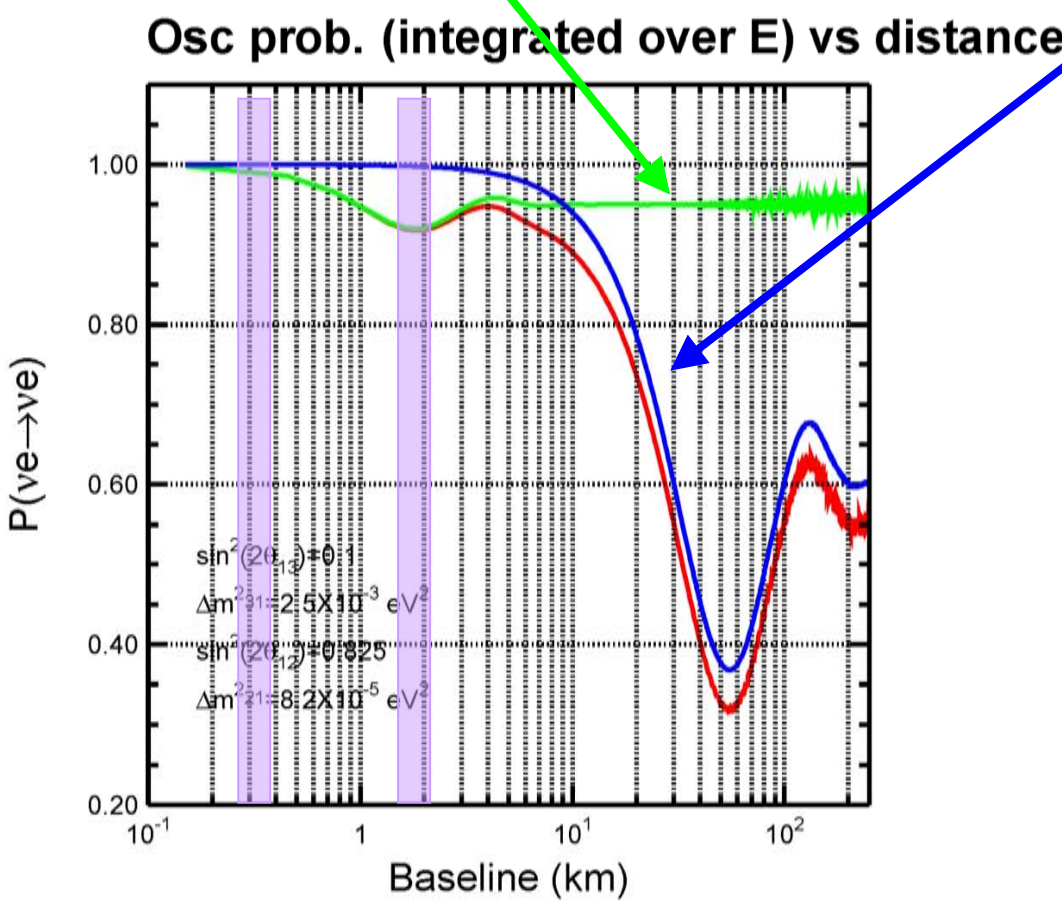
$\theta_{12} = \sim 32°$ | $\theta_{13} = ?$ | $\theta_{23} \sim 45°$

θ_{13} is the gateway of CP violation in lepton sector!

Measuring θ_{13} Using Reactor Anti-neutrinos

Electron anti-neutrino survival probability

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



Large oscillation >50 km; negligible <2 km

$\overline{\nu}_e$ disappearance at short baseline(~2 km): unambiguous measurement of θ_{13}

Objective of Near Term θ_{13} Measurement

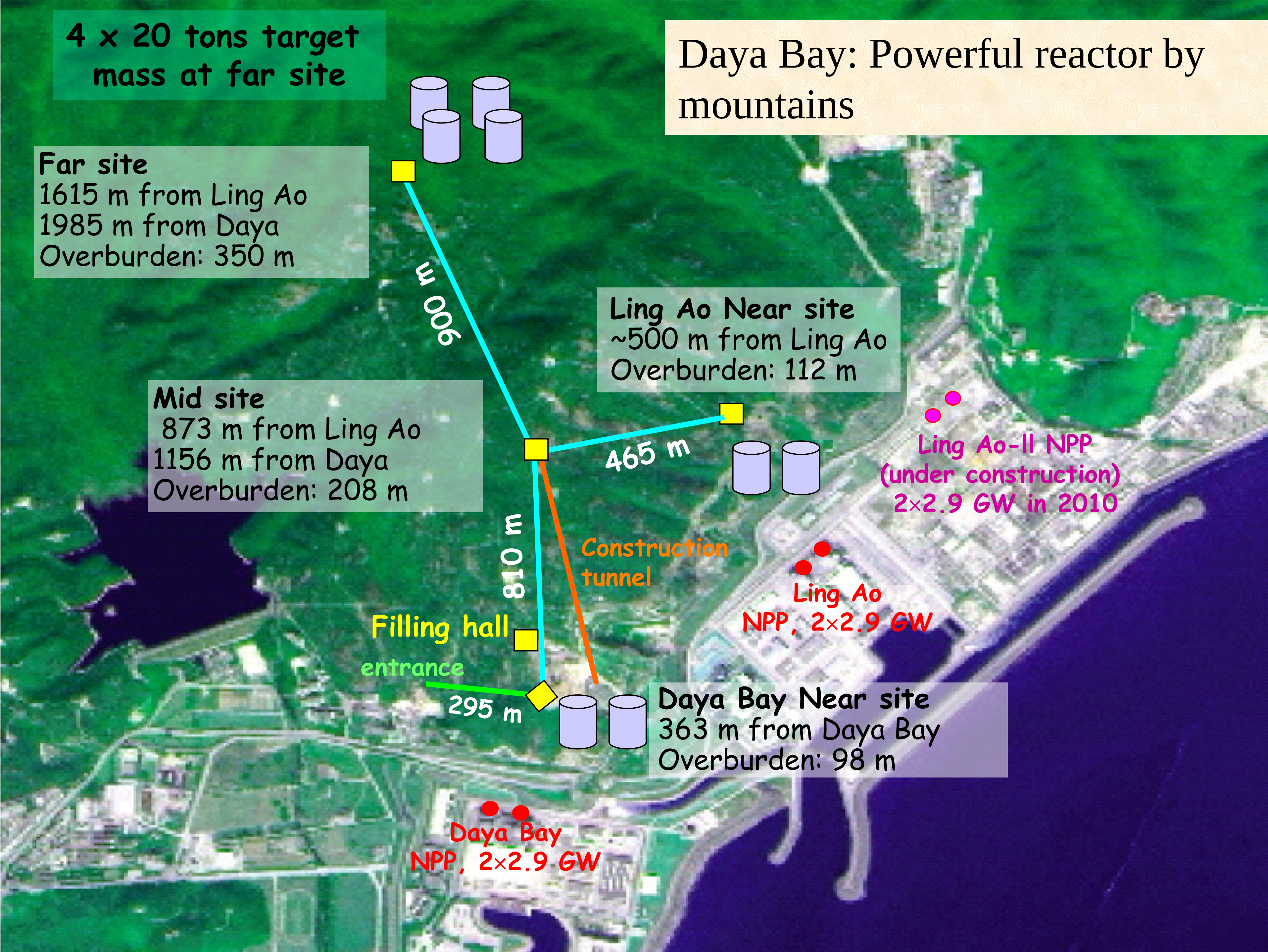
Previous best experimental limits from Chooz: $\sin^2(2\theta_{13}) < 0.17$ ($\Delta m^2_{31} = 2.5\times10^{-3}$ eV, 90% c.f.)

Build an experiment to ≤ 0.01 sensitivity to $\sin^2(2\theta_{13})$

- **Increase statistics: Use powerful reactors & large target mass**
- **Suppress background:**
  - Go deeper underground
  - High performance veto detector to MEASURE the background
- **Reduce systematic uncertainties:**
  - Reactor-related:
    Utilize near and far detectors to minimize reactor-related errors
  - Detector-related:
    - Use "Identical" pairs of detectors to do *relative* measurement
    - Comprehensive program in calibration/monitoring of detectors

Daya Bay Experiment Overview

Daya Bay: Powerful reactor by mountains



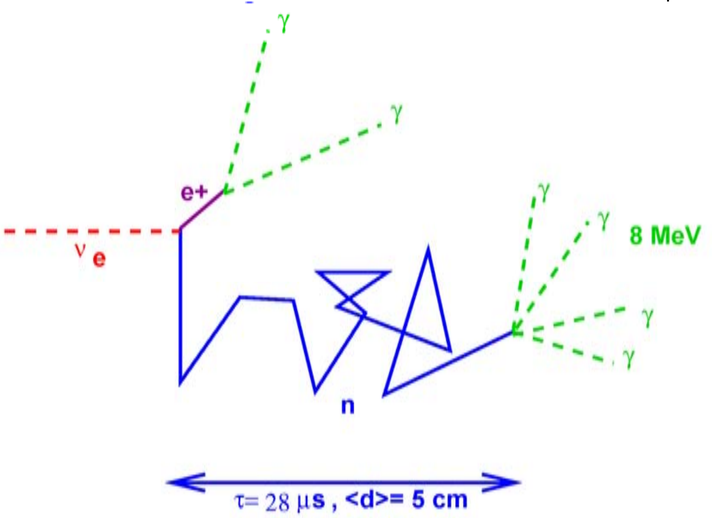
Detection of $\overline{\nu}_e$

Inverse β-decay in Gd-doped liquid scintillator:

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

$\rightarrow$ + p $\rightarrow$ D + γ(2.2 MeV) (t~180 μs) 0.3b

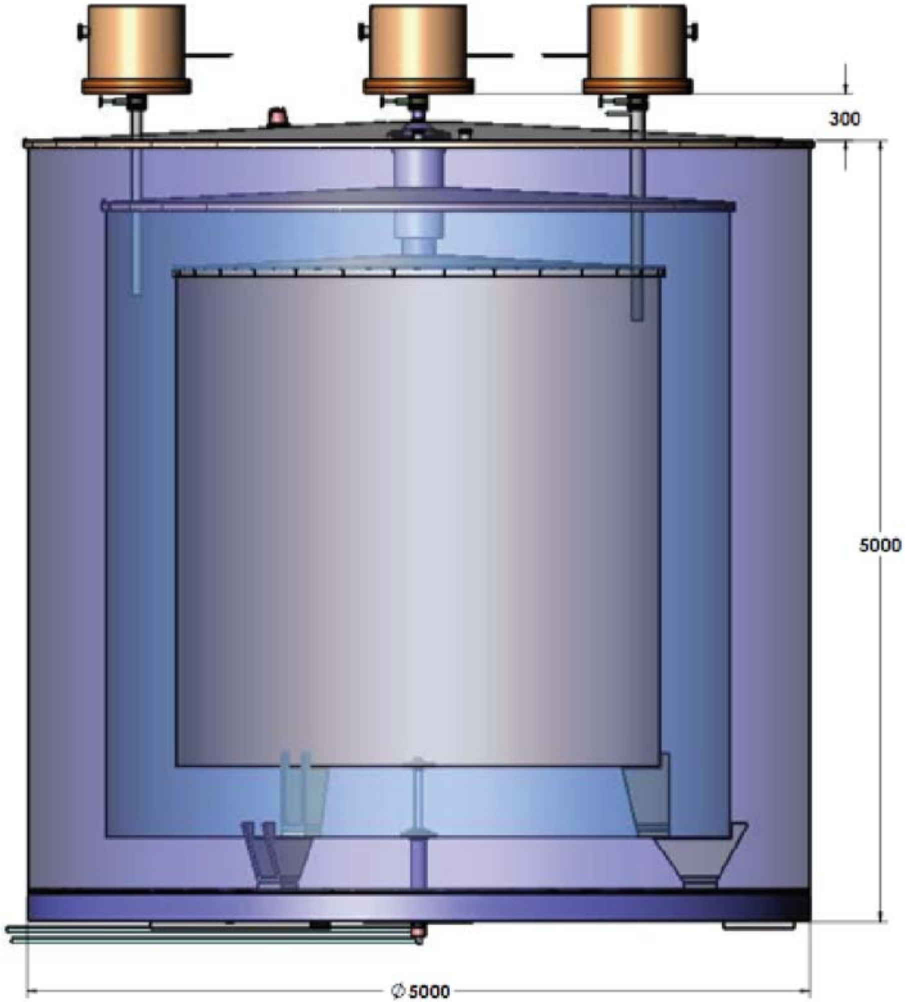
$\rightarrow$ + Gd $\rightarrow$ Gd* $\rightarrow$ Gd + γ's(8 MeV) (t~30 μs) 50,000b



Time, space and energy-tagged signal
⇒ suppress background events.

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

Antineutrino Detector



Cylindrical 3-Zone Structure separated by acrylic vessels:

- **I. Target: 0.1% Gd-loaded liquid scintillator, radius=half height= 1.55 m, 20 ton**
- **II. γ-catcher: liquid scintillator, 42.5 cm thick**
- **III. Buffer shielding: mineral oil, 48.8 cm thick**

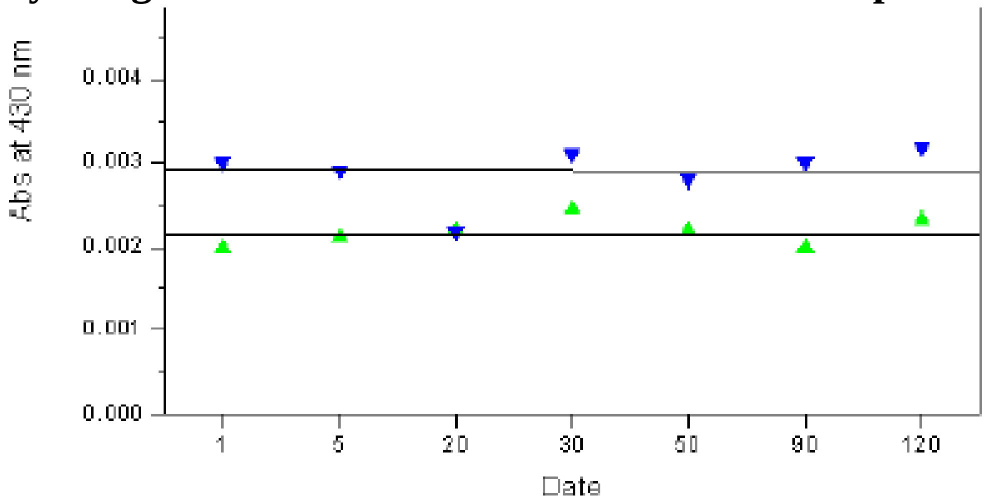
With 224 PMT's on circumference and reflective reflectors on top and bottom:

$$\frac{\sigma}{E} \sim \frac{12.2\%}{\sqrt{E(\mathrm{MeV})}}, \quad \sigma_{\mathrm{vertex}} = 13\mathrm{cm}$$

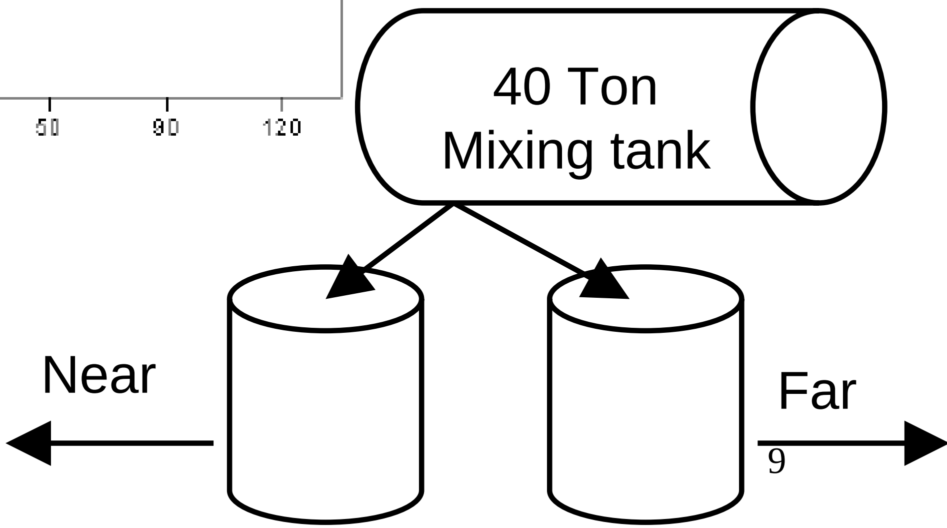
Gd-loaded Liquid Scintillator

- Baseline recipe: Linear Alkyl Benzene (LAB) doped with organic Gd complex (0.1% Gd mass concentration)
- LAB (suggested by SNO+): high flashpoint, safer for environment and health, commercially produced for detergents.

Stability of light attenuation two Gd-loaded LAB samples over 4 months



- Filling **detectors in pair**



Inverse-beta Signals

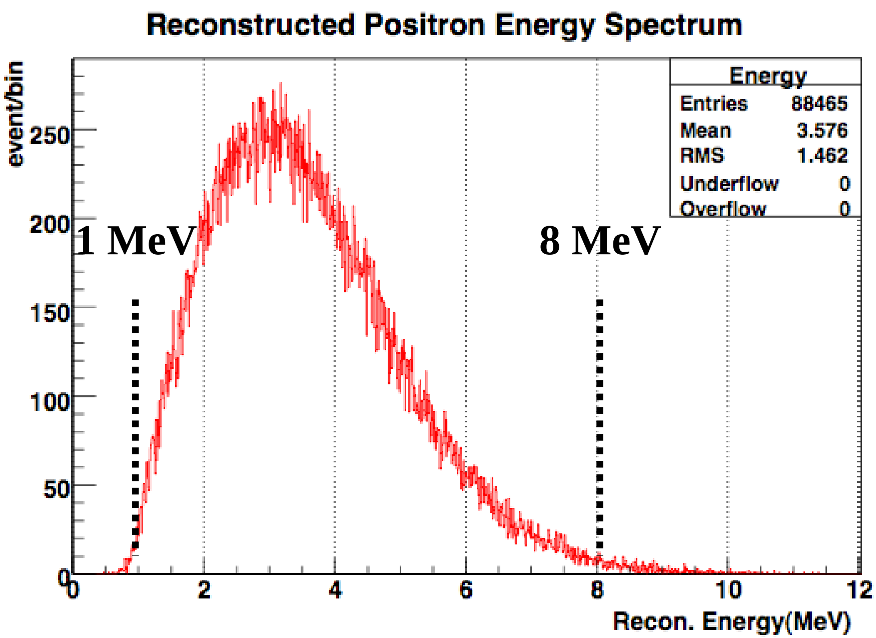
Antineutrino Interaction Rate (events/day per 20 ton module)	
Daya Bay near site	960
Ling Ao near site	760
Far site	90

E_{e+}("prompt") $\in$[1,8] MeV

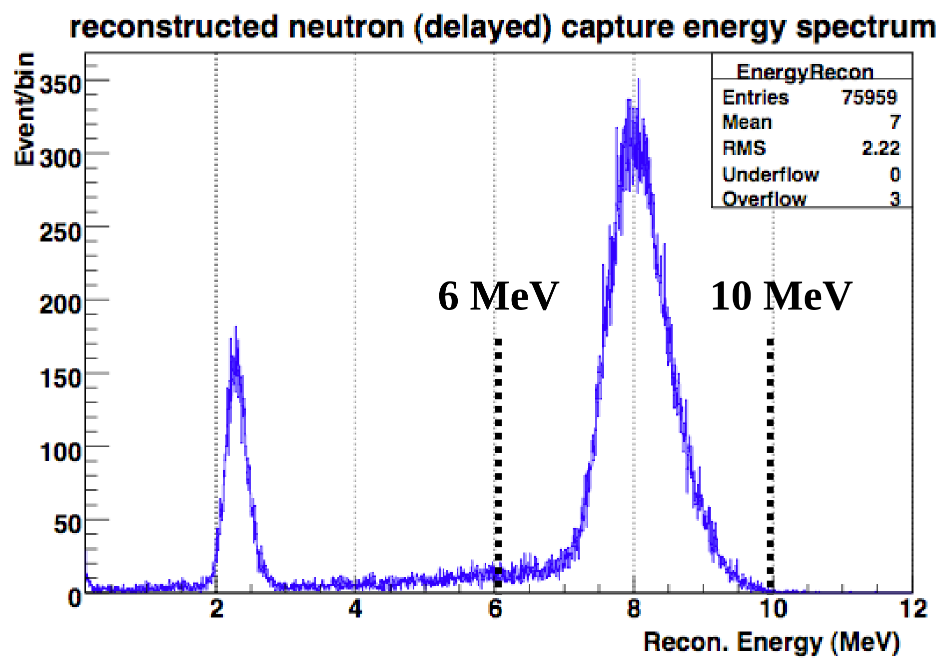
$E_{n\text{-}cap}$ ("delayed") $\in$ [6,10] MeV

$t_{delayed}$-t_{prompt} $\in$ [0.3,200] μs

Prompt Energy Signal



Delayed Energy Signal

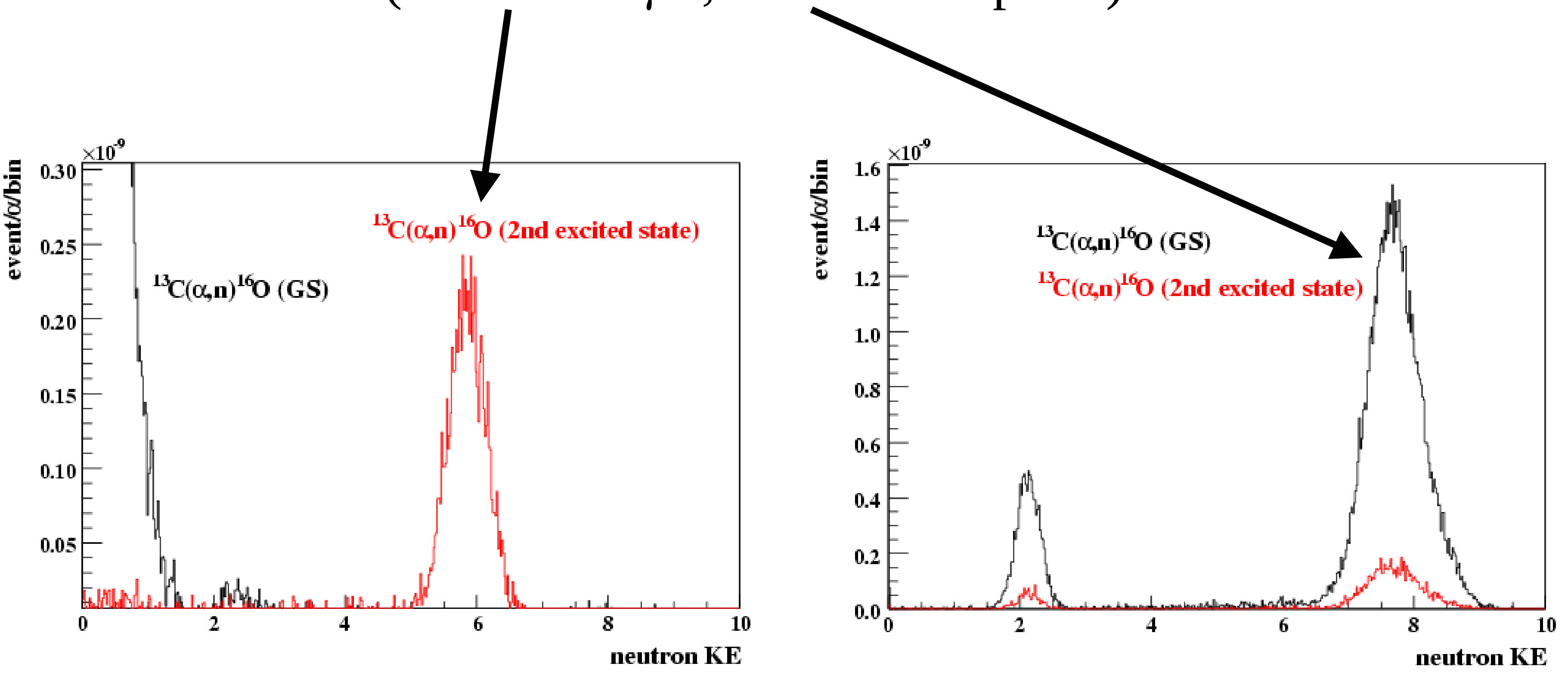


Statistics comparable to a single module at far site in 3 years.

Calibrating Energy Cuts

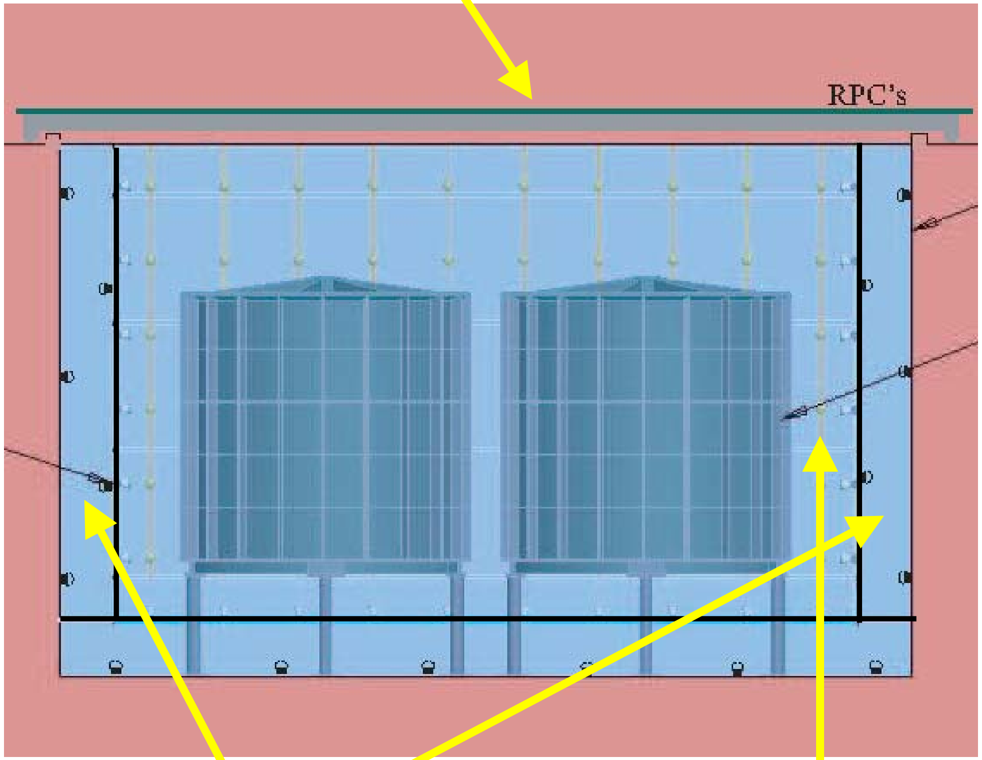
Automated deployed radioactive sources to calibrate the detector energy and position response within the entire range.

- ^{68}Ge (0 KE $e^+ = 2 \times 0.511$ MeV γ's)
- ^{60}Co (2.506 MeV γ's)
- ^{238}Pu-^{13}C (6.13 MeV γ's, 8 MeV n-capture)



Muon "Veto" System

Resistive plate chamber (RPC)



Outer water sheild   Inner water shield

- Surround detectors with at least 2.5m of water, which shields the external radioactivity and cosmogenic background
- Water shield is divided into two optically separated regions (with reflective divider, 8" PMTs mounted at the zone boundaries), which serves as two active and independent muon tagger
- Augmented with a top muon tracker: RPCs
- Combined efficiency of tracker > 99.5% with error measured to better than 0.25%

Background and Systematics

Backgrounds

Background = "prompt"+"delayed" signals that fake inverse-beta events

Three main contributors, **all can be measured:**

Background type	Experimental Handle
Muon-induced fast neutrons (prompt recoil, delayed capture) from water or rock	>99.5% parent "water" muons tagged ~1/3 parent "rock" muons tagged
^{9}Li/^{8}He ($T_{1/2}$= 178 msec, β decay w/neutron emission, delayed capture)	Tag parent "showing" muons
Accidental prompt and delay coincidences	Single rates accurately measured

B/S:

	DYB site	**LA site**	**Far site**
Fast n / signal	0.1%	0.1%	0.1%
^{9}Li-^{8}He / signal	0.3%	0.2%	0.2%
Accidental/signal	<0.2%	<0.2%	<0.1%

Systematics Budget

Detector-related

Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*) Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	< 0.01	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

Baseline: currently achievable **relative** uncertainty without R&D
Goal: expected **relative** uncertainty after R&D
Swapping: can reduce **relative** uncertainty further

Reactor-related

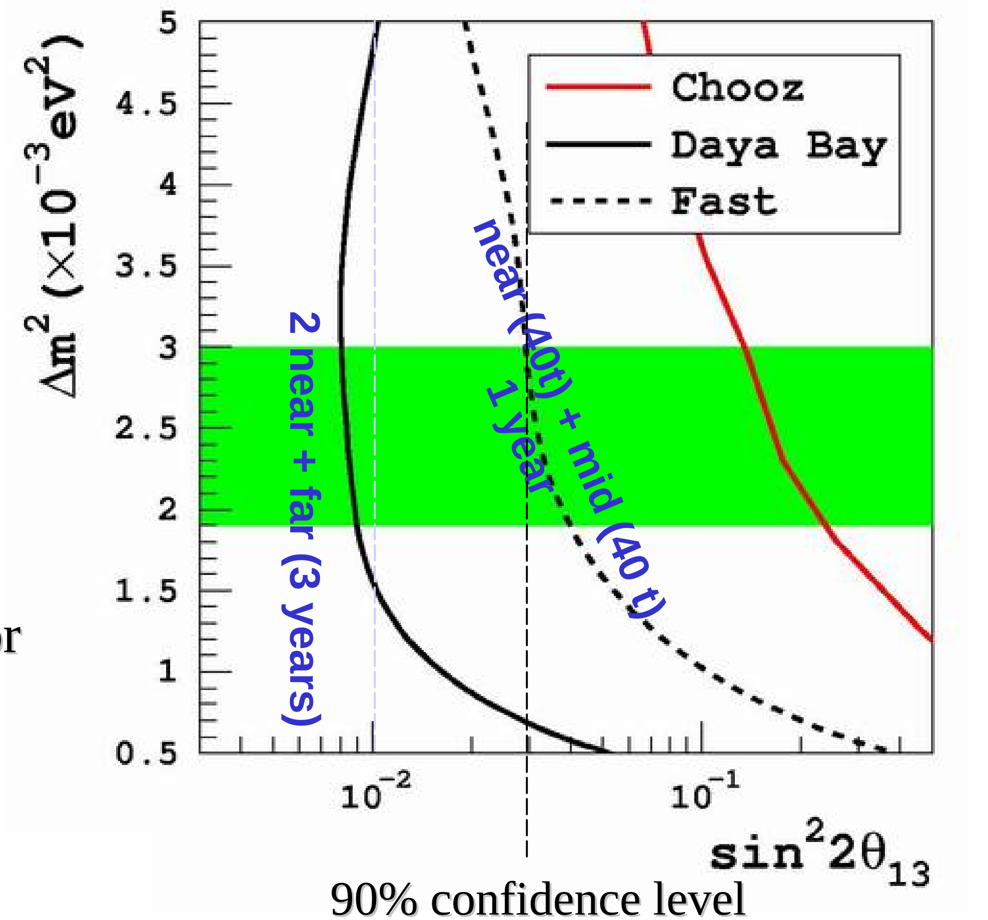
Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

Daya Bay Sensitivity

Daya Bay Sensitivity

Source	Uncertainty
Reactor Power	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Signal Statistics	0.2%

- Assume backgrounds are measured to<0.2%.
- Use rate and spectral shape.
- Input relative detector systematic error of 0.2%.



90% confidence level

1 year of data taking = 300 days

Milestones

Summer 07 Begin civil construction

June 09 Start commissioning first two detectors

June 10 Begin data taking with near-far


Collaboration Institutes: Asia (17), US (14), Europe (3)
~130 collaborators

Backups

Daya Bay Site

Daya Bay NPP 2.9GW×2

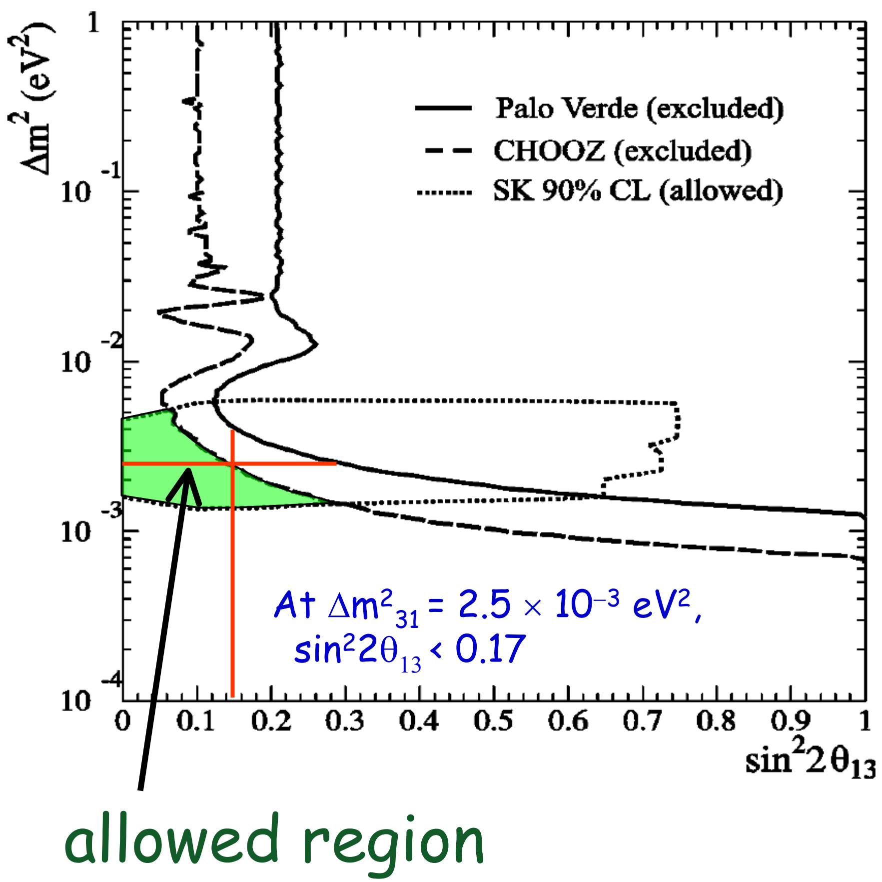
LingAo NPP 2.9GW×2

1 GW_{th} generates 2 × 10^{20} $\bar{\nu}_e$ per sec

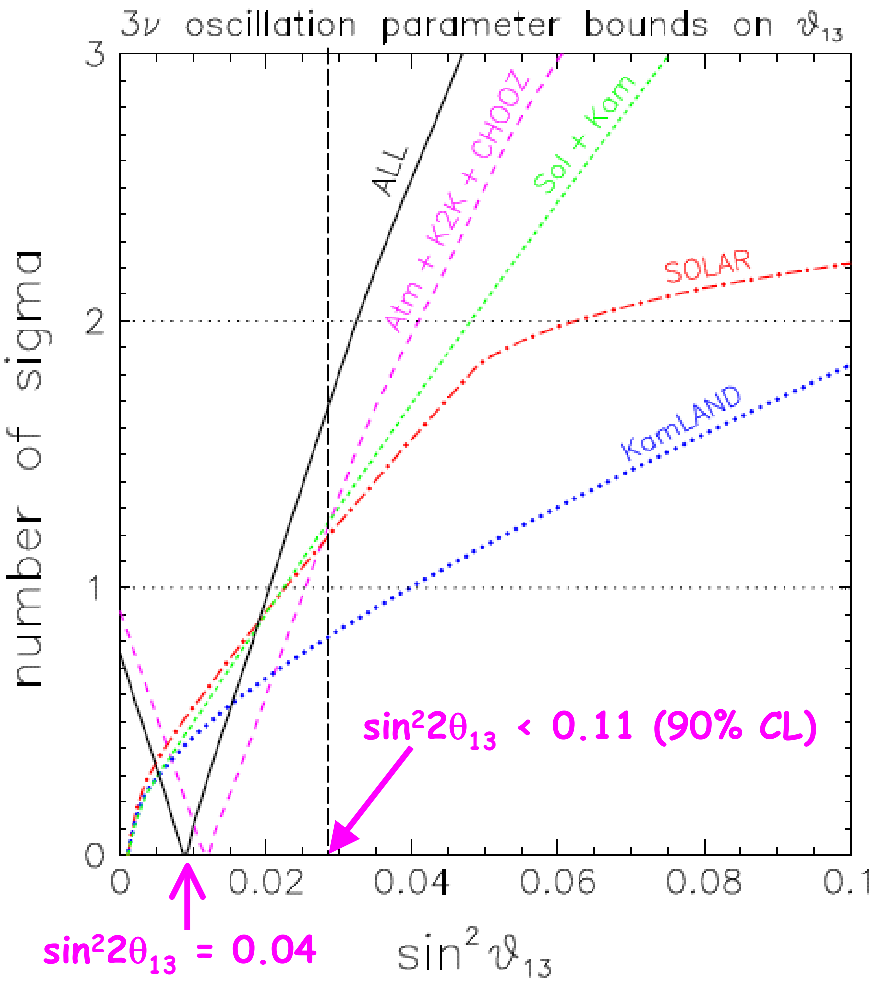
Powerful reactor by mountain (horizontal tunnels are easier and cheaper to construct)!

Current Knowledge of θ_{13}

Direct search



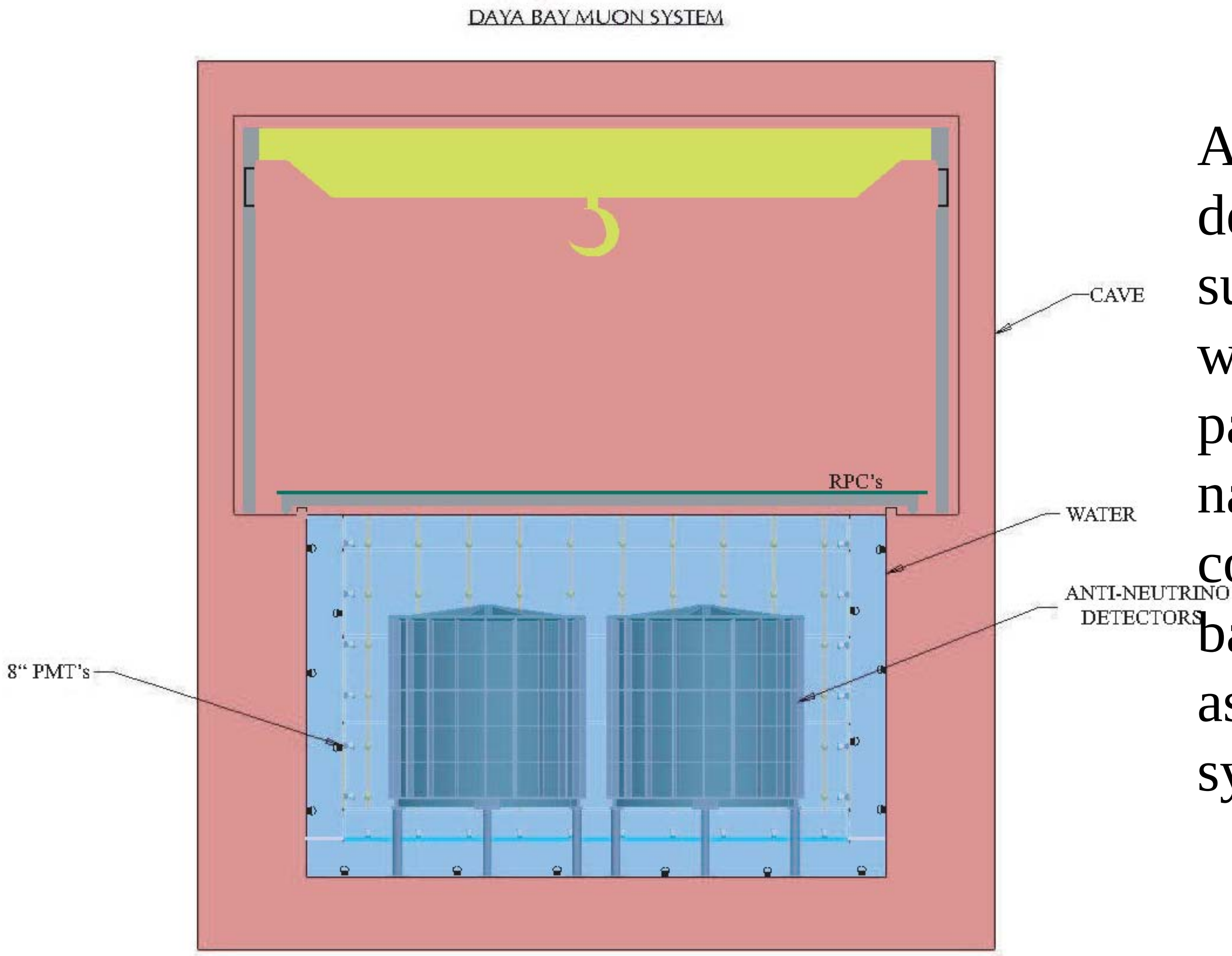
Global fit



Best fit value of $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

Fogli etal., hep-ph/0506083

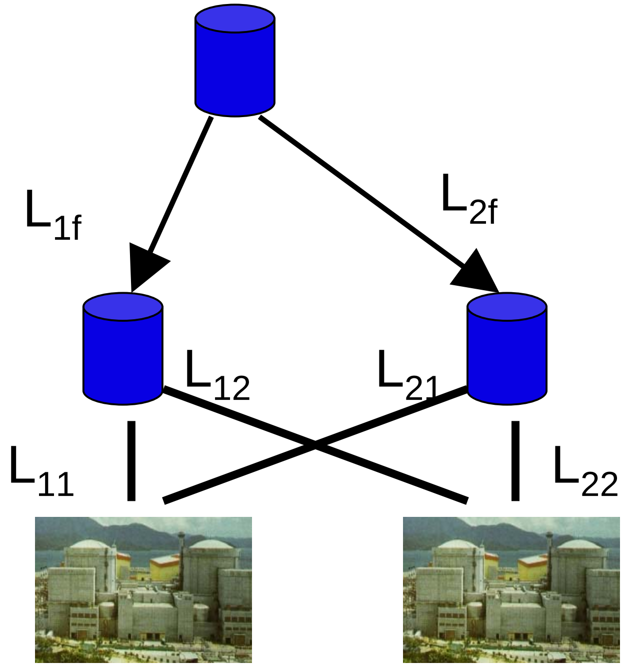
Daya Bay Detector Hall Layout



Anti-neutrino detector tanks surrounded by water, which act as a passive shield of the natural and cosmogenic background, as well as active veto system.

Reactor Related Systematic Uncertainty

*For multi cores, apply a trick to **deweight oversampled** cores to maximize near/far cancellation of the reactor power fluctuation.*



$$\alpha = \frac{\frac{1}{L_{22}^2 L_{1f}^2} - \frac{1}{L_{21}^2 L_{2f}^2}}{\frac{1}{L_{11}^2 L_{2f}^2} - \frac{1}{L_{12}^2 L_{1f}^2}}$$

$$\frac{\text{Near}}{\text{Far}} = \alpha \frac{\text{Near1}}{\text{Far}} + \frac{\text{Near2}}{\text{Far}}$$

Assuming 30 cm precision in core position

Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

Monitoring/Calibration Program

- Load sensors, level sensors, thermometers, flow meters, mass flow meters to measure the mass, volume, and other physical property of the target.

- Automated deployed LED diffuser balls to calibrate the optical parameters of the detectors (attenuation length, reflectivity, phototube QE, etc) accurately.

- Automated deployed radioactive sources to calibrate the detector energy and position response within the entire range.
  - ^{68}Ge (0 KE e^{+} = 2×0.511 MeV γ's)
  - ^{60}Co (2.506 MeV γ's)
  - ^{238}Pu-^{13}C (6.13 MeV γ's, 8 MeV n-capture)

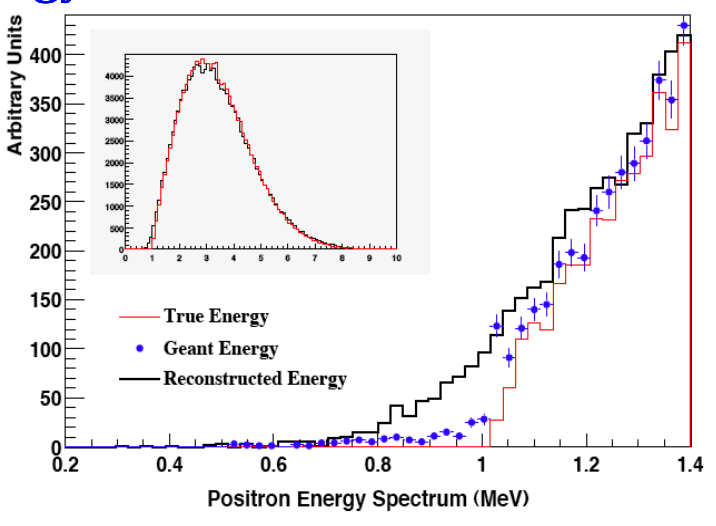
- Using data: spallation neutrons, ^{12}B, Michel electrons. Uniformly sample the entire fuducial

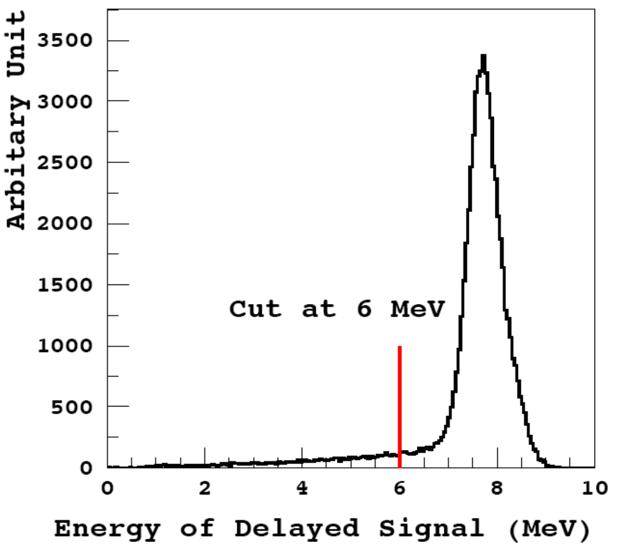
Detector Related Systematic Uncertainty

Number of Protons

- Mass: volume flow < 0.02%, mass flow < 0.1%
- H/C ratio: filling near/far pair detectors underground with liquid from same batch

Energy Cuts

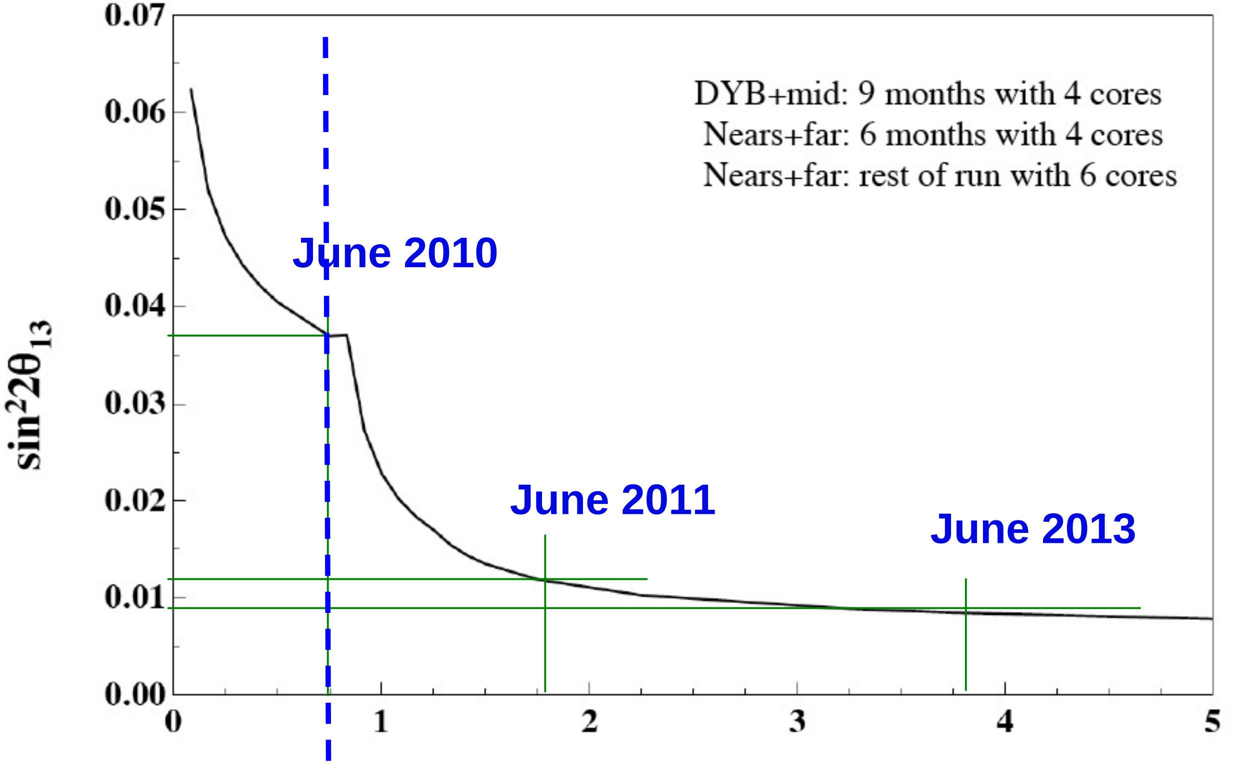


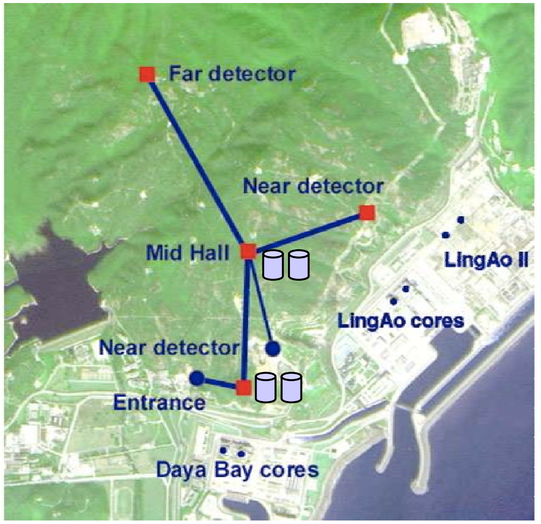


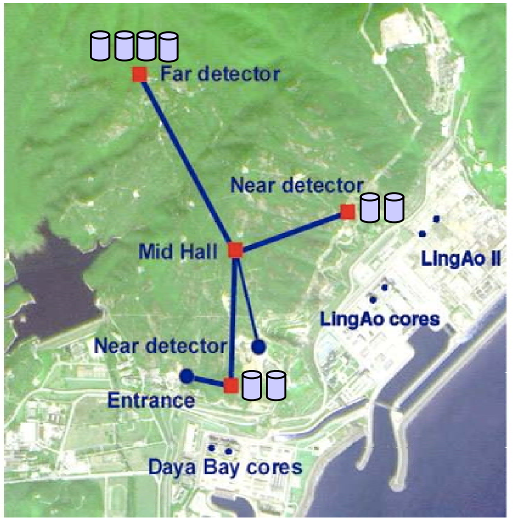
Routine monitoring with ^{68}Ge source nails the positron threshold → positron efficiency < 0.05%

Use 6 MeV gamma from ^{238}Pu-^{13}C source to nail the neutron energy cut → neutron efficiency < 0.2%

Daya Bay Sensitivity by Year







Baseline Deployment plan

9 months with near-mid

3 years with near-far

20 t detector module