大亚湾中微子探测器

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On behalf of Daya Bay Collaboration
2010-08-14

提纲

- 大亚湾中微子实验
- 中微子探测研制与进展
  - 原理与结构
  - 安装
  - 液闪
  - PMT
  - 电子学
  - 刻度
  - dryrun
- 总结

目标

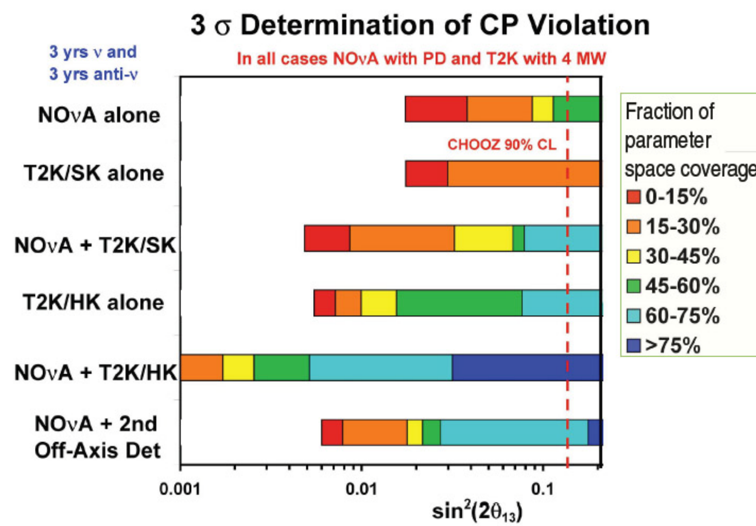
- 一句话：测量$\sin^2 2\theta_{13}$达到0.01的敏感度
- 为什么测量 $\sin^2 2\theta_{13}$？
  - 中微子的6个参数，3个半已知，2个半未知

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.	Reactor Accelerator	Solar KamLAND
$\theta_{23} \sim 45^\circ$	$\theta_{13} < 12^\circ$	$\theta_{12} \sim 30^\circ$

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

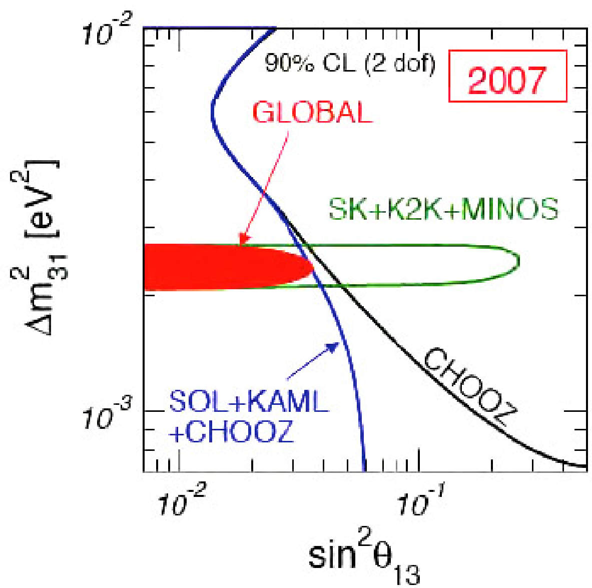
"We recommend, as a high priority, …, An expeditiously deployed multi-detector reactor experiment with sensitivity to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13}$=0.01"
---- APS Neutrino Study, 2004

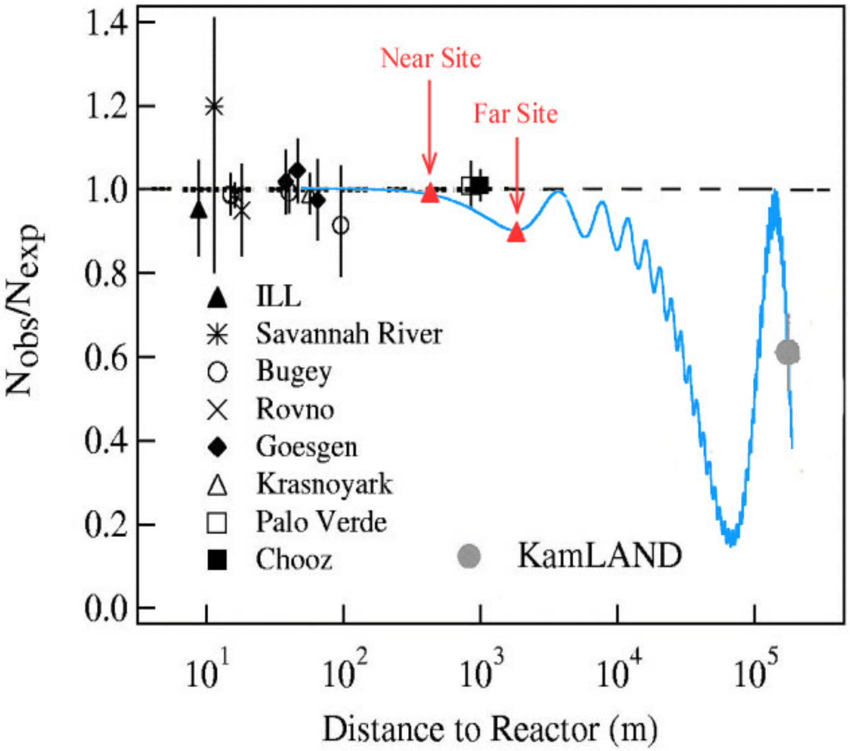
为什么用反应堆中子测量 θ_{13}？

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

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

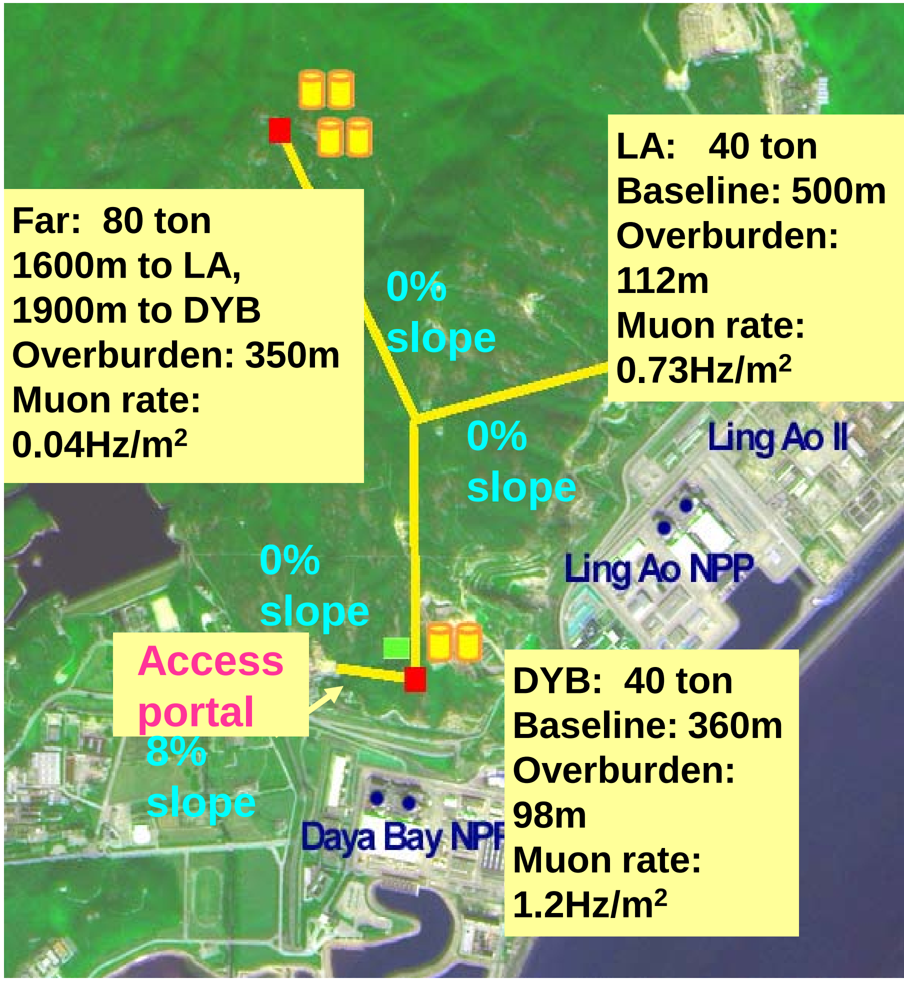
- 加速器中微子：中微子产生，还与CP相角、质量次序相关





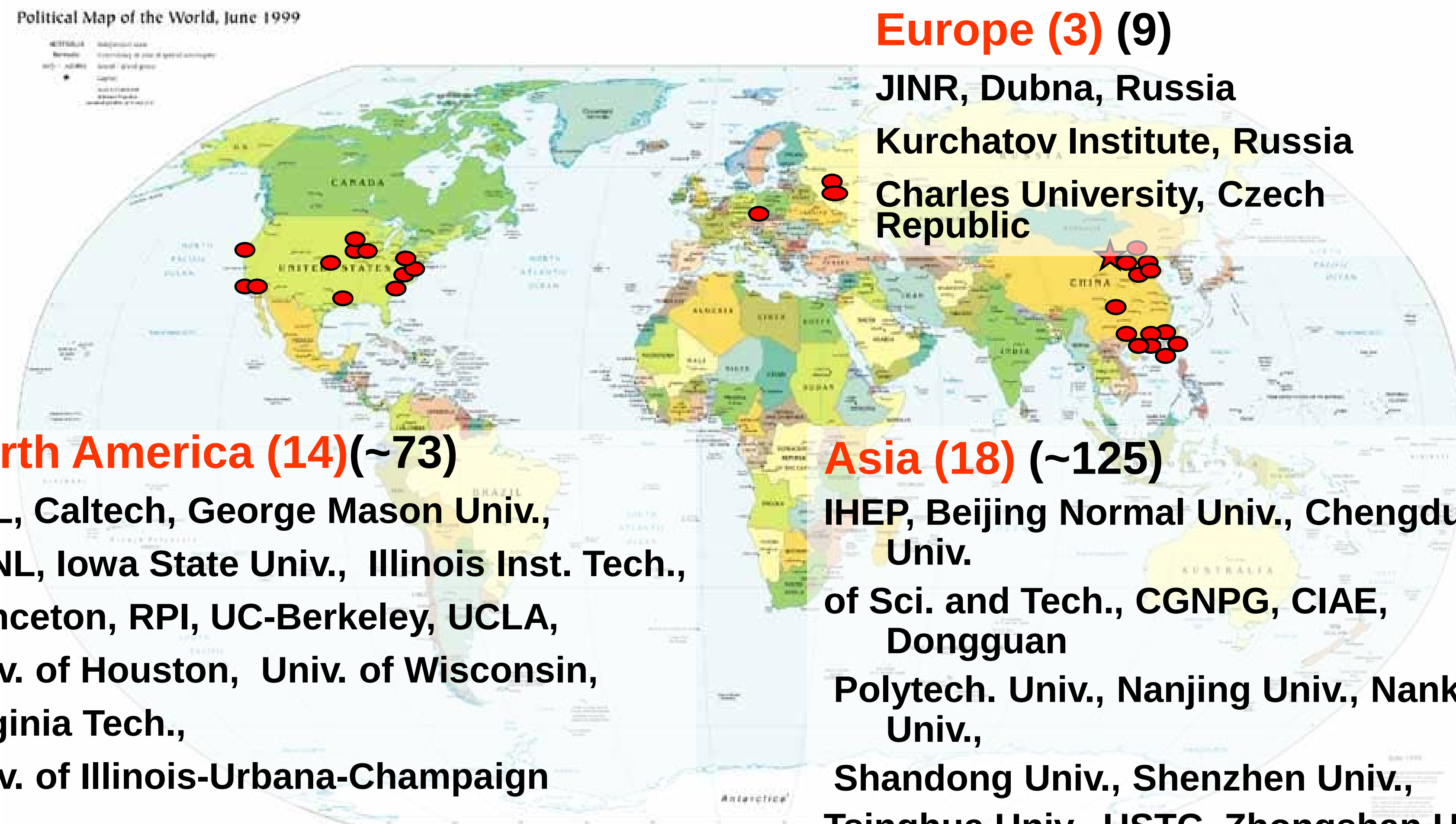
为什么在大亚湾反应堆？

- 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

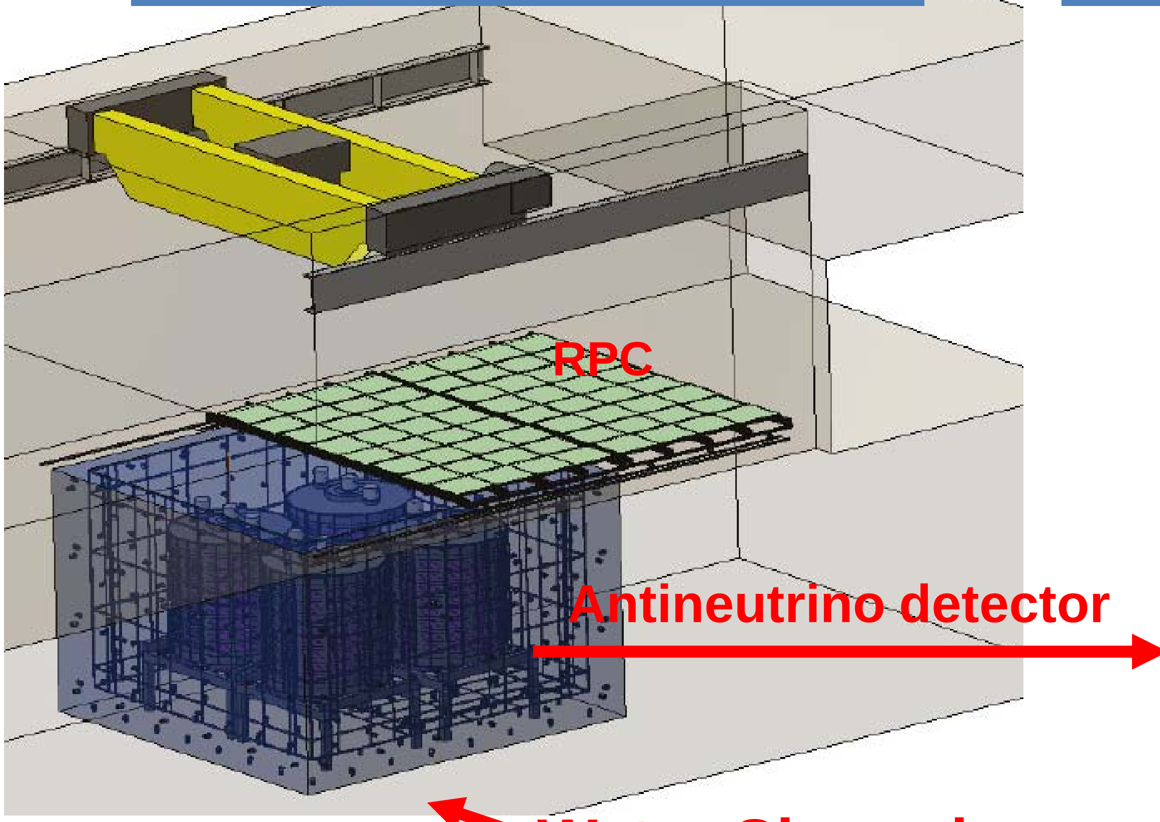
Table Comparison of three experiments

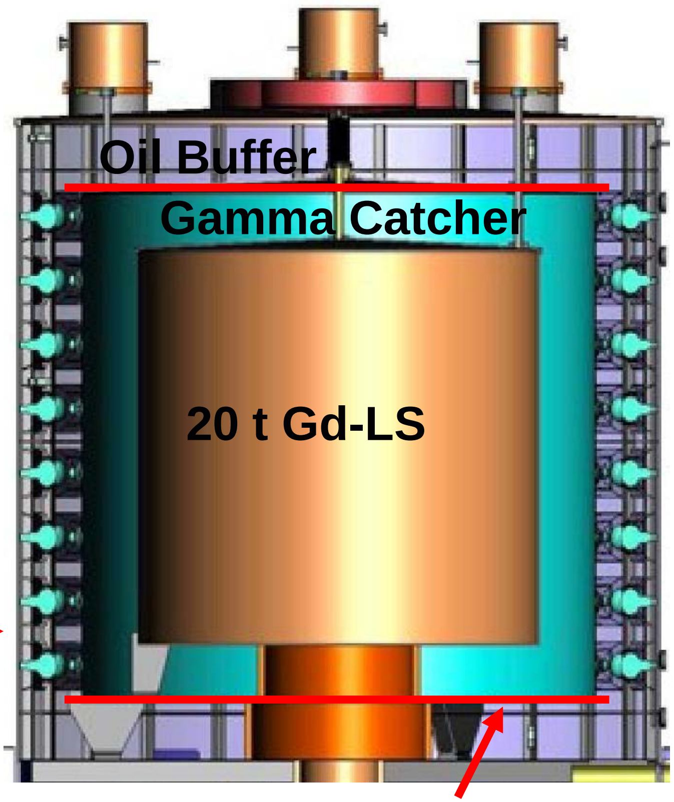
Experiment	Power (GW)	Baseline near/far(m)	Target mass near/far(t)	Overburden (MWE)	Sensitivity (90%C.L.)
Double Chooz	8.4	150/1050	10/10	60/300	0.03
Dayabay	17.4	400/1800	40/80	300/1000	0.01
RENO	17.3	150/1500	20/20	230/675	0.03

大亚湾实验的探测器

反符合探测器:
Totally reject 99.5% cosmic ray
• RPC,
•Water Cherenkov

中微子探测器
Anti-neutrino Detector （AD）
也叫中心探测器





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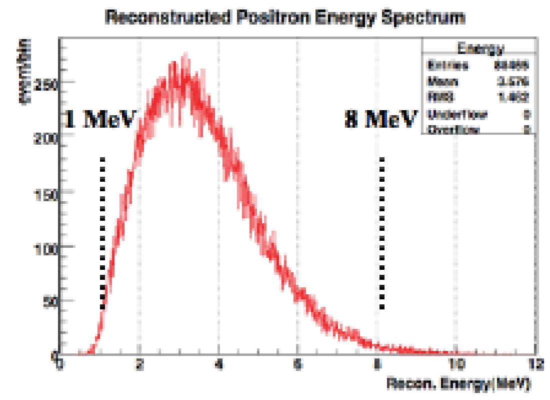
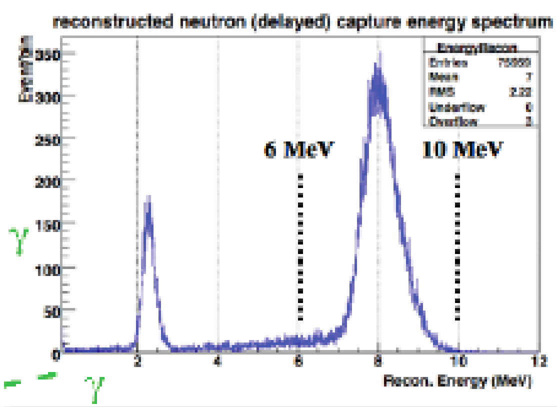
原理

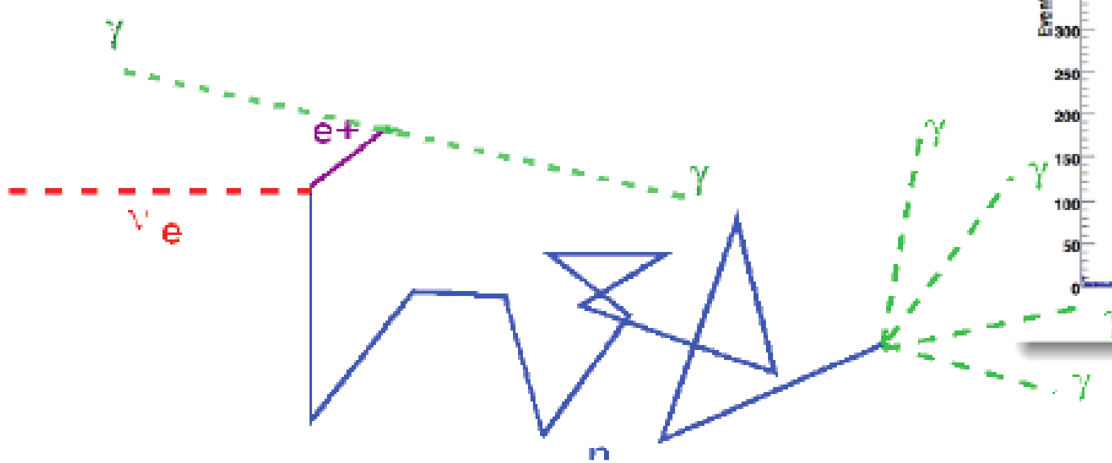
- Inverse β-decay :
  $\bar{\nu}_e + p \rightarrow e^+ + n$
- Trigger on 2-fold coincidence:
  - Prompt signal from e^+
  - Delayed signal from n capture on Gadolinium $\approx 30\mu s$
- Detector with Gd doped Liquid Scintillator (LS)

Prompt signal



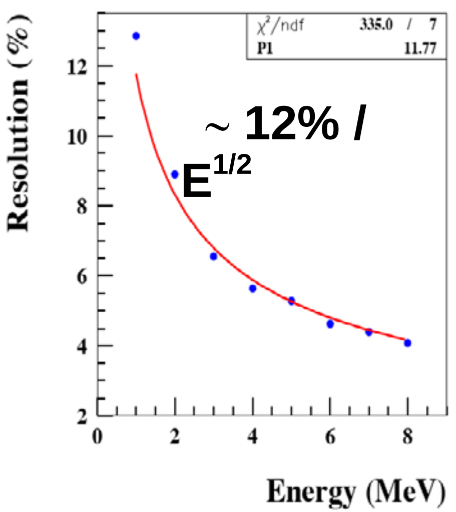
Delayed signal

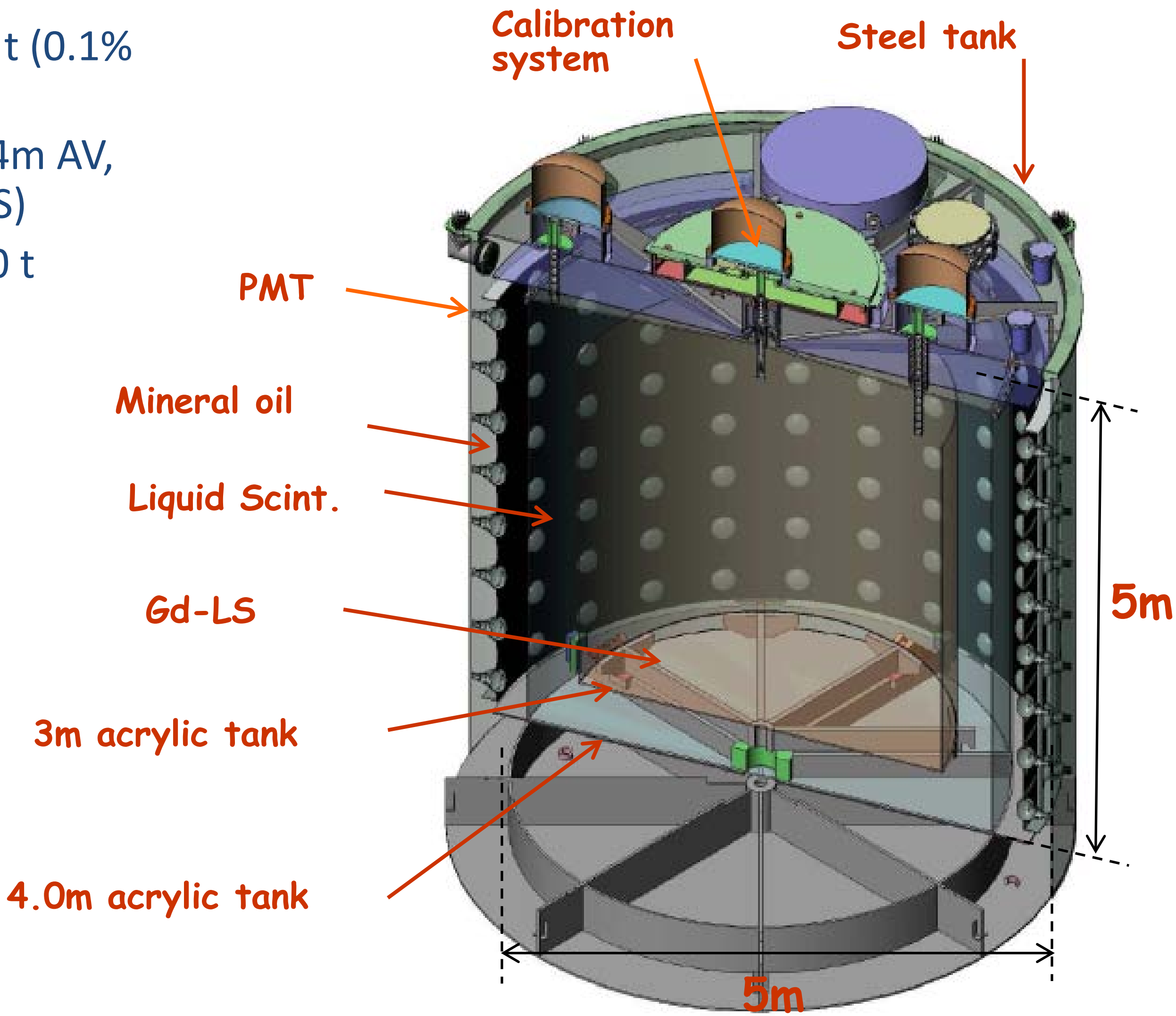




结构

- 三层嵌套桶型结构
  - 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)
- 低本底 8” PMT: 192
- 特色：上下反射板





AD的三个要求

- **材料的低放射性要求**
  - 所有AD内材料要求检查放射性ppm~ppb量级
  - 清洁要求：灰尘中的放射性也不能忽略：
    - 所有部件安装前要清洁
    - 3m罐、反射板、液闪的生产过程要求清洁
    - 安装清洁间万级清洁间
- **材料与液体的兼容性要求**
- **不漏：4种液体，3个罐，上千个O圈**
  - 检漏几乎处处进行：3mAV、4mAV、SSV、PMT、刻度装置、monitor装置等等
  - 检漏方法多样：

Samples from Daya Bay	Date received	Al Smith label	Date measured	Weight (gm)	Detector ID	Data file	Count time	U238	Th232	K
Daya Bay rock sample (granitc)			5-Jan-04	203	MERLIN			10.4(1) ppm	33.0(2) ppm	3.66(1) pct
Hamamatsu #TA2116 glass			26-Sep-05					100 ppb	150 ppb	130 ppm
Photonis glass sample			early in 2006	26	MAEVE			0.18(1) ppm	0.056(6) ppm	0.011(1) pct
Nanjing glass sample 1			30-Mar-05					105 ppb	70 ppb	300 ppm
Nanjing glass sample 2	2-Jun-06			236	MAEVE	CL-17	403920	28(1) ppb	85(4) ppb	135(6) ppm
ET PMT glass				568	MERLIN	21217	174000	81 ppb	73 ppb	130 ppm
IHEP S-308 (E-308-16) weld rod coating				64.4	MERLIN	21495	22800	15.5(3) ppm	18.8(10) ppm	3.62(5) pct
IHEP SW-308L (E308LT1-1/-4) welding wire				85.5	MERLIN	21501	24300	7.6(2) ppm	4.0(2) ppm	0.13(1) pct
IHEP ST-308L (ER308L) welding wrie				130	MERLIN	21529	686400	0.08(1) ppm	0.06(1) ppm	0.008(1) pct
ET PMT internal parts				128	MERLIN	21249	82200	20 ppb	<30 ppb	30 ppm
Hong Kong SST	13-Sep-07			485						
BNL GdCl3 sample		GDCL-01		1000	MAEVE	CM-73	502952	0.5(2) ppb	3.9(4) ppb	ND(3) ppm
IHEP GdCl3 (99.995%) w/o purification 江苏盐城阜宁	22-Oct-07	GDCL-02A		1040	MERLIN	22116	75600	<1 ppb	8 ppb	ND ppm
IHEP GdCl3 w purification 江苏盐城阜宁	22-Oct-07	GDCL-02B	10-Feb-08	992	MAEVE	CM-96	304095	1.5(3) ppb	<0.6 ppb	<0.4 ppm
Metglas 2714A	19-Nov-07		17-Jan-08	1132	Merlin	22182	67800	5(2) ppb	30(5) ppb	5(2) ppm
Photonis XP1806, SN 971	4-Dec-07		12-Dec-07	884	MERLIN	22146	34200	0.229(5) ppm	0.081(5) ppm	0.017(1) pct
IHEP Gd2O3 (99.99%) Guangdong Huizhou 广东惠州瑞尔	19-Dec-07	GDCL-03	17-Feb-08	1000	MAEVE	CN-08	245729	<0.2 ppb	1.4(6) ppb	0.8(5) ppm
IHEP Gd2O3 C3N5 Kanzhou Deshi 江西赣州德施普	19-Dec-07	GDCL-04								
IHEP Gd2O3 (99.995%) Jiangxi Jiasheng 江西佳盛	19-Dec-07	GDCL-05	17-Feb-08	1000	MAEVE	CN-10	171767	<0.3 ppb	12(2) ppb	1.1(6) ppm
IHEP GdCl3.xH2O (99.99%) Guangdong Huizhou 广东惠州	19-Dec-07	GDCL-06	17-Feb-08	1000	MAEVE	CN-12	168659	<0.3 ppb	1.8(8) ppb	<0.4 ppm
IHEP SST SF05764 (4 circular pieces)	11-Jan-08		1-Feb-08	1405	MERLIN	22309	162001	<1 ppb	<2 ppb	5(1) ppm
IHEP SST SF05765 (4 circular pieces)	11-Jan-08		1-Feb-08	1176	MERLIN	22287	162000	<1 ppb	<2 ppb	3(1) ppm
IHEP SST SF05766 (4 circular pieces)	11-Jan-08		1-Feb-08	1397	MERLIN	22285	98445	<1 ppb	<2 ppb	5(1) ppm

表 所用材料的放射性测量的一角

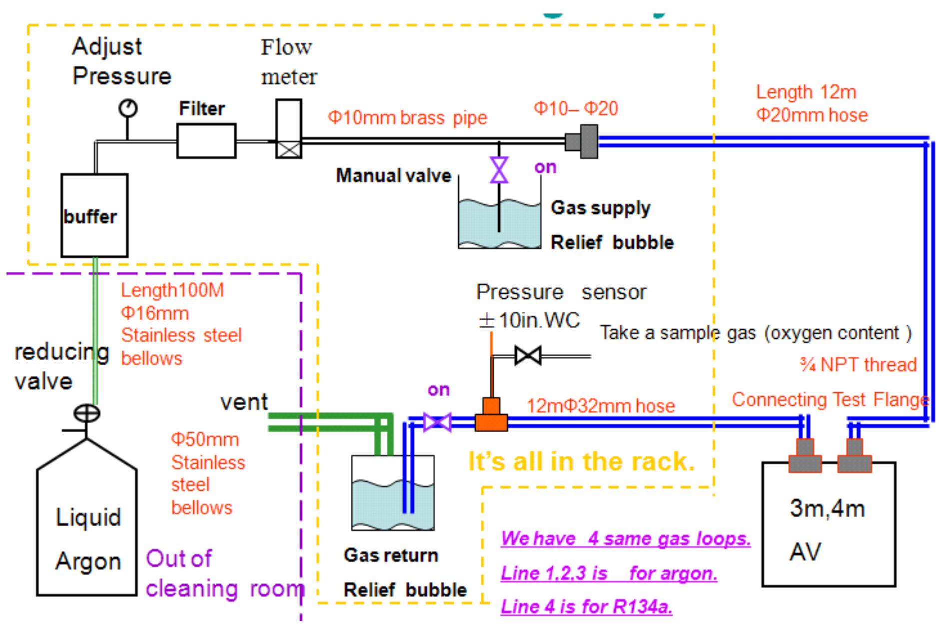


图 检漏气体系统框图

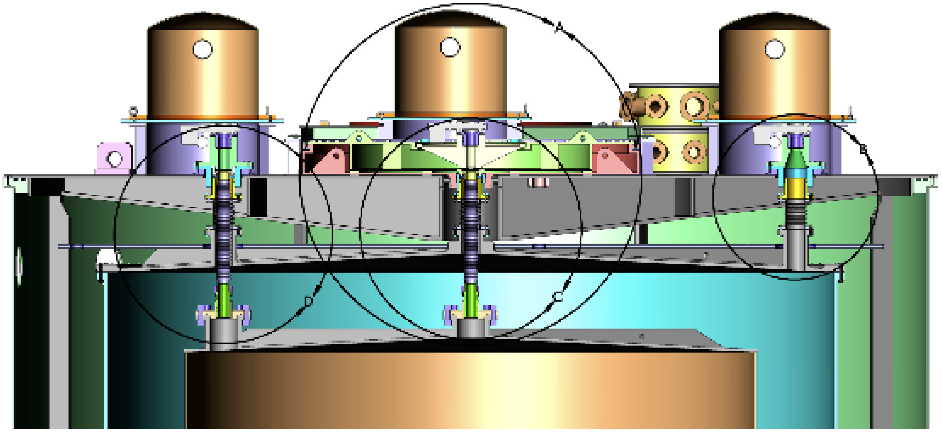


图 需要检漏的刻度孔

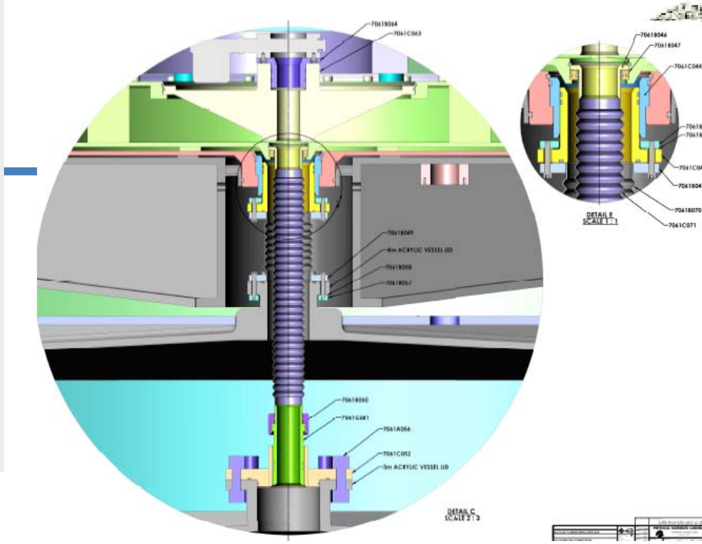


图 需要检漏的中心刻度孔

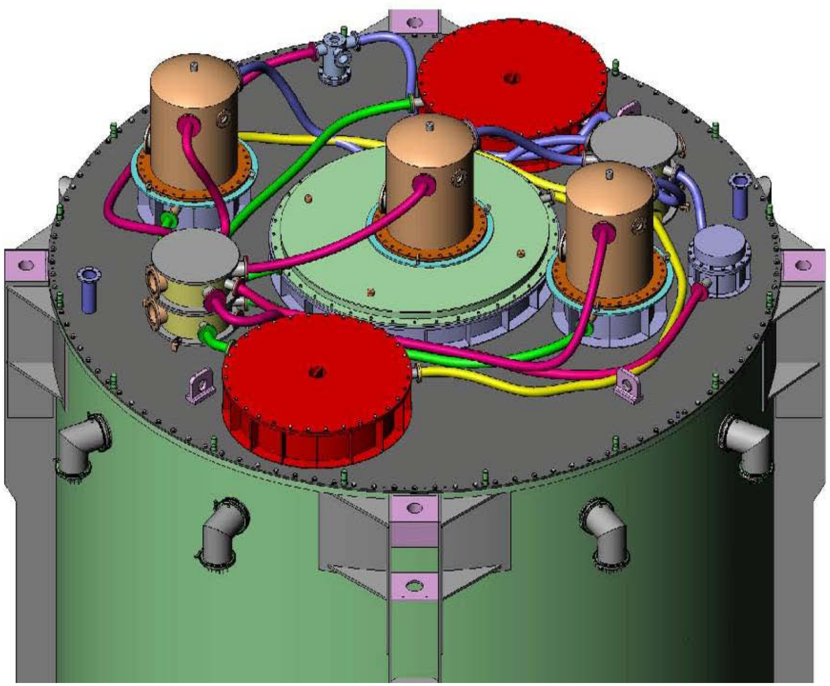


图 要检漏的设备

图 钢盖上设备的检漏

AD部件加工进展

- 主要部件研制进展：
  - 钢罐（IHEP）：已完成6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
  - 液闪设备（IHEP）：就绪
  - PMT（LBL）：R5912全面到货、检查完成
  - IAV（台湾）：完成2个，第3、4个已经到货
  - OAV（UW）：完成2个，第3、4进行中
  - 灌装设备（UW）：2010年底完成并运到
  - 自动刻度装置（Caltech）：加工完成
  - 手动刻度装置（原子能院）：明年完成
  - Monitor（香港中文大学、东莞理工）：完成2套，还差6套

大型部件的生产

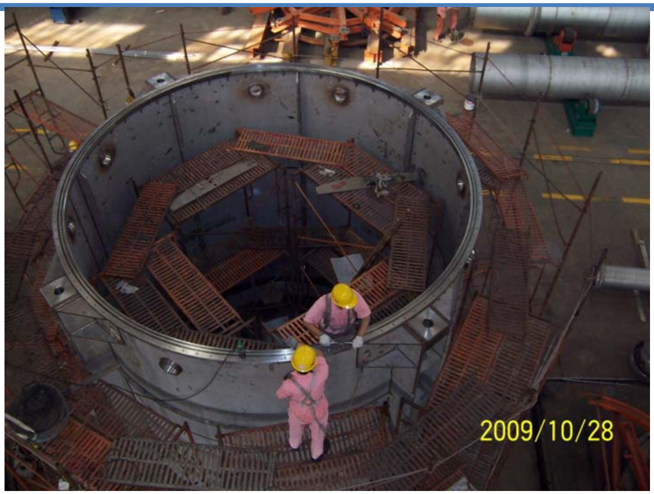


图 5m钢罐的生产（广东）

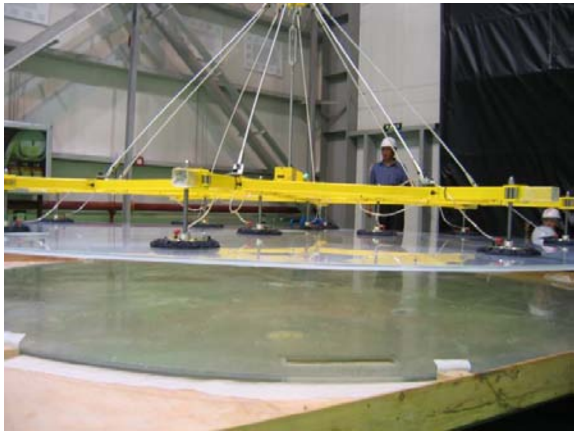


图 反射板的生产（福建）

图 3mAV的生产（台湾）

图 4mAV的生产（美国）

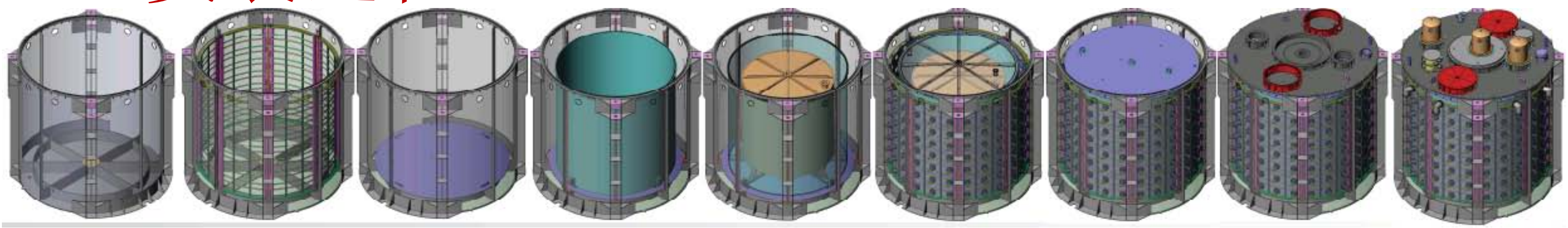
AD大型部件运输

AD运入地下实验完成

- AGV车：可以运输装满液体的110吨AD
- 实验：隧道、5号厅、1号厅

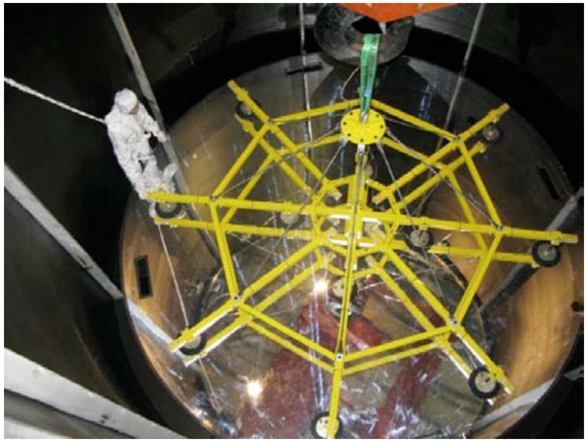
AD安装

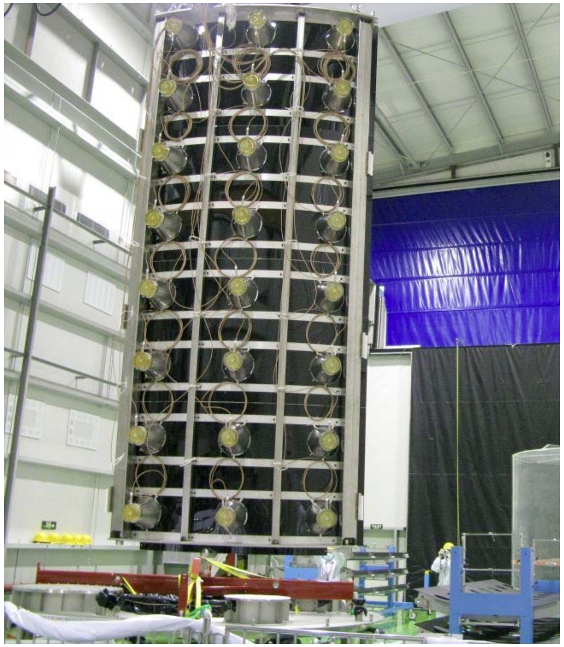
- AD安装过程



- 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，目前已经接近组成完成
- 计划：2012年完成8个AD的安装

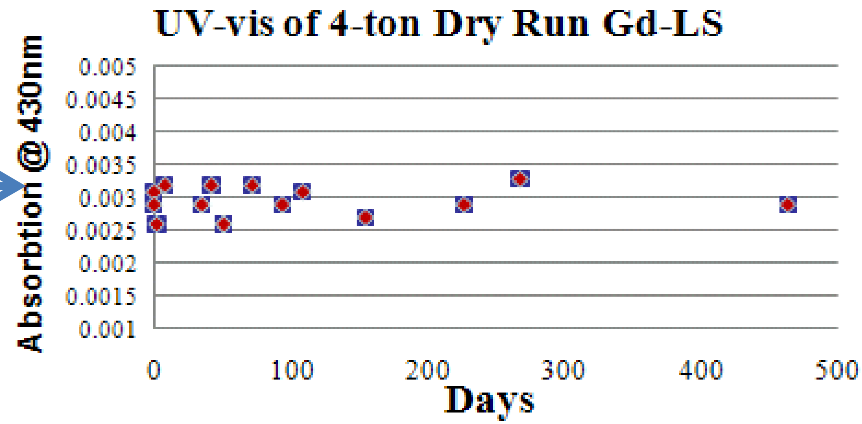
AD 组装的一些图片





液闪（高能所）

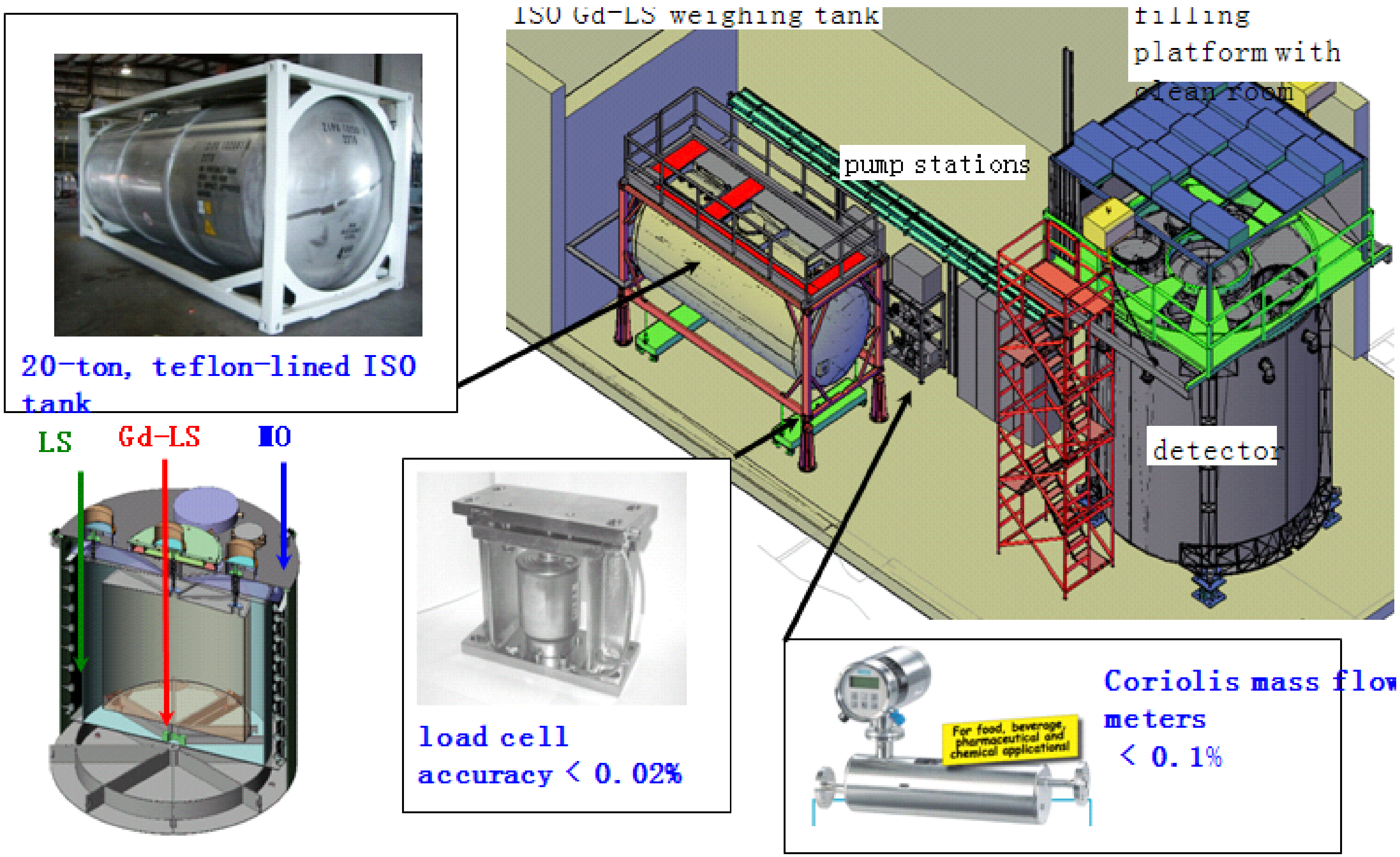
- 共需要 185吨 0.1% 掺钆液闪，生产后统一存放保证8个中微子探测器的一致性
- 4吨试生产在高能所进行多次，质量监测良好



- 现场生产设备和主要原料已经就位，泄漏问题已经解决
- 生产人员培训已经完成

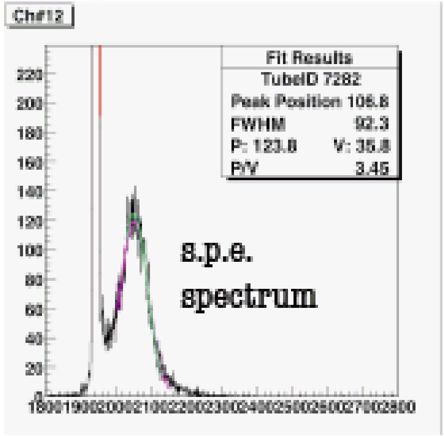
液闪灌装设备(UW)

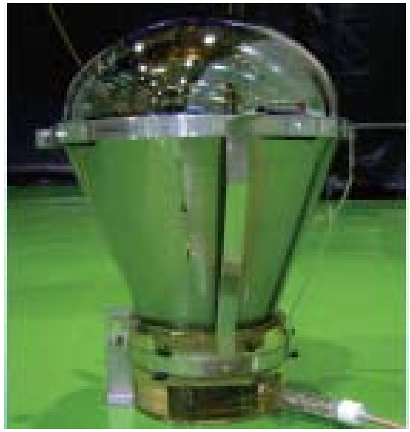
- 靶物质掺钆液闪：要求质量精度0.1%
- 三种液体同时灌装，液面差<15mm，防止有机玻璃罐破裂



PMT（Berkeley）

- PMT R5912： 192X8
  - 量子效率：>25%@420nm
  - 峰谷比:>2.5
  - 增益：2X10^7
  - 阈值：1 /4光电子
  - 暗计数率：<10kHz
  - 防止反射，周围黑板吸光
  - 环氧浇注，防油
  - 放磁场薄膜包裹
- 进展：
  - PMT全部检测完成（东莞理工）
  - 梯架、rails等部件全部加工完成
  - 电缆引出drybox全部加工完成
  - AD1和AD2已经安装完成





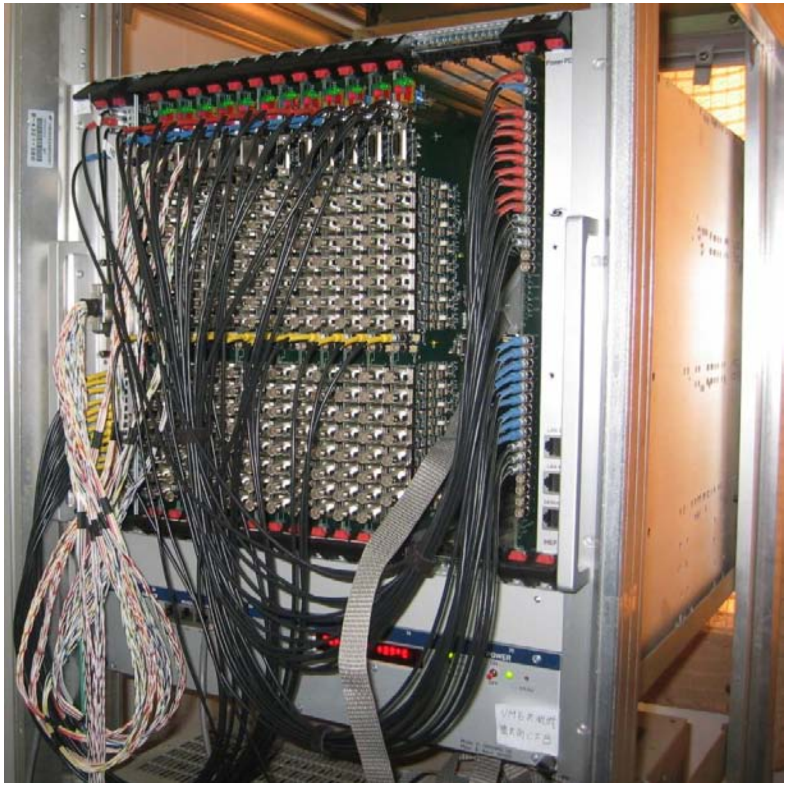
PMT电子学要求

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

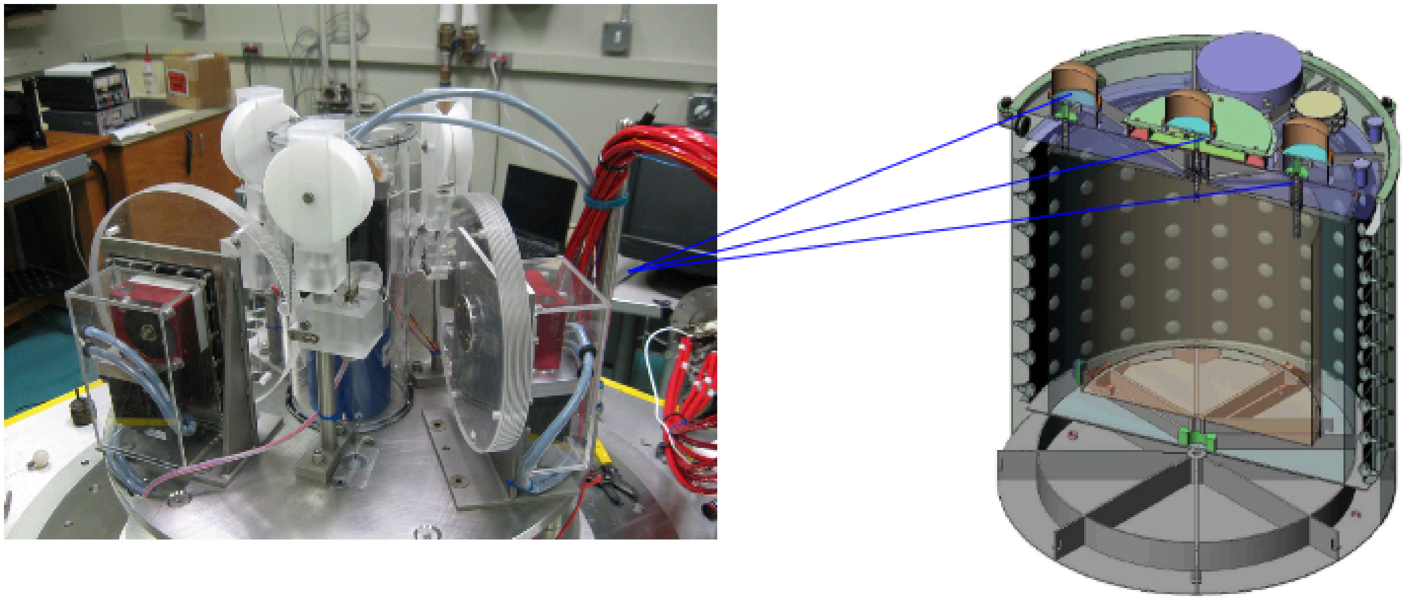
电子学进展

- 单机箱测试OK， 已用于dryrun

- Electronic subsystem for 1 AD was setup at IHEP in last 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



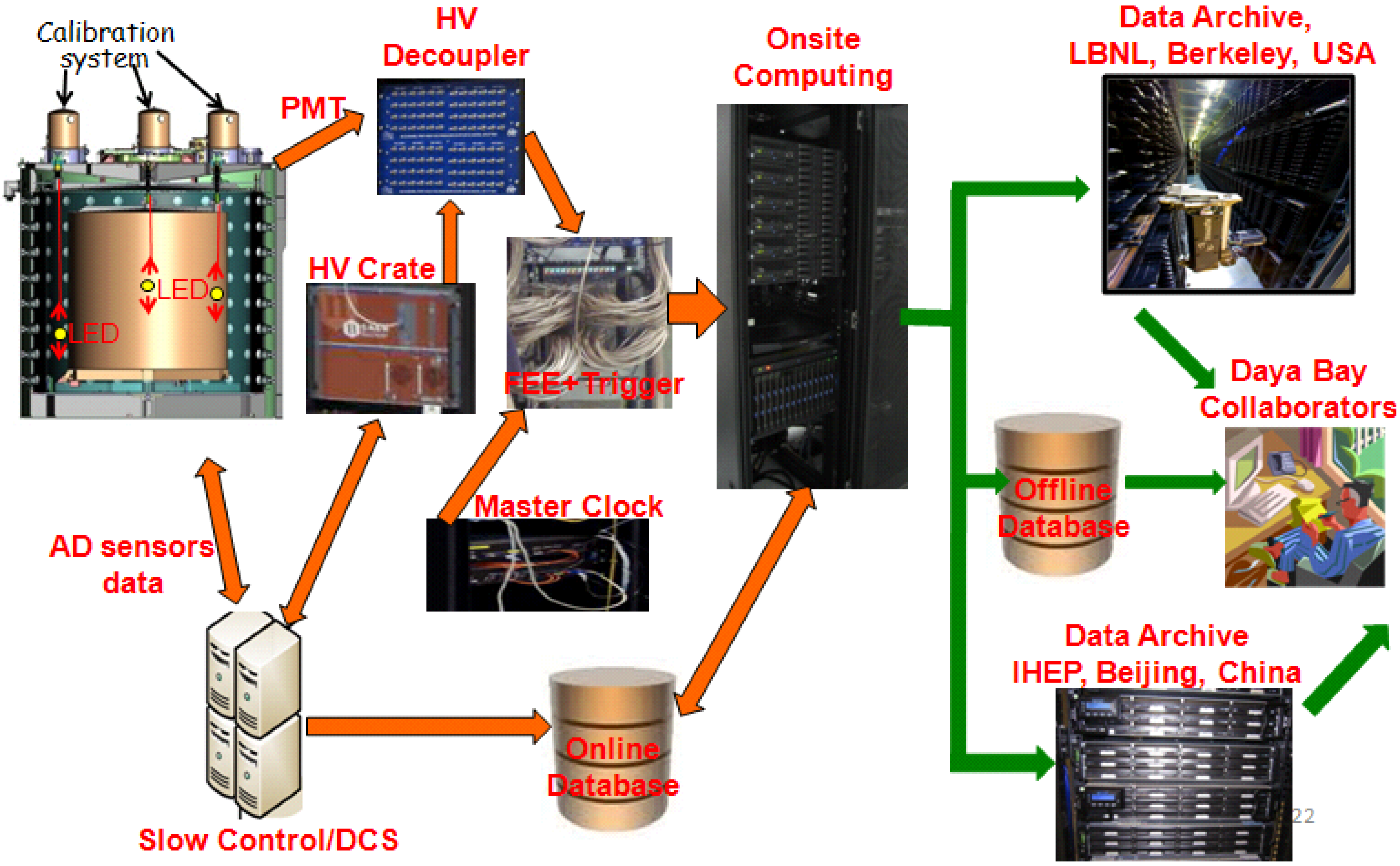
自动刻度装置（加州理工）



- Accuracy: ~1 cm
- Sources
  - LED
  - AmC(n) + Co60(γ)
  - Ge68(e^+)
- Deployment plan
  - Weekly deployment
  - several positions per axis
  - 3-5 mins per position

AD#1 Dry Run 完成（2010年7月）

- 探测器、刻度、电子学、满控制、触发、DAQ、在线与离线数据库都进行了测试，除了没有液闪，证明了系统可以工作。



AD#1 Dry Run 数据分析 (I)

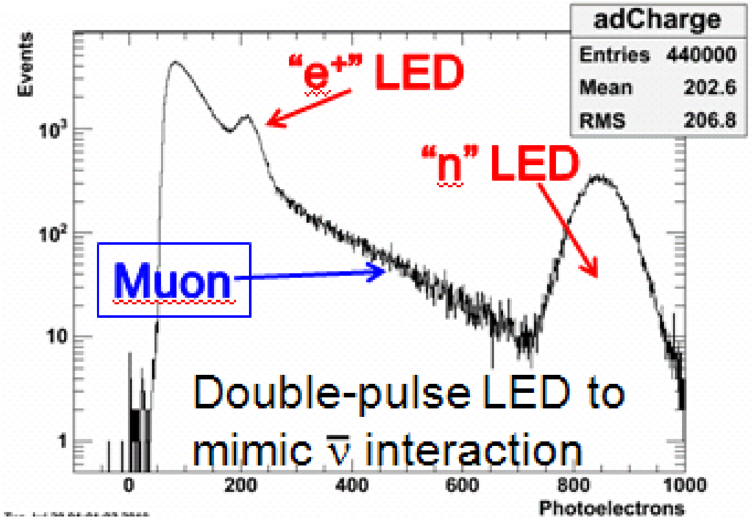


图 LED模拟的中微子谱

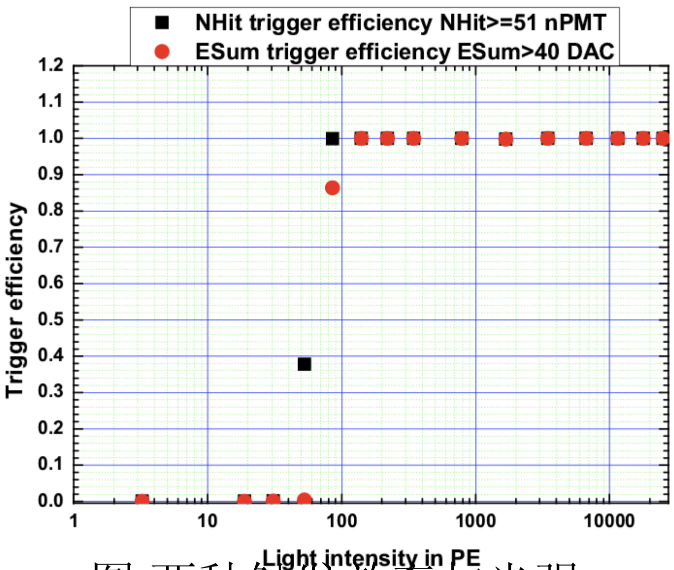


图 两种触发效率与光强

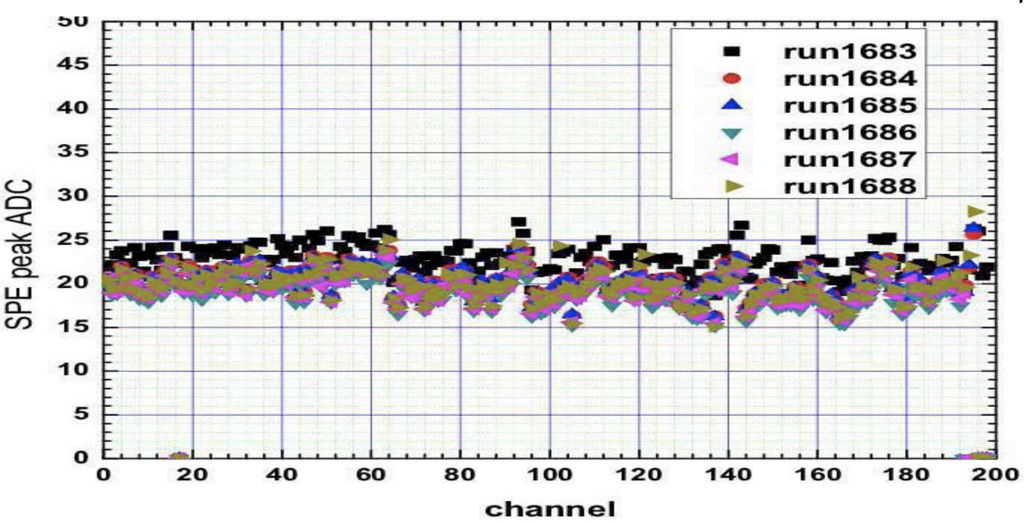


图 192个PMT的单光电子谱

AD#1 Dry Run 数据分析 (II)

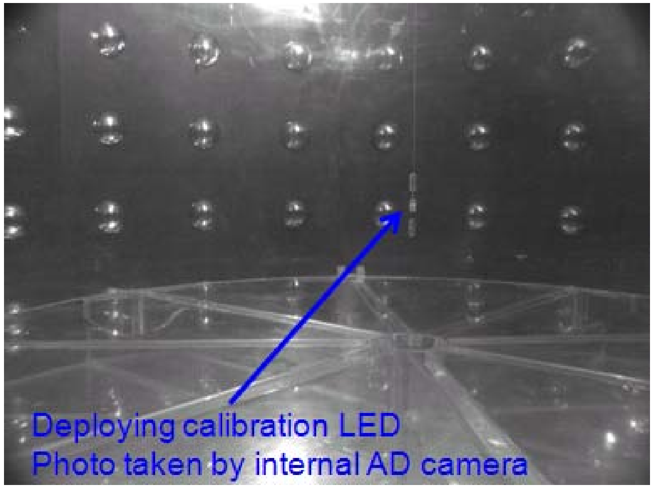


图 AD内照相机所照LED图像

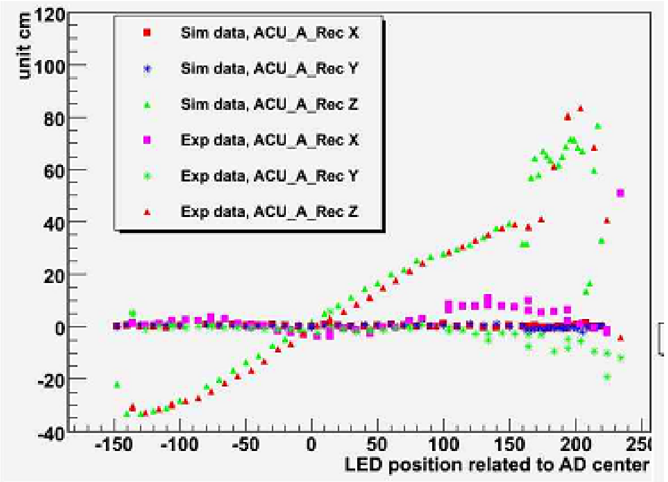


图 离线重建LED顶点与模拟的对比

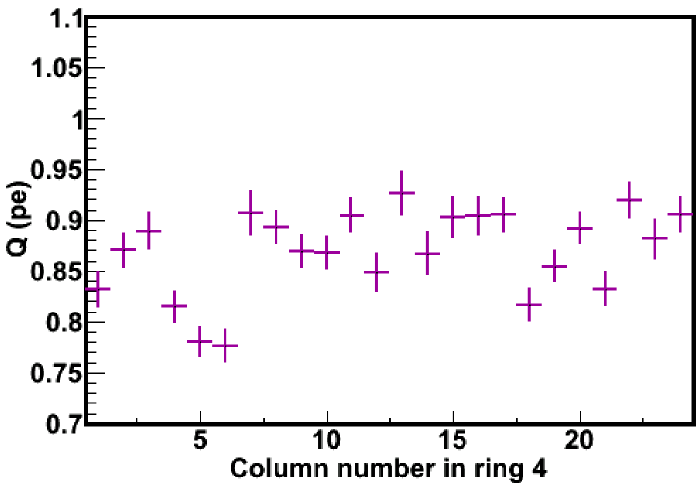


图 利用LED调整PMT增益

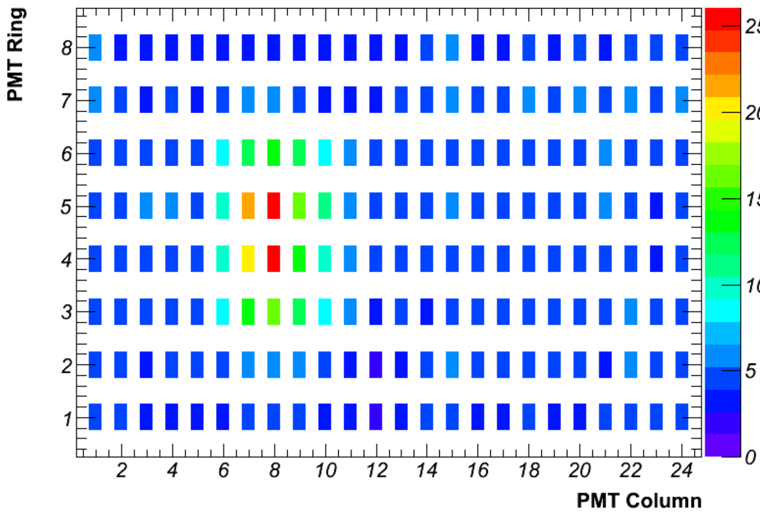


图 LED着火数与本底计数（4kHz）

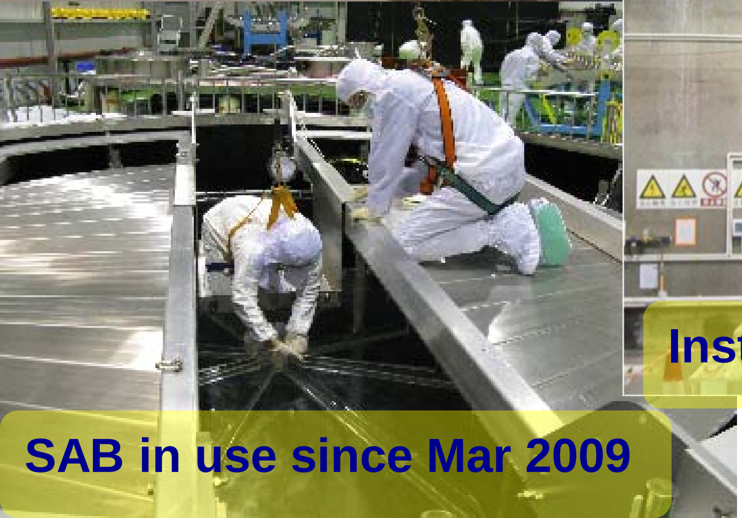
总结

- 大亚湾实验物理意义显著
- 大亚湾中微子探测器研制的特点与难点
  - 极低本底探测器：材料放射性低、安装与内部部件清洁、隧道与地下实验大厅
  - 液体（4种）探测器：要求材料兼容、所有接口不漏
  - 首次与美方完全交叉合作的大型探测器
  - 异地工作，长期出差，人员、后勤与运行保障吃力
- 进展与计划：
  - 2010年10月完成首对AD的安装，电子学、DAQ系统已经可以工作
  - 2010年基本完成土建一标的工作
  - 液闪主要原料LAB就位，生产设备就位，即将开始生产
  - Muon系统安装即将开始
  - 2011年夏天，开始一号厅2个AD 的取数
  - 2012年完成8个AD的安装

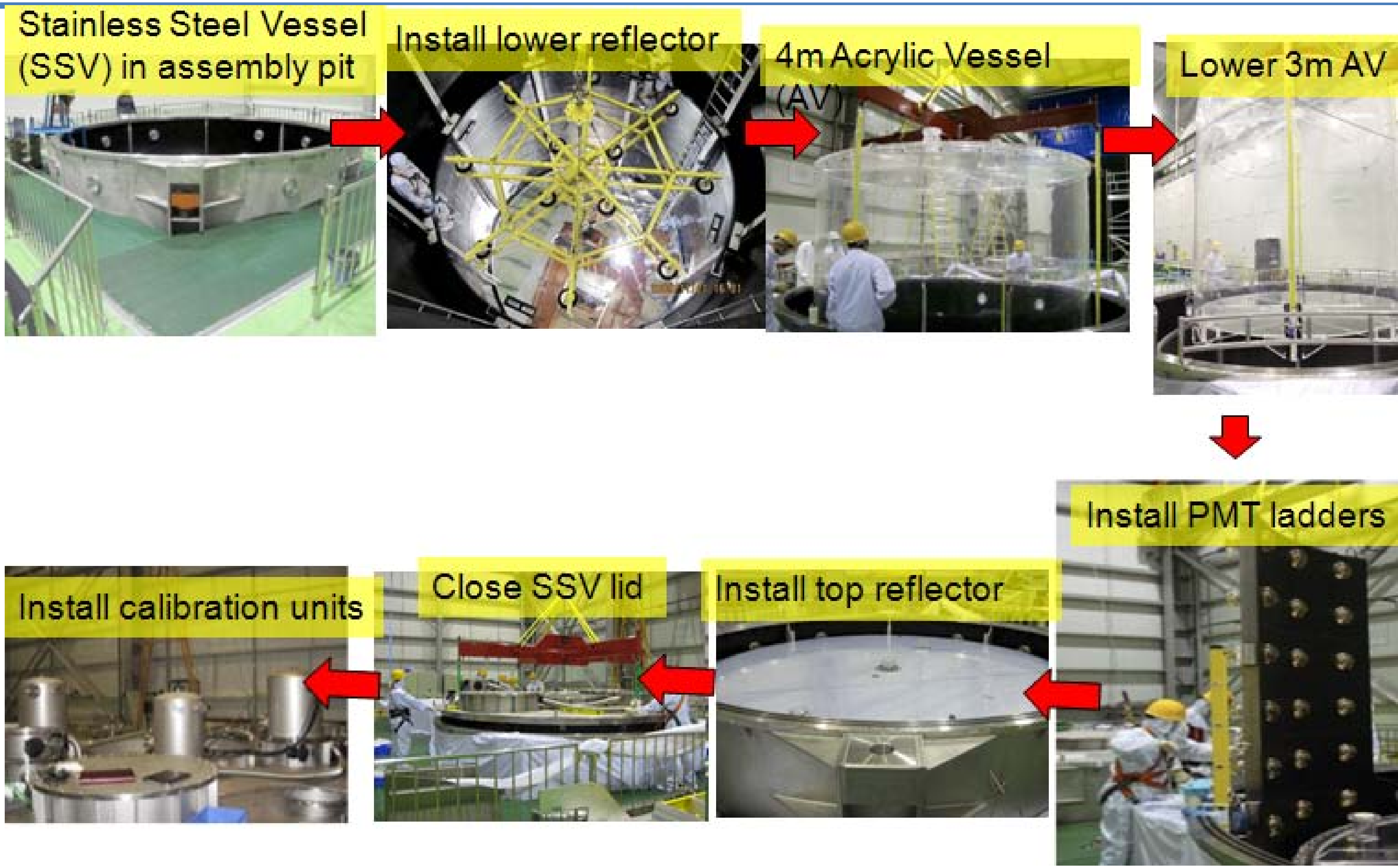
谢谢大家！

下面是备用！

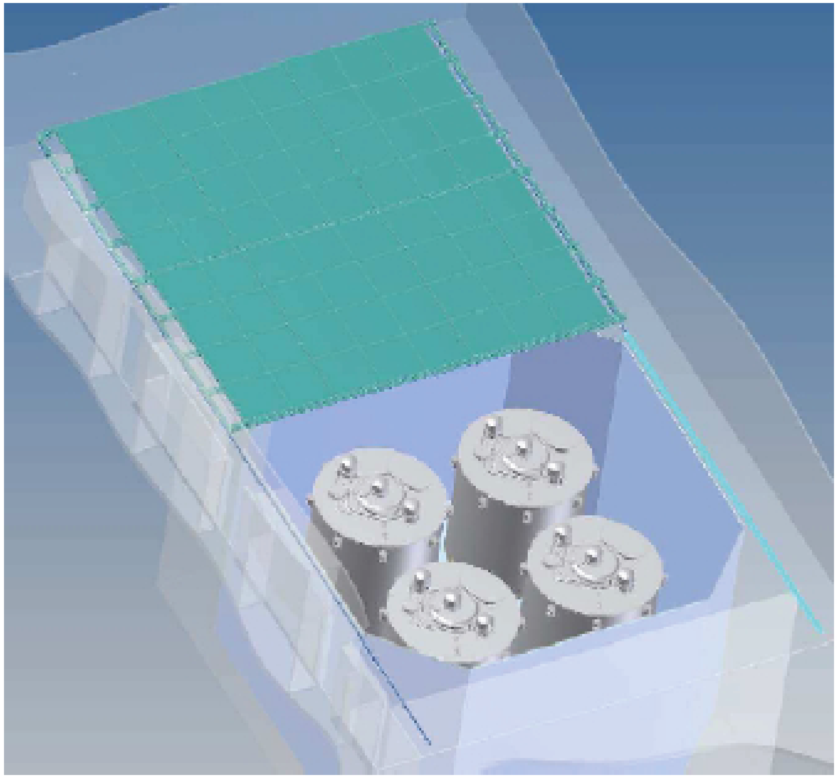
Status of Civil Construction



AD主要安装步骤


Stainless Steel Vessel (SSV) in assembly pit
Install lower reflector
4m Acrylic Vessel (AV)
Lower 3m AV
Install PMT ladders
Install top reflector
Close SSV lid
Install calibration units

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 $> 99.5\%$

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%

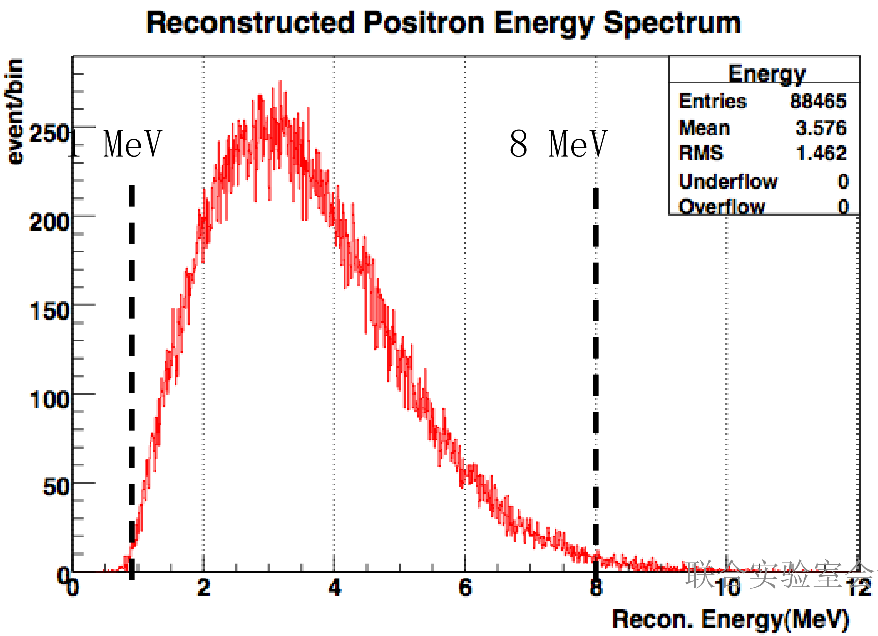
Antineutrino Detection principle

ν_e + p □ e^+ + n

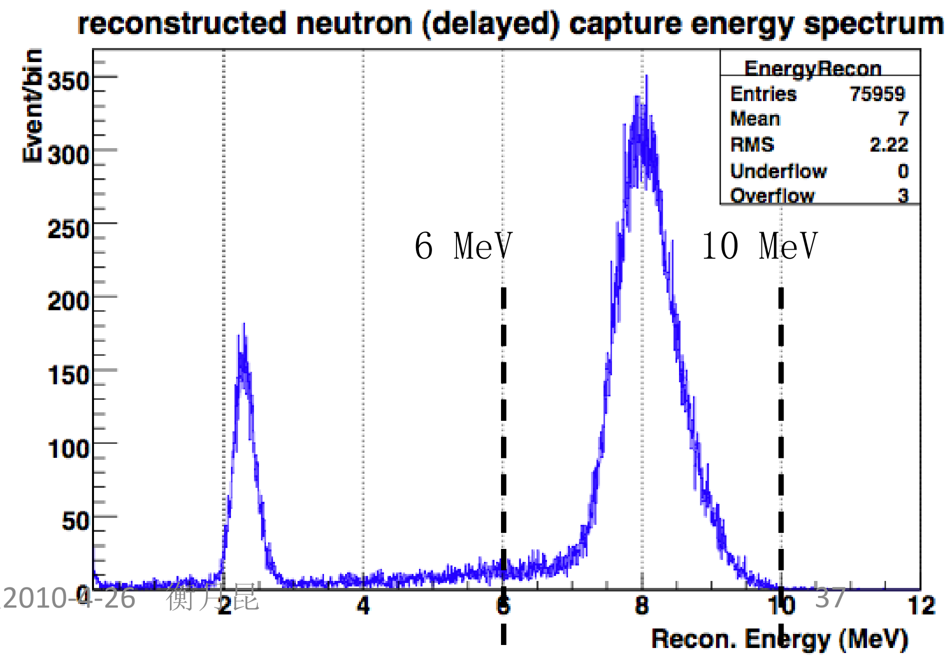
0.3 b → + p □ D + © (2.2 MeV) (delayed)

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

Prompt Energy Signal

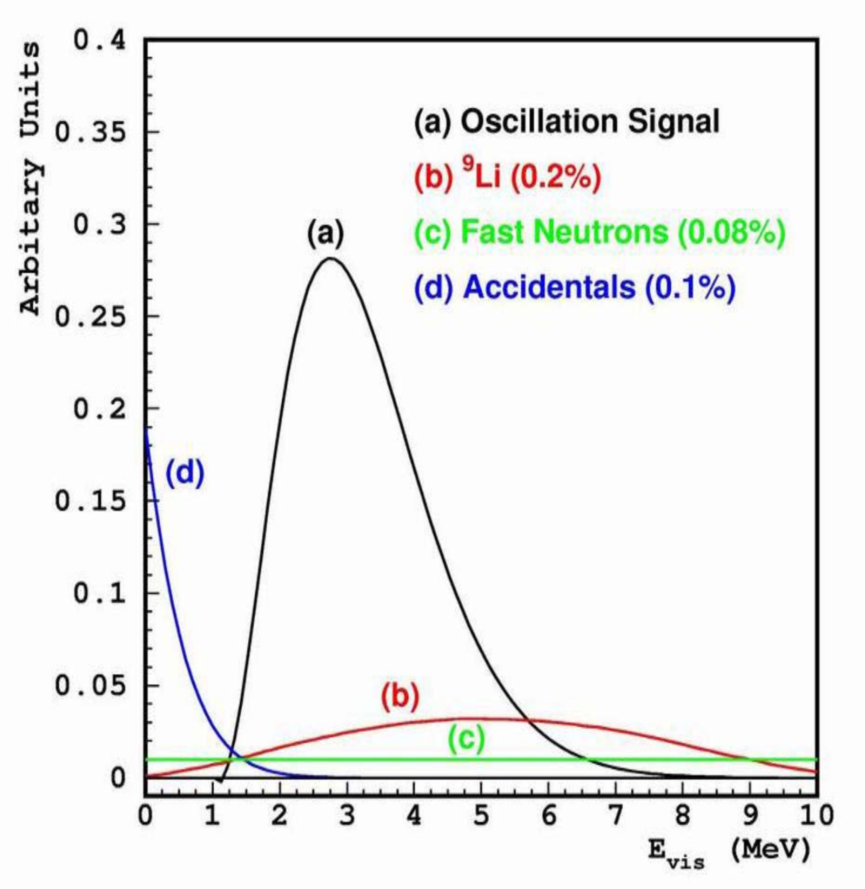


Delayed Energy Signal



Signal and background

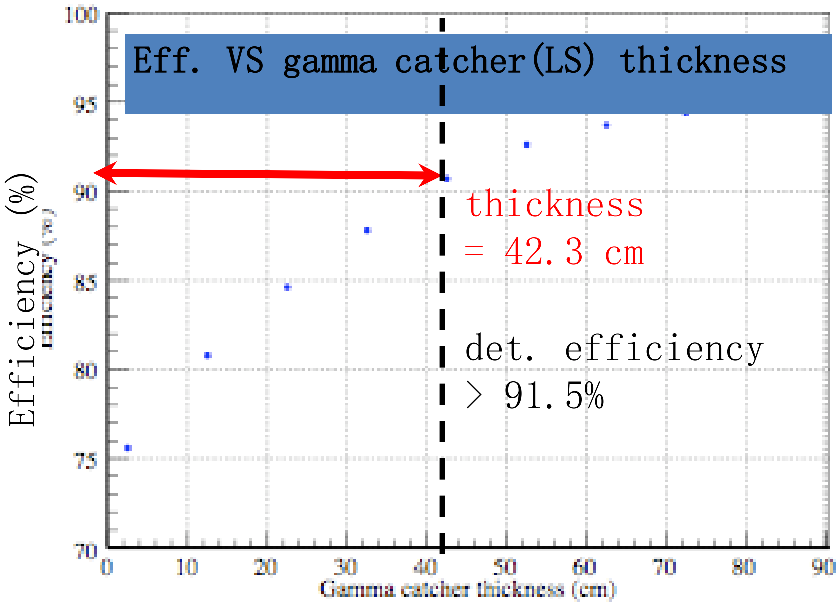
- ID
  - No position reconstruction
  - Time windows for two prompt and delayed signals:
  - Energy cuts
- BG
  - ^{8}**He and** ^{9}**Li:** generated by cosmic ray, decays to βand n
  - **Fast Neutrons:** generated by cosmic ray, proton hit out give prompt signal, and slow neutron give delayed signal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

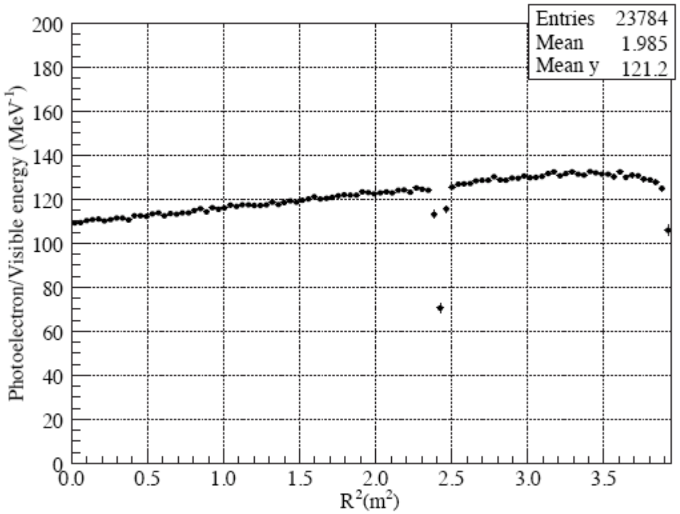


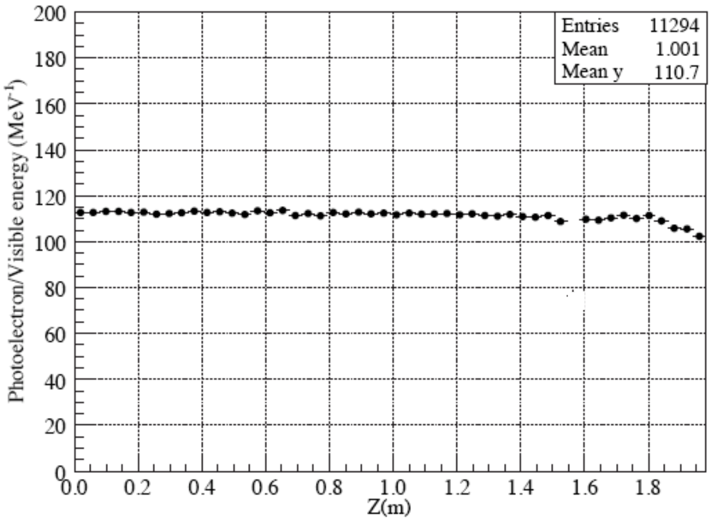
Simulation on AD

Uniformity of PE in R and Z direction

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



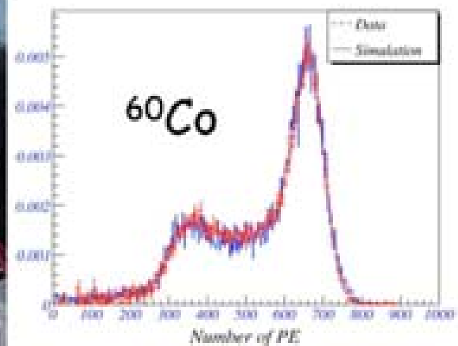


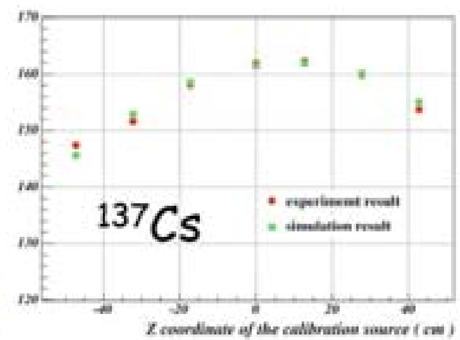


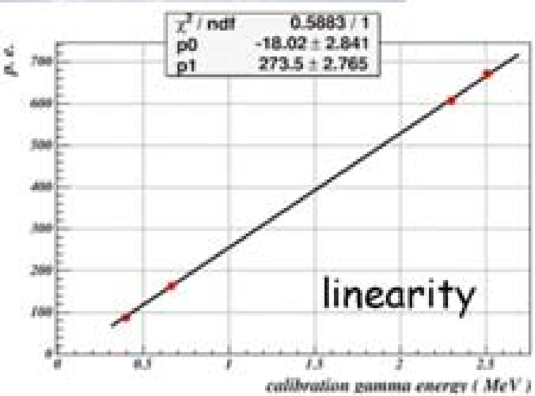
Prototype test (1)

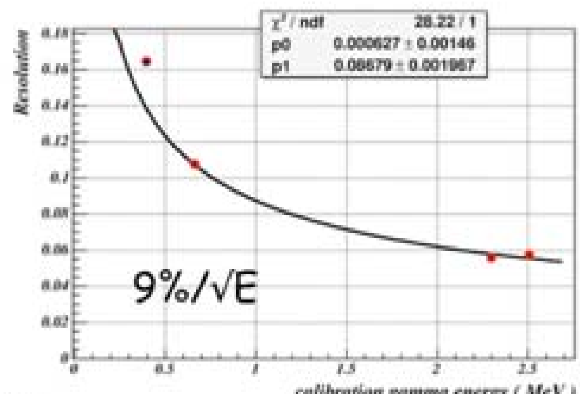
- 0.5 ton unloaded LS
- 45 8" PMTs with reflecting top and bottom

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





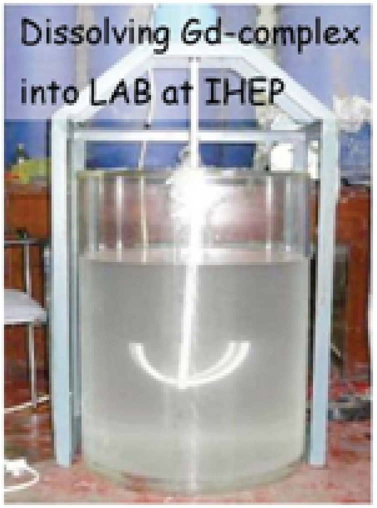




Kam-Biu Luk

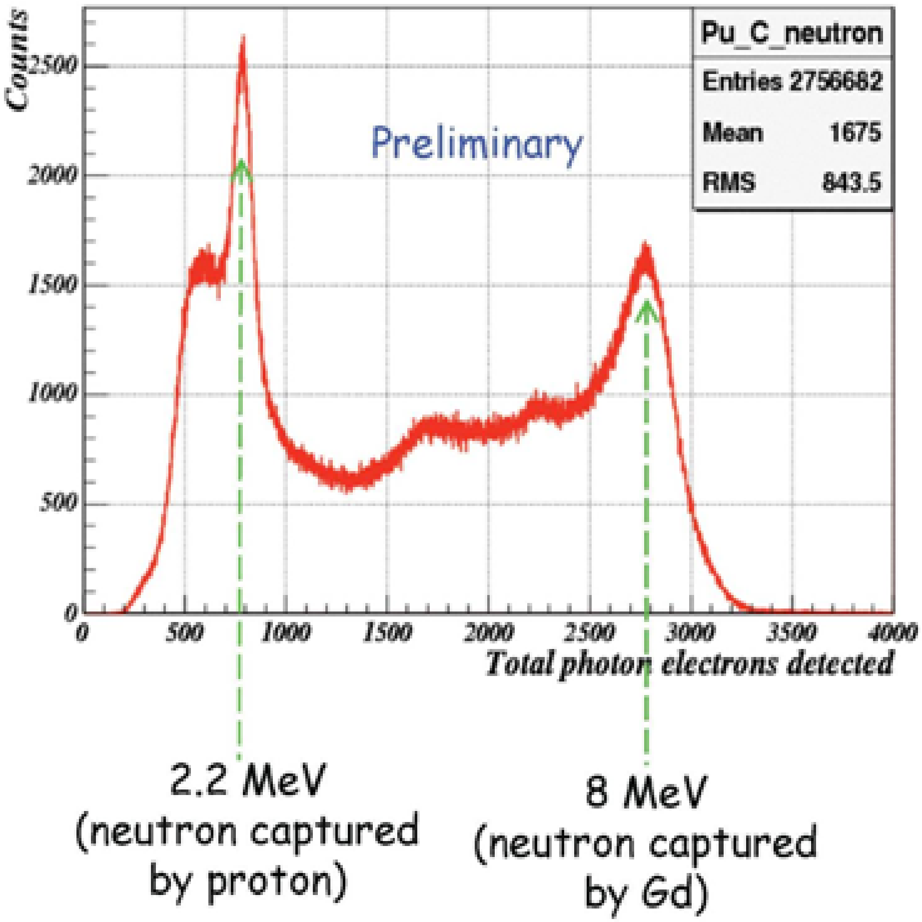
Daya Bay

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.

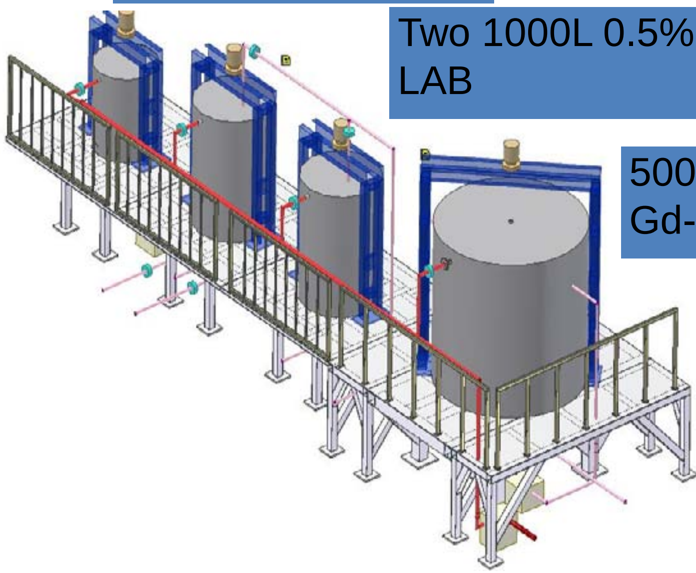


Gd-Liquid Scintillator Test Production

500L fluor-LAB

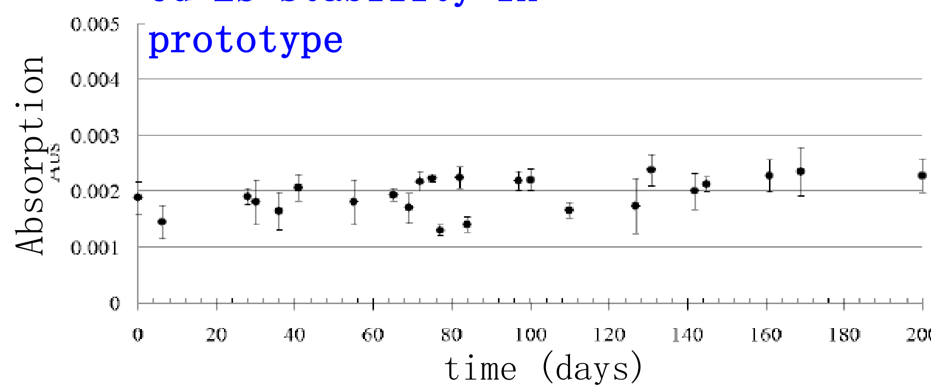
Two 1000L 0.5% Gd-LAB

5000L 0.1% Gd-LS



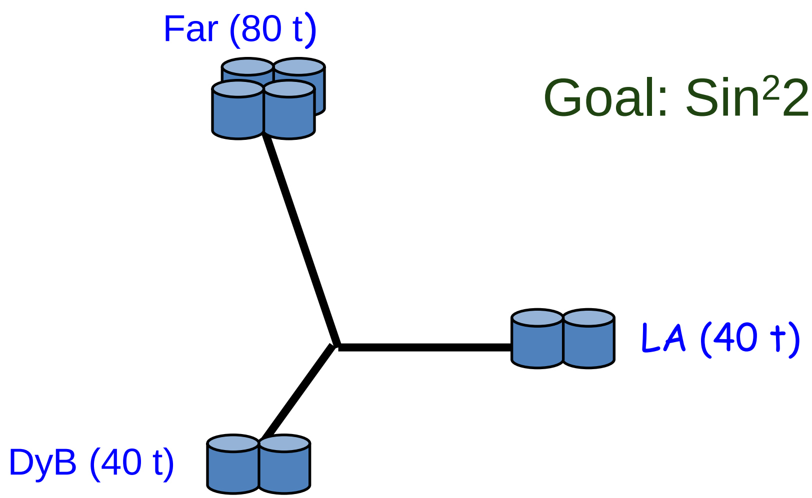
0.1% Gd-LS in 5000L tank

Gd-LS stability in prototype



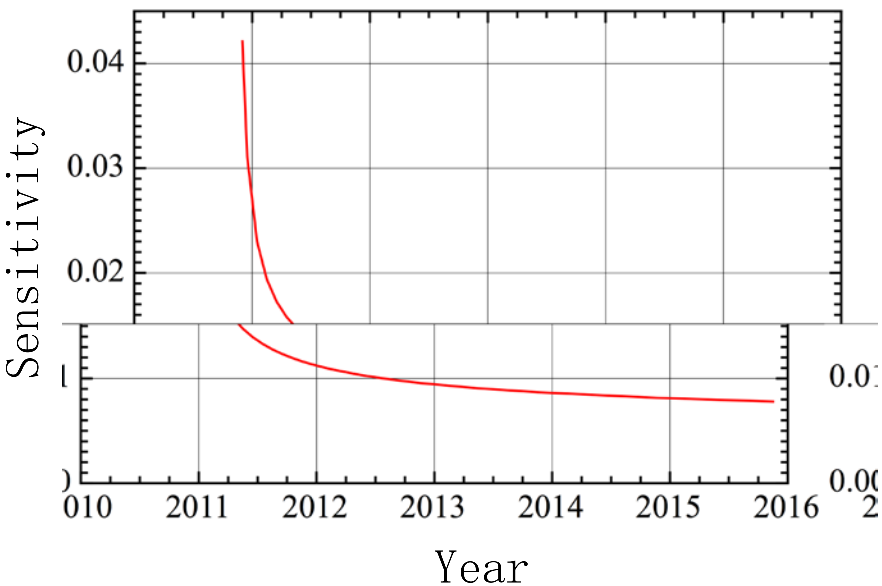
Gd-LS will be produced in multiple batches but mixed in reservoir on-site, to ensure identical detectors.

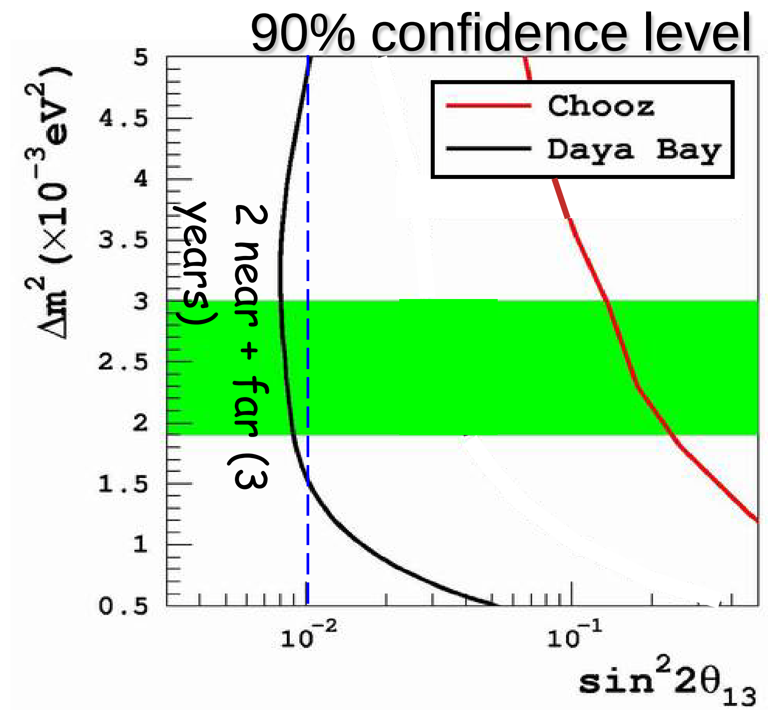
Sensitivity of Daya Bay



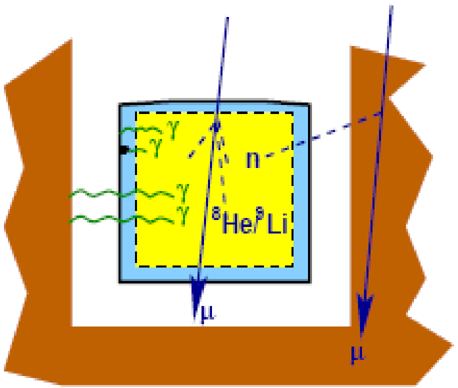
Goal: $\sin^2 2\theta_{13} < 0.01$

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





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:

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

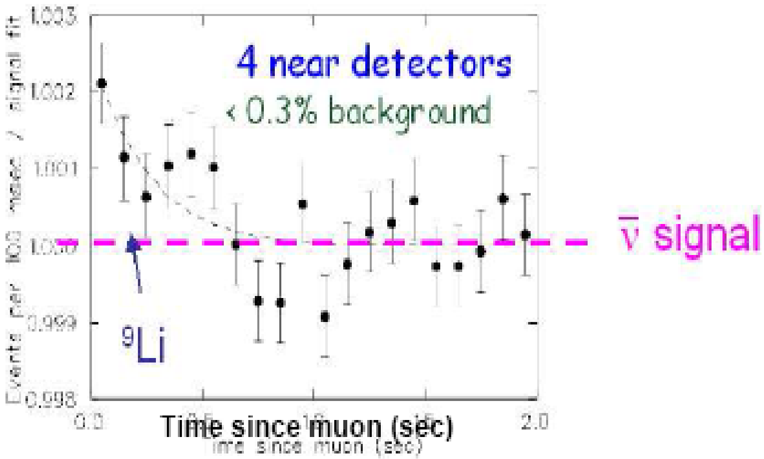
Q= 13 MeV, $\tau = 178$ msec $\Rightarrow$ poor spatial correlation with μ track.

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

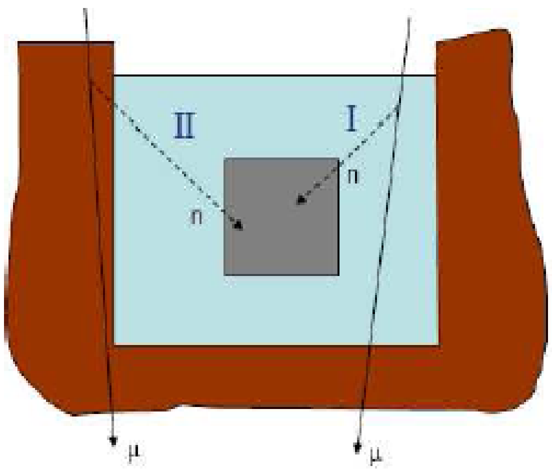
But it can be measured ! $\longrightarrow$

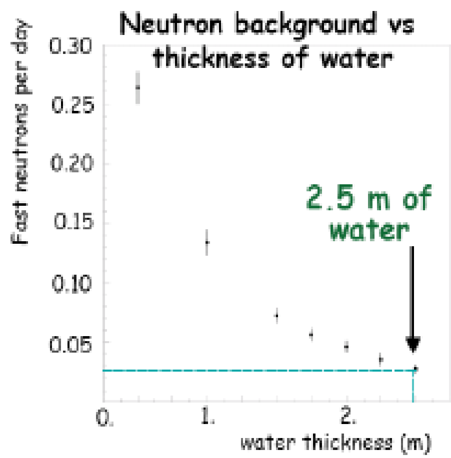
$B/S \approx 0.3\%$



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) :

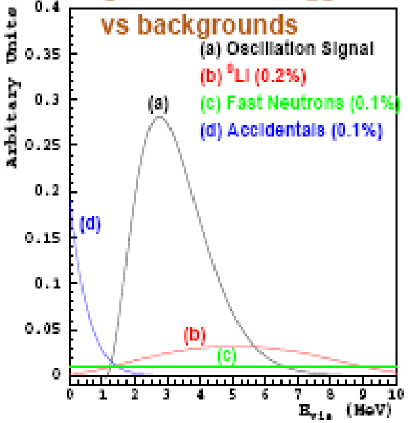
	I: From untagged μ	II:Rock neutrons	II:Total/Signal
DYB	0.10	0.5	6×10^{-4}
LA	0.07	0.35	6×10^{-4}
Far	0.01	0.03	4×10^{-4}

Accidental background rates

Prompt: $\gamma > $ 1MeV 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 $(\alpha, n, \gamma[6 - 10\text{ MeV}])$

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