Measuring $\sin^2 2\theta_{13}$ with the Daya Bay nuclear power reactors

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for Daya Bay collaboration

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Daya Bay Neutrino Experiment

- Measure $\sin^2 2\theta_{13}$ with a sensitivity of 0.01 at 90% CL, an improvement of an order of magnitude over previous experiments
- 4 reactor cores, 2 more in 2011, a total of 17.4 GW
- Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds
- 60 km from Hong Kong, Convenient Transportation, Living conditions, communications

Layout of the experiment

Near-Far detector schemes:
- To cancel reactor-related errors
- Residual error ~0.1%

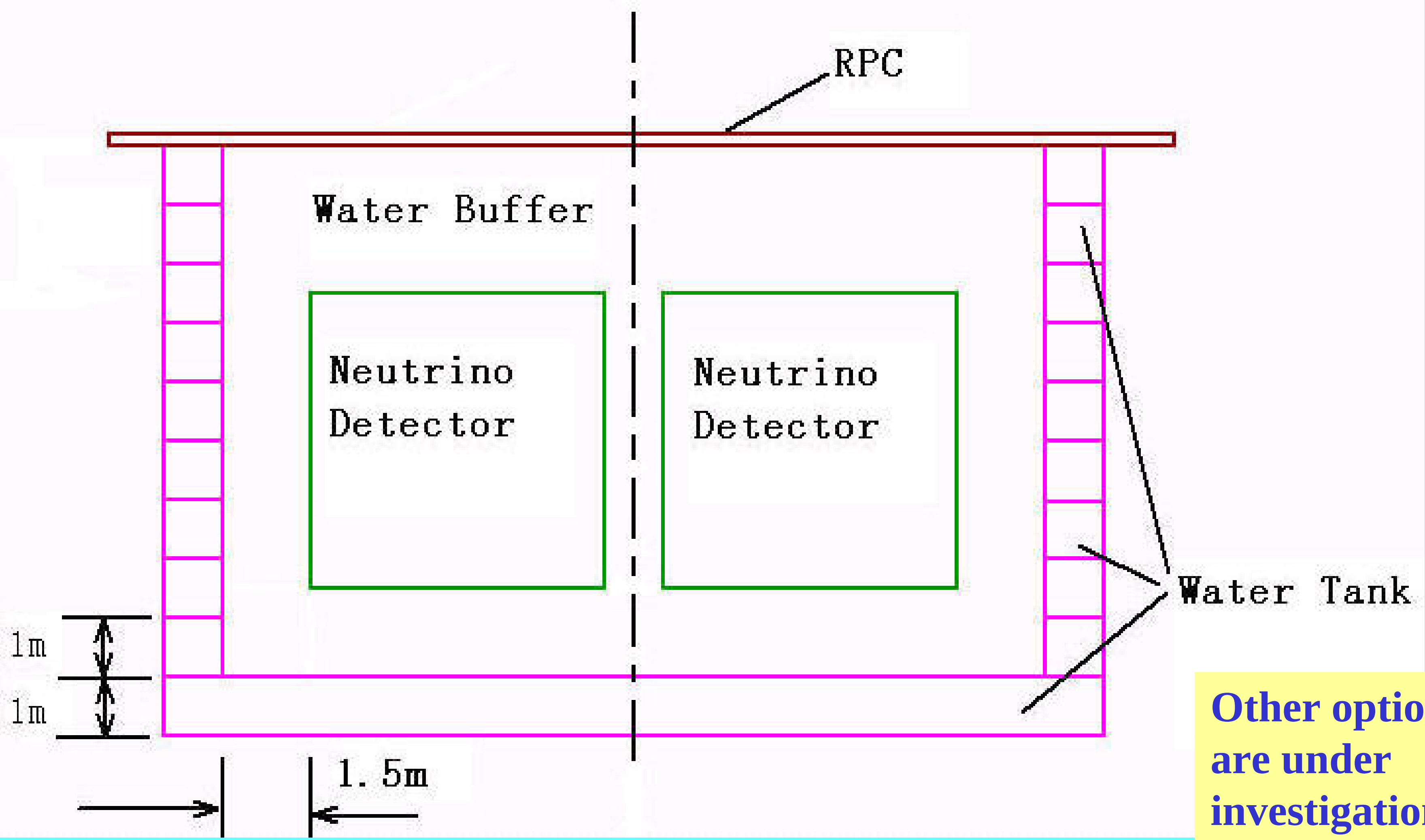
Swap near-far detectors
- To cancel detector-related errors.
- Residual error ~0.2%

Detector deep undergrounds
- To reduce backgrounds
- B/S at near site: ~0.5%
- B/S at far site: ~0.2%

Fast Measurement
- DYB+Mid, 2008-2009
- Sensitivity (1 year) ~0.03

Full Measurement
- DYB+LA+Far, from 2010
- Sensitivity (3 year) <0.01

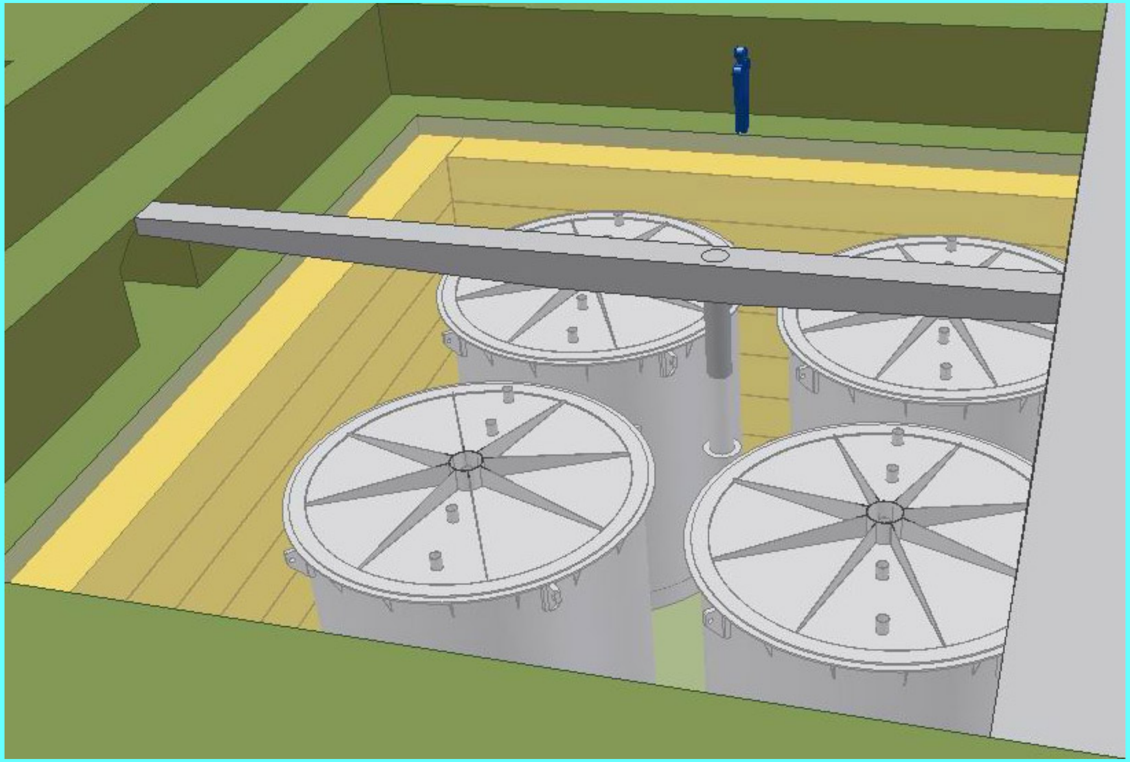
Baseline detector design: multiple neutrino modules and multiple vetos



Other options are under investigation

Redundancy is a key for the success of this experiment

Neutrino detector: multiple modules

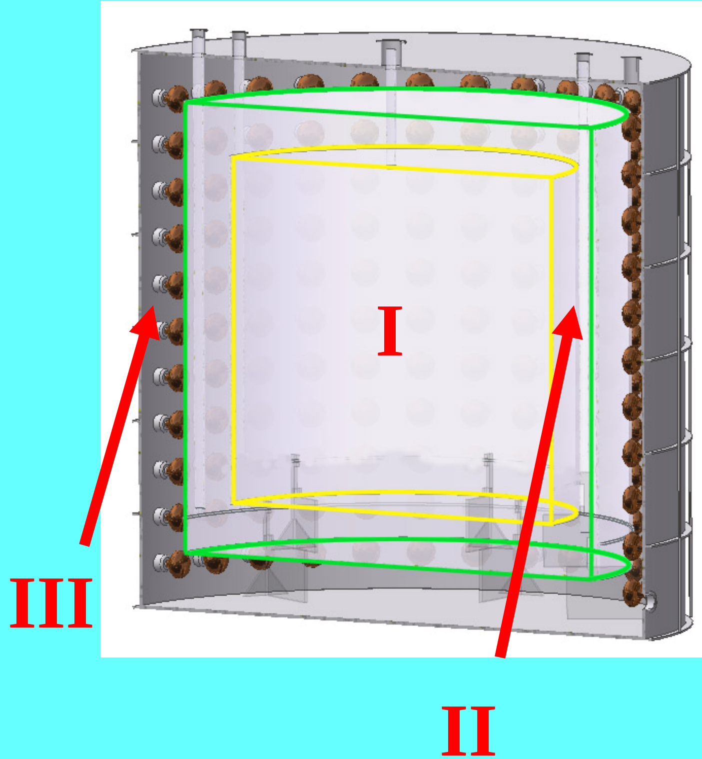


Two modules at near sites
Four modules at far site

- Multiple modules for side-by-side cross check
- Reduce uncorrelated errors
- Smaller modules for easy construction, moving, handing, …
- Small modules for less sensitivity to scintillator aging, details of the light transport, …

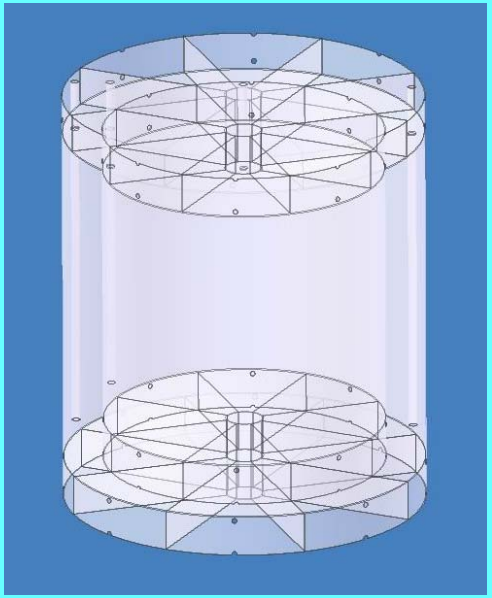
Central Detector modules

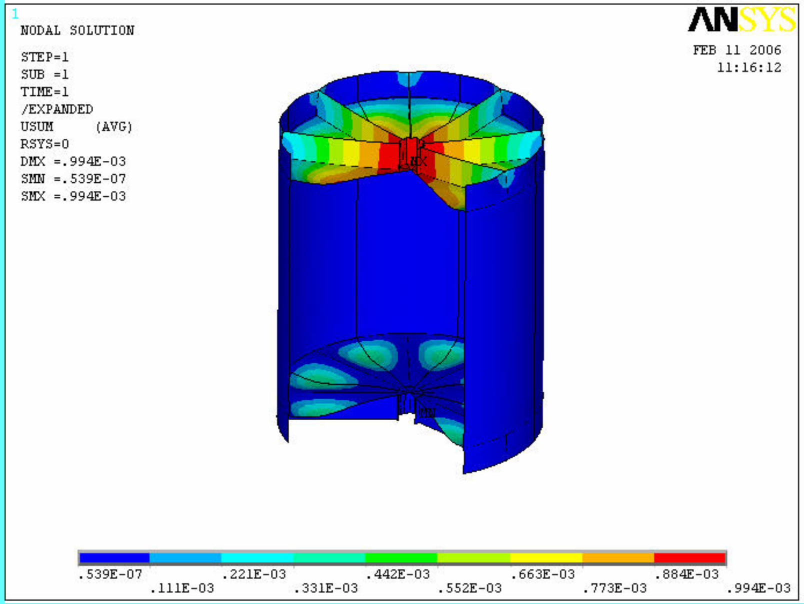
- Three zones modular structure:
  - I. target: Gd-loaded scintillator,
  - II. γ-ray catcher: normal scintillator
  - III. Buffer shielding: oil
- Advantages: neutrino events on target are determined by capture time, not position
- Cylindrical module for easy construction
- Light reflector at top and bottom for cost saving
- Module dimension:
  - Target: 3.2 m high, 3.2 m diameter, determined by the limit of statistical errors
  - γ-ray catcher: 0.45 m thick, determined by the limit of efficiency error
  - Buffer: 0.45 cm thick, determined by backgrounds from PMT glass
- ~ 200 8”PMT/module
- Photocathode coverage: 5.6 % ➔ 10%(with light reflector)
- Performance: energy resolution 5%@8MeV, position resolution ~ 14 cm



Acrylic tanks

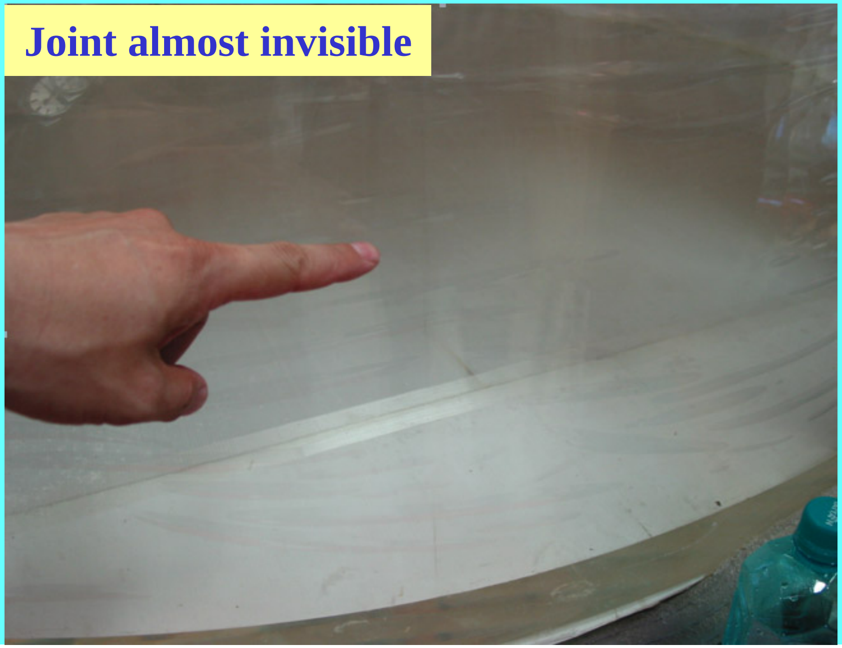
Design:





Manufacture

A 2m cylinder



Joint almost invisible

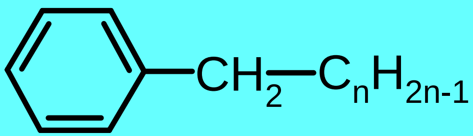
R&D of Gd-loaded scintillator

- **Requirements:**
  - Gd-loading: ~ (0.1-0.15)%
  - light yield: > 50% Anthracene
  - Attenuation length: > 10m
  - Stability: < 3%/year
- **R&D Efforts:**
  - PC+MO/DC(BNL)
  - MT+MO/DC(IHEP)
  - LAB+PC(BNL)
  - LAB(IHEP, BNL, Dubna)

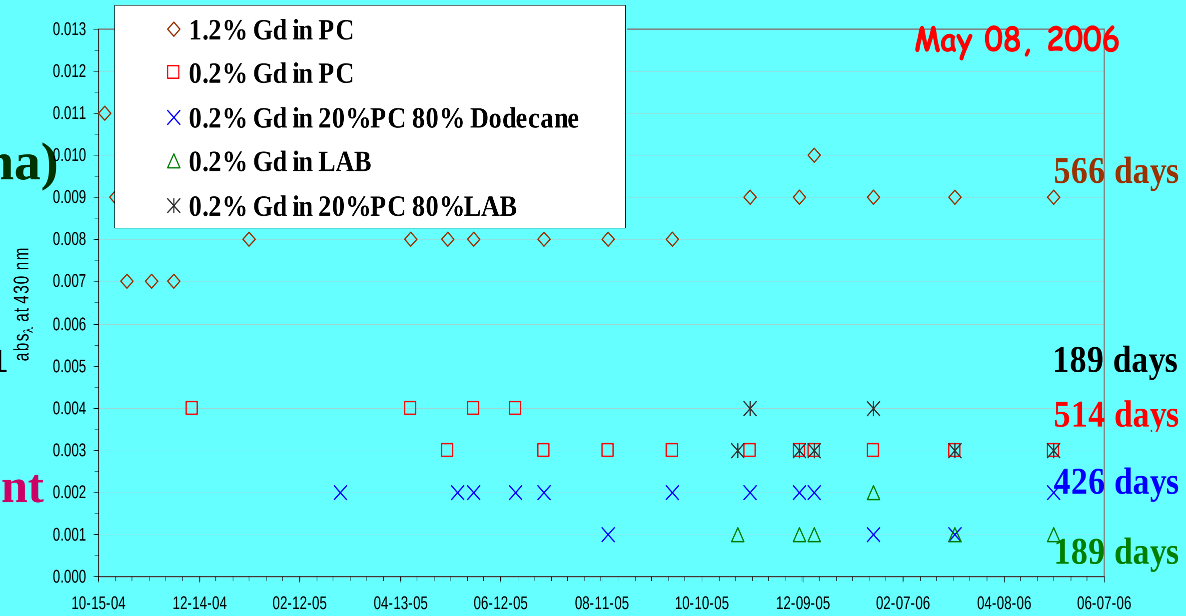
Gd-loaded scintillator developed at IHEP

Sample	Atten. Len. (m)	Light yield
2: 8 mesitylene: dodecane(LS)	15.0	-
LAB	-	-
PPO+ bis-MSB(Flour) in LS	11.3	0.459
0.2% Gd-EHA + Flour + LS	8.3	0.528
Flour + LAB	23.7	0.542
0.2%Gd-TMHA+Flour+LAB	19.1	0.478

LAB



High light yield, very transparent
High flash point 147^{o}C,
environmentally friendly
Low cost



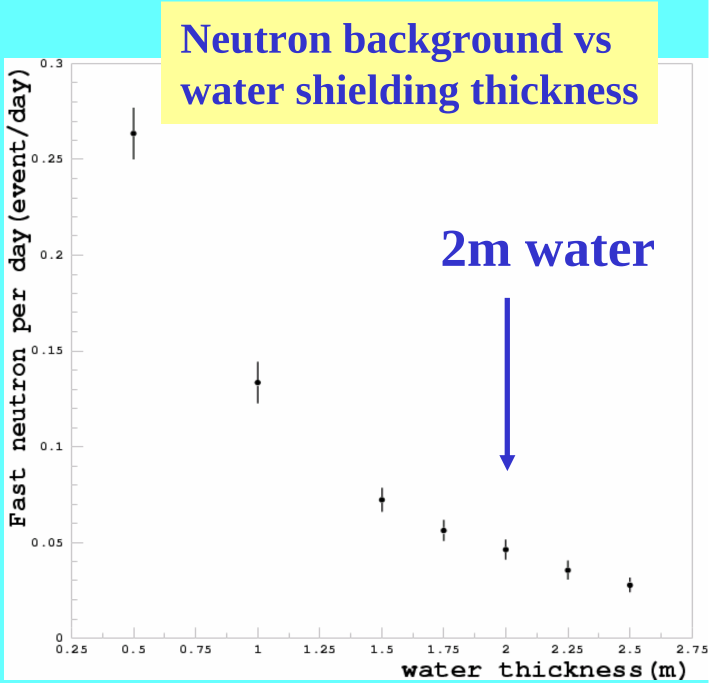
Stability of Gd-loaded scintillator developed at BNL

Calibration and Monitoring

- **Source calibration: energy scale, resolutions, …**
  - **Deployment system**
    - **Automatic: quick but limited space points**
    - **Manual: slow but everywhere**
  - **Choices of sources: energy(0.5-8 MeV), activity(<1KHz), γ/n,…**
  - **Cleanness**
- **Calibration with physics events:**
  - **Neutron capture**
  - **Cosmic-rays**
- **LED calibration: PMT gain, liquid transparency, …**
- **Environmental monitoring: temp., voltage, radon, …**
- **Mass calibration and high precision flow meters**
- **Material certification**

Water Buffer & VETO

- At least 2m water buffer to shield backgrounds from neutrons and γ's from lab walls
- Cosmic-muon VETO Requirement:
  - Inefficiency < 0.5%
  - known to <0.25%
- Solution: Two active vetos
  - Active water buffer, Eff.>95%
  - Muon tracker, Eff. > 90%
    - RPC
    - Water tanks
    - scintillator strips
  - total ineff. = 10%*5% = 0.5%
- Two vetos to cross check each other and control uncertainty
- Baseline options: Water pool + tracker



Background related error

- Need enough shielding and active vetos
- How much is enough ? ➔ error < 0.2%
  - Uncorrelated backgrounds: U/Th/K/Rn/neutron

    Single gamma rate @ 0.9MeV < 50Hz

    Single neutron rate < 1000/day

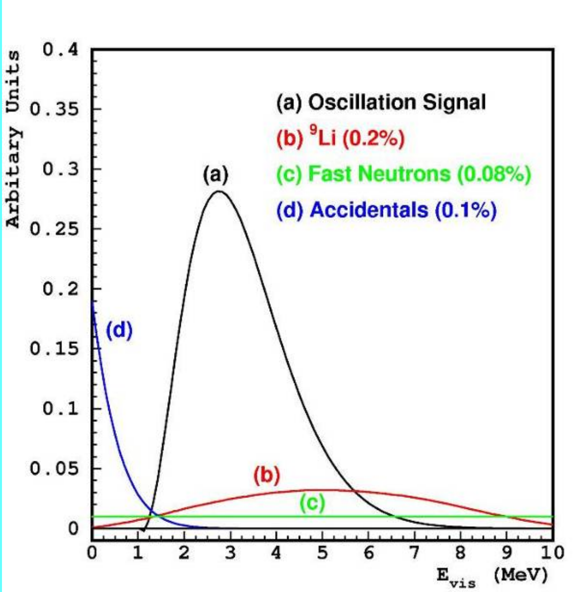
    2m water + 50 cm oil shielding
  - Correlated backgrounds: $n \propto E_\mu^{0.75}$

    Neutrons: >100 MWE + 2m water

    Y.F. Wang et al., PRD64(2001)0013012

    ^{8}He/^{9}Li: > 250 MWE(near), >1000 MWE(far)

    T. Hagner et al., Astroparticle. Phys. 14(2000) 33



	Near	far
Neutrino signal rate(1/day)	560	80
Natural backgrounds(Hz)	45.3	45.3
Accidental BK/signal	0.04%	0.02%
Correlated fast neutron Bk/signal	0.14%	0.08%
^{8}He+^{9}Li BK/signal	0.5%	0.2%

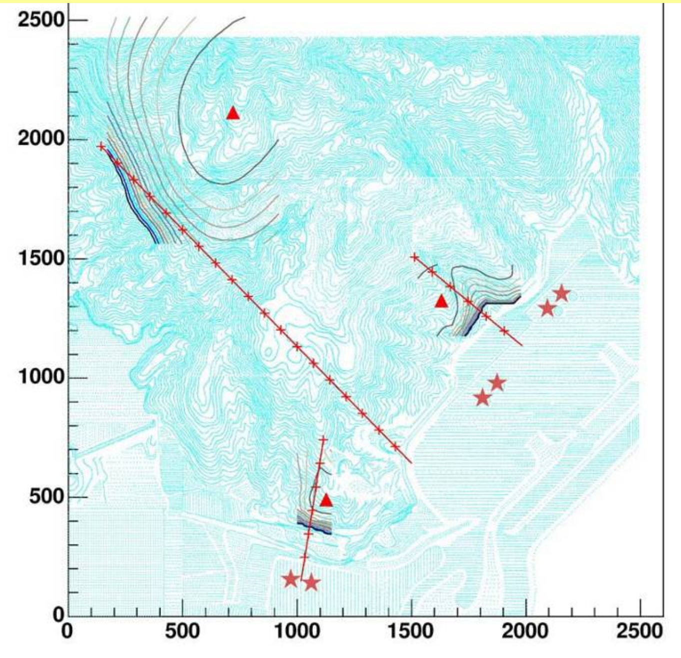
Systematic errors

		Chooz	Palo Verde	KamLAND	Daya Bay
Reactor power		0.7	0.7	2.05	<0.13%
Reactor fuel/ν spectra		2.0	2.0	2.7	
ν cross section		0.3	0.2	0.2	0
No. of protons	H/C ratio	0.8	0.8	1.7	0.2 → 0
	Mass	-	-	2.1	0.2 → 0
Efficiency	Energy cuts	0.89	2.1	0.26	0.2
	Position cuts	0.32		3.5	0
	Time cuts	0.4		0.	0.1
	P/Gd ratio	1.0		-	0.1 → 0
	n multiplicity	0.5		-	<0.1
background	correlated	0.3	3.3	1.8	0.2
	uncorrelated	0.3	1.8	0.1	<0.1
Trigger		0	2.9	0	<0.1
livetime		0	0.2	0.2	0.03

Baseline optimization and Sensitivity to $\sin^2 2\theta_{13}$

- **Reactor-related correlated error: $\sigma_c \sim 2\%$**
- **Reactor-related uncorrelated error: $\sigma_r \sim 1\text{-}2\%$**
- **Neutrino spectrum shape error: $\sigma_{shape} \sim 2\%$**
- **Detector-elated correlated error: $\sigma_D \sim 1\text{-}2\%$**
- **Detector-related uncorrelated error: $\sigma_d \sim 0.5\%$**
- **Background-related error:**
- **fast neutrons: $\sigma_f \sim 100\%$,**
- **accidentals: $\sigma_n \sim 100\%$,**
- **isotopes(^{8}Li, ^{9}He, …) : $\sigma_s \sim 50\text{-}60\%$**
- **Bin-to-bin error: $\sigma_{b2b} \sim 0.5\%$**

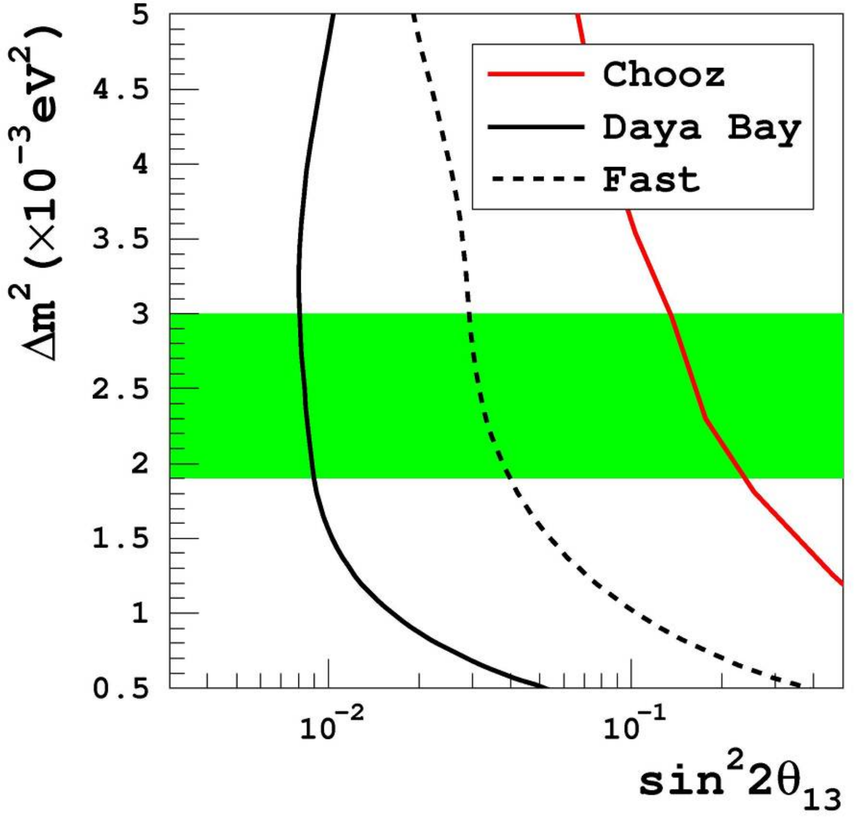
Many are cancelled by the near-far scheme and detector swapping

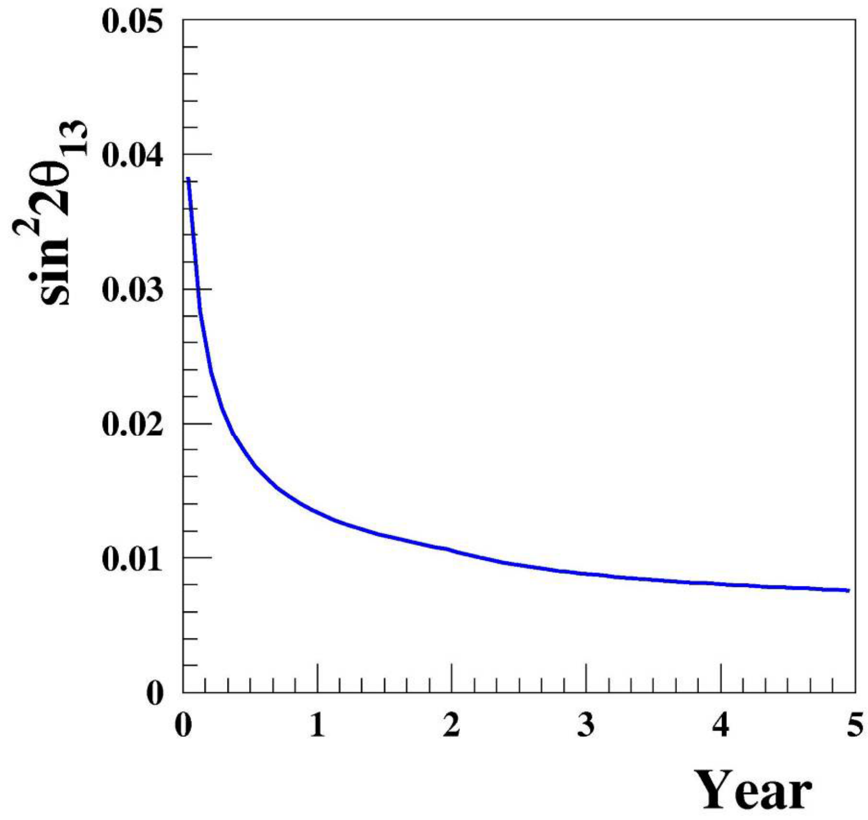


$$\chi^2 = \min_{\alpha's} \sum_{i=1}^{Nbin} \sum_{A=1,3} \frac{\left[M_i^A - T_i^A \left(1 + \alpha_D + \alpha_c + \alpha_d^A + c_i + \sum_r \frac{T_i^{rA}}{T_i^A}\alpha_r\right) - b^A B_i^A \right]^2}{T_i^A + T_i^{A2}\sigma_b^2 + B_i^A}$$

$$+ \frac{\alpha_D^2}{\sigma_D^2} + \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{i=1}^{Nbin} \frac{c_i^2}{\sigma_{shape}^2} + \sum_{A=1,3}\left(\frac{\alpha_d^{A2}}{\sigma_d^2} + \frac{b^{A2}}{\sigma_B^2} \right)$$

Sensitivity to $\sin^2 2\theta_{13}$

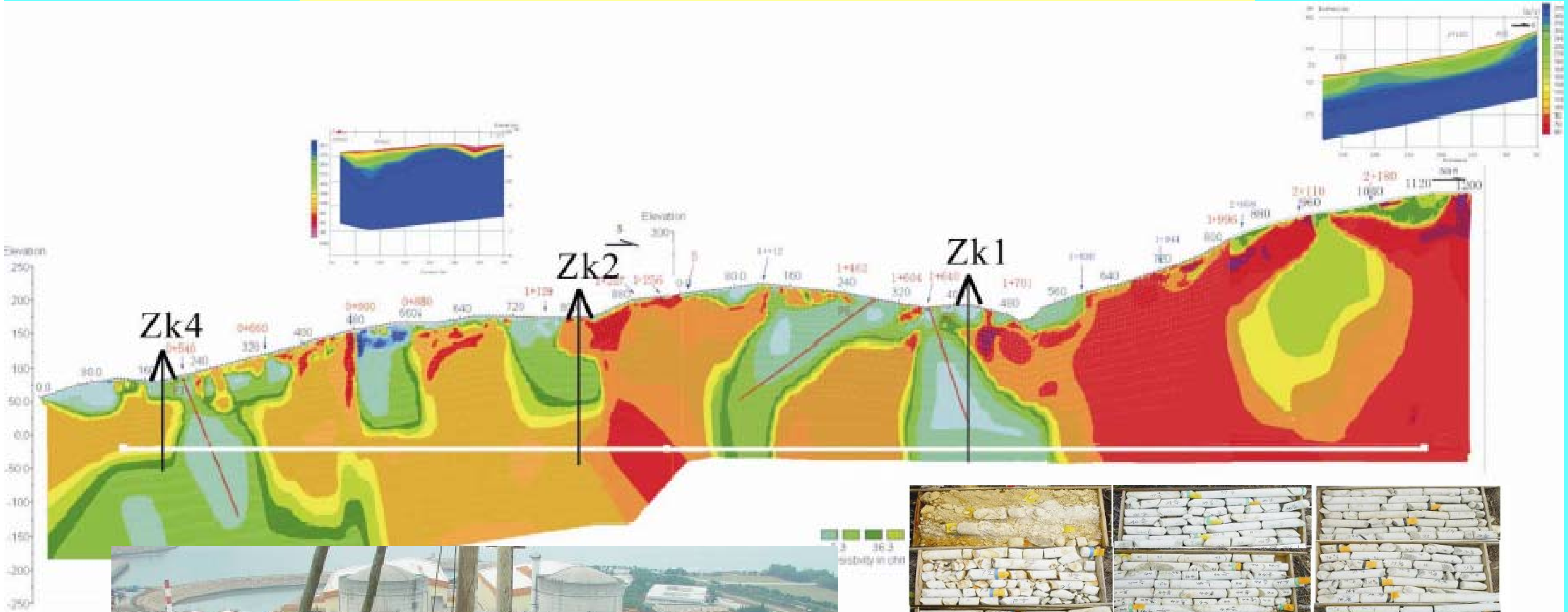


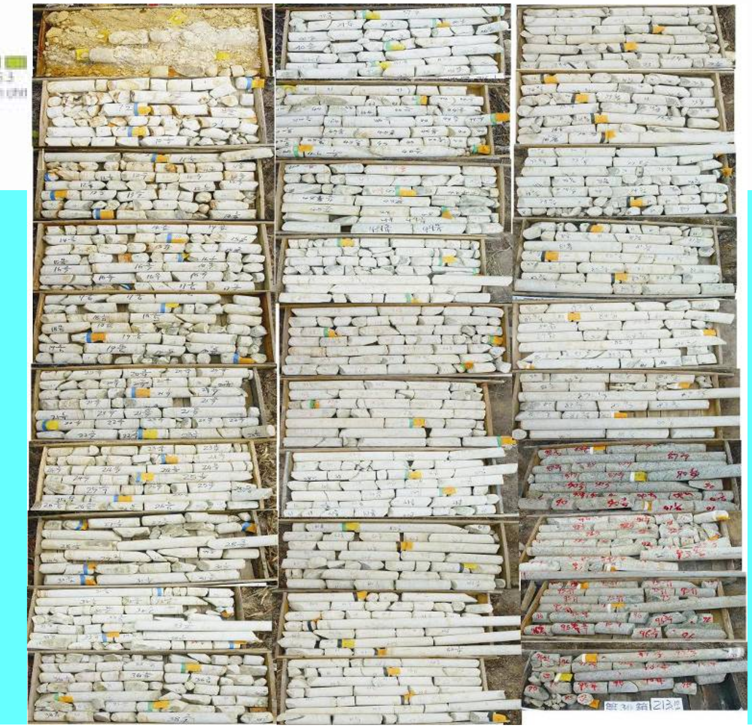


Other physics capabilities:

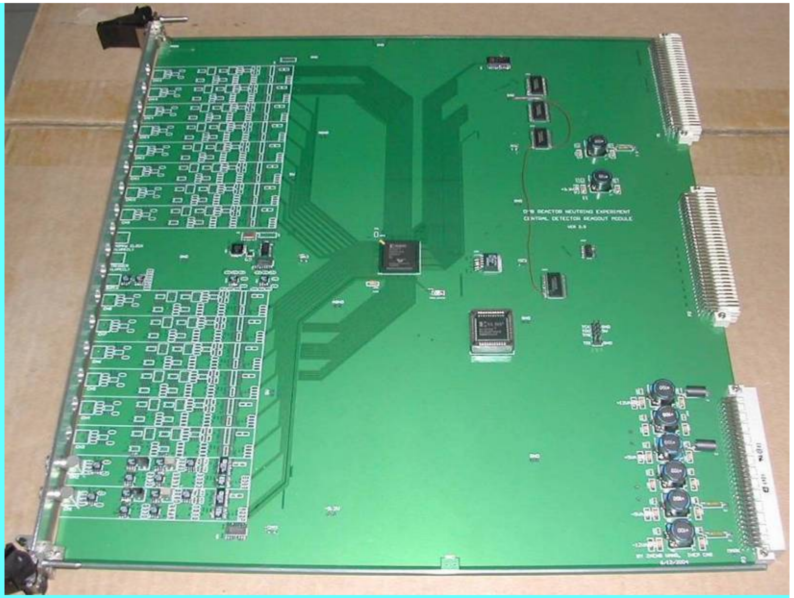
Supernova watch, Sterile neutrinos, …

Site investigation completed

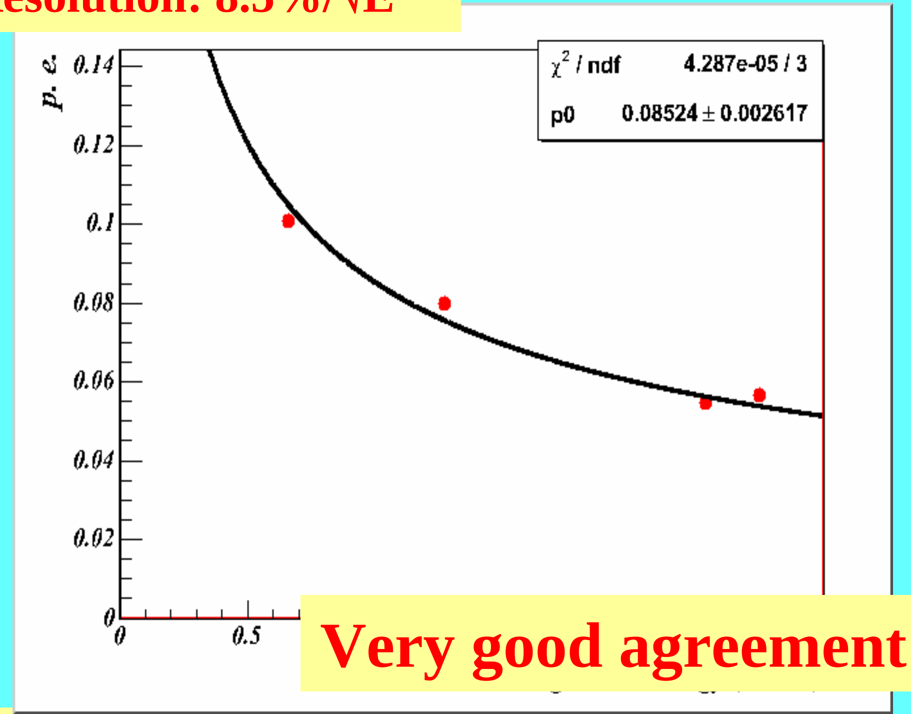




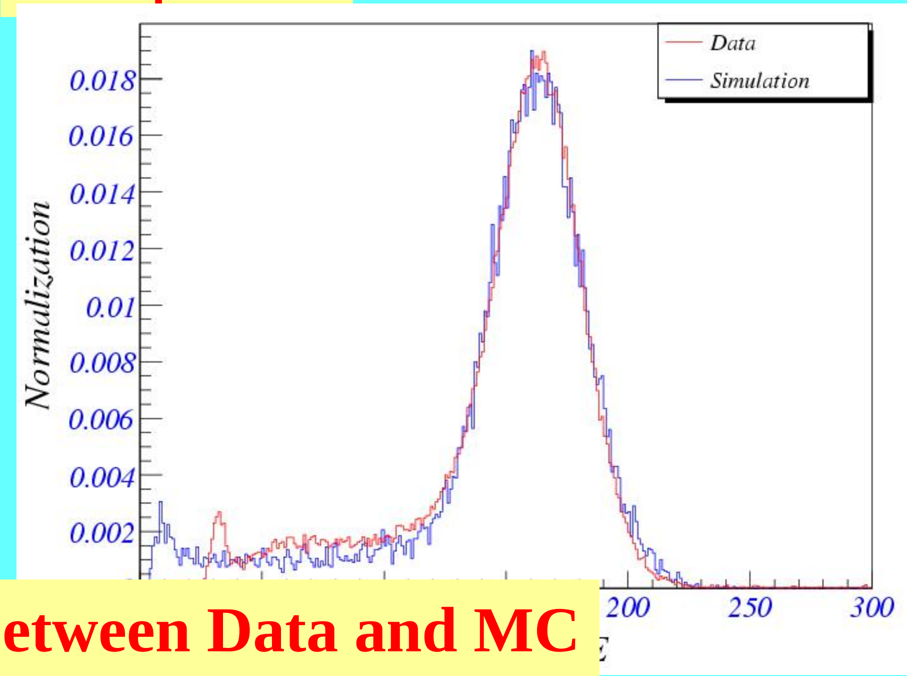
Daya Bay Prototype:
45 PMT for 0.6 t LS



Resolution: 8.5%/√E

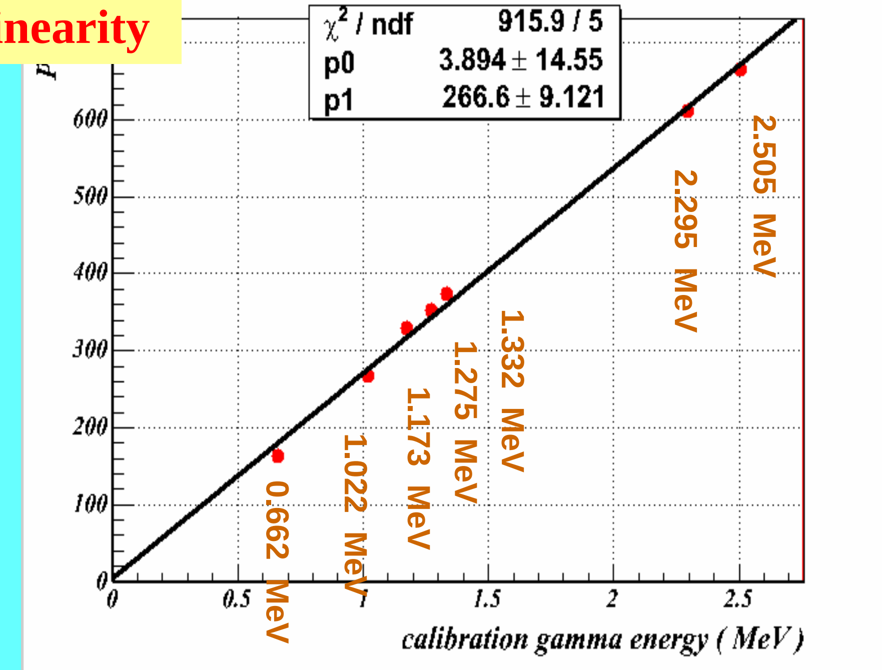


^{137}Cs spectrum

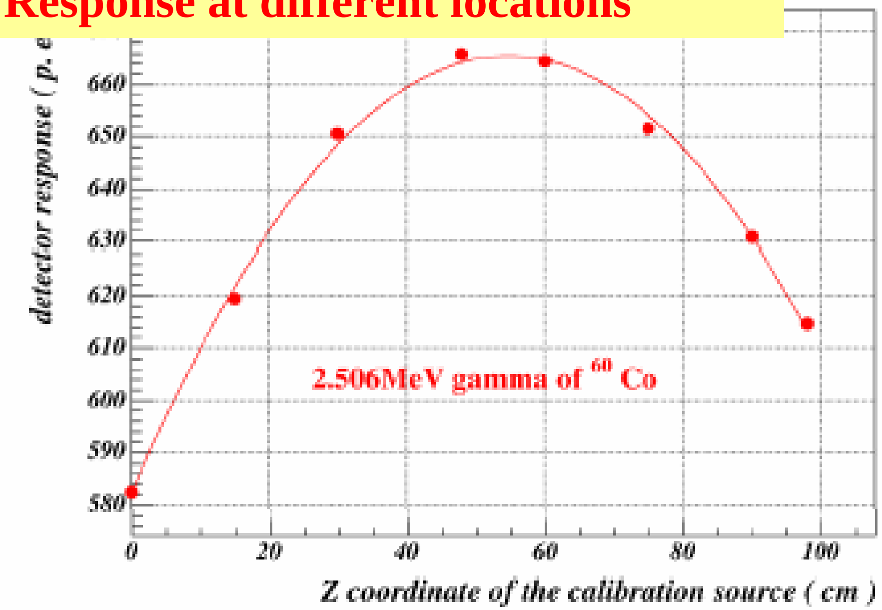


Very good agreement between Data and MC

linearity



Response at different locations



Daya Bay collaboration

Europe (3)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (9)

LBNL, BNL, Caltech, UCLA

Univ. of Houston, Iowa state Univ.

Univ. of Wisconsin, Illinois Inst. Tech. ,

Univ. of Illinois

Asia (12)

IHEP, CIAE,Tsinghua Univ.

Zhongshan Univ.,Nankai Univ.

Beijing Normal Univ.,

Shenzhen Univ., Hong Kong Univ.

Chinese Hong Kong Univ.

Taiwan Univ., Chiao Tung Univ.,

National United Univ.

~ 100 physicists

Status of the project

- **CAS officially approved the project**
- **Chinese Atomic Energy Agency and the Daya Bay nuclear power plant are very supportive to the project**
- **Funding agencies in China are supportive, R&D funding in China approved and available**
- **R&D funding from DOE approved**
- **Site survey including bore holes completed**
- **R&D started in collaborating institutions, the prototype is operational**
- **Proposals to governments under preparation**
- **Good collaboration among China, US and other countries**

Schedule of the project

- **Schedule**
  - **2004-2007 R&D, engineering design, proposals for funding**
  - **2007-2008 Civil Construction**
  - **2007-2009 Detector construction**
  - **2009-2010 Installation and testing (one Near hall running)**
  - **2010 Begin operations with full detector**

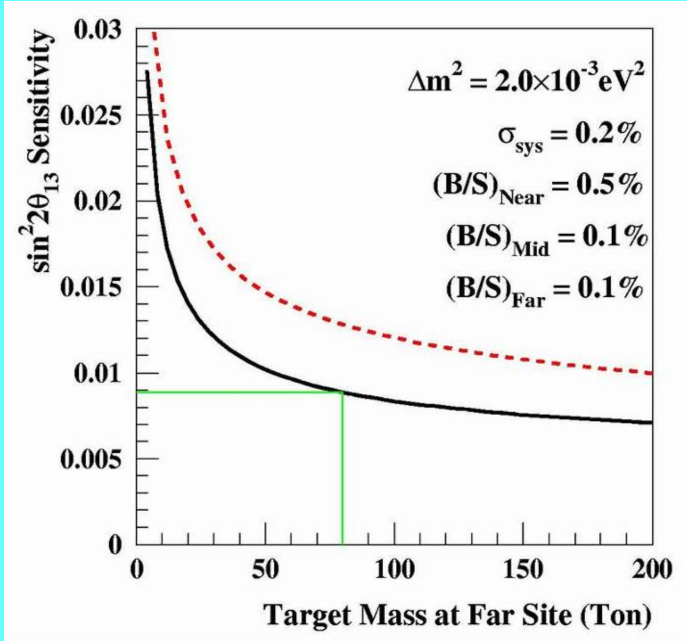

Daya Bay Collaboration Meeting
IHEP,Beijing,Feb.13-15,2006

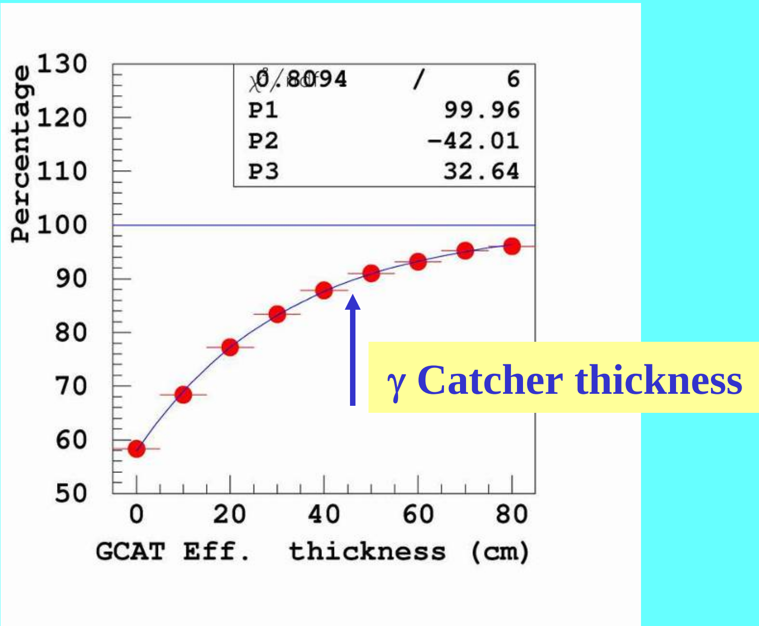
Detector dimension

Target mass: 20 t

Dimension of target:

3.2 m × 3.2m

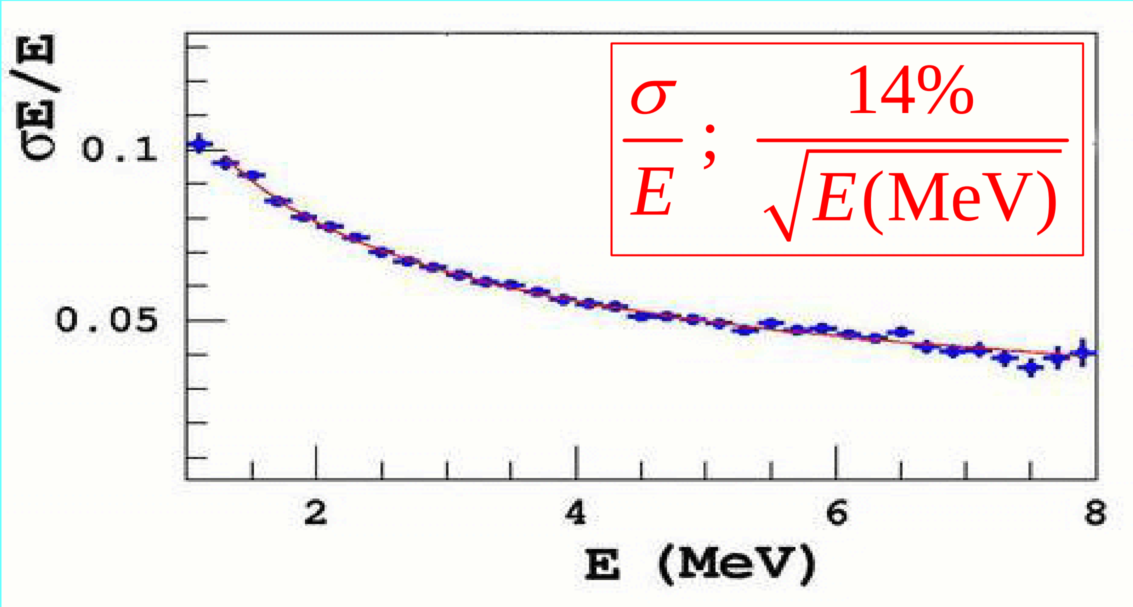




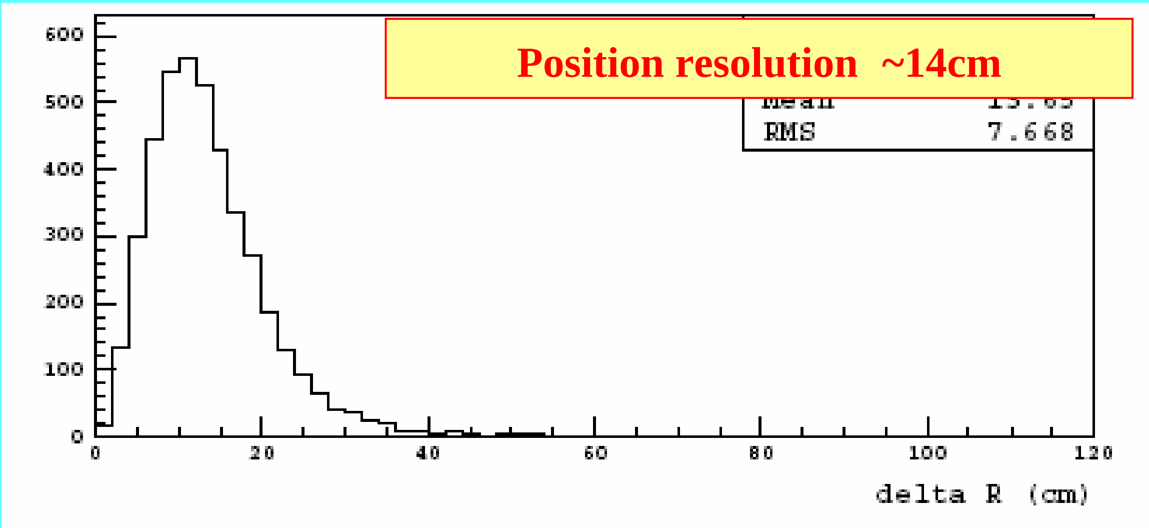
Oil buffer thickness

Isotopes	Purity (ppb)	20cm (Hz)	25cm (Hz)	30cm (Hz)	40cm (Hz)
^{238}U(>1MeV)	50	2.7	2.0	1.4	0.8
^{232}Th(>1MeV)	50	1.2	0.9	0.7	0.4
^{40}K(>1MeV)	10	1.8	1.3	0.9	0.5
Total		5.7	4.2	3.0	1.7

Resolution

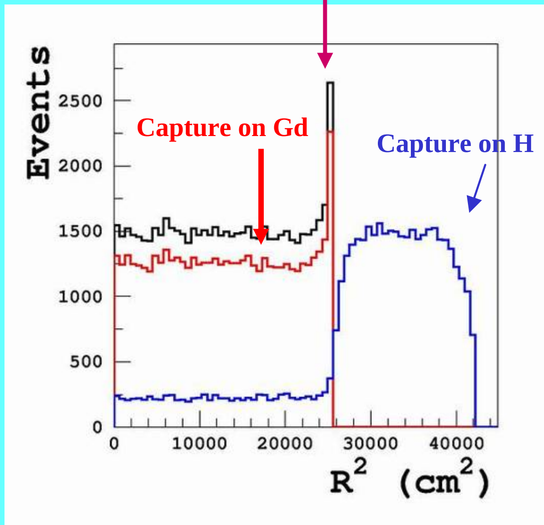


σE/E
0.1
0.05
2
4
6
8
E (MeV)
$\frac{\sigma}{E} ; \frac{14\%}{\sqrt{E(\text{MeV})}}$



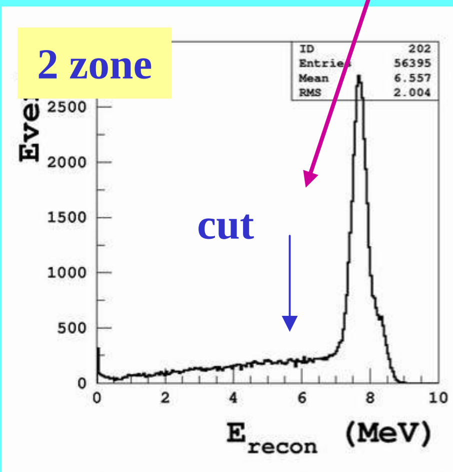
Position resolution ~14cm
RMS 7.668
0
100
200
300
400
500
600
0
20
40
60
80
100
120
delta R (cm)

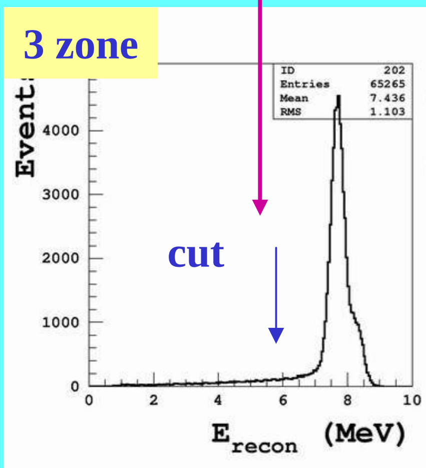
Why three zones ?

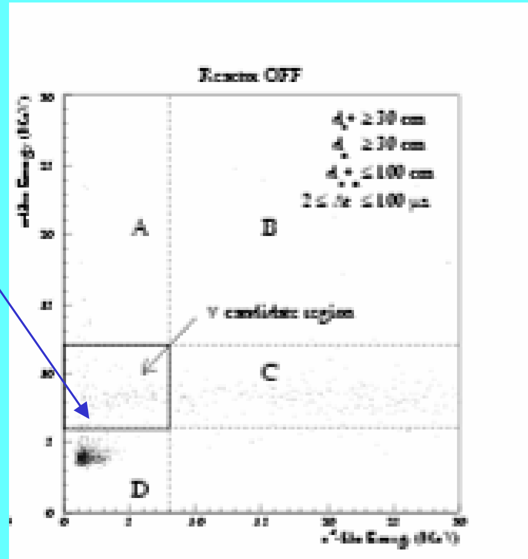


- Three zones:
  - Complicated acrylic tank construction
  - γ backgrounds on walls
  - Less fiducial volume
- Two zones:
  - Neutrino energy spectrum distorted
  - Neutron efficiency error due to energy scale and resolution:

    two zones: 0.4%, three zones 0.2%
  - Using 4 MeV cut can reduce the error by a factor of two, but backgrounds from β+γ do not allow us to do so







Reactor-related Uncertainties of Daya Bay

- The error due to power fluctuations of the reactors is given by:

$$\sigma_{sys} = \sigma_p \sqrt{\sum_r \left(f_F^r - f_N^r\right)^2}$$

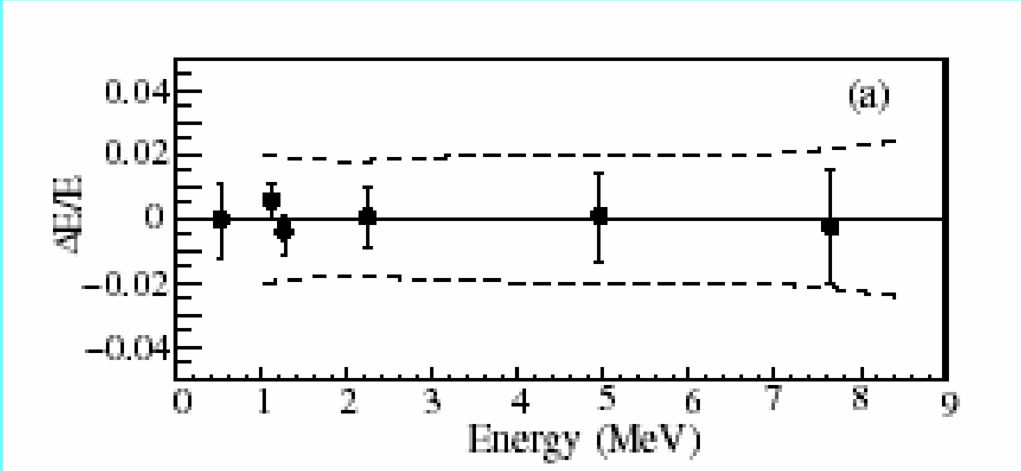
Based on experience of past experiments, due to uncertainty in measuring the amount of thermal power produced, the uncorrelated error per reactor core $\sigma_p \approx 2\%$.

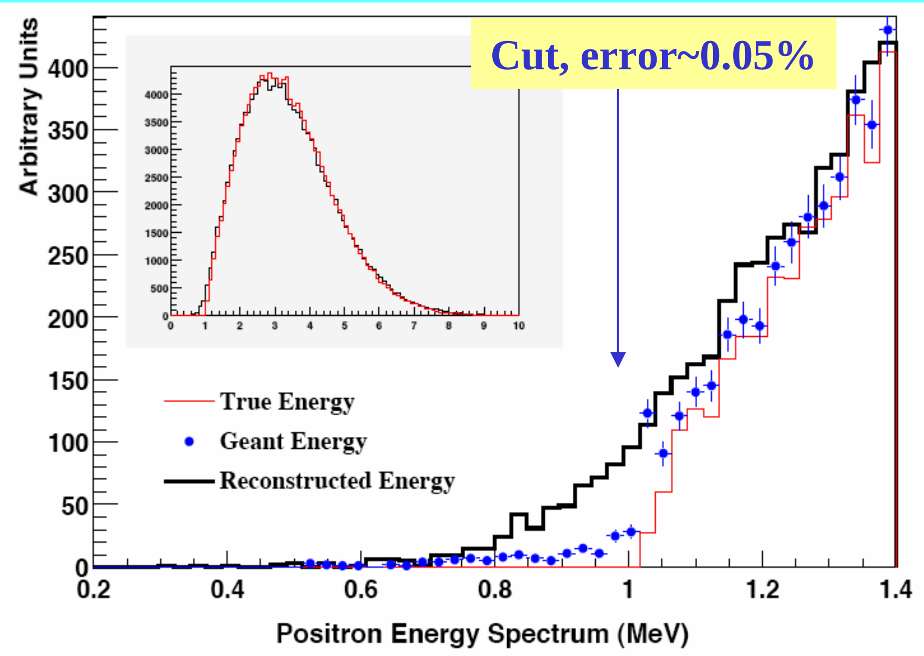
f^r_F and f^r_N are fractions of the events at the far and near site from reactor r respectively.

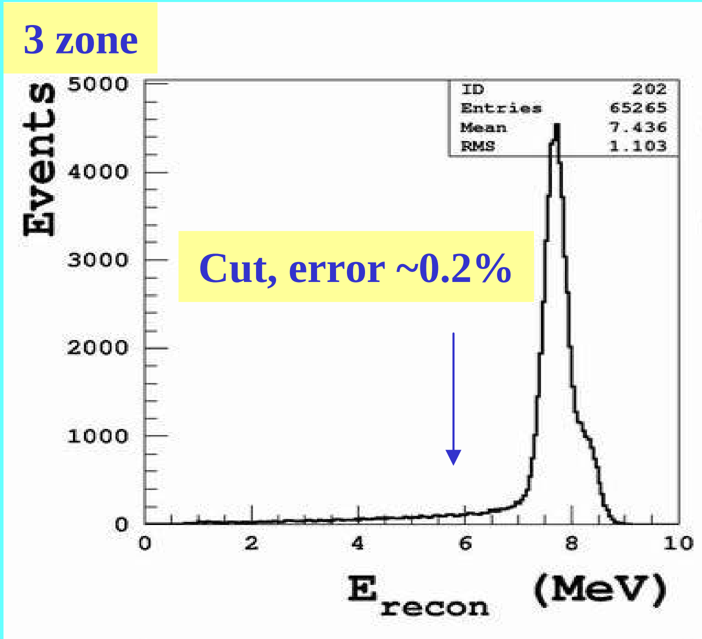
# Reactor Cores	Syst. error due to Power Fluctuations	Syst. error due to Core Positions	Total syst. error
4	0.035%	0.08%	0.087%
6	0.097%	0.08%	0.126%

Energy Cuts

Dominated by energy scale
KamLAND ~ 1%





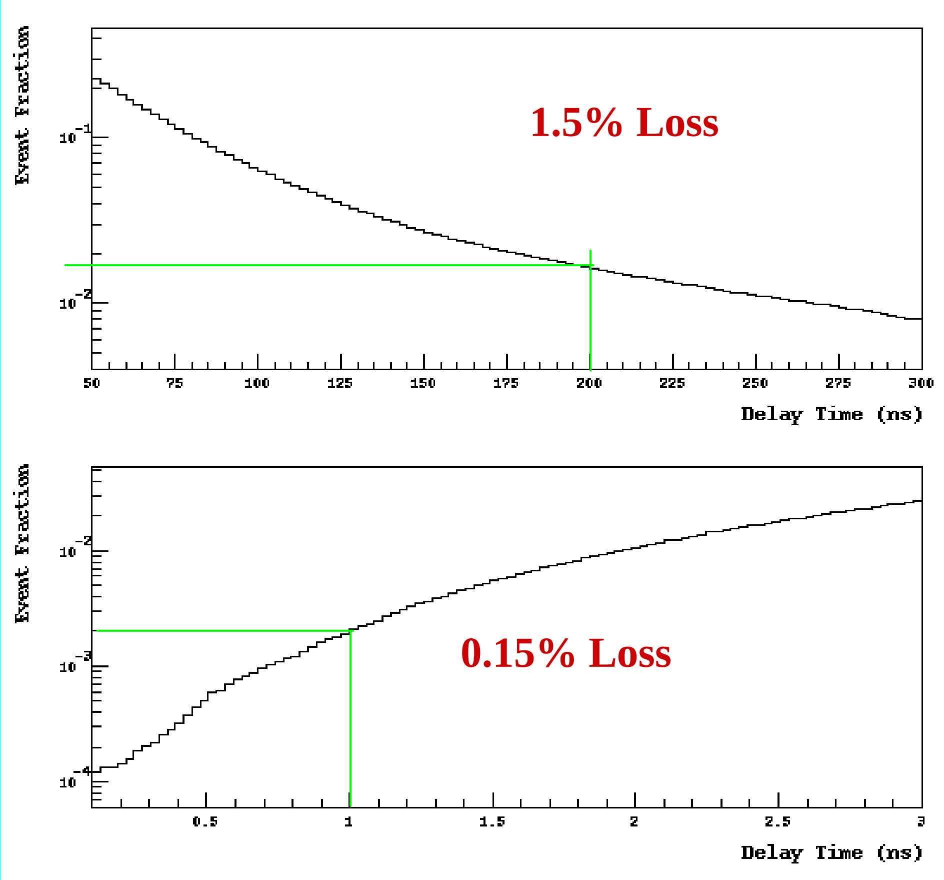


Time Cuts

Neutron time window uncertainty:

- Δt = 10 ns $\rightarrow$ 0.03% uncertainty
- Use common clock

→ Baseline = 0.1%
→ Goal = 0.03%



Livetime

- Measure relative livetimes using accurate common clock
- Use LED to simulate neutrino events
- Should be negligible error

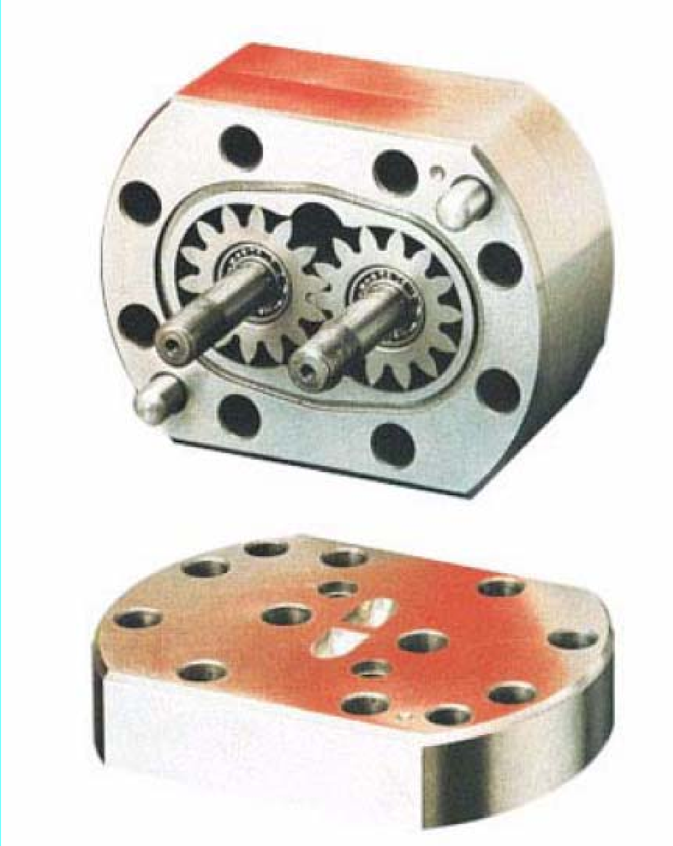
Target Volume

Can be cancelled by swapping

- KamLAND: ~1%
- CHOOZ: 0.02%?

- Flowmeters – 0.02% repeatability

→ Baseline = 0.2%
→ Goal = 0.02%

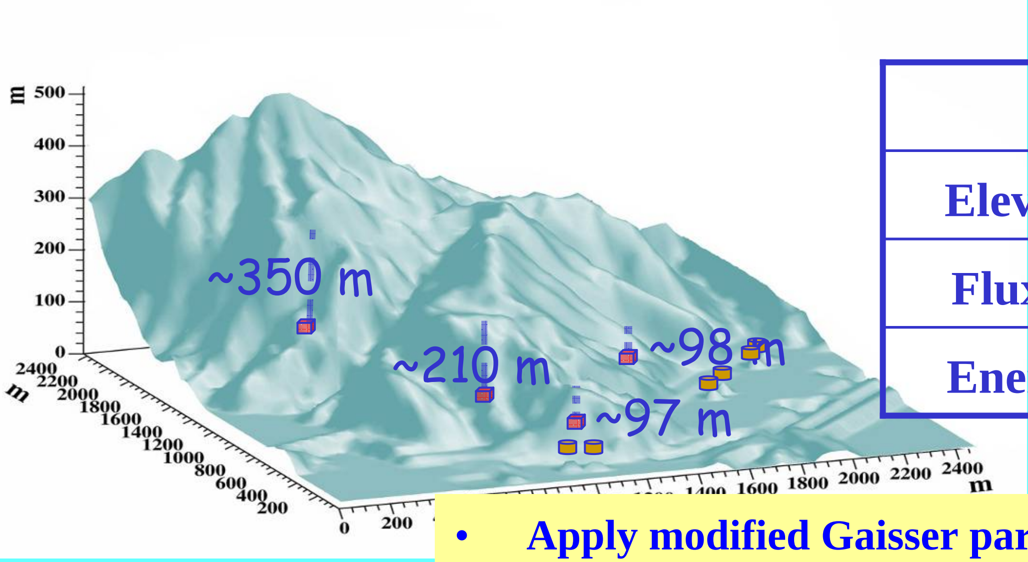


H/C and H/Gd ratio

Can be cancelled by swapping

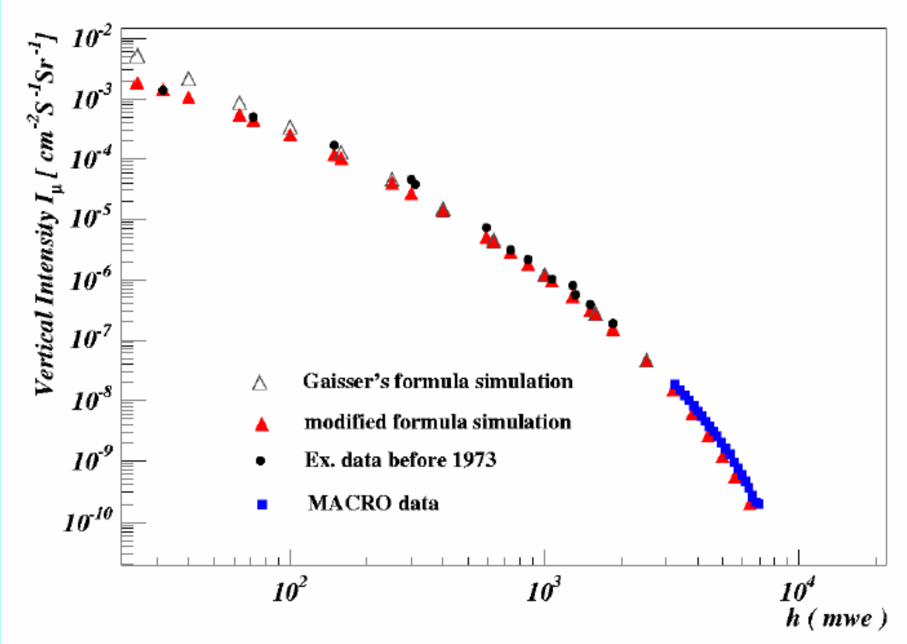
- H/C ratio
  - CHOOZ claims 0.8% absolute based on multiple lab analyses (combustion)
  - Use well defined liquid such as LAB and dodecane
  - R&D: measure via NMR or neutron capture
  - Expected error: 0.1%-0.2%
- H/Gd ratio
  - Can be measured by neutron activated x-rays and neutron capture time
  - For $\Delta t = 0.5\ \mu s$, ➔ error ~ 0.02%

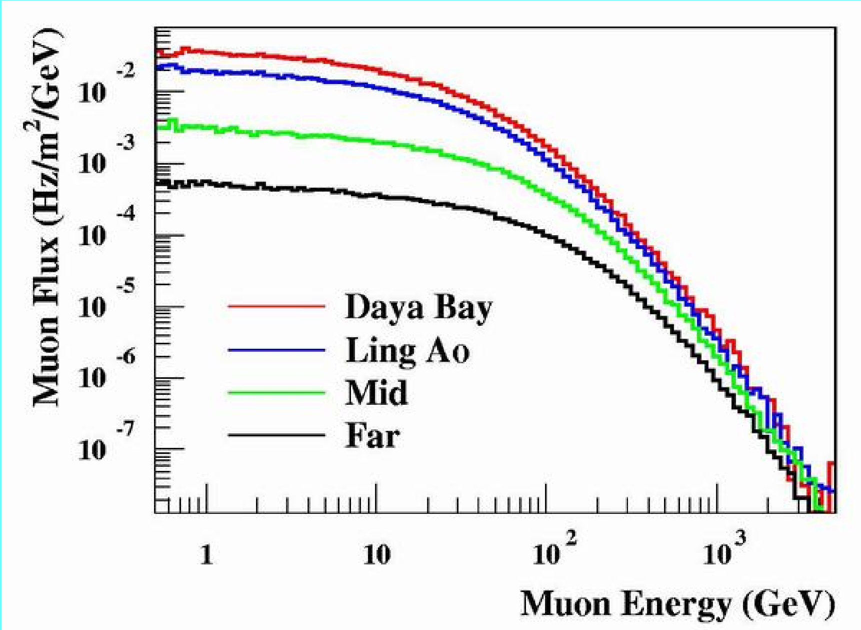
Cosmic-muons at the laboratory



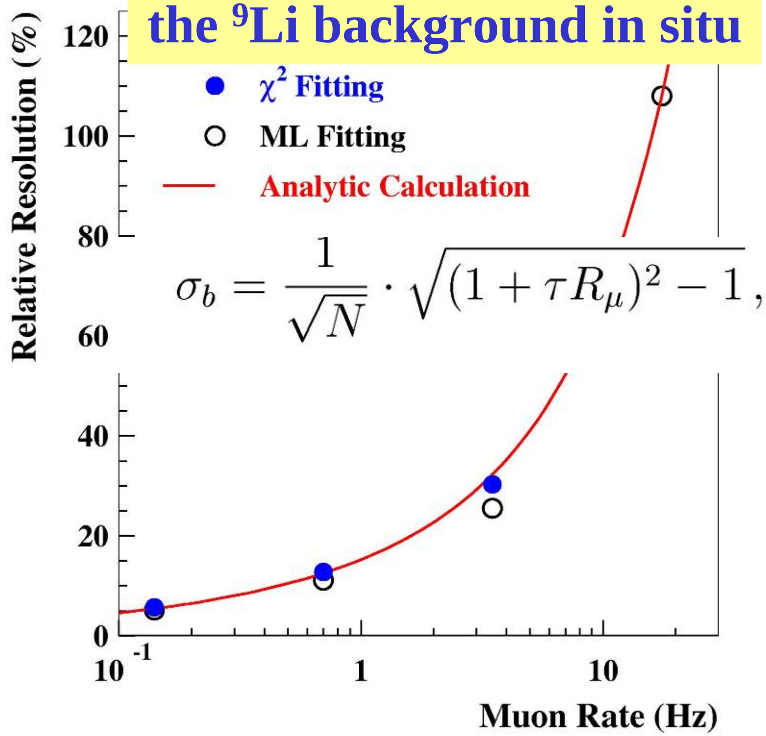
	DYB	LA	Mid	Far
Elevation (m)	97	98	208	347
Flux (Hz/m²)	1.2	0.73	0.17	0.045
Energy (GeV)	55	60	97	136

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

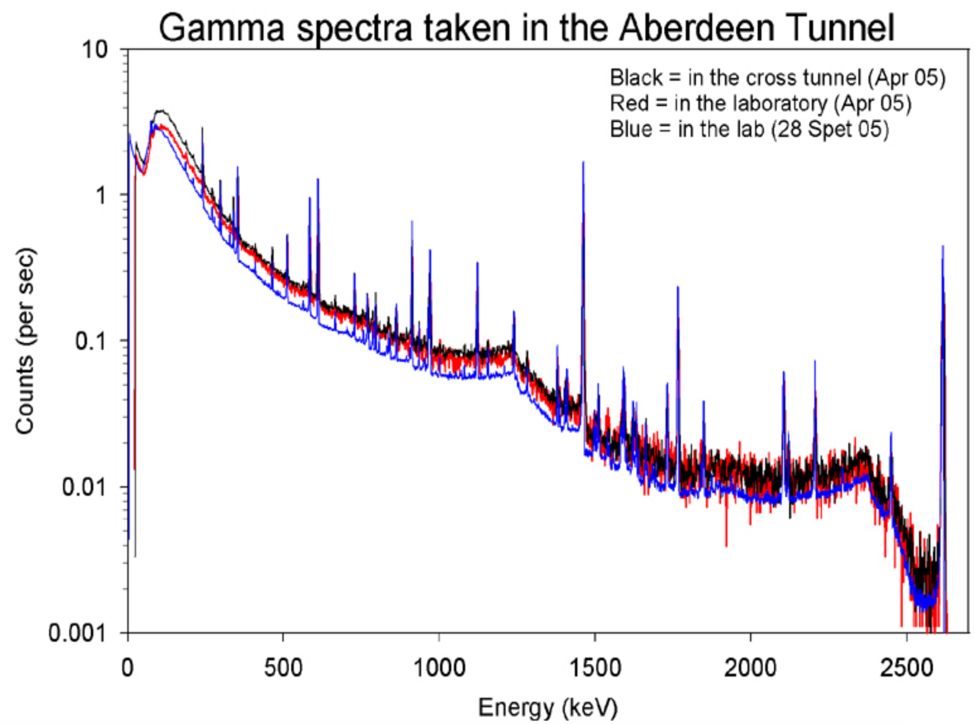




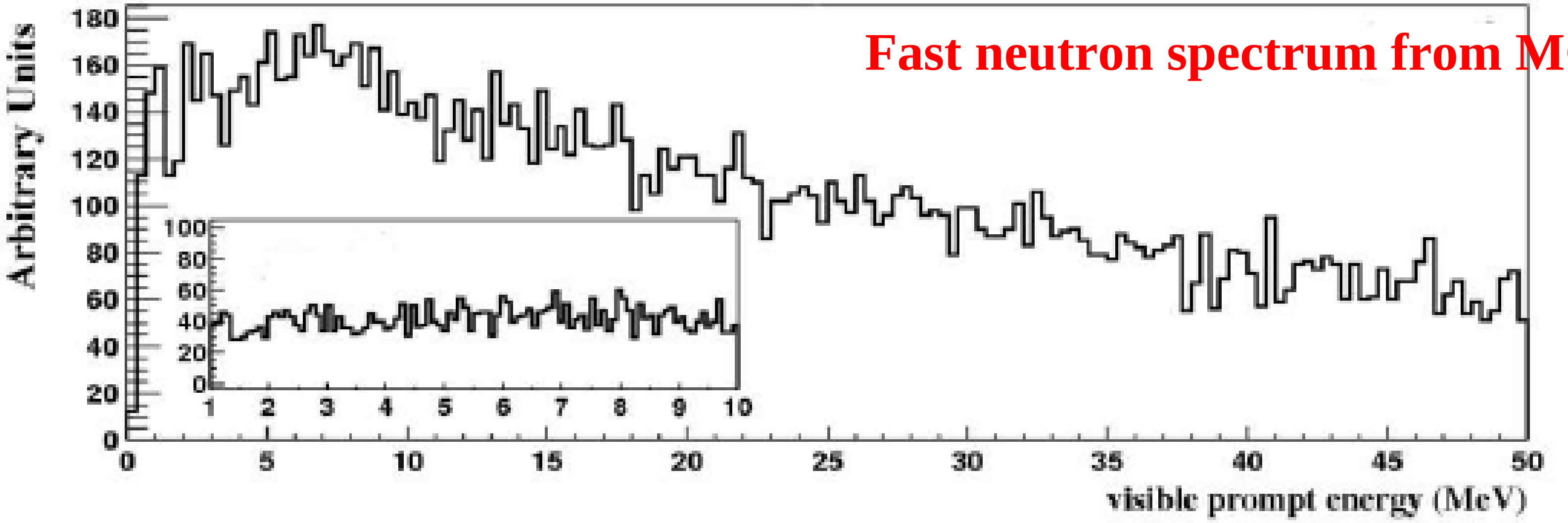
Precision to determine the ^{9}Li background in situ



Spectrum of accidental background



Fast neutron spectrum from MC



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