Daya Bay Neutrino Experiment

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Physics Goal

- Neutrino Mixing: PMNS Matrix

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

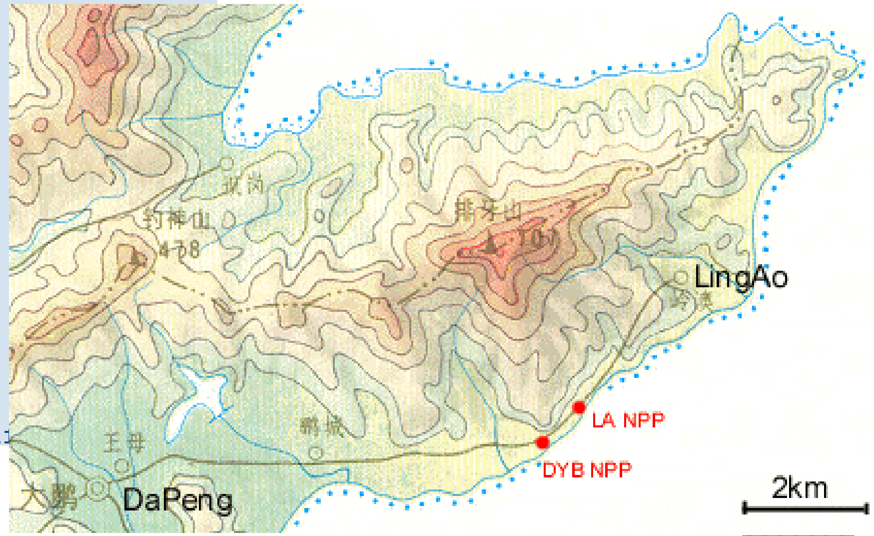
Atmospheric | Reactor and LBL | Solar

- Value of measuring $\sin^2 2\theta_{13}$ to 0.01 using reactor antineutrino has been well documented: Clean, Fast, and Cheap!

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$$

- Daya Bay Experiment will measure $\sin^2 2\theta_{13}$ to 0.01 or better at 90% C.L. in a three-year run (2001).

Location of Daya Bay



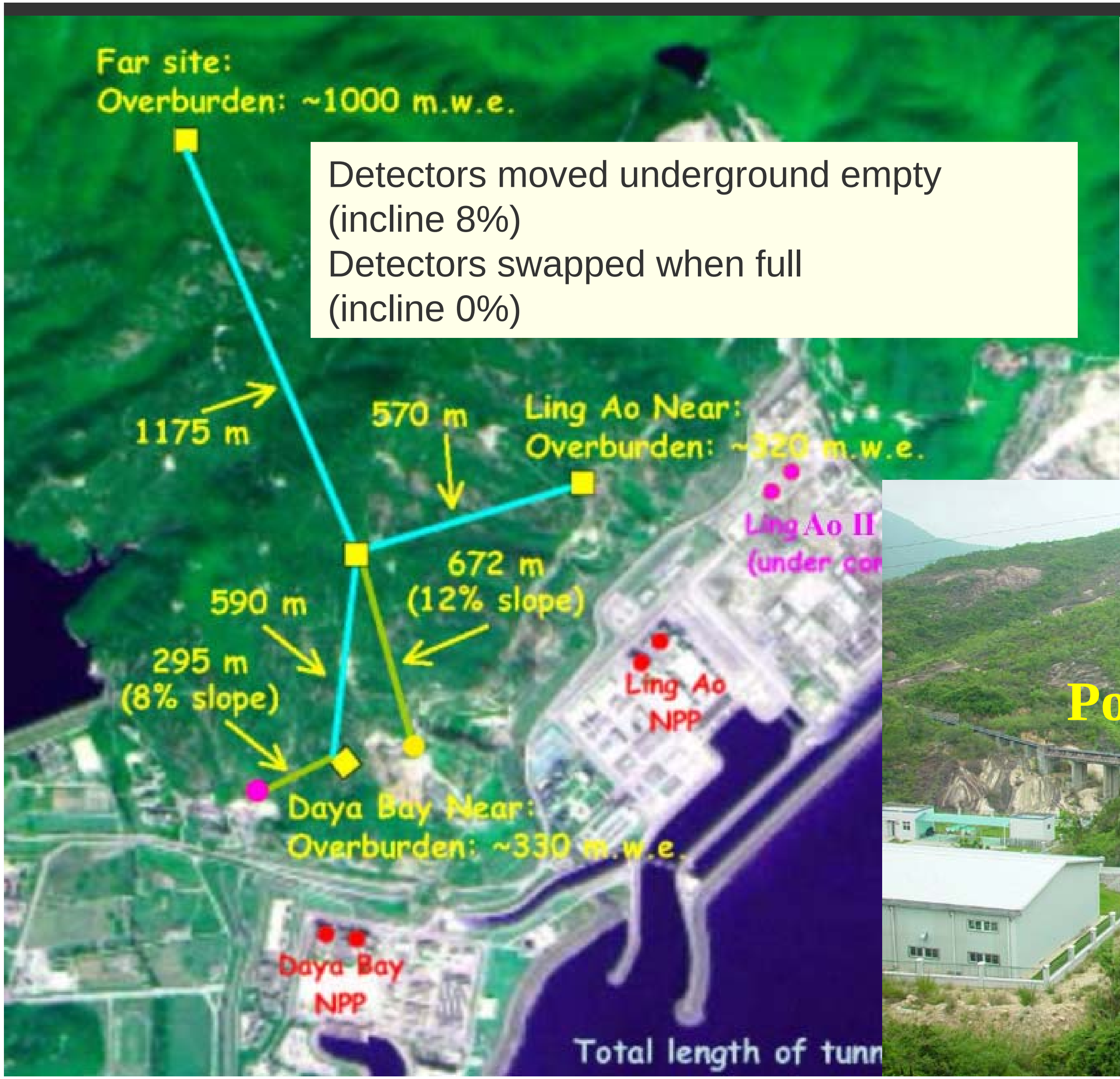
Two metropolises

- Hong Kong 55 km
  - θ_{12} maximum
- ShenZhen 45 km

The Site


LingAo II NPP 2.9GW×2
Under construction (2010)
Daya Bay NPP 2.9GW×2
LingAo NPP 2.9GW×2

Tunnel Design



Detectors moved underground empty
(incline 8%)
Detectors swapped when full
(incline 0%)

Horizontal tunnel
(approved by NPP)

0% slope to transport detector easily

Portal elevation 13m

Tunnel elevation –10m

Reactor Error

- Reactor correlated error ~2%, uncorrelated error ~2%
- Correlated error will cancel out with near/far measurement.
- Uncorrelated error may cancel out for 1 or 2 core reactor, if choose the detector sites carefully.
- Daya Bay has 4 cores currently, another 2 cores will start in 2010. The layout is irregular. Uncorrelated error will partially cancel out.
- Near (500m)/Far(2000m), residual error **~ 0.06%** (6 cores and 4 cores)
- Near (300m)/Far(2000m), residual error ~ 0.12%
- Mid(1000m)/Far(2000m), residual error ~ 0.16%
- A fast measurement with a single near site: DYB(500m) + Mid(1000m), residual error ~ 0.7%

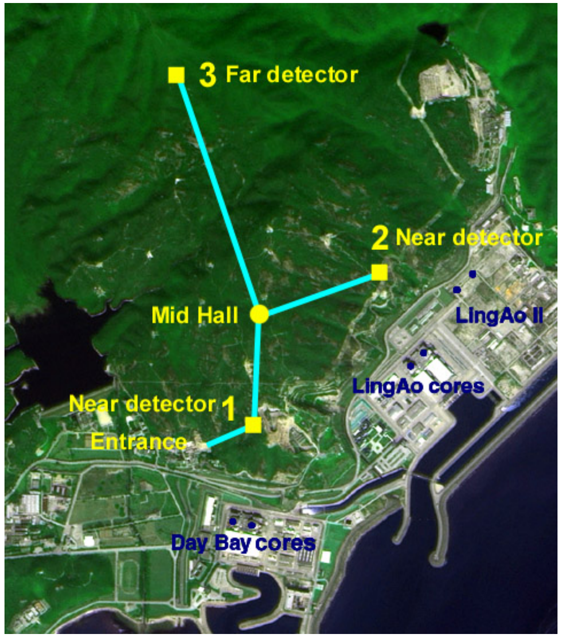
A Versatile Site

Fast measurement:

One near site + mid site

Sensitivity ~ 0.03 in a one year run

40 ton/site, reactor error 0.7%

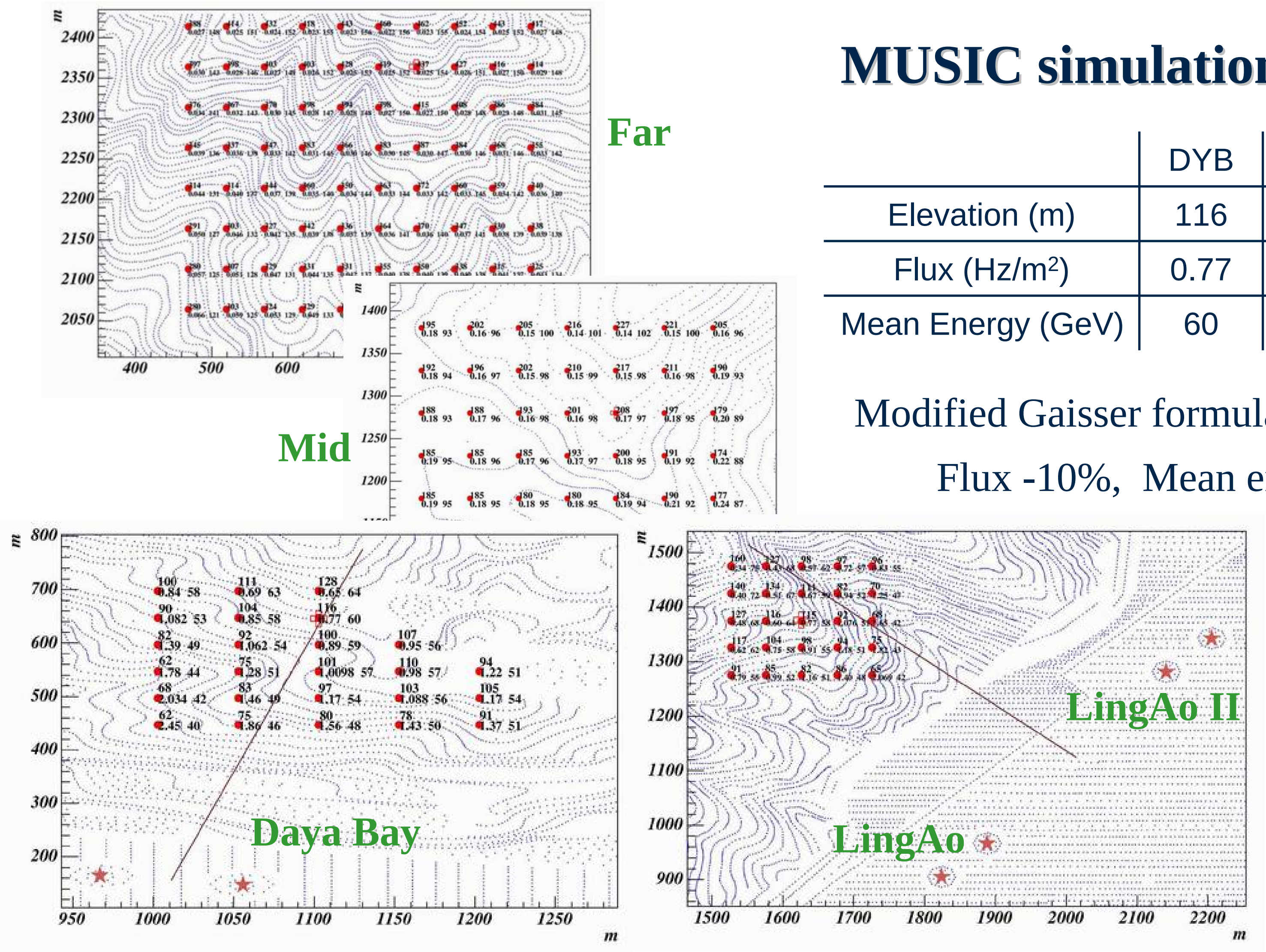


Full operation: (Goal)

- Two near sites + Far site ($\sin^2 2\theta_{13} < 0.01$)
- Mid site + Far site ($\sin^2 2\theta_{13} \sim 0.01$)
- Two near sites + Mid site + Far site ($\sin^2 2\theta_{13} < 0.01$)

Different systematics

Muon Simulation



MUSIC simulation

	DYB	LA	Mid	Far
Elevation (m)	116	115	208	437
Flux (Hz/m^2)	0.77	0.77	0.17	0.025
Mean Energy (GeV)	60	58	97	154

Modified Gaisser formula (low E, high θ)

Flux -10%, Mean energy unchanged.

Rock density
2.6 g/cm^3

Detector Design (I)

Option I: Vertical, cylindrical modules

- Easier to fabricate
- Easier to calibrate
- Size limited by tunnel cross section
- Multiple modules to control systematics and gain enough statistics.

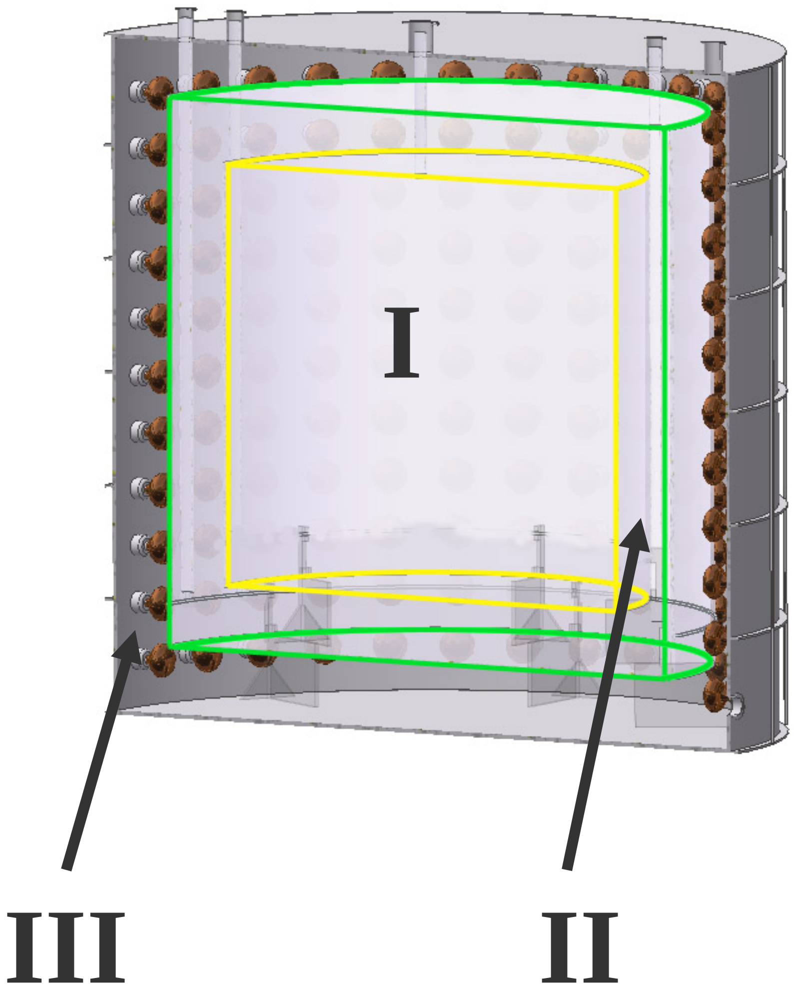
Three-layer structure:

I. target: Gd-loaded scintillator
II. gamma catcher: normal scintillator
III. Buffer shielding: oil

Reflection on top and bottom

~20t each, ~200 8"PMT/module

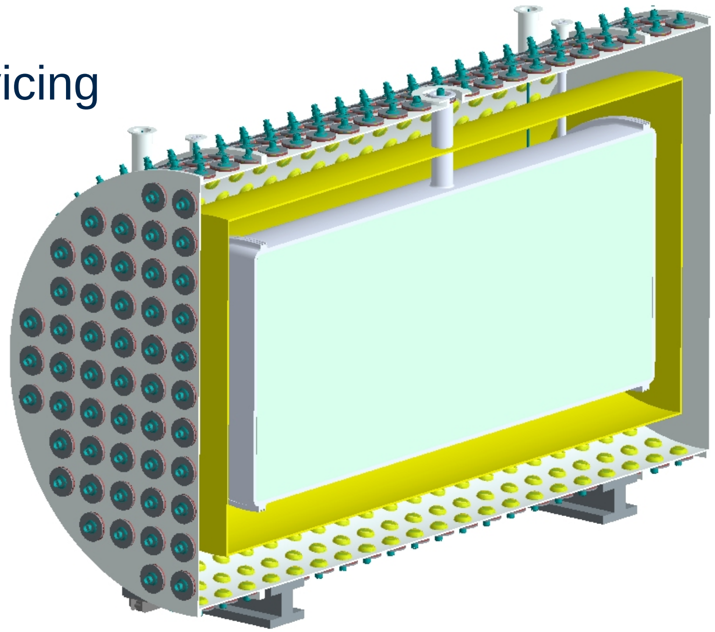
$$\frac{\sigma}{E} \sim \frac{14\%}{\sqrt{E(\mathrm{MeV})}}, \quad \sigma_{\mathrm{vertex}} = 14\mathrm{cm}$$

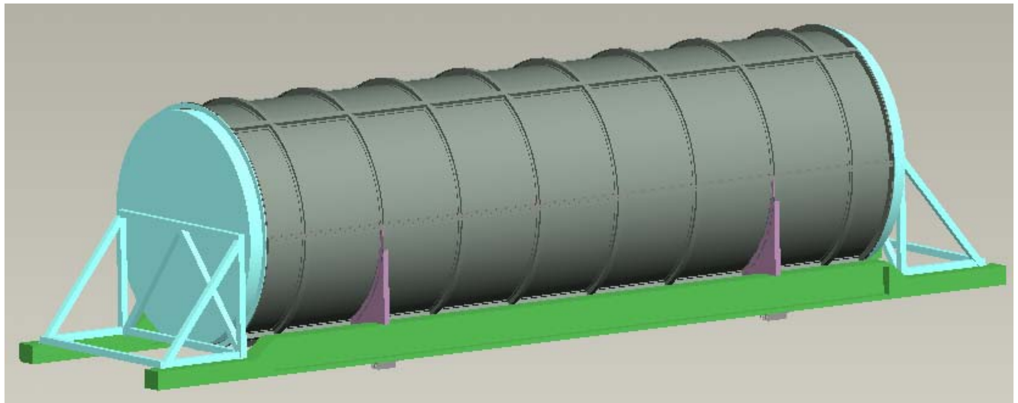


Detector Design (II)

Option II: Horizontal, cylindrical modules

- PMTs mounted on outside with window for servicing
- large fiducial volume per module
- fit to tunnel cross section





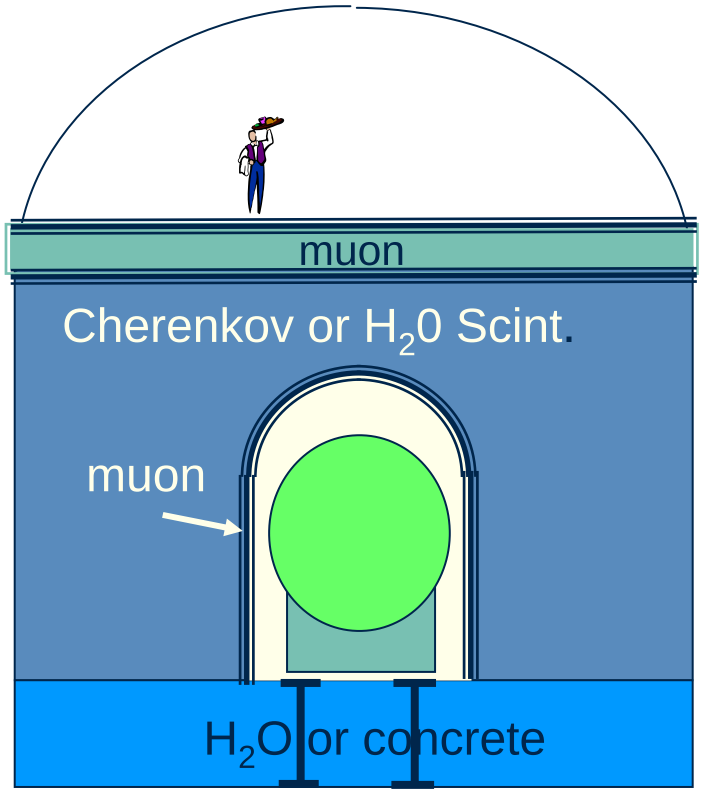
12% PMT coverage:

$$\frac{\sigma}{E} \sim \frac{7\%}{\sqrt{E(\text{MeV})}}$$

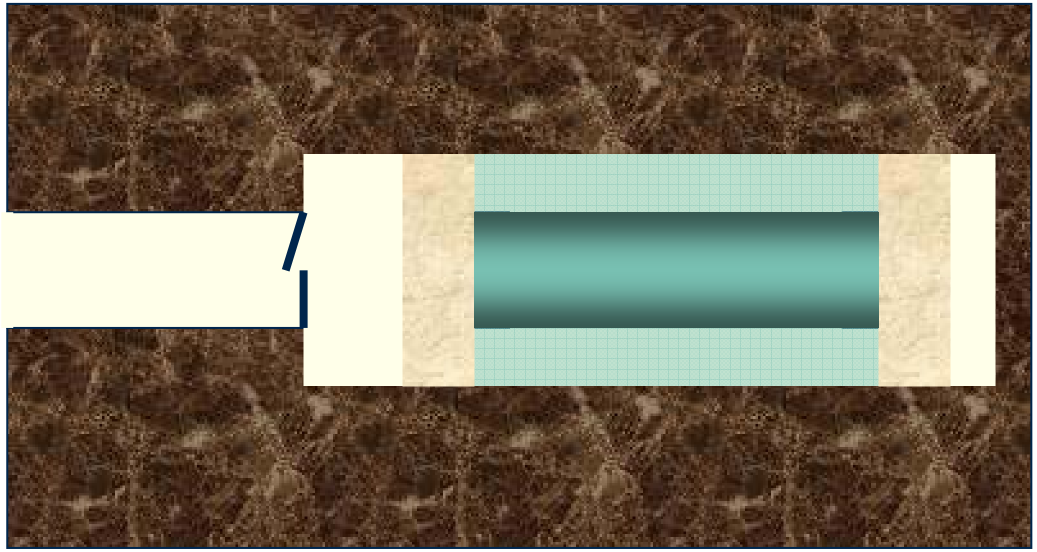
Veto (I)

Option I: Shielding Bath

- Muon chambers surround detector in "tunnel".
- Cover ends with H_20 plug
- Access to opposite end over top.

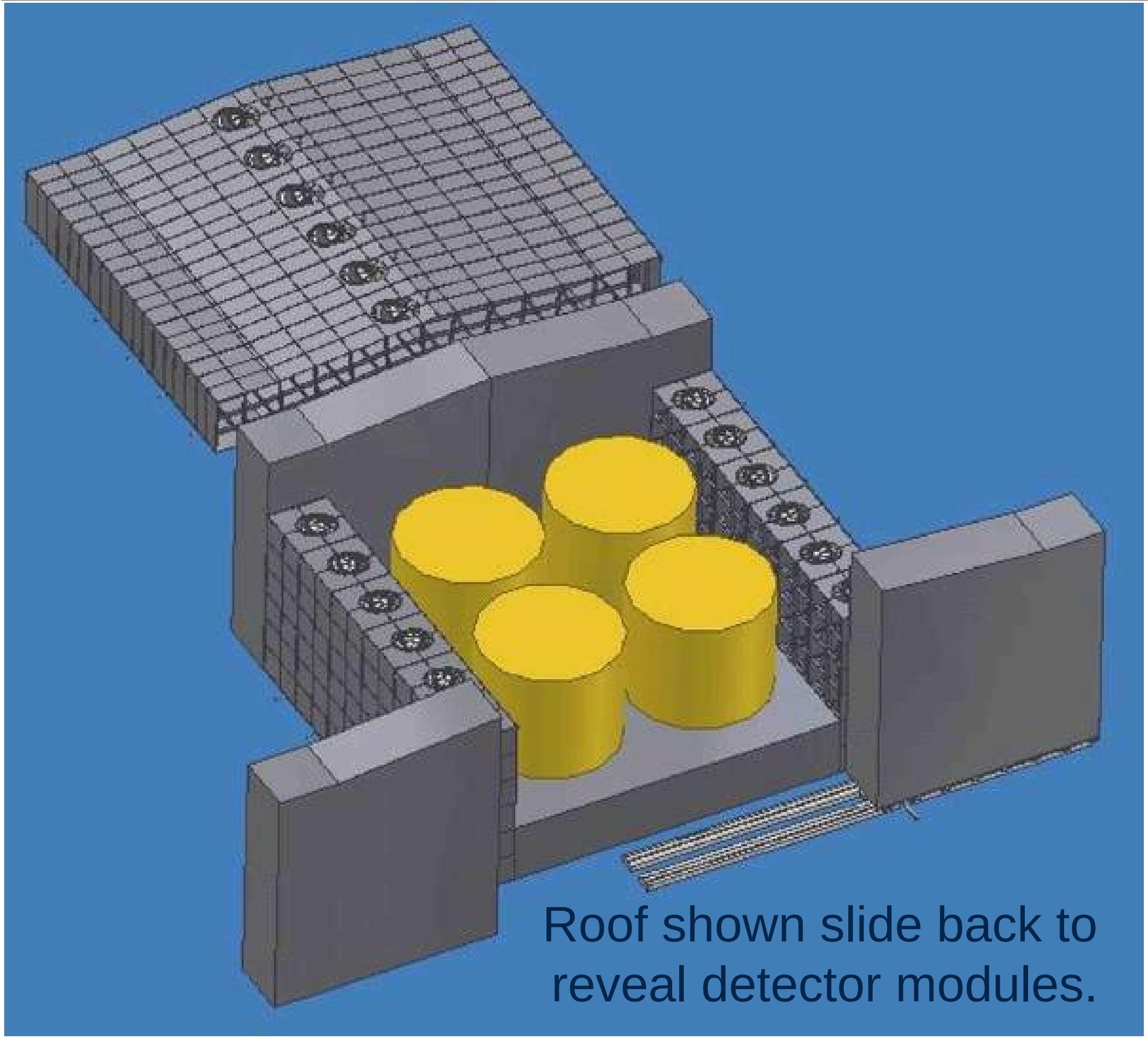


Muon chambers or scin. bar at top and
Immediate vicinity of detector.



Top View of the Experimental Hall

Veto (II)



Option II: Water House

consists of 2m×2m water Cherenkov tanks.

2-layer RPC tracking outside the water tank.

Expected muon efficiency
- 95% water cerenkov
- 90% RPC
- Combined 99.5%

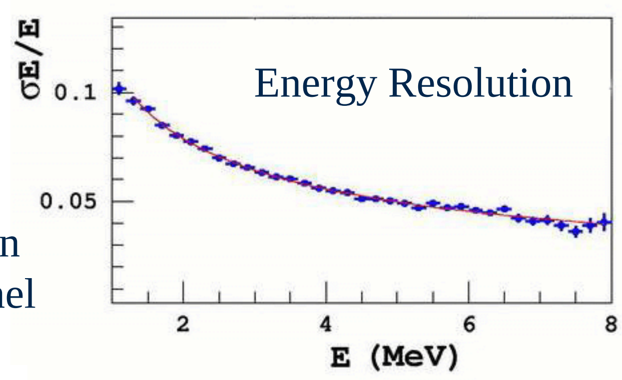
Common in Options

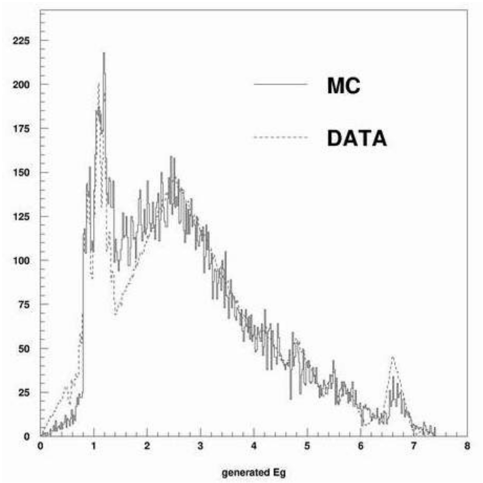
- Movable detector
- Three-layer cylindrical detector
- Gamma-catcher ~ 45cm
- Oil buffer ~ 45cm
- Passive water shielding $\geq$ 2m
- Water Cherenkov + another muon veto (RPC, muon chamber, or plastic scintillation bar) > 99% efficiency

Based on full Monte Carlo studies

Detector Monte Carlo

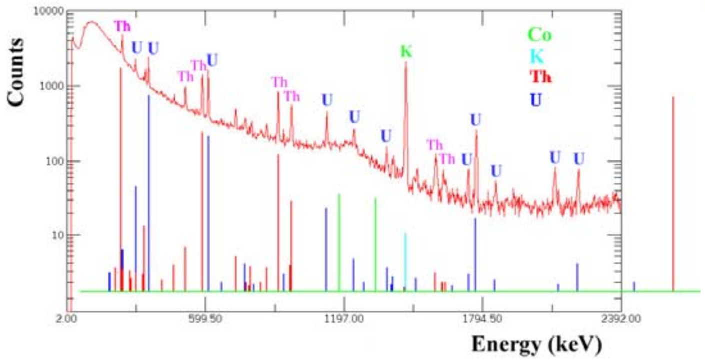
- **GEANT3 + GCALOR**
- **Optical photon transportation + Digitization**
- **Event reconstruction**

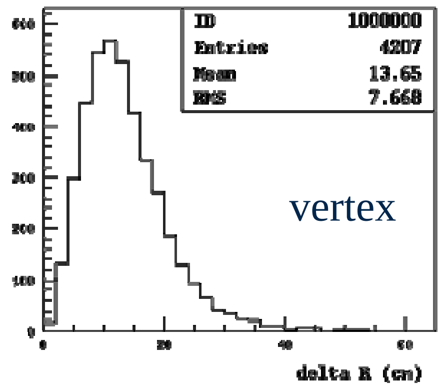




γ spectrum of n(Gd) capture

γ spectrum of U/Th/K decay chain and radioactivity of Aberdeen tunnel rock, similar to DYB





Positron Efficiency

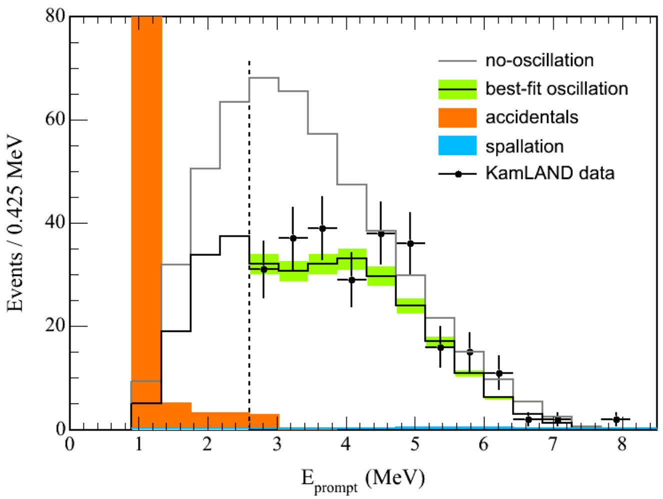
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\quad \hookrightarrow e^+ + e^- \rightarrow 2\gamma$$

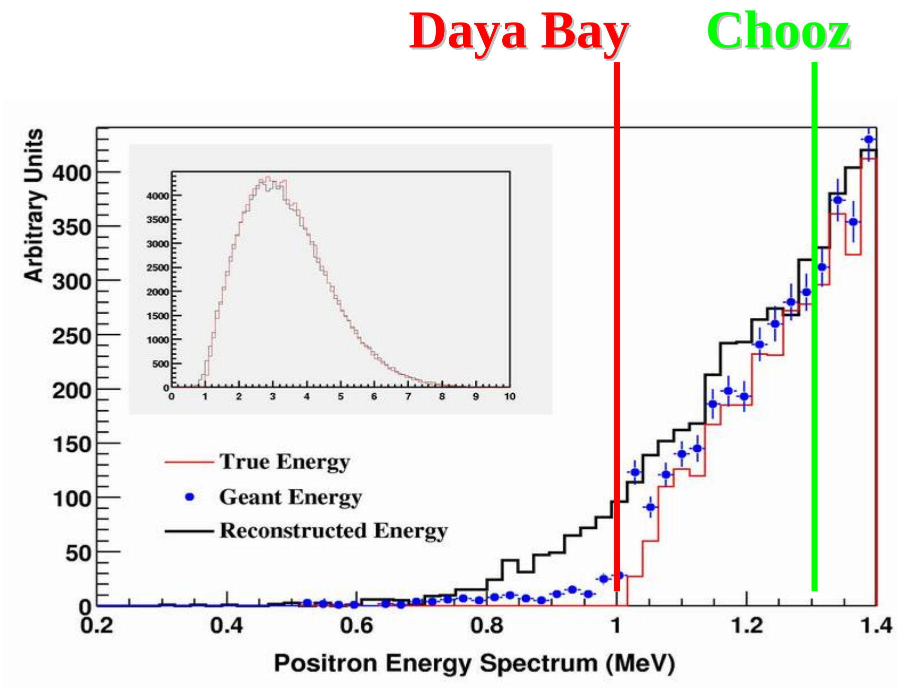
Positron Efficiency 99.6%

Error ~0.05% (Assuming 2% energy scale error)

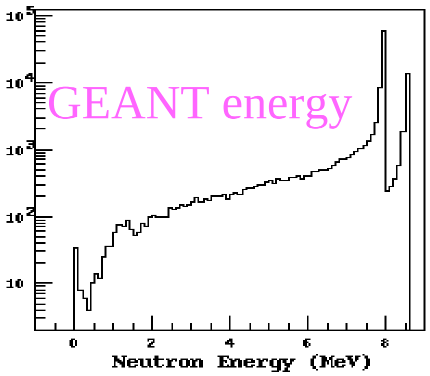
Chooz 1.3MeV, error 0.8%（bad LS)

KamLAND 2.6MeV, error 0.26%

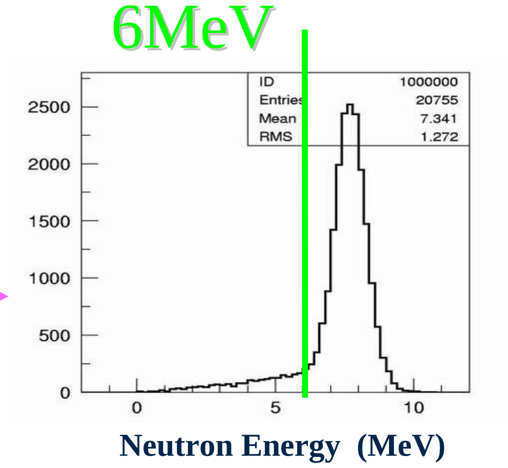




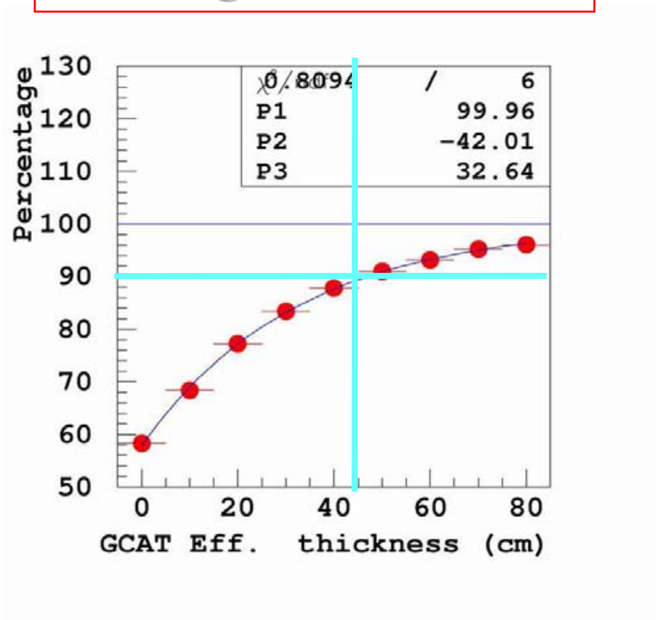
Gamma Catcher



Recon



45 cm gamma catcher



Neutron-capture energy cut efficiency 91%, Error ~0.2% (Assuming 1% energy scale error)

CHOOZ 5 ton detector with 70cm gamma catcher, efficiency (94.6±0.4)%

(vertex cut and larger edge effects for smaller detector)

MC reproduced CHOOZ efficiency -> correct gamma spectrum

^{8}He/^{9}Li Backgrounds

Cosmogenic long-lived isotopes, can not be rejected by muon veto, can not be shut out with passive shielding. Dominant background.

- ^{8}He half-life 0.12s, ^{9}Li half-life 0.18s
- 16% ^{8}He and 49.5% ^{9}Li decay with beta-neutron cascade
- Cross section @190GeV σ (^{8}He+^{9}Li)=2.12±0.35 μ barn (Hagner et. al.)
- Extrapolate according to power law $\sigma(E_\mu) \propto E_\mu^{0.73}$
- KamLAND found ~85% isotopes produced by shower muons and the contribution of ^{8}He relative to ^{9}Li is less than 15%
- ^{8}He can be tagged by double cascade ^{8}He->^{8}Li->^{8}Be (D-chooz)

Can We measure ^{9}Li in-situ, as KamLAND did?

- Far detector muon rate ~ 0.25Hz (0.025 Hz/m^2, 10 m^2)
- Mid detector ~ 2Hz
- Near detector ~ 8Hz

Measuring ^{9}Li in-situ

^{9}Li can be measured in-situ even if muon rate is high.

– Neutrino rate and ^{9}Li rate is much lower than muon rate. Each neutrino-like event (and the adjacent-in-time muons) can be viewed as independent (no entanglement)

$$ML : \log L = \sum_i \log\left[B \cdot e^{-t_i/\lambda}/\lambda + (1-B)\cdot e^{-t_i/T}/T \right]$$

$$1/\lambda = 1/\tau + 1/T, \qquad T = 1/R_\mu$$

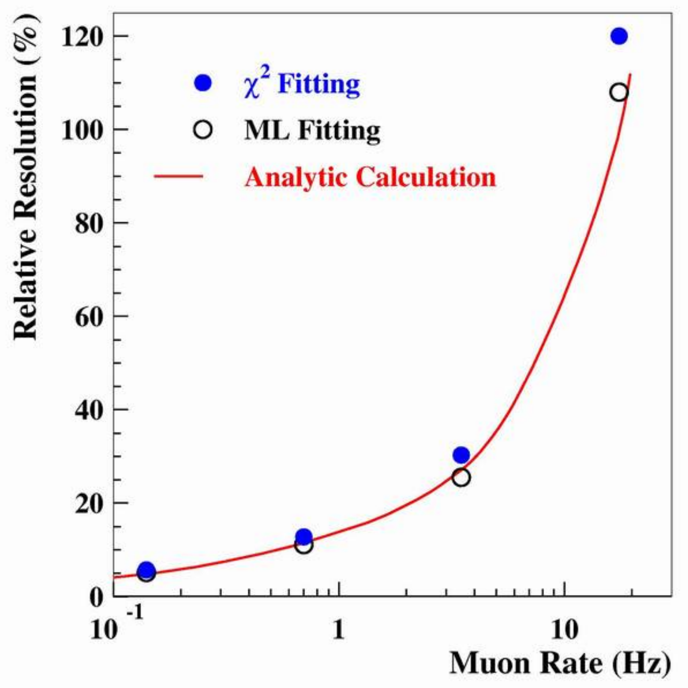
Or a better ML with timing of several precedent muons. Variance estimation for ML:

If B<<$\tau/(\tau$+T), then $\sigma_{est} = \frac{1}{\sqrt{N}}\sqrt{(1+\tau R_\mu)^2 - 1}$

N: total neutrino-like events, τ : lifetime of ^{9}Li, R_μ : muon rate.

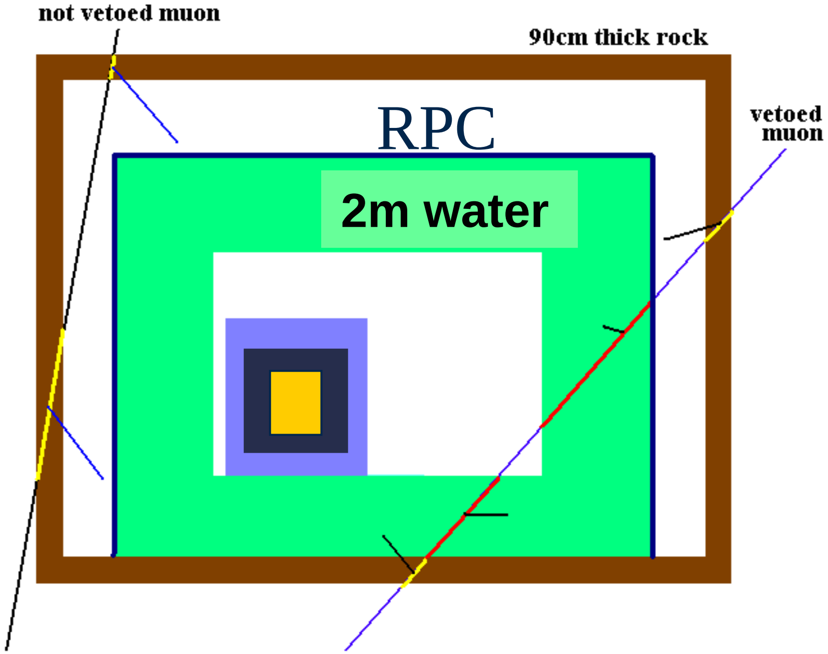
DYB Near site: 60% resolution

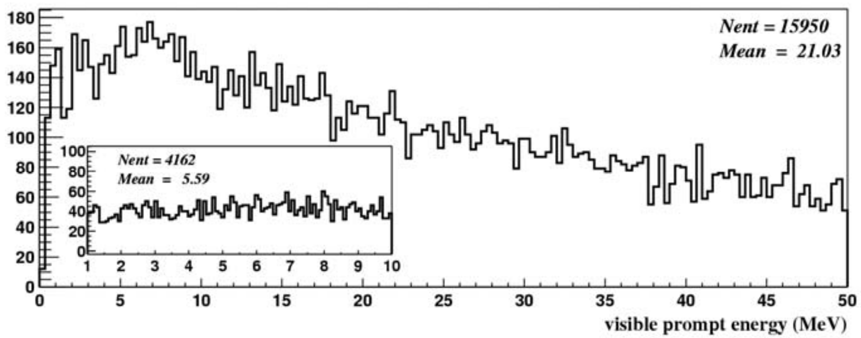
DYB Far site: 30% resolution



MC with 250,000 events and B/S=1%

Neutron Backgrounds





Full MC simulation

- Muons from MUSIC simulation.
- Neutron produced by muons in water and rock
- Neutron yield, energy spectrum, and angular distribution. Accurate to 10~20%

Y. Wang et al., PRD64, 013012(2001)

- Event selection (E cut and Δ T cut):
  - Single neutrons
  - Fast neutron backgrounds

← Energy spectrum of fast neutron backgrounds

Neutron Backgrounds

		Near Site (events/day)	Far Site (events/day)
Single Neutrons	Pass Veto det	975.3	59.2
	Not Pass Veto det	19.4	1.33
Fast Neutron Backgrounds	Pass Veto det	41.3	2.4
	Not Pass Veto det	0.59	0.05

Two veto detectors with efficiency 99.5%, then

Background = (Not Pass Veto det) + 0.5% (Pass Veto det)

Fast Neutron backgrounds
Near Site B/S ~ 0.15%
Far Site B/S ~ 0.1%

Radioactivity

MC + Reconstruction, 45 cm oil buffer

- PMT glass (low radioactivity, U: 50ppb Th: 50ppb K: 10ppb)
  Total rate ~ 7 Hz (>1 MeV)
- Daya Bay Rock (U: 8.8ppm Th: 28.7ppm K: 4.5ppm)
  Detector shielded by oil buffer and 2m water
  Total rate ~ 8 Hz (>1 MeV)
- Radon is a little bothersome. It will be controlled by ventilation.
- Requirement: total radioactivity < 50 Hz

Since single neutron flux is low, radioactivity is not a problem.

Background Summary

	Near Site	Far Site
Radioactivity (Hz)	<50	<50
Accidentals B/S	<0.05%	<0.05%
Fast Neutron backgrounds B/S	0.15%	0.1%
^{8}He/^{9}Li B/S	0.55%	0.25%

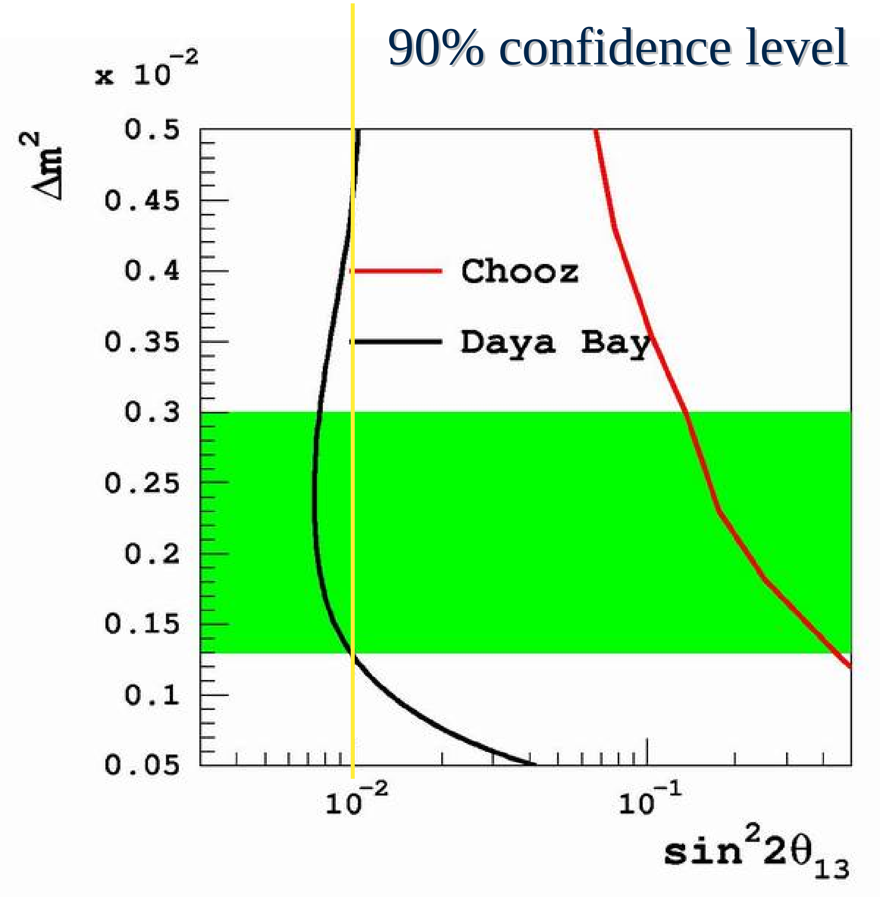
In sensitivity analysis, we assume that all backgrounds carry 100% error.

Detector Swapping

- **Detector systematic error no longer important for Daya Bay.**
- **With detector swapping, detector normalization error cancel out, even if we don't know its size.**
- **Energy scale may change before and after swapping. The normalization error can be controlled to be <0.2% by calibration system. (corresponding to 1% energy scale error @ 6MeV.)**
- **Side-by-side calibration will**
  - Understand the detector systematic error
  - "Measure" systematic error relatively, depends on statistics (thus we only care about statistical error, not systematic errors.
  - monitor detector swapping

Sensitivity

- Near/Far configuration
- Three-year run (0.2% statistical error)
- Two near sites, 40 ton each
- 80 ton at Far site
- Detector residual error 0.2%
- Far site background error 0.2%
- Near site background error 0.5%

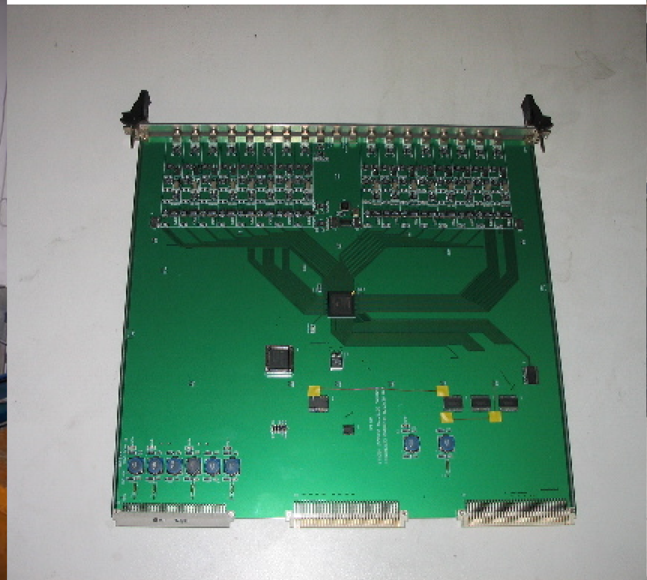


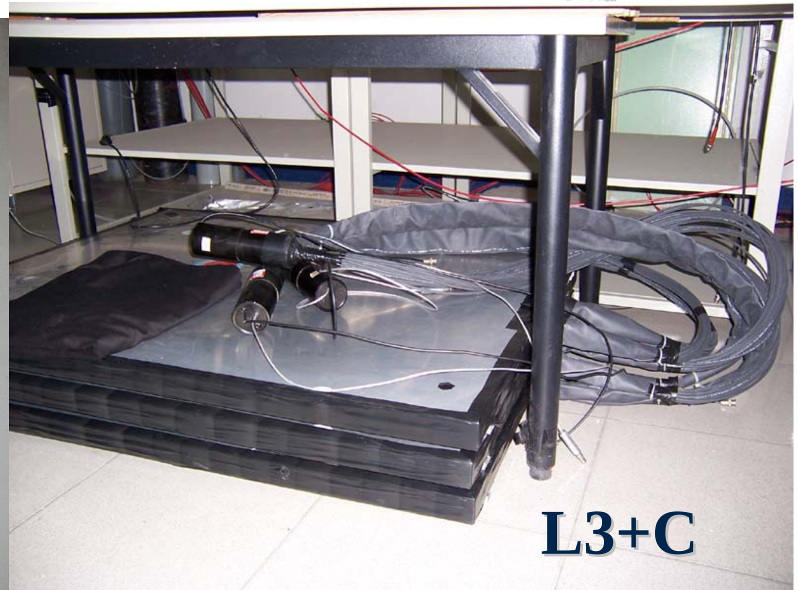
Detector Prototype

To test LS, energy reconstruction, calibration, reflection, electronics, …

- Inner acrylic vessel: 1m in diameter and 1m tall, filled with Gd doped liquid scintillator.
- Outer stainless steel vessel: 2m in diameter and 2m tall, filled with mineral oil. PMTs mount in oil.
- Plastic scintillator muon veto

Detector Prototype



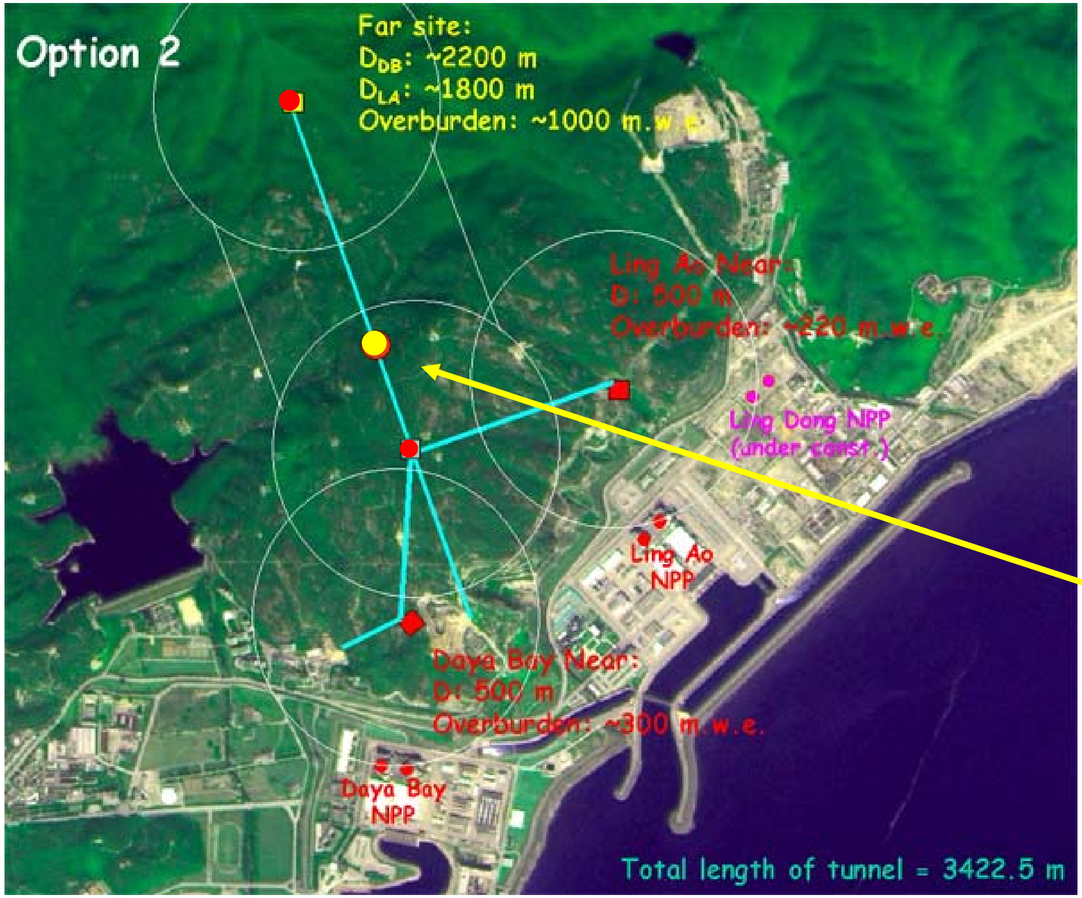


L3+C

BES

Geological Survey

- Geological survey started earlier in this month
- Borehole drilling will start in July



Borehole drilling:

4 sites +

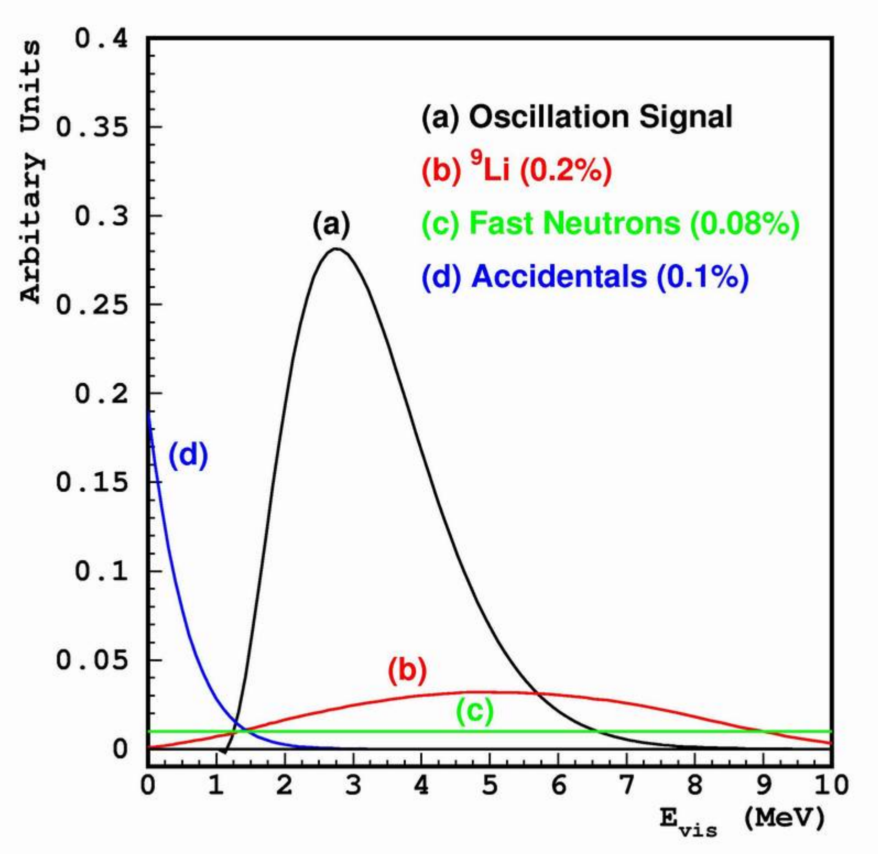
1 fault

Timeline

Sep. 2005	completed geological survey
2006	begin civil construction
Early 2007	complete tunnels and underground laboratories for Daya Bay near site
2007	construction of tunnels for mid- and far site
2008	complete tunnels and experimental halls
2008/2009	begin data taking with all facilities operational

Thanks!

Spectrum of Backgrounds



- Beta energy spectrum of ^{8}He/^{9}Li is known.
- Accidentals can be measured
- Spectrum of fast neutron backgrounds can be estimated using tagged muons (statistics is 50 times larger than backgrounds)
- The spectrum error of backgrounds are not important in shape analysis, comparing with statistical error of neutrinos.

Shape analysis

$$\chi^2 = \min_{\alpha's} \sum_{A=1}^{3}\sum_{i=1}^{N_{bins}} \frac{\left[M_i^A - T_i^A\left(1+\alpha_c+\sum_r \omega_r^A\alpha_r+\beta_i+\varepsilon_D+\varepsilon_d^A\right) - \eta_f^A F_i^A - \eta_n^A N_i^A - \eta_s^A S_i^A\right]^2}{T_i^A}$$

$$+ \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_u^2} + \sum_{i=1}^{N_{bins}}\frac{\beta_i^2}{\sigma_{\rm shp}^2} + \frac{\varepsilon_D^2}{\sigma_D^2} + \sum_{A=1}^{3}\left[\left(\frac{\varepsilon_d^A}{\sigma_d}\right)^2 + \left(\frac{\eta_f^A}{\sigma_f^A}\right)^2 + \left(\frac{\eta_n^A}{\sigma_n^A}\right)^2 + \left(\frac{\eta_s^A}{\sigma_s^A}\right)^2\right]$$

Reactor

Detector

Backgrounds

Neutrino Spectrum

How swapping improves sensitivity

- Example: one reactor, one near detector, one far detector.
- Swapping can't improve backgrounds, not shown here.
  In Run A, det 1 at the near site and det 2 at the far site. In Run B swap detectors.

$$\chi^2 = \frac{[O_1^A - T_n(1+\alpha_{\det}^1 + \alpha_r^A)]^2}{T_n} + \frac{[O_2^A - T_f(1+\alpha_{\det}^2 + \alpha_r^A)]^2}{T_f}$$

$$+ \frac{[O_2^B - T_n(1+\alpha_{\det}^2 + \alpha_r^B)]^2}{T_n} + \frac{[O_1^B - T_f(1+\alpha_{\det}^1 + \alpha_r^B)]^2}{T_f} + \left(\frac{\alpha_{\det}^1}{\sigma_{\det}}\right)^2 + \left(\frac{\alpha_{\det}^2}{\sigma_{\det}}\right)^2 + \left(\frac{\alpha_r^A}{\sigma_r}\right)^2 + \left(\frac{\alpha_r^B}{\sigma_r}\right)^2$$

- If run A has equal events to run B, equivalently, it can be written as

$$\chi^2 = \frac{[2O_n - 2T_n(1+\frac{\alpha_{\det}^1 + \alpha_{\det}^2}{2} + \frac{\alpha_r^A + \alpha_r^B}{2})]^2}{2T_n} + \frac{[2O_f - 2T_f(1+\frac{\alpha_{\det}^1 + \alpha_{\det}^2}{2} + \frac{\alpha_r^A + \alpha_r^B}{2})]^2}{2T_f} + \left(\frac{\alpha_{\det}^1}{\sigma_{\det}}\right)^2 + \ldots$$

- Now ($\alpha^1_{\det} + \alpha^2_{\det}$) is correlated between the near and far detectors. That is to say, detector normalization error all cancel out, even we don't know its size.