Daya Bay Reactor Neutrino Oscillation Experiment

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

(on behalf of the Daya Bay Collaboration)

International Workshop on "Double Beta Decay and Neutrinos" Osaka, Japan, June 11-13, 2007

Outline

- Physics case for a precise θ_{13} measurement
- The proposed Daya Bay neutrino oscillation experiment
- Schedule and expected sensitivity of the Daya Bay experiment

What we have learned from neutrino oscillation experiments

1) Neutrinos are massive

$$\Delta m_{21}^2 = m_2^2 - m_1^2 = (7.9 \pm 0.7) \times 10^{-5}\,\mathrm{ev}^2 \quad (90\%\,\mathrm{c.l.})$$

$$|\Delta m_{32}^2| = |m_3^2 - m_2^2| = (2.4 \pm 0.6) \times 10^{-3}\,\mathrm{ev}^2 \quad (90\%\ \mathrm{c.l.})$$

2) Neutrinos do mix with each other

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$(c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij})$$

$\theta_{12} \,\square\, 34^\circ, \ \theta_{23} \,\square\, 45^\circ, \ \theta_{13} \le 13^\circ$ for the lepton MNSP Matrix

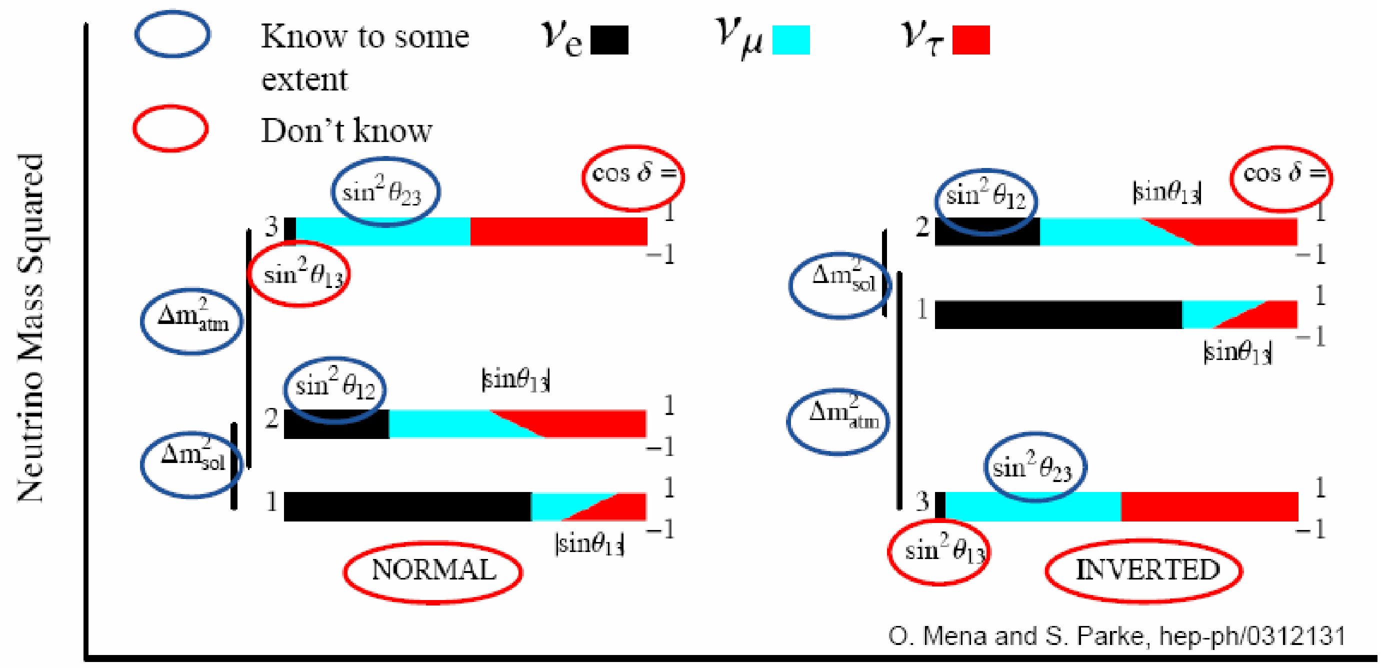
$\theta_{12} \,\square\, 13^\circ, \ \theta_{23} \,\square\, 2.2^\circ, \ \theta_{13} \,\square\, 0.22^\circ$ for the quark CKM Matrix

3) Neutrino masses and mixings have provided clear evidence for physics beyond the Standard Model

What we do not know about the neutrinos

- Dirac or Majorana neutrinos?
- Mass hierachy and values of the masses?
- Existence of sterile neutrinos?
- Value of the θ_{13} mixing angle?
- Values of CP-violation phases?
- Origins of the neutrino masses?
- Other unknown unknowns …..

What we know and do not know about the neutrinos



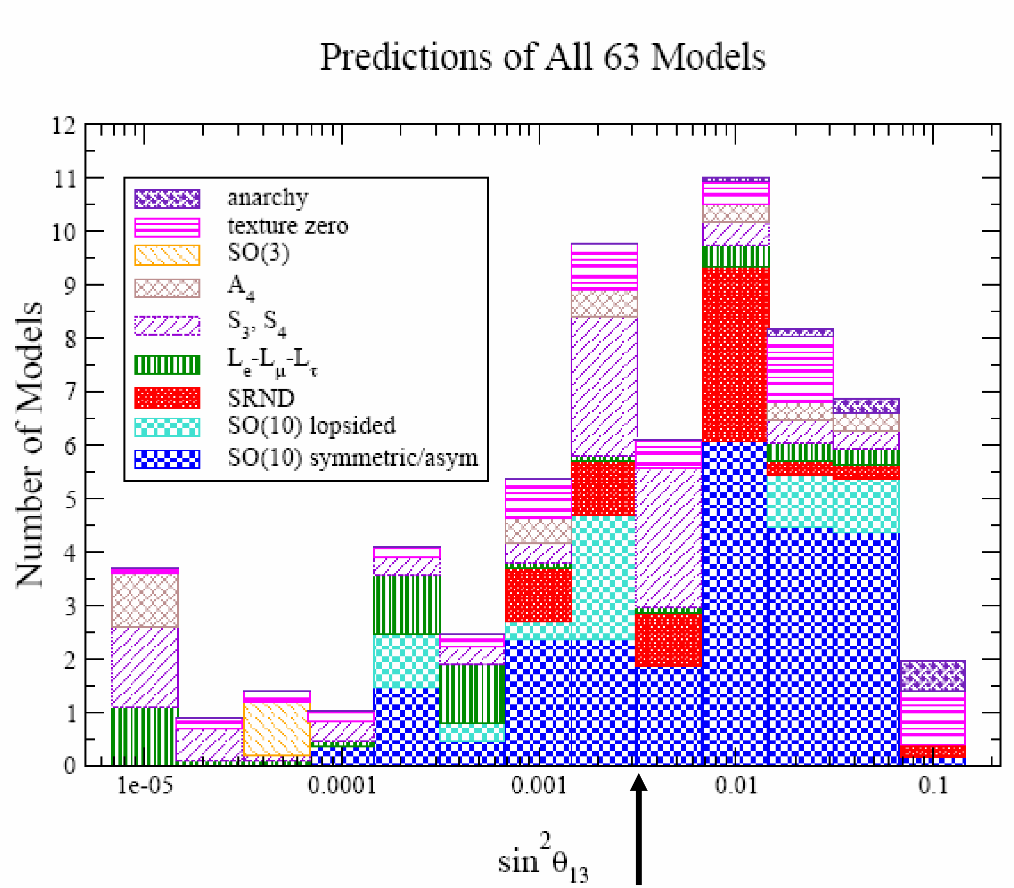
- What is the ν_e fraction of ν_3? (proportional to $\sin^2\theta_{13}$)
- Contributions from the CP-phase δ to the flavor compositions of neutrino mass eigenstates depend on $\sin^2\theta_{13}$)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Why measuring θ_{13}?

A recent tabulation of predictions of 63 neutrino mass models on $\sin^2\theta_{13}$

(hep-ph/0608137)



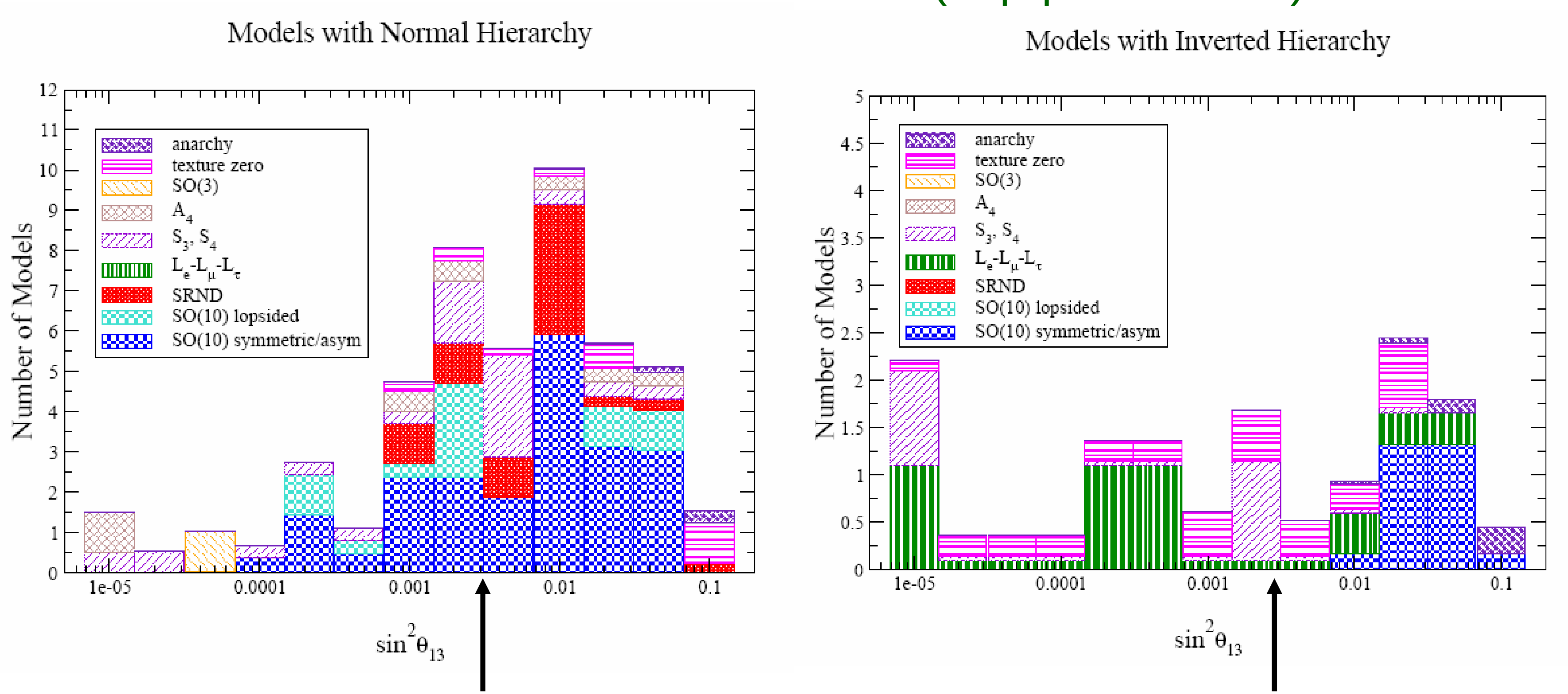
- Models based on the Grand Unified Theories in general give relatively large θ_{13}
- Models based on leptonic symmetries predict small θ_{13}

A measurement of $\sin^2 2\theta_{13}$ at the sensitivity level of 0.01 can rule out at least half of the models!

Why measuring θ_{13}?

A recent tabulation of predictions of 63 neutrino mass models on $\sin^2\theta_{13}$

(hep-ph/0608137)



A measurement of $\sin^2 2\theta_{13}$ AND the mass hierarchy can rule out even more models!

Why measuring θ_{13}?

Leptonic CP violation

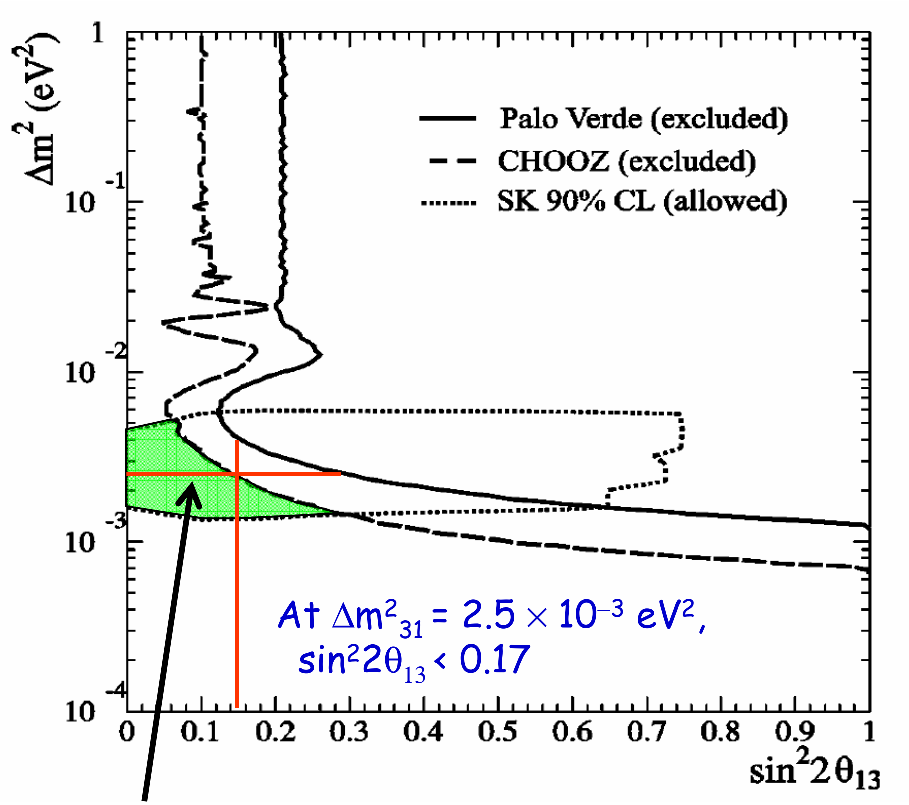
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

If $\sin^2 2\theta_{13} > 0.02\text{-}0.03$, then NOvA+T2K will have good coverage on CP δ.

Size of $\sin^2 2\theta_{13}$ sets the scale for future leptonic CP violation studies

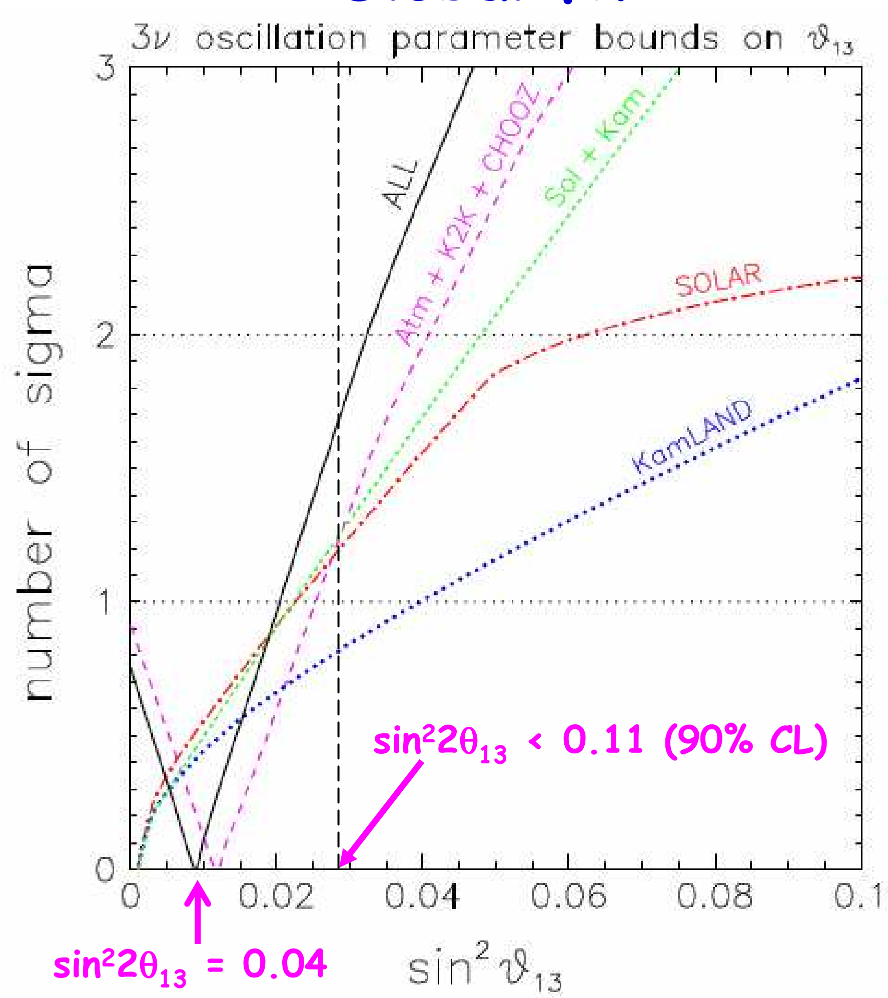
Current Knowledge of θ_{13}

Direct search



allowed region

Global fit

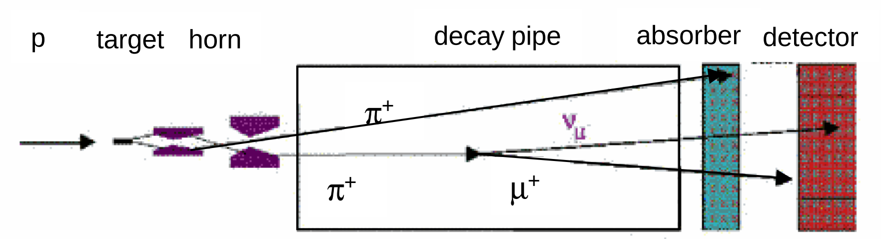


Best fit value of $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

Fogli etal., hep-ph/0506083

Some Methods For Determining θ_{13}

Method 1: Accelerator Experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \ldots$$

- $\nu_\mu \to \nu_e$ appearance experiment
- need other mixing parameters to extract θ_{13}
- baseline *O(100-1000 km)*, matter effects present
- expensive

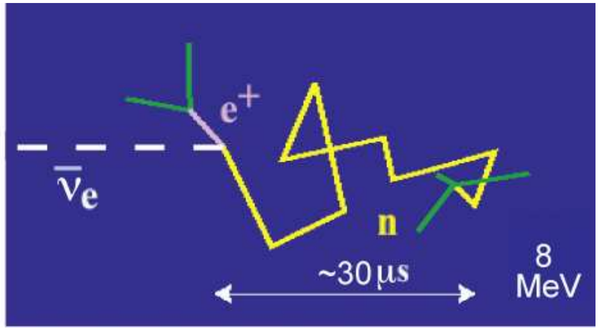
Method 2: Reactor Experiments

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

- $\bar{\nu}_e \to X$ disappearance experiment
- baseline *O(1 km)*, no matter effect, no ambiguity
- relatively cheap

Detecting $\bar{\nu}$: Inverse β Decay

- The reaction is the inverse β-decay in 0.1% Gd-doped liquid scintillator: $\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt)



0.3b $\rightarrow$ + p $\rightarrow$ D + γ(2.2 MeV) (delayed)

50,000b $\rightarrow$ + Gd $\rightarrow$ Gd*

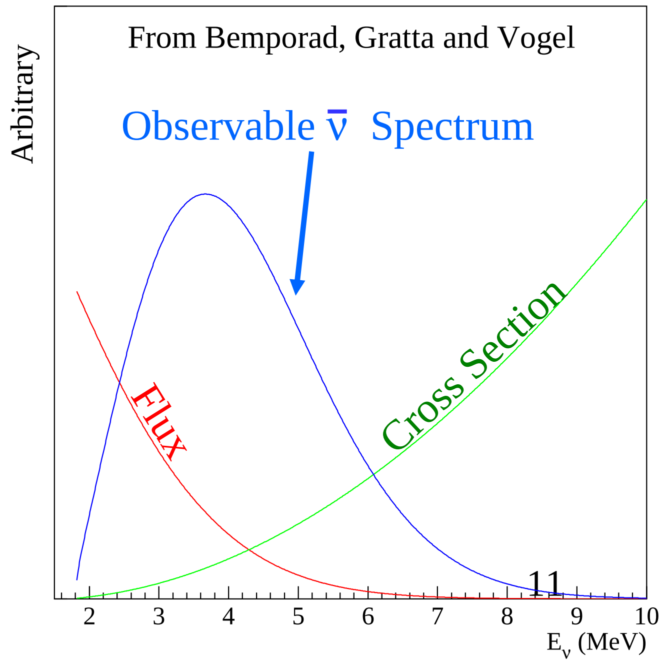
$\rightarrow$ Gd + γ's(8 MeV) (delayed)

- Time- and energy-tagged signal is a good tool to suppress background events.

- Energy of $\bar{\nu}_e$ is given by:

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

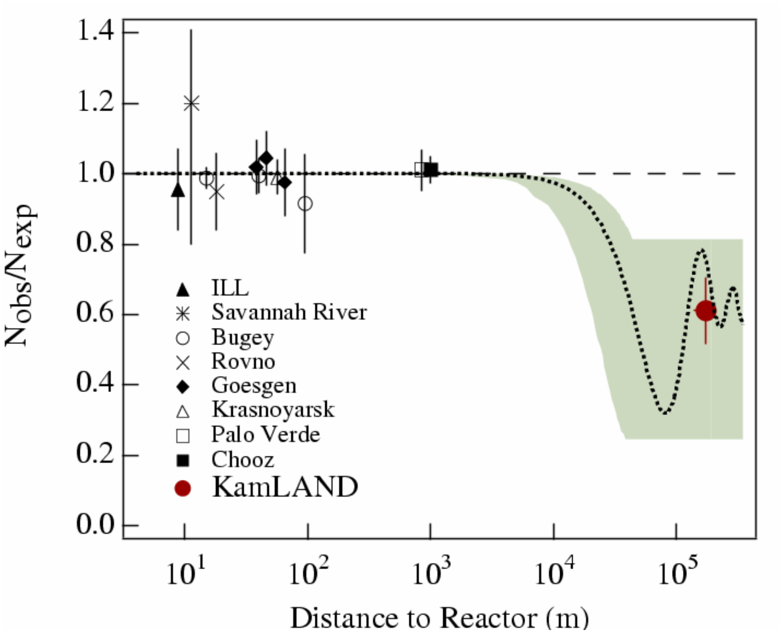
10-40 keV (under T_n)



Measuring θ_{13} with Reactor Neutrinos

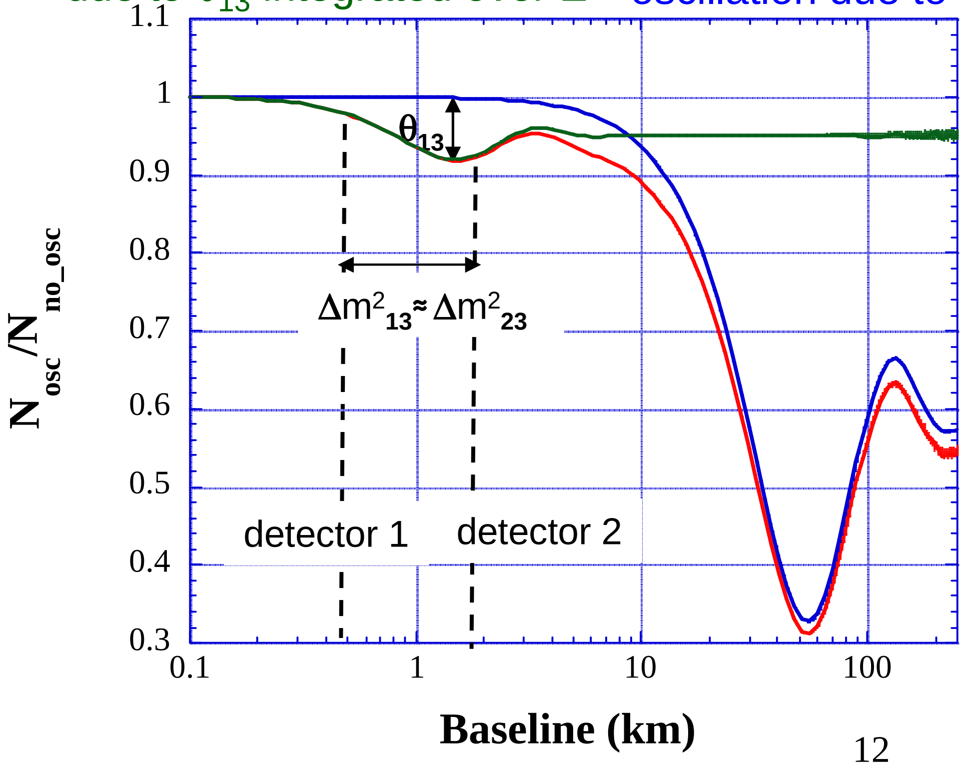
Search for θ_{13} in new oscillation experiment

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

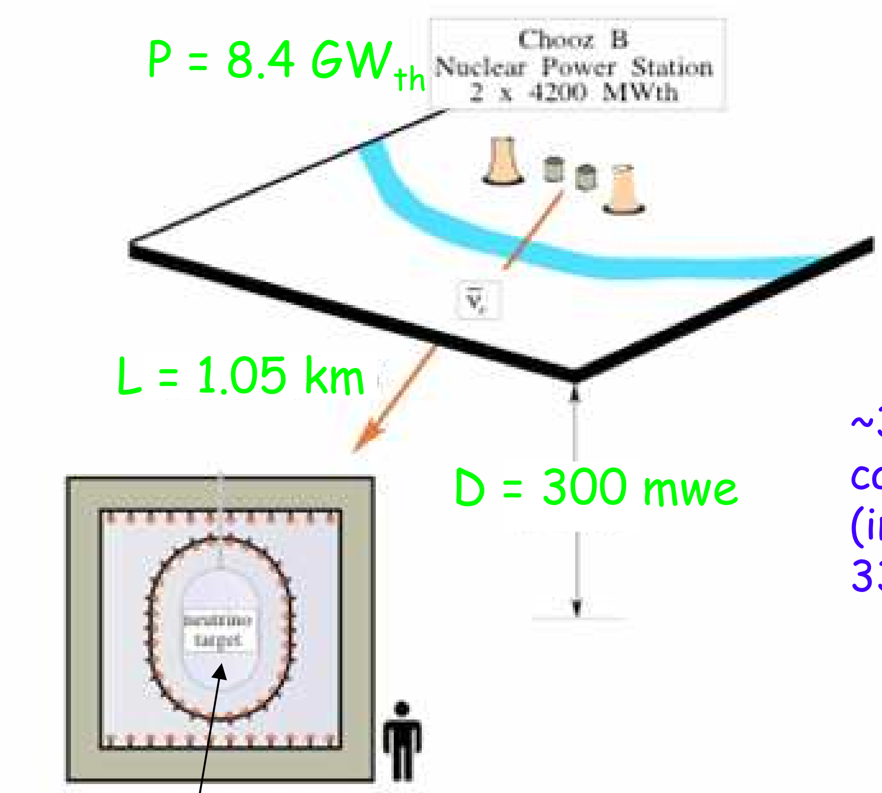


Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}



Results from Chooz

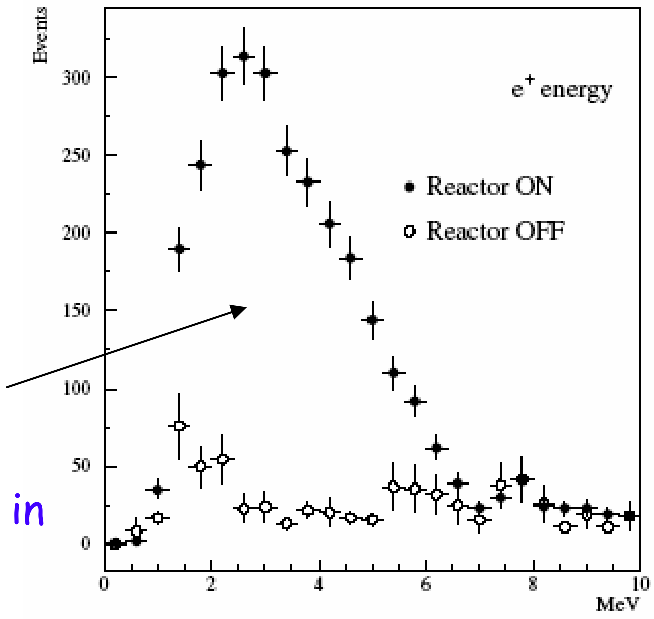


5-ton 0.1% Gd-loaded liquid scintillator to detect $\bar{\nu}_e + p \rightarrow e^+ + n$

Rate:

~5 evts/day/ton (full power)
including 0.2-0.4 bkg/day/ton

~3000 $\bar{\nu}_e$ candidates (included 10% bkg) in 335 days



Systematic uncertainties

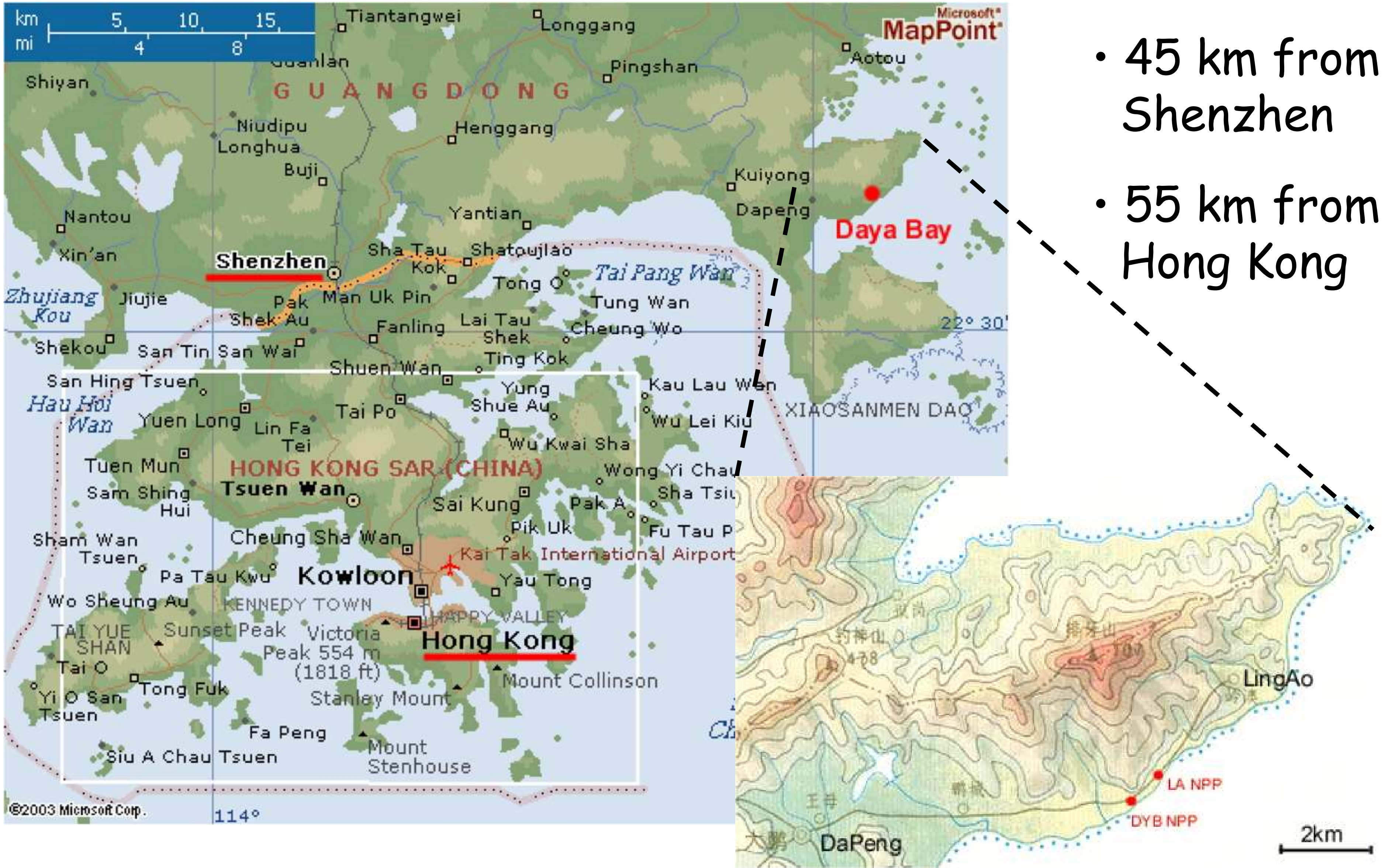
parameter	relative uncertainty (%)
reaction cross section	1.9
number of protons	0.8
detection efficiency	1.5
reactor power	0.7
energy released per fission	0.6
combined	2.7

How to Reach a Precision of 0.01 in $\sin^2 2\theta_{13}$?

- **Increase statistics:**
  - Use more powerful nuclear reactors
  - Utilize larger target mass, hence larger detectors
- **Suppress background:**
  - Go deeper underground to gain overburden for reducing cosmogenic background
- **Reduce systematic uncertainties:**
  - Reactor-related:
    - Optimize baseline for best sensitivity and smaller reactor-related errors
    - 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
    - Interchange near and far detectors (optional)

World of Proposed Reactor Neutrino Experiments

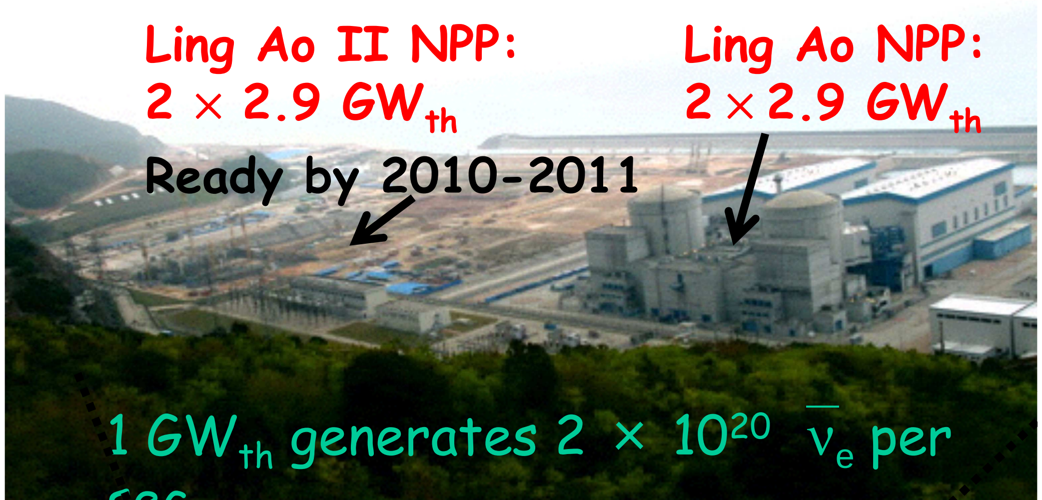
Location of Daya Bay

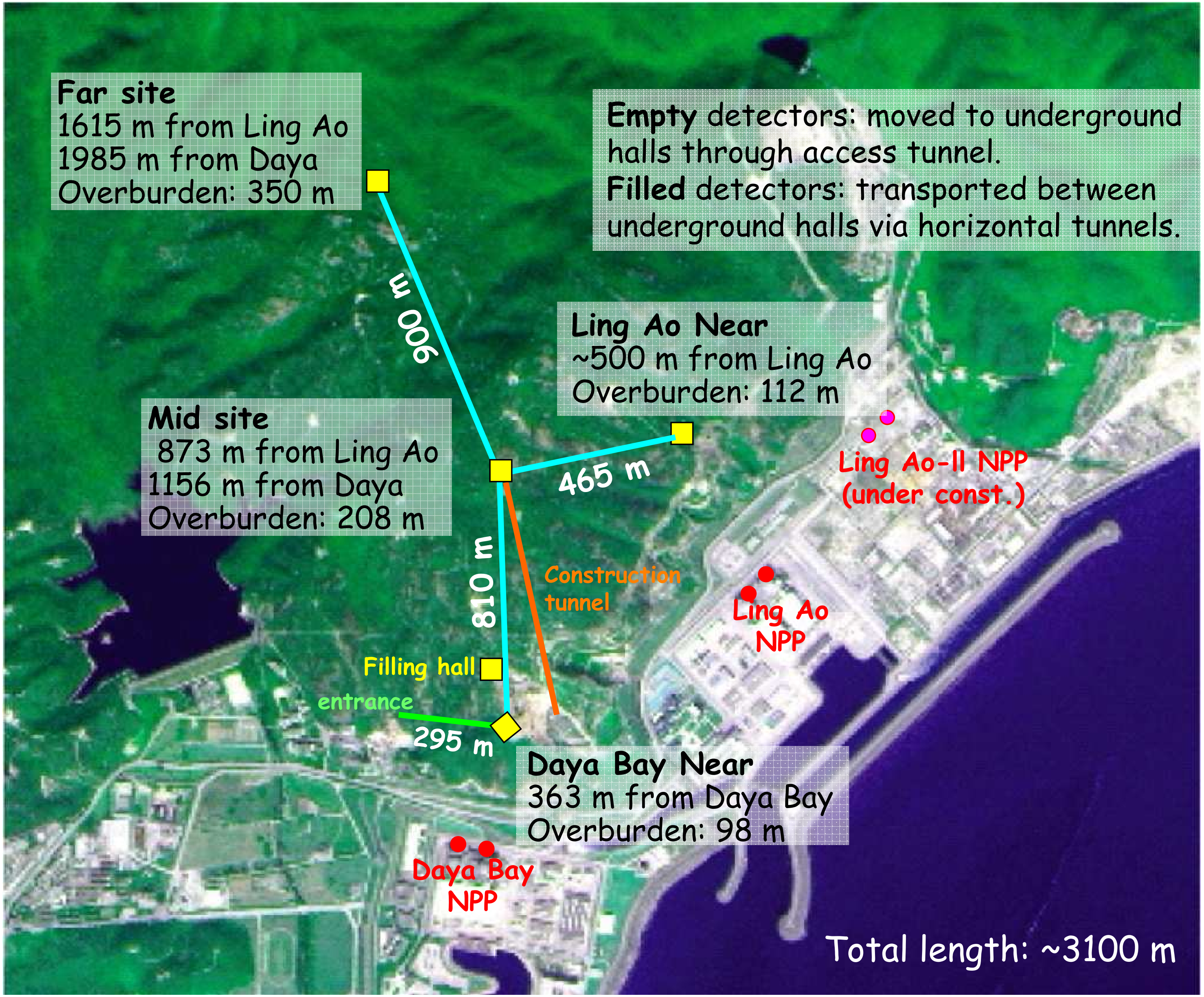


- 45 km from Shenzhen
- 55 km from Hong Kong

The Daya Bay Nuclear Power Complex

- 12th most powerful in the world (11.6 GW_{th})
- Fifth most powerful by 2011 (17.4 GW_{th})
- Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays




Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
Empty detectors: moved to underground halls through access tunnel.
Filled detectors: transported between underground halls via horizontal tunnels.
900 m
Ling Ao Near
~500 m from Ling Ao
Overburden: 112 m
Mid site
873 m from Ling Ao
1156 m from Daya
Overburden: 208 m
465 m
Ling Ao-II NPP
(under const.)
810 m
Construction tunnel
Ling Ao
NPP
Filling hall
entrance
295 m
Daya Bay Near
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP
Total length: ~3100 m

Daya Bay Collaboration

Europe (3) (9)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (14)(50)

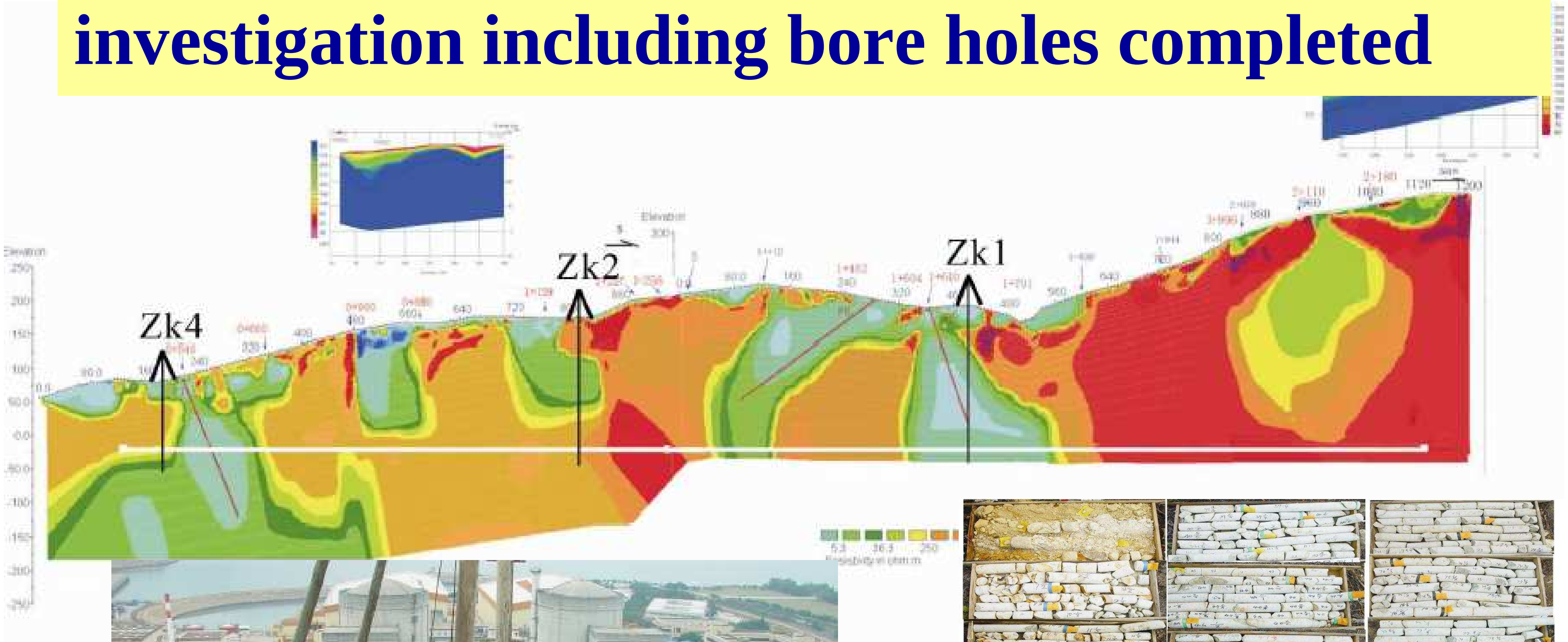
BNL, Caltech, George Mason Univ., LBNL, Iowa state Univ. Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign

Asia (15) (86)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ.,Nankai Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Hong Kong Univ., Chinese Hong Kong Univ., National Taiwan Univ., National Chiao Tung Univ., National United Univ.

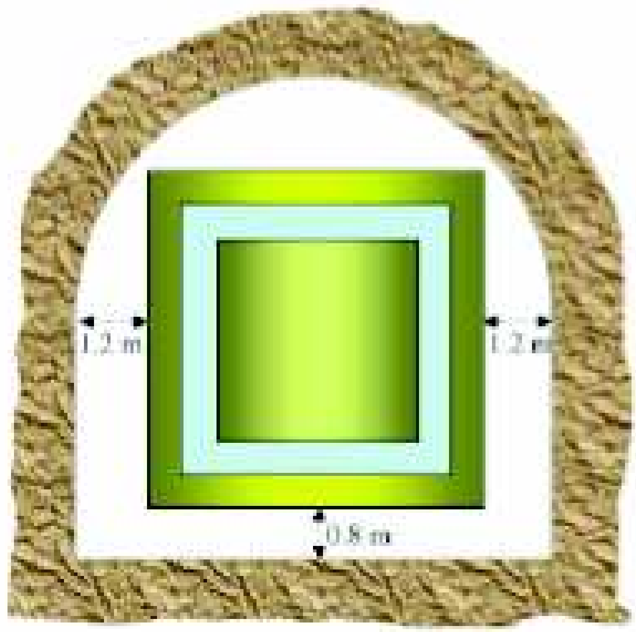
~ 145 collaborators

Conceptual design of the tunnel and the Site investigation including bore holes completed



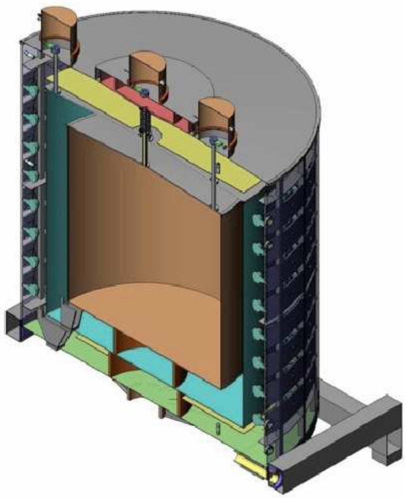
Tunnel construction

- **The tunnel length is about 3000m**
- **Local railway construction company has a lot of experience (similar cross section)**
- **Cost estimate by professionals, ~ 3K $/m**
- **Construction time is ~ 15-24 months**
- **A similar tunnel on site as a reference**



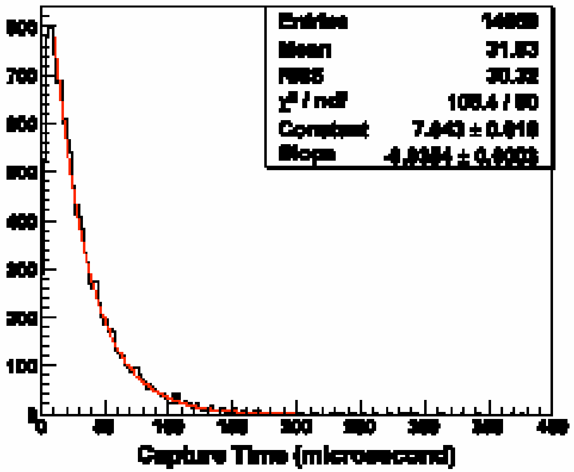
Antineutrino Detectors

- Three-zone cylindrical detector design
  - Target zone, gamma catcher zone (liquid scintillator), buffer zone (mineral oil)
  - Gamma catcher detects gamma rays that leak out



- 0.1% Gd-loaded liquid scintillator as target material
  - Short capture time and high released energy from capture, good for suppressing background
- Eight ‘identical’ detector modules, each with 20 ton target mass
  - ‘Identical’ modules help to reduce detector-related systematic uncertainties
  - Modules can cross check the performance of each other when they are brought to the same location

Detector Target



0.1% Gadolinium-Liquid Scintillator

- Proton-rich target
- Easily identifiable n-capture signal above radioactive backgrounds
- Short capture time ($\tau \sim 28\ \mu s$)
- Good light yield

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

Text

0.3 b → $+ p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

49,000 b → $+ Gd \rightarrow Gd^*$

→ $Gd + \gamma$'s (8 MeV) (delayed)

	fraction by weight
C	0.8535
H	0.1288
N	0.0003
O	0.0164
Gd	0.0010

Isotopic Abundance

Gd(152)	*0.200*
Gd(154)	*2.18*
Gd(155)	*14.80*
Gd(156)	*20.47*
Gd(157)	*15.65*
Gd(158)	*24.84*
Gd(160)	*21.86*

^{155}Gd $\Sigma\gamma$=7.93 MeV

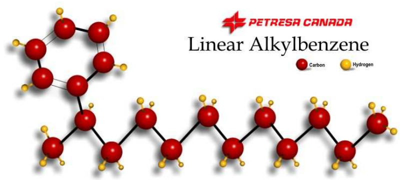
^{157}Gd $\Sigma\gamma$=8.53 MeV

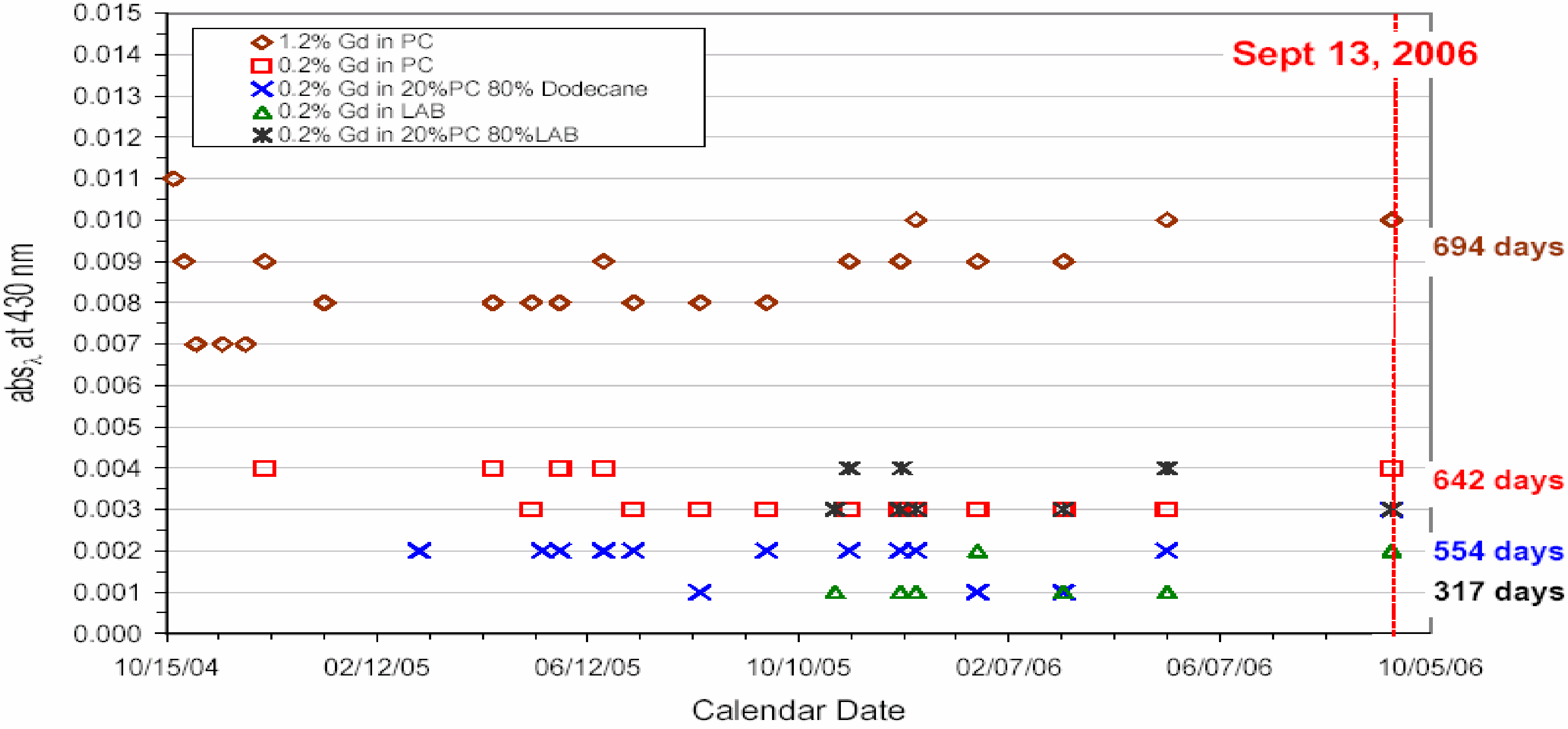
other Gd isotopes with high abundance have very small neutron capture cross sections

Gd capture	86.7%
H capture	13.2%
C capture	0.08%

BNL Gd-LS Optical Attenuation: Stable So Far ~700 days

- Gd-carboxylate in PC-based LS stable for ~2 years.
- Attenuation Length >15m (for abs < 0.003).
- Promising data for Linear Alkyl Benzene, LAB
  (LAB use suggested by SNO+ experiment).





Event Rates and Signal

Distances to Sites (m)

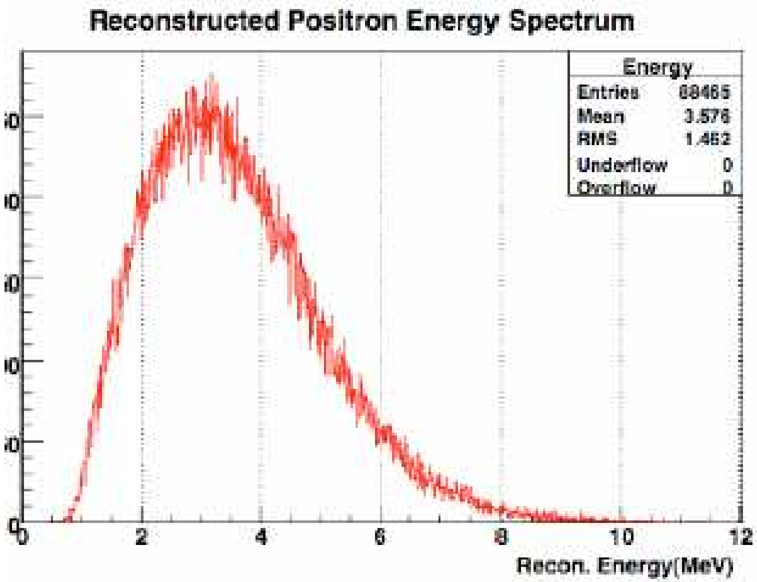
Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

Antineutrino Interaction Rates

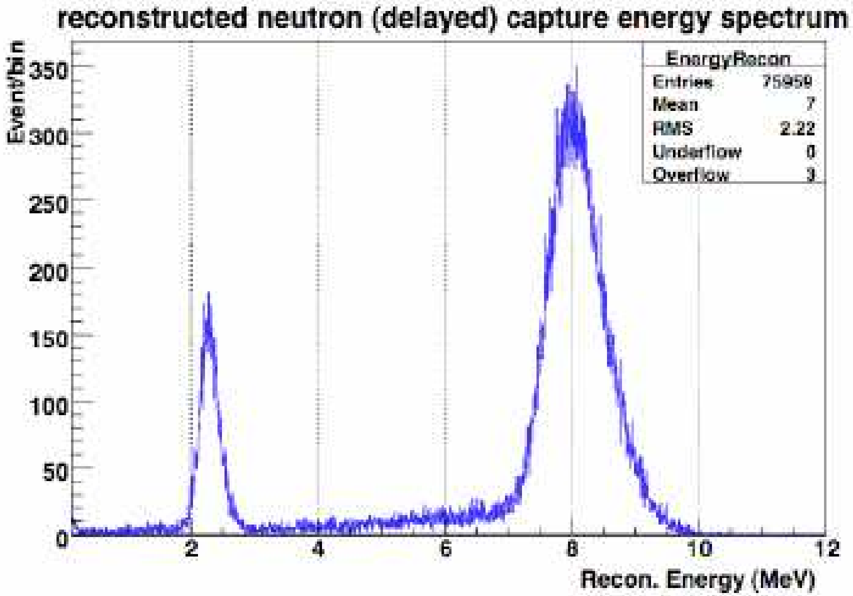
(events/day per 20 ton module)

Daya Bay near site	960
Ling Ao near site	~760
Far site	90

Prompt Energy Signal



Delayed Energy Signal



Statistics comparable to single detector in far hall

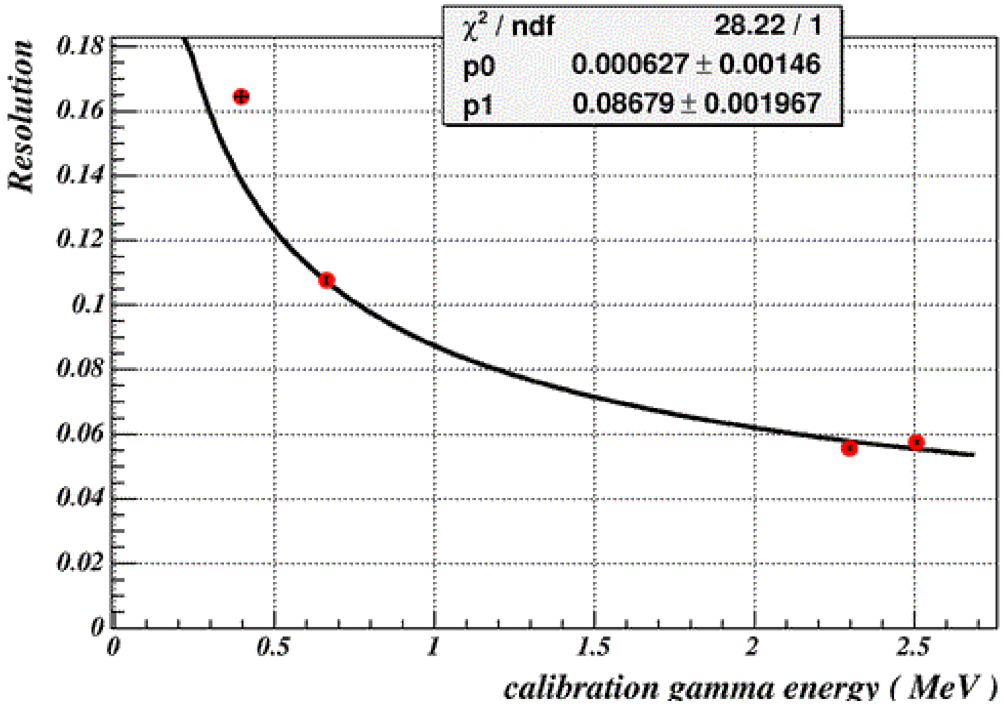
Detector Prototype at IHEP

- 0.5 ton prototype
  (currently unloaded liquid scintillator)
- 45 8” EMI 9350 PMTs:
  14% effective photocathode coverage with top/bottom reflectors

prototype detector at IHEP

- ~240 photoelectron per MeV :
  9%/√E(MeV)

Energy Resolution



Background Sources

1. Natural Radioactivity: PMT glass, steel, rock, radon in the air, etc

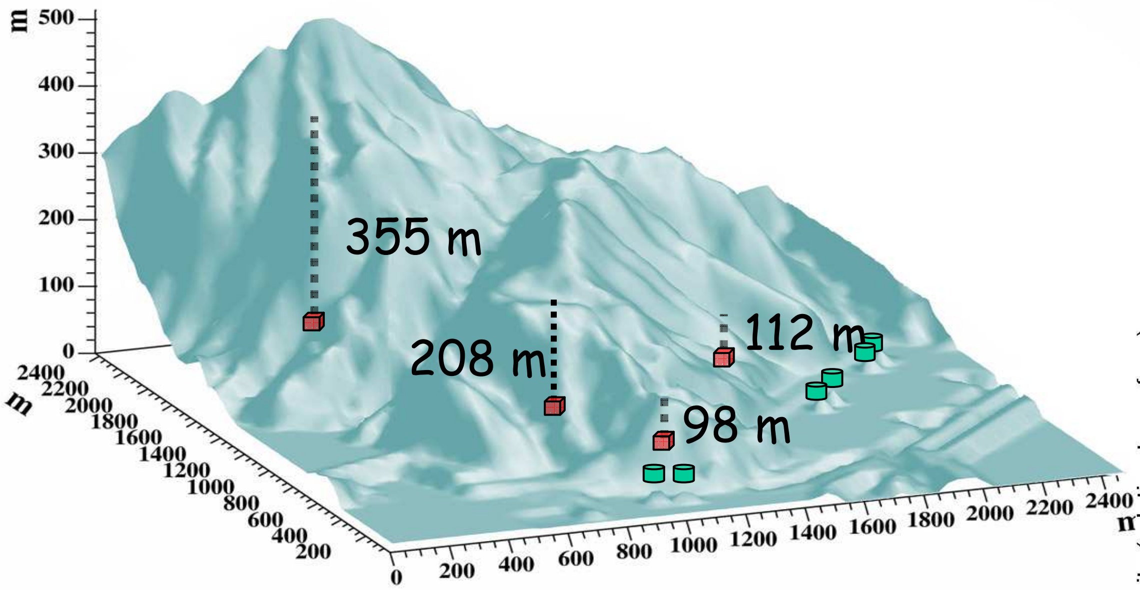
2. Slow and fast neutrons produced in rock & shield by cosmic muons

3. Muon-induced cosmogenic isotopes: ^{8}He/^{9}Li which can β-n decay

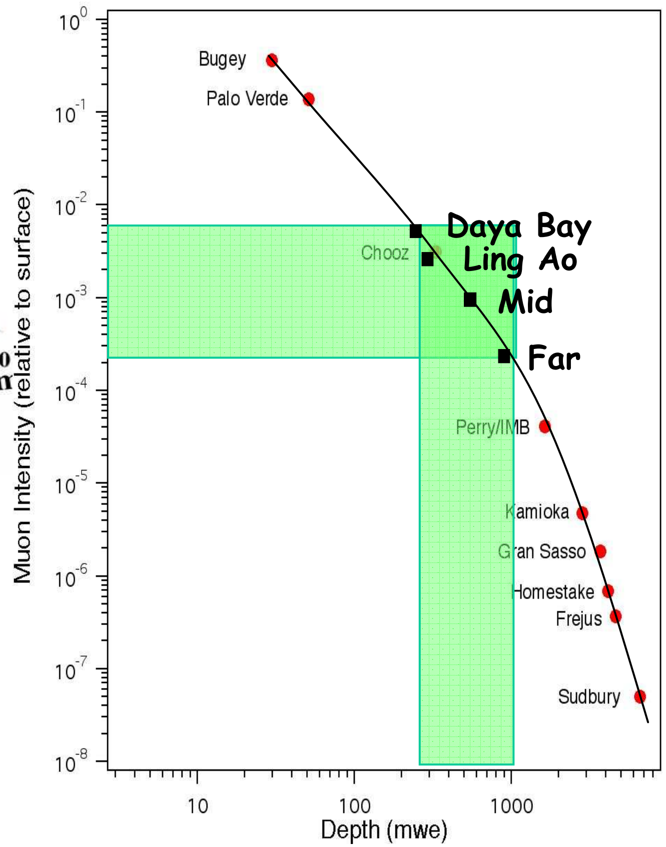
- Cross section measured at CERN (Hagner et. al.)
- Can be measured in-situ, even for near detectors with muon rate ~ 10 Hz

Cosmic-ray Muon

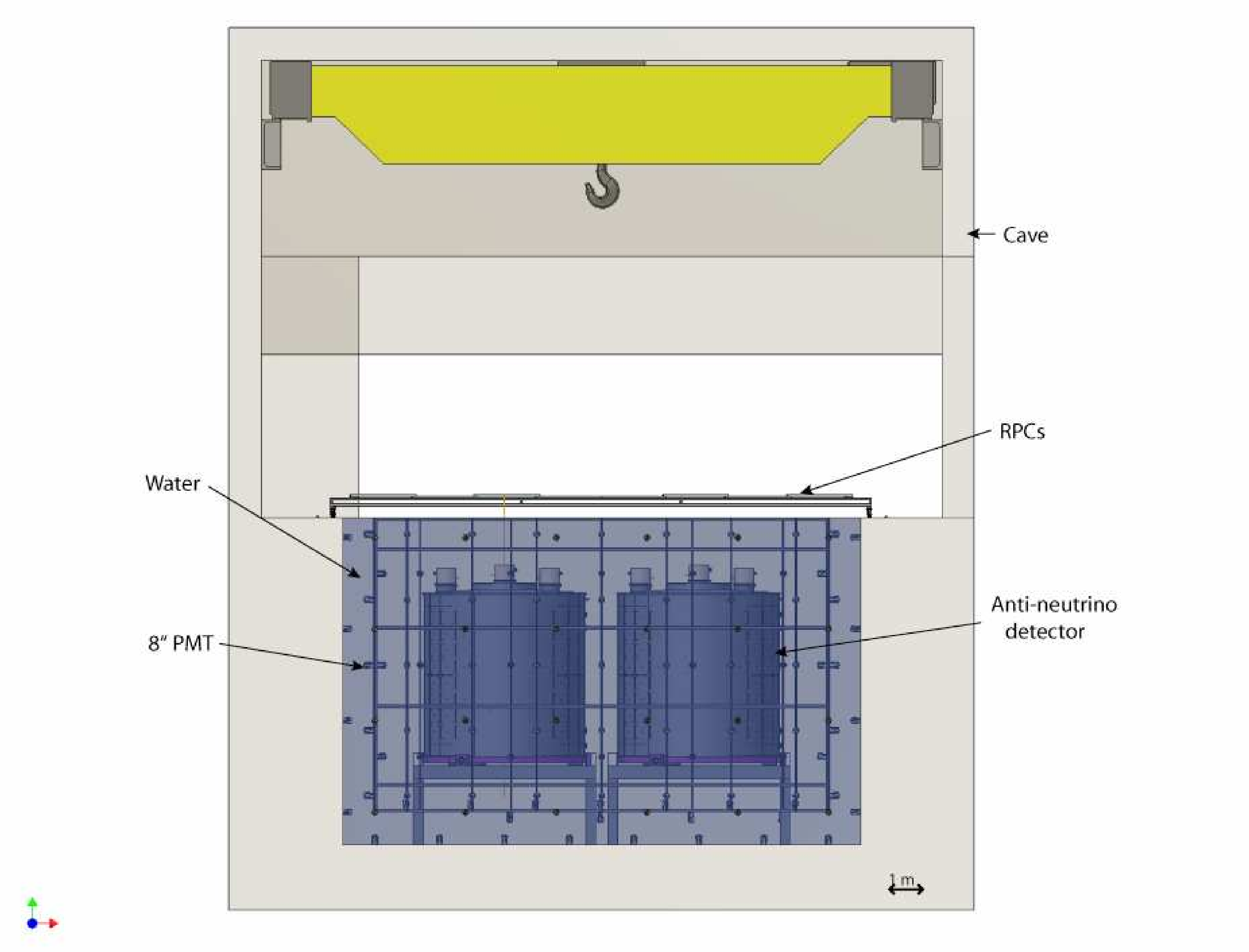
- Use a modified Geiser parametrization for cosmic-ray flux at surface
- Apply MUSIC and mountain profile to estimate muon intensity & energy



	DYB	Ling Ao	Mid	Far
Overburden (m)	98	112	208	355
Muon intensity (Hz/m^2)	1.16	0.73	0.17	0.041
Mean Energy (GeV)	55	60	97	138



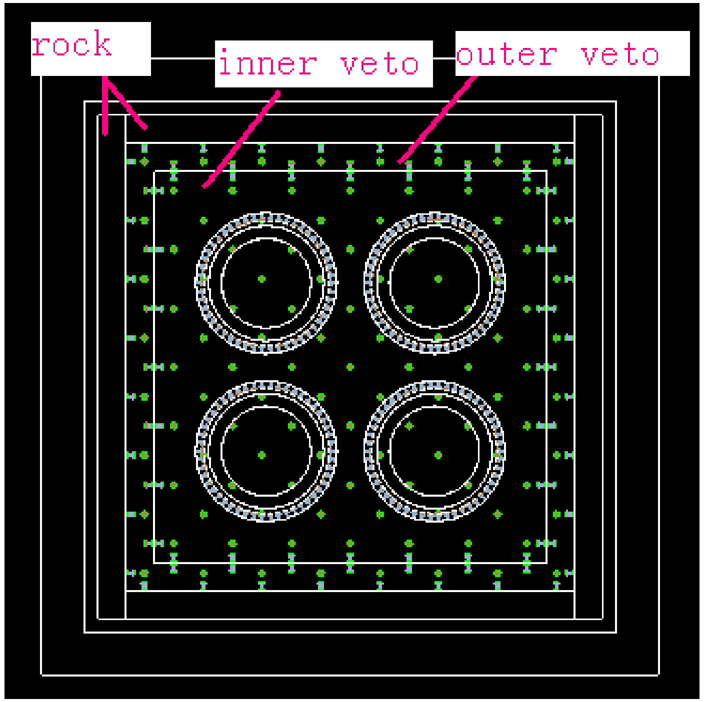
Muon System



Water Shield

- Pool around the central detectors - 2.5m water in all directions.
- Side, bottom & AD surfaces are reflective (Tyvek or equivalent)
- Outer shield is optically separated 1m of water abutting sides and bottom of pool
  - PMT coverage ~1/6m^2 on bottom and on two surfaces of side sections
- Inner shield has ≥1.5m water buffer for AD's in all directions but up, there the shield is 2.5m thick
  - 8" PMTs 1 per 4m^2 along sides and bottom - 0.8% coverage

Far Hall



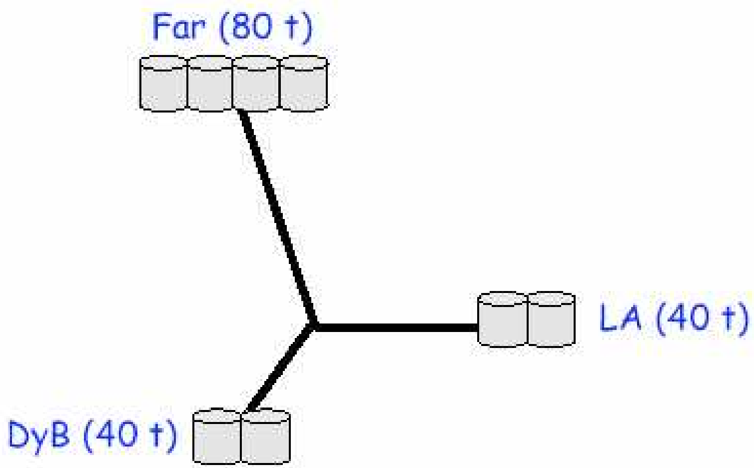
Muon System Active Components

- Inner water shield
  - 415 8” PMTs
- Outer water shield
  - 548 8” PMTs
- RPCs
  - 756 2m $\times$ 2m chambers in 189 modules
  - 6048 readout strips

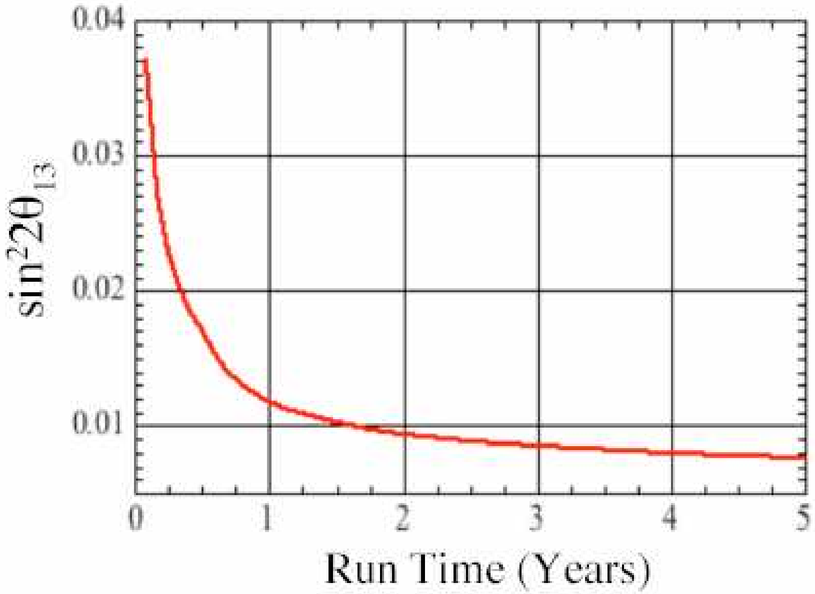
Summary of Systematic Uncertainties

sources	Uncertainty
Reactors	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal statistics	0.2%

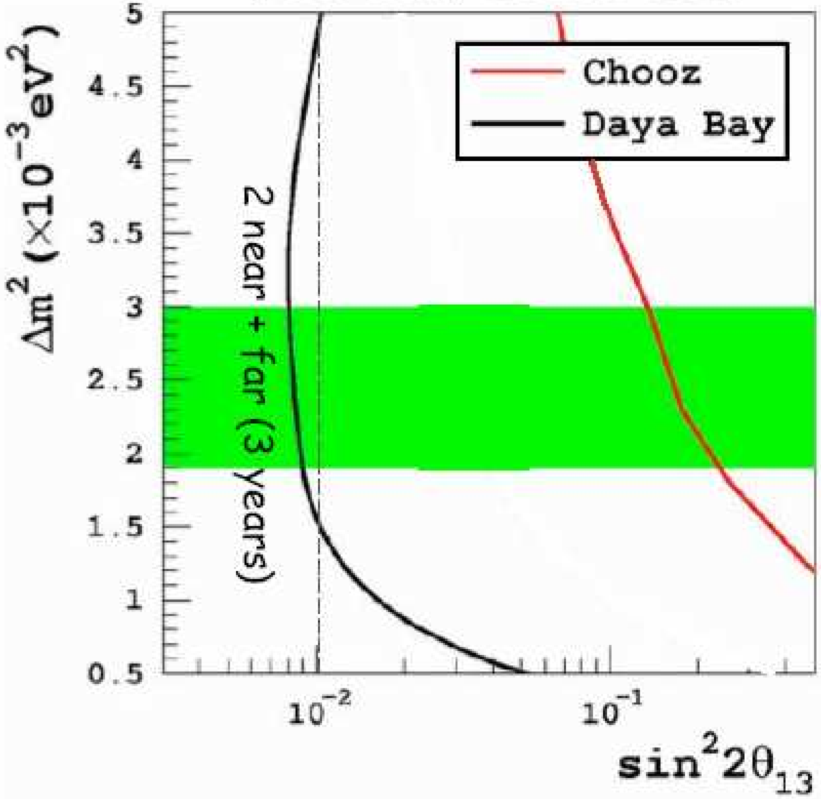
Sensitivity of $Sin^2 2\theta_{13}$



- Use rate and spectral shape
- input relative detector syst. error of 0.38%/detector



90% confidence level



Daya Bay: Status and Plan

- Passed DOE scientific review — Oct 06
- Passed US CD-1 review — Apr 07
- Passed final nuclear safety review in China — Apr 07
- Began to receive committed project funding for 3 years from Chinese agencies — Apr 07
- Start civil construction — Jun 07
- Anticipate US CD-2/3a review — Oct 07
- Start data taking with 2 detectors at Daya Bay near hall — May 09
- Begin data taking with 8 detectors in final configuration — Apr 10

Daya Bay Conceptual Design Report (hep-ex/0701029)