Detector Module Simulation
and
Baseline Optimization

- Determine module geometric parameters
- Event reconstruction and energy resolution
- Background simulation

- Systematic error analysis
- Baseline optimization

1. Basic idea on module designa

- 8 tons fiducial volume (Gd loaded scintillator)

  CHOOZ 5t, Palo Verde 12t, KamLAND 1000t

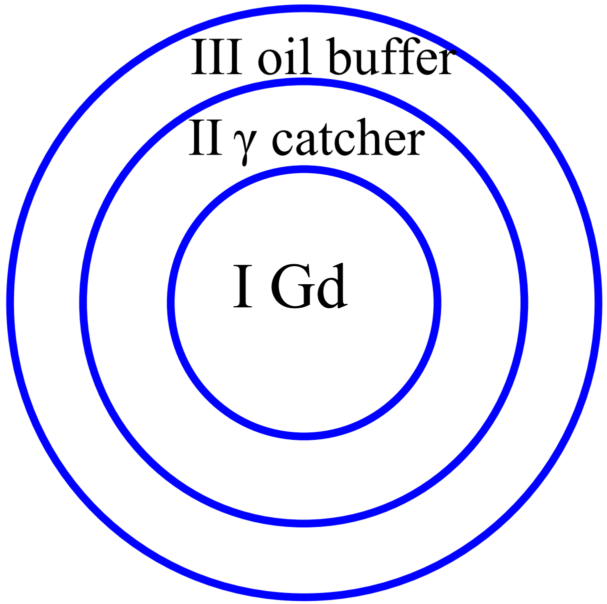
- Three layers:

  1. Gd loaded scintillator as target
  2. Normal scintillator to contain gamma
  3. Mineral oil buffer to reduce background and mis-reconstruction

- Energy resolution 5% at 8MeV
- Background (>1MeV) less than 50 Hz

2. Question to Answer

- Module shape (cubic or cylindric?)
- PMT coverage
- Reflection on Cap/Wall?
- Attenuation length
- Thickness of Gamma catcher
- Thickness of Oil Buffer



3. Event Reconstruction

No vertex reconstruction: use total charge to get energy.

Reconstruct vertex: Fit vertex and energy at the same time.

Maximum Likelihood fitting to reconstruct vertex and energy.

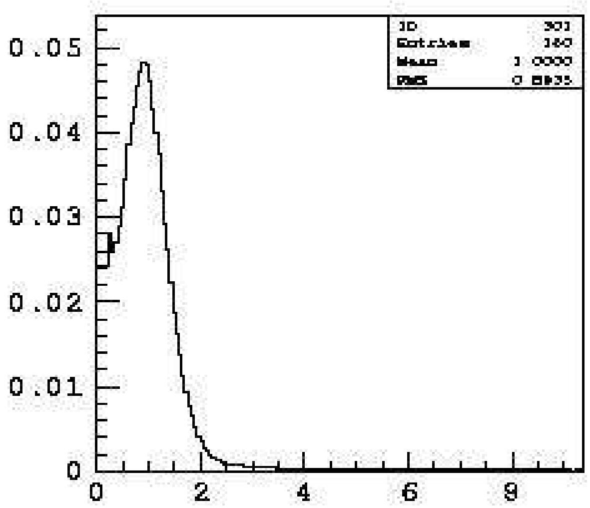
For an event, assuming all scintillation photons are emited from a single point(vertex). Then the expected charge on a given PMT is

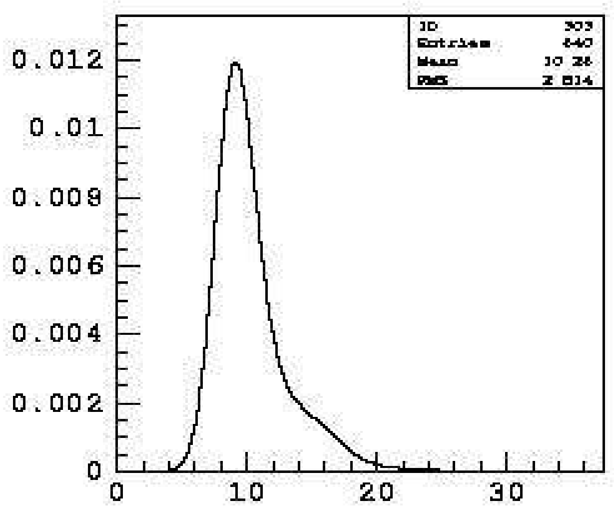
$$\mu_i = C e^{-r_i/L} \cos(\alpha_i)/r_i^2$$

Assuming poisson distribution, log likelihood of a PMT with measured charge q_i and expected μ_i is

$$f_i = \mu_i - q_i \ln(\mu_i)$$

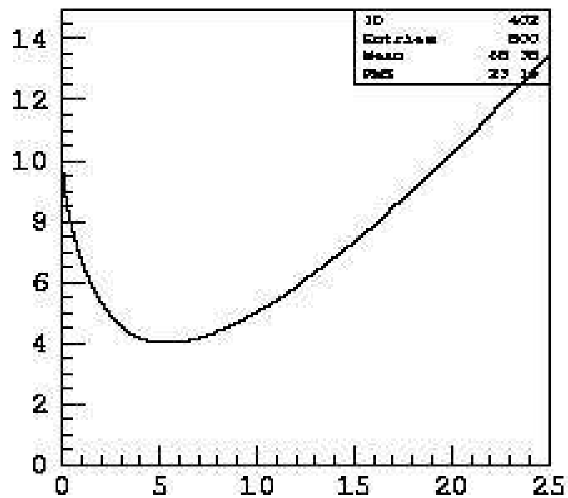
If taking into account electronics, charge measured will have a distribution. Suppose we measure single PE charge response, then we can generate multiply PE charge response and charge likelihood table. f_i will be got by looking up the 2 dimentional table.





Single PE response

10 PE response



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1. Measured single PE response
2. Generated multiply PE response(e.g. 10PE)
3. Generated charge likelihood table.
   e.g. q=5 in 0.25 PE bin

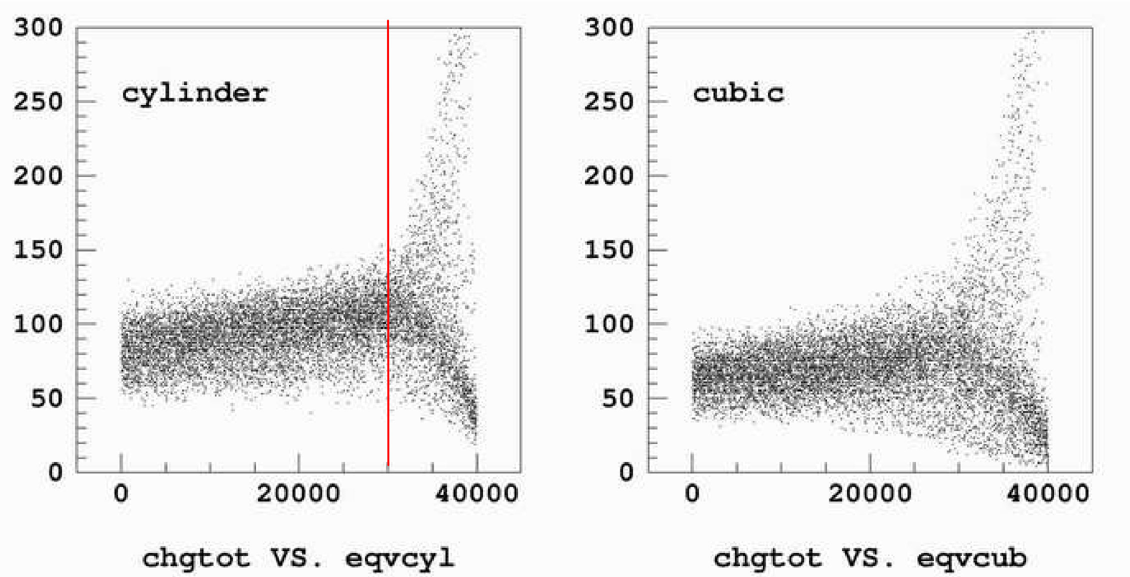
$$P(\mu_i, q) = \sum P(\mu, n) P(n, q)$$

P(μ,q): Probability of measured q, expected μ
P(μ,n): charge response
P(n,q): poisson density function

Input parameters:

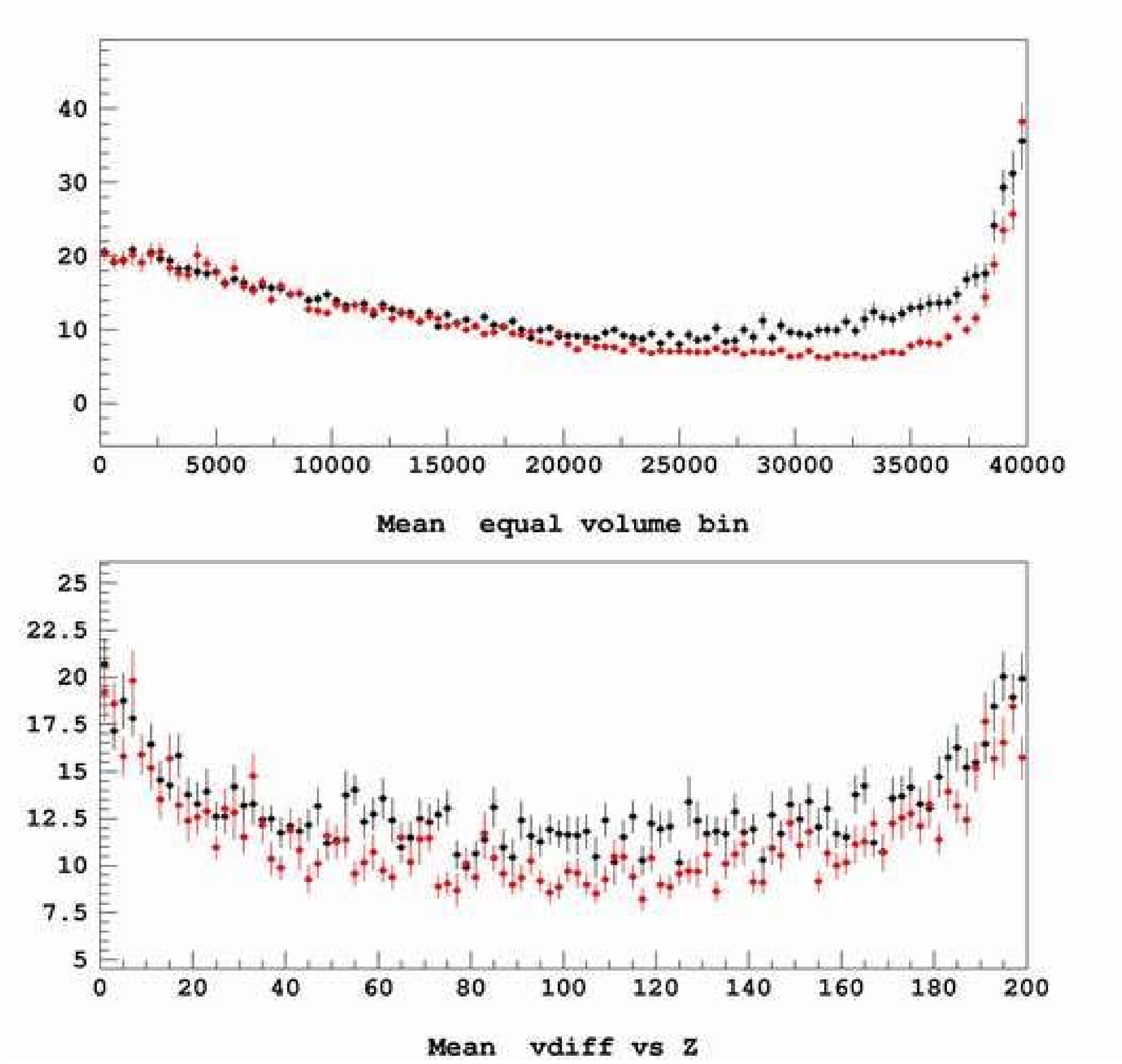
- Scintillation yield: 7000 photons/MeV
- Attenuation length: 7m or 11m
- Quantum Efficiency of PMT: 0.2
- Efficiency of first dynode: 0.6
- PMT suface radius: 9.5cm (8" PMT)

Total charge vs. equal volume bin in radius direction:



Red line corresponds to 15cm away from PMT.

Vertex resolution (1MeV, only layer I, no reflection)



For $8m^3$ target + 50cm buffer, Energy 8 MeV, 100 PMTs

cylindric size = π * (112cm + 50cm)^2 * 200cm : 10% coverage

cubic size = (200cm + 2*50cm)^2 * 200cm : 7% coverage

		TotalCharge	Charge RMS	FitEnergy RMS	Vertex RMS
1	No reflection	Cyl= 338	14.90%	7.90%	11cm
	Attenuation 7m	Cub = 278	17.00%	10.00%	14.78cm
2	No reflection	Cyl= 419	14.20%	7.70%	11.14cm
	11m	Cub = 301	16.20%	9.70%	15.07cm
3	Cap reflection 0.9	Cyl= 646	5.80%	5.20%	
	7m	Cub = 466	9.00%	7.70%	
4	Cap reflection 0.9	Cyl= 718	5.30%	5.00%	
	11m	Cub = 519	8.50%	7.20%	
5	Cap 0.9, wall0.8	Cyl= 1156	4.80%	4.00%	
	7m	Cub = 827	7.20%	5.60%	
6	Cap 0.9, wall0.8	Cyl= 1422	4.10%	3.60%	
	11m	Cub = 1034	6.10%	6.10%	

- Attenuation is not a big deal.
- Use reflection is better even for fitters. (with z correction now)
- Cylindric module is always much better than cubic one.

4. Background from PMT glass

low radioactivity glass:

U 50 ppb, 146.52 gammas/100 decays, 0.911Hz/kg glass(>1MeV)
Th 50 ppb, 170.59 gammas/100 decays, 0.345Hz/kg glass(>1MeV)
K 10 ppb, 10.5 gammas/100 decays , 0.271Hz/kg glass(>1MeV)

Oil buffer =	20cm	25cm	30cm	40cm
U (>1MeV)	3.00%	2.18%	1.59%	0.88%
Th (>1MeV)	3.35%	2.50%	1.90%	1.15%
K (>1MeV)	6.77%	4.84	3.51%	1.90%
Total Rates (200PMT)	5.7Hz	4.2Hz	3.0Hz	1.7Hz

Total rates << 50Hz
Radiation from PMT glass is not a problem.
Thickness of oil buffer is determined by energy reconstruction protection.

5. Background from rock

Measured rock radioactivity at Daya Bay(preliminary):

U: 8.8 ppm, 160 gammas/kg

Th: 28.7 ppm, 198 gammas/kg

K: 4.5 ppm, 121 gammas/kg

Gammas that can penetrate 2m water and 50cm oil buffer and deposit greater than 1 MeV energy in module:

U: 11 per $3*10^8$ gammas

Th: 34 per $3*10^8$ gammas

K: 5 per $3*10^8$ gammas

This is done by 20cm bins in rock until events rate is small enough.

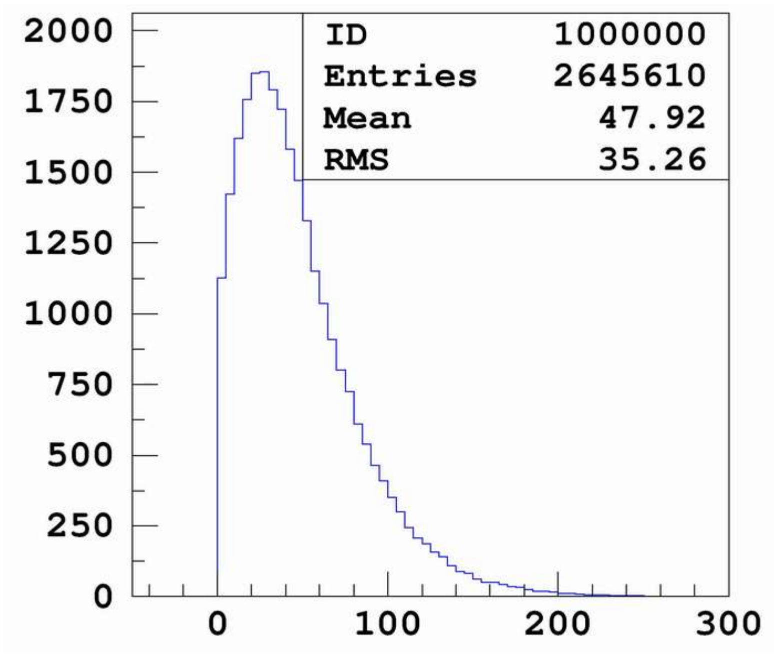
Sample is small. Estimated event rates in module:

U: 5.4 Hz Th: 20.4 Hz K: 1.8 Hz

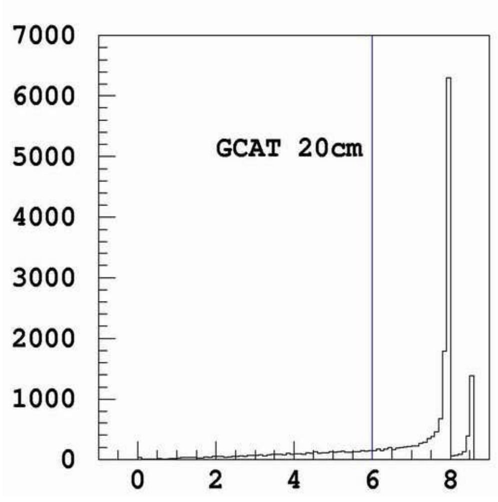
Radiation from Th is dominant because it has more high energy gammas.

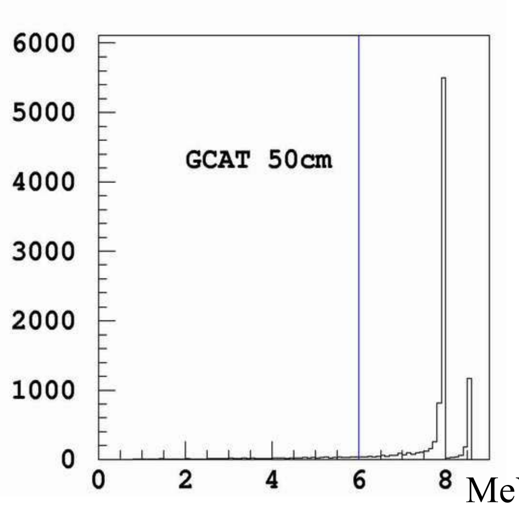
6. gamma catcher

Gamma deposit energy in scintillator by compton scattering. The “track” may be long.
To clearly identify a neutron capture on Gd from natural radiation background, we will apply a cut at around 6MeV. Gamma catcher is designed to contain energy deposition on the tail of gamma track while keeping target mass well defined.

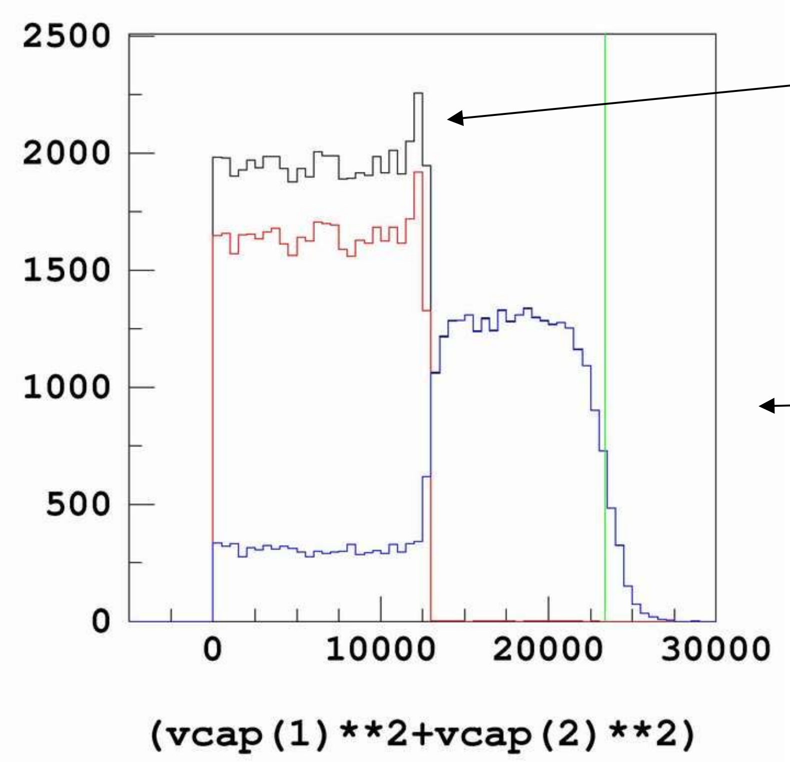


Distribution of hit distance from vertex



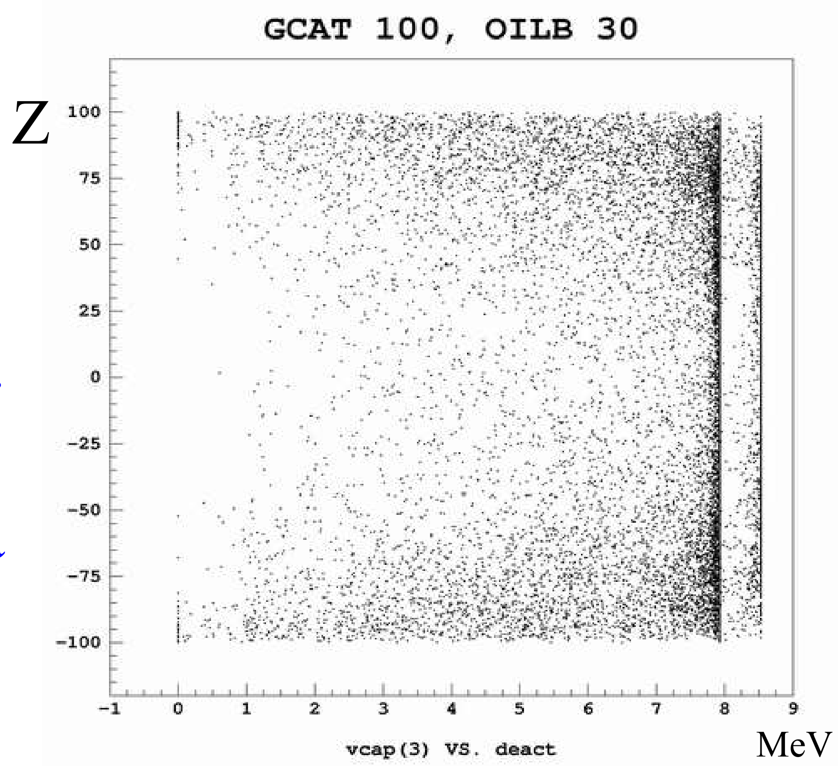


Two examples of energy deposit in scintillator for Gd capture. Two peaks correspond to two major isotopes of Gd. (GEANT3/GCARLO)



Spill in/Spill Out Effect

Neutron capture in module
Red line shows capture on Gd
Blue one is capture on H



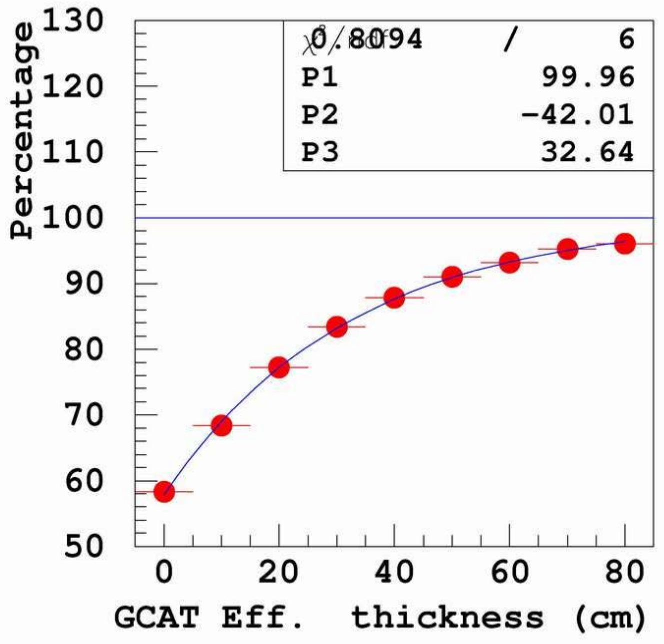
Module height is a major concern for civil construction of detector hall. However, We can't waive the gamma catcher on end cap side.

Efficiency of neutron Gd capture when cut at 6 MeV. Inefficiency reduce one half as Gamma catcher increase 20cm.

40cm: 87.80%

50cm: 91.04%

70cm: 95.23%



Compare with CHOOZ:

70cm with efficiency (94.6±0.4)%

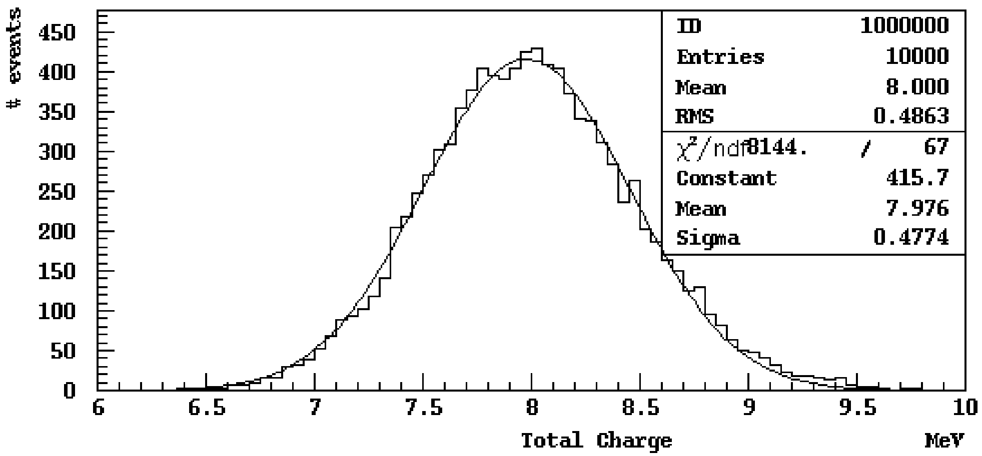
We could do better since

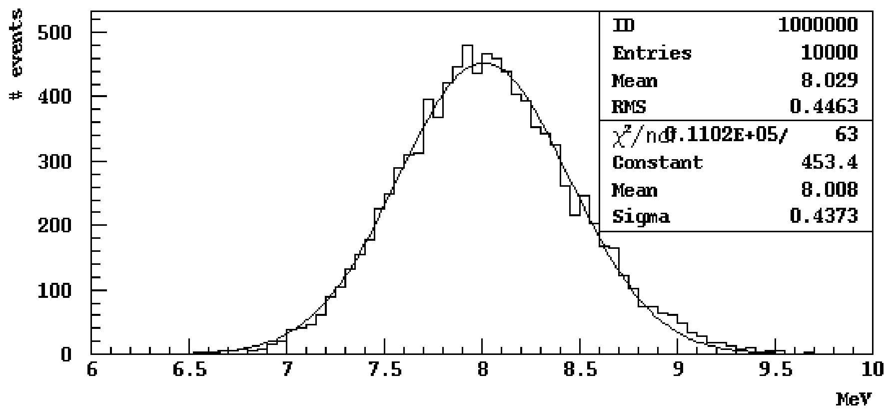
- no reconstructed vertex cut and
- partial far-near cancellation.

Preferred tank geometry:

- Gd loaded scintillator: 110cm radius, 200cm height, around 6.8ton.
- Normal scintillator (gamma catcher): 50cm (both radiant and cap.)
- Mineral oil: 45cm (only radiant)
- 150 8in PMTs placed in mineral oil. (PMT height is around 25cm)
- 7.5% PMT coverage.
- Use reflection on cap.

Energy resolution at 8MeV: 150PMTs, radius=112+50+25cm.
left: use total charge, sigma=5.9%
right: use fit, sigma=5.5%





7. Systematic Error analysis.
A conceptional method (by Suekane)

correlated error from reactor $\Delta\nu/\nu$: 2%
uncorrelated error $\delta\nu/\nu$: 2%
For two detector case: Expected events at far detector: $\bar{\mu}_f = \rho\mu_n$
where μ_n is events measured at near detector and

$$\rho = (\sum T_{fr}\nu_r)/(\sum T_{nr}\nu_r)$$

ν_r is events at unit distance from reactor r, calculated with reactor power, which carry larger error. Obviously correlated error cancels since they appear in the same way in both numerator and denominator.
Uncorrelated error is $\delta\mu_f/\mu_f = \sqrt{\sum(\omega_f^r - \omega_n^r)^2}(\delta\nu/\nu)$
ω^r is fraction of contribution from reactor r at near/far detector.
For two reactors case, given the site of far detector, we can always find an appropriate site for near detector to exactly cancel uncorrelated error.
For multiply reactor case, the residue error is small.
Three detector case is similar, while $\bar{\mu}_f = \rho_a\mu_a + \rho_b\mu_b$

Full χ^2 analysis: (Huber et al., Sugiyama, Yasuda et al.)

$$\chi^2 = \min_{\alpha's}\left[\sum_{i=1,3}\left[\frac{M^i - T^i\left(1+\alpha_D+\alpha_c+\sum \omega_r^i \alpha_r\right)}{T^i \sigma_d}\right]^2 + \frac{\alpha_D^2}{\sigma_D^2} + \frac{\alpha_c^2}{\sigma_c^2} + \frac{\sum \alpha_r^2}{\sigma_u^2}\right]$$

M^i: measured events at detector i
T^i: expected events at detector i

α_D: parameter to introduce detector correlated error.
α_c: parameter to introduce reactor correlated error.
α_r: parameters to intorduce uncorrelated error from reactor r

σ_u: uncorrelated error of reactor
σ_c: correlated error of reactors
σ_D: correlated error of detector
σ_d: uncorrelated error of detector

ω^i_r: fraction of events from reactor r to detector i

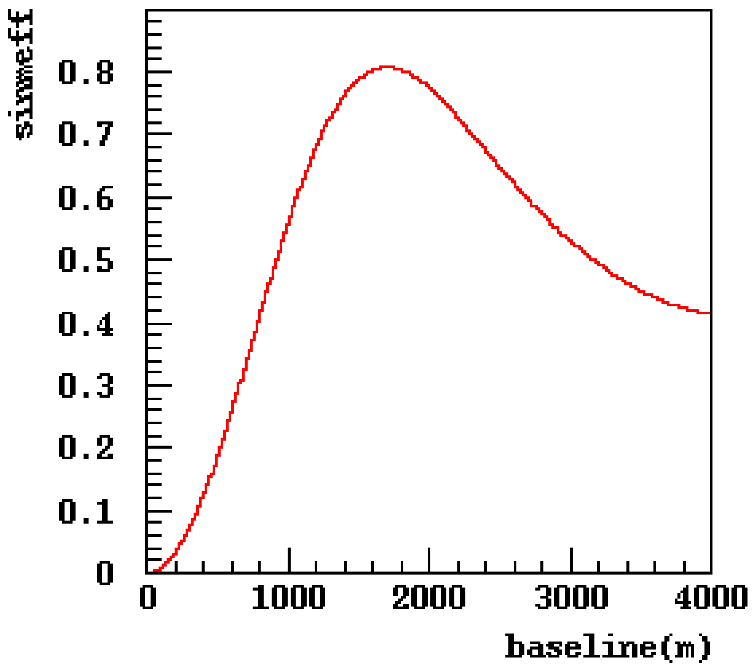
For one reactor, two detector case:

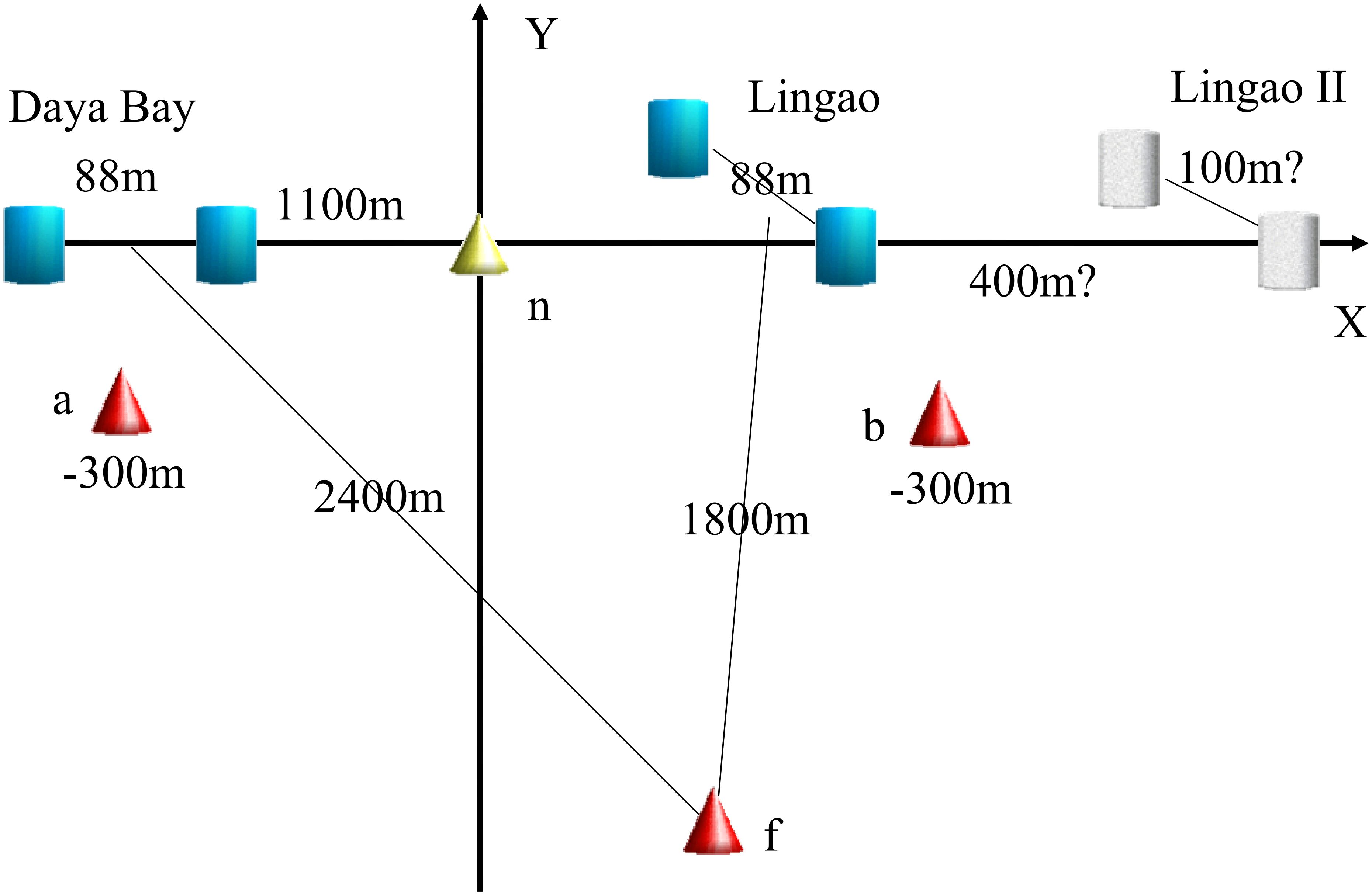
$$\chi^2 = \frac{(y_n - y_f)^2}{2\sigma_d^2} + \frac{(y_n + y_f)^2}{2\sigma_d^2 + 4(\sigma_D^2 + \sigma_c^2 + \sigma_u^2)} \approx \frac{y_f^2}{2\sigma_d^2\left(1 - \frac{\sigma_d^2}{\sigma_d^2 + \sigma_D^2 + \sigma_c^2 + \sigma_u^2}\right)}$$

Where y is (M-T)/T. It is slightly better than using only information from detectors.

$$y = \frac{M - T}{T} = \sin^2(2\theta_{13}) \left\langle \sin^2(1.27\,\Delta m^2 L/E) \right\rangle$$

<...> means average over observed neutrino energy spectrum. We will call it sinmeff as a short hand. It peaks at 1.7km-1.8km, around 0.80(y_f). At 300-400m it is around 0.1(y_n)





Daya Bay reactors and detectors configuration

For two detectors configuration:

near detector lies in the middle of two clusters of reactors, uncorrelated error reduction factor is 0.06. i.e. Systematic error 0.12%. However, if the third cluster is on, optimized systematic error will be 0.38%.

Three detectors configuration we will use:

- more detectors, smaller error from detectors.
- w/ or w/o the third cluster, both systematic errors are around 0.13%.
- Baseline is too long for near detector if use two detectors only.

When uncorrelated error of detectors σ_d taken into account, it is

$$\sigma_{det} = \sqrt{1+\rho_a^2+\rho_b^2}\,\sigma_d$$

For two detector case, σ is $1.414\sigma_d$. For three detector case, the best one is $1.22\sigma_d$. For our asymmetric far detector configuration, it is $1.24\sigma_d$ w/o new reactors and $1.31\sigma_d$ w/ new reactors.

We will put at least 4 modules at far detector and 2 at each near detectors. Now

$$\sigma_{det} = \sqrt{1/4+\rho_a^2/2+\rho_b^2/2}\,\sigma_d$$

The best one is $0.707\sigma_d$, and Daya Bay, it's $0.72\sigma_d$ w/o new reactors and $0.78\sigma_d$ w/ new reactors.

Now we fix the y coordinate of far detector at -1800m, near detector at -300m. For different xf, fit the best x coordinate of two near detectors a and b.

	Xf(m)	Xa(m)	Xb(m)	reduction(off)	reduction(on)	
1	0	-587	425	1.00E-9	-	Optimized for 4
2	900	-580	455	2.80E-7	-	reactors
3	0	-573	797	0.062	0.054	optimized for 6
4	500	-560	814	0.068	0.061	reactors
5	900	-550	832	0.069	0.066	
6	1100	-545	841	0.070	0.069	
7	900			0.068	0.039	y5=-50m
8	900			0.026	0.080	y5=-50m
9	900			0.070	0.083	y6=50m
10	900			0.070	0.050	y6=-50m

Furthermore, consider the sensitivity to the site of near detectors:
for case 5, randomly move the near detectors in 10m range, the resulted reduction factor range from 0.065 to 0.070. So it is not sensitive to accuracy of the site.

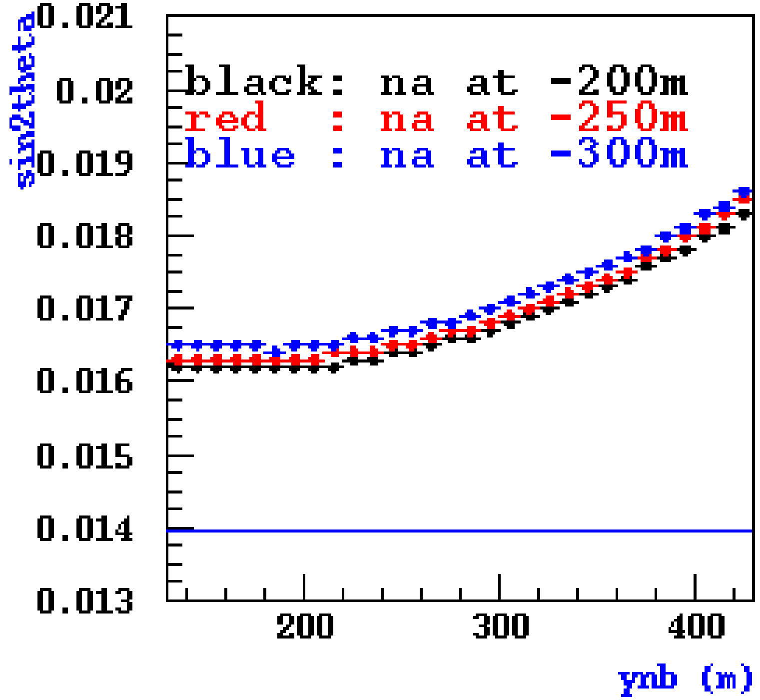
$\sin^2(2\theta_{13})$ limit (90%CL) with only systematic error (One Module):

Assuming detector uncorrelated error is 0.5%, reactor uncorrelated error is 2%.

fix far detector. Fix y coordinates of near detector a at -200m, -250m, -300m. Fix y coordinate of near detector b at -130m to -430m. fit x coordinates of near detectors to get the best reactor error cancellation.

For configuration 5, sinmeff is 0.153 for detector a, 0.137 for detector b, 0.782 for far detector.

$$\sin^2(2\theta_{13})_{limit} = \frac{\sqrt{2.7}\,\sigma_{eff}}{sinmeff}$$



Compare with Japanese proposal:
$\sin^2(2\theta_{13})$limit=0.018 with σ_d=0.6%, near detector at 300m, far detector at 1.3km.

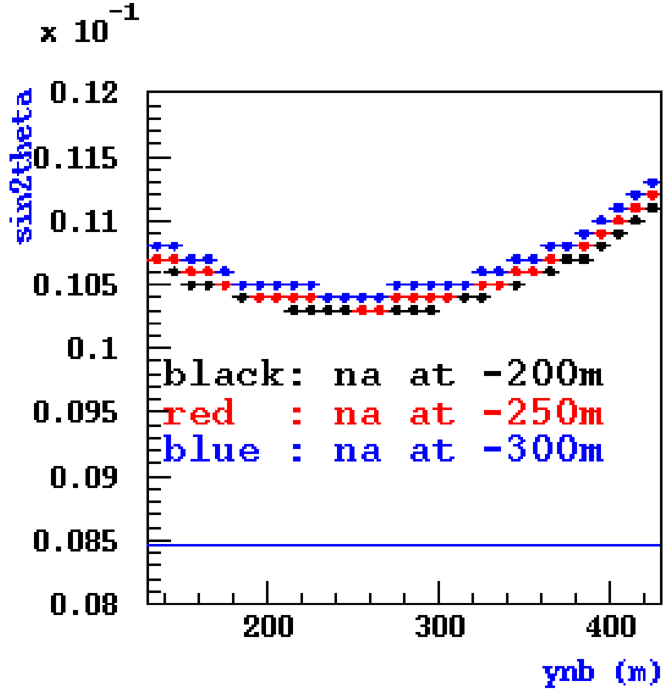
Since error cancellation is good, place near detectors nearer is better.

$\sin^2(2\theta_{13})$ limit (90%CL) with only systematic error (Daya Bay):

Assuming:

- module uncorrlated error is 0.5%
- Reactor uncorrlated error: 2%(could be as good as 1%)
- 4 modules at far detector and 2 at each near detector.

Now residue error of reactors can not be ignored.



Very promising!!!