Daya Bay Reactor Neutrino Experiment

Precise Measurement of θ_{13}

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DOANOW, Honolulu, Hawaii, March 24, 2007

Outline

- Physics Motivation
- Requirements
- The Daya Bay experiment
  - Layout
  - Detector design
  - Backgrounds
  - Systematic errors and Sensitivity
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- Summary

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:

$$\underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{12} \end{pmatrix}}_{\text{reactor and accelerator}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric, accelerator}} \underbrace{\begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{0\nu\beta\beta}$$

Solar, reactor — reactor and accelerator — Atmospheric, accelerator — 0νββ

$\theta_{12} = \sim 32^\circ$ $\theta_{13} = ?$ $\theta_{23} \sim 45^\circ$

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

Measuring $\sin^2 2\theta_{13}$ at reactors

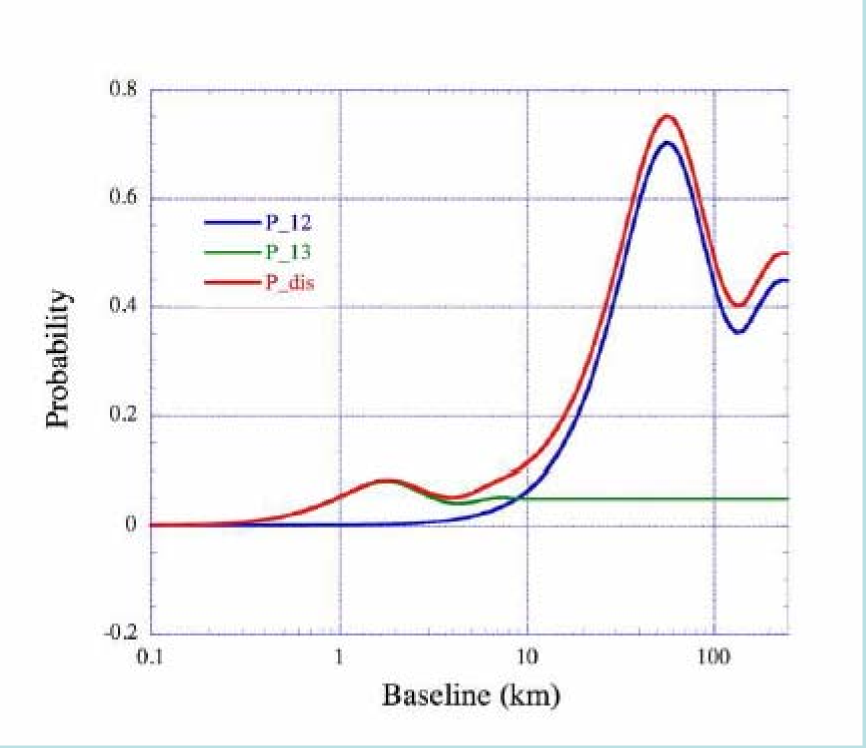
- Clean signal, no cross talk with δ and matter effects
- Relatively cheap compared to accelerator based experiments
- Provides the direction to the future of neutrino physics
- Rapidly deployment possible

at reactors:

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

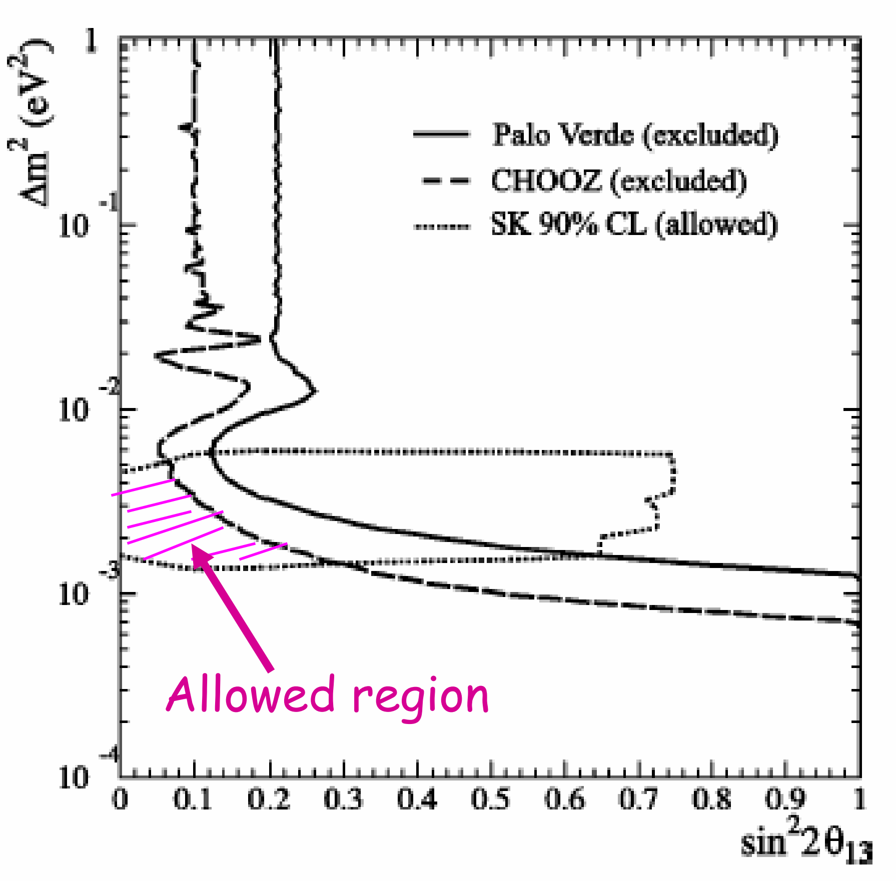
at LBL accelerators:

$$P_{\mu e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{23} L/E) + \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E) - A(\rho) \bullet \cos^2\theta_{13} \sin\theta_{13} \bullet \sin(\delta)$$

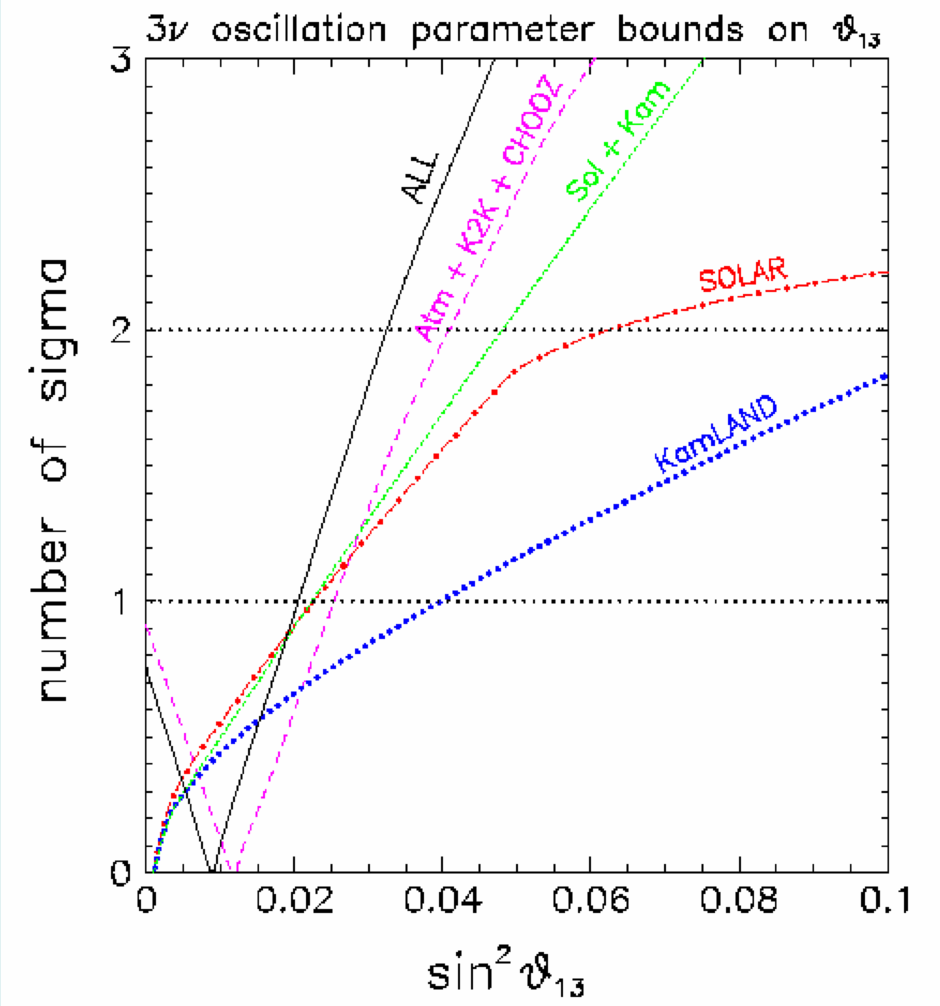


Current Knowledge of θ_{13}

Direct search
PRD 62, 072002

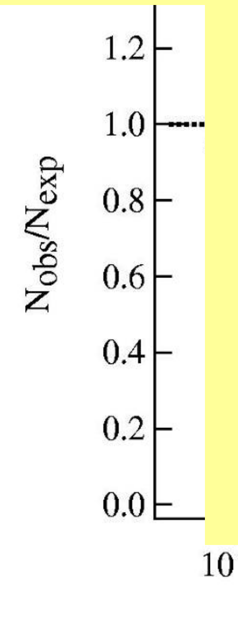


Global fit
fogli etal., hep-ph/0506083

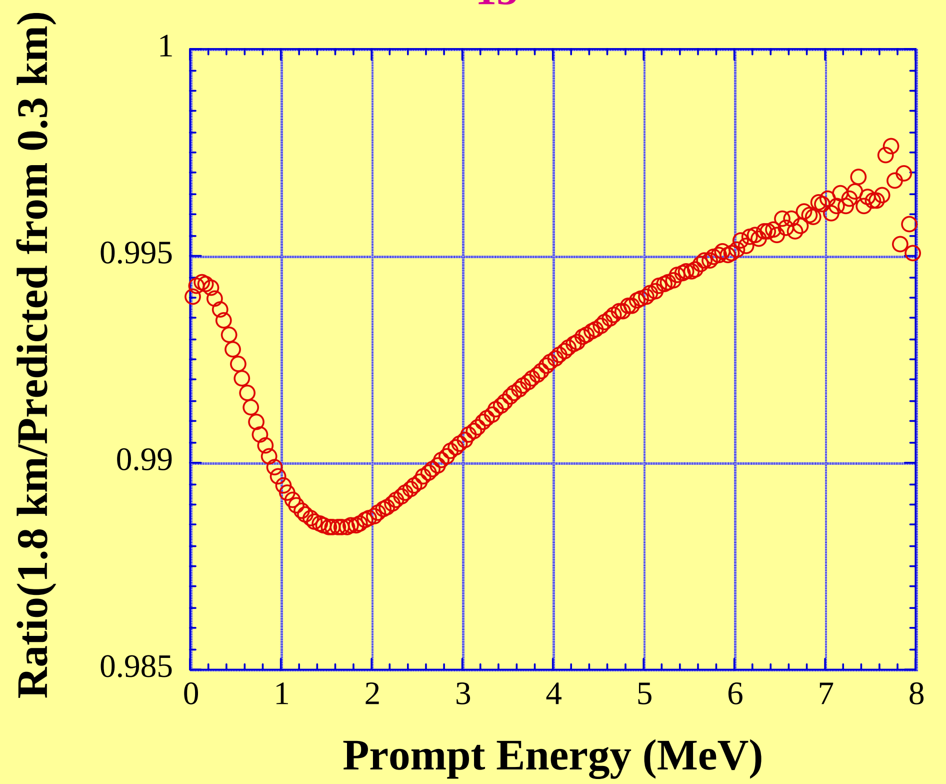


- No good reason(symmetry) for $\sin^2 2\theta_{13} = 0$
- Even if $\sin^2 2\theta_{13} = 0$ at tree level, $\sin^2 2\theta_{13}$ will not vanish a… e correcti…
- Theoreti… ~ 0.001-0.1

Typical pr…



$\sin^2 2\theta_{13} = 0.01$



…eriment with …ion for $\sin^2 2\theta_{13}$ …han 0.01 is desired

…provement of an …of magnitude over …us experiments

How to reach 1% precision ?

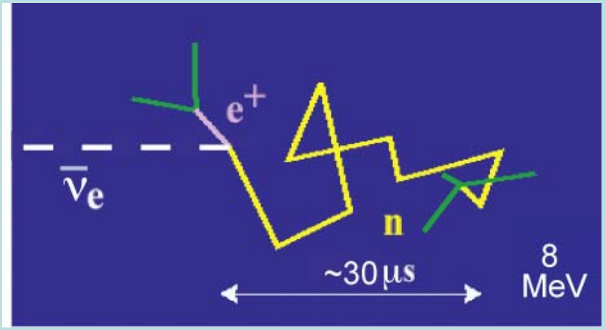
- **Increase statistics:**
  - **Utilize larger target mass, hence larger detectors**
- **Reduce systematic uncertainties:**
  - **Reactor-related:**
    - **Optimize baseline for best sensitivity and smaller residual errors**
    - **Near and far detectors to minimize reactor-related errors**
  - **Detector-related:**
    - **Use “Identical” pairs of detectors to do *relative* measurement**
    - **Comprehensive program in calibration/monitoring of detectors**
    - **Interchange near and far detectors (optional)**
  - **Background-related**
    - **Go deeper to reduce cosmic-induced backgrounds**
    - **Enough active and passive shielding**
  - **Use more powerful nuclear reactors**

Daya Bay nuclear power plant

- 4 reactor cores, 11.6 GW
- 2 more cores in 2011, 5.8 GW
- Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds

neutrino detection:
Inverse- β reaction in liquid scintillator

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



τ ≈ 180 or 28 μs(0.1% Gd)

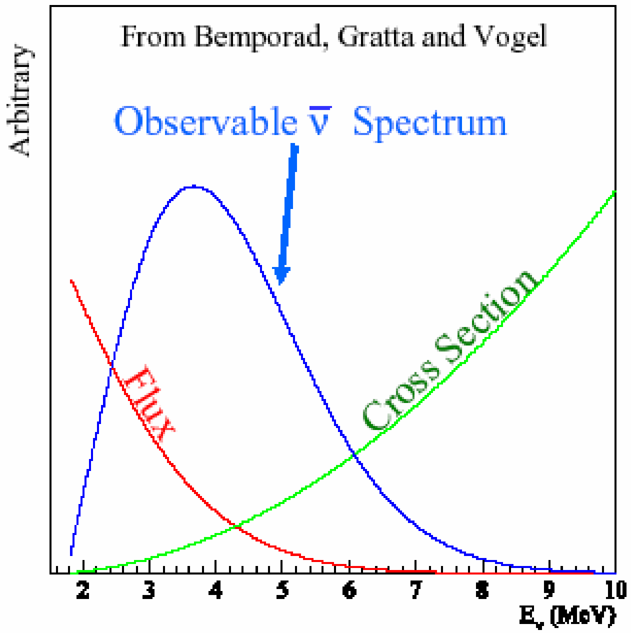
n + p → d + γ (2.2 MeV)
n + Gd → Gd* + γ's (8 MeV)

Neutrino Event: coincidence in time, space and energy

Neutrino energy:

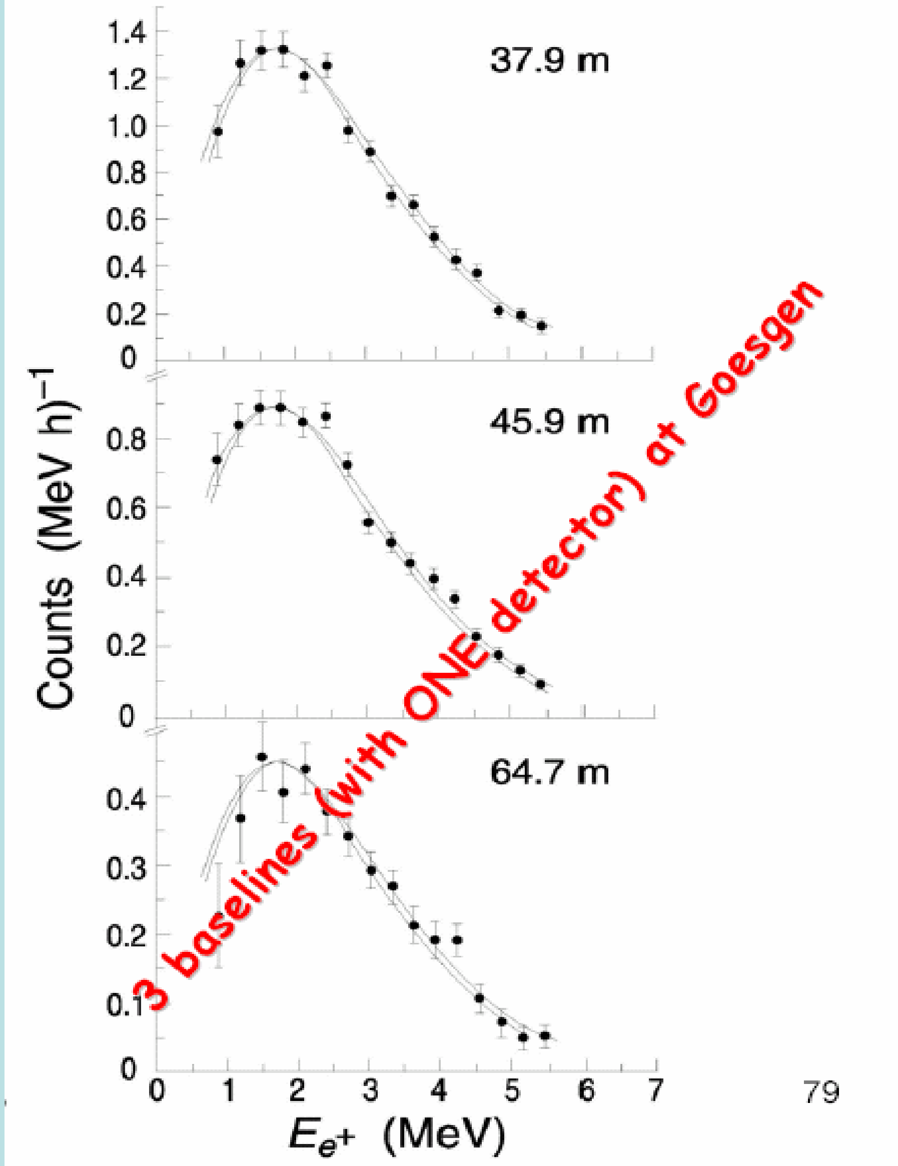
$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV: Threshold}}$$

10-40 keV   *1.8 MeV*: Threshold



Prediction of reactor neutrino spectrum

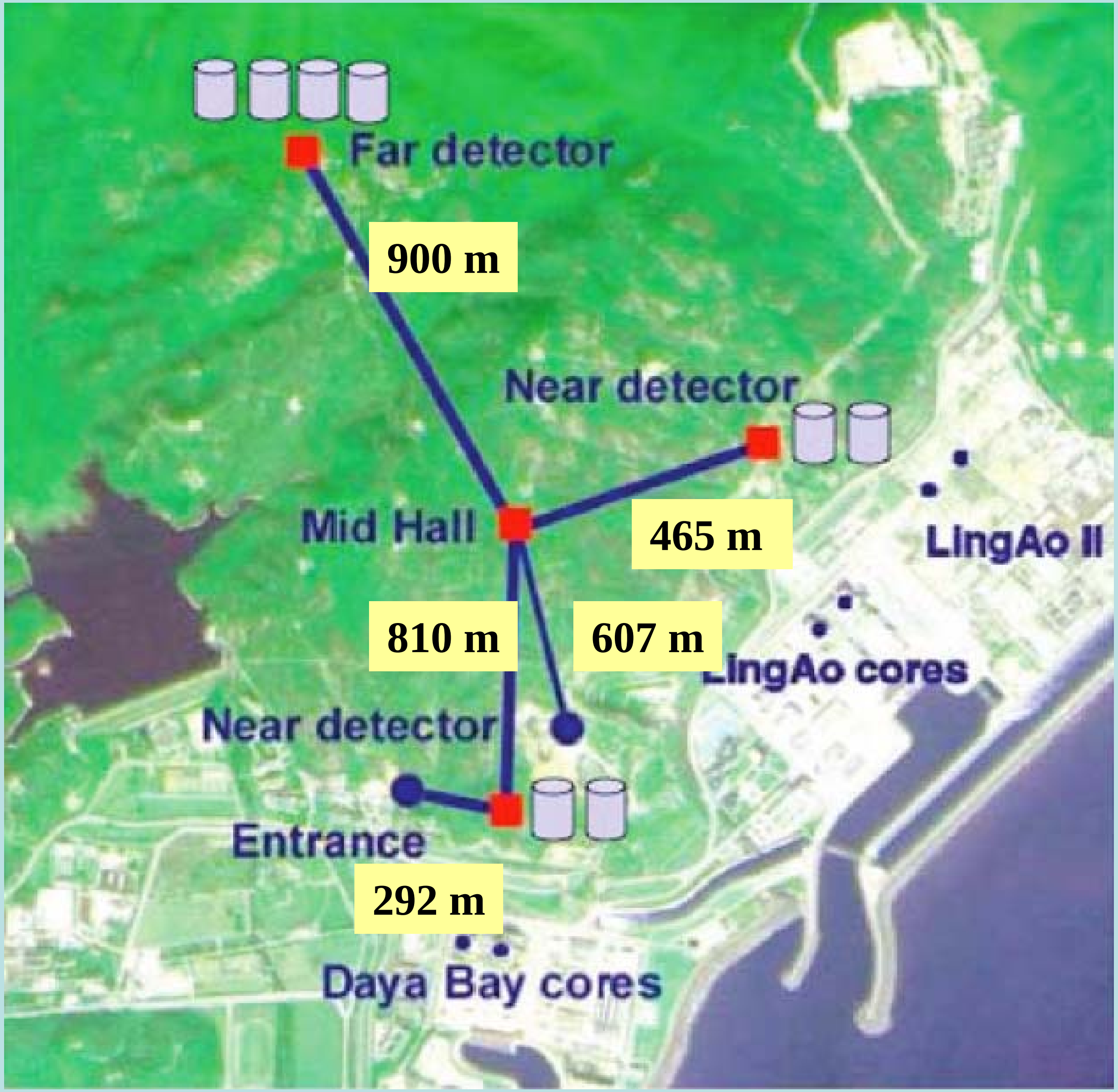
- **Reactor neutrino rate and spectrum depends on:**
  - **The fission isotopes and their fission rate, uncorrelated ~ 1-2%**
  - **Fission rate depends on thermal power, uncorrelated ~ 1%**
  - **Energy spectrum of weak decays of fission isotopes, correlated ~ 1%**
- **Three ways to obtain reactor neutrino spectrum:**
  - **Direct measurement at near site**
  - **First principle calculation**
  - **Sum up neutrino spectra of ^{235}U, ^{239}Pu, ^{241}Pu(from measurement) and ^{238}U(from calculation, ~ 1%)**
- **They all agree well within 3%**



Design considerations

- ***Identical near and far detectors*** to cancel reactor-related errors
- ***Multiple modules*** for reducing detector-related errors and cross checks
- ***Three-zone detector modules*** to reduce detector-related errors
- ***Overburden and shielding*** to reduce backgrounds
- ***Multiple muon detectors*** for reducing backgrounds and cross checks
- ***Movable detectors*** for swapping

Experiment Layout

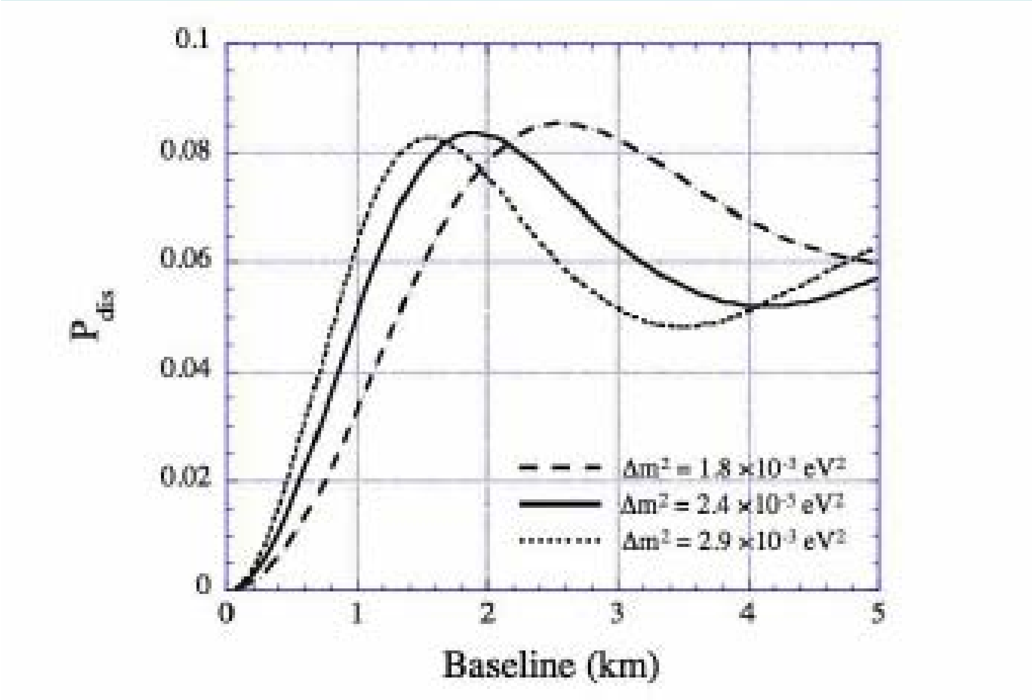


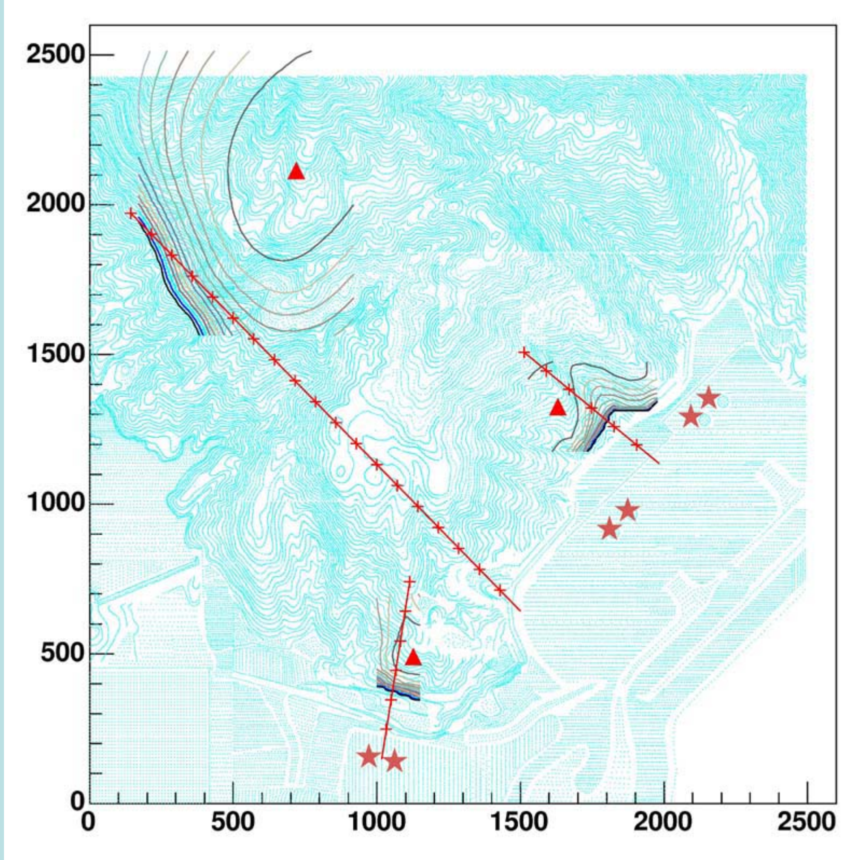
Total Tunnel length ~ 3000 m

- Multiple detectors per site facilitates cross-check of detector efficiency

- Two near sites to sample neutrino flux from reactor groups

Baseline optimization and site selection

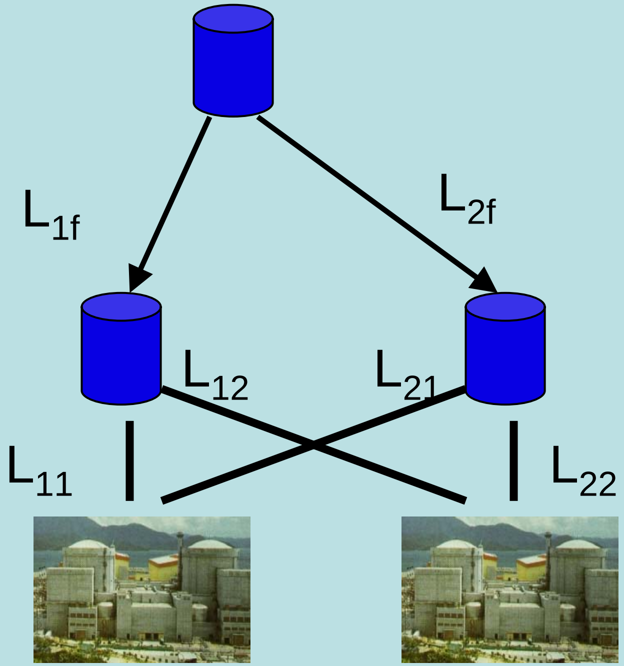




- **Neutrino flux and spectrum**
- **Detector systematical error**
- **Backgrounds from environment**
- **Cosmic-rays induced backgrounds (rate and shape) taking into mountain shape: fast neutrons, 9Li, …**

Reactor Related Systematic Uncertainty

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



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

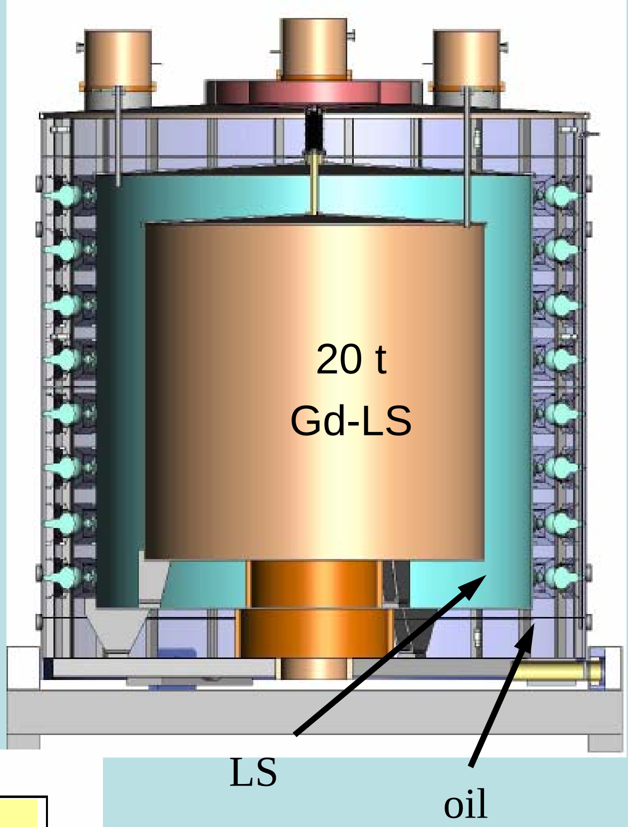
$$\frac{\text{Near}}{\text{Far}} = \alpha \frac{\text{Near1}}{\text{Far}} + \frac{\text{Near2}}{\text{Far}}$$

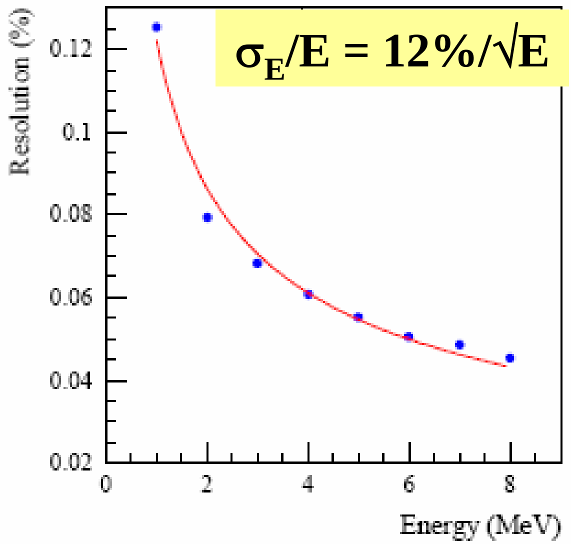
Assuming 30 cm precision in core position

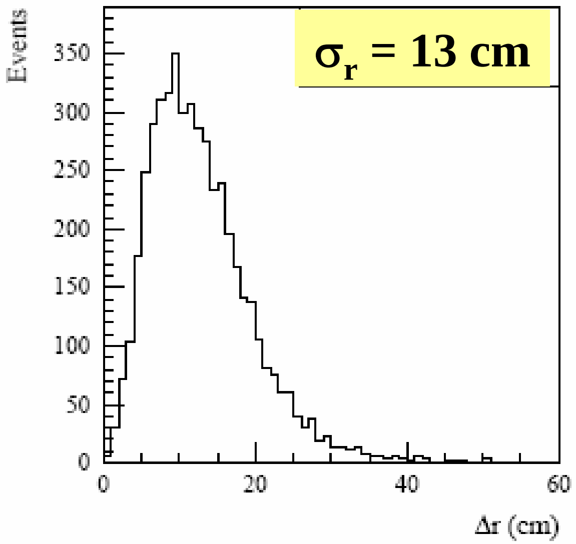
Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

Central Detector modules

- **Three zones modular structure:**
  - **I. target: Gd-loaded scintillator**
  - **II. γ-catcher: normal scintillator**
  - **III. Buffer shielding: oil**
- **Reflector at top and bottom**
- **192 8”PMT/module**
- **Photocathode coverage:**
  - **5.6 % ➔ 12%(with reflector)**







Target: 20 t, 1.6m
γ-catcher: 20t, 45cm
Buffer: 40t, 45cm

Inverse-beta Signals

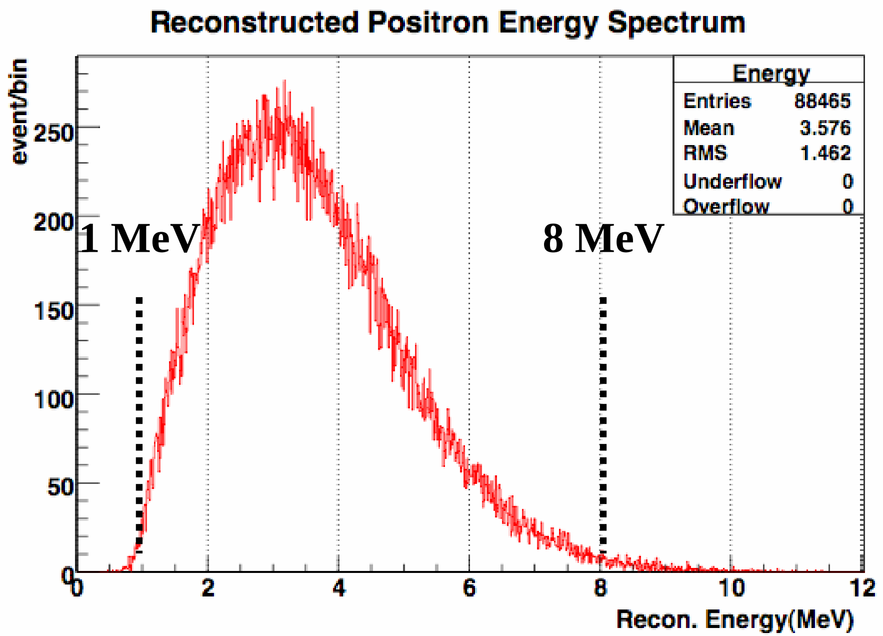
Antineutrino Interaction Rate (events/day per 20 ton module)	
Daya Bay near site	960
Ling Ao near site	760
Far site	90

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

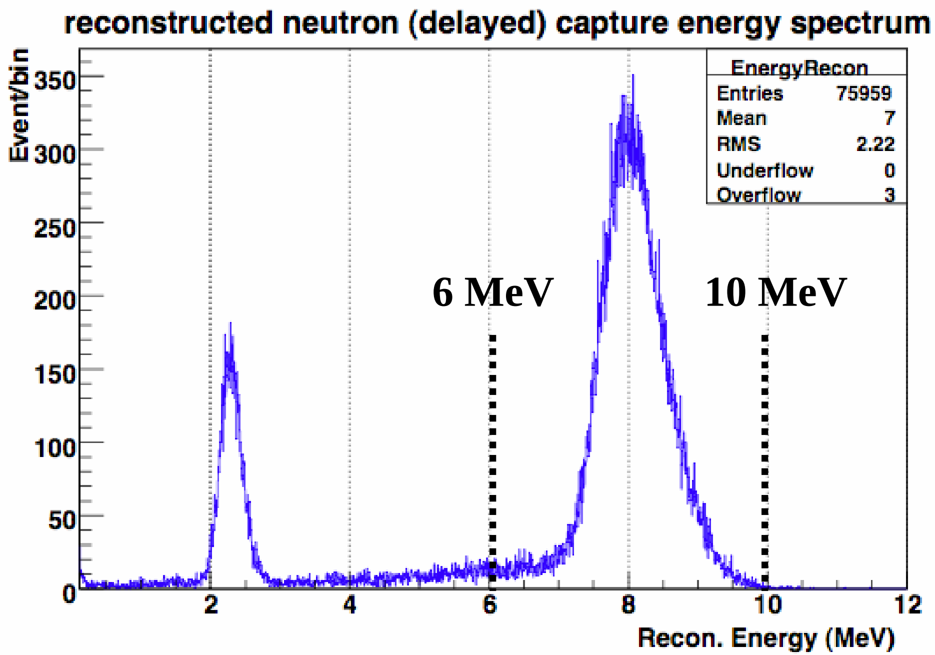
$E_{n\text{-}cap}$ ("delayed") $\in [6,10]$ MeV

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

Prompt Energy Signal



Delayed Energy Signal

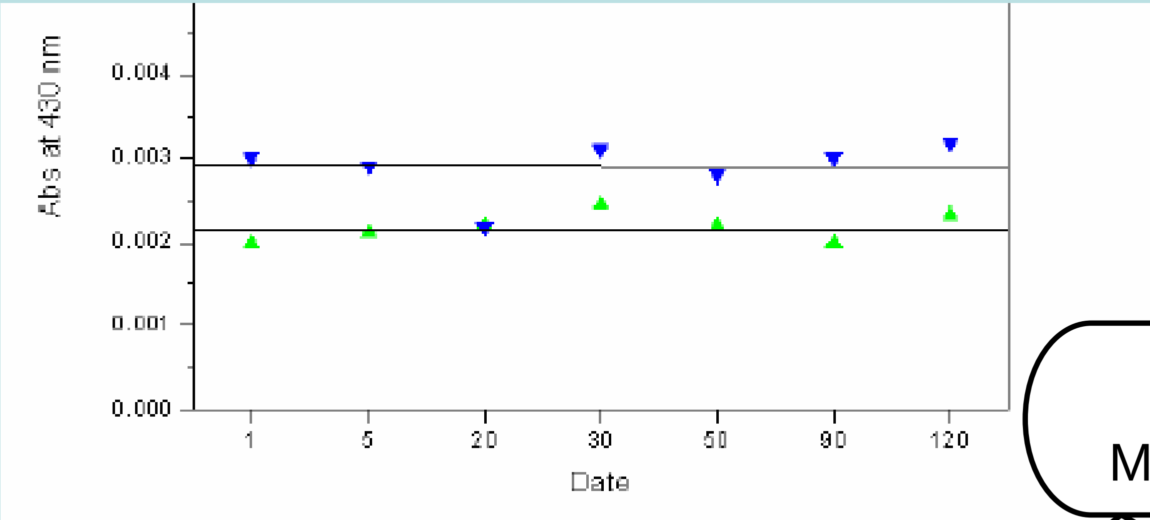


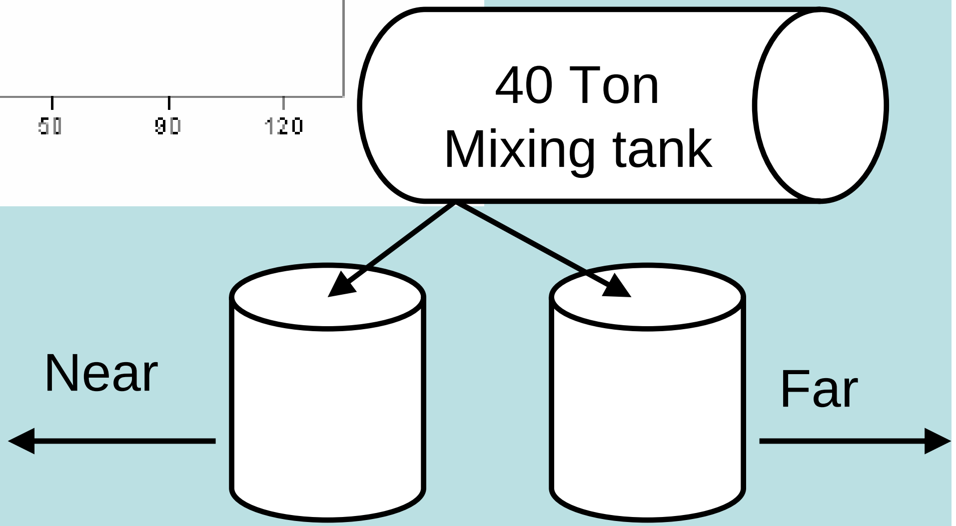
Statistics comparable to a single module at far site in 3 years.

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



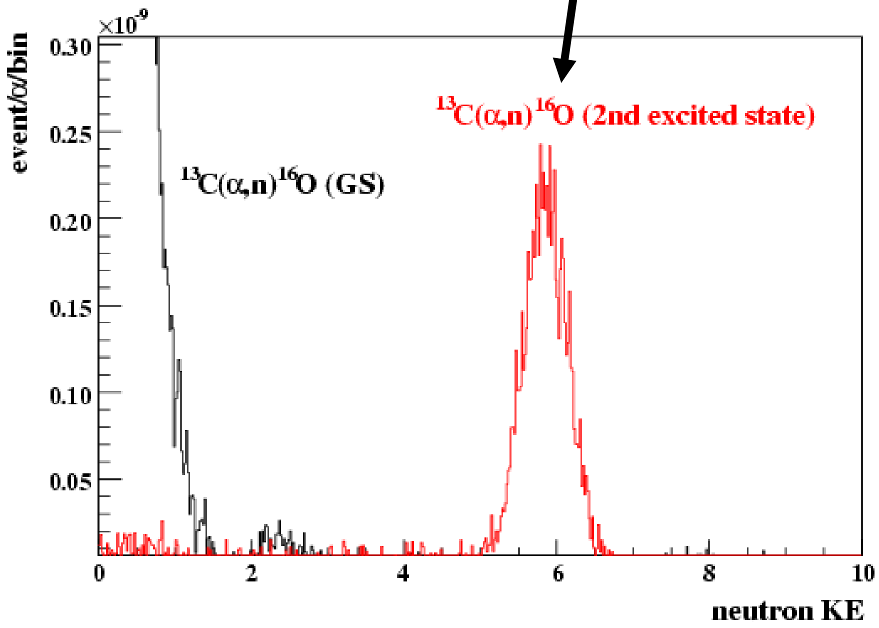


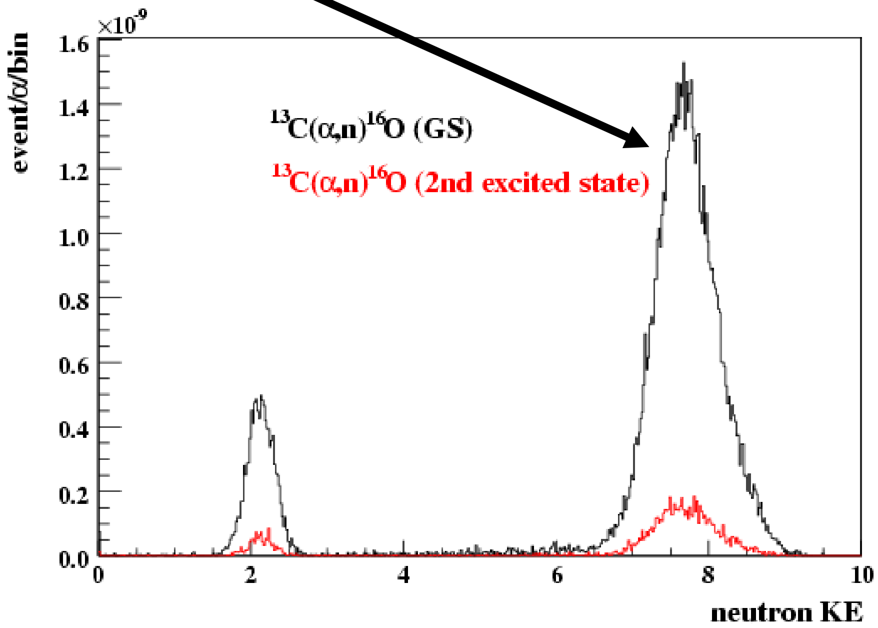
- Filling **detectors in pair**

Calibrating Energy Cuts

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

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





Systematics Budget

Detector-related

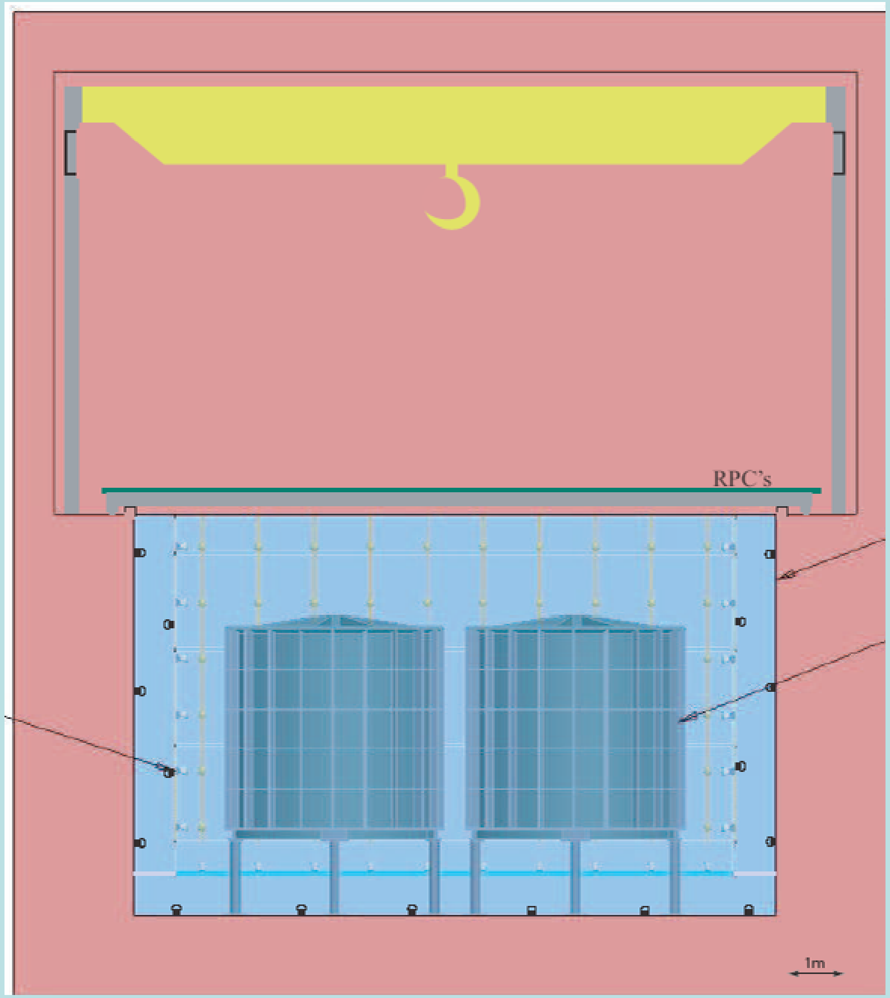
Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*) Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	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%

Background reduction: redundant and efficient muon veto system



Multiple muon tagging detectors:

- Water pool as Cherenkov counter has inner/outer regions
- RPC at the top as muon tracker
- Combined efficiency

  > (99.5 ± 0.25) %

Background related errors

- **Uncorrelated backgrounds:**

  U/Th/K/Rn/neutron

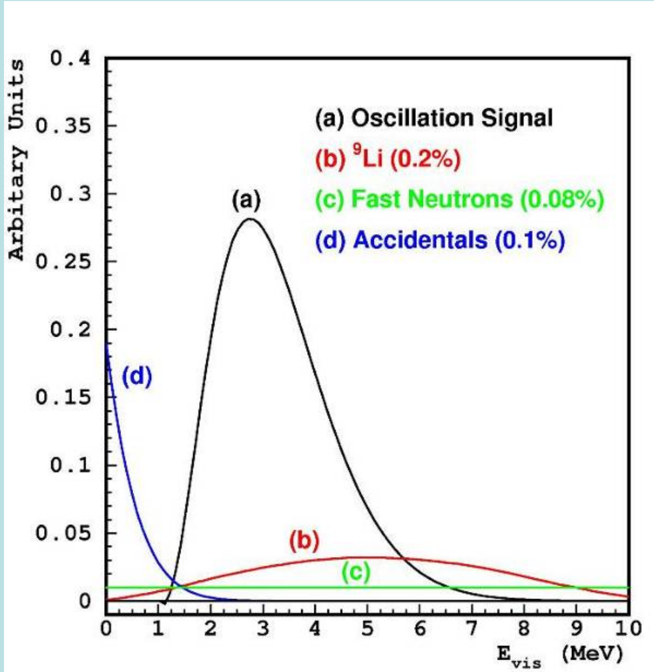
  Single gamma rate @ 0.9MeV < 50Hz

  Single neutron rate < 1000/day

- **Correlated backgrounds:**

  Fast Neutrons: double coincidence

  ^{8}He/^{9}Li: neutron emitting decays



	Daya Bay Near	Ling Ao Near	Far Hall
Baseline (m)	363	481 from Ling Ao 526 from Ling Ao II	1985 from Daya Bay 1615 from Ling Ao's
Overburden (m)	98	112	350
Radioactivity (Hz)	<50	<50	<50
Muon rate (Hz)	36	22	1.2
Antineutrino Signal (events/day)	930	760	90
Accidental Background/Signal (%)	<0.2	<0.2	<0.1
Fast neutron Background/Signal (%)	0.1	0.1	0.1
^{8}He+^{9}Li Background/Signal (%)	0.3	0.2	0.2

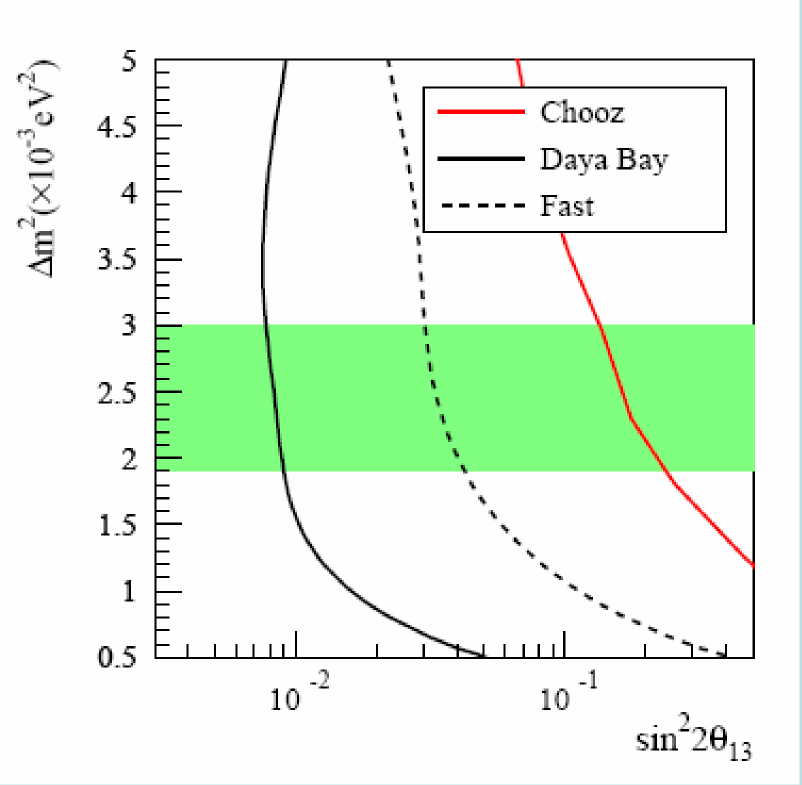
Summary of Systematic Uncertainties

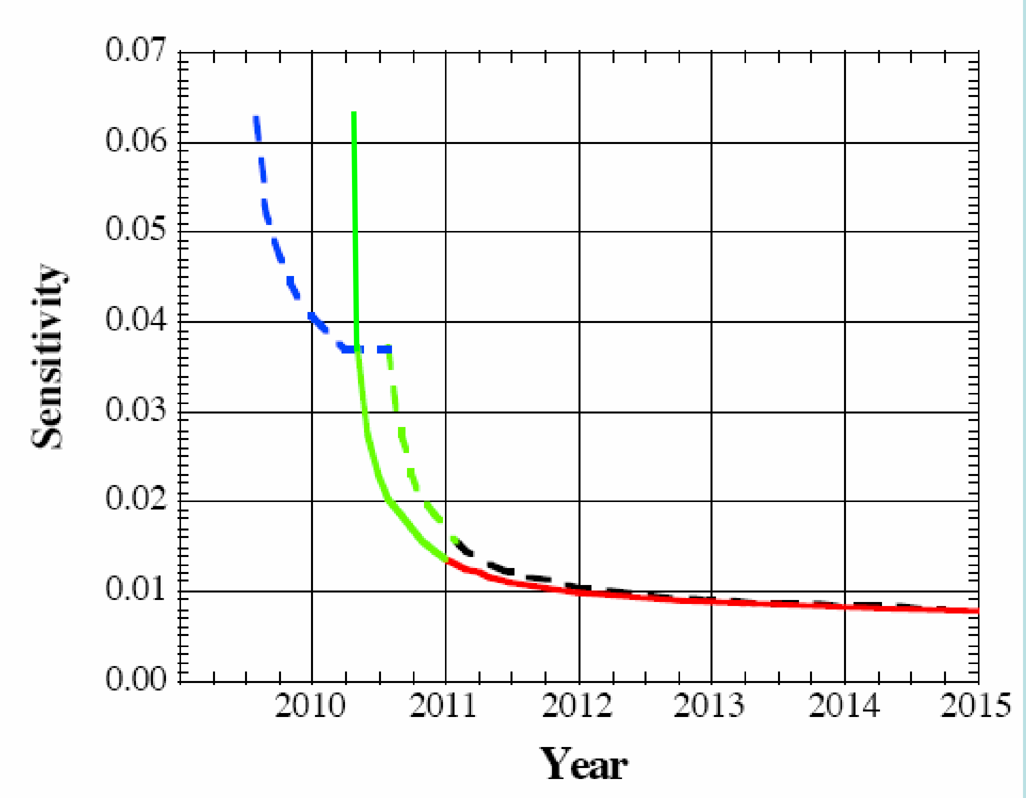
sources	Uncertainty
Neutrinos from Reactor	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal statistics	0.2%

Schedule

- begin civil construction — April 2007
- Bring up the first pair of detectors — Jun 2009
- Begin data taking with the Near-Mid configuration — Sept 2009
- Begin data taking with the Near-Far configuration — Jun 2010

Sensitivity to $\mathrm{Sin}^2 2\theta_{13}$

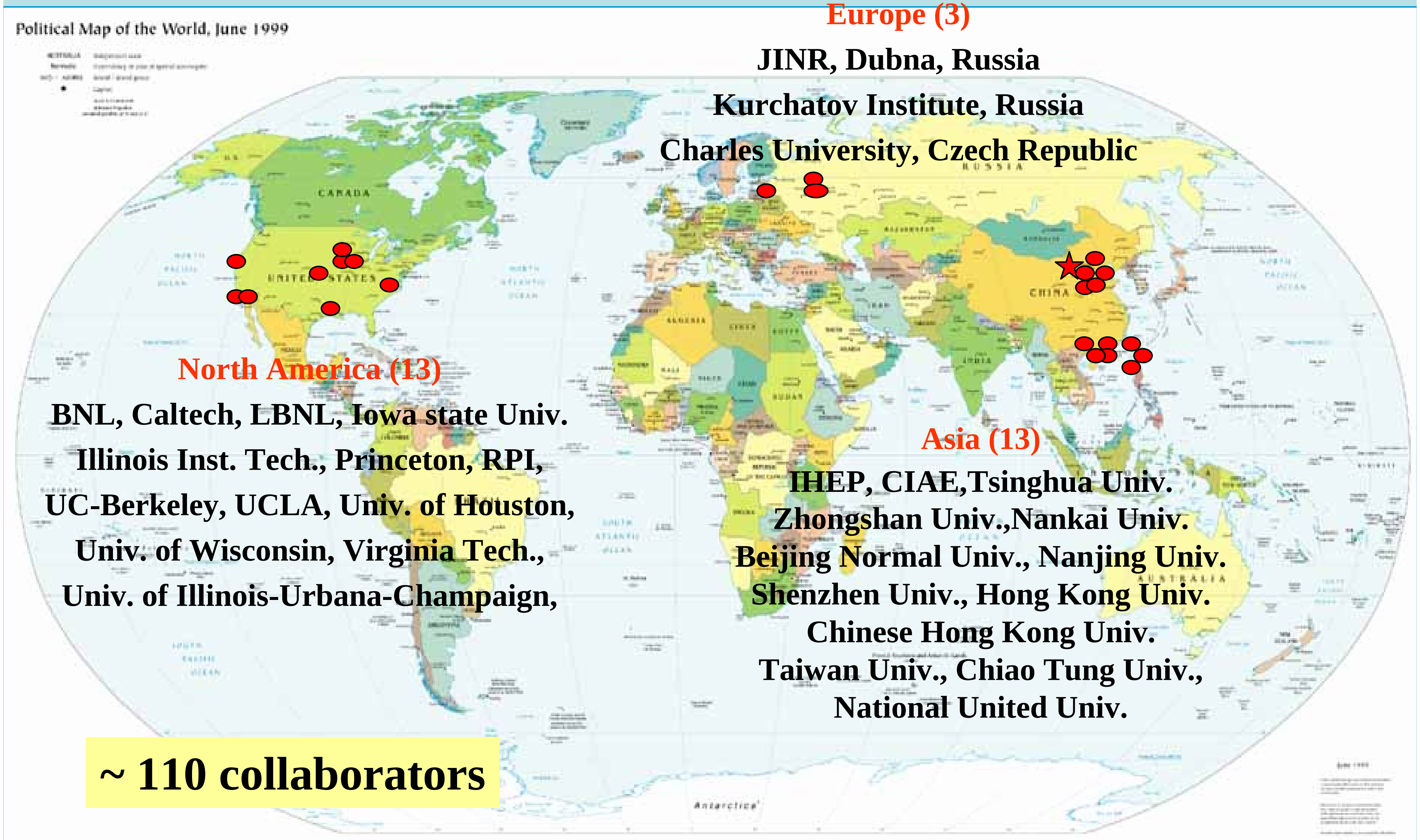




Other physics capabilities:

Supernova watch, Sterile neutrinos, …

Daya Bay collaboration



Europe (3)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (13)

BNL, Caltech, 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 (13)

IHEP, CIAE,Tsinghua Univ.
Zhongshan Univ.,Nankai Univ.
Beijing Normal Univ., Nanjing Univ.
Shenzhen Univ., Hong Kong Univ.
Chinese Hong Kong Univ.
Taiwan Univ., Chiao Tung Univ.,
National United Univ.

~ 110 collaborators

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

Summary

- **The Daya Bay experiment will reach a sensitivity of $\leqslant$ 0.01 for $\sin^2 2\theta_{13}$**
- **Design of detectors is in progress and R&D is ongoing**
- **Detailed engineering design of tunnels and infrastructures underway**
- **Received commitment from Chinese funding agencies**
- **Passed US Physics Review – CD-1 scheduled for April 2007**
- **Start civil construction in 2007, deploy detectors in 2009, and begin full operation in 2010**