大亚湾反应堆中微子实验进展

衡月昆　中科院高能所

On behalf of Daya Bay Collaboration

2010-04-19

提纲

- 实验目标与设计
- 进展
  - 土建
  - 中心探测器
  - 反符合探测器
  - 在线与离线
- 总结

目标

- 一句话：测量$\sin^2 2\theta_{13}$ 达到0.01的敏感度
- 为什么测量 $\sin^2 2\theta_{13}$ ？
  - 中微子的6个参数，3个半已知，2个半未知

Neutrino Mixing: PMNS Matrix

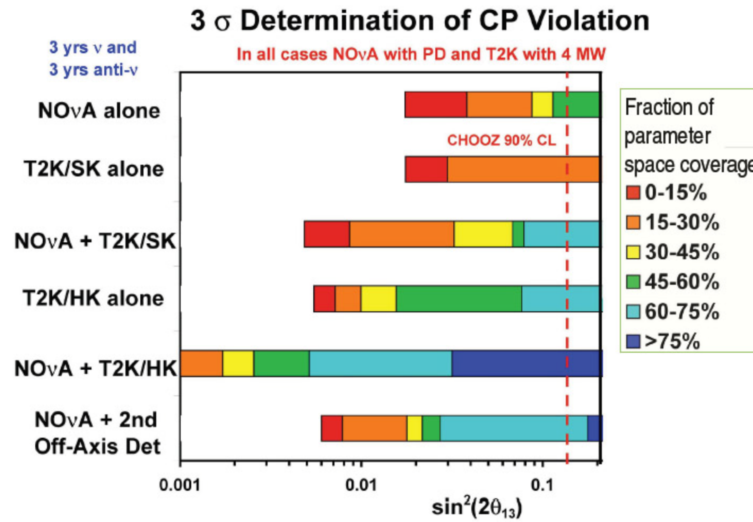
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12}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

Atmospheric, K2K, MINOS, T2K, etc. $\theta_{23} \sim 45^o$

Reactor Accelerator $\theta_{13} < 12^o$

Solar KamLAND $\theta_{12} \sim 30^o$

已知：$|\Delta m^2_{32}|$，$\sin^2 2\theta_{23}$，Δm^2_{21}，$\sin^2 2\theta_{12}$
未知：$\sin^2 2\theta_{13}$，δ_{CP}，Sign of Δm^2_{32}



- 为什么$\sin^2 2\theta_{13}$ 达到0.01的敏感度？
  - 决定着长基线中微子实验的方向

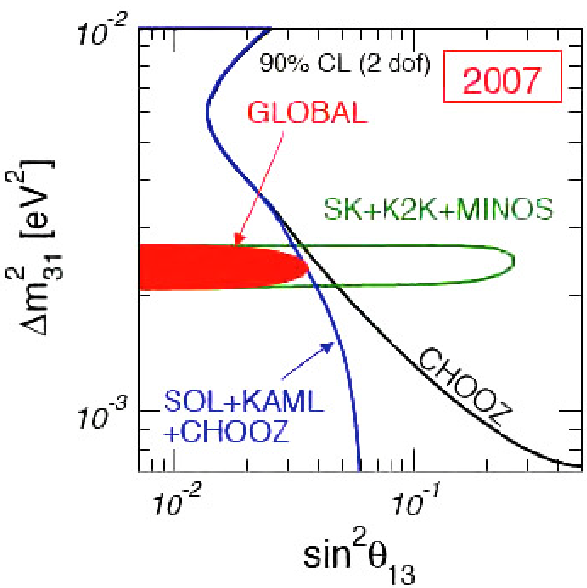
"We recommend, as a high priority, …, An expeditiously deployed multi-detector reactor experiment with sensitivity to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13}=0.01$"
---- APS Neutrino Study, 2004

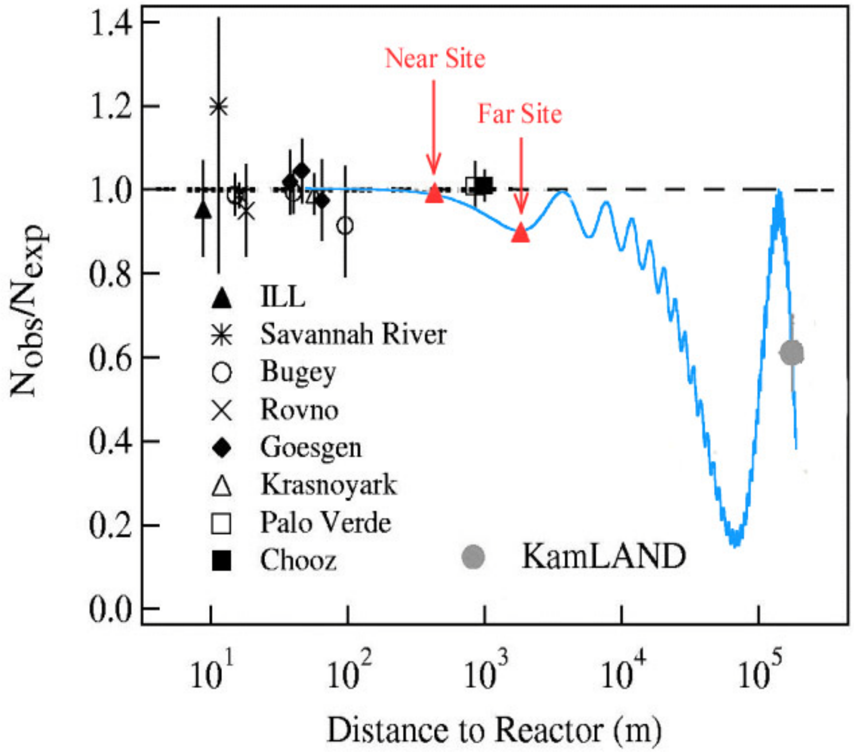
为什么用反应堆中子测量θ_{13}？

- 反应堆：$\bar{\nu}_e$ 消失
  - 物理上，干净
  - 经济上，便宜

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

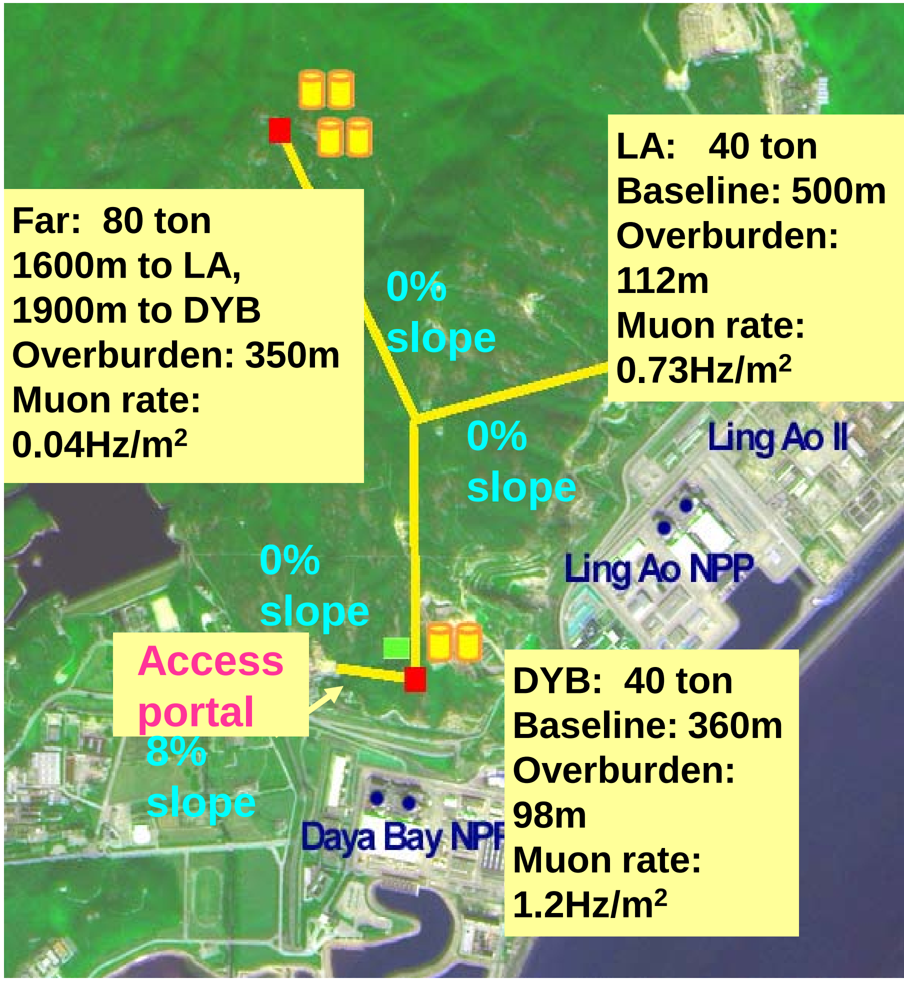
- 加速器中微子： 中微子产生，还与CP相角、质量次序相关





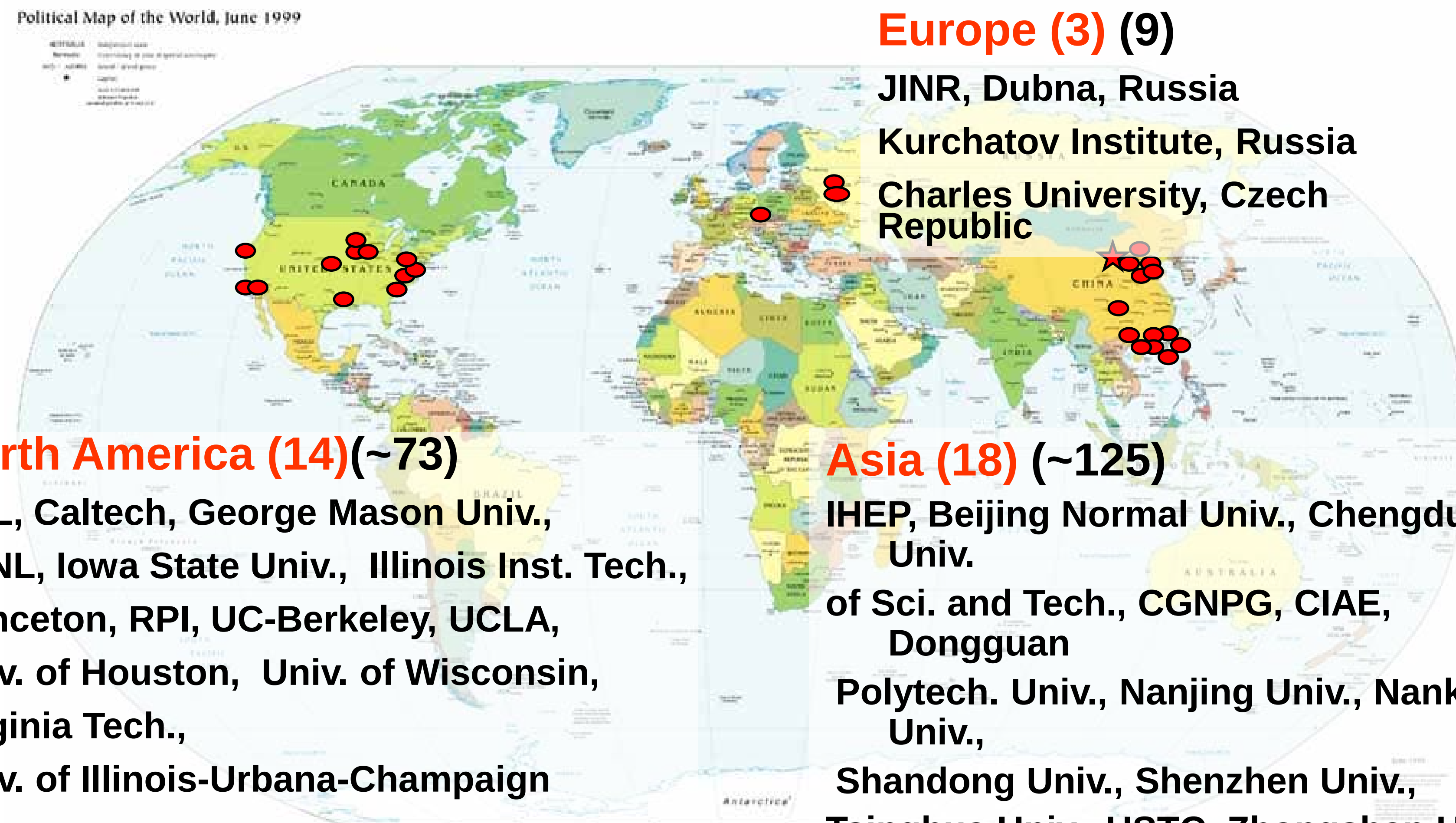
为什么在大亚湾反应堆？

- 强大的功率，降低统计误差
  - 统计量正比于反应堆功率、探测器靶质量、取数时间
  - 大亚湾反应堆，3期、6个反应堆
- 附近多山的环境，降低系统误差
  - 300m地下降低宇宙线本底2个量级



DayaBay and LingAo NPP

The Daya Bay Collaboration



Europe (3) (9)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (14)(~73)

BNL, Caltech, George Mason Univ.,
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 (18) (~125)

IHEP, Beijing Normal Univ., Chengdu Univ.
of Sci. and Tech., CGNPG, CIAE, Dongguan
Polytech. Univ., Nanjing Univ., Nankai Univ.,
Shandong Univ., Shenzhen Univ.,
Tsinghua Univ., USTC, Zhongshan Univ.,
Univ. of Hong Kong,
Chinese Univ. of Hong Kong,
National Taiwan Univ., National Chiao Tung Univ., National United Univ.

~ 207 collaborators

世界上的竞争

- 8项提议，3项进行中
  - 法国，Double Chooze
  - 韩国，Reno
  - 中国，DayaBay
- 预期结果比较

我们的特点

Power Plant
4 cores 11.6 GW
6 cores 17.4 GW from 2011
Three experimental halls
Multiple detectors at each site
Side-by-side calibration
Horizontal Tunnel
Total length 3200 m
Movable Detector
w/ the same batch of Gd-LS, w/ a reference tank
Event Rate:
~1200/day Near
~350/day Far
Backgrounds
B/S ~0.4% Near
B/S ~0.2% Far

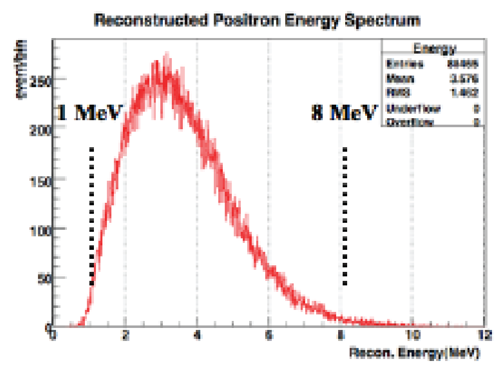
Table Comparison of three experiments

Experiment	Power (GW)	Baseline near/far(m)	Target mass near/far(t)	Overburden (MWE)	Sensitivity (90%C.L.)
Double Chooz	8.4	150/1050	10/10	60/300	0.03
Dayabay	17.4	400/1800	40/80	300/1000	0.01
RENO	17.3	150/1500	20/20	230/675	0.03

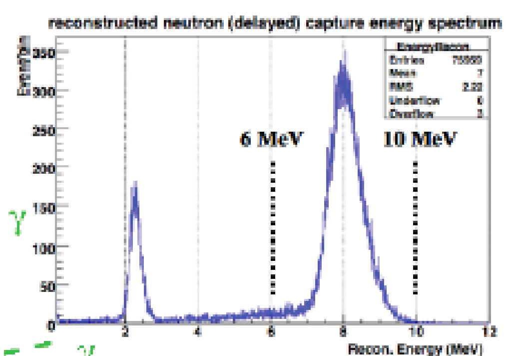
探测方法

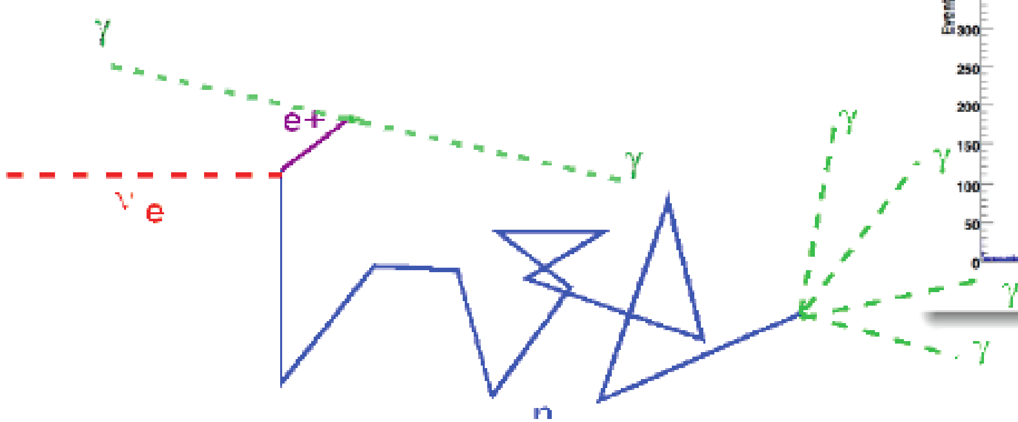
- Inverse β-decay :
  $\bar{\nu}_e + p \rightarrow e^+ + n$
- Trigger on 2-fold coincidence:
  - Prompt signal from e^+
  - Delayed signal from n capture on Gadolinium $\approx 30\mu s$
- Detector with Gd doped Liquid Scintillator (LS)

Prompt signal



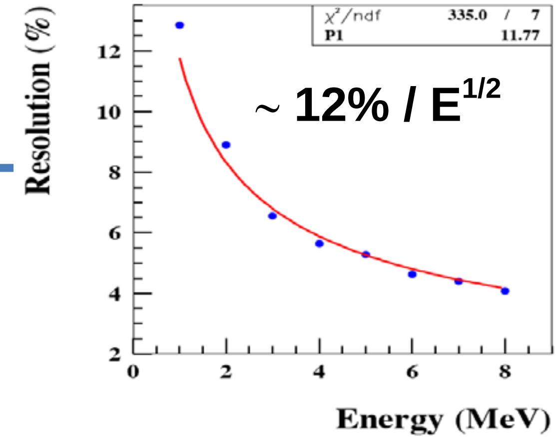
Delayed signal

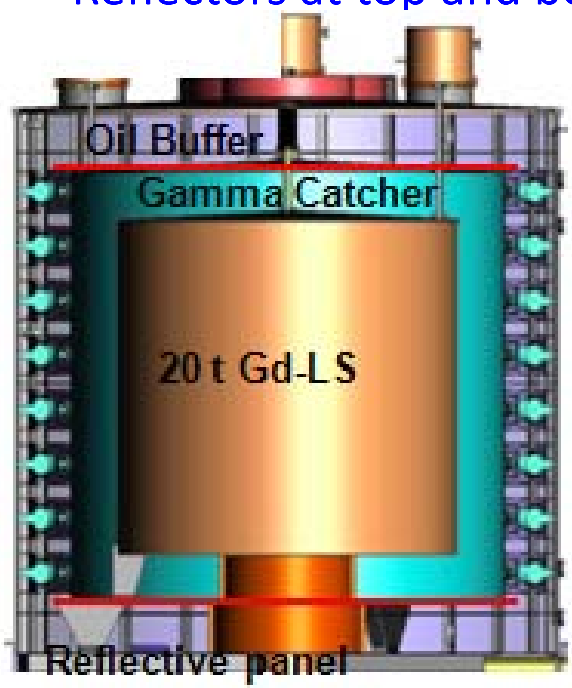




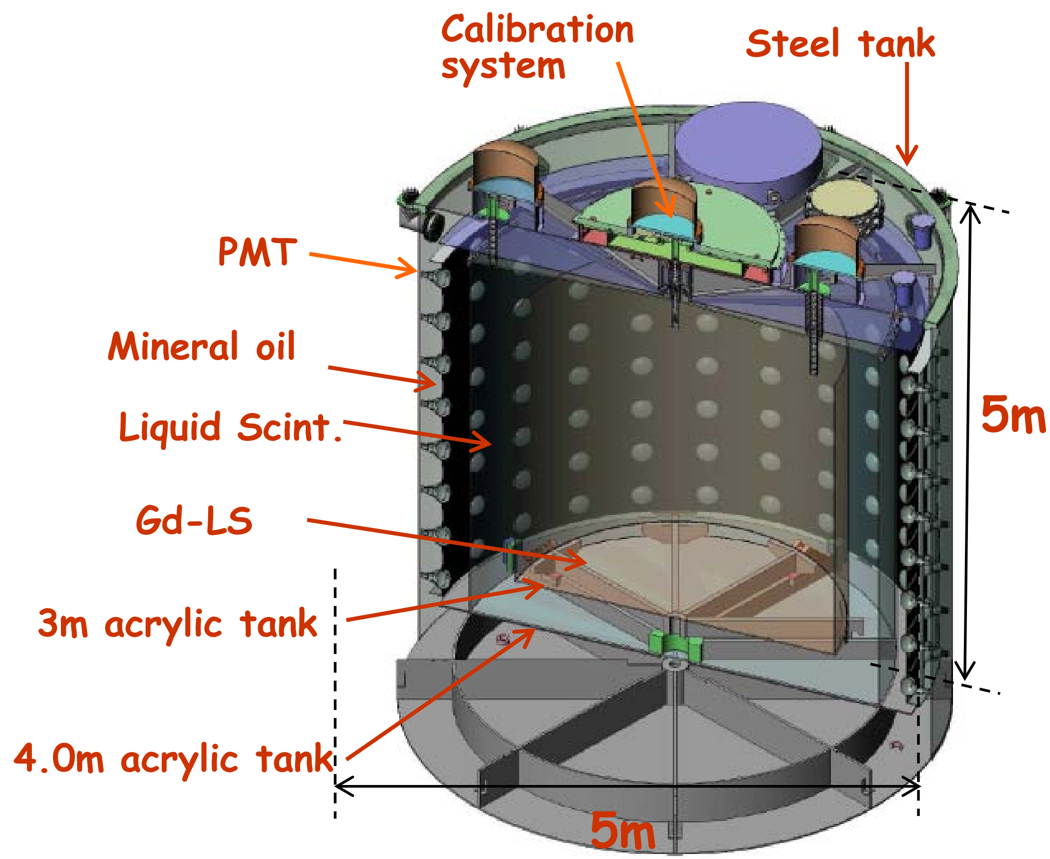
中心探测器

- Three-zone nested cylindrical detector design
  - Target: 3m AV, 20 t (0.1% Gd LAB-based LS)
  - Gamma catcher: 4m AV, 20 t (LAB-based LS)
  - Buffer :5m SSV, 40 t (mineral oil)
- Low-background 8” PMT: 192
- Reflectors at top and bottom

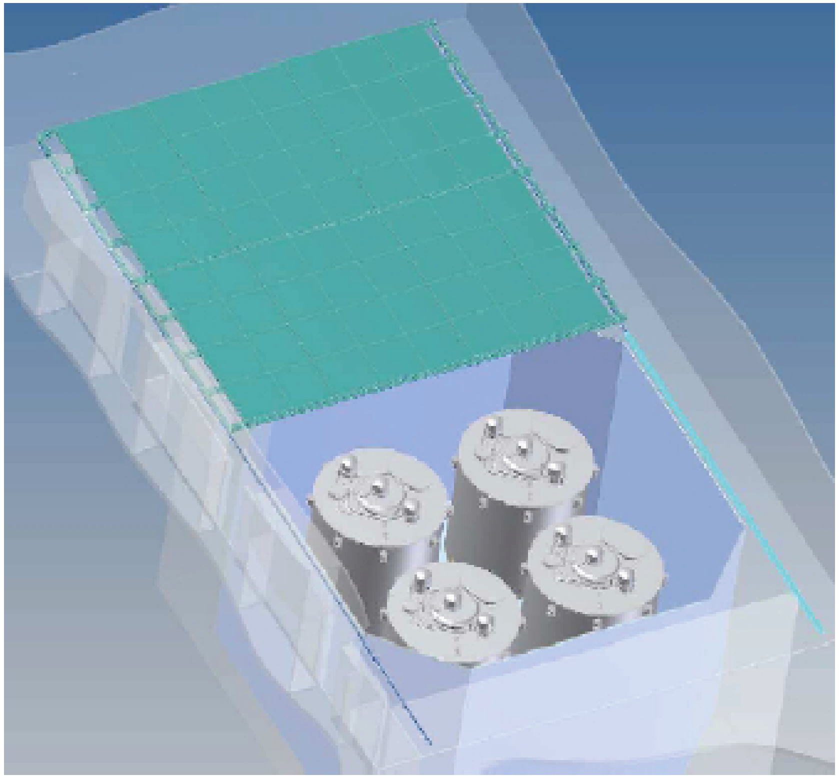




Antineutrino detector



Muon 反符合探测器



- Water Čerenkov
  - ADs submerged in water, provide $\geq$ 2.5m shielding against radioactivity
  - Inner/Outer regions optically separated
  - 8-inch PMTs on frames (289/near, 384/far site)
- RPC—Resistive Plate Chamber
  - 4 layers in modules
  - Layer of modules covers water pool
  - Provides independent veto system
- Combined efficiency of both systems $>$ 99.5%

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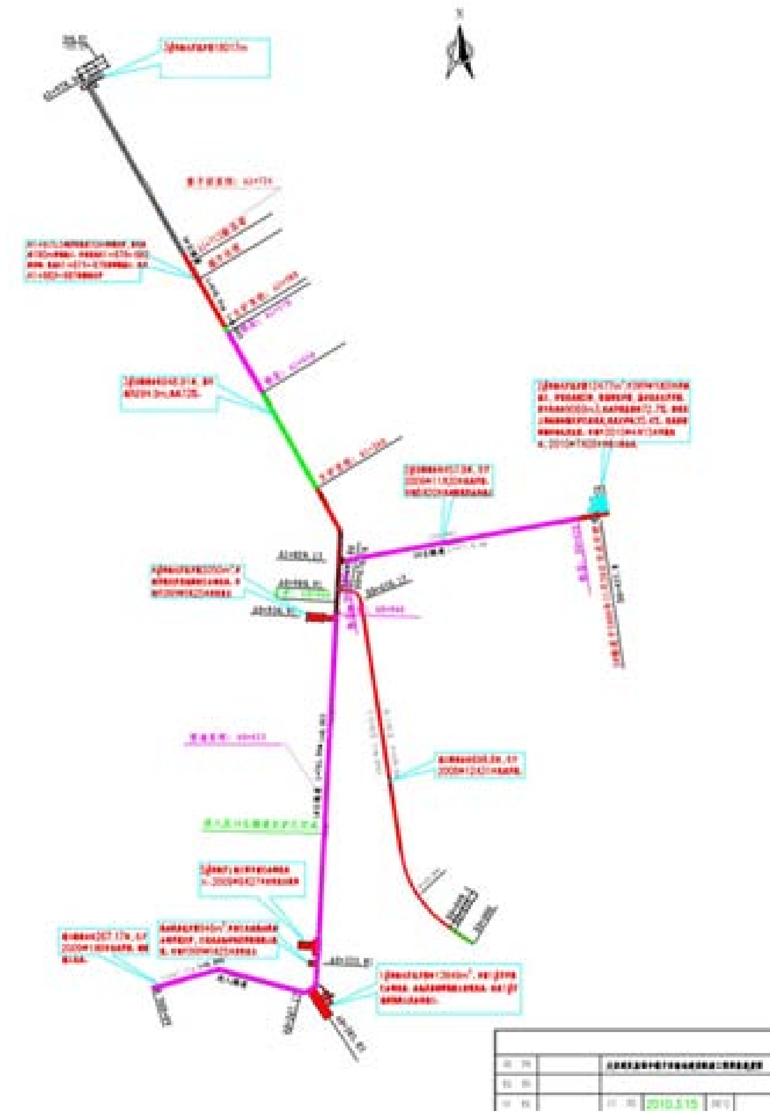
土建进展（1）

- 地面主要设施已经完成
  – 装配大厅
  – 控制楼
  – 空调、消防等附属
- 隧道：总长3.2km，大部完成
- 大厅
  – #1实验厅：13849立米，完成，待BO
  – #2实验厅：12477立米，基本完成
  – #3实验厅：18017立米，未到
  – #4水厅：2010立米
  – #5液闪厅：完成



土建进展（2）

图片 5#厅外隧道

土建（3）

图 2#厅下部开挖

图 3#隧道塌方段处理

图 1#厅大门防火墙

图 隧道塌方防护

土建进展（4）

图 1#实验大厅

图 1#厅疏散通道和辅助洞室

图 1#实验大厅桥机大梁安装

AD进展（1）

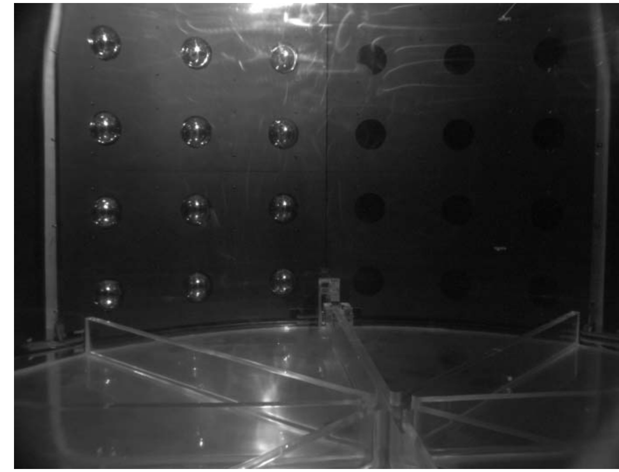
- 主要部件研制进展：
  - 钢罐（IHEP）：已完成5个，今年将全部完成8个
  - 反射板（IHEP）：全部完成
  - 支持平台（IHEP）：全部完成
  - PMT（LBL）：R5912全面到货、检查完成
  - IAV（台湾）：完成2个，第3、4进行中
  - OAV（UW）：完成2个，第3、4进行中
- 2009年3月开始现场组装，8月Prototype组装完
- 2009年9月开始AD#1和AD#2的正式组装

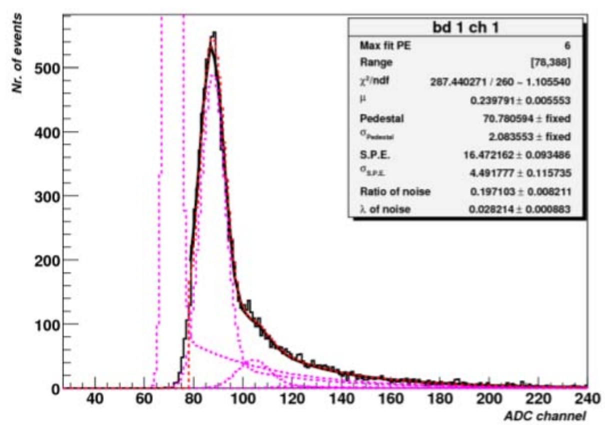
AD大型部件运输

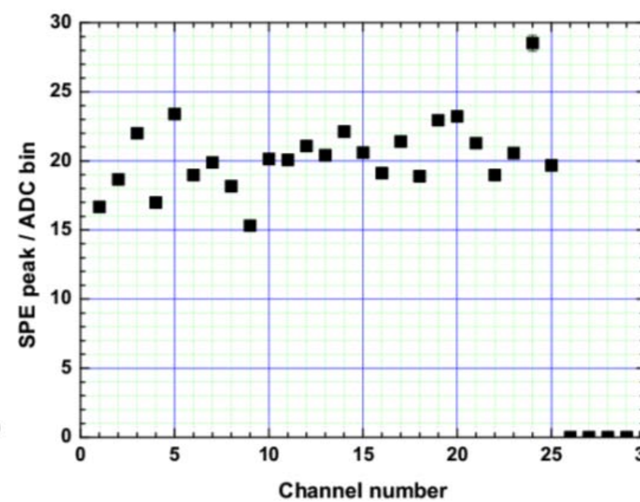
AD 进展（2）：正式组装

AD进展（3）：mini dryrun

- 测试AD系统
  - AD#1
  - 24 PMTs
  - 电子学
  - DAQ
  - 数据分析
- 完成了
  - 系统调试
  - 刻度研究
  - 噪声研究
  - 触发研究







AD进展（4）：液闪进展

- 8批测试生产在高能所完成
- 09年10月生产设备开始安装，目前并大部已经就位
- 主要材料LAB生产完成，并运输就位

RPC进展

- 1600个裸室大部完成生产

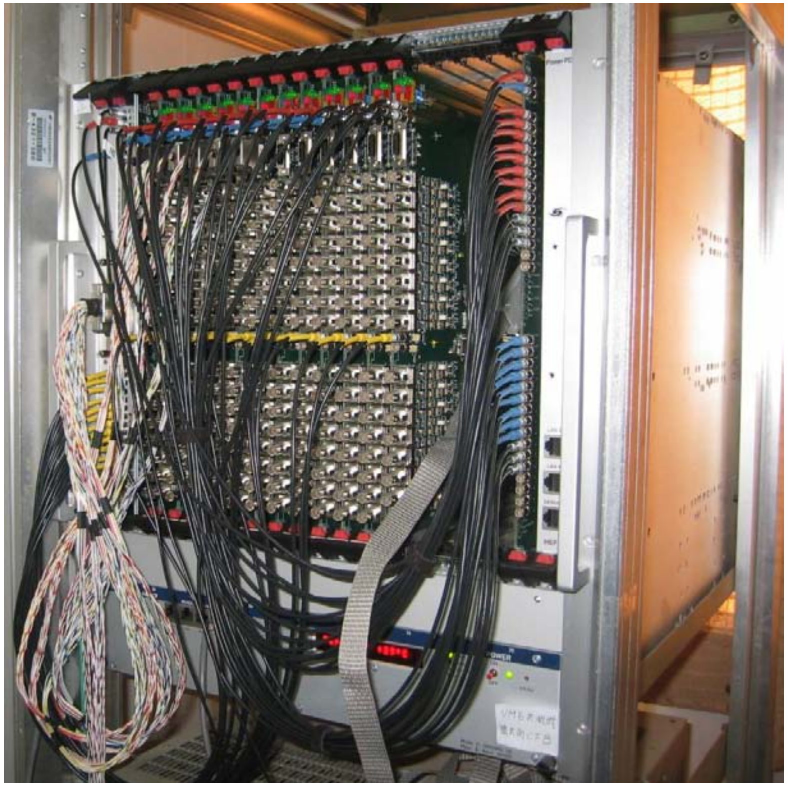
	Efficiency	SCR(Hz/cm²)	Current(uA/m²)
RPC bare ch.	95.46%	0.178	2.711

- 在高能所进行组装与测试

电子学进展

- 单机箱测试OK，可用于dryrun

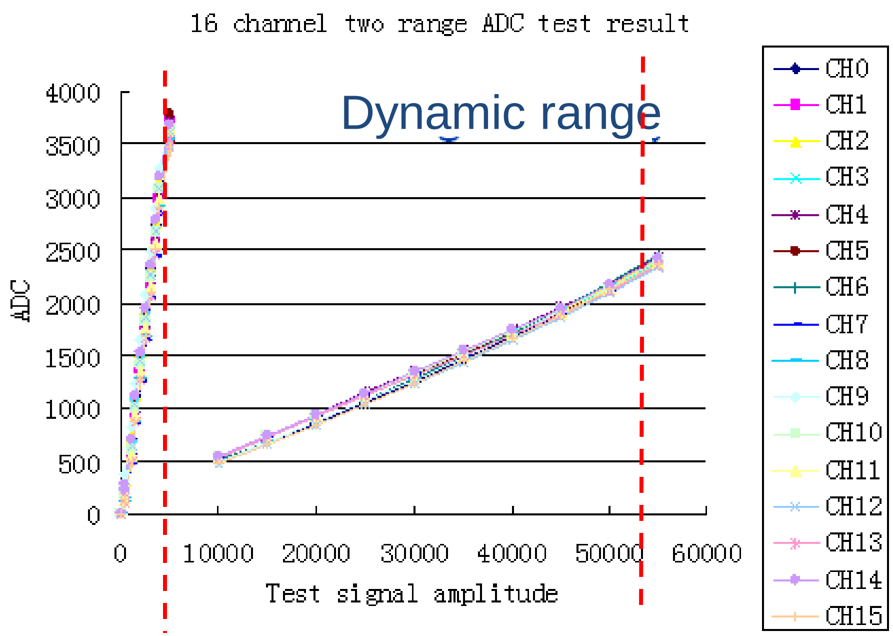
- Electronic subsystem for 1 AD was setup at IHEP in Oct.
- Consists of 12 FEEs + 1 LTB + 1FANOUT +1 PPC
- 8 hours * 7 days aging done
- Tests done
  - CBLT function test
  - FEE self-test
  - Different trigger mode were tested
    - ESUM、nPMT、periodical



FEE Specifications for PMT

Quantity		Specification
Charge dynamic range		0-1800 pC
	Fine Range	0-160 pC (100pe@PMTgain 2E7)
	Coarse range	160-1800 p.C
Shaping width		<325ns down to 1%
Peak error		< 4% @ 40MSPS
ADC bit resolution		< 10% @ 1.6 pC
ADC Bits		12 bits for fine range 12 bits for coarse range
ADC Sampling rate		40 MSPS
Disc. threshold		0.25 p.e. (programmable each chnl.)
Time range		0-500 ns
Time bin		1.5625ns
Timing Precision (RMS)		<1 ns
Multi-hit separation		Yes
Multi-hit resolution		25 ns

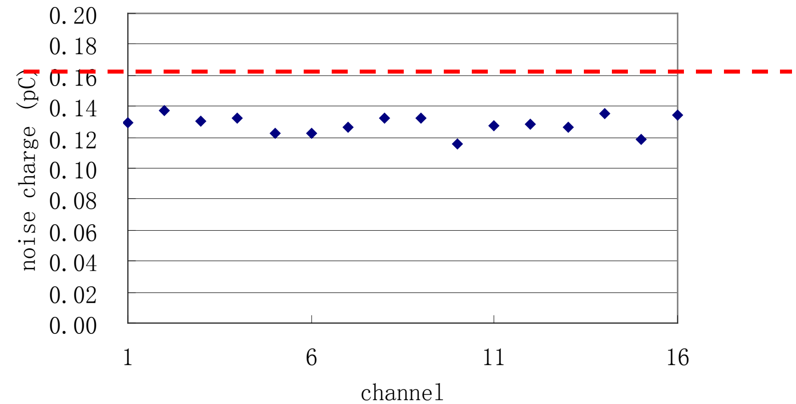
Charge and time measure test

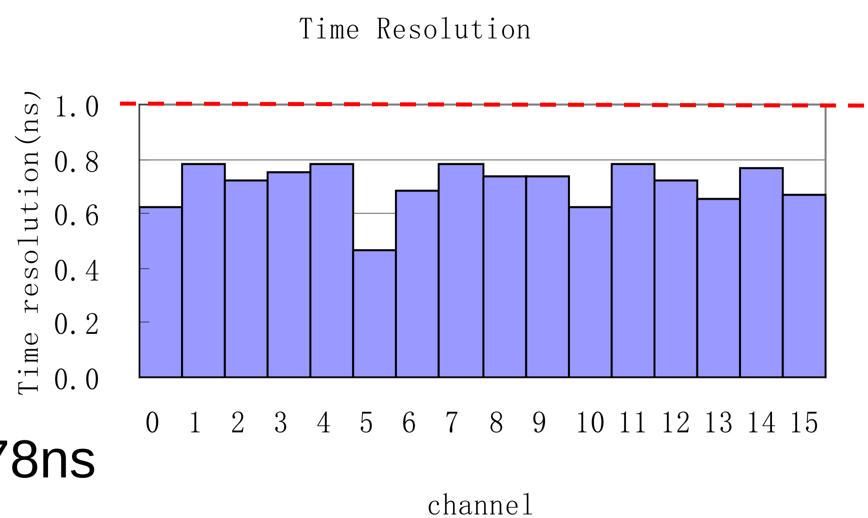


160pC
(100p.e.)

1800pC
(9000p.e.)

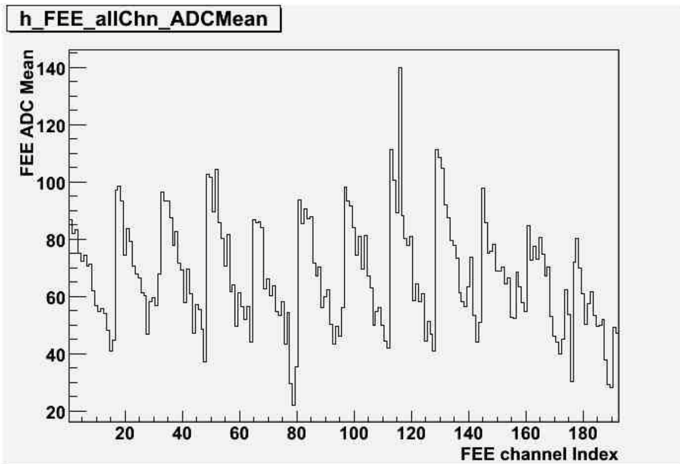
Noise charge

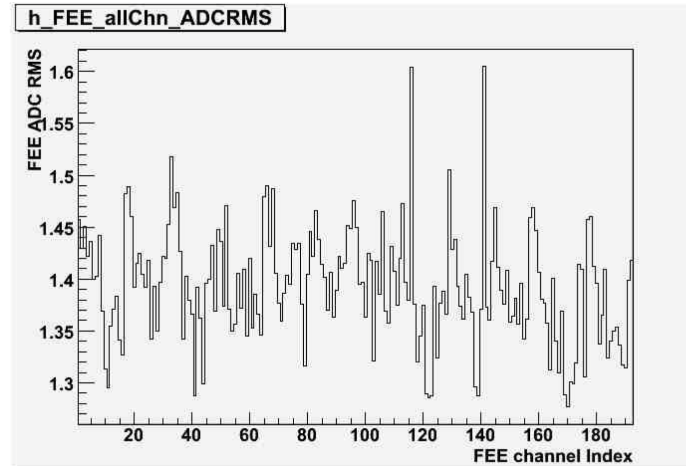




time resolution: 0.78ns

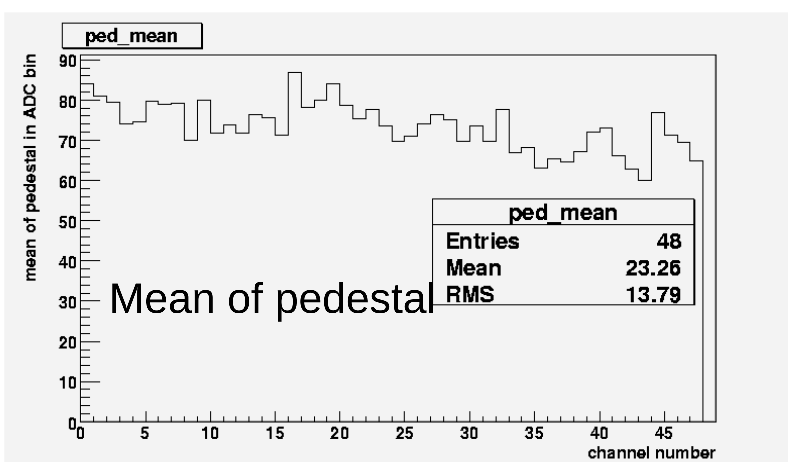
Charge measurement

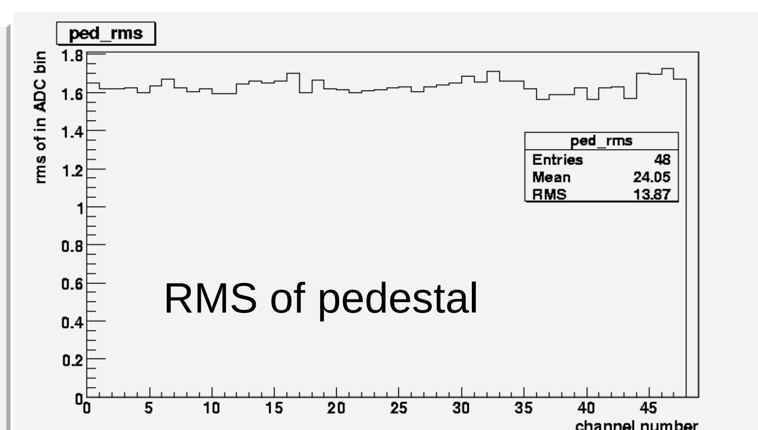




Fine range ADC RMS < 1.61 count

1.61 ADC count ~ 0.037 p.e. (1p.e.=44 ADC count)



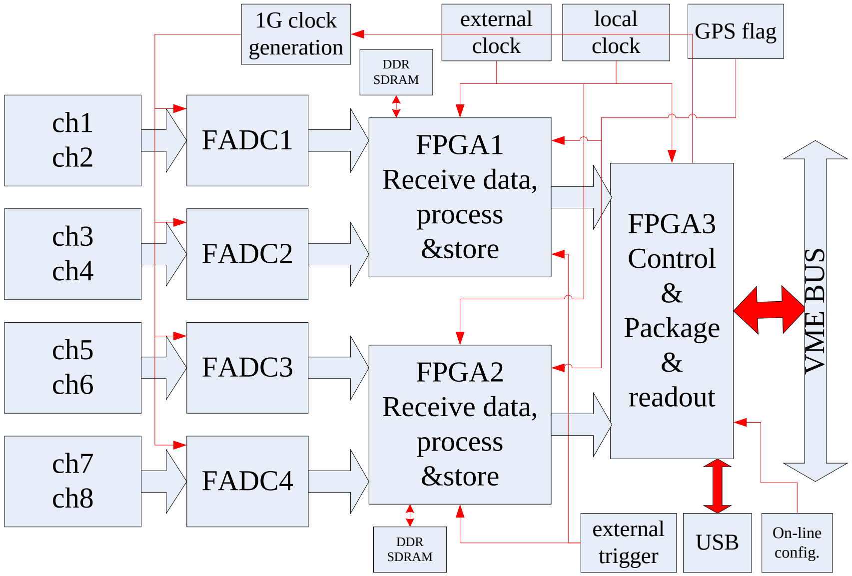


Onsite electronic system

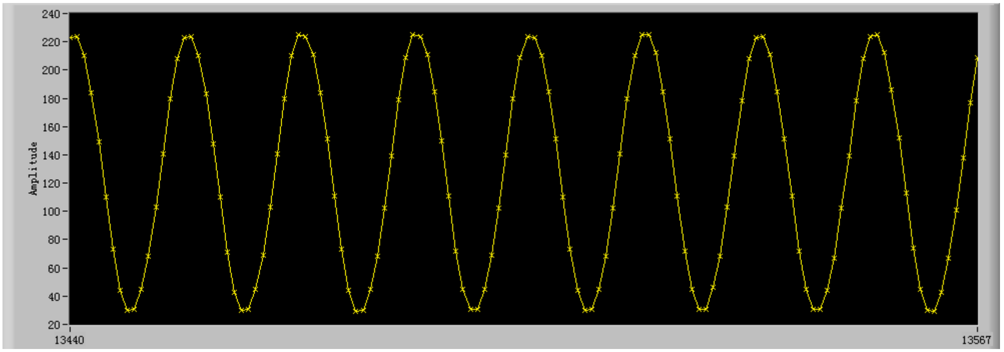
- As request by PMT group, one system is setup in SAB
- Crate Installation
  - VME crate 1 PPC+3FEEs+1LTB +1 FanOut
  - mainly for PMT testing
  - Decoupler Box(192 channels)
  - CAEN HV unit
  - Converter board (for external trigger)
- Power PC hardware and software configuration
- Online console to run daq software

FADC board

- Requirements
  - 8 channel, 1Gsps/ch
  - Local/external clock
  - **Self/external trigger**
  - Extended RAM
  - On-line configuration
  - VME/USB readout



- Performance
  - Noise (baseline fluctuate): 0.42LSB
  - ENOB: 7.07bits (Fin=31.25MHz, Fs=1GHz)
  - Nonlinearity (INL): 0.26%



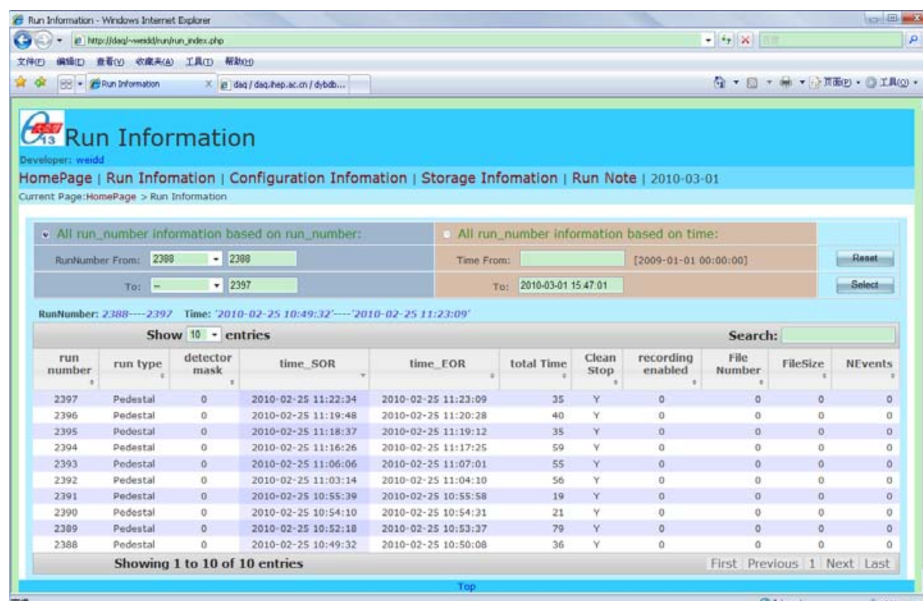
Reconstructed waveform (62.5MHz Sine)

RPC 电子学进展

- Testing system @ USTC
  - 14FECs+1ROT+1ROM+1RTM
  - Function Test
    - Trigger mapping
    - External trigger
    - Full/Error
  - 18 Hours continuous working test
  - Noise Immunity test
- Testing system setup at IHEP for RPC detector measurement
- FEC for DB near hall
  - 54 FEC and 10 for spare
  - Finished soldering
  - Aging is in process at USTC

Online 进展

- 现场计算机已经就位
- Switches & firewall 就位并调试完成
- 所有服务器操作系统OS(SLC4.7)安装完成
- 电源系统完成
- SAB、控制楼、地下光纤网络完成
- Mini Dryrun 表明，DAQ已经可以工作

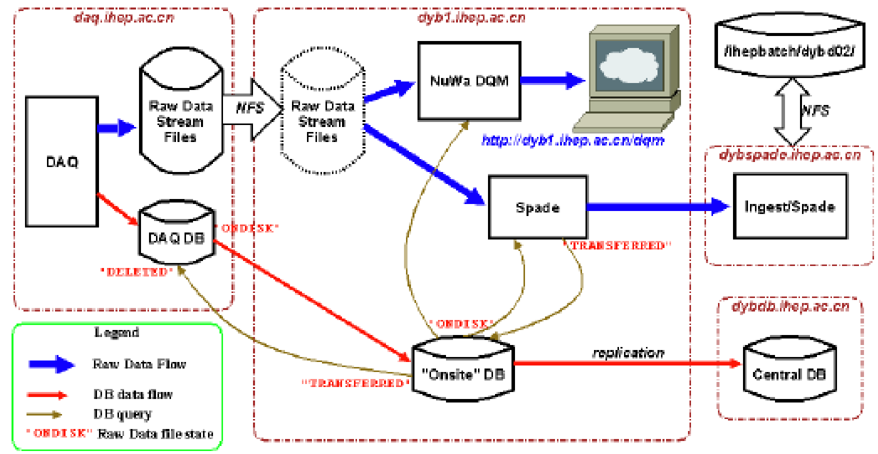


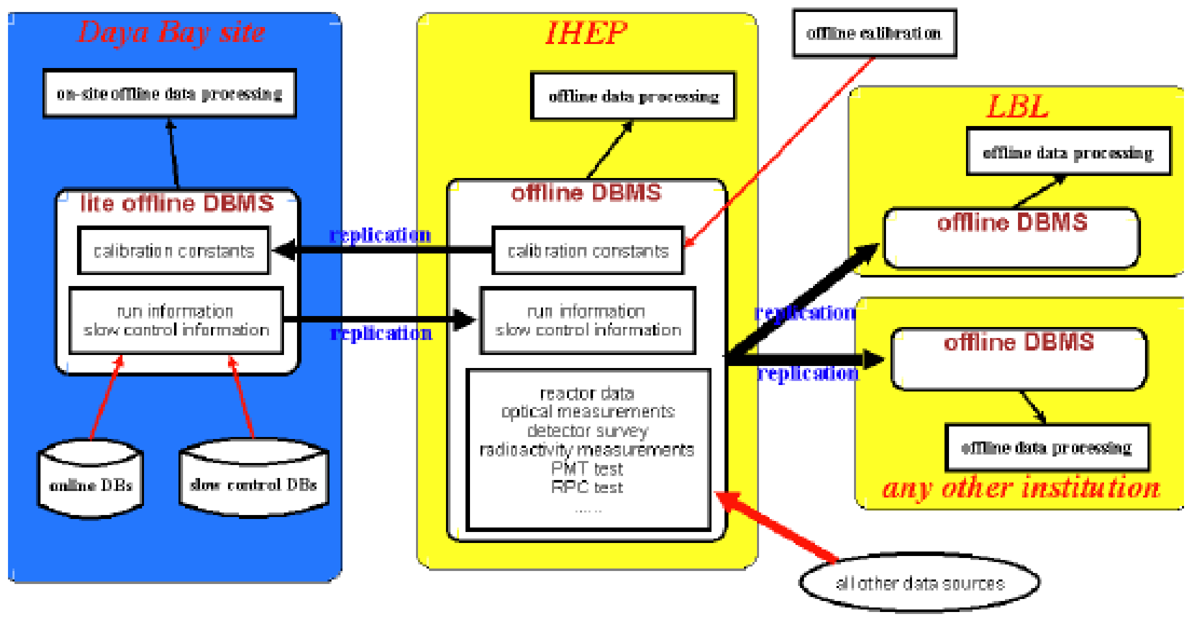
run number	run type	detector mask	time_SOR	time_EOR	total Time	Clean Stop	recording enabled	File Number	FileSize	NEvents
2397	Pedestal	0	2010-02-25 11:22:34	2010-02-25 11:23:09	35	Y	0	0	0	0
2396	Pedestal	0	2010-02-25 11:19:48	2010-02-25 11:20:28	40	Y	0	0	0	0
2395	Pedestal	0	2010-02-25 11:18:37	2010-02-25 11:19:12	35	Y	0	0	0	0
2394	Pedestal	0	2010-02-25 11:16:26	2010-02-25 11:17:25	59	Y	0	0	0	0
2393	Pedestal	0	2010-02-25 11:06:06	2010-02-25 11:07:01	55	Y	0	0	0	0
2392	Pedestal	0	2010-02-25 11:03:14	2010-02-25 11:04:10	56	Y	0	0	0	0
2391	Pedestal	0	2010-02-25 10:55:39	2010-02-25 10:55:58	19	Y	0	0	0	0
2390	Pedestal	0	2010-02-25 10:54:10	2010-02-25 10:54:31	21	Y	0	0	0	0
2389	Pedestal	0	2010-02-25 10:52:18	2010-02-25 10:53:37	79	Y	0	0	0	0
2388	Pedestal	0	2010-02-25 10:49:32	2010-02-25 10:50:08	36	Y	0	0	0	0

Offline进展

- 结构：现场、高能所和LBL三地实现数据传输与备份
- 框架与分析软件基本完成
- 2009年8月完成在线、离线集成测试

Online/Offline Integration Test @IHEP





总结

- 大亚湾实验物理意义显著
- 09年3月起探测器现场安装工作已经真正开始了，完成了：
  - AD prototype的安装，AD#1 和AD#2安装过半
  - 液闪主要原料LAB就位，主要生产设备基本就位
  - 电子学、DAQ小系统已经可以工作
  - RPC裸室大部生产完成，组装进行中
- 这一年来，在困难中前行：
  - 二标的质量、进度、接口等困难
  - 合作组内部众多合作机构间的接口的检查
  - 异地建设的困难，人员、配套等
- 本年的计划
  - 土建：本年全部完成，所有实验厅ready
  - #1实验厅：本年完成探测器安装，明年初开始取数
    - 中心探测器AD：完成AD#1和AD#2的现场组装，完成液闪生产，AD#1和AD#2罐好液闪、在一号厅就位
    - 反符合探测器：水切伦克夫探测器和RPC安装完成

谢谢大家！

下面是备用！

How to measure $\sin^2 2\theta_{13}$ to 0.01 of sensitivity—

- Near and far detectors, check the reactor power
- Good and stable Gd-LS
- Background: Go deeper, good muon system
- Lower threshold
- Identical detectors: can be swapped to subtract the non-correlated error, like protons' number and efficiencies.

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%

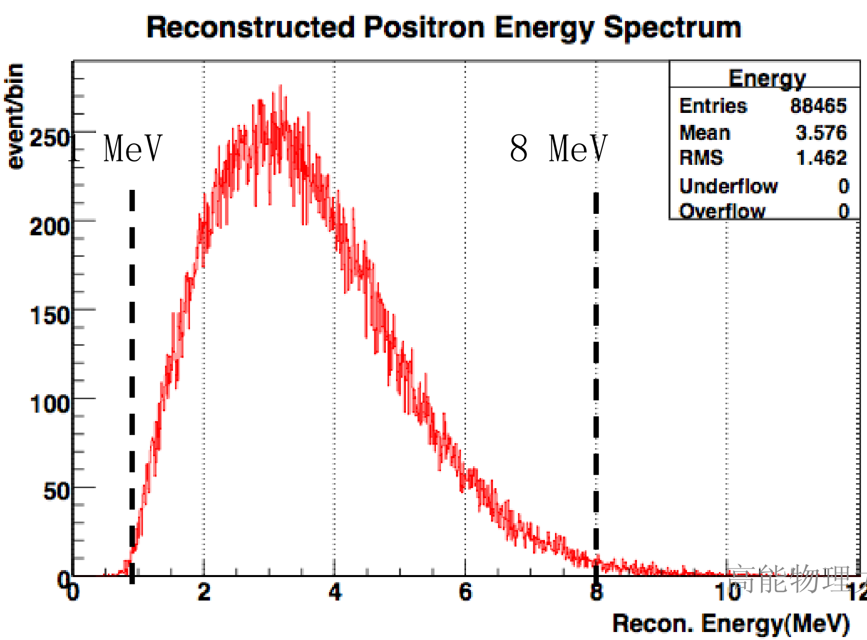
Antineutrino Detection principle

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

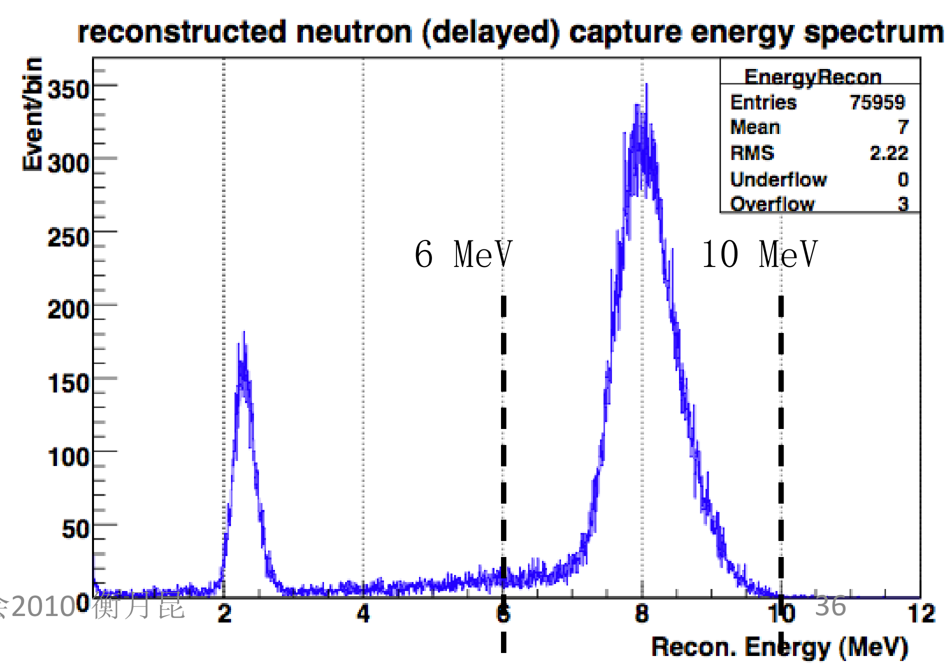
0.3 b → + p → D + γ (2.2 MeV) (delayed)

49,000 b → + Gd → Gd* → Gd + γ's (8 MeV) (delayed)

Prompt Energy Signal

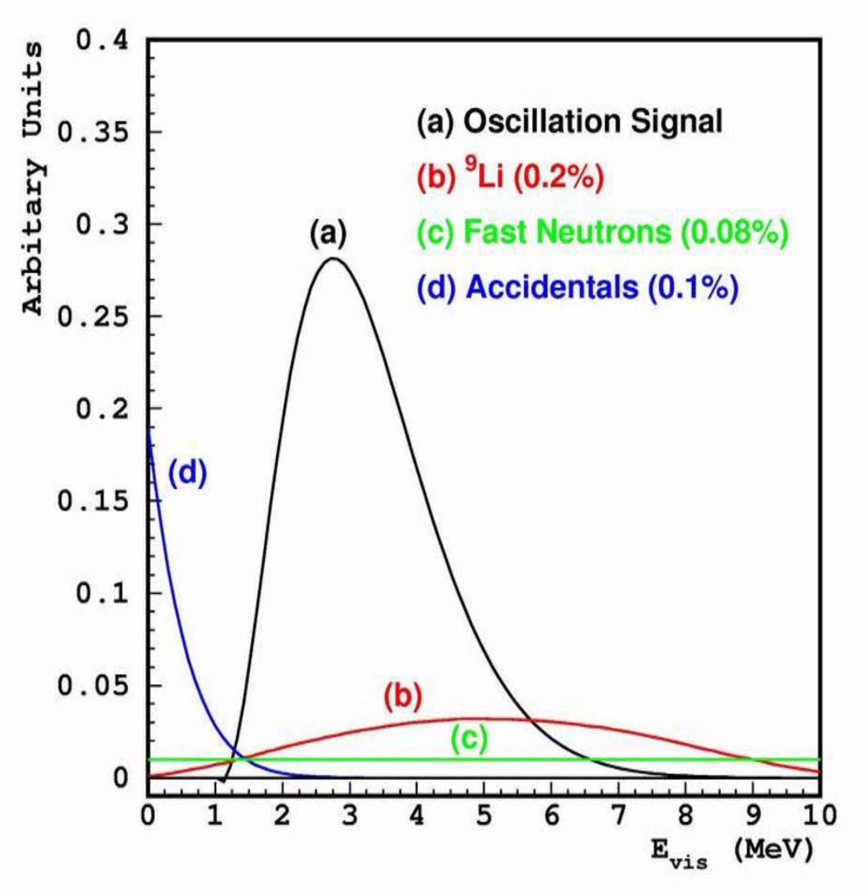


Delayed Energy Signal



Signal and background

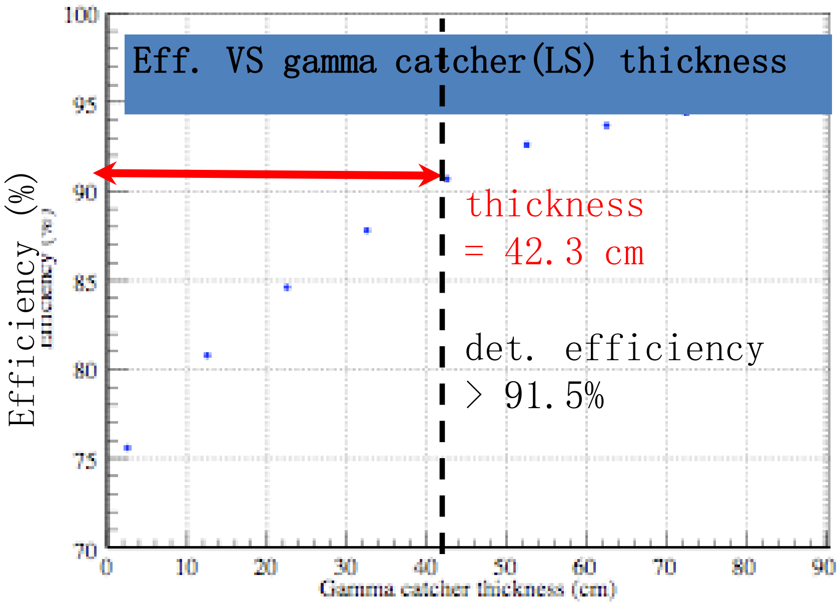
- ID
  - No position reconstruction
  - Time windows for two prompt and delayed signals:
  - Energy cuts
- BG
  - **^{8}He and ^{9}Li:** generated by cosmic ray, decays to β and n
  - **Fast Neutrons:** generated by cosmic ray, proton hit out give prompt signal, and slow neutron give delayed signal
  - **Occidentals:** natural radiation give prompt signal, cosmogenic neutron or β ray give delayed signal

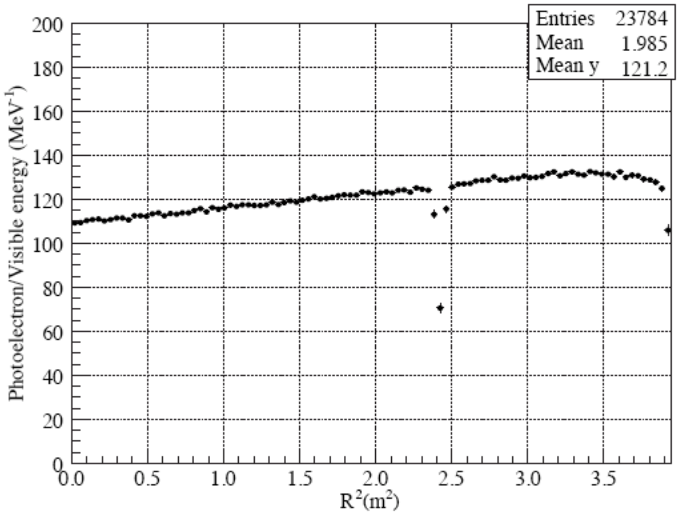


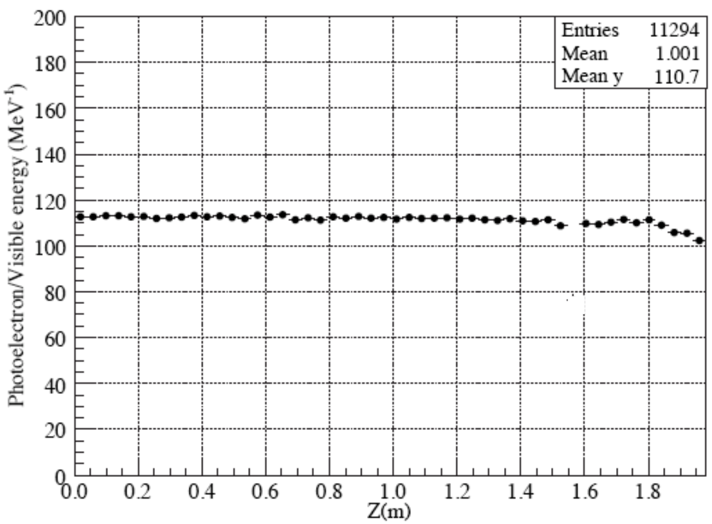
Simulation on AD

Uniformity of PE in R and Z direction

- GEANT4-based simulations
- Idealized 3-zone detector plus reflectors
- Developing realistic geometry in simulations



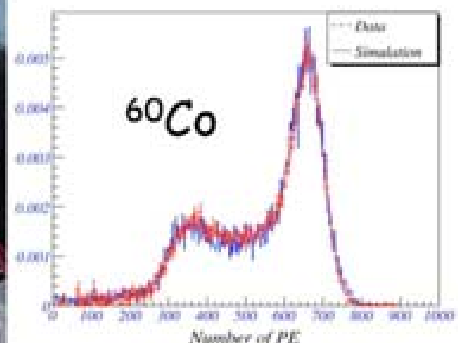


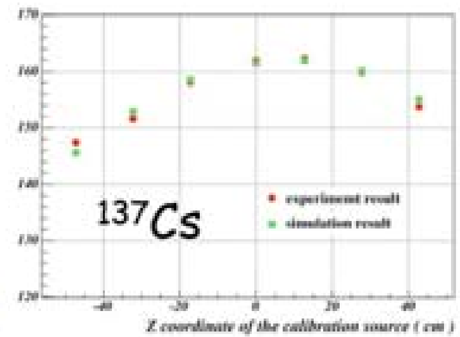


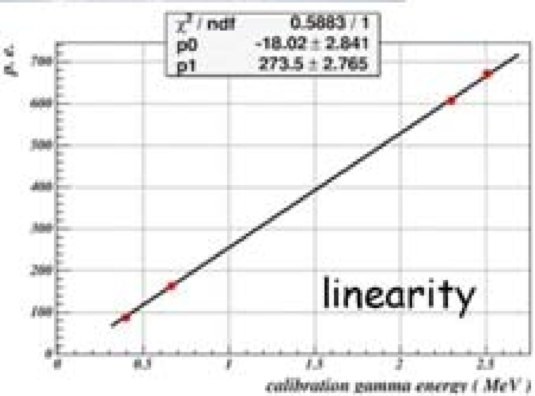
Prototype test (1)

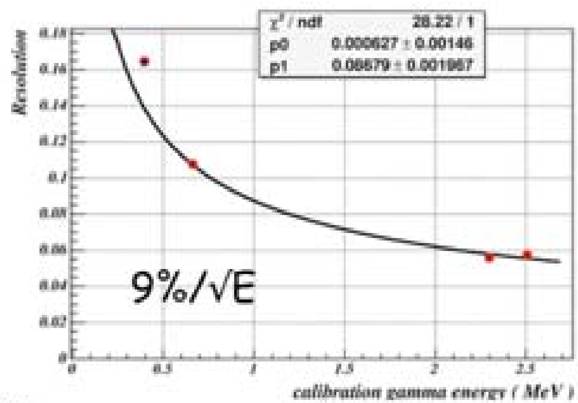
- 0.5 ton unloaded LS
- 45 8" PMTs with reflecting top and bottom

Phase-I, started in 2006, ended in Jan. 2007





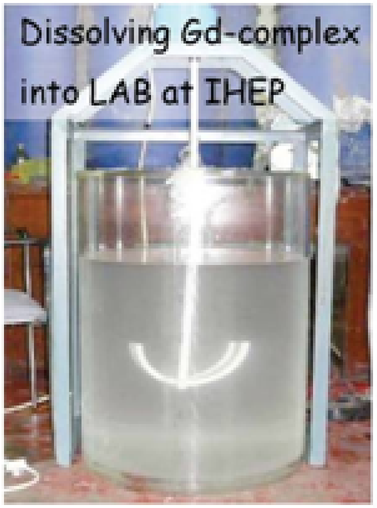




Kam-Biu Luk

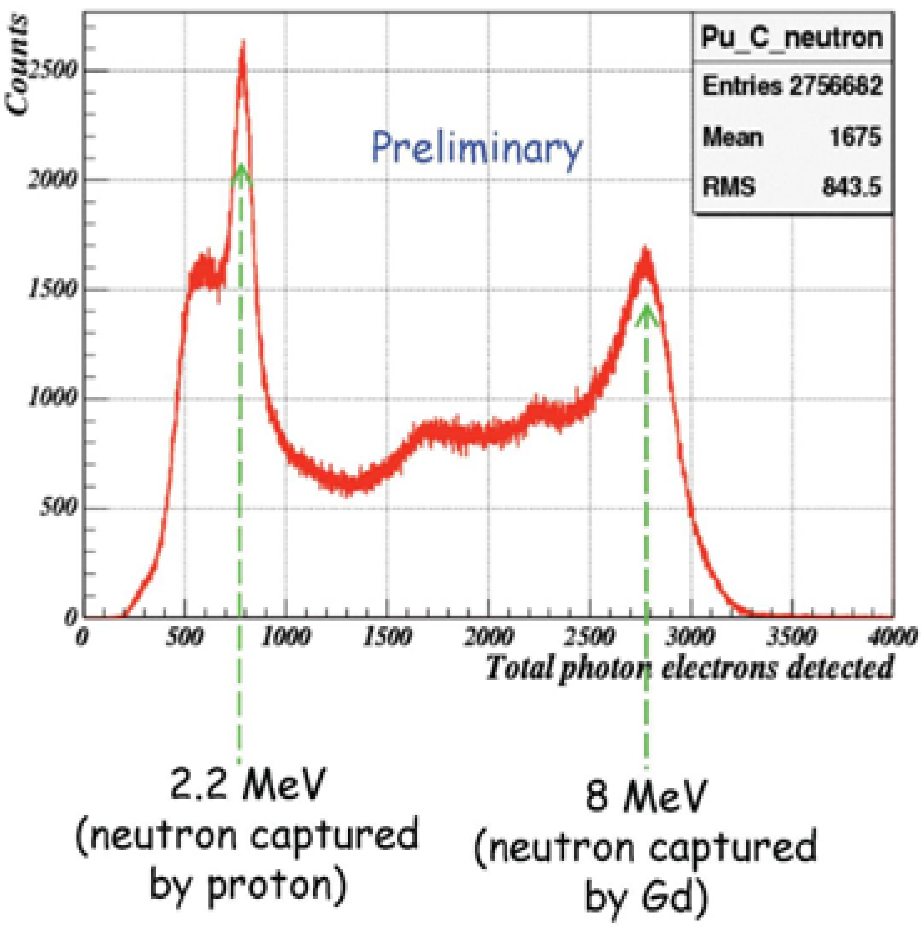
Daya Bay

Prototype test (2)

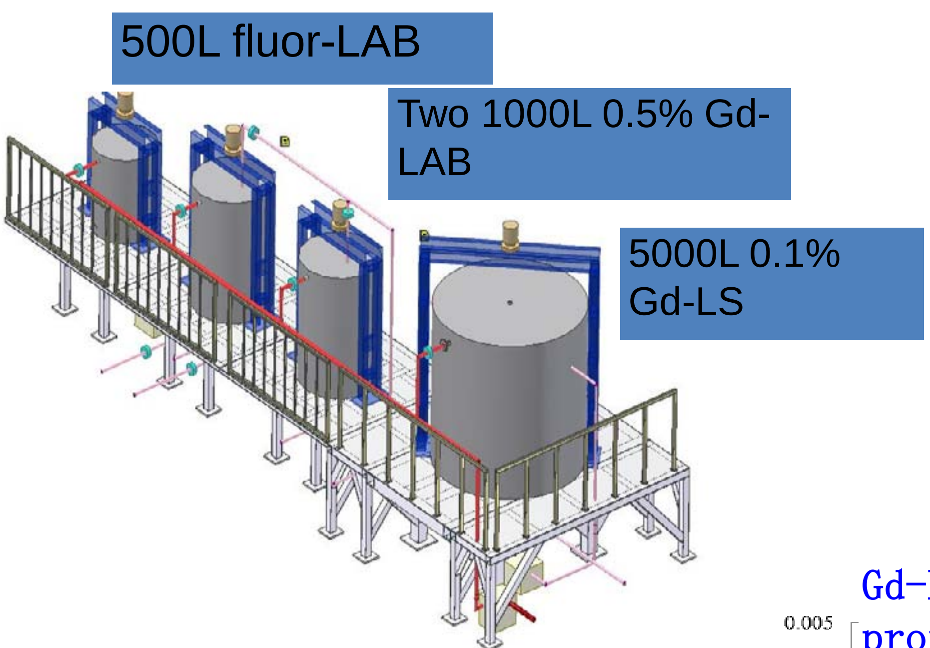


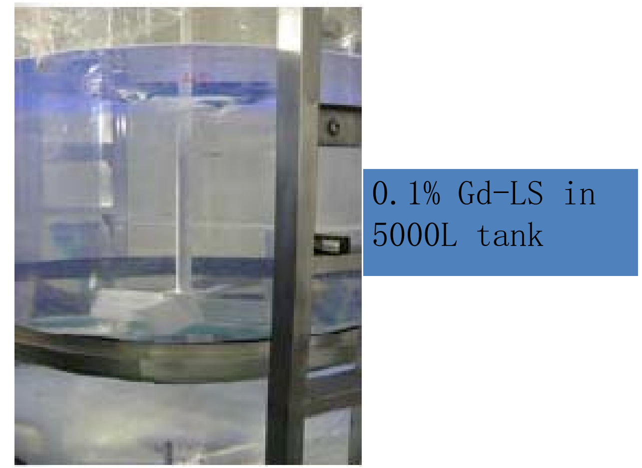
Phase-II, filled with half-ton 0.1% Gd-LS, started in Jan. 2007 and keep running until now.

The prototype is also used for the FEE and Trigger boards testing.

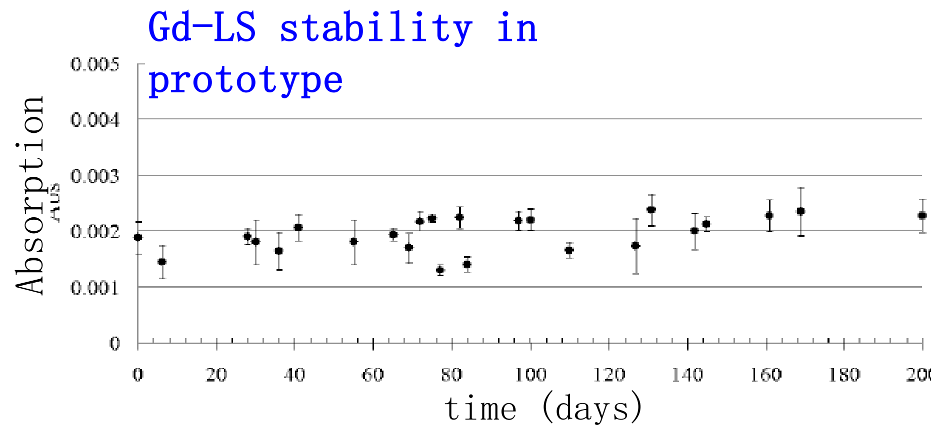


Gd-Liquid Scintillator Test Production



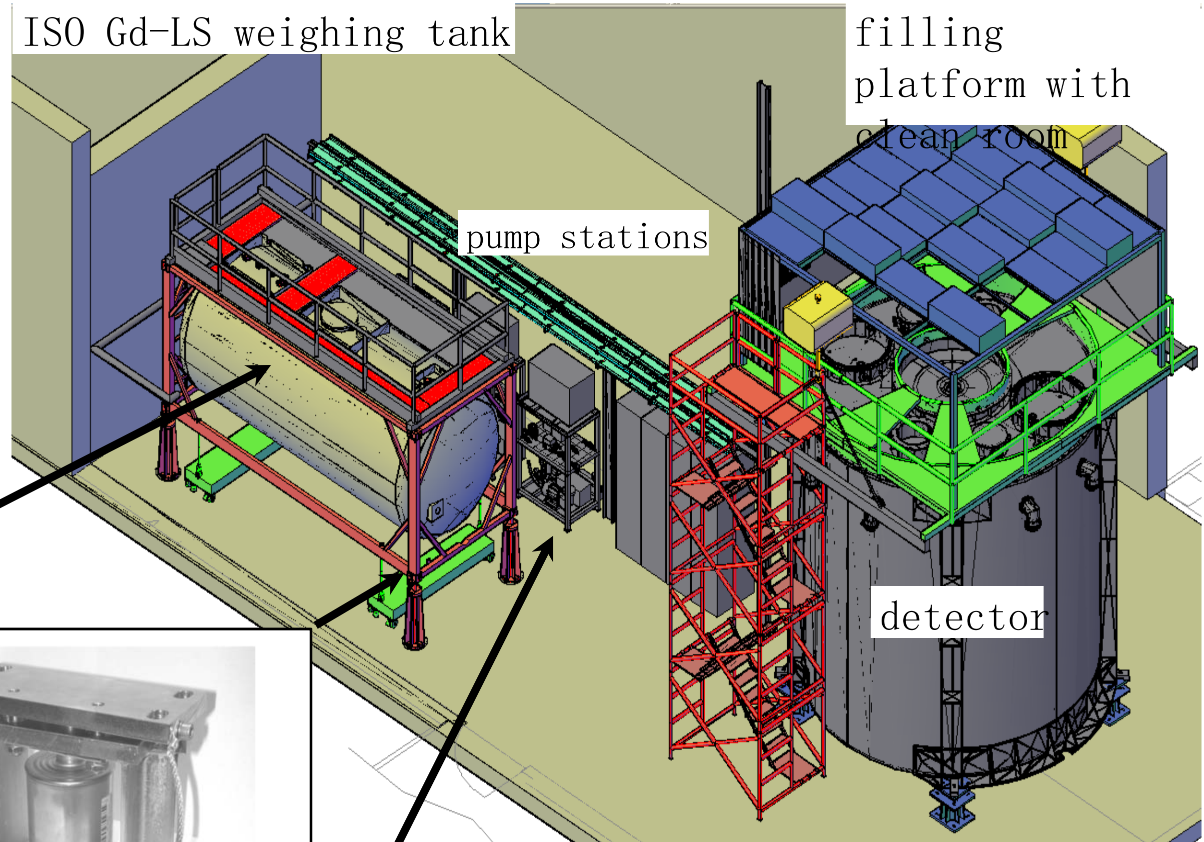


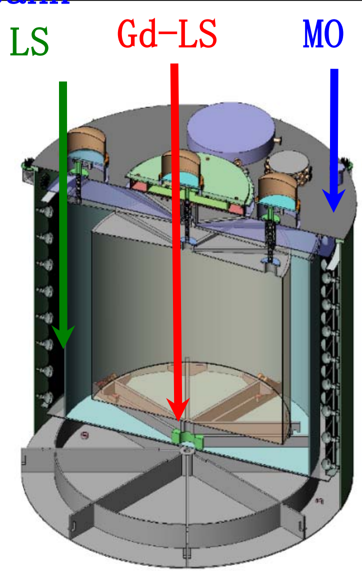
Gd-LS will be produced in multiple batches but mixed in reservoir on-site, to ensure identical detectors.



Target Mass Measurement

20-ton, teflon-lined ISO tank

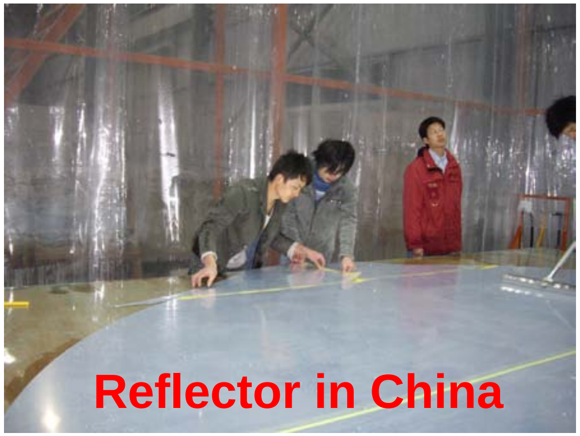




load cell
accuracy < 0.02%

Coriolis mass flow meters
< 0.1%

AD components

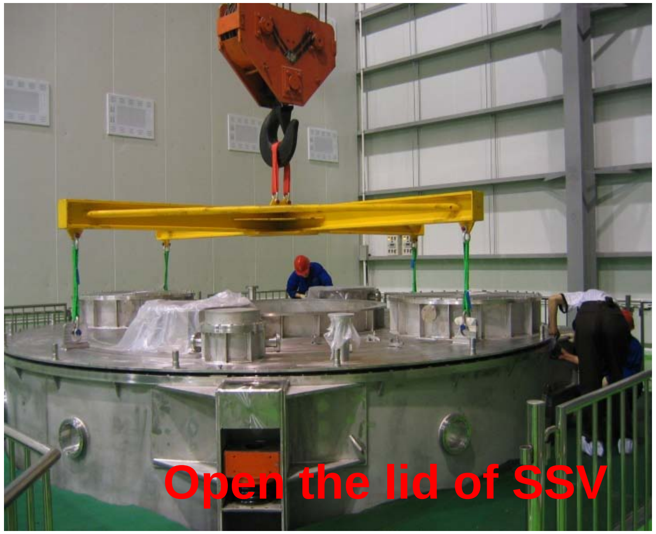

Reflector in China

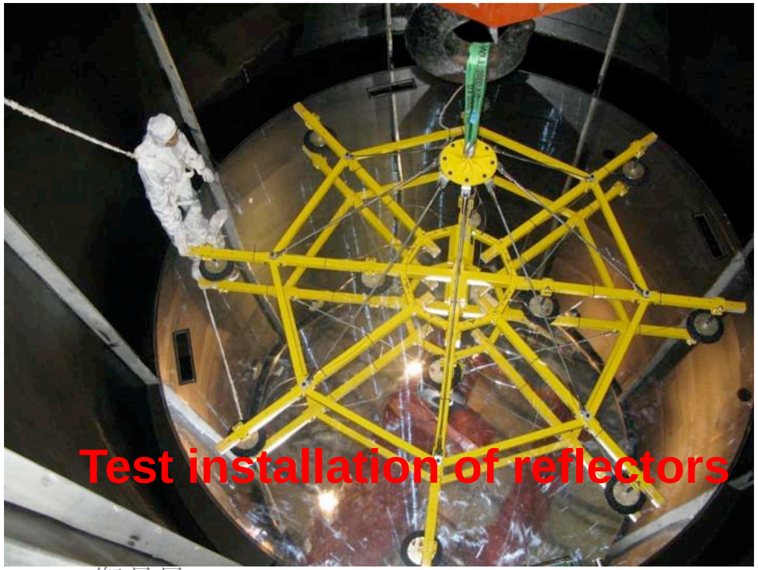

1st SSV arriving at Dayabay


3m AV in Taiwan


4m AV in US

Test Assembly





Civil constru

Summary

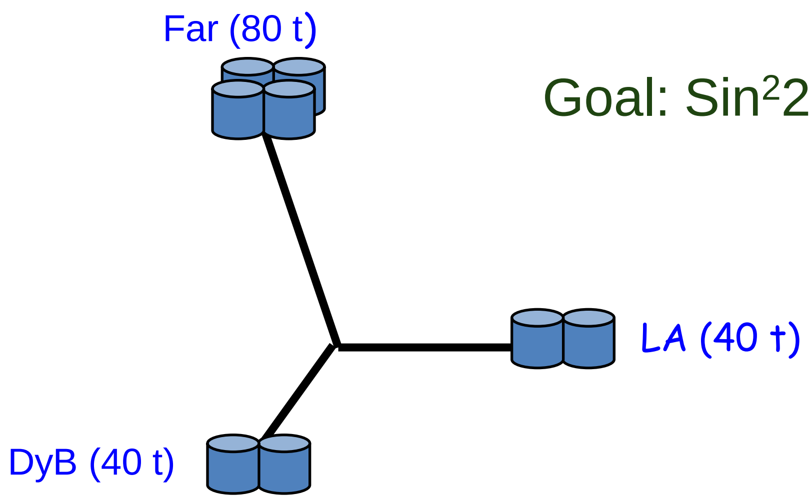
- Daya Bay experiment is designed to measure $\sin^2 2\theta_{13}$ to a sensitivity of <0.01 at 90% CL in 3 years of data taking. It is the most sensitive reactor θ_{13} experiment under construction.
- Special characters:
  - High powerful reactor and Relative big target mass, give low statistical error
  - Mountains around are useful to reduce the BG
  - 3-zone nested detector design of AD allows observation of antineutrino signal without position and fiducial cuts.
  - AD Relative detector systematic error < 0.38%.
- Civil and detector construction are progressing. Data taking at near site will begin in 2010.

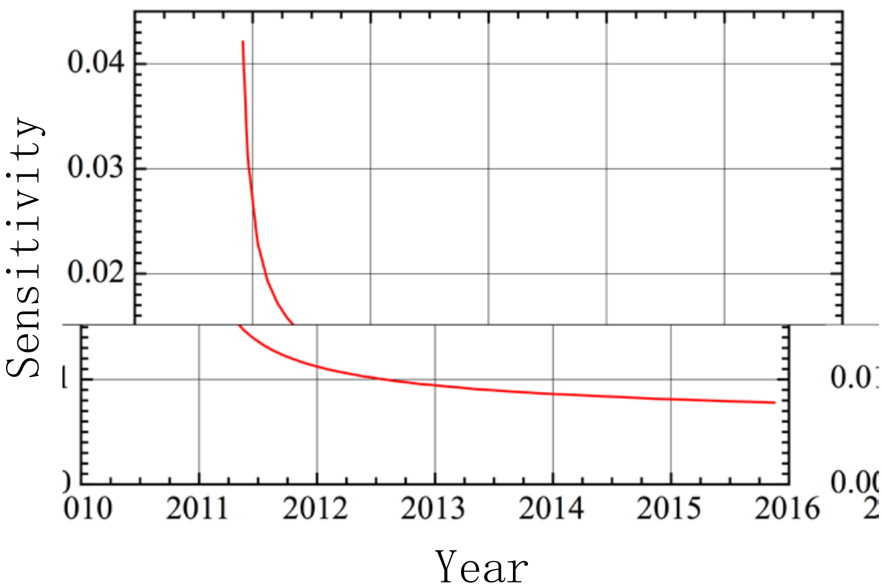
Thank you for your attention !

Sensitivity of Daya Bay

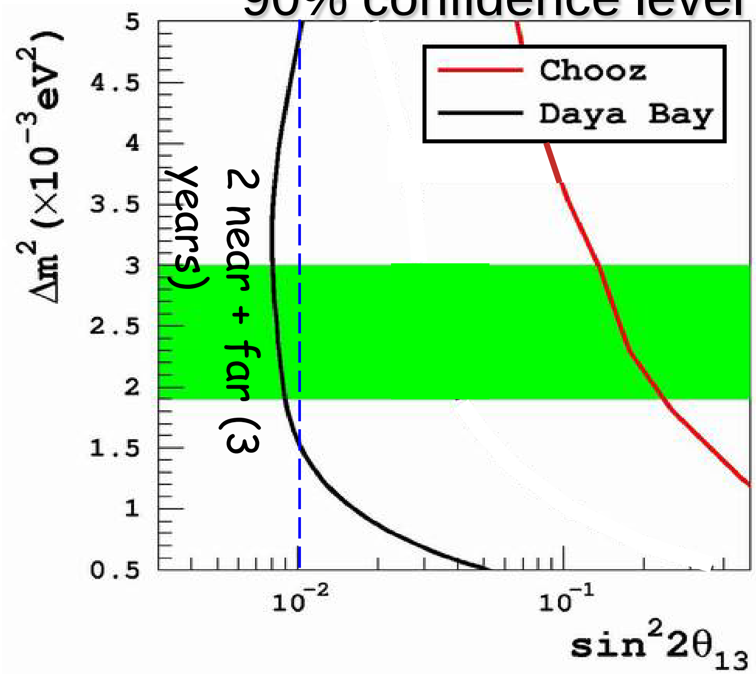
Goal: $\sin^2 2\theta_{13} < 0.01$

- Use rate and spectral shape
- input relative detector syst. error of 0.38%/detector

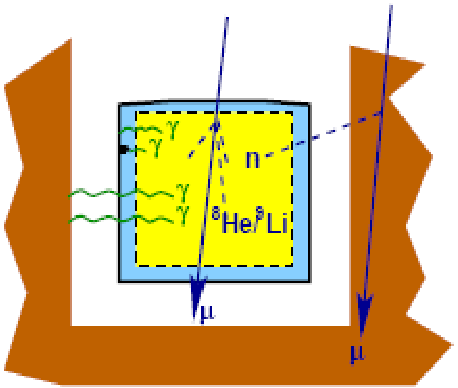




90% confidence level



Background sources in the AD



Using a modified Gaisser parameterization and the DYB mountain profile the cosmic ray rates are:

	DYB	LA	Far
Overburden (m)	98	112	355
Muon intensity (Hz/m^2)	1.16	0.73	0.041
Mean Energy (GeV)	55	60	138

Source	Type	Rate/20T module (DYB/LA/FAR)
Rock	U/Th/K $\gamma > 1$ MeV	$\mathcal{O}$(MHz) w/o shielding!
SS vessel and welds	U/Th/K/Co	$\sim$ 20 Hz
PMT glass R5912	U/Th/k	$\sim$ 12 Hz
Cosmic muons	^{12}B/^{12}N β only	396/267/28
Cosmic muons	^{8}He/^{9}Li β-n	3.7/2.5/0.26
Cosmic muons	fast neutrons (2 subevents)	depends on shielding
Cosmic muons	neutrons (1 subevent)	depends on shielding

GOAL: Use a thick water shield to reduce neutron and rock γ bkgds

The He^8/Li^9 background

He^8/Li^9 generated by showers from cosmic muons in the AD LS:

$$^9Li \rightarrow \underbrace{e^-}_{\text{prompt}} + \bar{\nu}_e + {}^9Be^* \rightarrow {}^8Be + \underbrace{n}_{\text{delayed n-capture}}$$

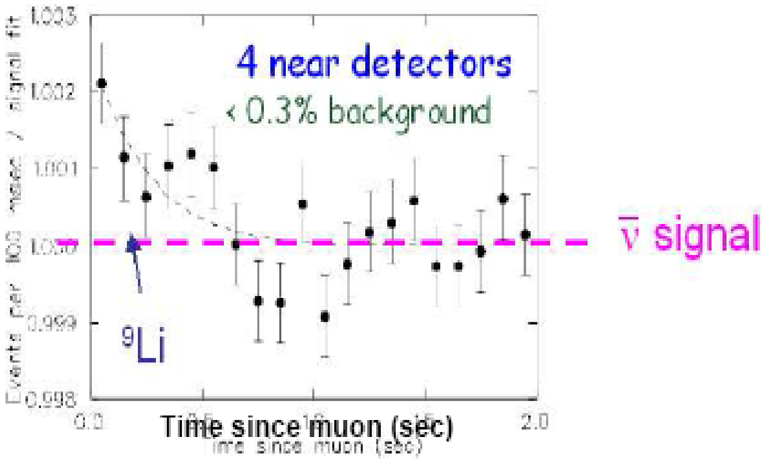
Q= 13 MeV, $\tau = 178$ msec $\Rightarrow$ poor spatial correlation with μ track.

Computed rates (Hagner et. al.) events/module/day:

	DYB	LA	Far
$\bar{\nu}_e$ IBD	840	740	90
$^9\mathrm{Li} + {}^8\mathrm{He}$	3.7	2.5	0.26

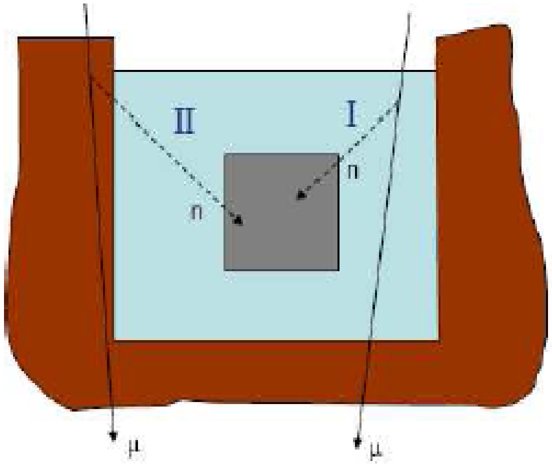
But it can be measured ! $\longrightarrow$

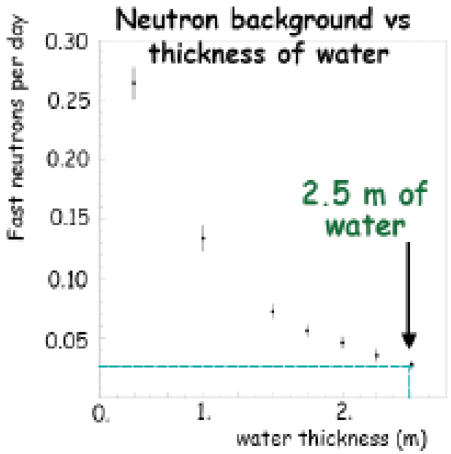
$B/S \approx 0.3\%$



Fast Neutron Background

$$n_{\text{fast}} + p/n \rightarrow \underbrace{p/n}_{prompt} + \underbrace{n^*}_{delayed}$$





Fast neutron simulation results assuming active water shield with 99.5% muon tagging eff (events/day/20T module) :

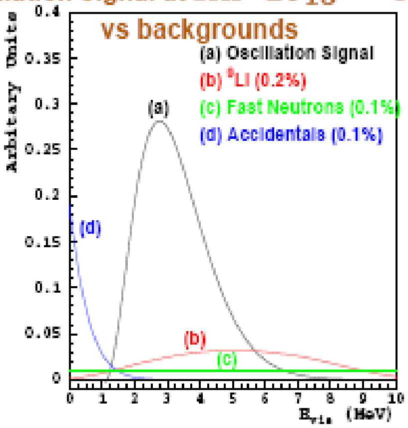
	I: From untagged μ	II:Rock neutrons	II:Total/Signal
DYB	0.10	0.5	6×10^{-4}
LA	0.07	0.35	6×10^{-4}
Far	0.01	0.03	4×10^{-4}

Accidental background rates

Prompt: $\gamma > 1$MeV from radioactivity $\sim$ 40Hz/AD module with shielding

Delayed:: 1) untagged single neutron capture 2) cosmogenic beta emmiters (6-10MeV, mostly ^{12}B/^{12}N) 3)U/Th $\longrightarrow$ O, Si ($\alpha, n, \gamma[6-10\ \mathrm{MeV}]$)

Oscillation signal at $\sin^2 2\theta_{13} = 0.01$



	DYB	LA	Far
Signal rates	840/day	740/day	90/day
1) neutrons (singles)	18/day	12/day	1.5/day
2) βs (singles)	210/day	141/day	14.6/day
3) $\alpha, n\gamma$ (singles)	$<$10/day	$<$10/day	$<$10/day
Coinc rate	2.3/day	1.3/day	0.26/day
B/S	$\sim 3 \times 10^{-3}$	$\sim 2 \times 10^{-3}$	$\sim 3 \times 10^{-3}$

Untagged background rates are tiny and subtractable