Large liquid scintillator detector with unprecedented energy resolution

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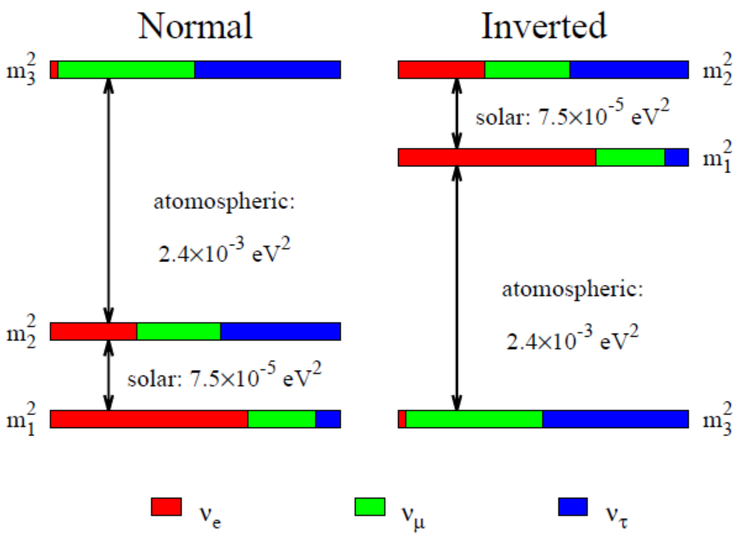
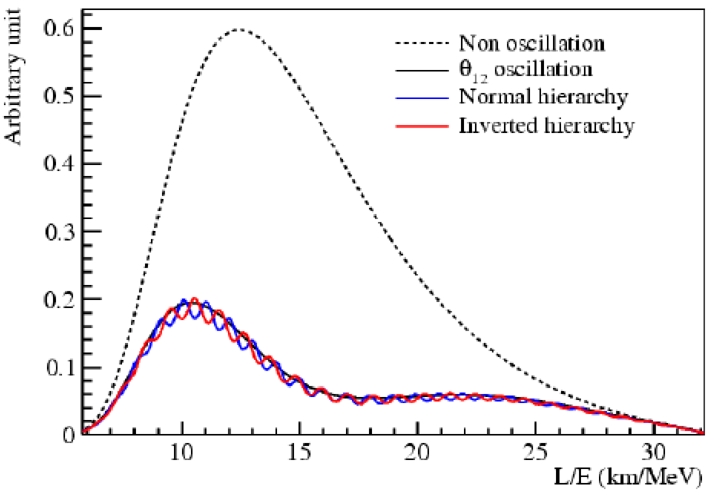
NNN15, October 28-31, 2015

Neutrino Mass Hierarchy

- Next generation neutrino experiments focus on mass hierarchy (MH) and CP violation
- MH determination experiments:
  - The medium baseline reactor anti-neutrino oscillation experiments
    - JUNO, RENO-50
  - The long-baseline accelerator (anti-)neutrino oscillation experiments
    - NOvA , DUNE
  - The atmospheric (anti-) neutrino oscillation experiments
    - INO, PINGU, Hyper-K

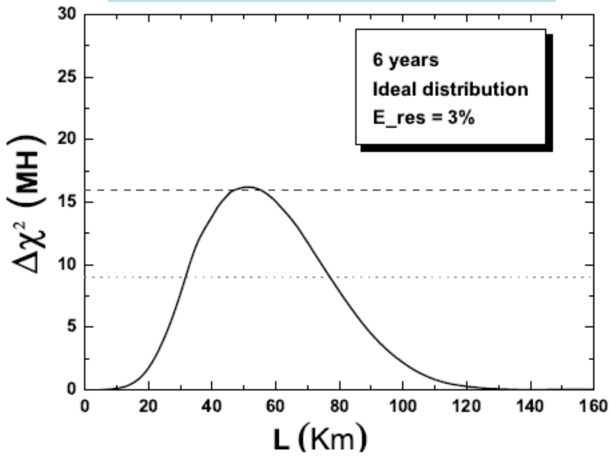




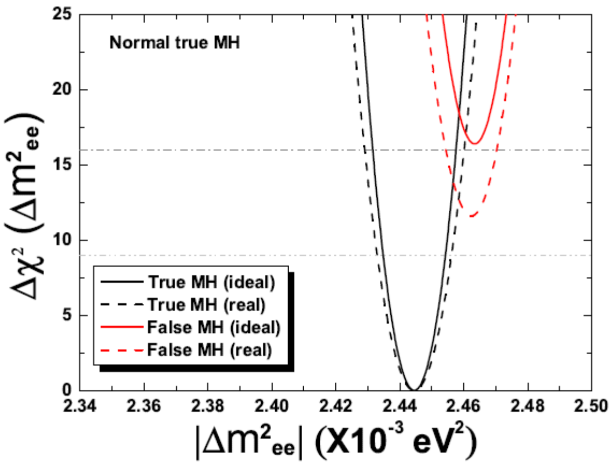
MH determination with reactor anti-neutrinos

- A large liquid scintillator detector
- Optimized baseline
- Factors to degrade sensitivity
  - Baseline differences to reactor cores
  - Background
    - Accidental, $^{9}Li/^{8}He$, fast neutron, Geo-neutrino

Baseline optimization



Effect of baseline distribution

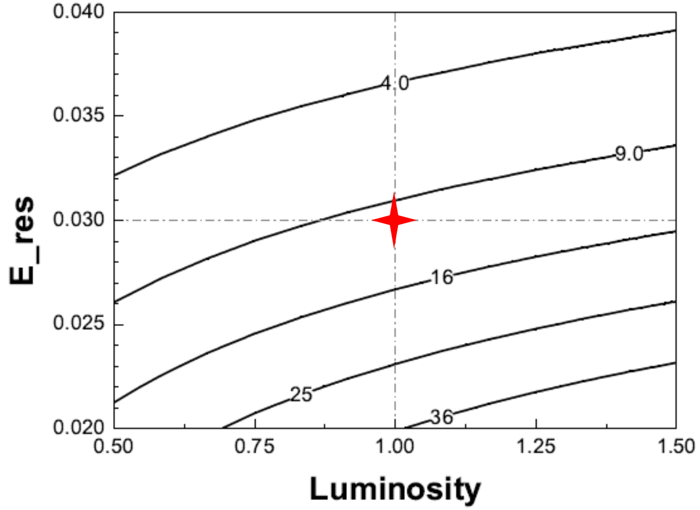


MH determination with reactor anti-neutrinos

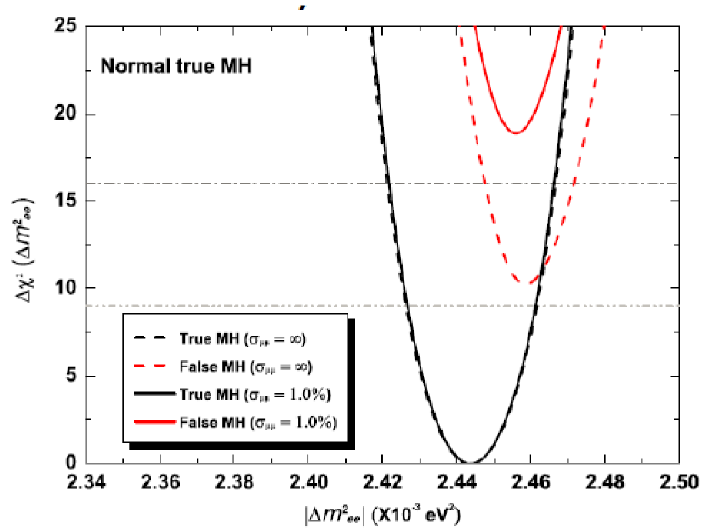
■ Factors to enhance sensitivity

- Higher statistics → larger detector and longer exposure
- Better energy resolution
  → more photoelectrons: stochastic term
  → control systematics: non-stochastic term
- Additional information of $\Delta m^2_{\mu\mu}$

Effect of statistics and energy resolution



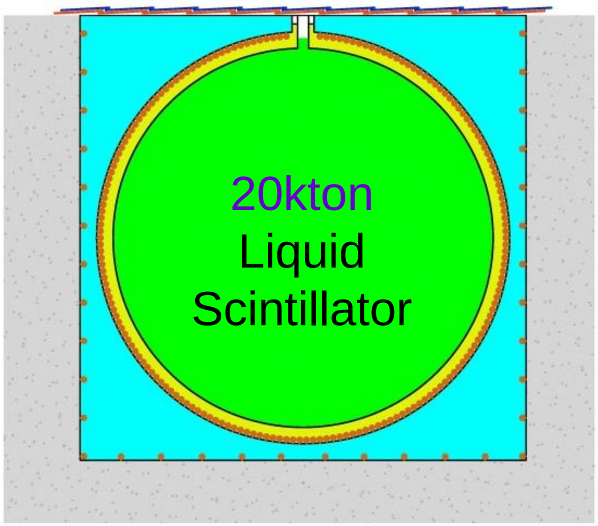
Effect of constrain $\Delta m^2_{\mu\mu}$



Nominal sensitivity at σ=3%/√E, 53km, 36GW, 20kton, 6years, eff.=80%: $\Delta\chi^2$~10

Yu-Feng Li, Jun Cao, Yifang Wang, and Liang Zhan, PRD 88, 013008 (2013)

Large liquid scintillator detector with unprecedented energy resolution



- 20 kton liquid scintillator
  - ~80 IBD candidates at 53km and 36GW
- ~1.5m buffer
  - Reduce PMT radioactivity
- Good energy resolution
  - More photoelectrons
    - LS: high light yield & transparency
    - PMT: high photocathode coverage & QE
    - High transparency LS vessel
    - High transparency buffer material
  - Control systematics
    - energy nonlinearity, PMT dark noise, PMT time resolution, vertex smearing, uniformity of QE
- Low radioactivity background
  - $^{238}U/^{232}Th/^{40}K/^{222}Rn/^{210}Pb/^{60}Co/^{85}Kr/^{39}Ar$
  - From LS, acrylic, water, stainless steel, PMT glass, rock, etc.

How many photonelectrons ?

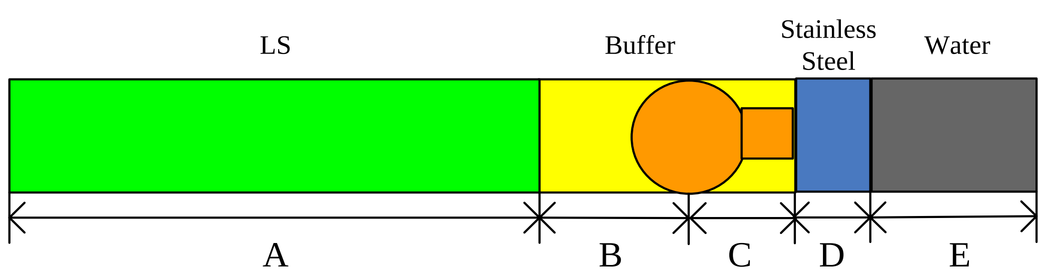
	KamLand	Borexino	Daya Bay
LS mass	~1000t	~500t	40x8 ton
Light yield	250 p.e./MeV	511 p.e./MeV	163 p.e./MeV
Energy resolution	$6\% / \sqrt{E}$	$5\% / \sqrt{E}$	$7.5\% / \sqrt{E}$

$3\% / \sqrt{E(\mathrm{MeV})}$ → ~1200 p.e./MeV

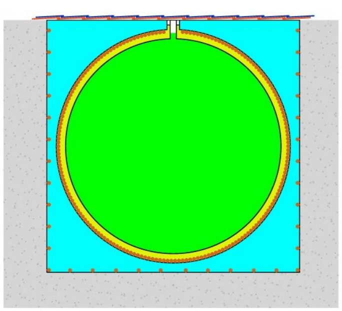
- How to design a detector with 3% energy resolution?
  - Scale light yield from running liquid scintillator detectors
  - Study detector performance with full detector simulation
    - Based on reliable MC simulation package, p.e. tuned to data
  - With expected geometry and optical parameters as input

Detector Simulation

- Full detector simulation
  - To study detector performance with Monte Carlo method
- Based on Geant4, physics processes from Daya Bay simulation package
  - EM, Hadronic processes
  - Optical processes
    - Scintillation(quenching included), Cerenkov, Absorption, Re-emission,
    - Rayleigh Scattering, Boundary Process
- Geometry
  - 20kton LS, radius: 17.7mm
  - Acrylic vessel: 12cm thickness
  - ~18000 20'' PMT



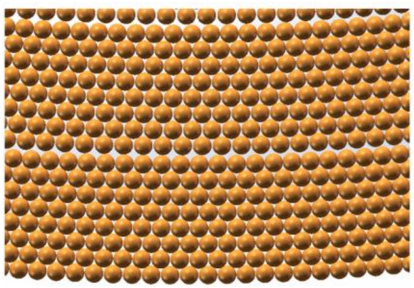
A=17.7m (LS)
A+B=19.5m (position of PMT sphere center)

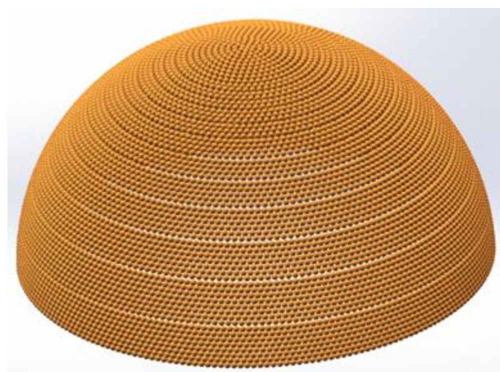


PMT coverage

PMT arrangement method	*(1)Layer-by-layer method*	*(2)9-layers' module layout method*
Optimal radius	Radius has no influence to coverage	Optimal radius: 18.7m
Symmetry	Less symmetry in theta	More symmetry in theta
Stainless steel bars	Arrange PMT optimally, then delete PMT where bars occupied	
Maximum coverage	~75.4%	

(1)





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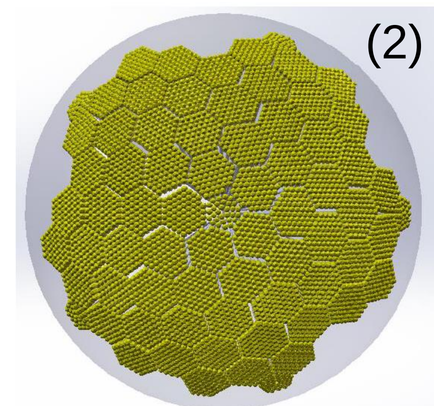
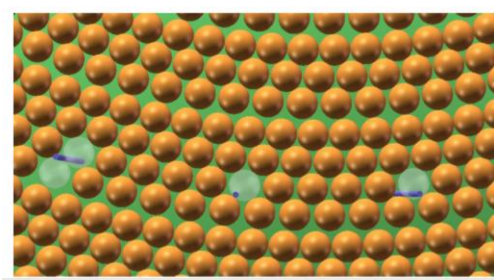
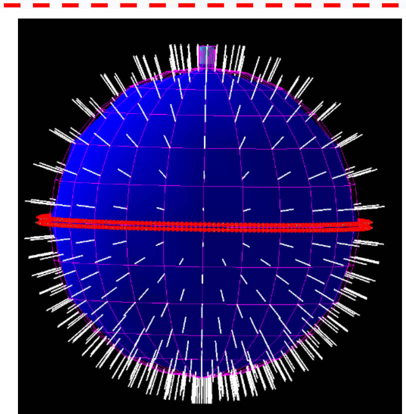
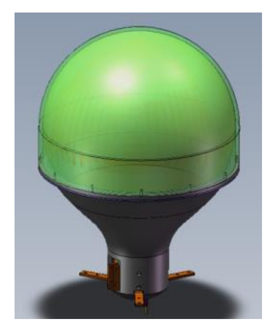






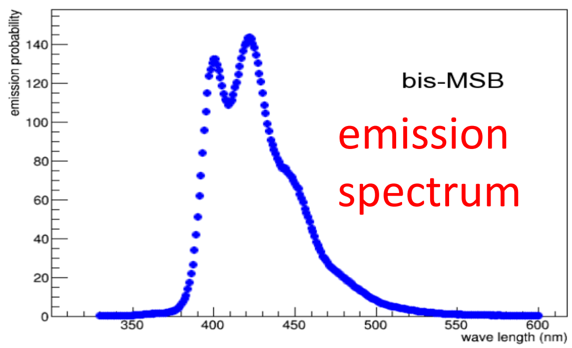


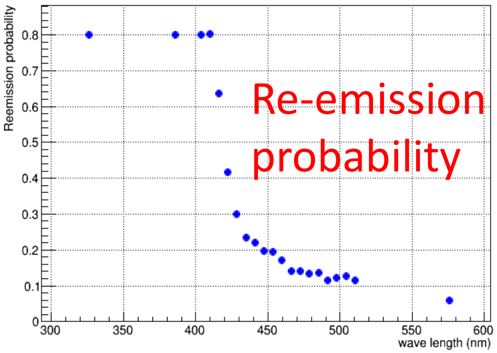
PMT with implosion protection

Detector Simulation

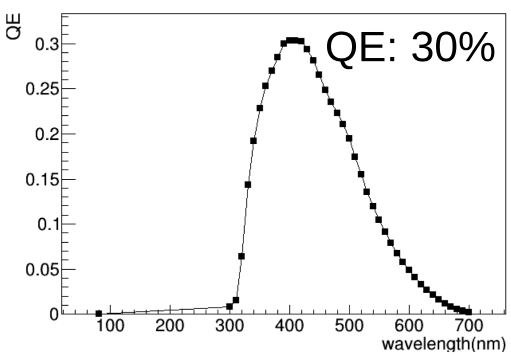
Optical parameters

- Configured with all the optical parameters of the materials
- LS light yield, decay time, emission spectrum, re-emission probability, birks law constants
- Refractive index, absorption length, rayleigh scattering length, PMT QE, PMT CE

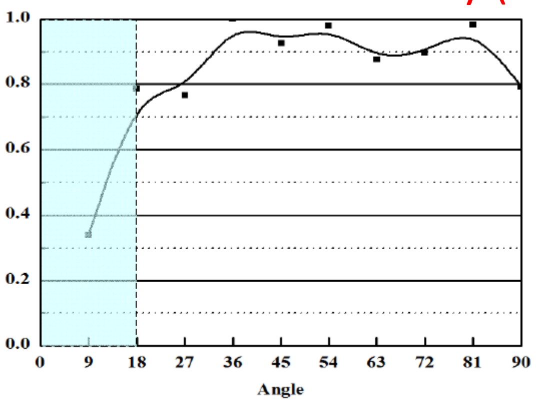




PMT quantum efficiency (QE)



PMT collection efficiency (CE)



Detector Simulation

■ Optical parameters

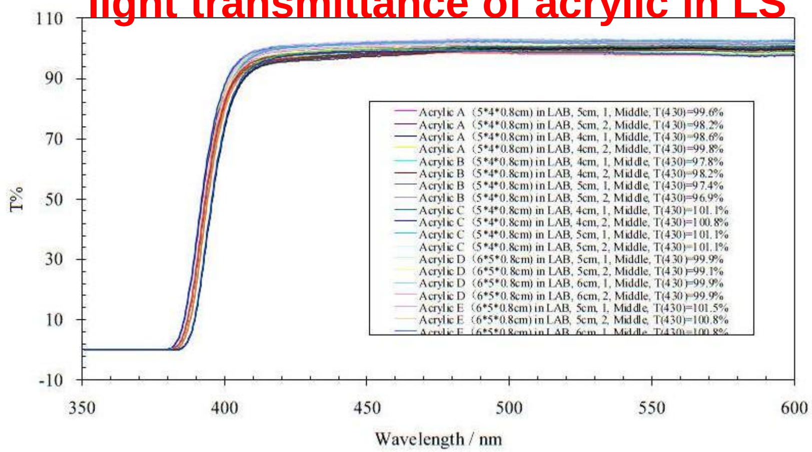
- LS attenuation length: 20m@430nm
  - Absorption length: 77m@430nm
  - Rayleigh scattering length: 27m@430nm
    - http://arxiv.org/abs/1504.00987

Linear Alky Benzene	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 column	18.6 m
Al_2O_3 column	22.3 m

- Water absorption length: 90m
  - Pure water with circulation system

- Acrylic absorption length: 4m

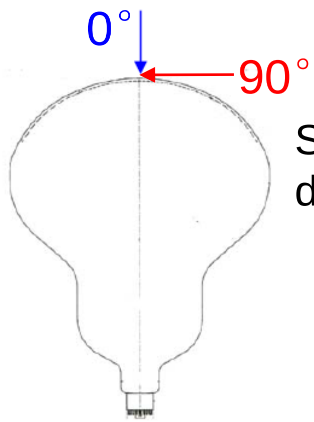
light transmittance of acrylic in LS



10cm LAB：100%
4cm Acrylic + 6cm LAB：97.8%~101.1%
5cm Acrylic + 5cm LAB ：96.6%~101.5%
6cm Acrylic + 4cm LAB ：97.3%~100.9%
8cm Acrylic + 2cm LAB ：96.1%~98.9%

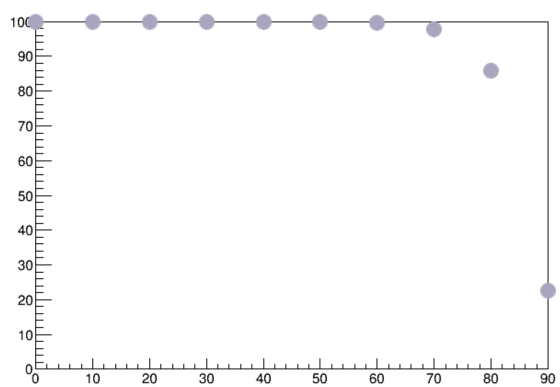
PMT angular response

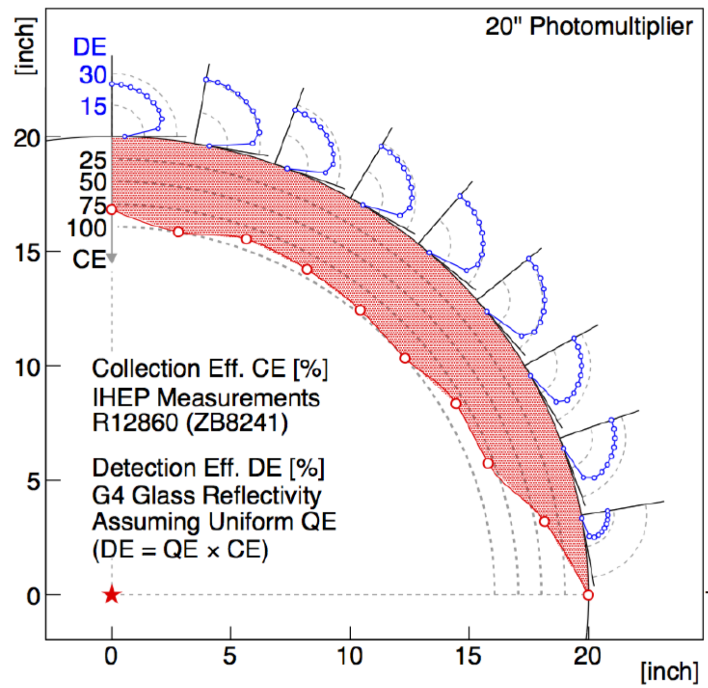
Light reflectivity at PMT glass done by Geant4



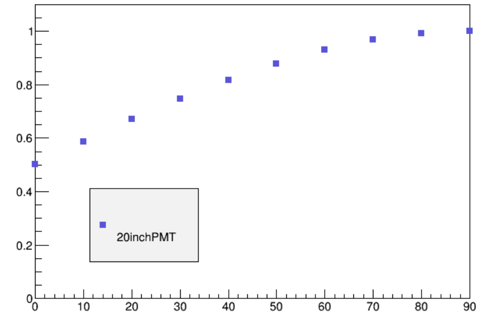
Same position, different angle

Light received by PMT at different incident angle

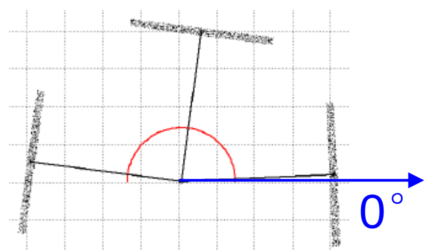




Parallel light, different angle

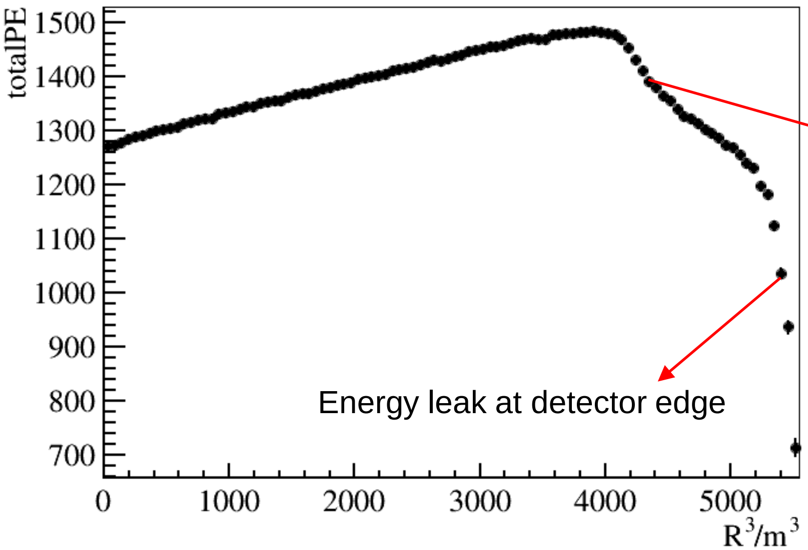


Red curve is photocathode

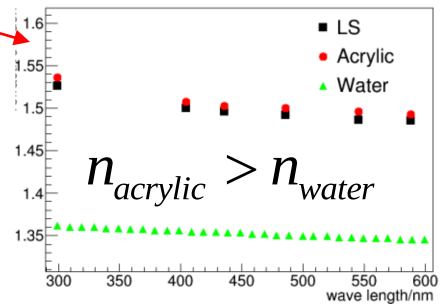


Detector Simulation

1MeV gamma uniformly generated at LS volume



Total internal reflection



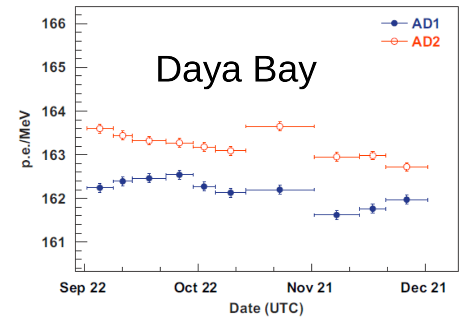


Fig. 17. The time stability of the energy calibration constants.

	Daya Bay MC simulation	NEW MC simulation
PMT coverage	6% photocathode coverage ~12% effective coverage with top and bottom reflector	75%
PMT quantum efficiency@430nm	0.2	0.29
absorption length@430nm	25m	77m
Rayleigh scattering length@430nm	40m	27m
LS radius	2m	17.7m
p.e./1MeV	163	1270

Roughly estimation: $$163 \times \frac{0.75 \times 0.29 \times \exp(\frac{-17.7}{77})}{0.12 \times 0.2 \times \exp(\frac{-2}{25})} = 1271$$

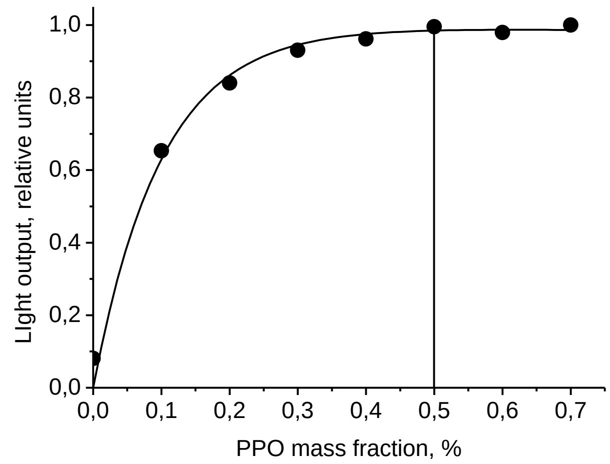
Higher LS Light yield

LS Recipe: LAB + PPO + bisMSB

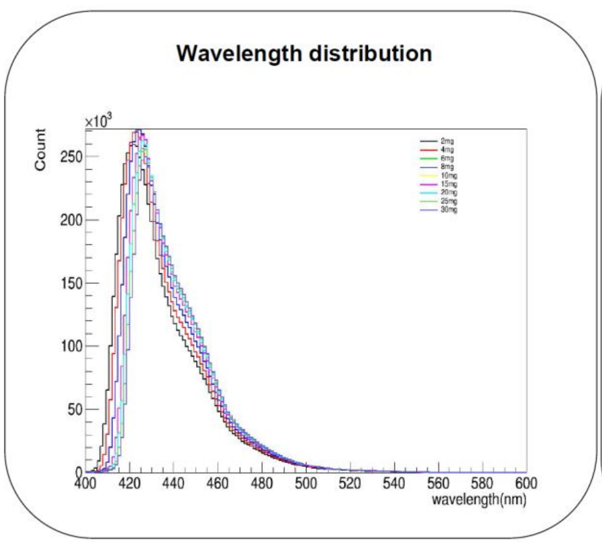
Increase light yield:

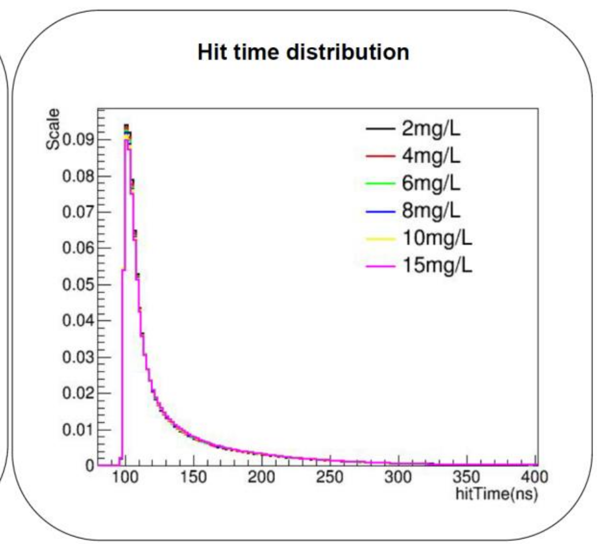
Optimization of fluors concentration

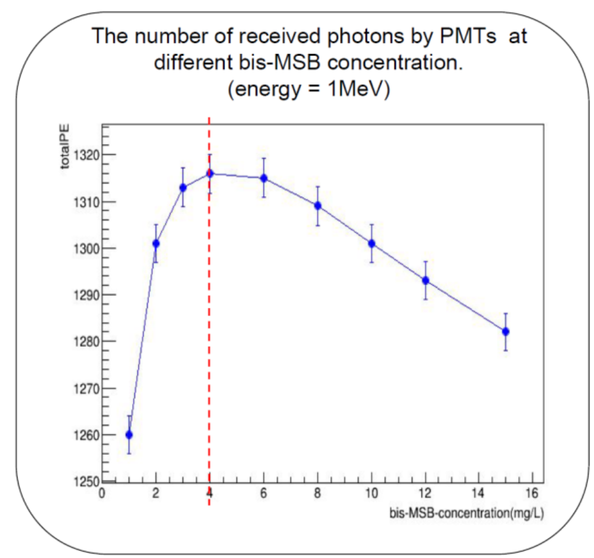
Fluor concentration optimization



bis-MSB concentration optimization

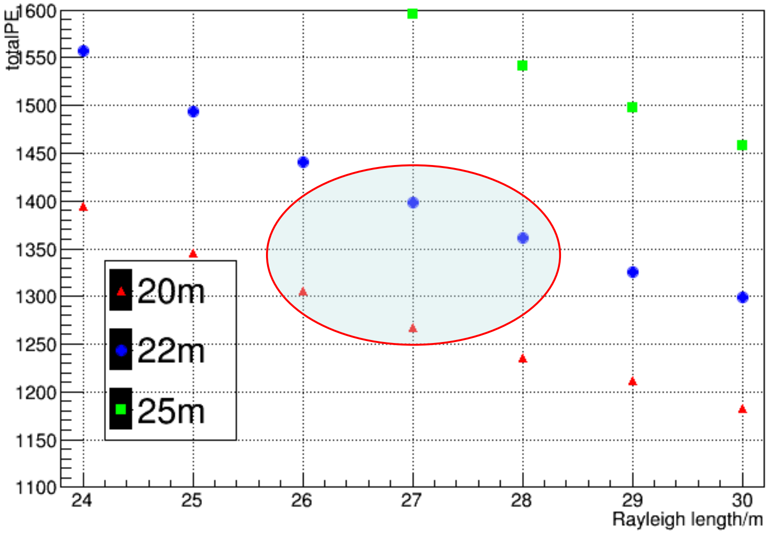






Longer LS attenuation length

- Good raw solvent LAB
  - Improve production processes: cutting of components
  - Using Dodecane instead of MO for LAB production
- Online handling/purification
- Distillation, Filtration, Water extraction, Nitrogen stripping, …

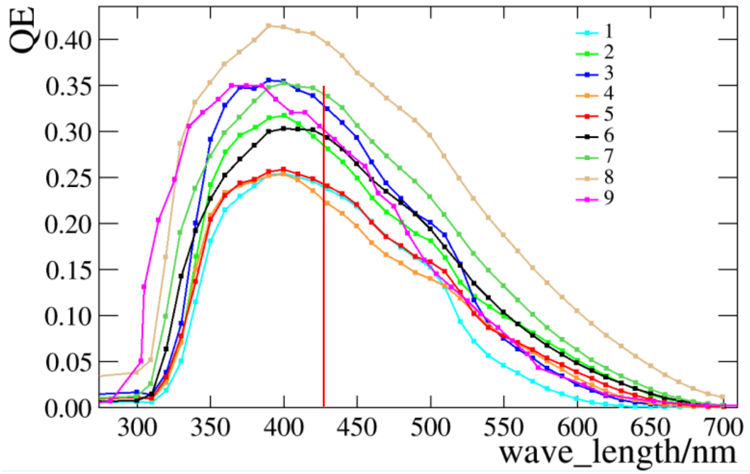


$$\frac{1}{l_{atten}} = \frac{1}{l_{absorb}} + \frac{1}{l_{ray}}$$

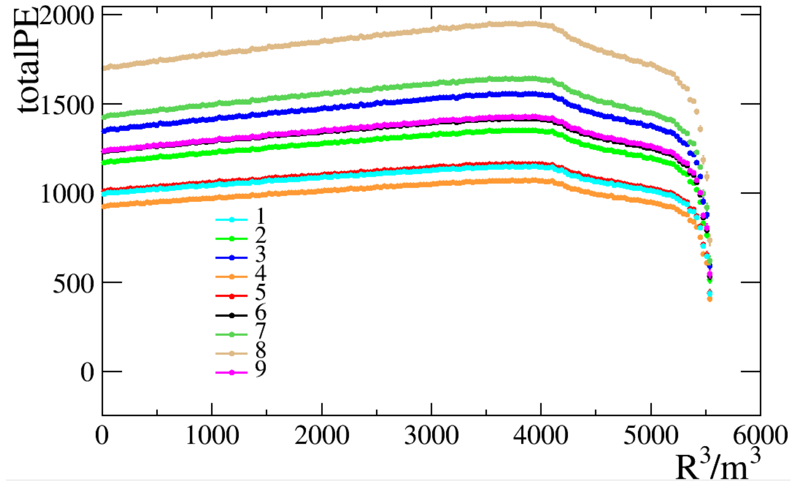
Total p.e. with LS A.L. = 20m, 22m, 25m

1MeV at (0,0,0)

Higher PMT QE & CE

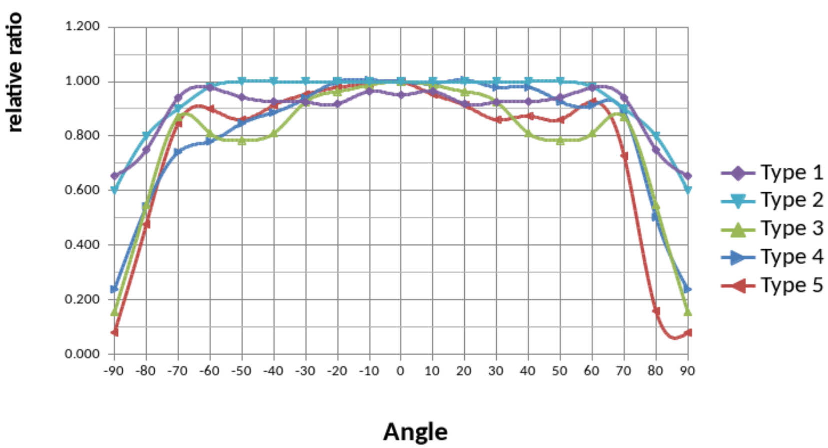


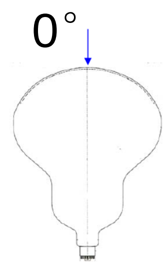
totalPE distribution for different CE



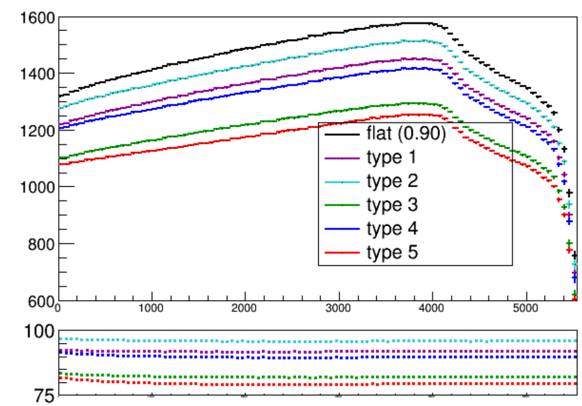
QE @430nm is most important

CE





totalPE distribution for different CE



CE at any PMT position can impact on the p.e.

Systematics of energy resolution

- Energy non-linearity
- PMT QE non-uniformity
- PMT dark noise
- PMT time resolution
- Vertex smearing

MC study of energy non-linearity

- Study non-linearity from Cherenkov and quenching
- Positron events generated position: the center of the LS volume, (0,0,0)
  - Fixed position, minimum non-uniformity
- Energy reconstruction

$$E_{rec} = E_0 \times \frac{totalPE}{N_0}$$

- Energy resolution fit function

$$\frac{\sigma}{E_{rec}} = \sqrt{\frac{A^2}{E_{rec}} + B^2 + \frac{C^2}{E_{rec}^2}}$$

A: Stochastic term

B: Constant term

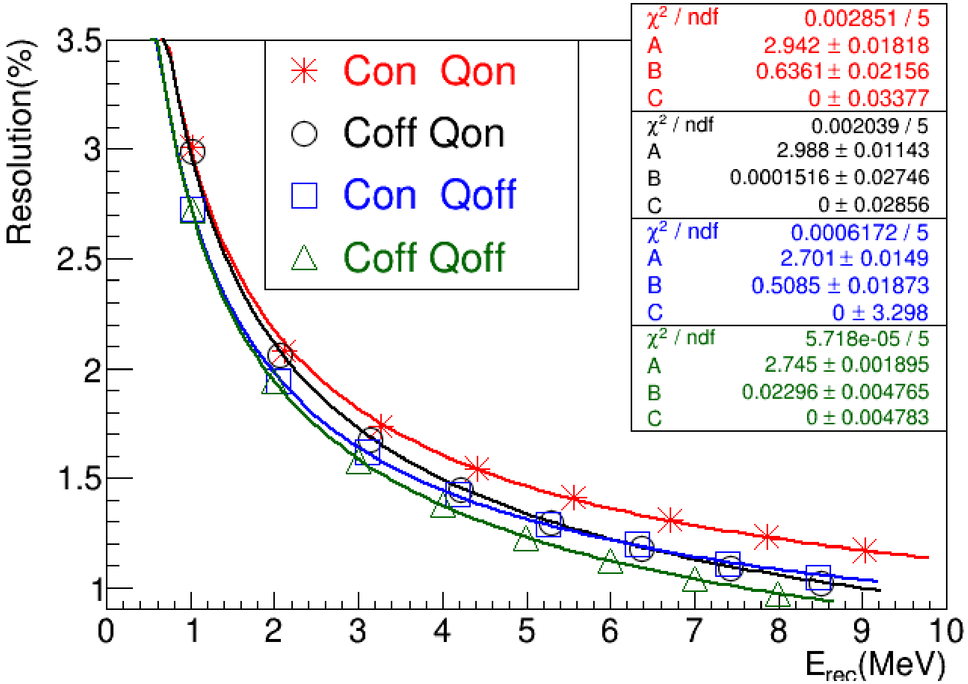
C: Noise term

Con: with Cherenkov process

Coff: without Cherenkov process

Qon: with quenching

Qoff: without quenching



Cherenkov light contribute to B term: 0.5%

MC study of other non-stochastic terms

Procedure to study detector effects by toy MC

- Expected p.e. caculation with very simple optical model

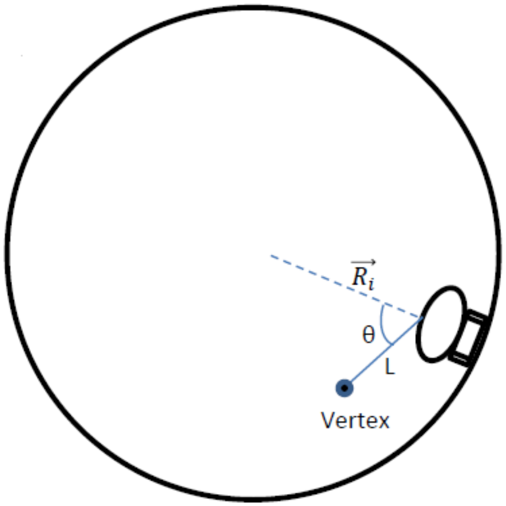
Light yield

Angular response

$$\mu_i = \varepsilon_i Y E_{vis} \frac{f(\cos\theta)\Omega(\vec{r},\vec{R}_i)}{4\pi} e^{-\frac{L}{\lambda}}$$

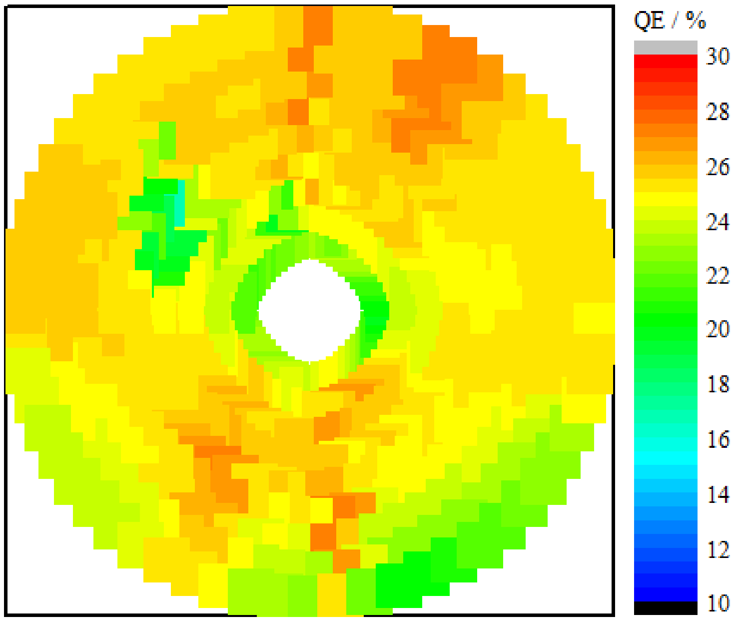
Quantum efficiency

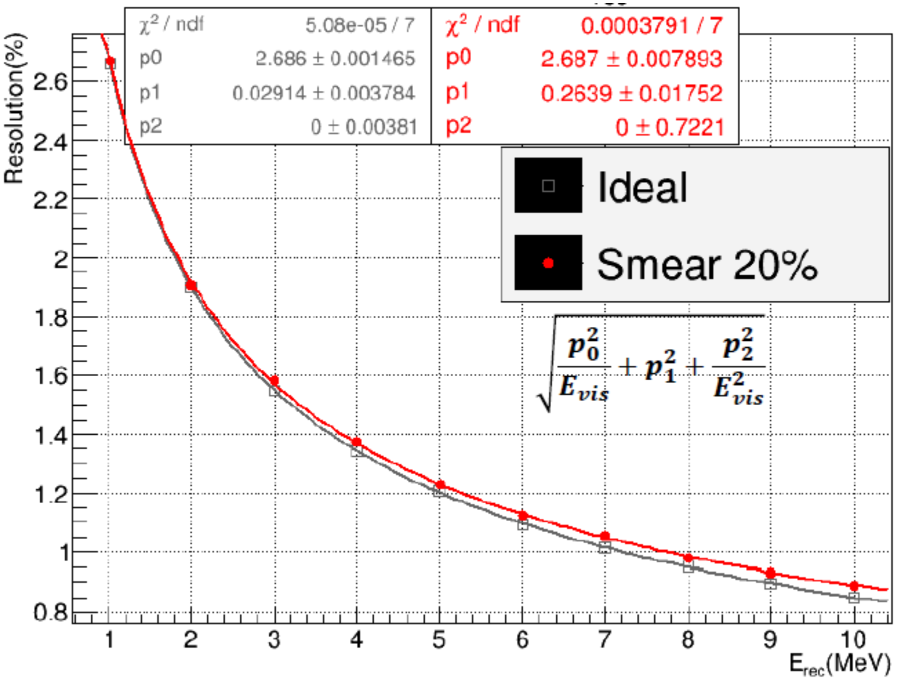
Attenuation length



- Measured p.e.: poisson
- Max-likelihood reconstruction: to get vertex and energy
- Effects can be inserted to above procedure one by one

PMT QE non-uniformity





$$\varepsilon_i \sim N(\varepsilon_0, (20\% \times \varepsilon_0)^2), \varepsilon_i \in (\varepsilon_0 \times 0.8, \varepsilon_0 \times 1.2)$$

$$\frac{\sigma}{E_{rec}} = \sqrt{\frac{A^2}{E_{rec}} + B^2 + \frac{C^2}{E_{rec}^2}}$$

A: Stochastic term

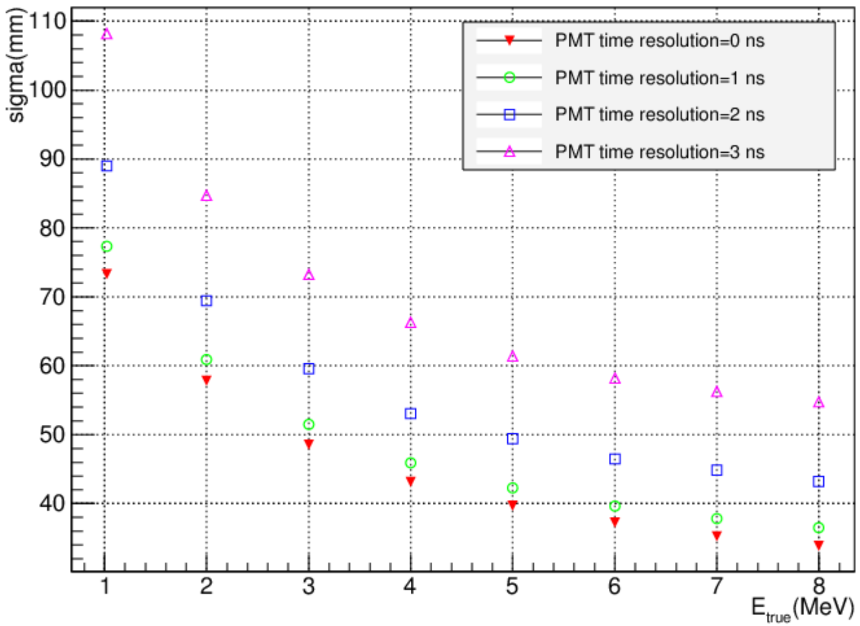
B: Constant term

C: Noise term

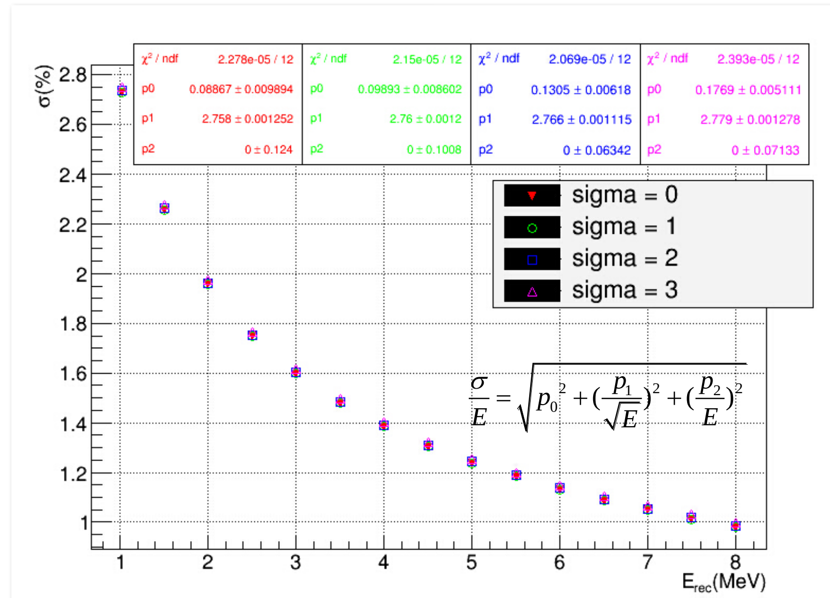
PMT QE non-uniformity	0	20%
B(%)	0.029	0.26

PMT time resolution

PMT time resolution impact on vertex resolution



Vertex smearing impact on energy resolution



Generated at LS uniformly

$$\frac{\sigma}{E_{rec}} = \sqrt{\frac{A^2}{E_{rec}} + B^2 + \frac{C^2}{E_{rec}^2}}$$

A: Stochastic term

B: Constant term

C: Noise term

PMT time resolution (sigma)	0ns	1ns	2ns	3ns
Vertex resolution@1MeV	7.3cm	7.7cm	8.9cm	10.8cm
B(%)	0.09	0.1	0.13	0.18

PMT dark noise

$$N_{tot} = E \times n_0 + n_{darkhit}$$

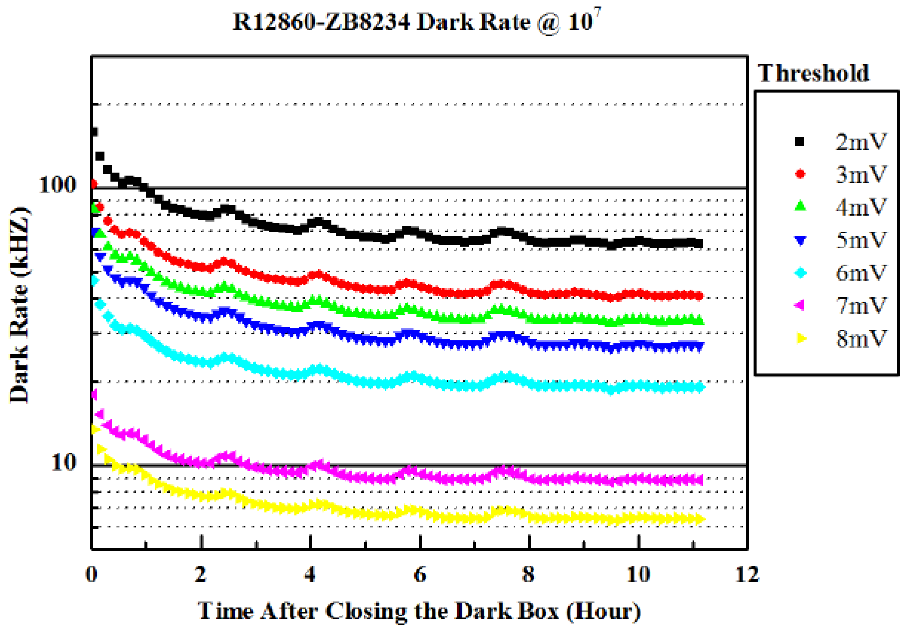
$$\sigma_{N_{tot}} = \sqrt{\sqrt{E \times n_0}^2 + \sqrt{n_{darkhit}}^2}$$

$$\frac{\sigma_{N_{tot}}}{N_{tot}} = \sqrt{\left(\frac{1}{\frac{\sqrt{n_0}}{\sqrt{E}}}\right)^2 + \left(\frac{\frac{\sqrt{n_{darkhit}}}{n_0}}{E}\right)^2}$$

$$C = \frac{\sqrt{n_{darkhit}}}{n_0}$$

$$n_{darkhit} = n_{PMT} \times timewindow \times darknoiseRate$$

$$n_{PMT} \approx 18000$$



$$\frac{\sigma}{E_{rec}} = \sqrt{\frac{A^2}{E_{rec}} + B^2 + \frac{C^2}{E_{rec}^2}}$$

A: Stochastic term

B: Constant term

C: Noise term

Dark noise	A (%)	B (%)	C (%)
10kHz/PMT 300ns time window	2.68	0	**0.53**
50kHz/PMT 200ns time window	2.68	0	**0.96**
50kHz/PMT 300ns time window	2.68	0	**1.18**

C term can be less if dark noise can be removed effectively during energy reconstruction.

Summary of energy resolution

Effects	A(%)	B(%)	C(%)
1400 p.e./MeV (average at LS volume)	2.68		
PMT charge resolution(30%)	2.8	0	0
Cerenkov light	0	0.5	0
PMT dark noise(50kHz, 200ns window)	2.68	0	0.96
PMT QE non-uniformity(20%)	2.68	0.26	0
Vertex smearing(11cm @1MeV)	2.68	0.18	0

Impact to MH sensitivity: $$\frac{\sigma_E}{E} = \sqrt{\left(\frac{A}{\sqrt{E}}\right)^2 + B^2 + \left(\frac{C}{E}\right)^2} \approx \sqrt{\left(\frac{A}{\sqrt{E}}\right)^2 + \left(\frac{1.6B}{\sqrt{E}}\right)^2 + \left(\frac{C}{1.6\sqrt{E}}\right)^2}$$

$$\sqrt{A^2 + (1.6B)^2 + \left(\frac{C}{1.6}\right)^2} < 3\%$$

- To get effective energy resolution: 3%/√E
  - LS attenuation length: >20m @430nm
  - PMT QE: >30%@430nm
  - PMT photocathode coverage: >75%
  - PMT charge resolution: <30%
  - PMT QE non-uniformity: <20%
  - PMT time resolution: <3ns
  - PMT dark noise: <50kHz/PMT

THANK YOU

backup

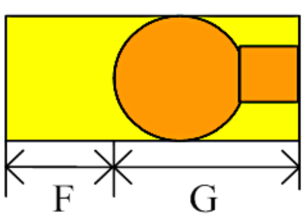
Radioactivity of Detector Materials

	U238	Th232	K40	Pb210 (Rn222)	Ar39	Kr85	Co60	Reference experiment
LS	10^{-6}	10^{-6}	10^{-7}	$1.4 \cdot 10^{-13}$	50 $\mu Bq/m^3$	50 $\mu Bq/m^3$	~	Borexino CTF, KamLAND
PMT Glass	22	20	3.54	~	~	~	~	Schott glass
Acrylic	10 ppt	10 ppt	10 ppt	~	~	~	~	SNO
Steel	0.0012 Bq/Kg (0.096)	0.008 Bq/Kg (1.975)	0.0134 Bq/Kg (0.049)	~	~	~	0.002 Bq/Kg	DYB
Copper	1.23 mBq/Kg	0.405 mBq/Kg	0.0377 mBq/Kg	~	~	~	~	CDEX
Film	2 ppt	4 ppt	1 ppt					
Dust	30 Bq/Kg	40 Bq/Kg	600 Bq/Kg					

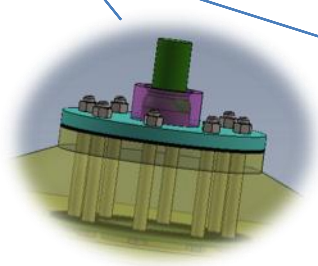
Default unit: ppb

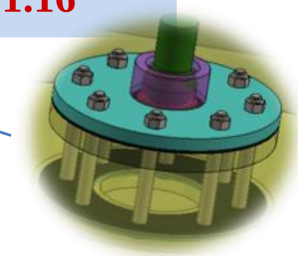
Radioactivity MC Simulation

LS R (m) (Cut 0.7MeV)	PMT (Schott) (Hz)	Acrylic (Hz) (10ppt)	Strut (steel) (Hz)	Fastener (copper) (Hz)	SUM (Hz)
<17.7	**2.43**	69.23	0.89	**0.82**	**73.37**
<17.6	**1.91**	41.27	0.66	**0.55**	**44.38**
<17.5	**1.03**	21.82	0.28	**0.32**	**23.45**
<17.4	**0.75**	12.23	0.22	**0.19**	**13.39**
<17.3	**0.39**	6.47	0.13	**0.12**	**7.10**
<17.2	**0.33**	3.61	0.083	**0.087**	**4.10**
<17.1	**0.23**	1.96	0.060	**0.060**	**2.31**
<17.0	**0.15**	0.97	0.009	**0.031**	**1.16**



PMT position = 19.5 m
Buffer thickness F=1.426 m
LS radius =17.7 m





External Radiation – Radon in water

- Besides the internal radioactivity discussed above, there' re also external radiations: one is radon in water.
  - simulate equilibrium of ^{222}Rn decay chain in ~2m water layer around LS

Rn concentration assumption	Rate of Singles (>0.7 MeV, all volume)	Rate of Singles (>0.7 MeV, in Fiducial volume)
0.2 Bq/m^3	**16 Hz**	**~1.3 Hz**
1 Bq/m^3	**80 Hz**	**~6.4 Hz**
12.5 Bq/m^3 (without any purification)	1000 Hz	~80 Hz

- Preliminary requirements to Radon in water pool
  - Good N_2 seal
  - Sufficient anti-Rn liner on the water pool walls
  - Control Rn permeation into water systems

External Radiation – Rock

250 cm Water

Estimation ------------------- Simulation

K40(5ppm): 4.922 Hz ----------- 9.07Hz

Th232(30ppm): 133.81 Hz ---------- 143.21 Hz

U238(10ppm): 17.67 Hz ---------- 35.65 Hz

320 cm Water

Estimation

K40(5ppm): 0.0742 Hz

Th232(30ppm): 6.739 Hz

U238(10ppm): 0.613 Hz

Sum:

~7.4 Hz(all volume)

~0.984 Hz (in Fiducial volume)

Radioactivity Summary

✧ Summary of singles rate in fiducial volume(R<17.2m)

Materials	Detector components	Water (Rn: 0.2Bq/m^3)	Rock (320cm water)	SUM
Acrylic (Hz)	~6.3	~1.3	~0.984	~8.58

	PMT	LS	Acrylic (10ppt)	Support	Dust	Film
Acrylic (Hz)	0.33	2.2	3.61	0.17	~	~

Accidental background by radioactivity: 1.1/day

Detector material	^{238}U	^{238}Th	^{40}K	^{60}Co
PMT glass	22 ppb	20 ppb	3.54 ppb	-
Acrylic	10 ppt	10 ppt	10 ppt	-
Polymer film	2 ppt	4 ppt	1 ppt	-
Steel	0.096 ppb	1.975 ppb	0.049 ppb	0.002 Bq/kg
Copper	1.23 mBq/kg	0.405 mBq/kg	0.0377 mBq/kg	-

LS	^{238}U	^{238}Th	^{40}K	^{210}Pb	^{85}Kr	^{39}Ar
No distillation	10^{-15} g/g	10^{-15} g/g	10^{-16} g/g	$1.4 \cdot 10^{-22}$ g/g	50 μBq/m^3	50 μBq/m^3
After distillation	10^{-17} g/g	10^{-17} g/g	10^{-18} g/g	10^{-24} g/g	1 μBq/m^3	-

Fiducial Cut	LS (Hz)	PMT (Hz)	Acrylic (Hz)	Strut (Hz)	Fastener (Hz)	Sum (Hz)
R<17.7 m	2.39	2.43	69.23	0.89	0.82	75.75
R<17.6 m	2.35	1.91	41.27	0.66	0.55	46.74
R<17.5 m	2.31	1.03	21.82	0.28	0.32	25.75
R<17.4 m	2.27	0.75	12.23	0.22	0.19	15.66
R<17.3 m	2.24	0.39	6.47	0.13	0.12	9.33
R<17.2 m	2.20	0.33	3.61	0.083	0.087	6.31
R<17.1 m	2.16	0.23	1.96	0.060	0.060	4.47
R<17.0 m	2.12	0.15	0.97	0.009	0.031	3.28

Fiducial Cut	Detector Components	Radon in water	Rock	Total
R<17.2 m	6.3 Hz	1.3 Hz	0.98 Hz	7.63 Hz