

# 高能物理中的探测器 及其应用

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# 高能物理中的探测器

半导体探测器

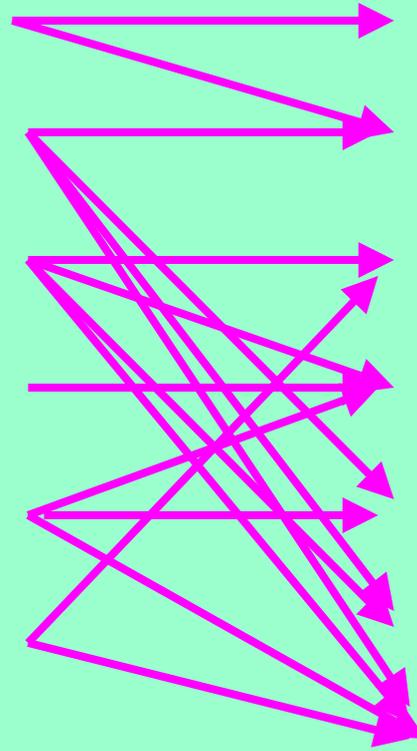
气体探测器

塑料闪烁探测器

晶体闪烁探测器

液体闪烁探测器

切伦科夫探测器



顶点室

径迹室

粒子鉴别

电磁量能器

强子量能器

**Muon** 室

中微子探测器

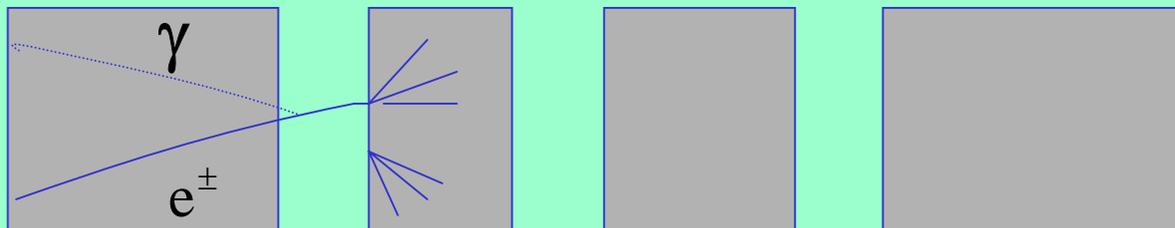
多丝  
径迹室

电磁  
量能器

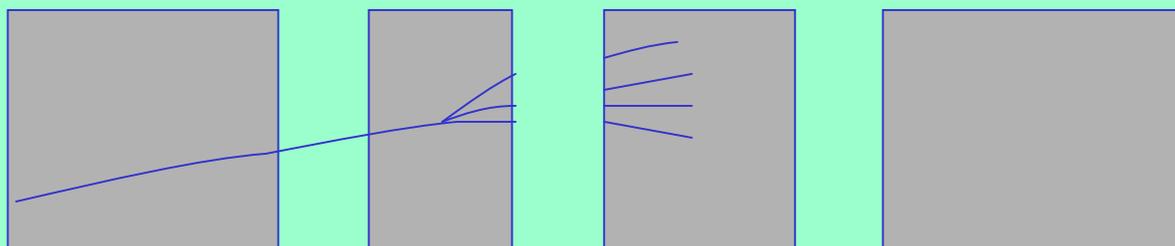
强子  
量能器

$\mu$  子室

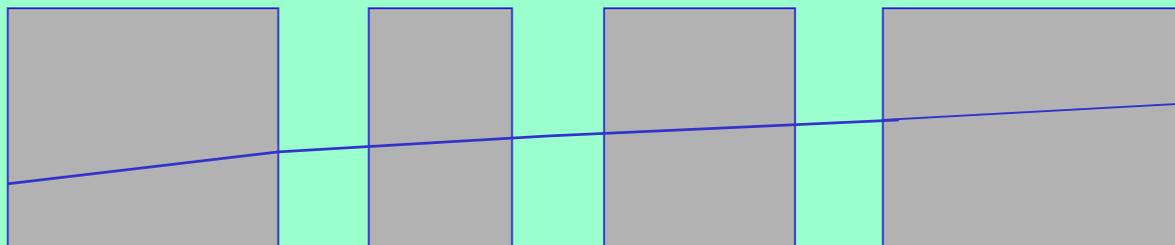
$\gamma / e^\pm$



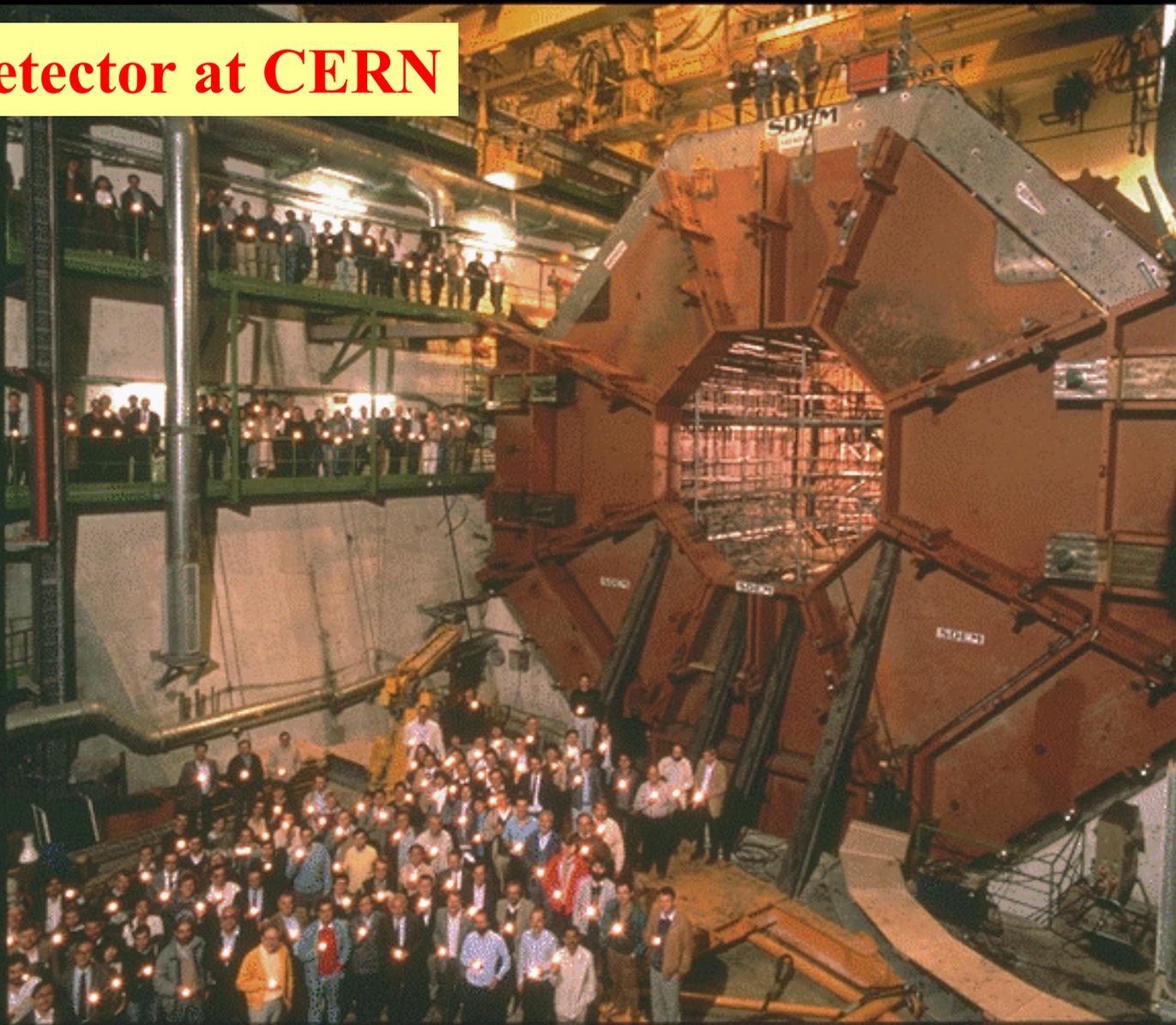
$h^\pm$



$\mu^\pm$



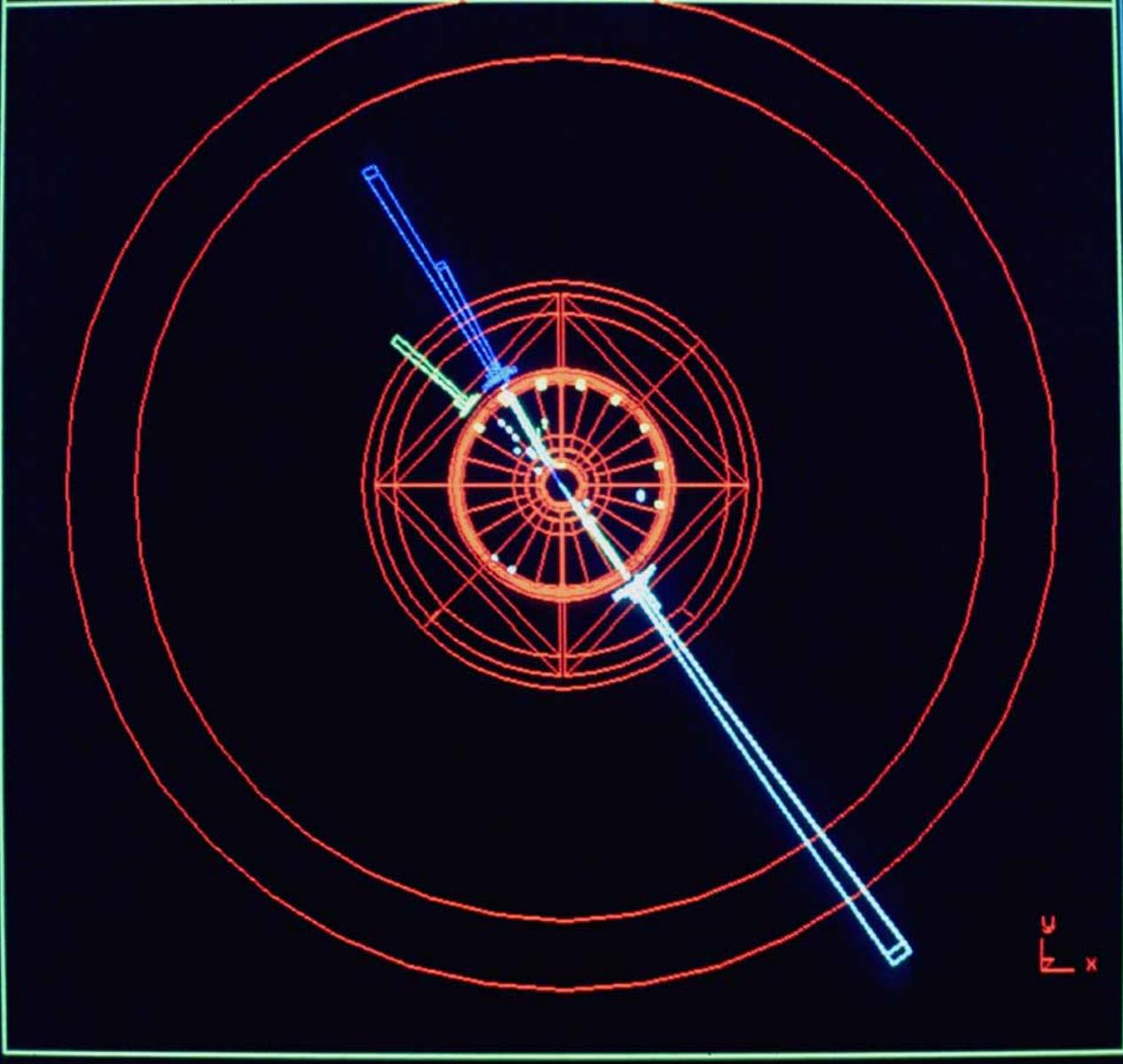
# L3 detector at CERN



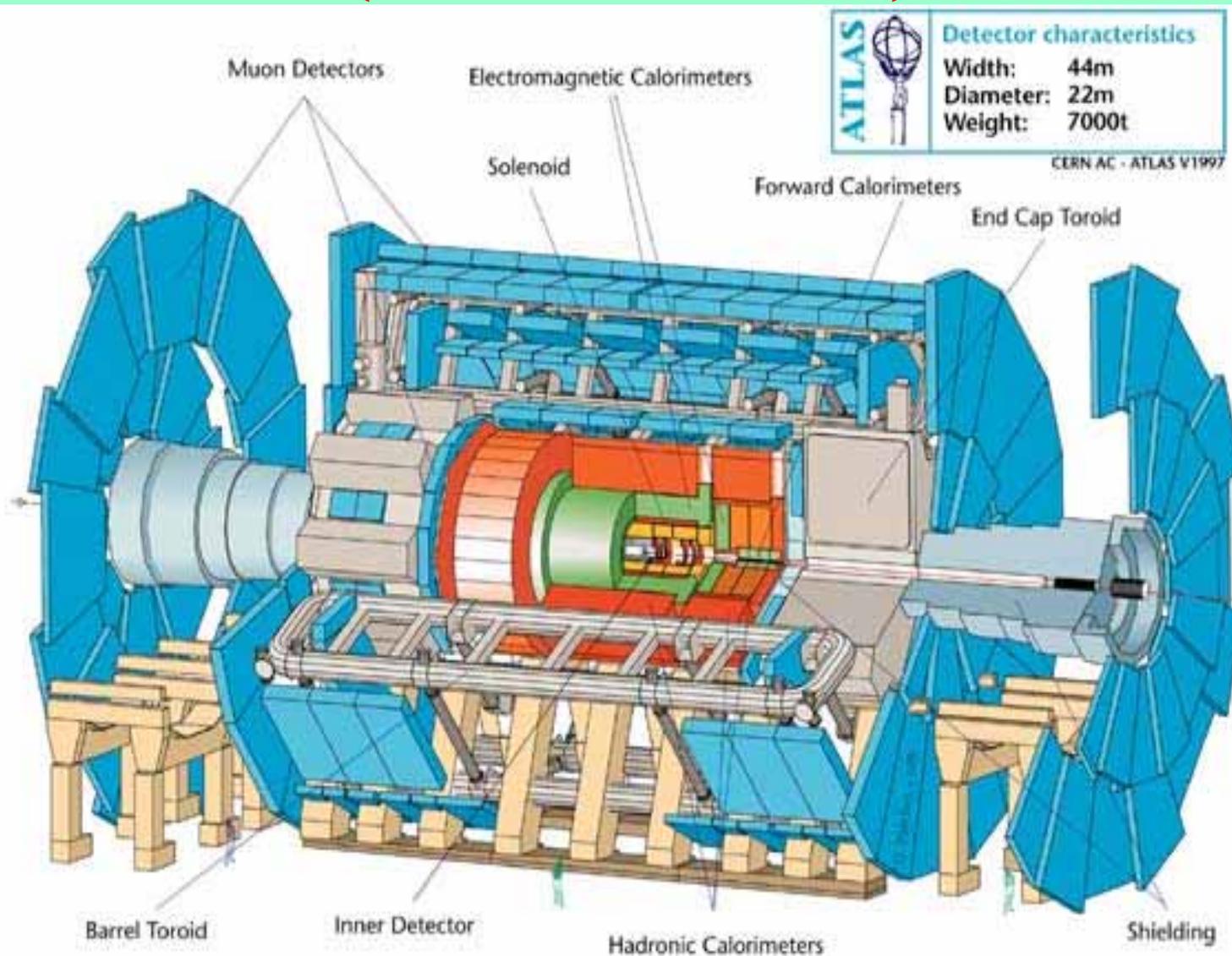
L<sub>3</sub>

RUN NR 149509  
EVENT NR 43736

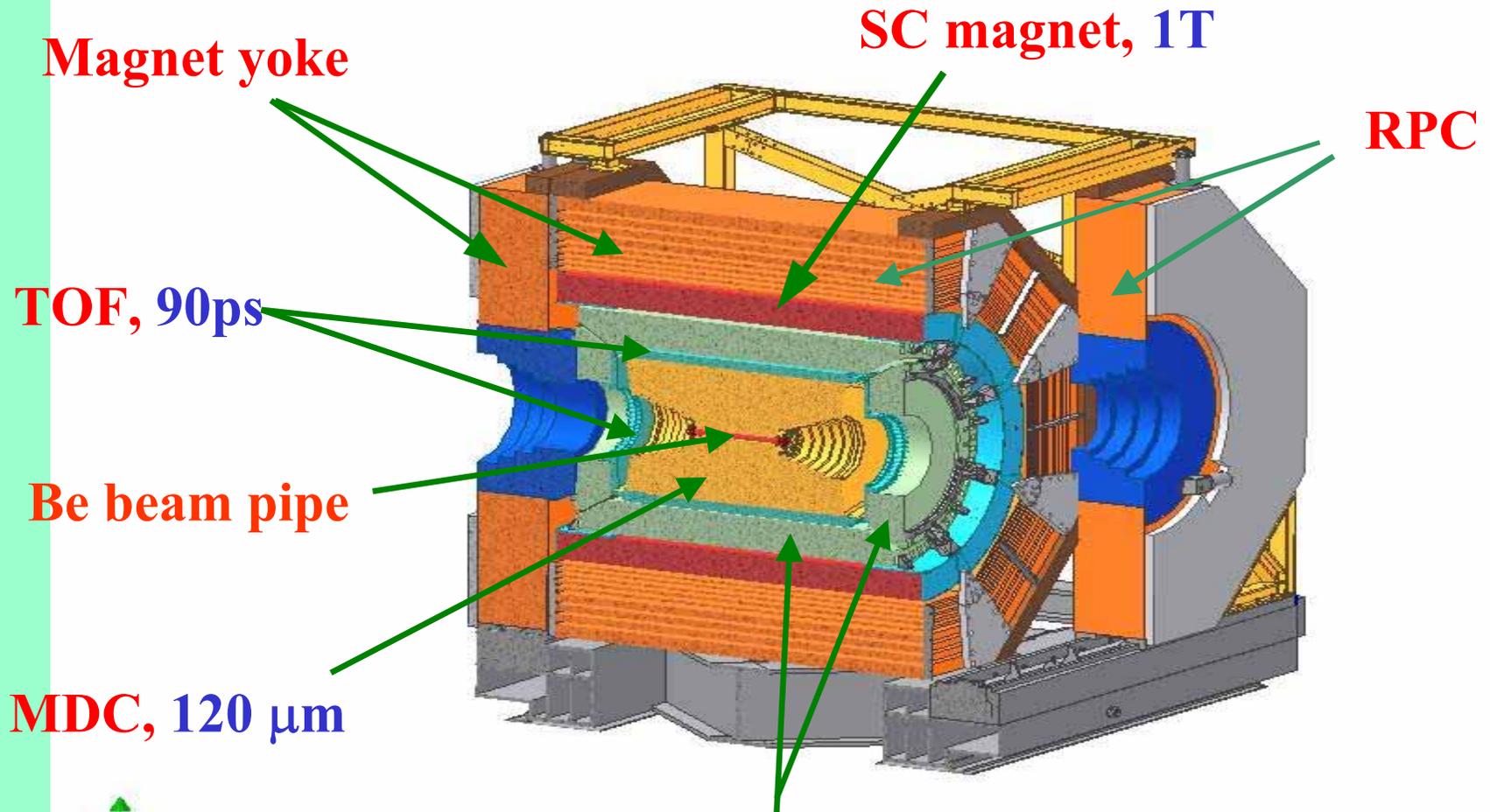
12/4/90  
07 13.03



# 建造中的 ATLAS 探测器 (CERN/LHC)



# 正在建造中的 BESIII 探测器



**CsI(Tl) calorimeter, 2.5 % @ 1 GeV**

# 安装中的BESIII探测器





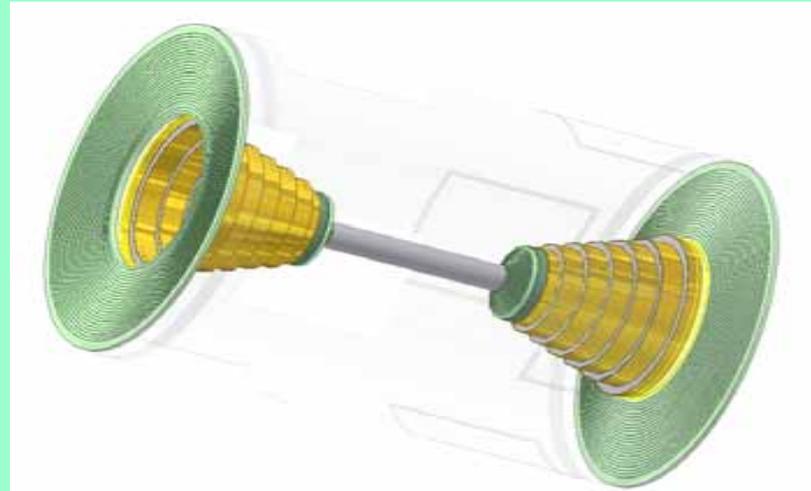
# 气体探测器

- **BESIII 气体漂移室**
- **RPC**
- **GEM**
- **阴极条室与漂移管**

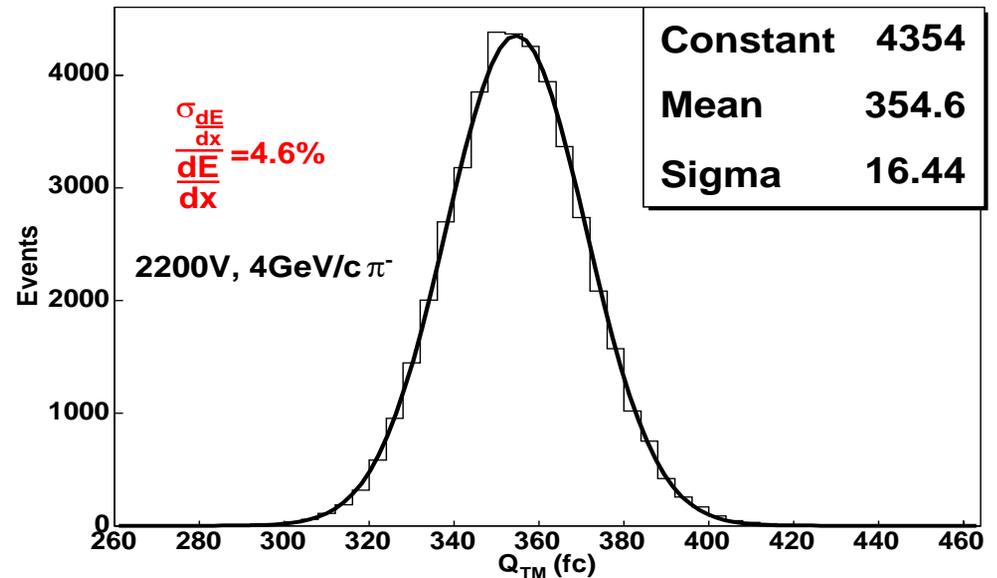
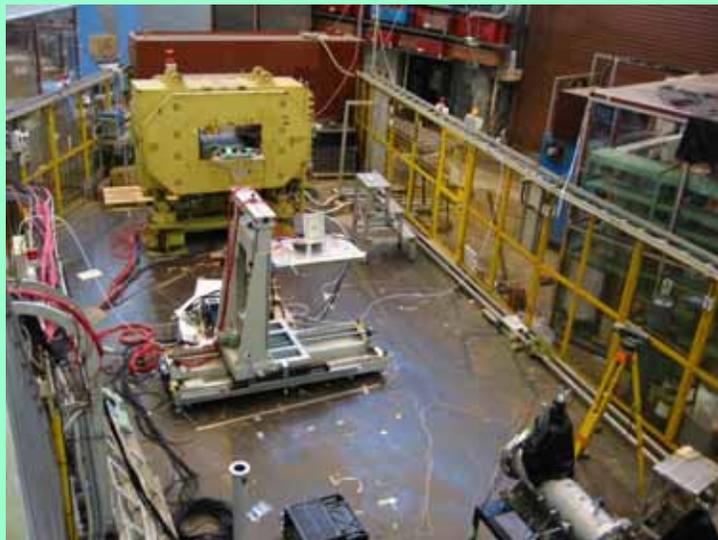
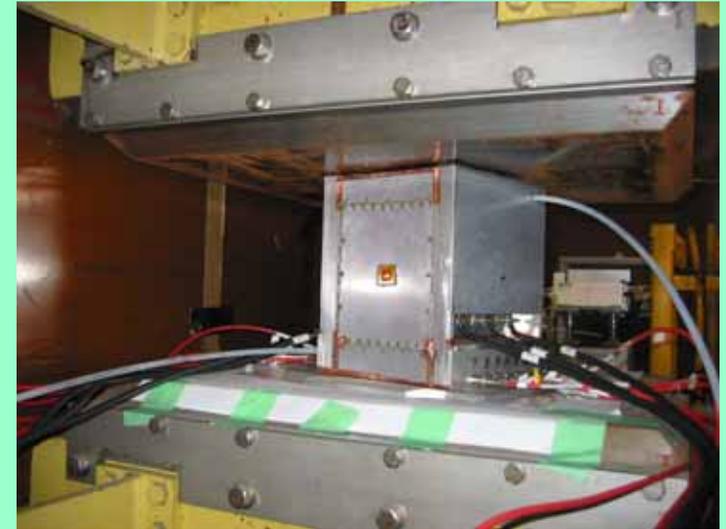
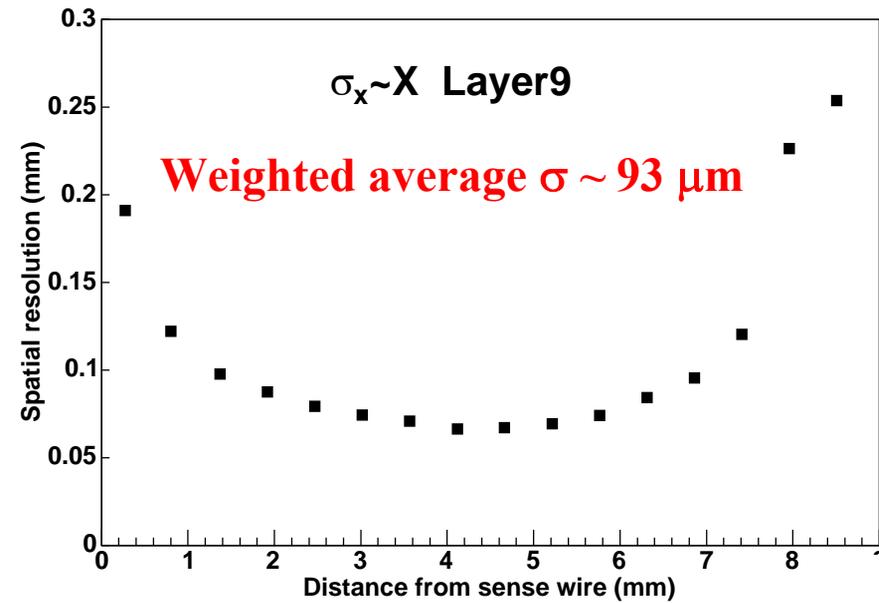
# BESIII 漂移室

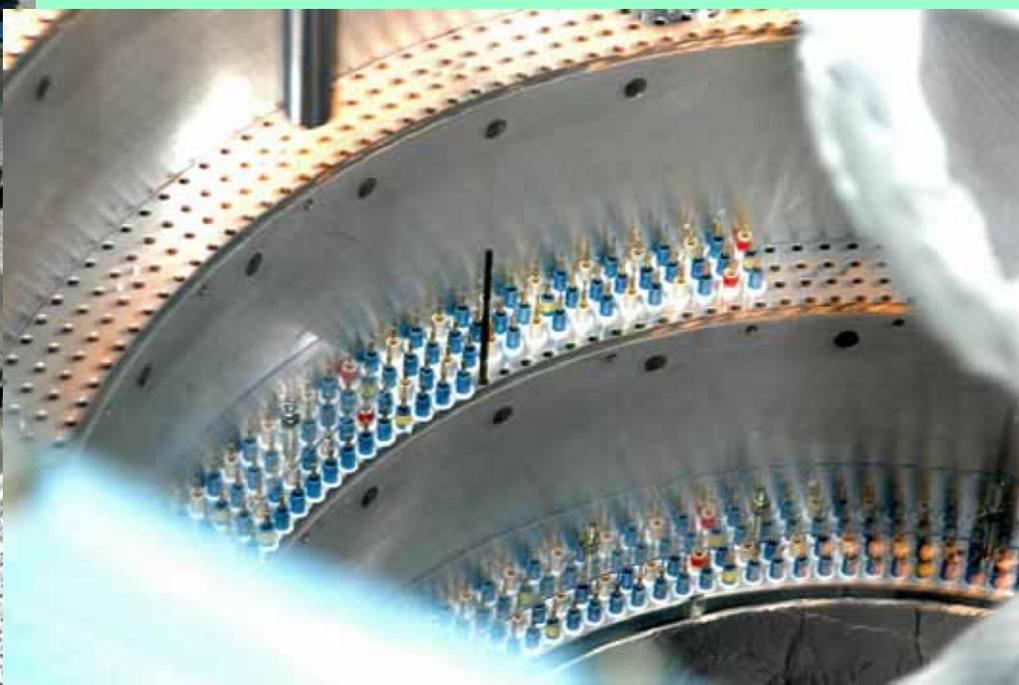
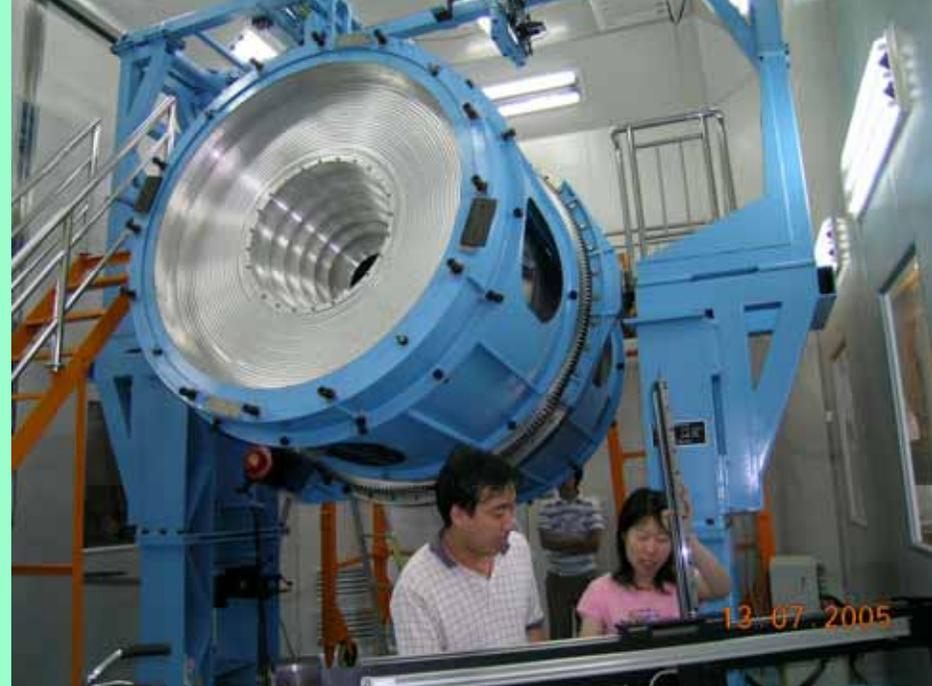
- 设计指标: 单丝分辨率  $130\mu\text{m}$ ,  $dE/dx$  6 %  
CLEO:  $\sim 85\mu\text{m}$ , 5.7%  
Babar:  $\sim 110\mu\text{m}$ , 6.2%  
Belle:  $\sim 130\mu\text{m}$ , 5.7%  
BESIII  $\sim 120\mu\text{m}$  6 %
- $R_{\text{in}} = 63\text{mm}$ ;  $R_{\text{out}} = 810\text{mm}$ ; length = 2400 mm
- 7000 Signal wires: 25(3% Rhenium)  $\mu\text{m}$  gold-plated tungsten
- 22000 Field wires: 110  $\mu\text{m}$  Al
- Gas: He + C<sub>3</sub>H<sub>8</sub> (60/40)
- **Momentum resolution@1GeV:**

$$\frac{\sigma_{P_t}}{P_t} = 0.32\% \oplus 0.37\%$$



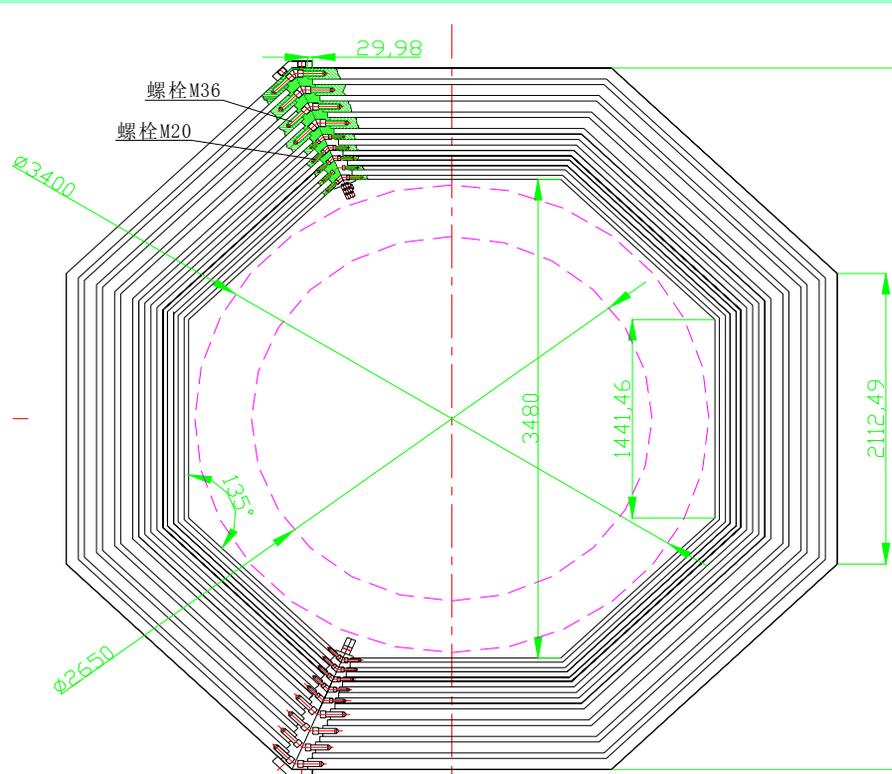
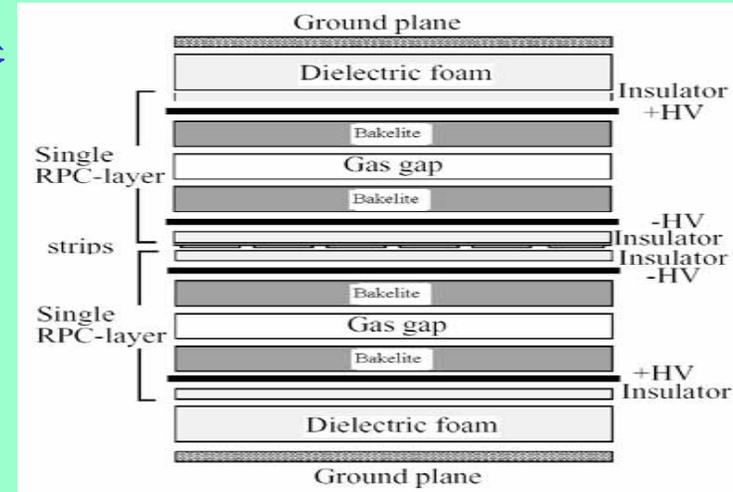
# Beam test at KEK





# BESIII $\mu$ system : RPC

- 阻性板室 (RPC) : 无丝气体探测器
- 造价低, 适用于大面积应用
- 9 layer, 2000 m<sup>2</sup>, 10000 channels
- Bakelite w/o lineseed oil
- Noise less than 0.1 Hz/cm<sup>2</sup>



• 国际上RPC可采用电木板 (L3, Babar, CMS, ...)或玻璃(Belle)

• Babar等实验发现寿命问题, 与RPC特殊制造工艺 --- 表面淋油有关;

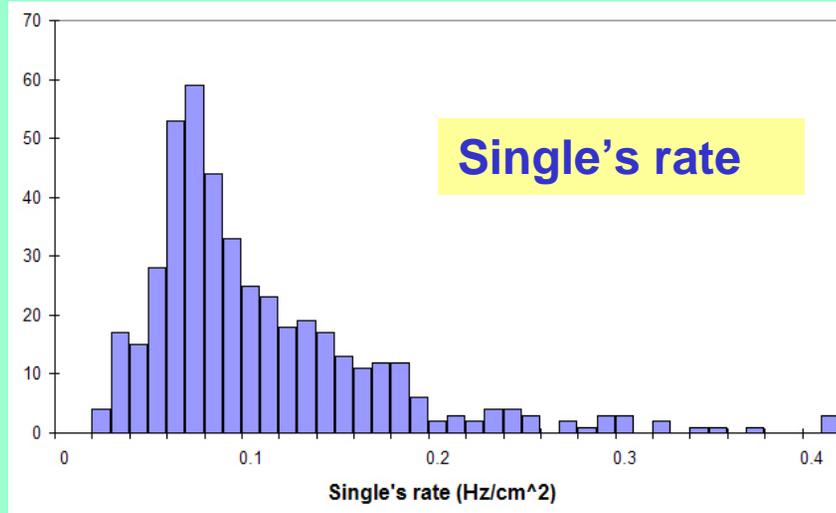
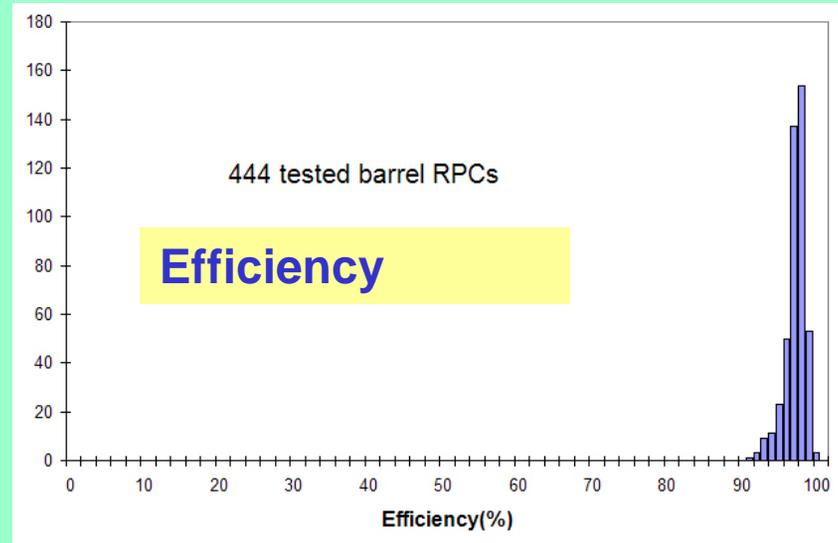
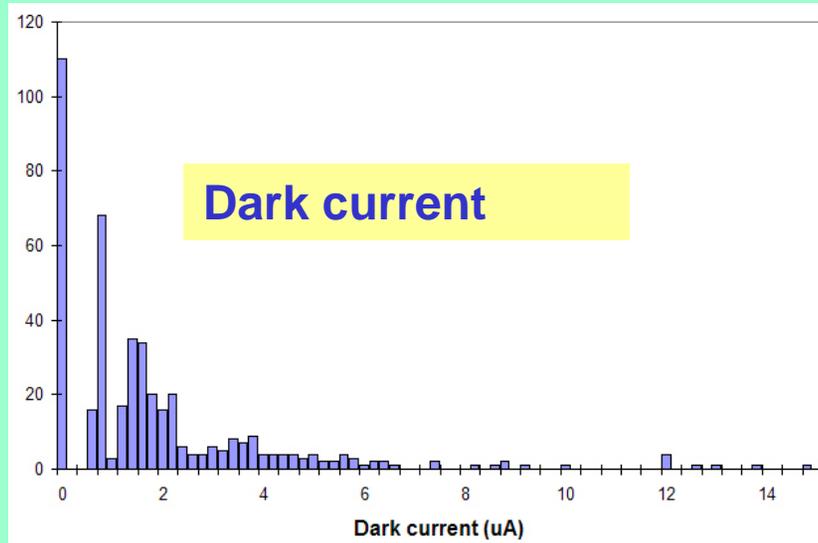
• BESIII RPC采用了新的不淋油工艺

# RPC production in the clean room



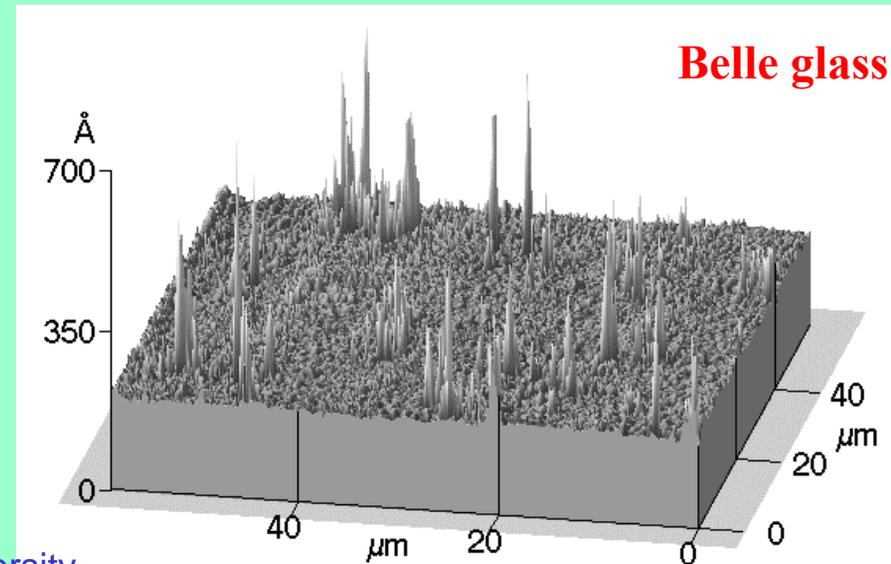
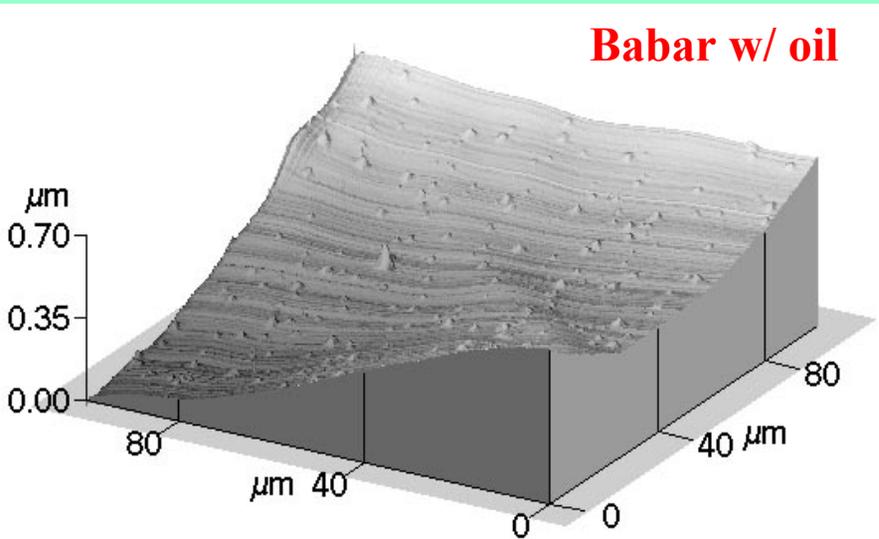
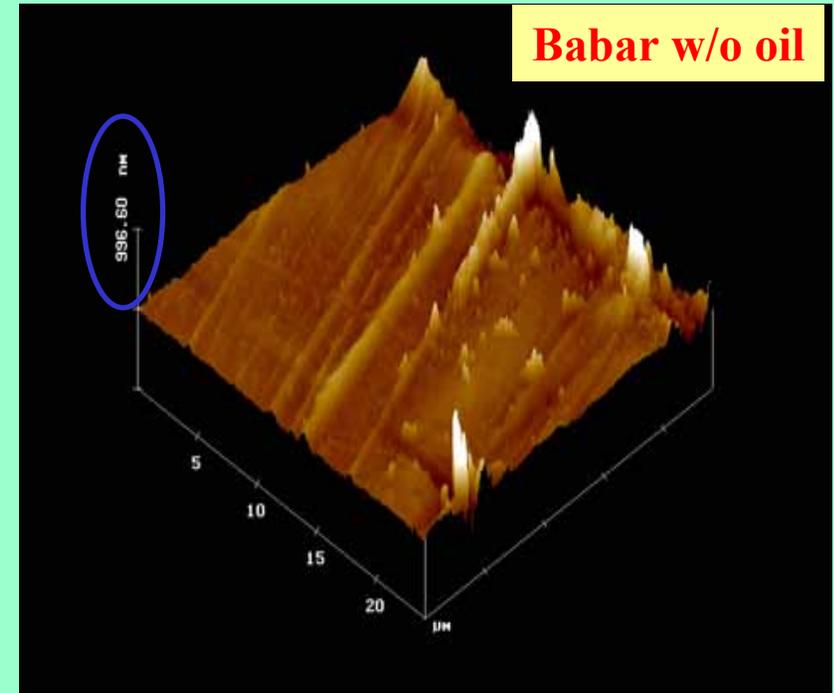
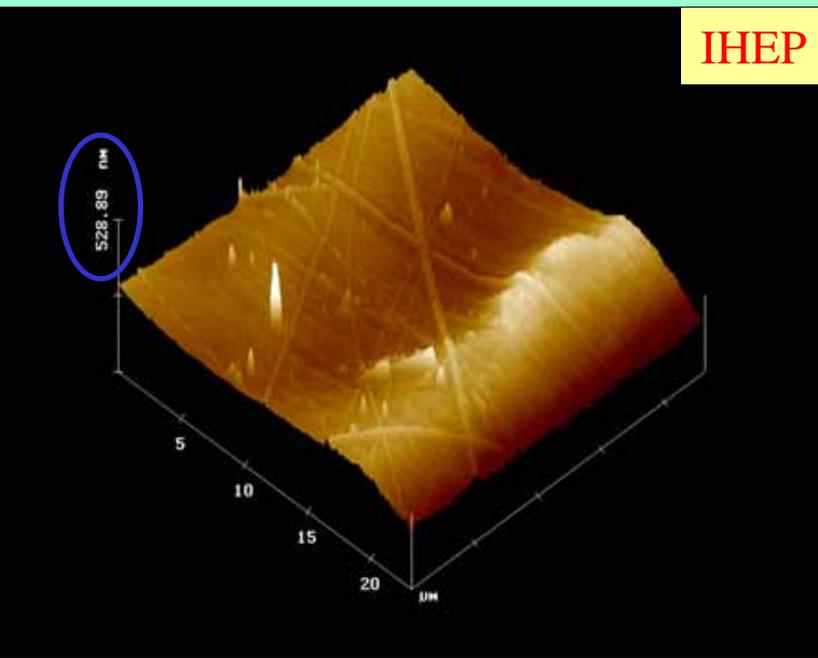
# Performance of RPCs

So far ~1000 RPCs fabricated, the average area for the endcap RPC is 1.3m<sup>2</sup>, barrel RPC 1.4m<sup>2</sup>. Maximum RPC is 1.2m x 2.4m. The performance statistics of the tested 444 barrel RPCs:



The performance is comparable to BaBar's new version of RPCs with Linseed oil coating.

# RPC surface seen by the atomic force microscope



# RPC and mechanics completed

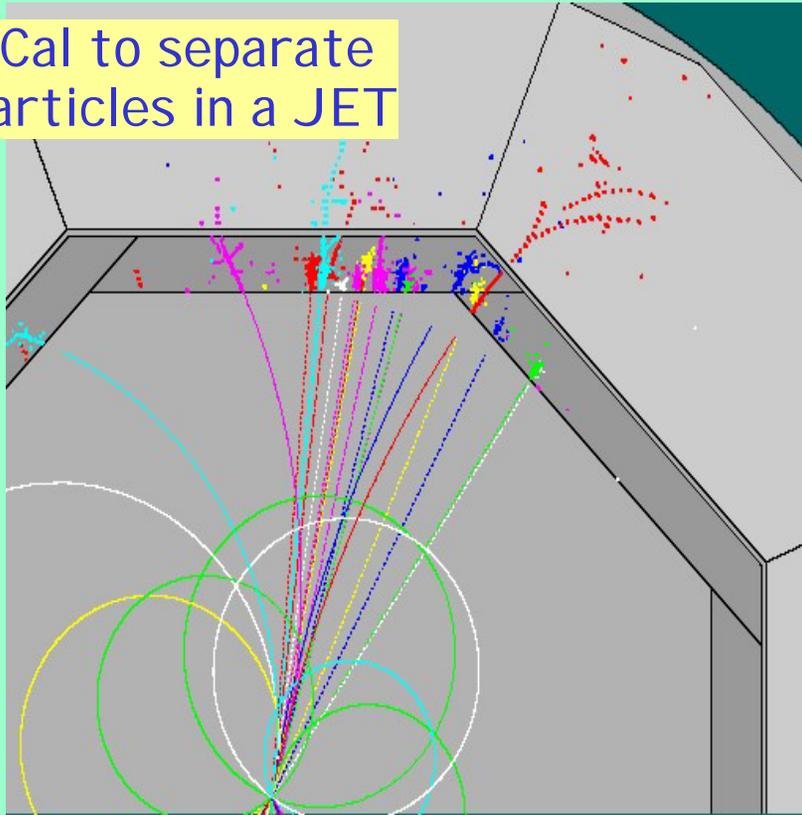


# **(m)RPC application in HEP**

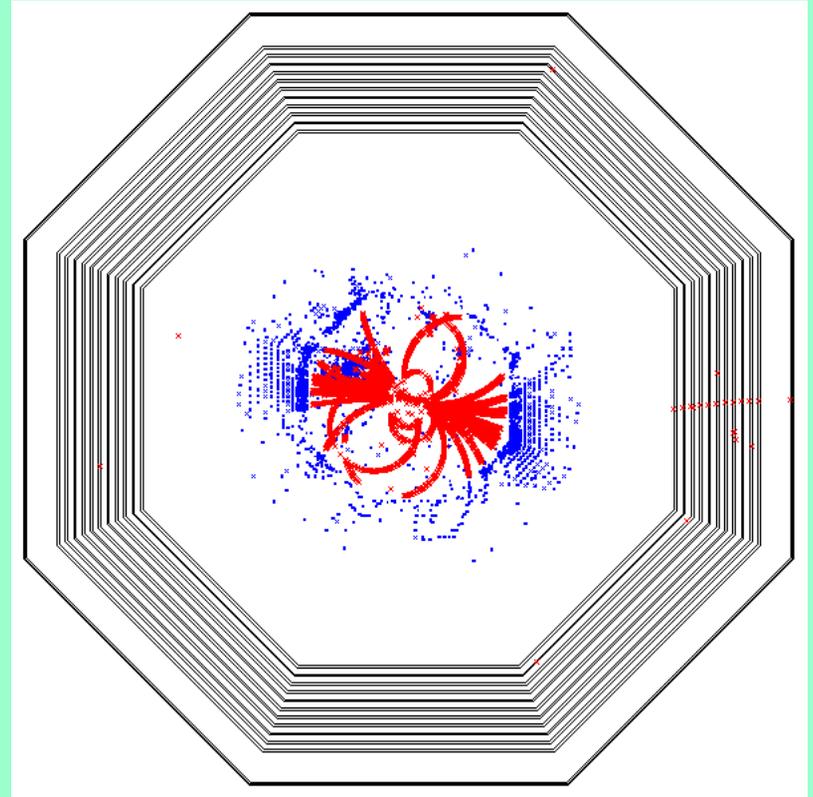
- **Muon chamber/muon trigger ( L3, CMS, Atlas, Phenix,...)**
- **Hadron calorimeter ( ILC )**
- **TOF ( Star, Alice...)**
- **Cosmic-ray exp. (羊八井, ...)**
- **Neutrino exp. (大亚湾, Opera, 印度,...)**

# Possible RPC application for ILC

HCal to separate  
particles in a JET

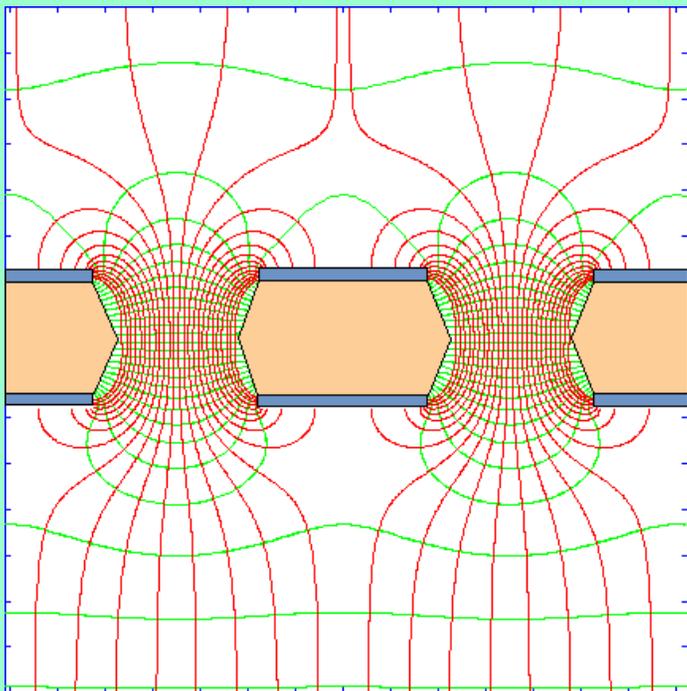


**RPC as the active detector  
of the digital hadron calorimeter**



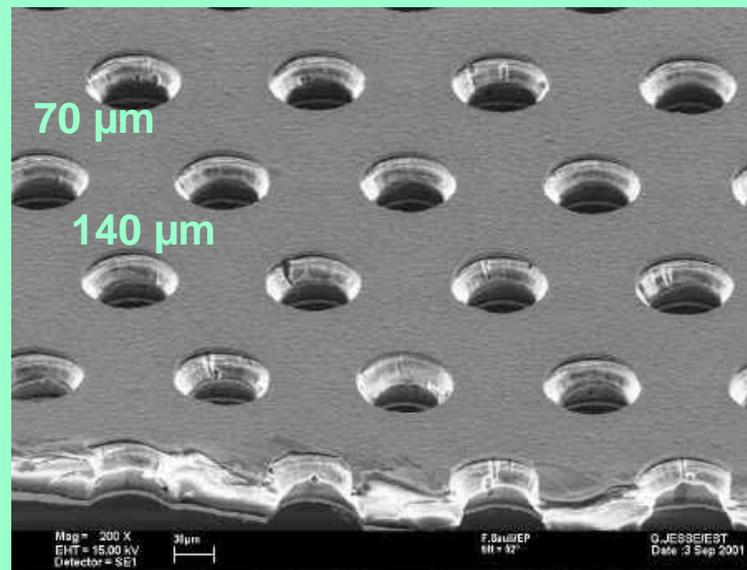
**RPC as the muon detector**

# GAS ELECTRON MULTIPLIER(GEM)



Thin metal-clad polymer foil  
with high density of holes

Gas gain ~ 100  
Two layers: 10,000



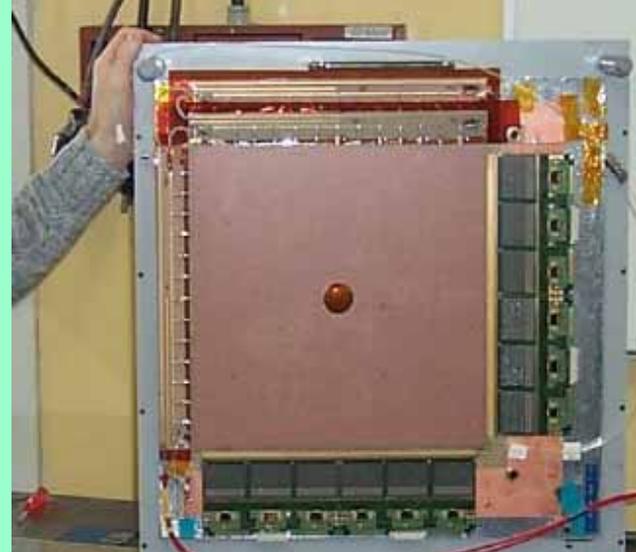
TYPICAL GEM GEOMETRY:

5 μm Copper on 50 μm Polymer

70 μm holes at 140 mm pitch

A cheap, simple, large area  $\gamma/e$  detector  
Can be used as tracker, gas chamber  
readout, image detector, ...

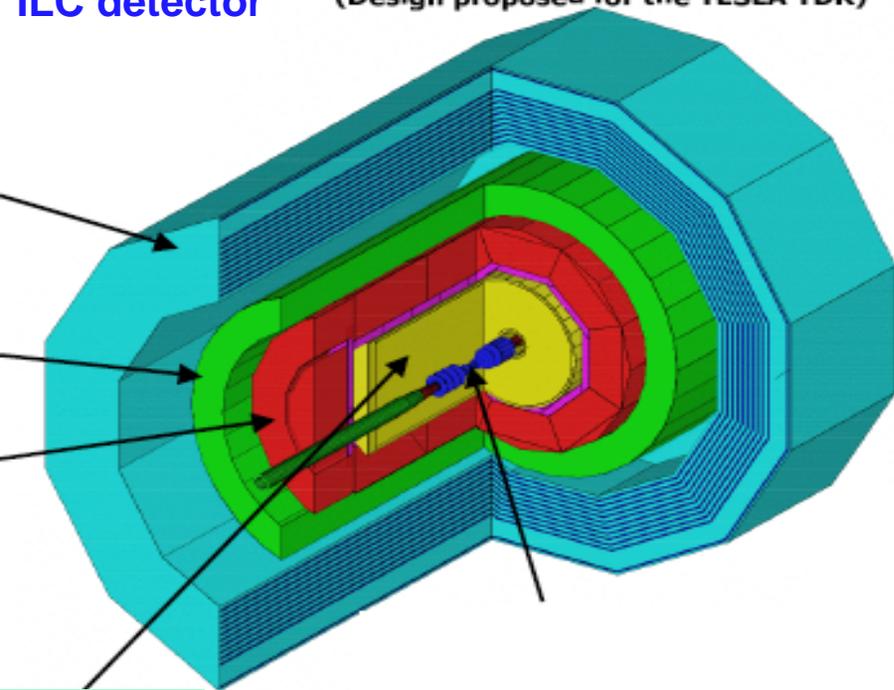
# GEM detector as tracking devices



Tracking detector for COMPASS

ILC detector

(Design proposed for the TESLA TDR)



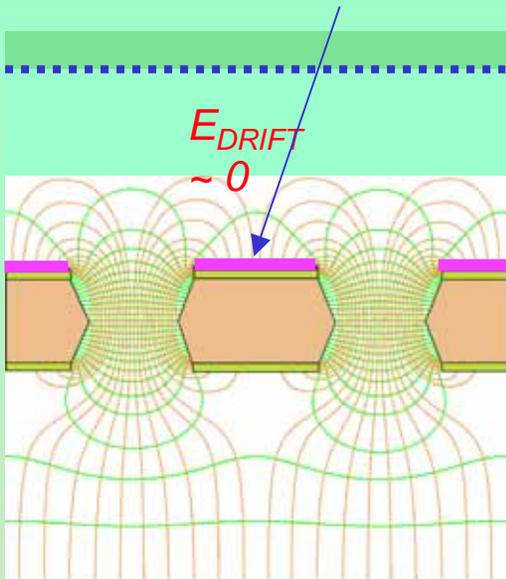
GEM TPC



Tracking detector for CMS

# GEM as a photon detector

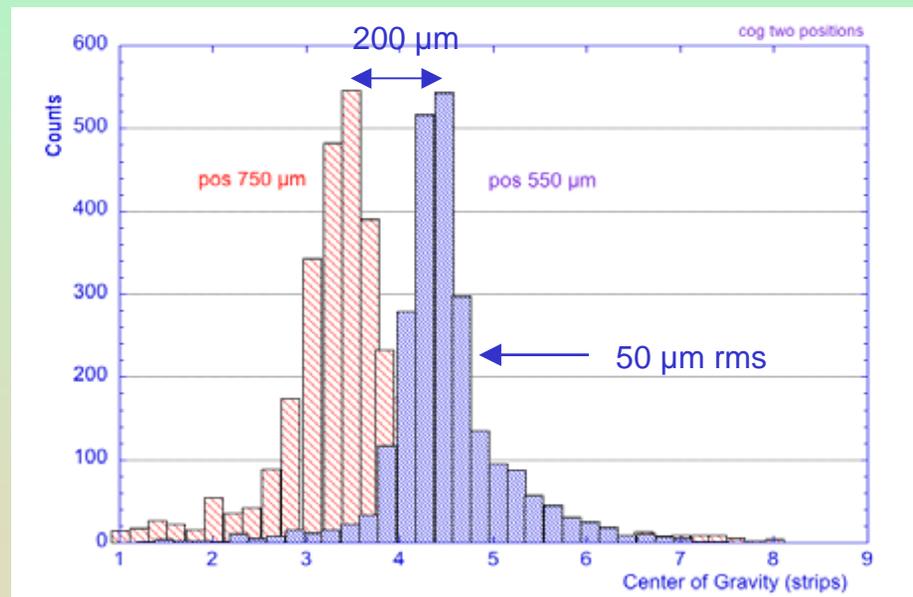
Reflective CsI photocathode:



R. Bouclier et al, *IEEE Trans. Nucl. Science NS-44(1997)646*

TRIPLE GEM WITH CsI PHOTOCATHODE

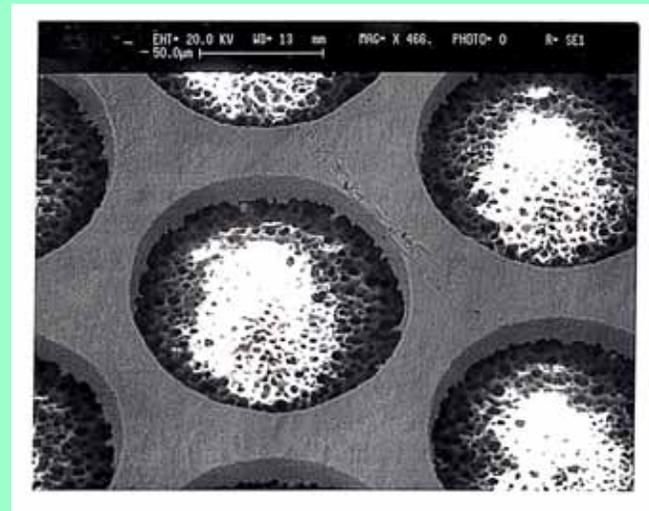
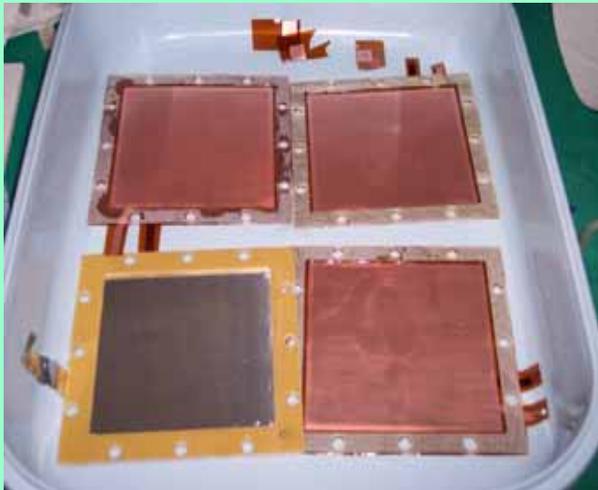
Single photon position accuracy: 50  $\mu\text{m}$



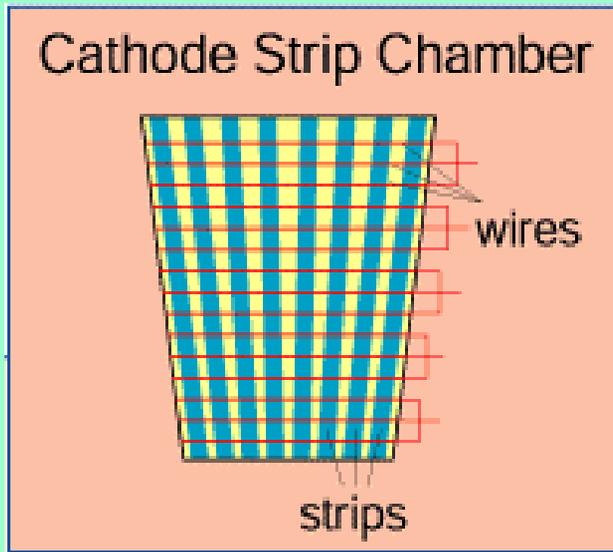
T. Meinschad, L. Ropelewski and F. Sauli, *Nucl. Instr. And Meth. A535(2004)324*

# 国内的研究状况

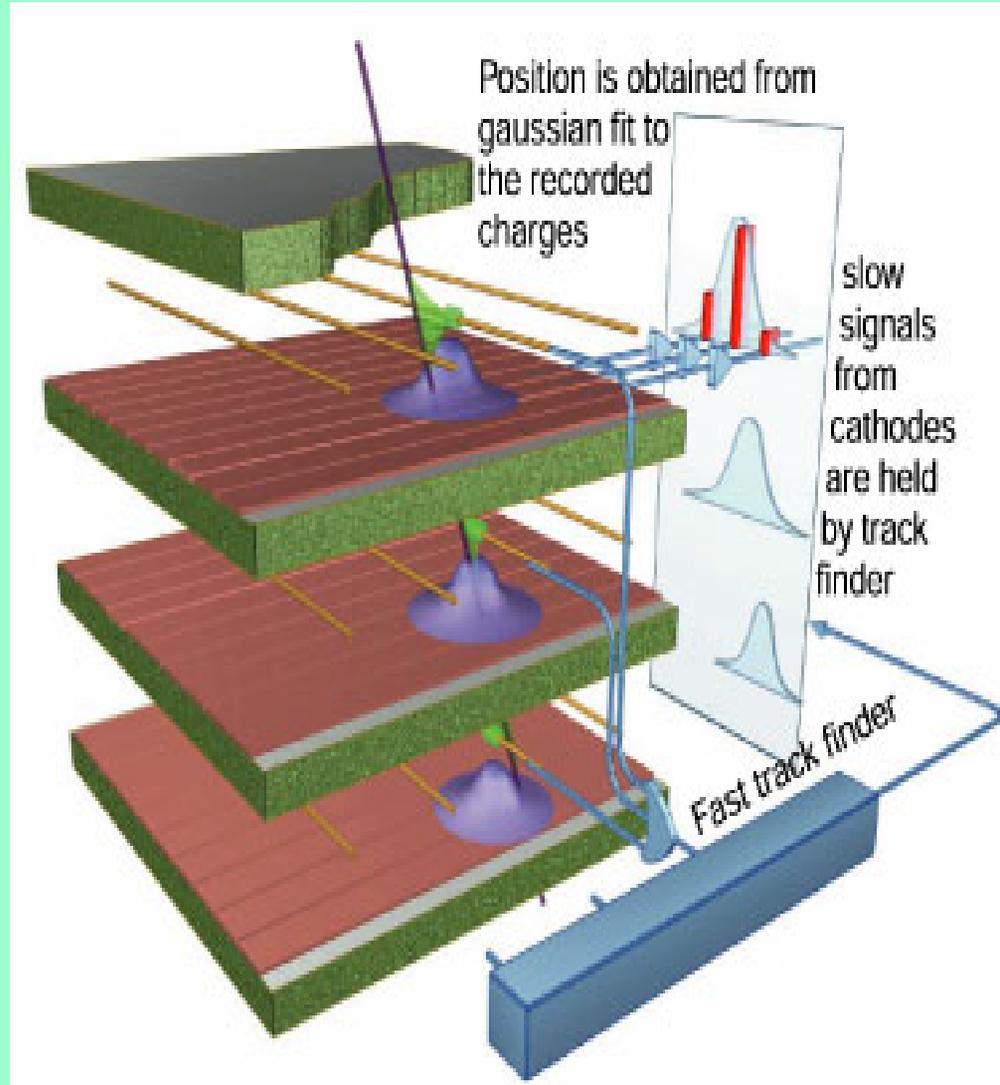
- 中国科技大学已完成模型室测试
- 清华大学与高能所合作，已完成模型室，正在测试
- 微孔膜的国产化已取得重要进展



# 为欧洲核子研究中心（CERN）上的 CMS实验建造的 $\mu$ 子探测器：阴极条室

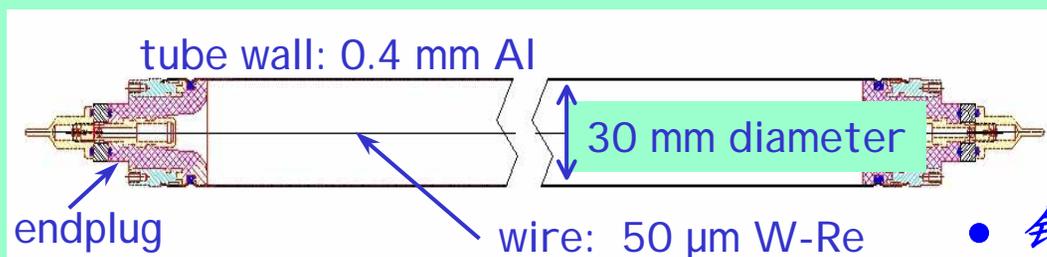


高计数率 ( $\sim 1\text{KHz}/\text{cm}^2$ )  
空间分辨率  $50\ \mu\text{m}$   
时间响应  $< 25\ \mu\text{s}$   
寿命  $> 10$ 年 (累计 $0.1\text{C}/\text{cm}$ )





# 为CERN的ATLAS实验建造 $\mu$ 子探测器: **MDT**



**MDT ( Monitored Drift Tube )**

**漂移管: 1—6米长**

- 铝管外径30mm, 壁厚0.4mm;
- 阳极丝直径50 $\mu$ m;
- 端头确定丝位置, 提供气体通路;

— 指标要求:

空间分辨	50 $\mu$ m
单管分辨	80 $\mu$ m
单管的丝定位精度	10 $\mu$ m r.m.s
室内丝定位精度	20 $\mu$ m r.m.s

— 主要工作参数:

混合气体      Ar/CO<sub>2</sub> (93/7)

气压            3 bar

增益             $2 \times 10^4$

工作电压       3080V

最大漂移时间 ~ 700ns

# 高能所MDT生产线



- ◇ 恒温恒湿洁净室：洁净度 10000级 温度  $(20 \pm 1) ^\circ\text{C}$  湿度  $(45 \pm 10) \%$
- ◇ MDT管组装平台
- ◇ MDT管测试：丝张力、漏气率、漏电流、丝定位
- ◇ MDT室组装平台：组装精度  $20\mu\text{m}$

# 晶体量能器

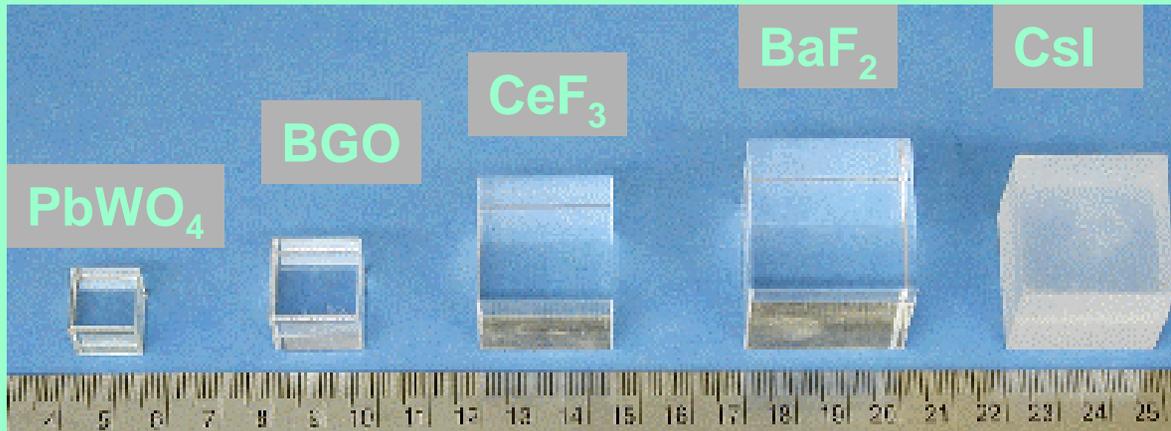
- CsI(Tl)
- BGO
- PbWO<sub>4</sub>
- LSO

# Summary of Crystals for HEP

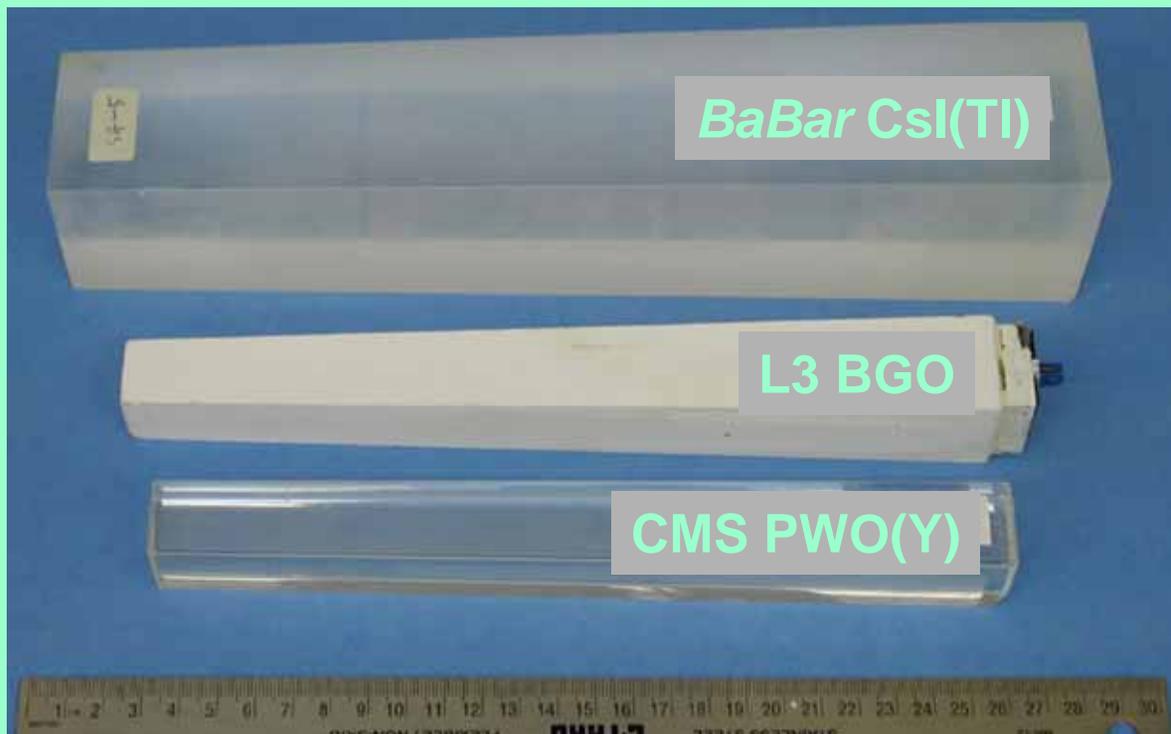
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF <sub>2</sub>	BGO	PbWO <sub>4</sub>	LSO(Ce)	GSO(Ce)
Density (g/cm <sup>3</sup> )	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (°C)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.12	0.9	1.14	1.37
Molière Radius (cm)	4.8	3.5	3.5	3.4	2.3	2.0	2.3	2.37
Interaction Length (cm)	41.4	37.0	37.0	29.9	21.8	18	21	22
Refractive Index <sup>a</sup>	1.85	1.79	1.95	1.50	2.15	2.2	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence <sup>b</sup> (nm) (at peak)	410	560	420 310	300 220	480	560 420	420	440
Decay Time <sup>b</sup> (ns)	230	1300	35 6	630 0.9	300	50 10	40	60
Light Yield <sup>b,c</sup> (%)	100	45	5.6 2.3	21 2.7	13	0.1 0.6	75	30
d(LY)/dT <sup>b</sup> (%/°C)	~0	0.3	-0.6	-2 ~0	-1.6	-1.9	-0.3	-0.1
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV	TAPS (L*) (GEM)	L3 BELLE PANDA?	CMS ALICE PANDA? BTev...	-	-

a. at peak of emission; b. up/low row: slow/fast component; c. measured by PMT of bi-alkali cathode.

# Crystal Density: Radiation Length



**1.5  $X_0$  Cubic**



**Full Size Samples**

***BaBar CsI(Tl)*: 16  $X_0$**

**L3 BGO: 22  $X_0$**

**CMS PWO(Y): 25  $X_0$**

# BESIII CsI(Tl) crystal calorimeter

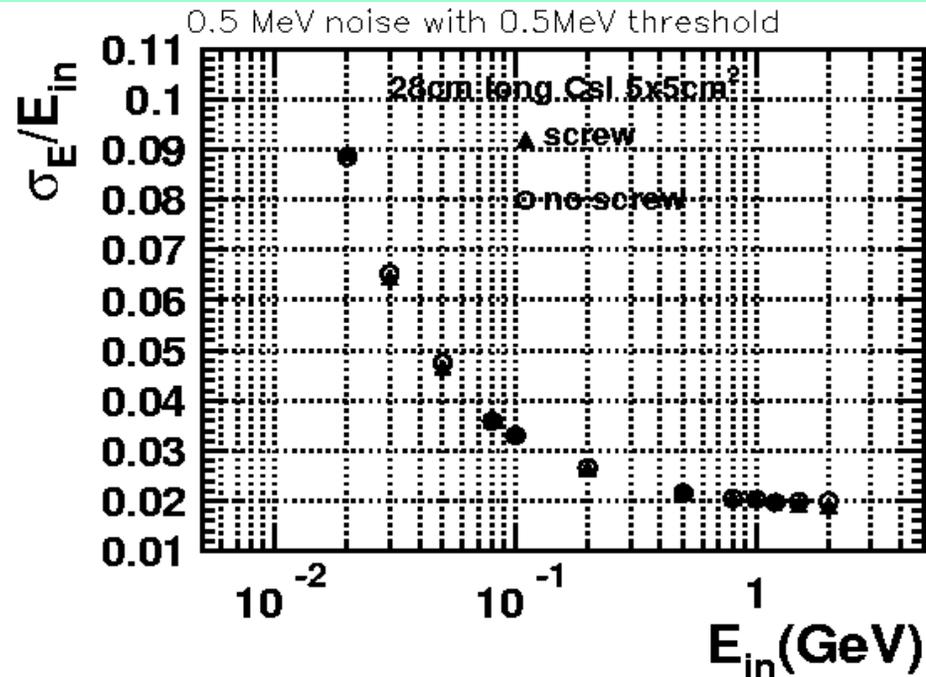
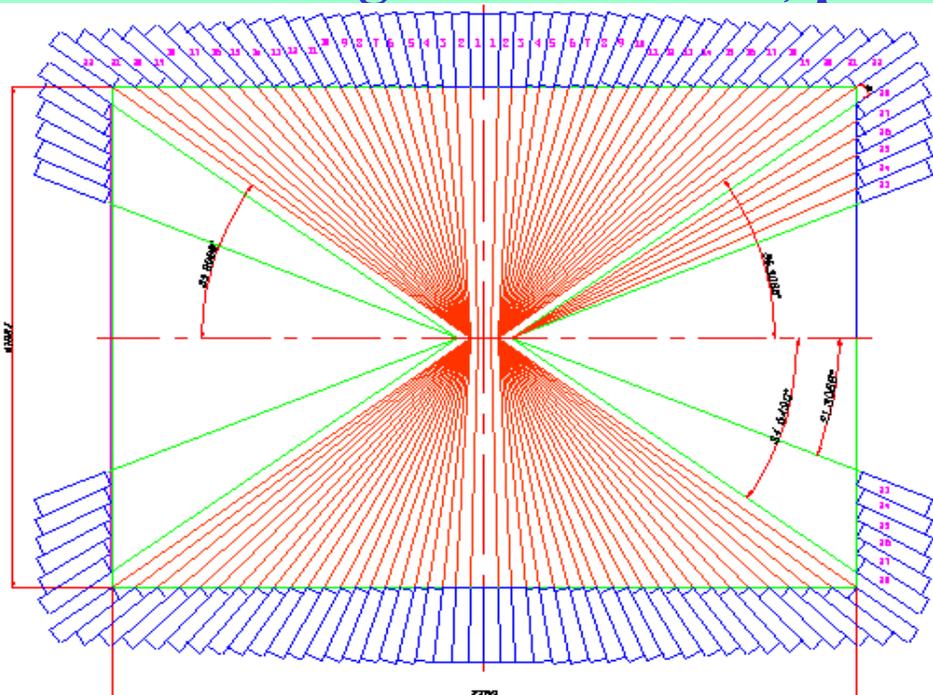
- Barrel: 5280 crystals, Endcap: 960 crystals
- Crystal:  $(5.2 \times 5.2 - 6.4 \times 6.4) \times 28 \text{cm}^3$
- Readout: 13000 Photodiodes,  $1 \text{cm} \times 2 \text{cm}$ ,
- Energy range: 20 MeV – 2 GeV
- position resolution:  $6 \text{ mm} @ 1 \text{ GeV}$
- Tiled angle:  $\theta \sim 1-3^\circ$ ,  $\phi \sim 1.5^\circ$

Babar:  $2.67\% @ 1 \text{ GeV}$

BELLE:  $2.2\% @ 1 \text{ GeV}$

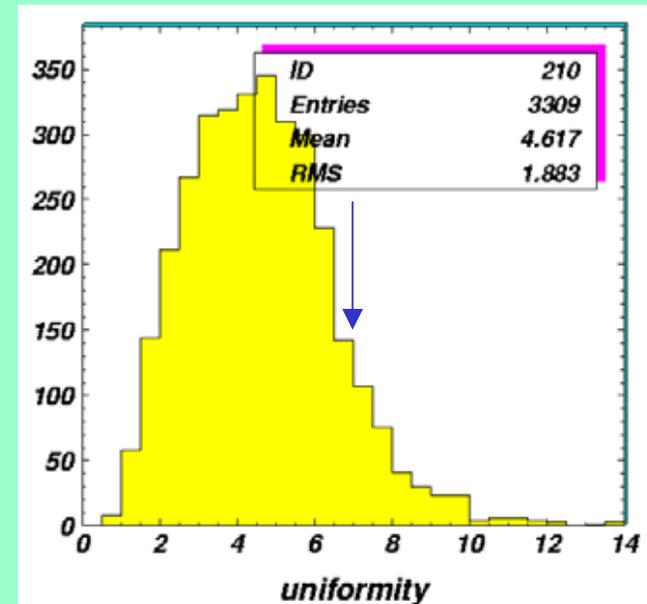
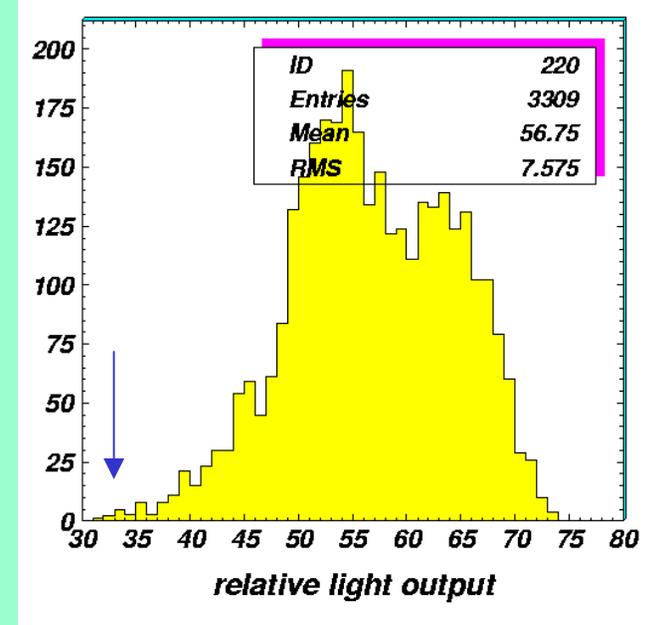
CLEO:  $2.2\% @ 1 \text{ GeV}$

BESIII:  $2.5\% @ 1 \text{ GeV}$



# Crystal production

Producer	quantity
Saint-Gobain	3000
SIC	1992
Hamamatzu, Beijing	1320



# Mechanical structure: no supporting walls for better resolution

A 1/60 prototype



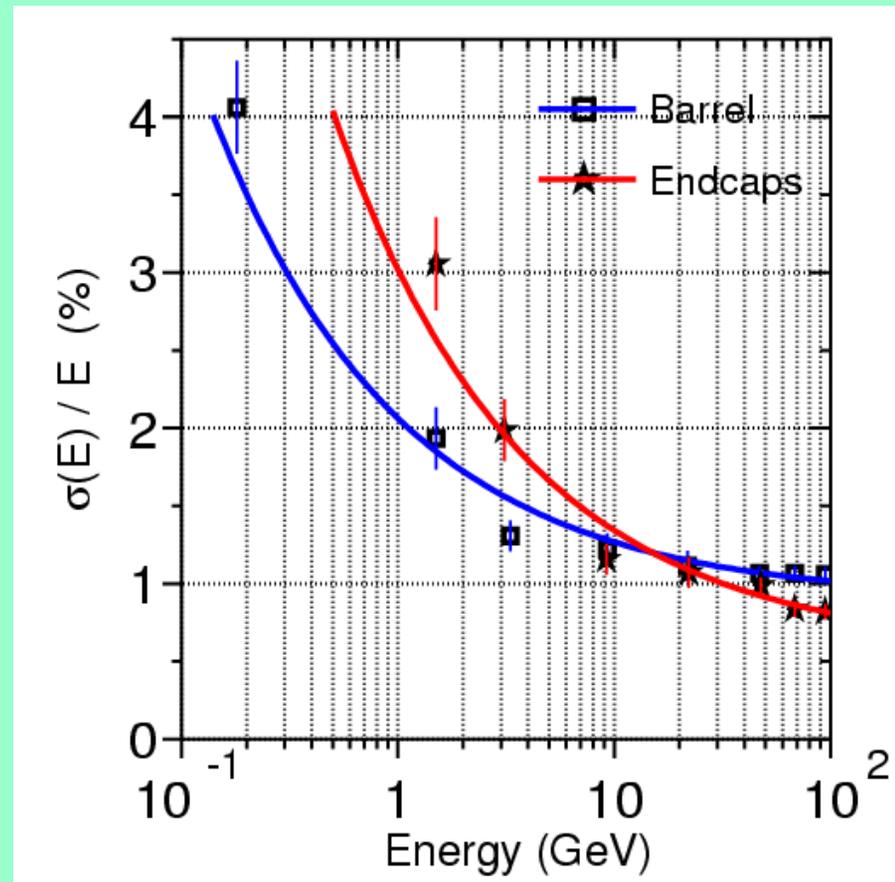
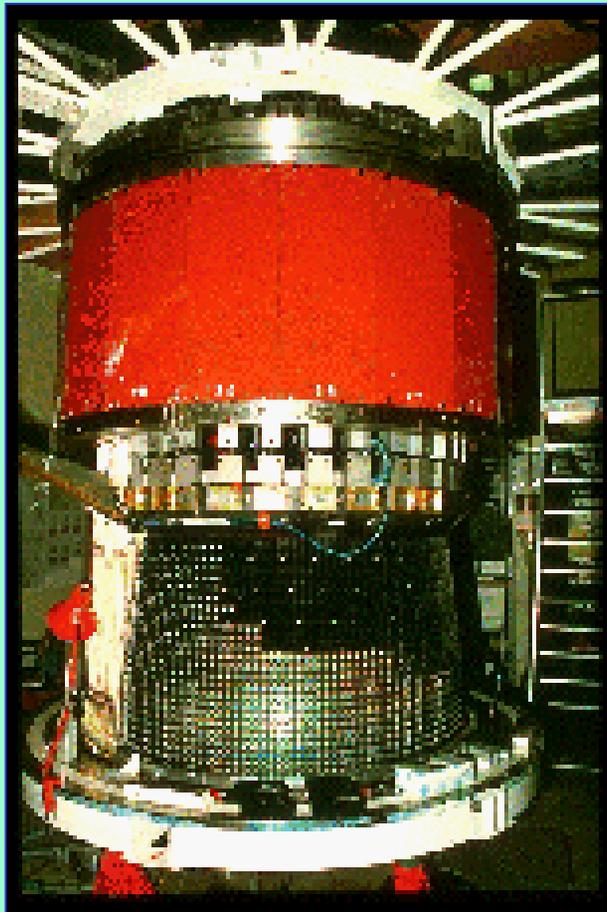
Three independent calculations + experiments



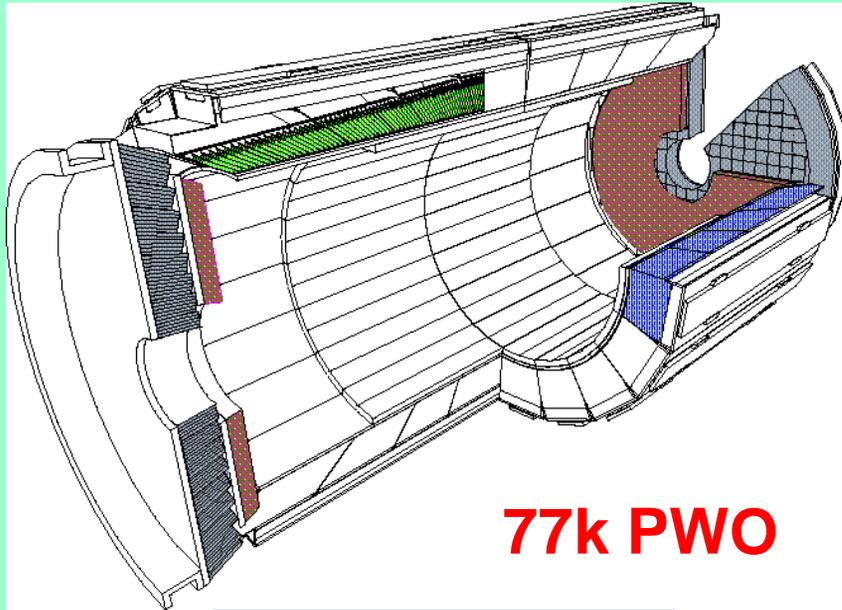
# L3 BGO calorimeter



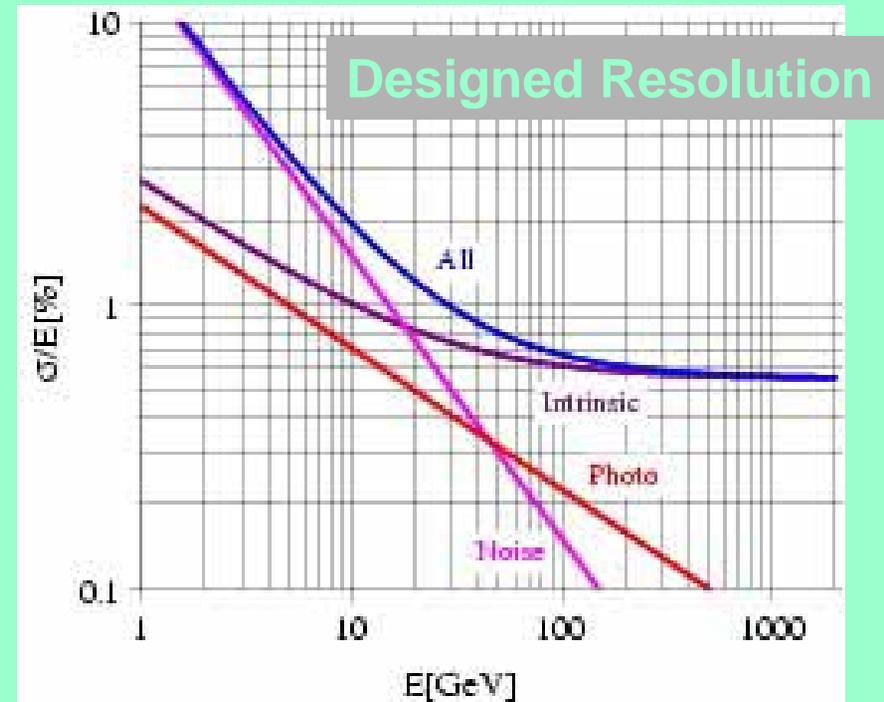
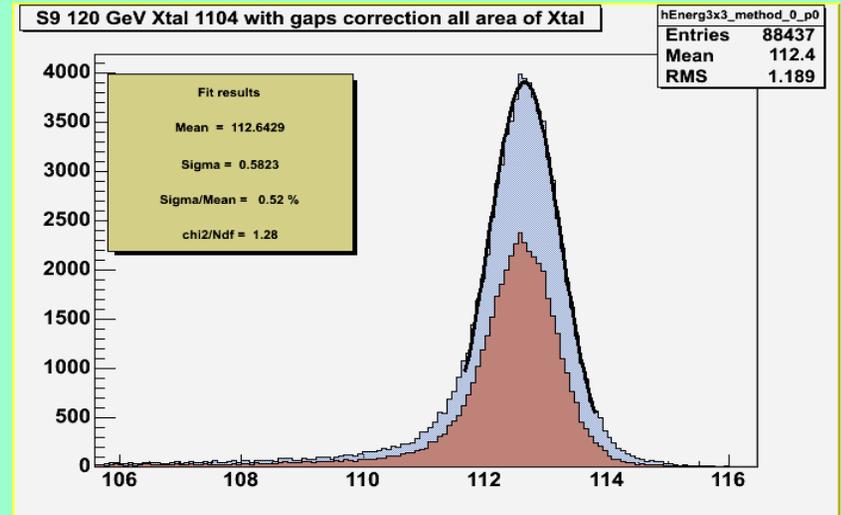
All 12,000 crystals produced by SIC



# CMS PWO crystal calorimeter



2004 Beam Test



# 未来高能物理实验与医学成像的 理想晶体：LSO

**Fast:** 40 ns  
**Dense:** 7.4 g/cm<sup>3</sup>  
**light yield:** 70% of NaI

**Costly:** 15\$/cc ?  
**Noisy:** ~ 1MeV



重庆26所样品

Φ 80 x 120

Large size LSO (Ce:Lu<sub>2</sub>SiO<sub>5</sub>) crystals are in production

# 闪烁探测器

- **BESIII TOF**
- **Plastic scintillator**
- **liquid scintillator**



# Structure of TOF

- Aim: particle identification (PID)

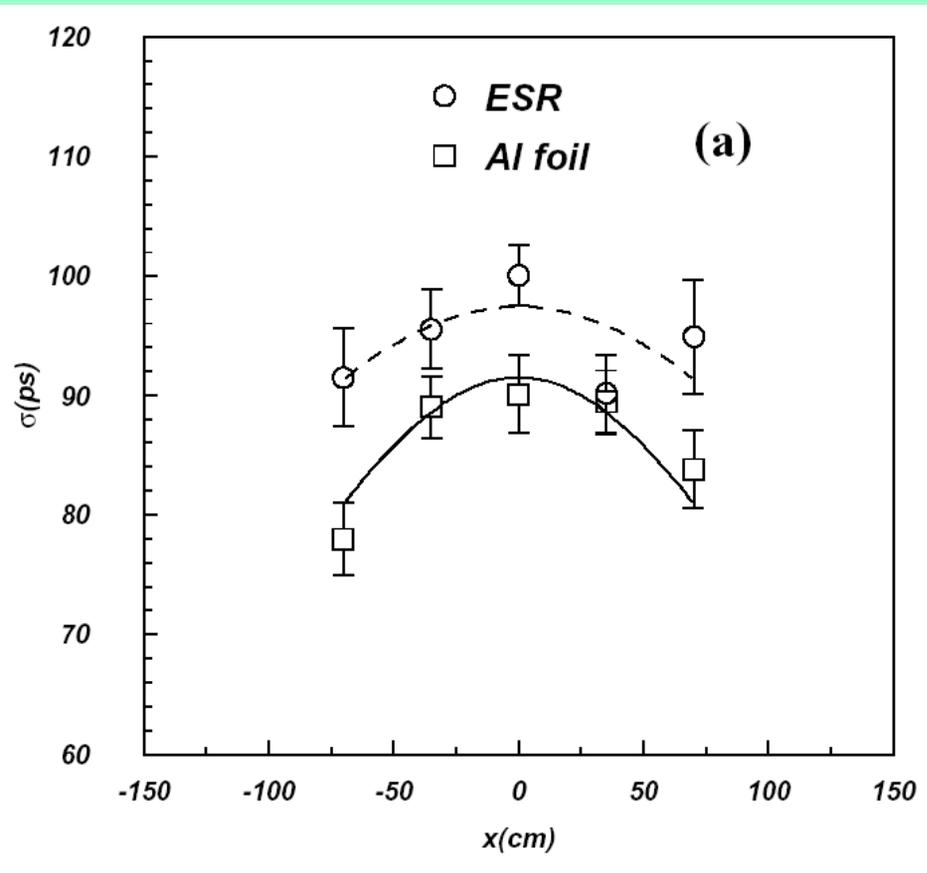
Barrel  
TOF

Endcap  
TOF

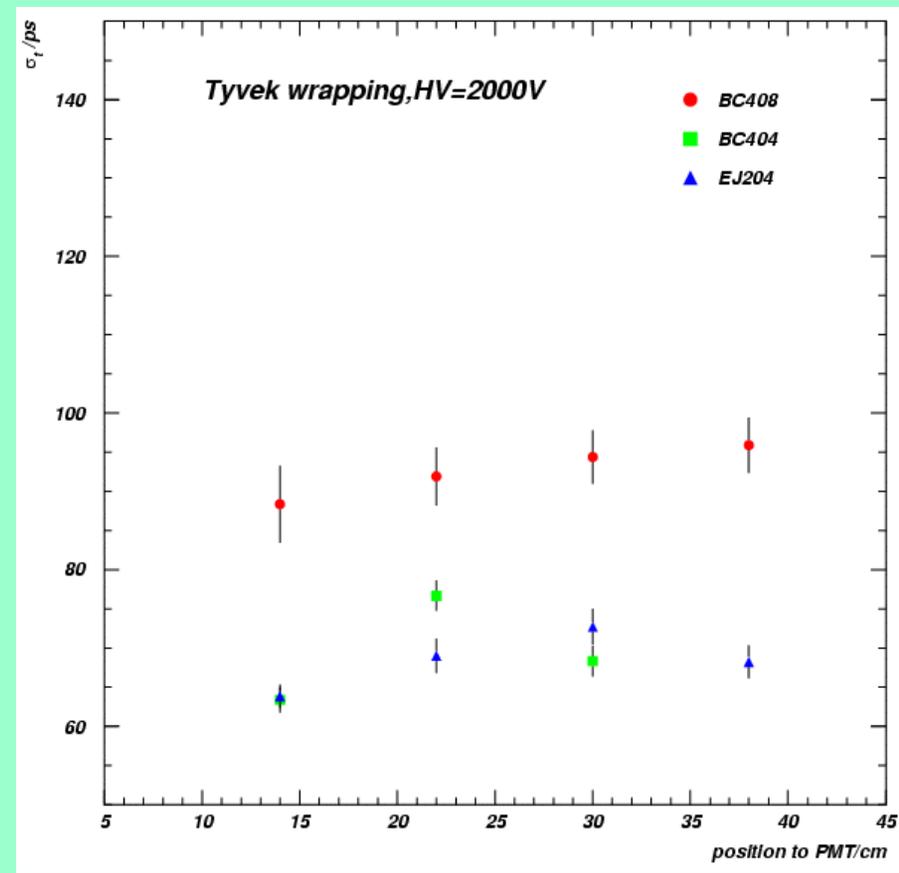
Scintillator: 2.4 m long, 5cm thick



# Test beam at IHEP: for various types of scintillators, thickness, wrapping materials, ...

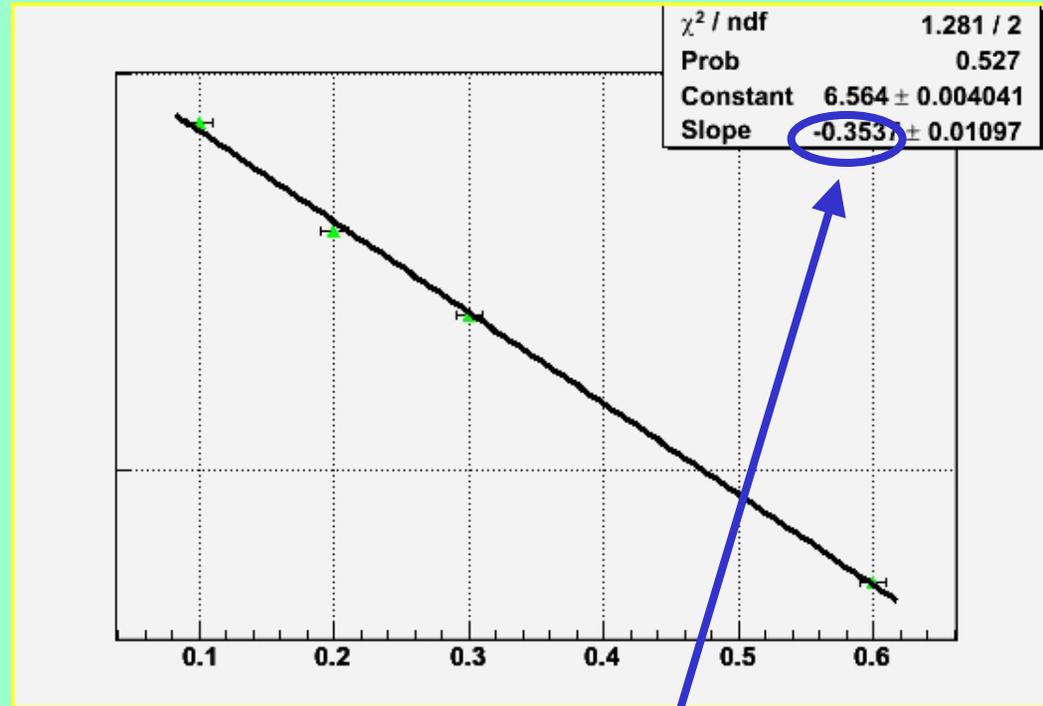


Barrel



Endcap

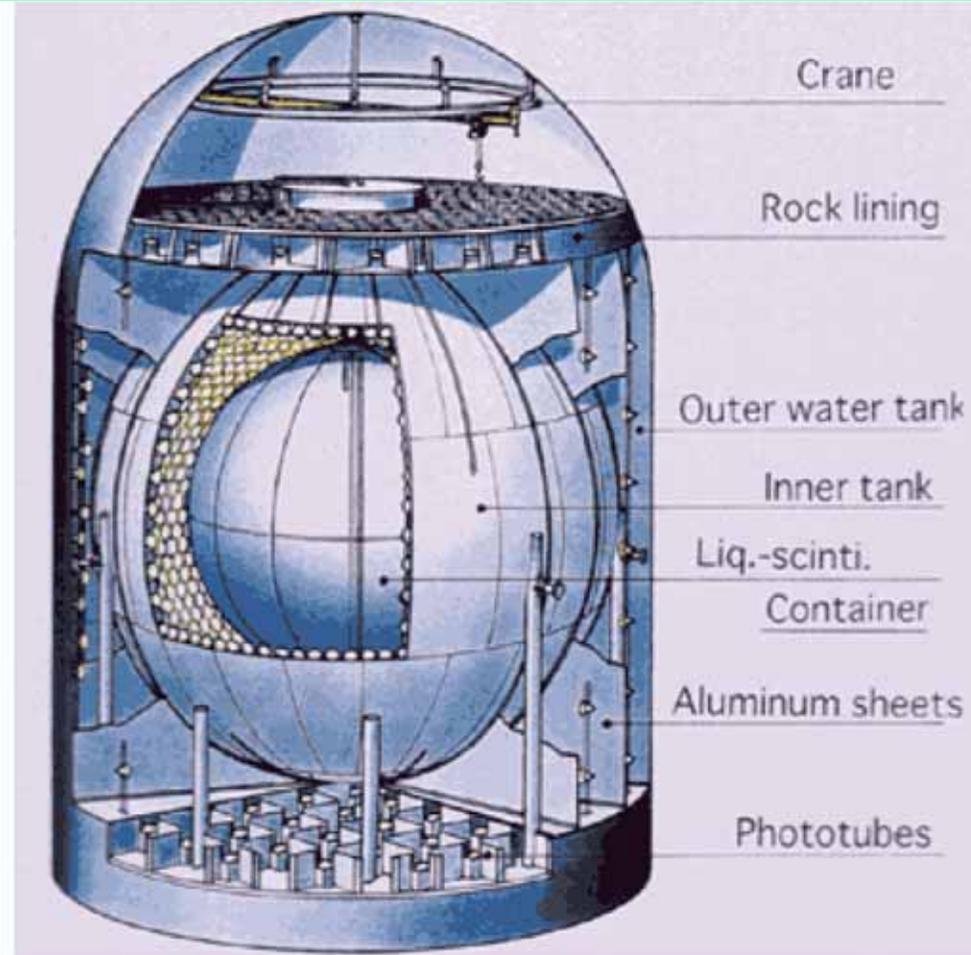
# 国产塑料闪烁体



衰减长度: 2.83m  
光产额: 40%蒽晶体

# KamLAND: the ultimate reactor neutrino oscillation experiment

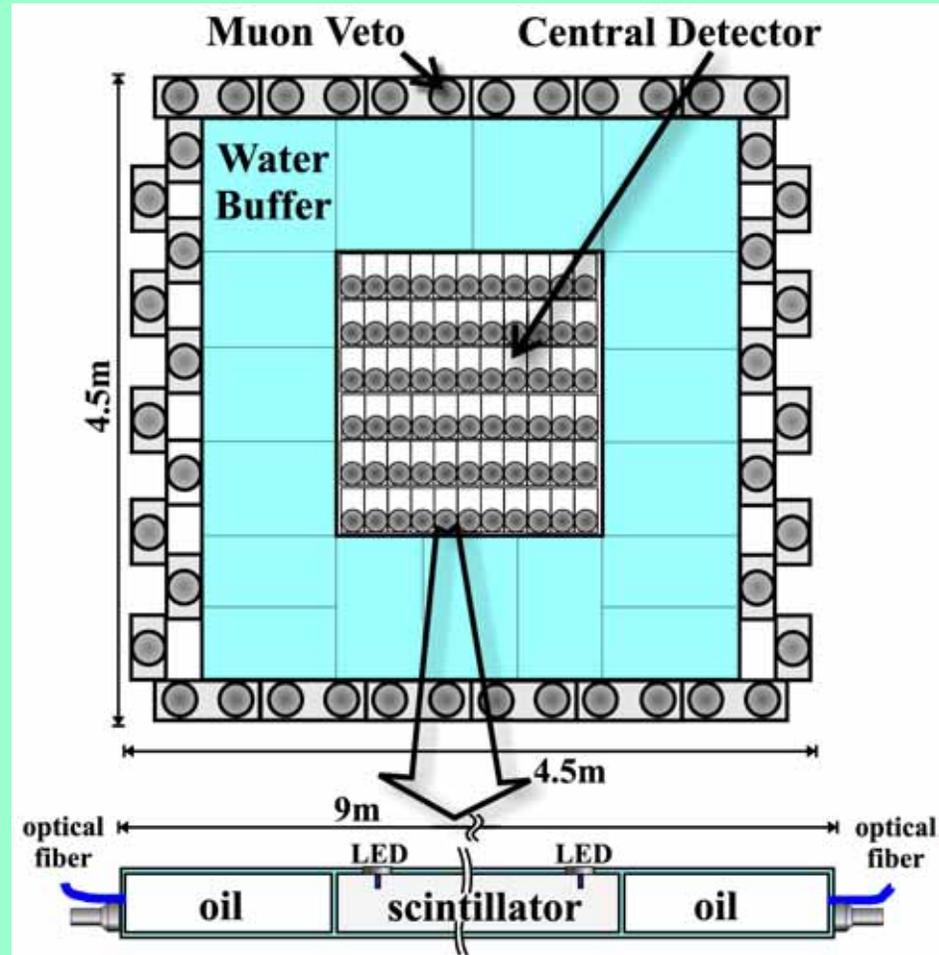
- 1 kton liq. Scinti. Detector in the Kamioka cavern
- ~1300 17" fast PMTs
- ~700 20" large area PMTs
- 30% photocathode coverage
- H<sub>2</sub>O Cerenkov veto counter
- Multi-hit deadtime-less electronics
- $\Delta m^2$  sensitivity  $7 \cdot 10^{-6} \text{ eV}^2$   
LMA-MSW solution  
within reach on the earth!





# Palo Verde

12 ton Gd loaded scintillating target

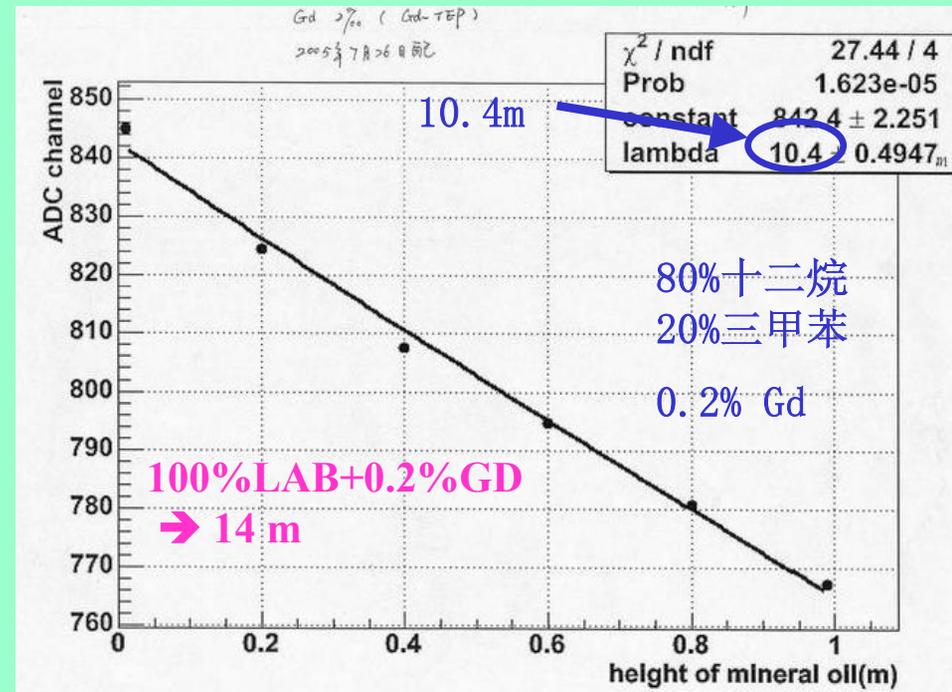


0.1% Gd-loading

- PV scintillator:  
 $\text{Gd}(\text{CH}_3(\text{CH}_2)_3\text{CH}(\text{C}_2\text{H}_5)\text{CO}_2)_3$
- Attenuation length: 11m
- Light yield: 55% antracene
- PV aging: 0.03%/day,
- Chooz aging: 0.4%/day

# 国产液体闪烁体

- 掺钆液闪在中子/中微子探测中有重要应用
- 目前国际上尚未解决液闪的稳定性问题
- **IHEP/科迪公司**联合研制的掺钆液闪在性能上已达到指标，正在进行长期稳定性研究
- 下一步要解决的问题：
  - 长期稳定性
  - 批量生产
    - liters → 200 t
    - **Mixing**
    - **Purification**
    - **Quality control**
    - **transportation**



# 大亚湾中微子探测器

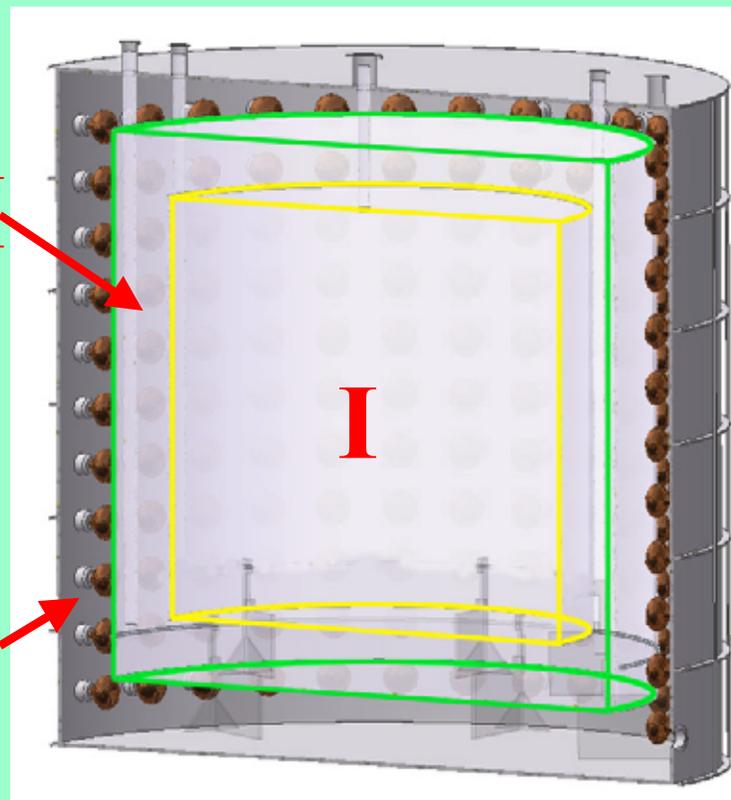
探测器模块的三层结构:

I. 靶层为掺钷液闪, 做为中微子反 $\beta$ 衰变的靶。**III**  
只有在钷上俘获的中子才被当成好事例

II. 集能层 ( $\gamma$ -catcher) 为普通液闪, 收集中子和正电子的伽马射线能量

III. 防护层为矿物油, 屏蔽PMT玻璃与氦气的天然放射性

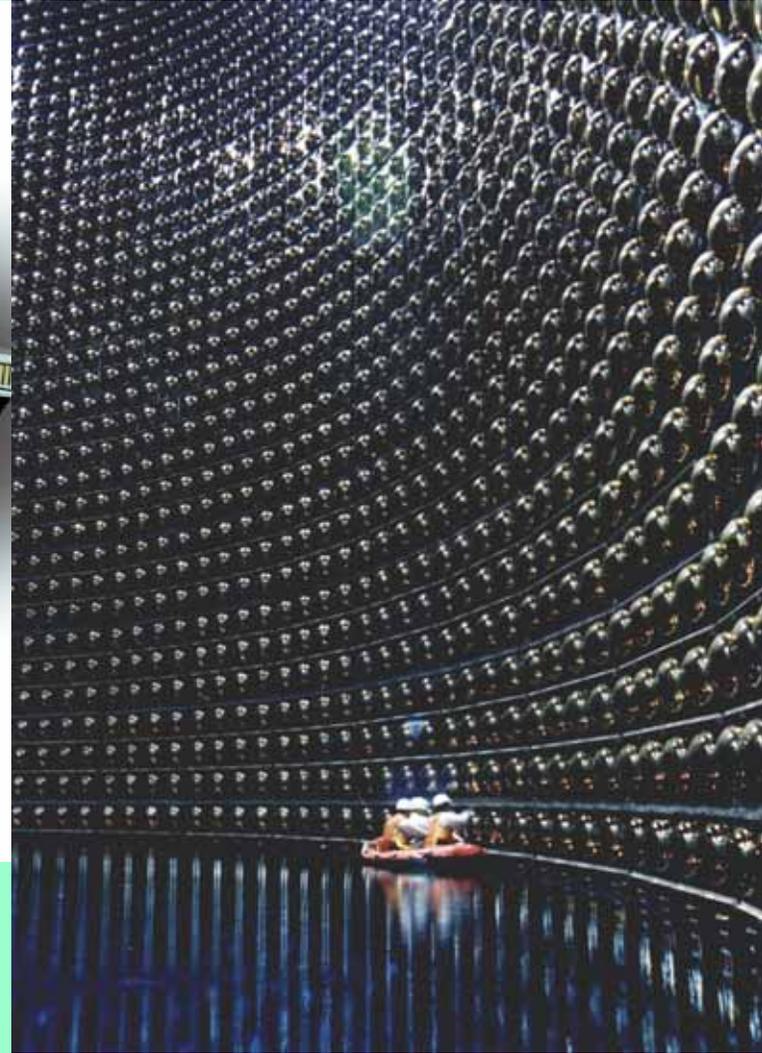
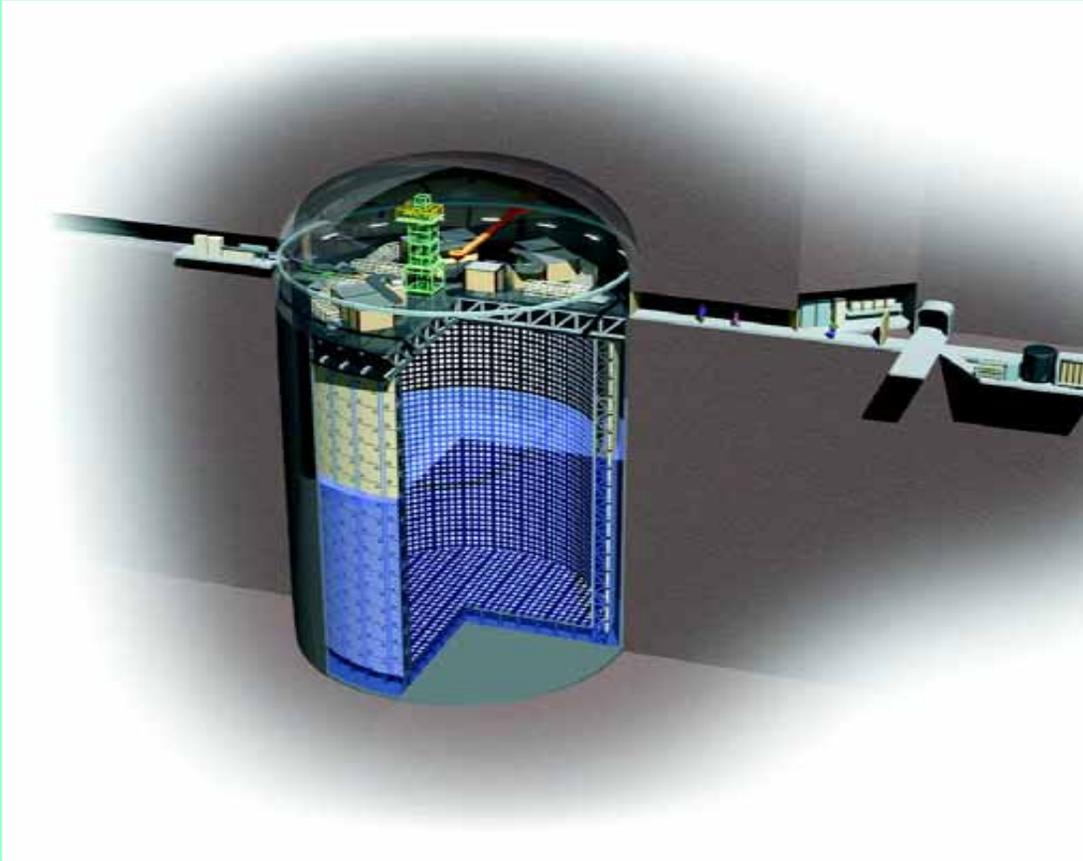
各层由有机玻璃隔开, PMT安装在矿物油中



# Cerenkov detector

- **Water Cerenkov imaging**
- **Water Cerenkov calorimeter**
- **DIRC**

# Super-Kamiokande detector



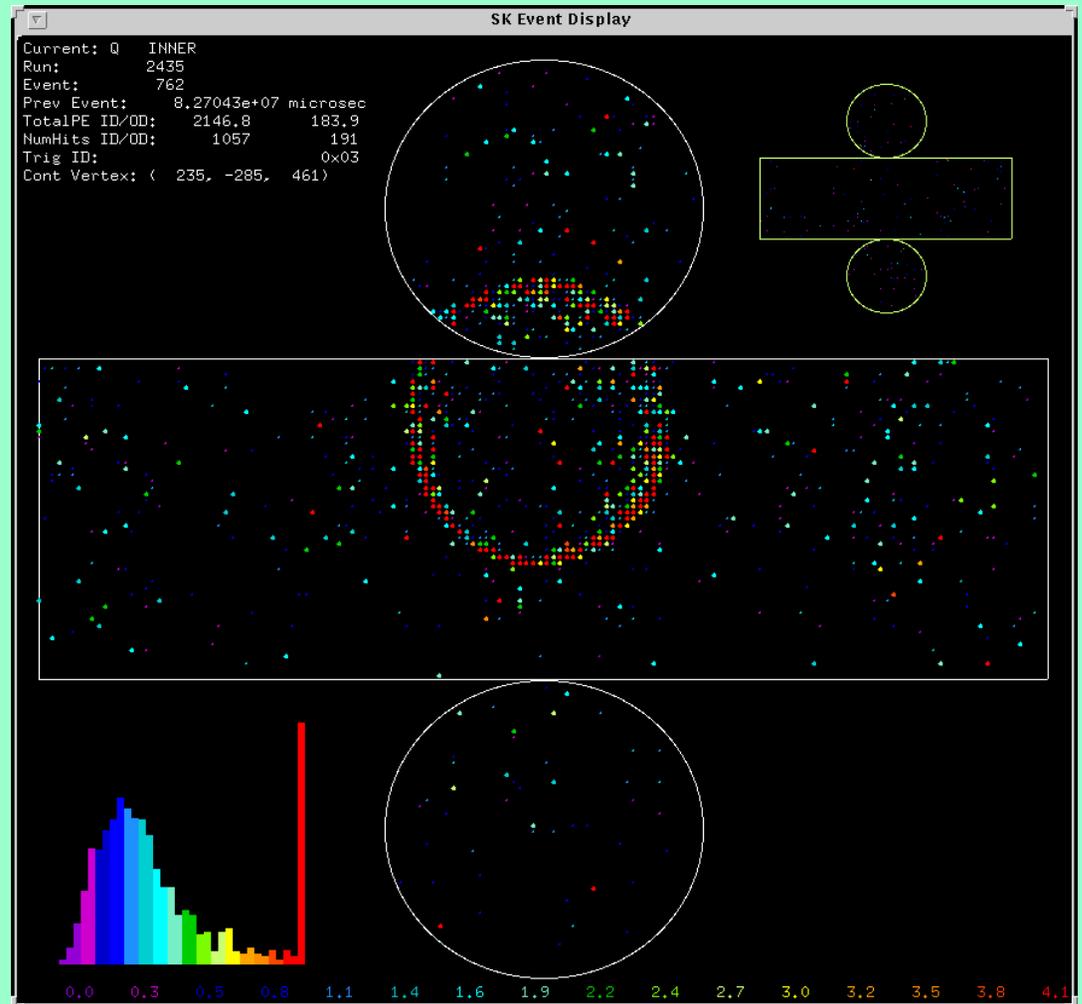
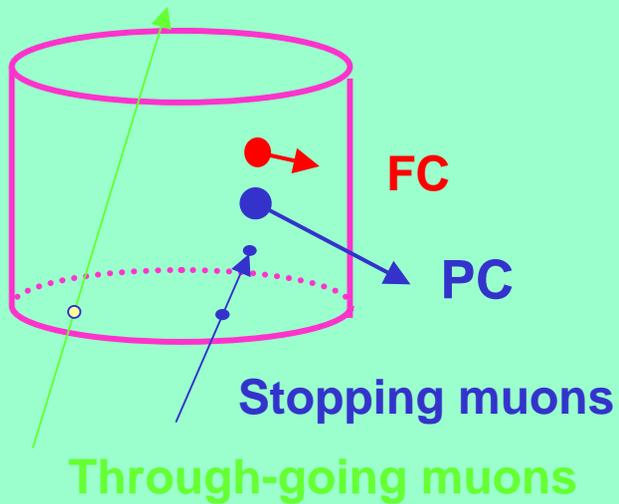
50 kt water Cherenkov (22.5 kt fiducial volume)

~ 10,000 20" PMT

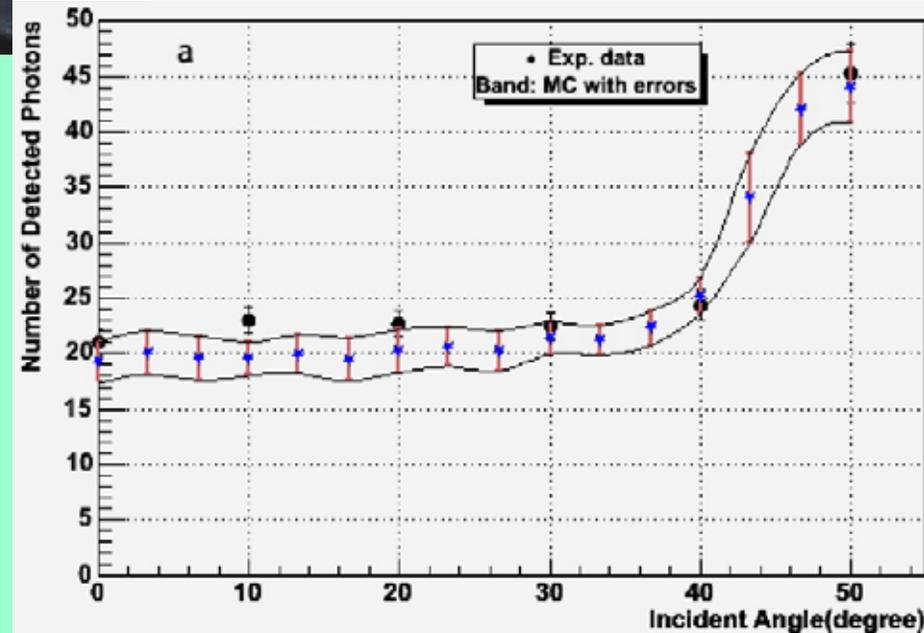
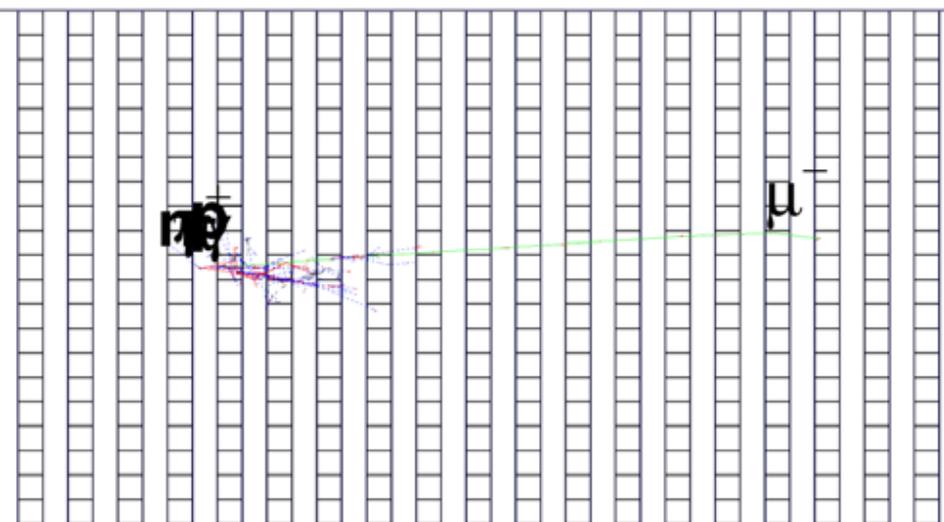
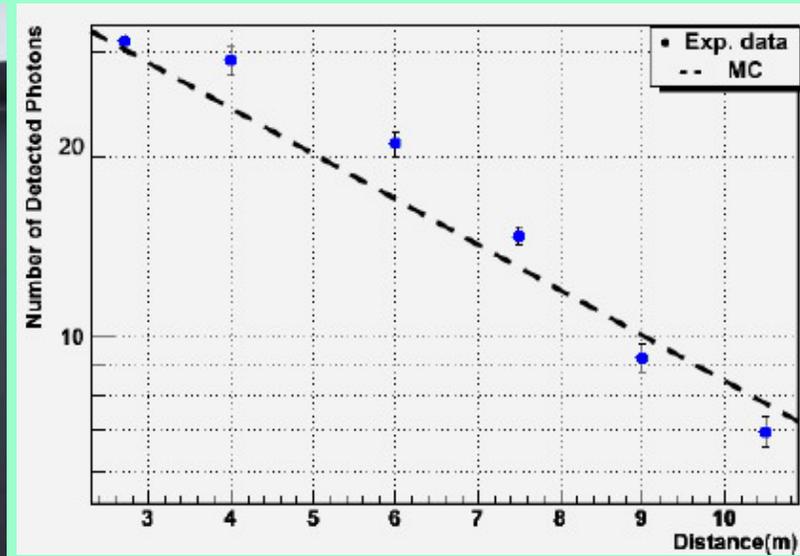
# Neutrino detection

$\nu + e$  scattering: **forward peaking**

**Cerenkov rings**

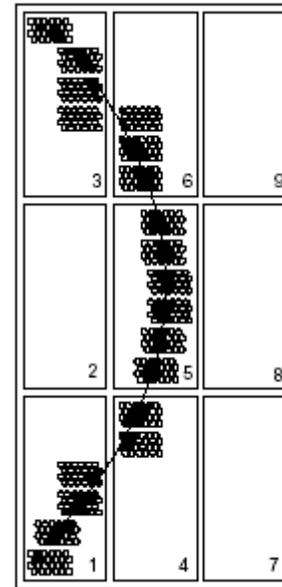
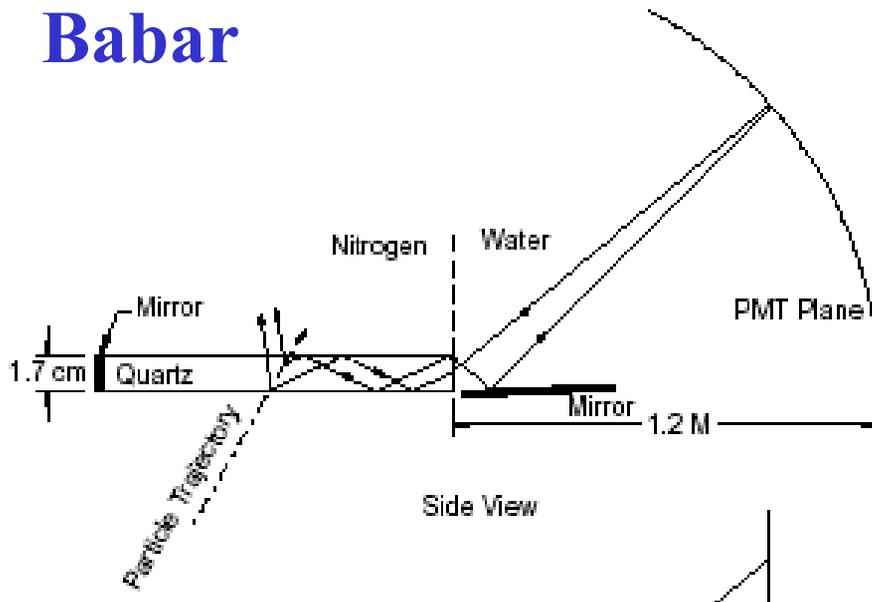


# Water cherenkov calorimeter

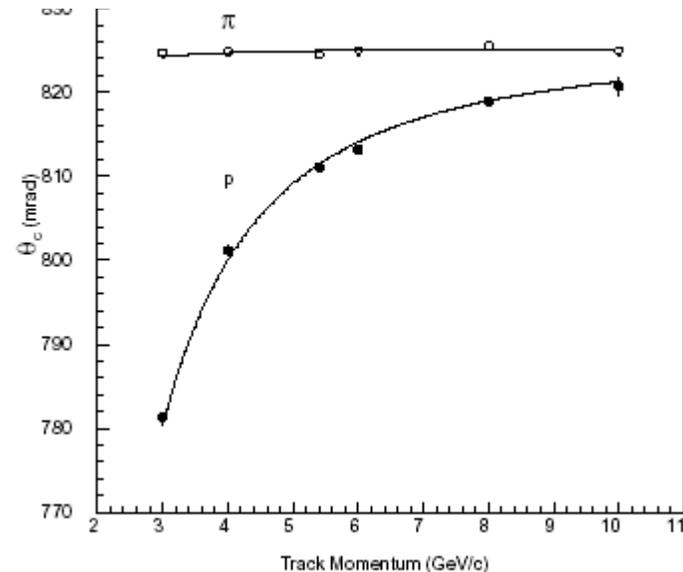
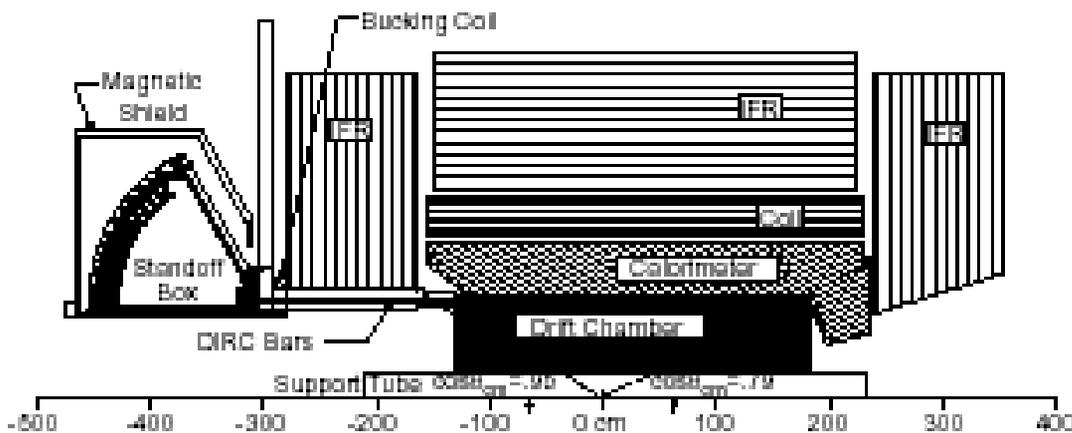


# DIRC (detection of internally reflected Cherenkov light)

## Babar



144 quartz bar,  
4.9 m long  
10751 1" PMT  
35 PE/track  
7 mrad angular reso.  
 $\pi/K @ 4 \text{ GeV} \rightarrow 3 \sigma$



# Ideas to reduce the cost

- **Radiator:**
  - high quality acrylic slabs instead of quartz bars
- **Readout:**
  - multi-anode PMT (single PE ?)
  - MCP + timing info. (100 ps ?)
  - a mirror + APD array (noise ?)

**A collaboration between IHEP and GSI, Germany**

# 小结

- 在BESIII建设的推动下，国内高能物理探测器的研究近年来得到很大的发展。部分探测器的研究，制造已进入世界先进水平。
- 一些新型探测器的预研正在展开，有望以我们自己独特的技术参与国际合作，在国际上占领一席之地
- 高能探测器也可以在各方面得到应用，有关技术的研发正在进行，国内厂家也已有一批高技术产品。
- 相信我国的高能探测器研究将能得到更大的发展，为我国的高能物理，核物理与粒子天体物理发展奠定基础，同时推广应用其技术，为国家安全、反恐、毒品爆炸物探测、核医疗成像、工业探伤与成像等众多应用领域服务。