Electromagnetic Calorimetry at LHC

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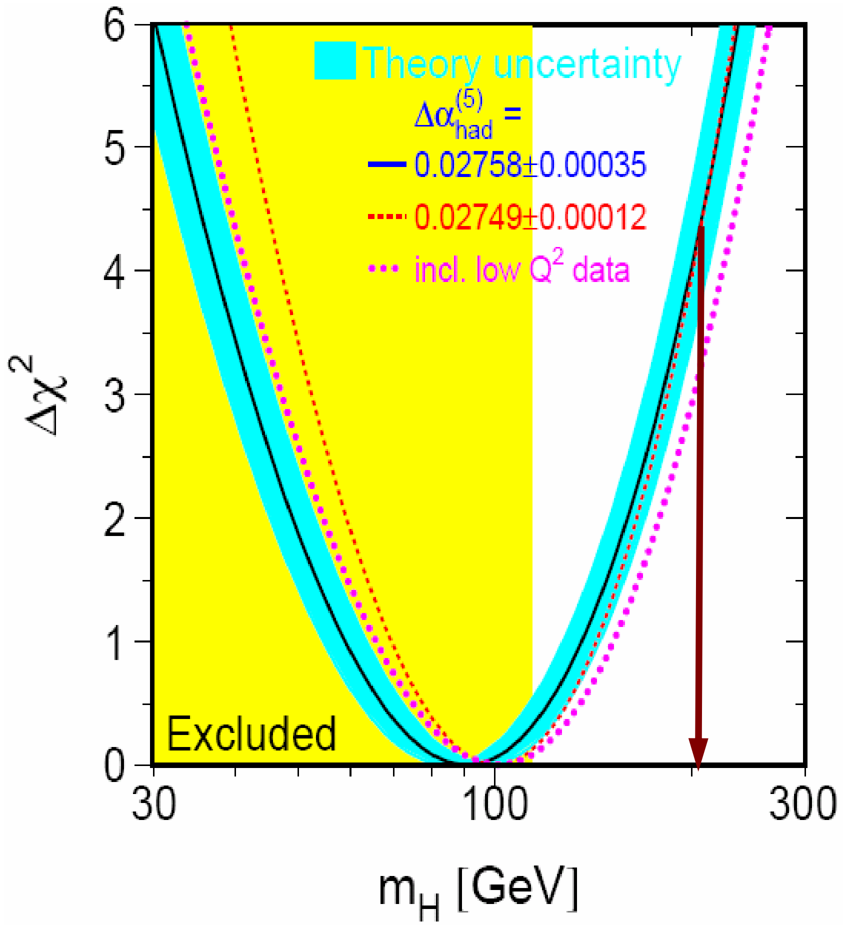
ATLAS and CMS ECAL

- Requirements
- Designs
- Constructions
- Test Beam Results
- Commissions

Status of the SM Higgs

Higgs Mass Fit to Precise EW Data from LEP, SLC, Fermilab



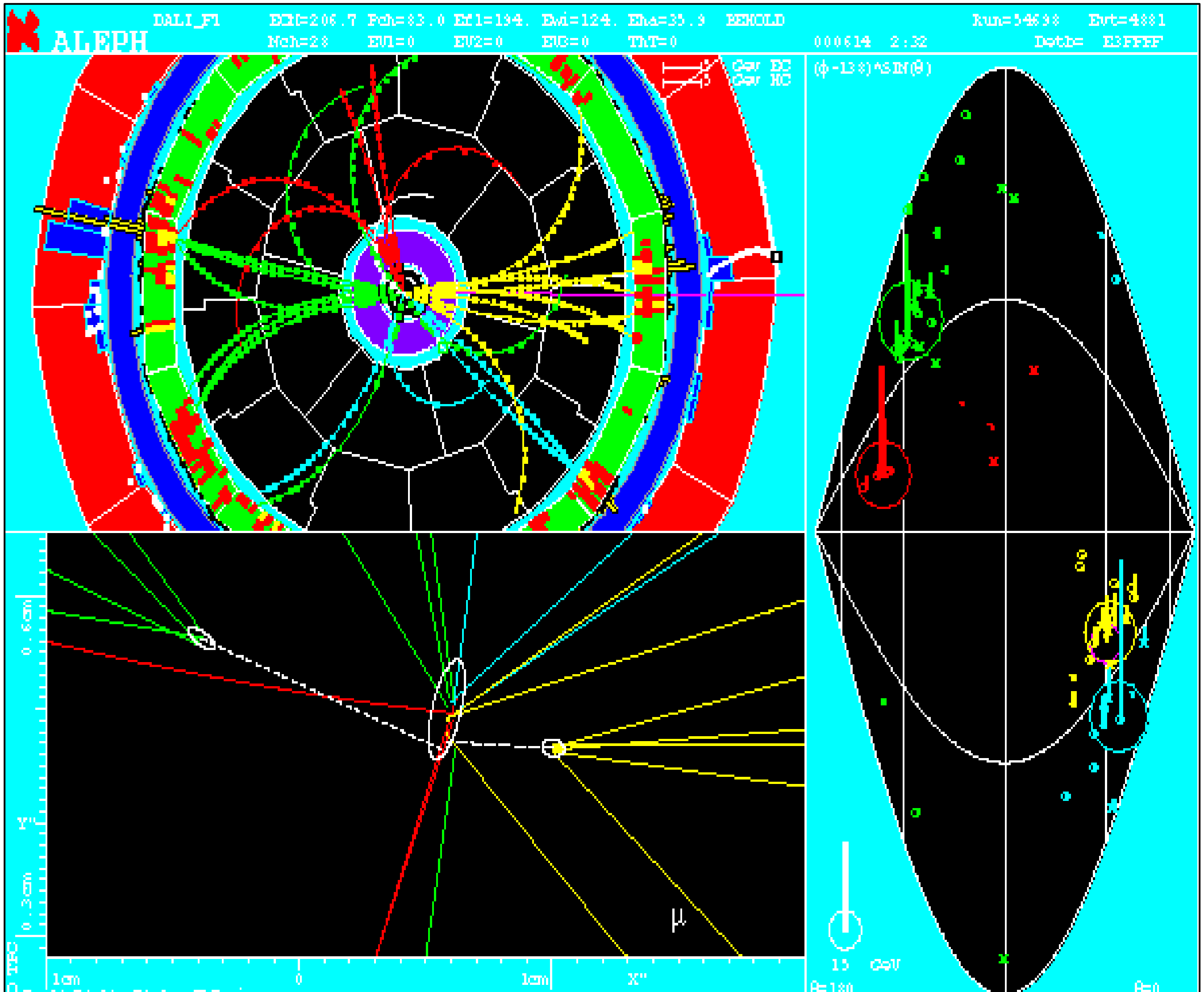
- Electroweak fit (incl. quantum corrections) to m_H is sensitive to m_{TOP}(=172.7 ± 2.9 GeV)
- Best-fit value:

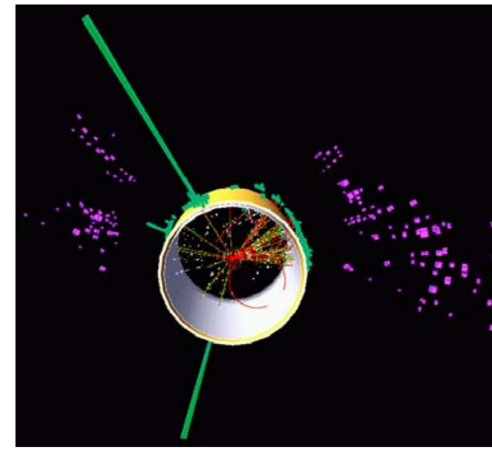
  $m_H = 89^{+42}_{-30}$ GeV
- Direct search limit:

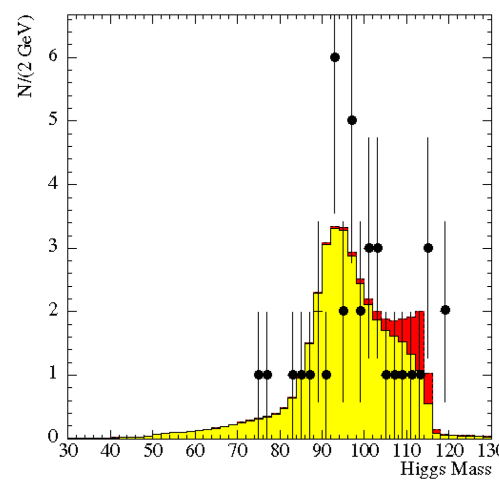
  $m_H > 114.4$ GeV
- 95% CL upper limit:

  $m_H < 207$ GeV

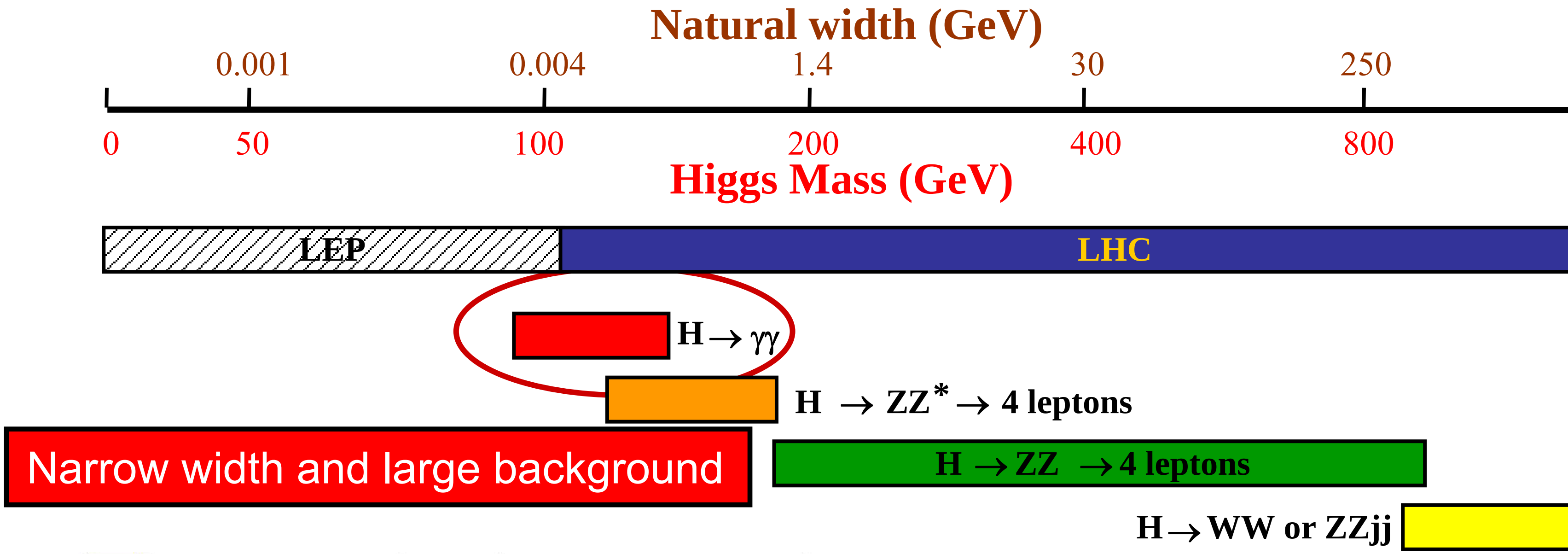
Evidence of M_H~115 GeV at LEP

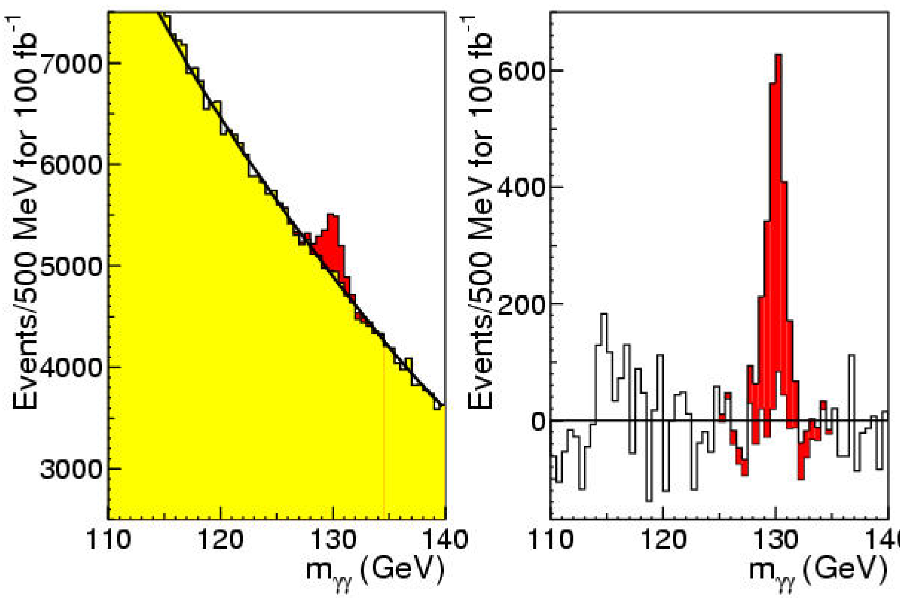


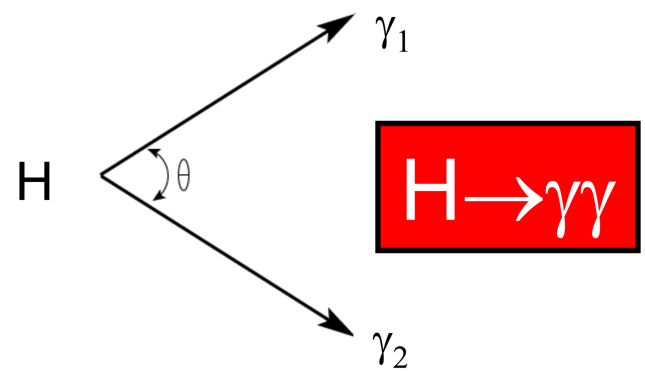




H→γγ Search Needs Precision ECAL







$\sigma m / m = 0.5\,[\sigma E_1/E_1 \oplus \sigma E_2/E_2 \oplus \sigma\theta / \tan(\theta/2)]$,
where $\sigma E / E = a/\sqrt{E} \oplus b \oplus c/E$ and E in GeV

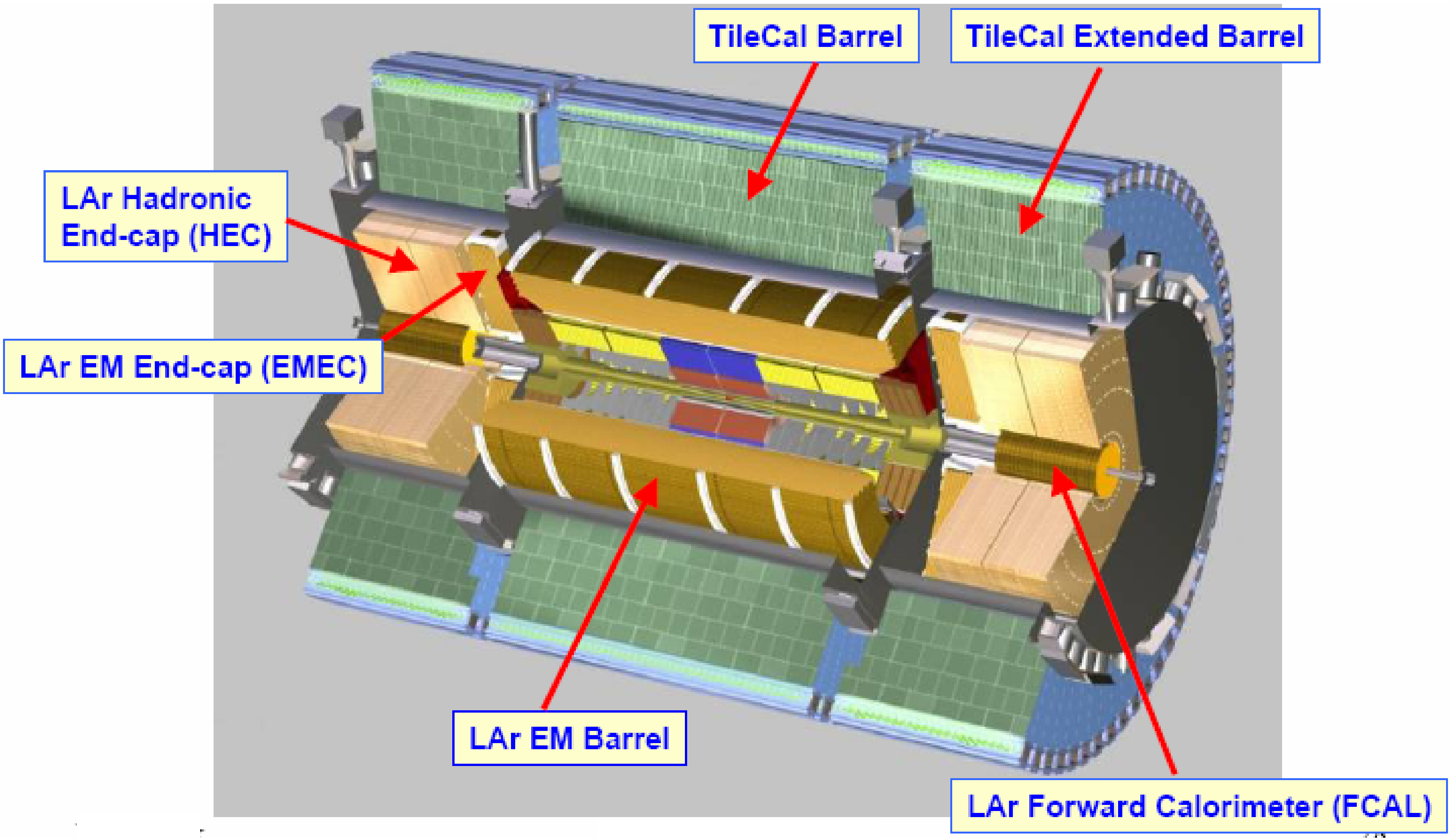
Requirements to ECAL at LHC

- Fast response: 25 ns between LHC bunch crossing
- Large coverage: up to $|\eta| = 3$
  - Barrel: $|\eta| < 1.5$, Endcaps: $1.5 < |\eta| < 3$
- Energy Resolution: $\sigma E / E = a / \sqrt{E} \oplus b \oplus c / E$
  - as small as possible stochastic term (a), constant term (b) and noise term (c)
- Photon Angular Resolution: $\delta\theta < 50$ mrad $/ \sqrt{E}$
  - LHC bunch length 7.5 cm →H vertex spread 5.3 cm
- Good particle ID: γ/jet, particularly π^0/γ discrimination
  - Strips and shower shape analysis
- Large dynamic range: 5 orders of magnitude
- Radiation resistance: 10^{13} n/cm^2 and 100 krad @ $\eta=0$, 2×10^{14} n/cm^2 and 5 Mrad @ $\eta=2.6$ in 10 years

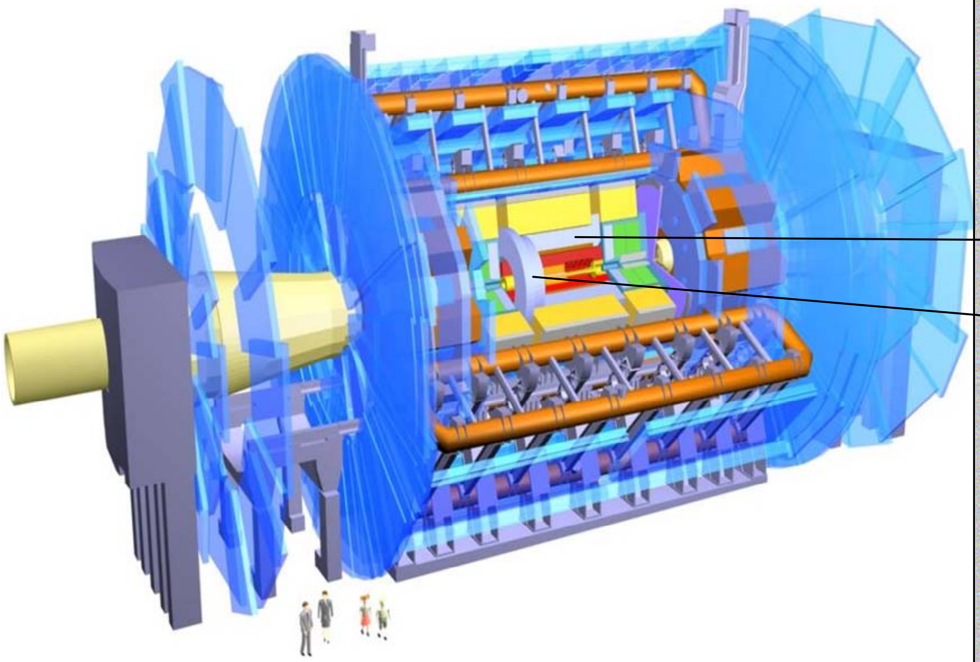
Parameters of ATLAS and CMS ECAL

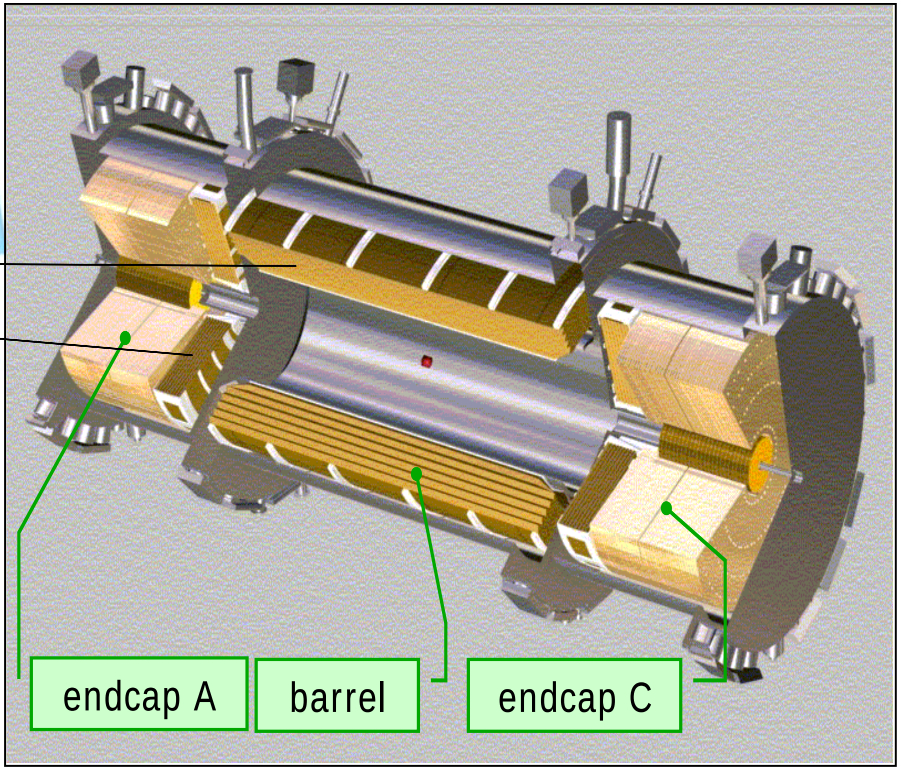
	ATLAS Lead/L. Ar ECAL		CMS PWO Crystal ECAL	
	Barrel	Endcaps	Barrel	Endcaps
# of Channels	110,208	83,744	61,200	14,648
Lateral Segmentation ($\Delta\eta \times \Delta\varphi$)				
Presampler	0.025 x 0.1			
Strip/Preshower	0.003 x 0.1	0.005 x 0.1		32 S /4 crystals
Main Body	0.025 x 0.025		0.0175 x 0.0175	Up to 0.05 x 0.05
Back	0.05 x 0.025			
Longitudinal Segmentation				
Presampler	10 mm L. Ar	2 x 2 mm L. Ar		
Strip/Preshower	~4.3 X_0	~4 X_0		3 X_0
Main Body	~16 X_0	~20 X_0	26 X_0	25 X_0
Back	~2 X_0	~2 X_0		
Designed Energy Resolution				
Stochastic: a	10%	10 - 12%	2.7%	5.7%
Constant: b	0.7%	0.7%	0.55%	0.55%
Noise: C	0.25 GeV	0.25 GeV	0.16 GeV	0.77 GeV

ATLAS Detector



ATLAS L. Ar Accordion ECAL





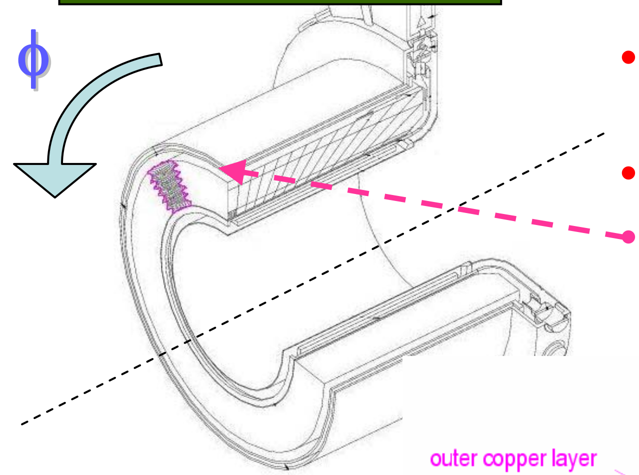
Three Cryostats

EM Barrel : $|\eta| < 1.475$

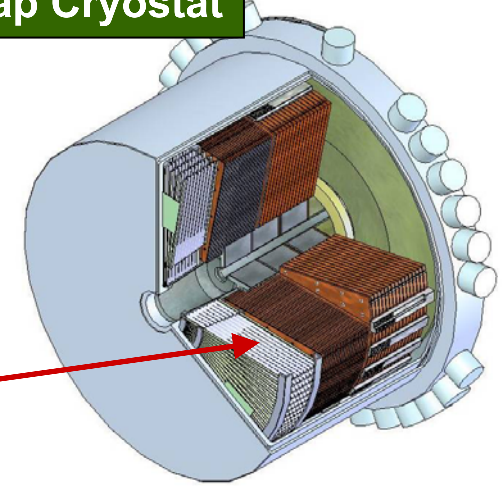
EM Endcaps : $1.4 < |\eta| < 3.2$

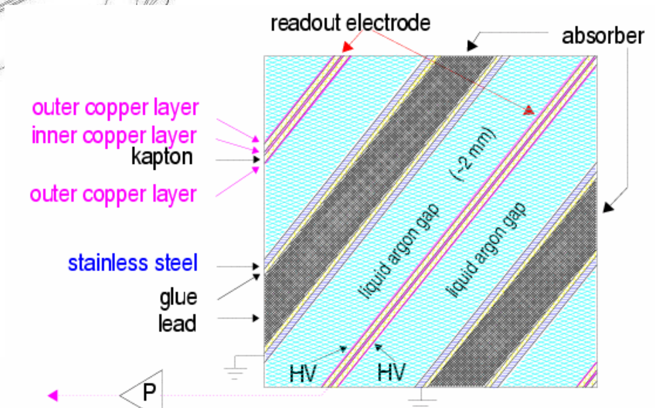
~190K readout channels

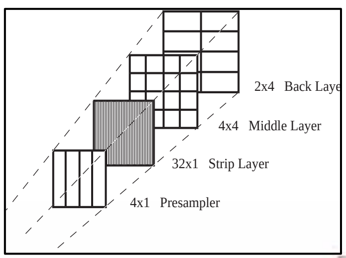
ATLAS L. Ar Accordion Structure

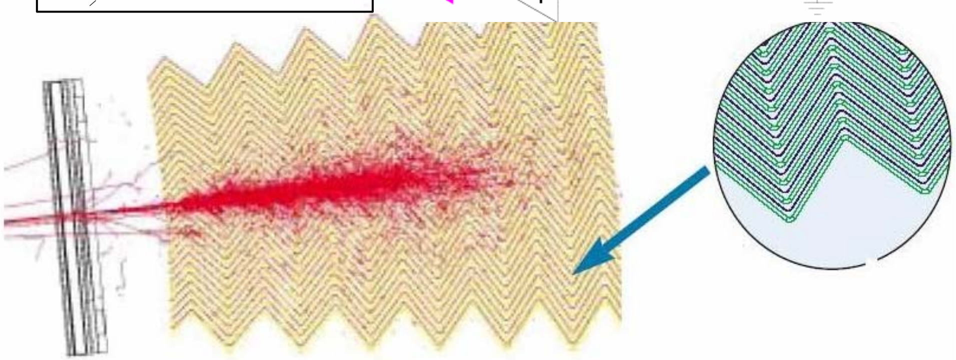


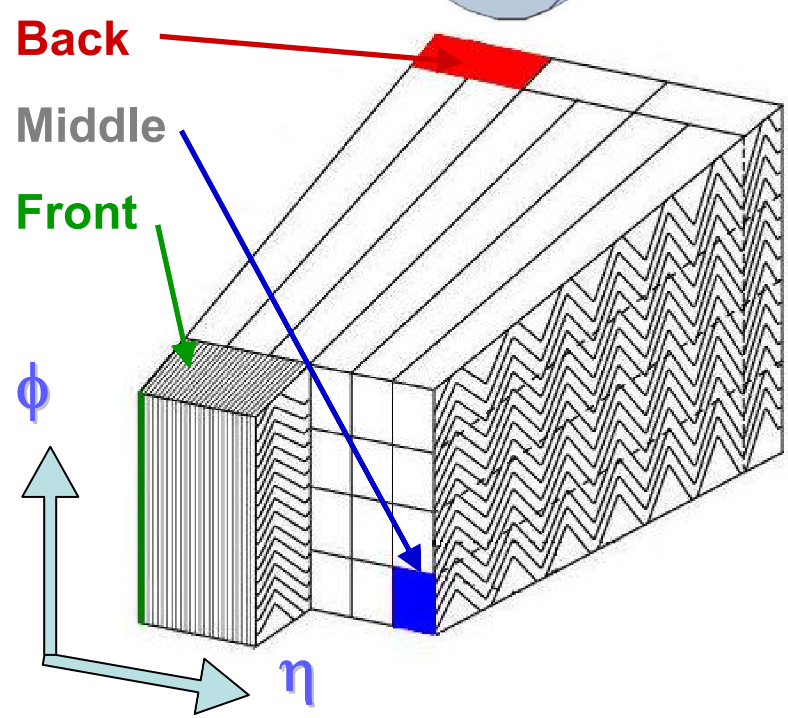
- Accordion electrodes
- 1 cryostat with 2 half barrels in η
- 16 modules in ϕ
- 1 module covers η: 0 to 1.4, ϕ: 0.4











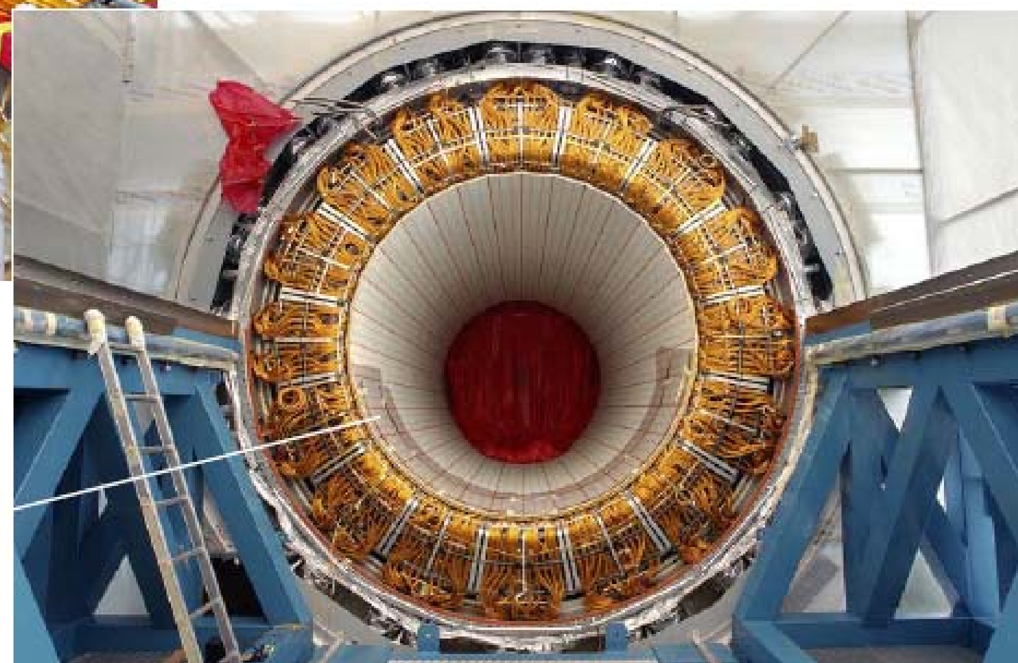
Why L. Ar Accordion

- Fast readout achieved with dedicated electronics and inherent cabling
- L. Ar as active material inherently linear
- Hermetic coverage
- Readout allows flexible longitudinal and lateral segmentations
- L. Ar is inherently radiation hard
- Challenges:
  - ➢Calibration to achieve linearity
  - ➢Readout noise with fast shaping

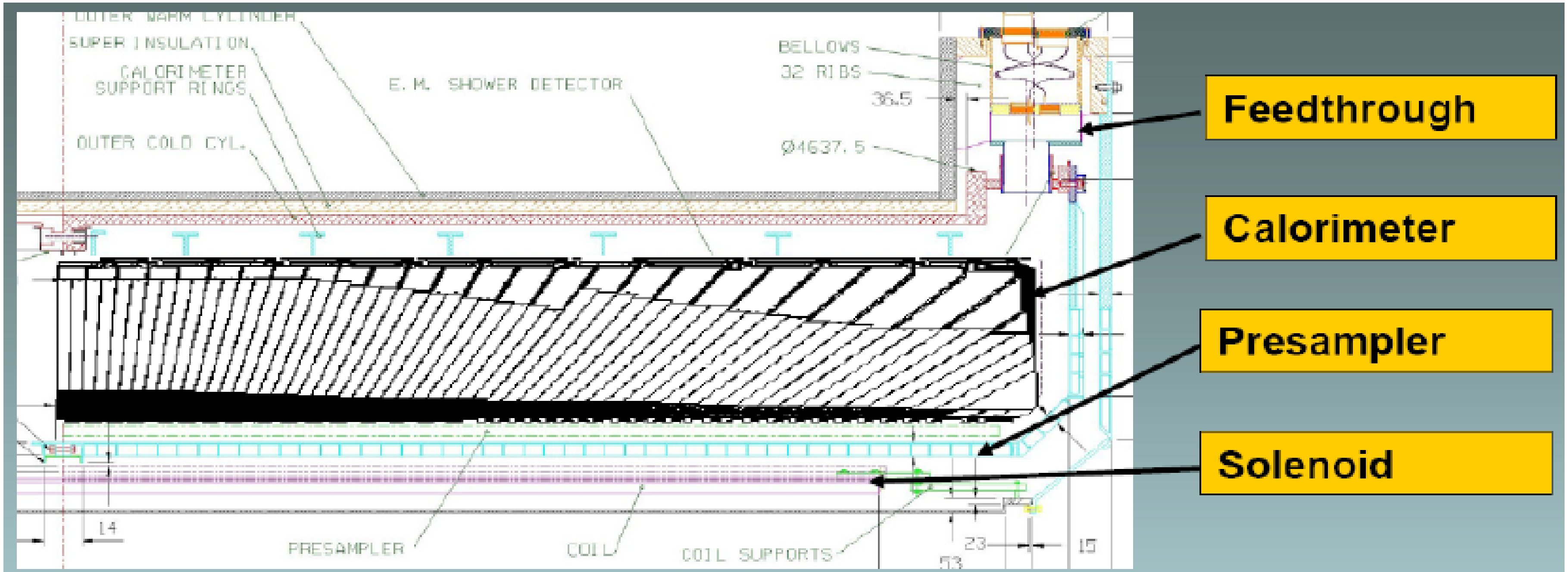
ATLAS L. Ar ECAL Barrel Module

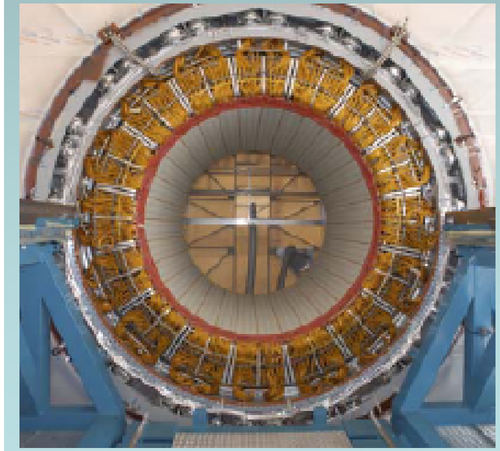
32 modules produced and tested at cold between 2001-2003
Assembly/insertion in cryostat end 2003

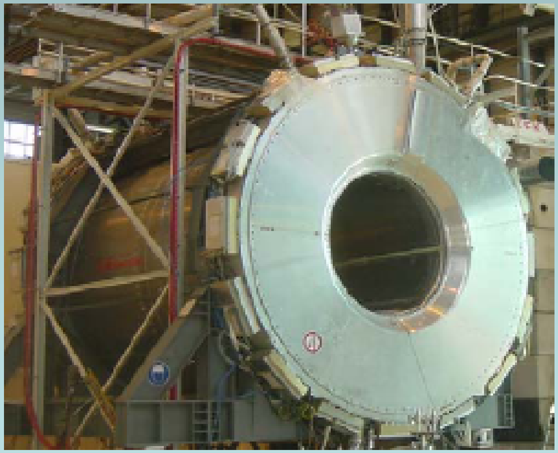
Presampler



ATLAS L. Ar ECAL Barrel

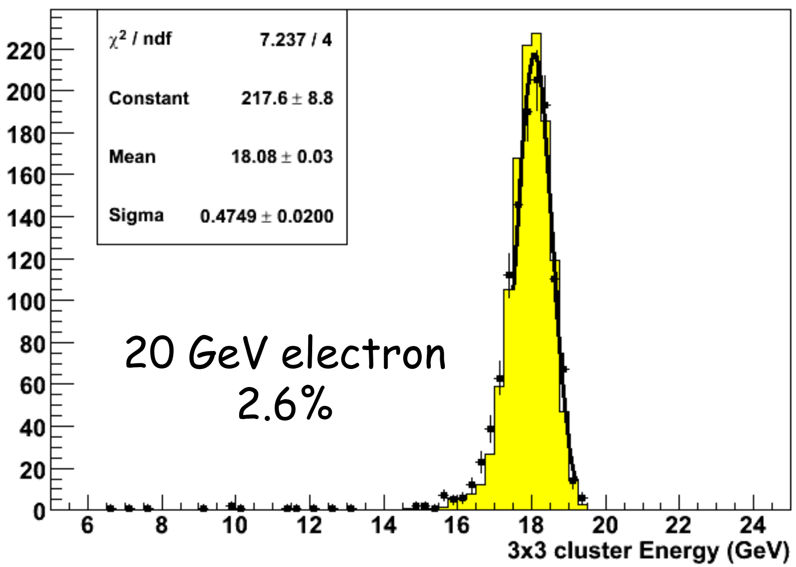


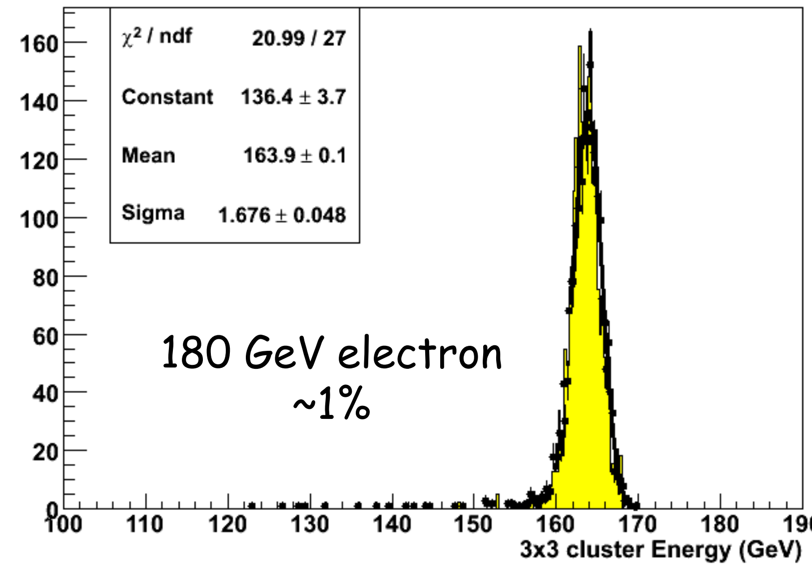




ATLAS L. Ar Beam Test Result

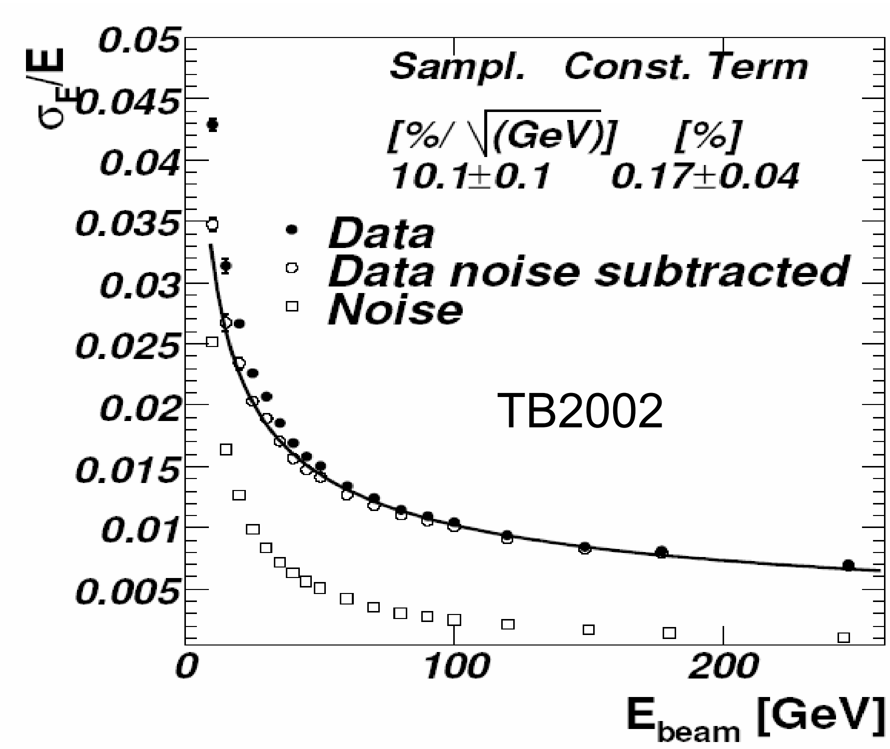
- Beam tests using a real detector module with the production version of the readout electronics have been carried out.
- Preliminary data indicate the electronics system is working up to its design spec:

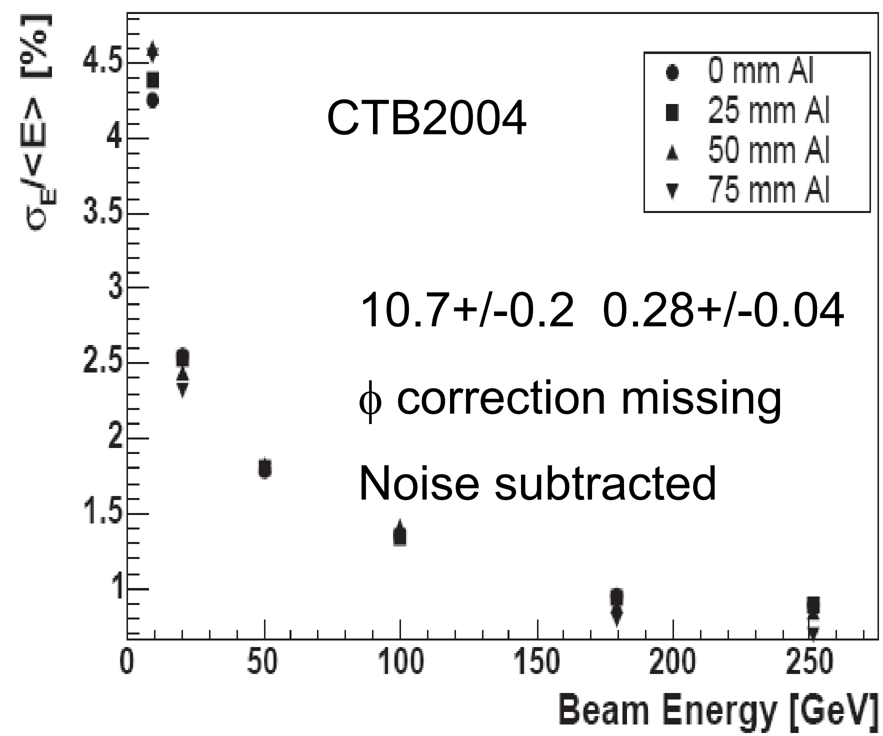




Data MC comparison

ATLAS L. Ar Test Beam Resolution



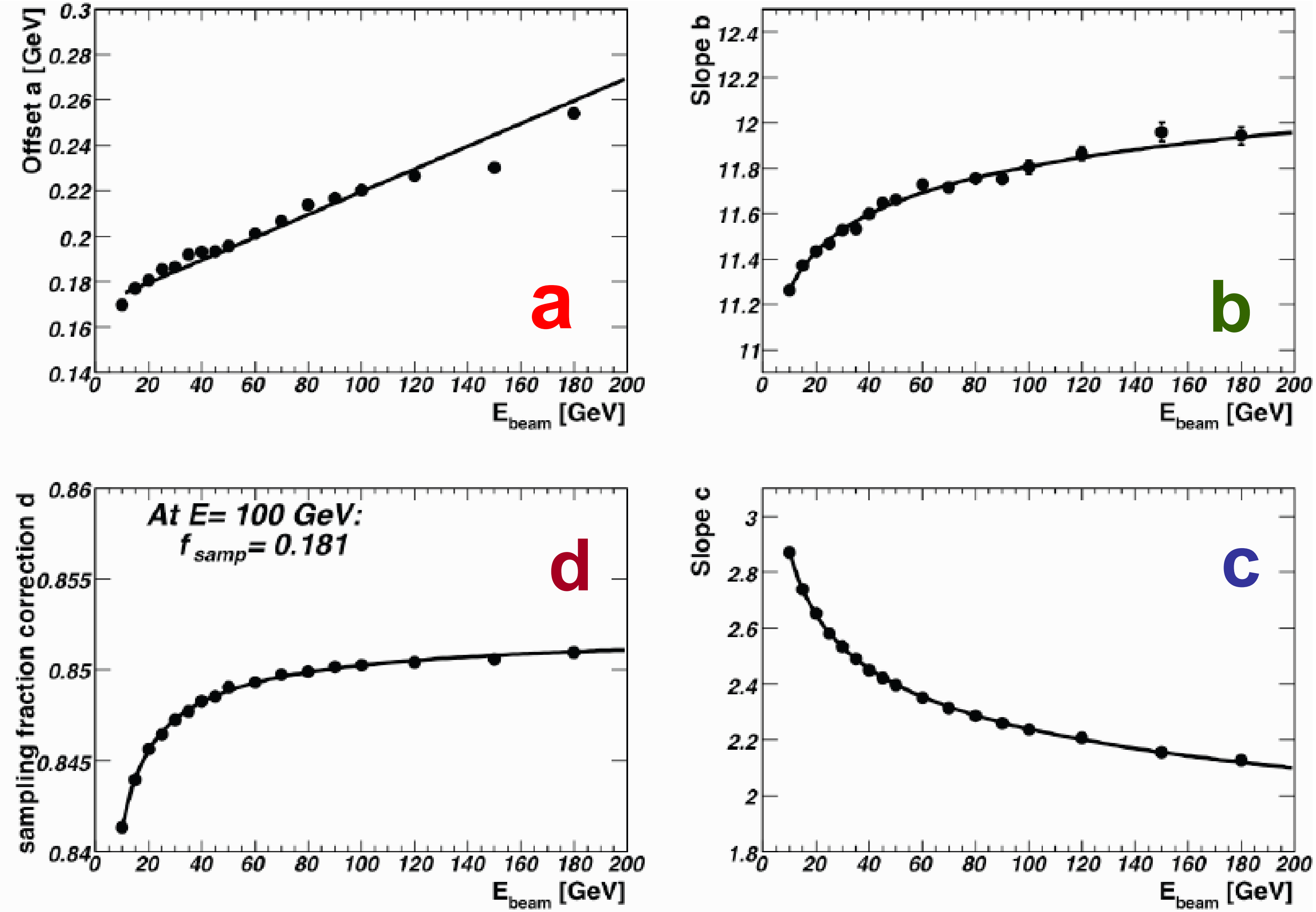


- 2002: study with production modules
- 2004: material study with 0 to 75 mm of Al in front of the calorimeter

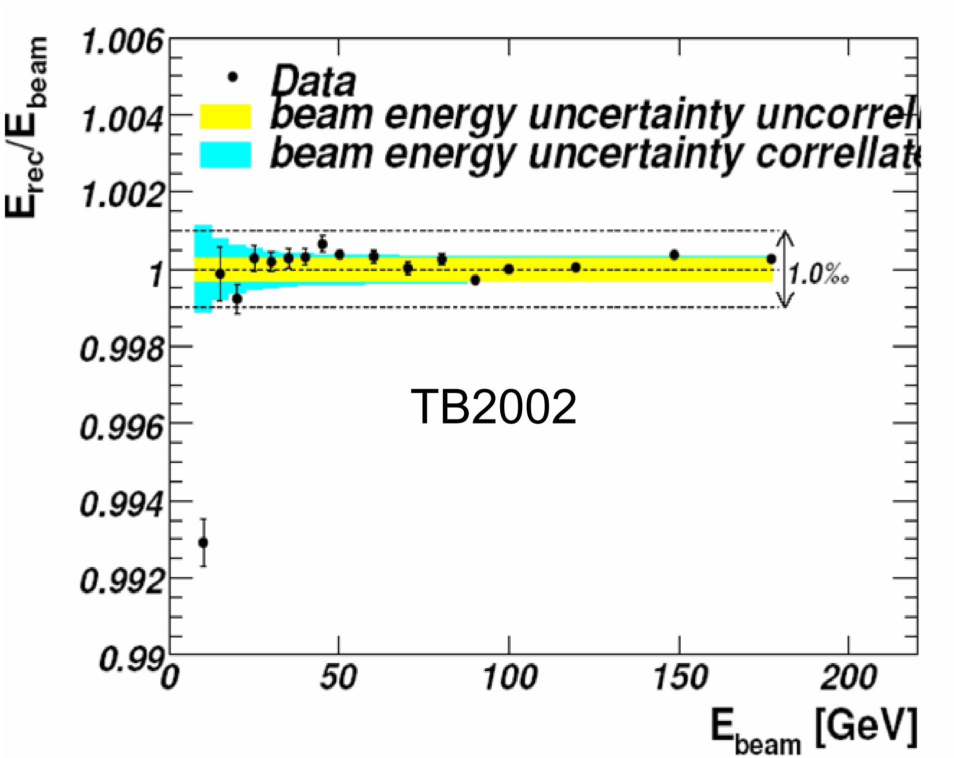
⇒ If amount of material is corrected, resolution is identical

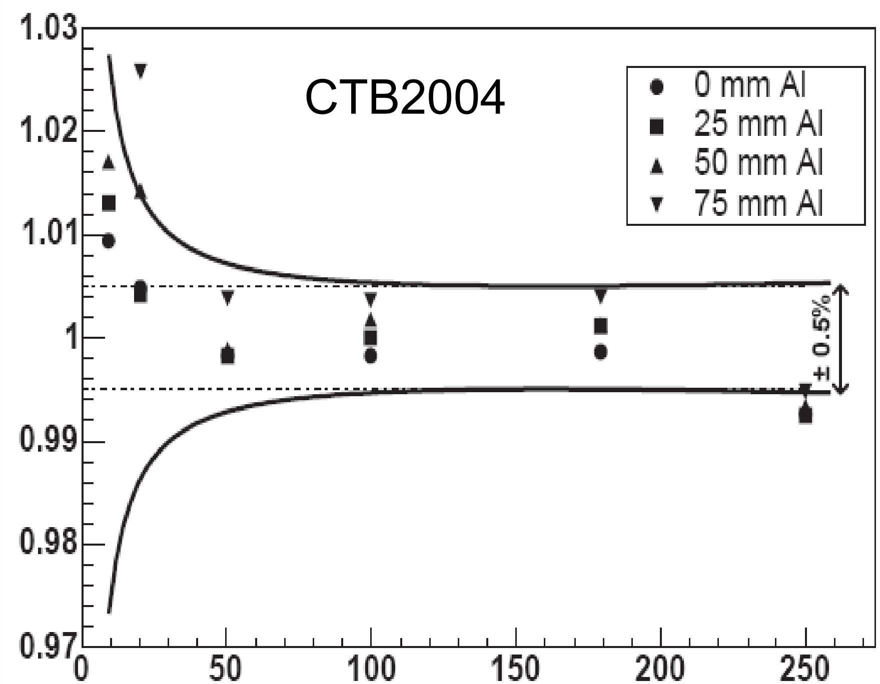
ATLAS L. Ar ECAL Calibration

$$E_{rec}^{Calo} = a_{E,\eta} + b_{E,\eta} E_{PS}^{Clus} + c_{E,\eta} \sqrt{E_{PS}^{Clus} . E_{1}^{Clus}} + d_{E,\eta} \sum_{i=1,3} E_{i}^{Clus}$$



ATLAS L. Ar ECAL Linearity



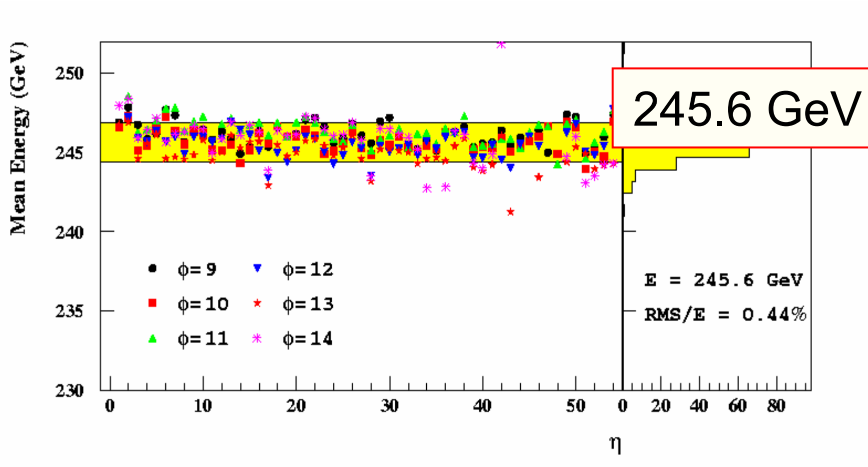


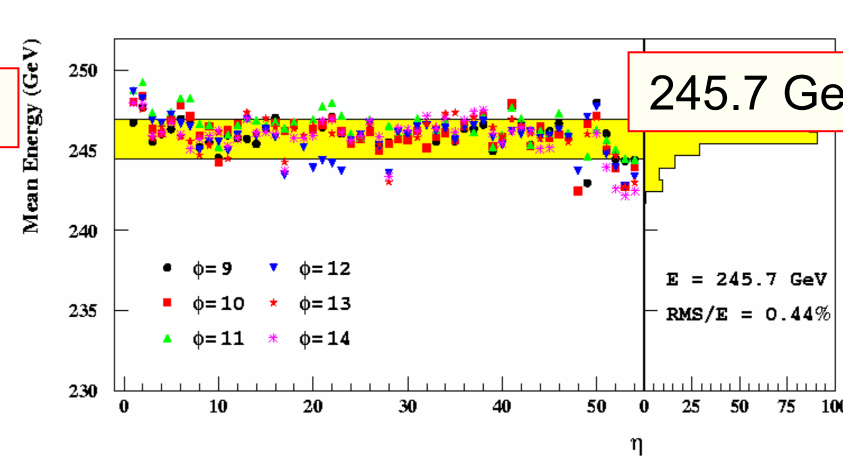
0.1% linearity achieved

- 2002: setup, so beam energy under was under control @0.03%
- 2004: 0.5% due to beam energy error (1%)
- 2004: Extended the study with different amounts of material

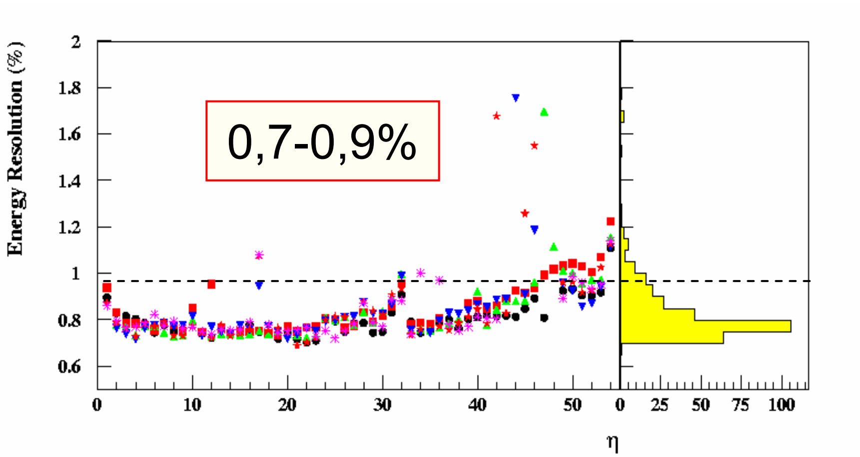
ATLAS L. Ar ECAL Uniformity

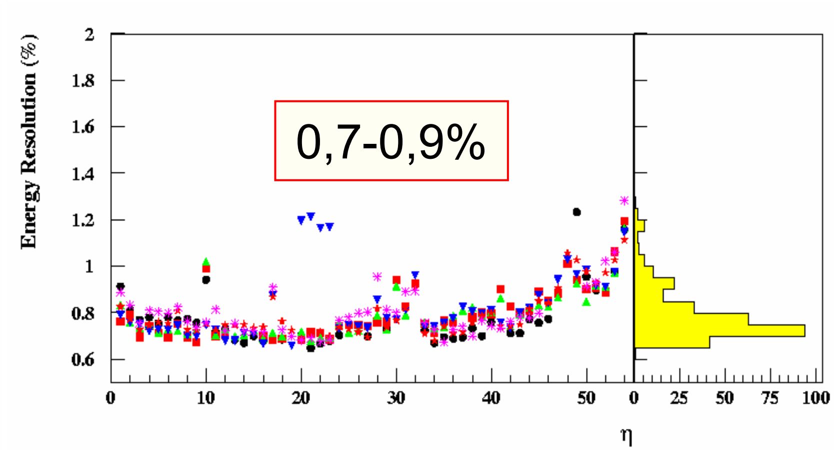
Uniformity





Resolution



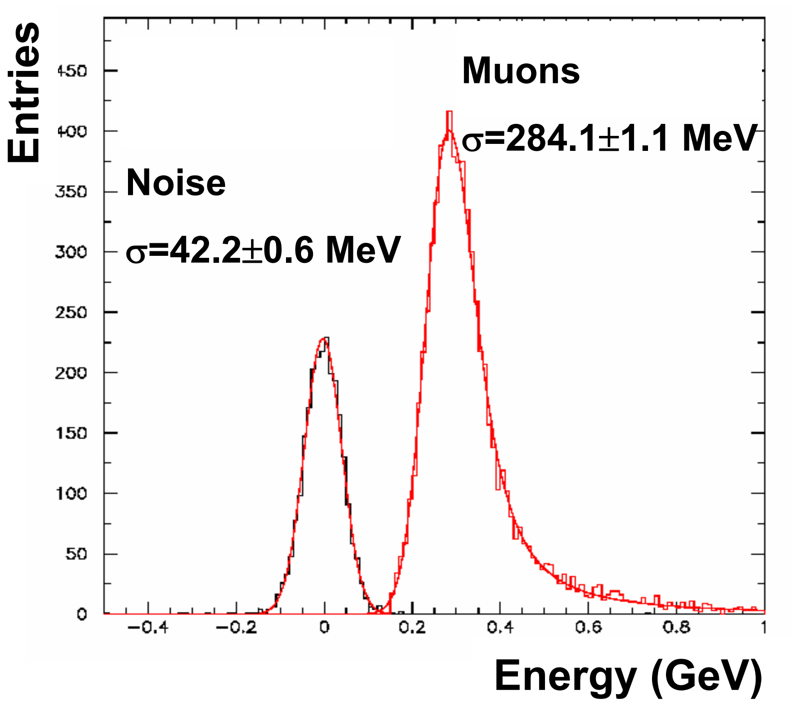


Module	P13	P15
Global constant term	0.62%	0.56%

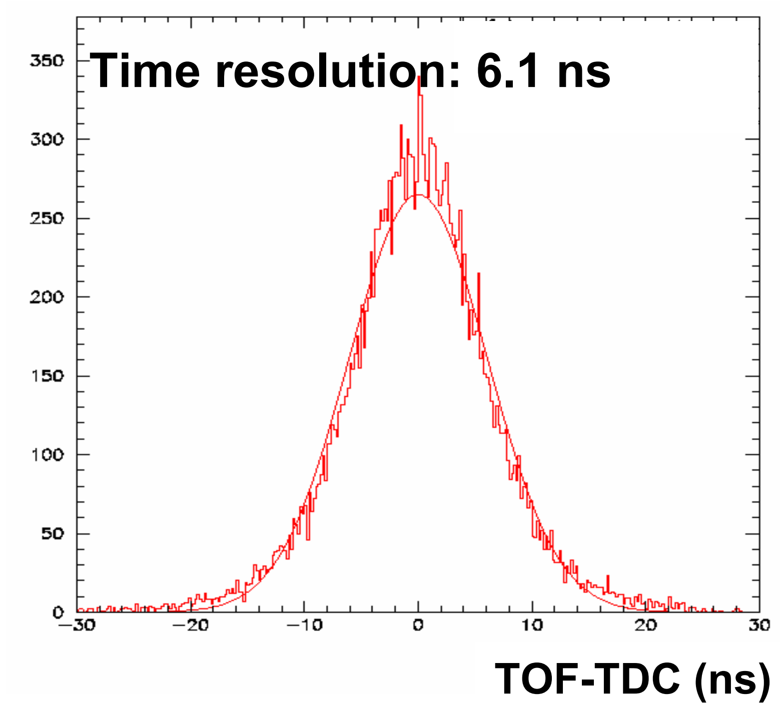
P13/P15 ~ 0.05%

ATLAS L. Ar Response to Muons

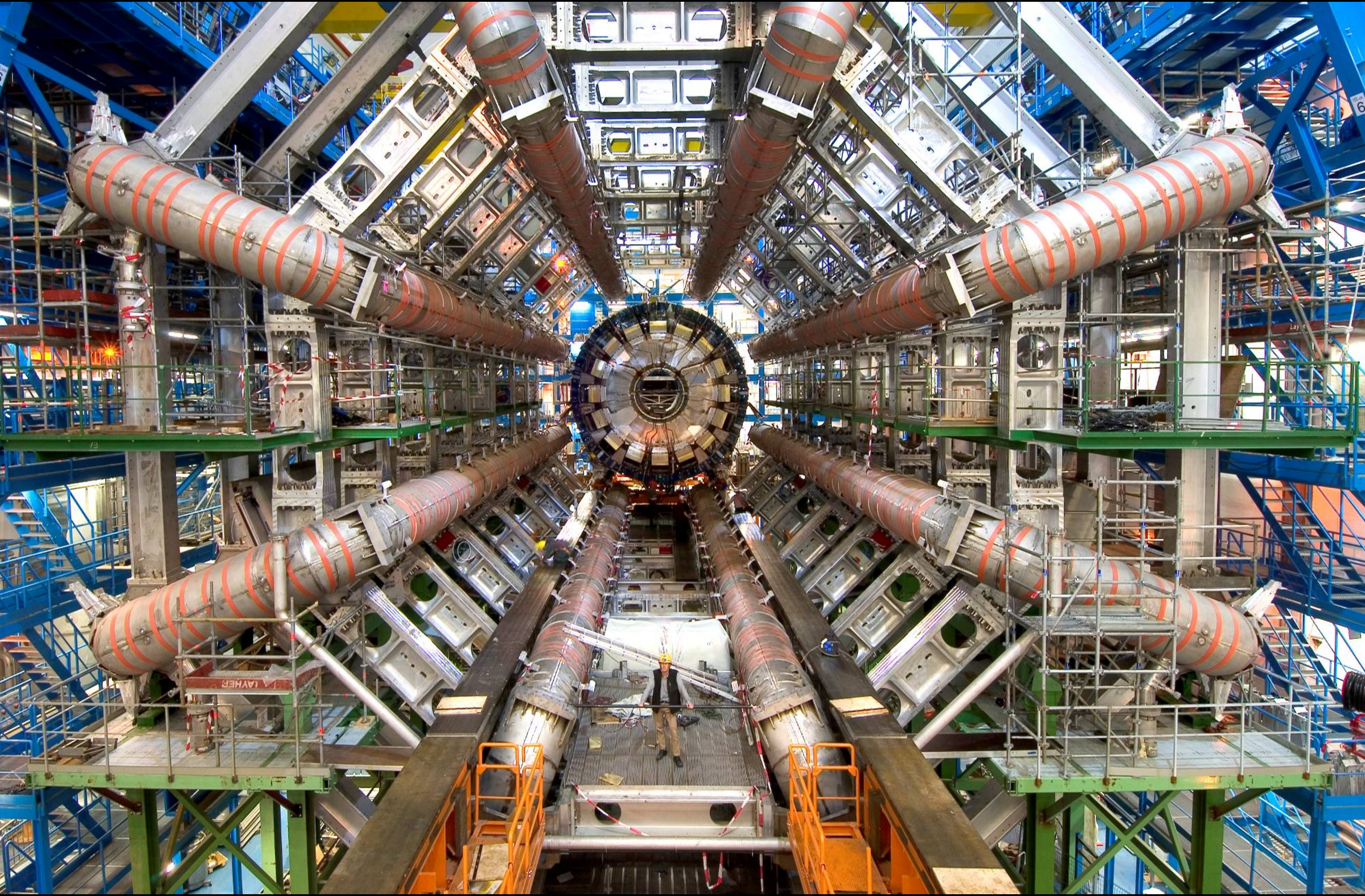
- Noise goes like $\approx \Delta\eta \times \Delta\varphi$,
- Signal goes like sampling depth $\Rightarrow$ Most favourable S/N : Middle layer



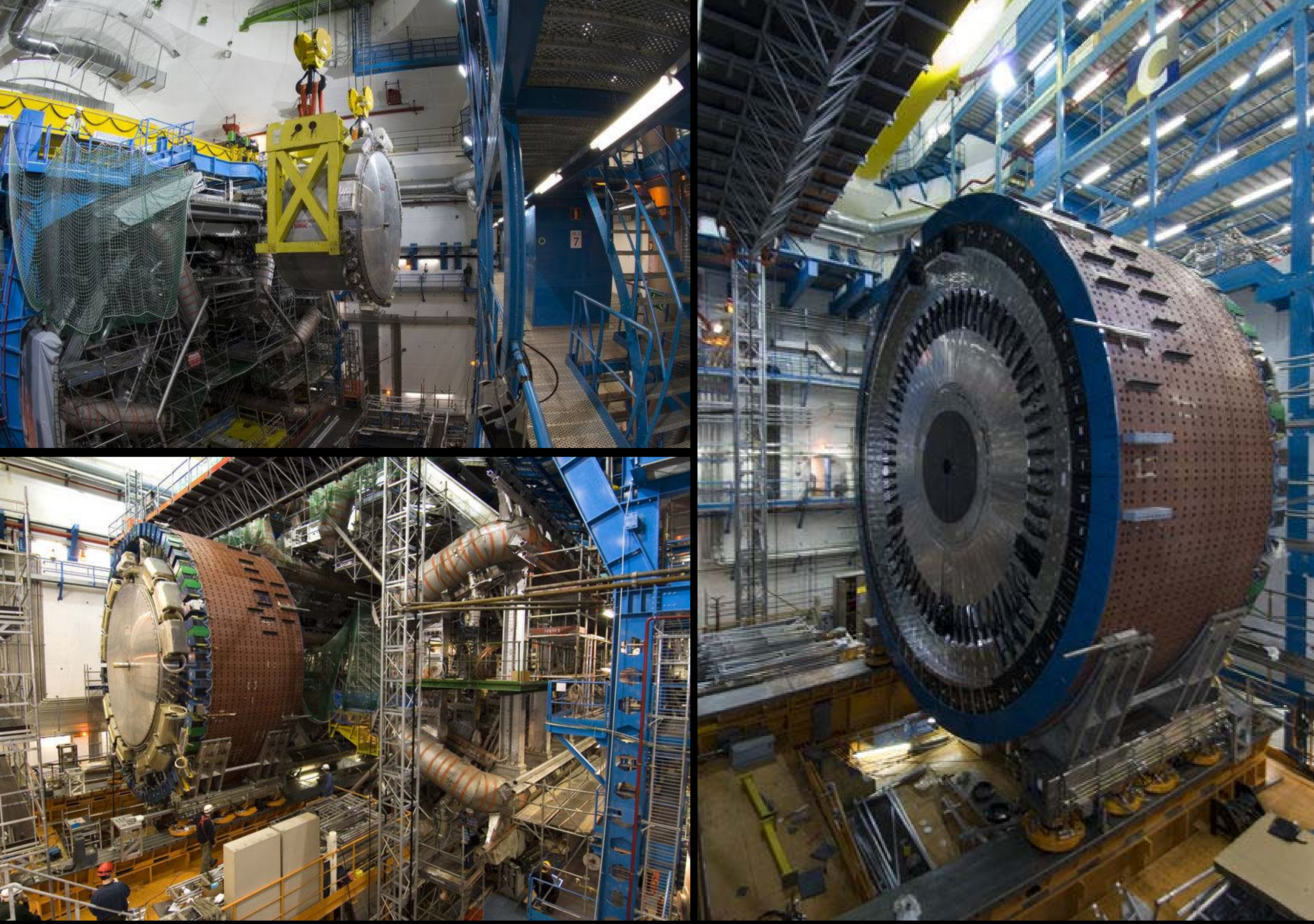
Muons at 6σ from noise



With 100 μ/cell: check physics timing to 0.6 ns for Commissioning with cosmics



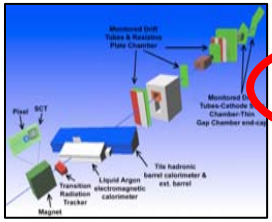
ATLAS barrel calorimeter being moved to the IP, Nov. 2005



ATLAS endcap calorimeters installation, winter-spring 2006

ATLAS L. Ar ECAL Road Map

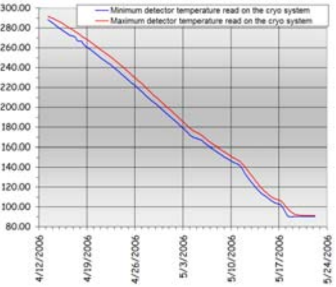
2005 2006 2007 2008

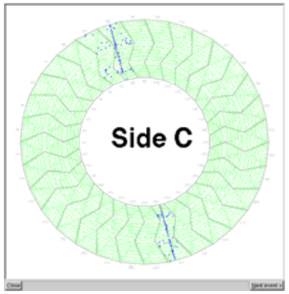


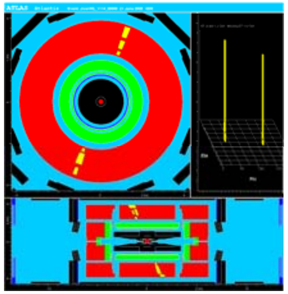
Combined test beam (1% of ATLAS)

Detector installation

Integration, from detector to off-line cosmic runs

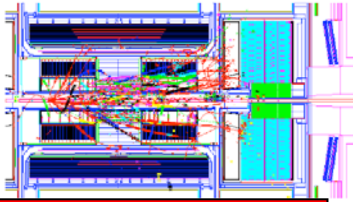






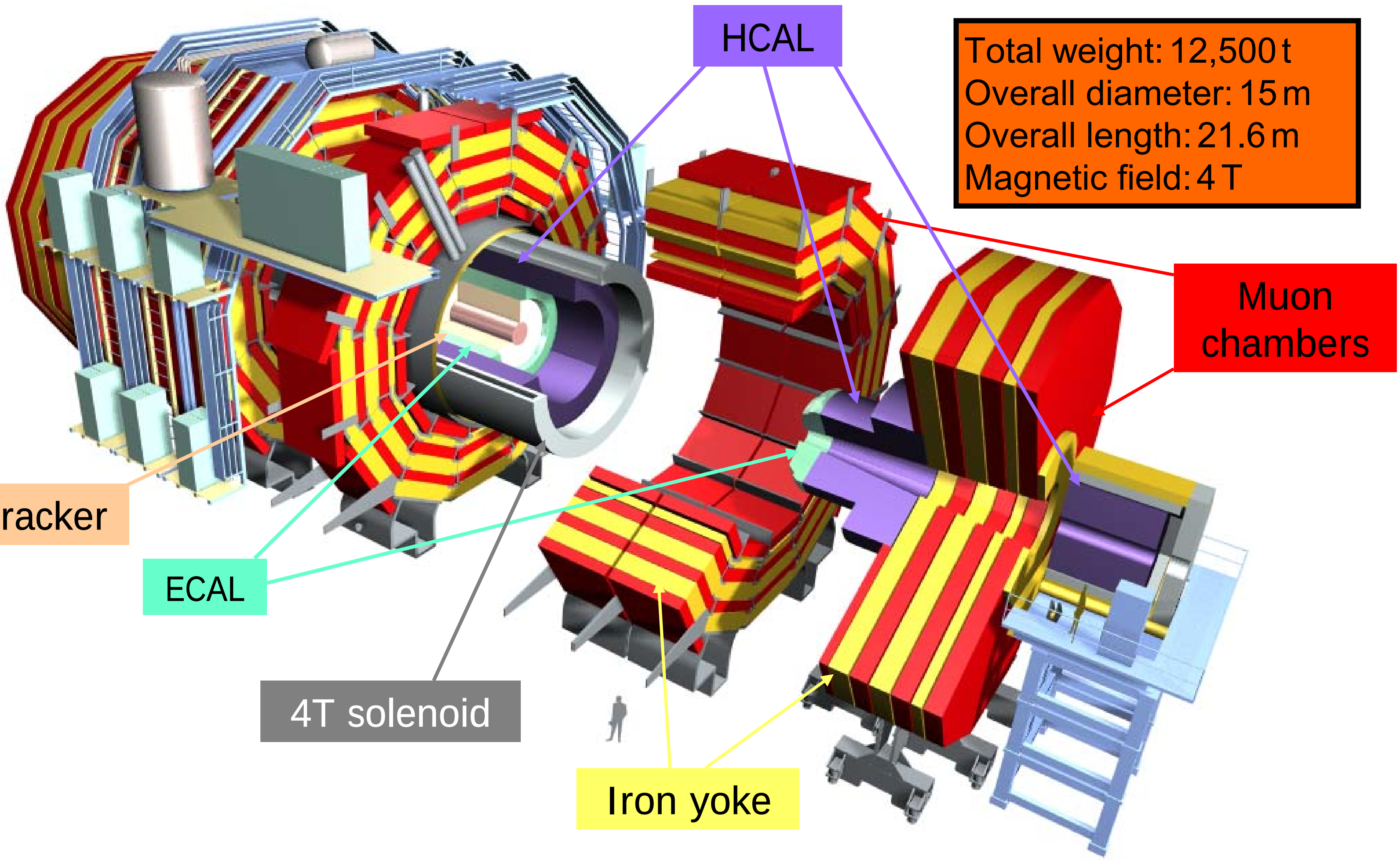
Global cosmic run

First beams



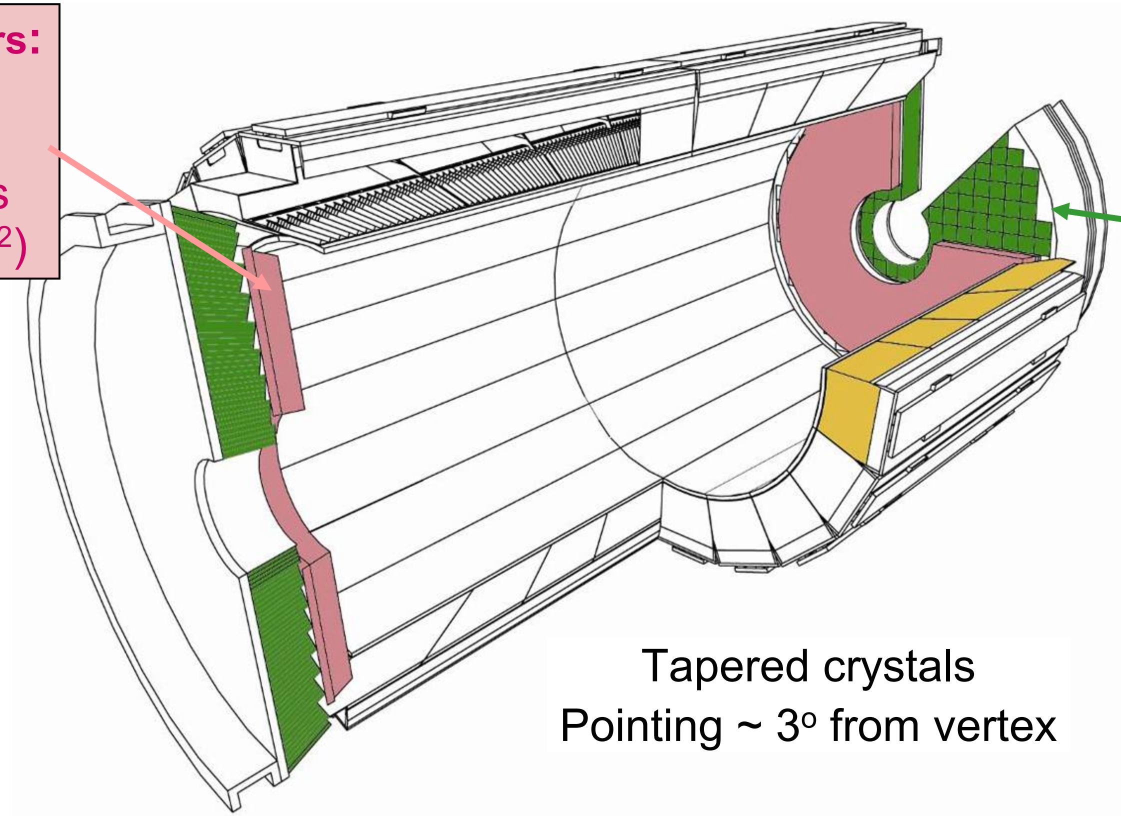
All L. Ar ECAL cryostats in cavern. Barrel is cold. Readout will grow with more power supplies. Data taking with cosmic starts 7/06 (barrel) and 12/06 (endcaps).

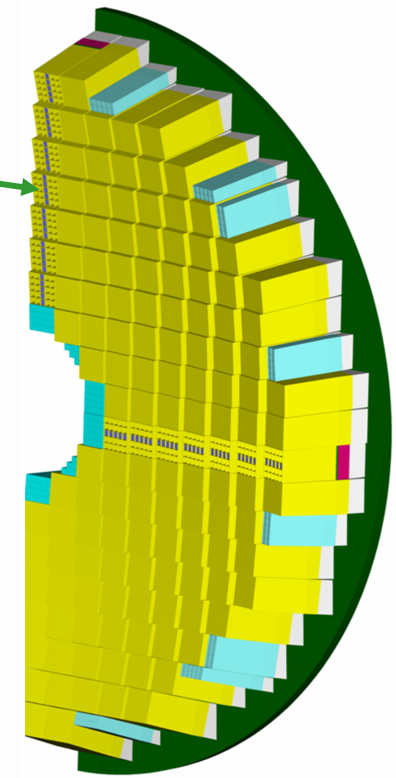
CMS Detector



CMS PWO Crystal ECAL

Pb/Si Preshowers:
4 Dees
(2/endcap)
4300 Si strips
(~ 63 x 1.9 mm^2)





Barrel: 36 Supermodules (18 per half-barrel)
61200 Crystals (34 types) – total mass 67.4 t
Dimensions: ~ 25 x 25 x 230 mm^3 (25.8 X^0)
$\Delta\eta \times \Delta\varphi$ = 0.0175 x 0.0175

Endcaps: 4 Dees (2 per endcap)
14648 Crystals (1 type) – total mass 22.9 t
Dimensions: ~ 30 x 30 x 220 mm^3 (24.7 X^0)
$\Delta\eta \times \Delta\varphi$ = 0.0175 x 0.0175 ↔ 0.05 x 0.05

Why PWO Crystals

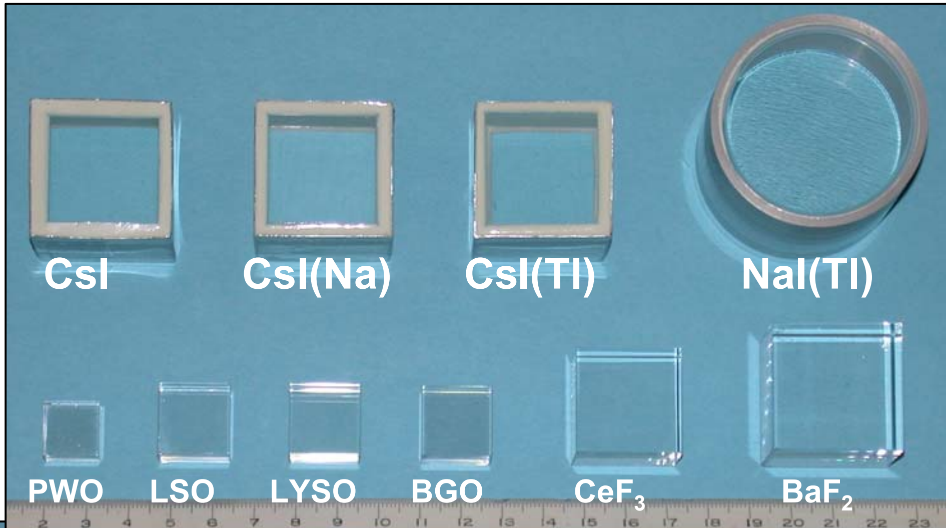
- Excellent resolutions for energy, position and photon angle (with vertex) measurements
- High density allows a compact detector
- Simple building blocks allow easy mechanical assembly, hermetic coverage and fine transverse granularity
- Single segment allows straightforward energy and position reconstruction
- Challenges:
  - Radiation damage of scintillating crystals
  - Temperature stabilization to 0.1^{o}C

Mass Produced Crystals

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	PWO(Y)	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (ºC)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	0.89	1.14	1.38
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.00	2.07	2.23
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.7	20.9	22.2
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	2.20	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	425 420	402	440
Decay Time [b] (ns)	230	1250	30 6	630 0.9	300	30 10	40	60
Light Yield [b,c] (%)	100	165	3.6 1.1	36 3.4	21	0.29 .083	83	30
d(LY)/dT [b] (%/ ºC)	-0.2	0.3	-1.3	-1.3	-0.9	-2.7	-0.2	-0.1
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV	TAPS (L*) (GEM)	L3 BELLE PANDA?	CMS ALICE PrimEx PANDA?	-	-

a. at peak of emission; b. up/low row: slow/fast component; c. PMT QE taken out.

PWO: Short Radiation Length



1.5 X_0 Samples:

Hygroscopic Halides

Non-hygroscopic

Full Size Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

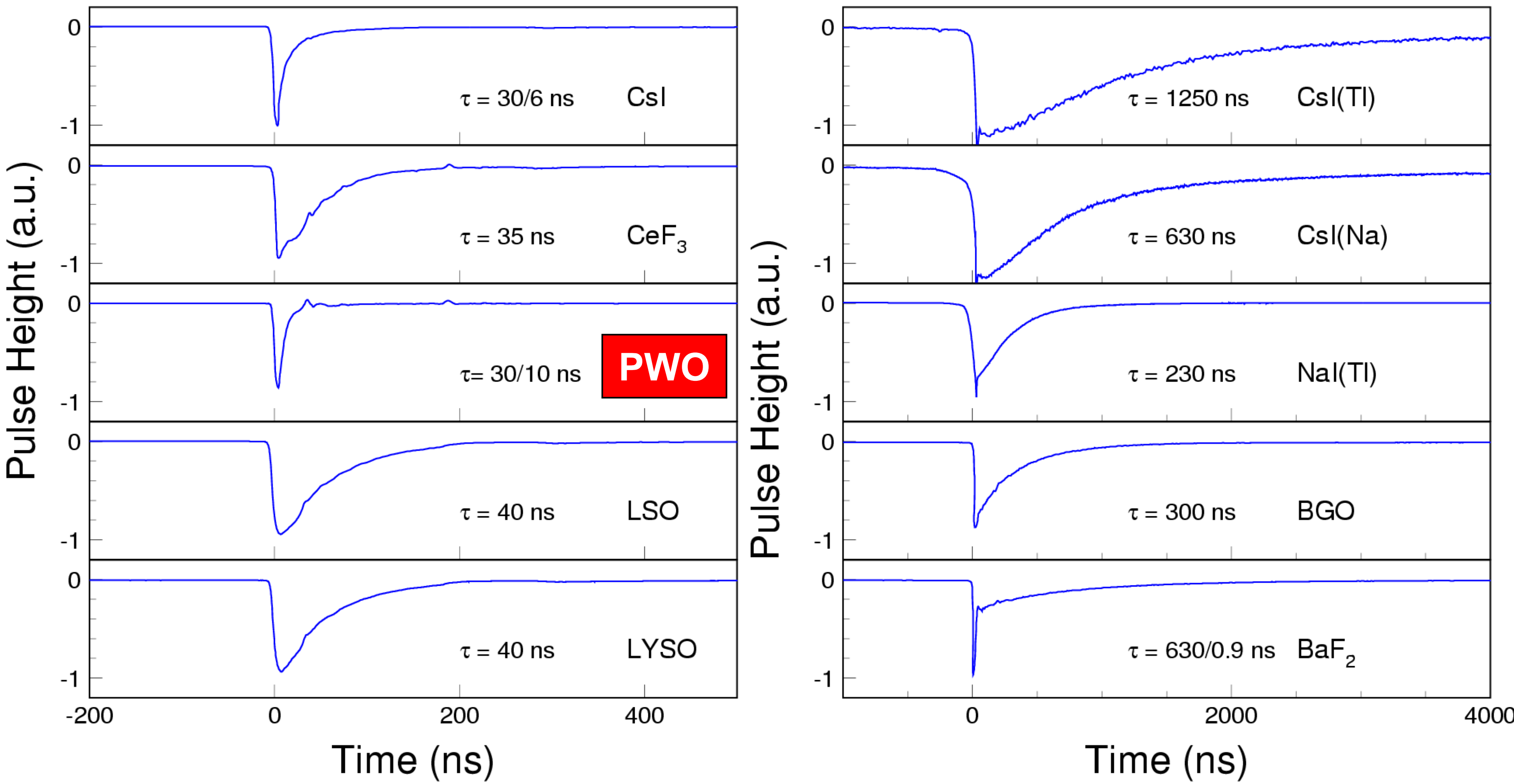
CMS PWO(Y): 26 X_0

PWO: Fast Scintillation

Recorded with Agilent 6052A digital scope

Fast Scintillators

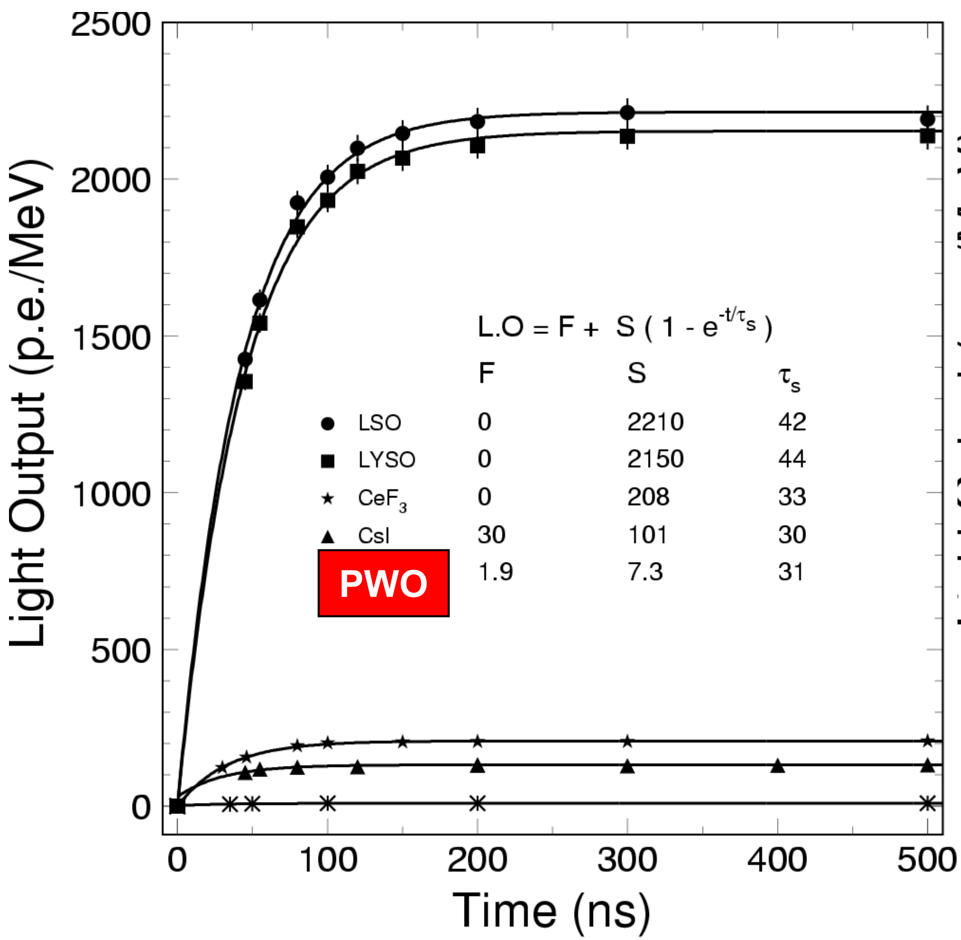
Slow Scintillators



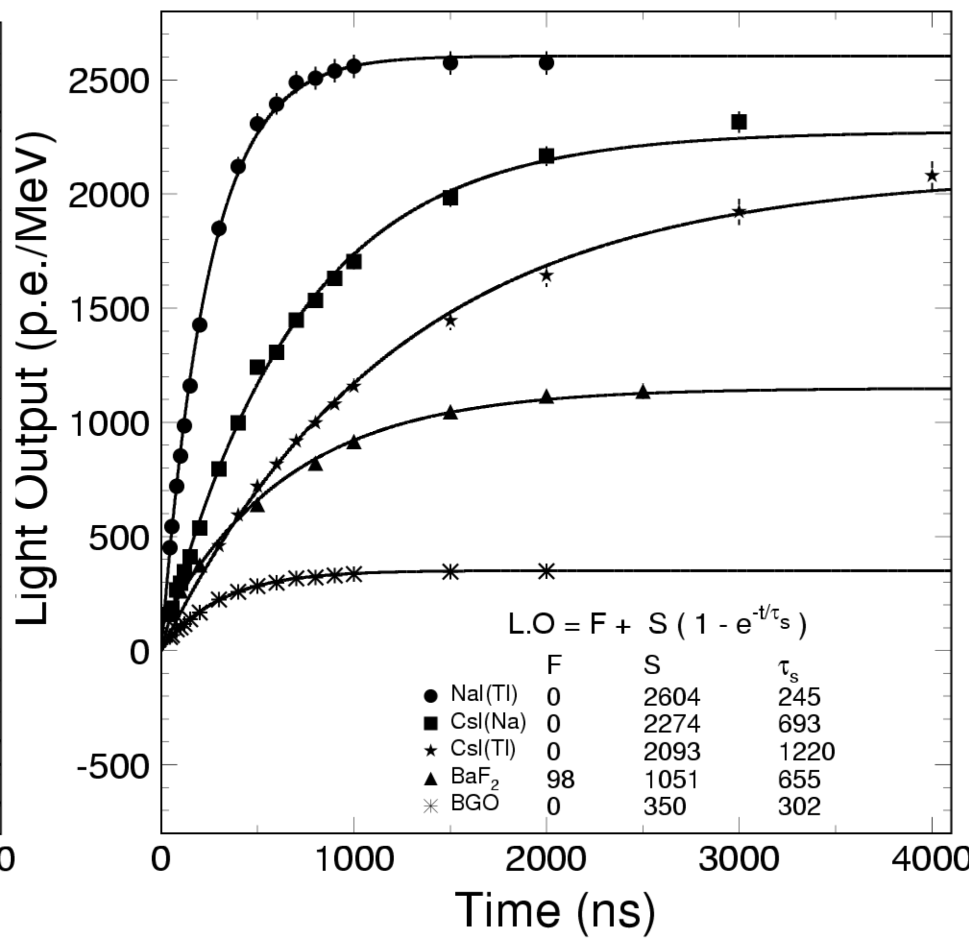
PWO: Low Light Output OK for LHC

Measured with a Philips XP2254B PMT (multi-alkali cathode)

Fast Scintillators

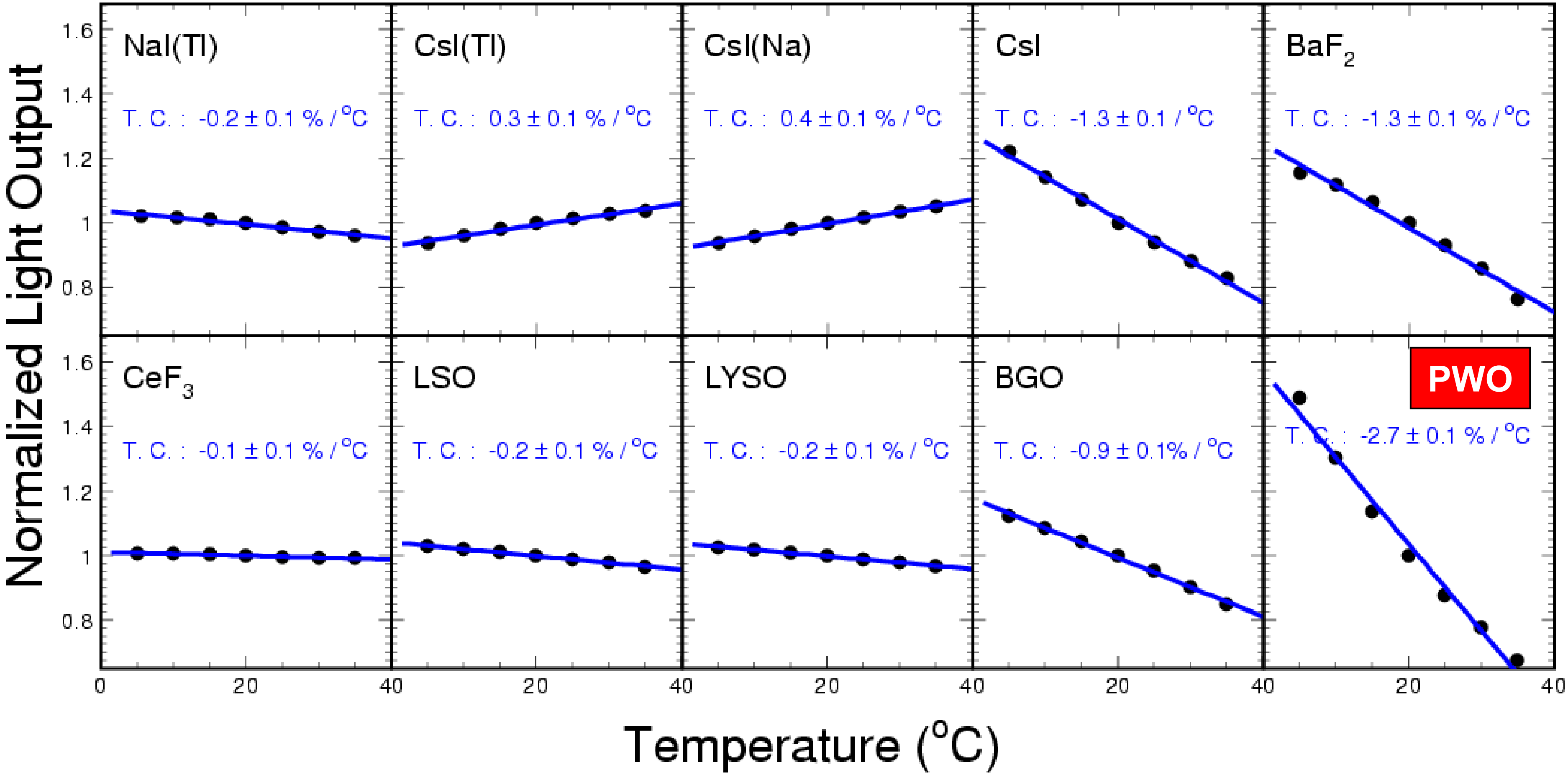


Slow Scintillators



Temperature Dependent Light Output

PWO light output has large temperature coefficient, requiring a temperature stabilized environment



PWO Crystal Production

Crystal delivery determines ECAL Critical Path

Two Suppliers:

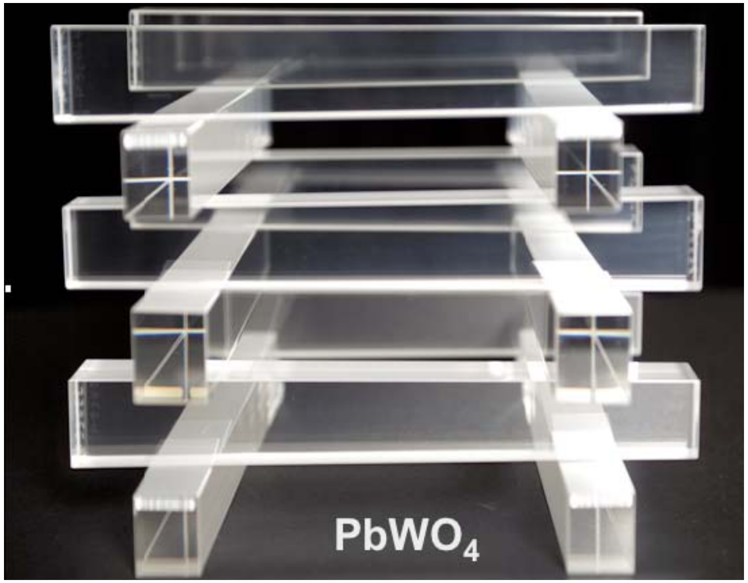
BTCP (Bogoroditsk, Russia) ~ 1,160/month

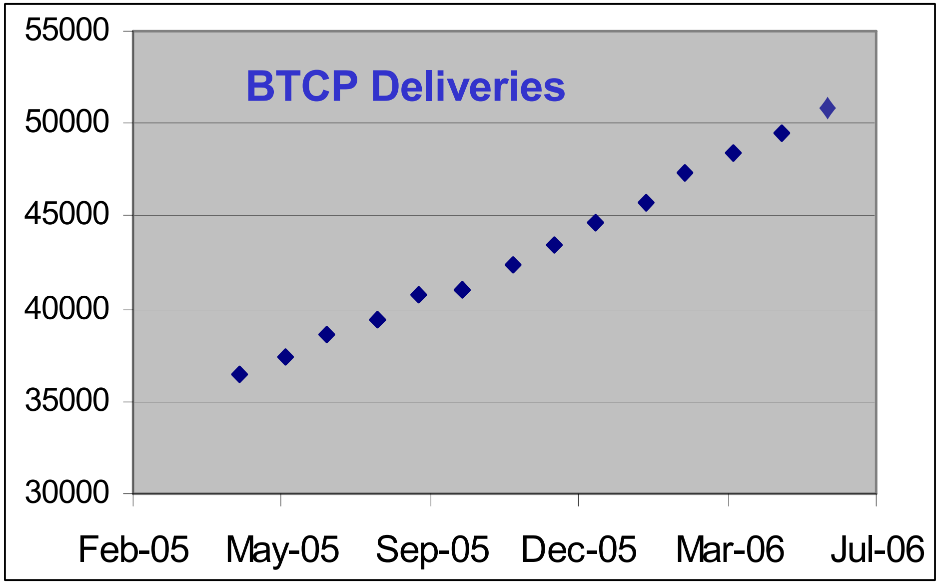
SIC (Shanghai, China) ~ 140/month

~ 85% of Barrel crystals already delivered (52k of 61k)

Preseries of Endcap crystals: 100 BTCP, 300 SIC

- Last Barrel crystal delivery Feb 2007, ready for 2007 pilot run
- Last Endcap crystal delivery Jan 2008, ready for 2008 physics run





Photodetectors

Barrel - Avalanche photodiodes (APD)

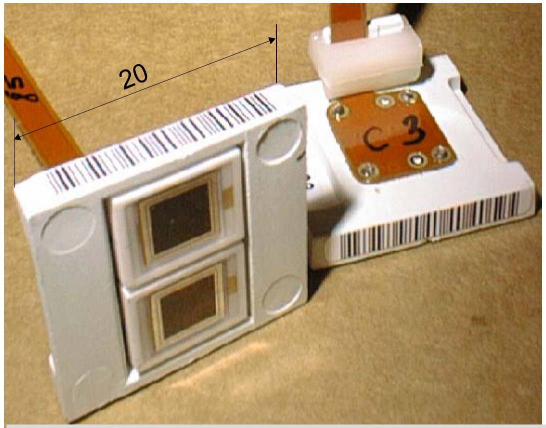
Two Hamamatsu S8664-55 APDs/crystal

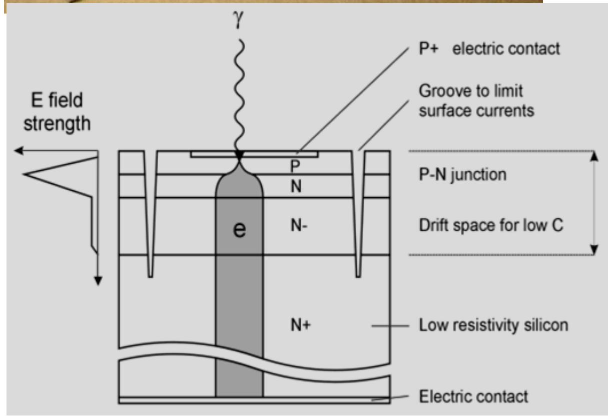
- Gain: 50   QE for PWO: ~75%
- Temperature dependence: -2.4%/^{O}C
- Delivery complete

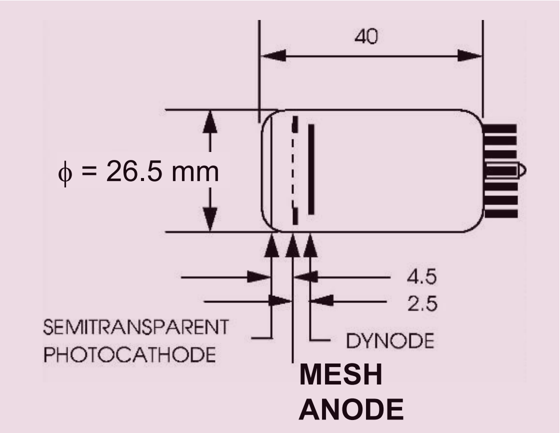
Endcaps: - Vacuum phototriodes (VPT)

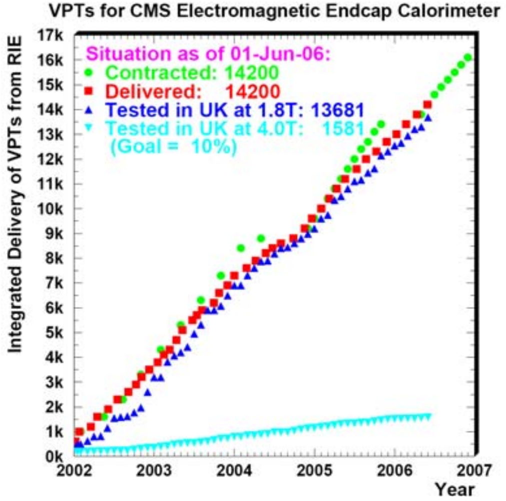
More radiation resistant than Si diodes (with UV glass window)

- Active area ~ 280 mm^2/crystal
- Gain 8 -10 (B=4T)   Q.E. for PWO: ~20%
- Delivery ~92%

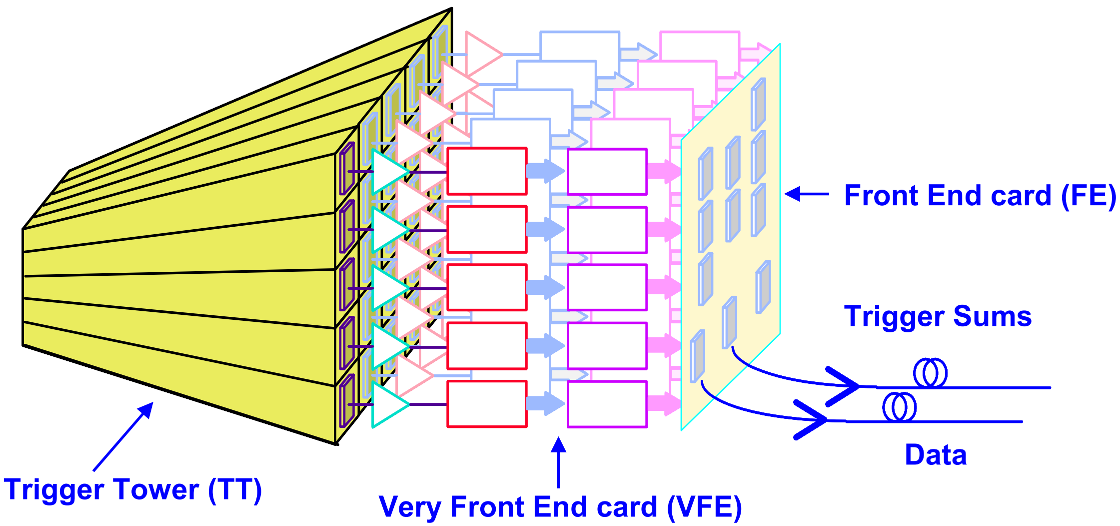


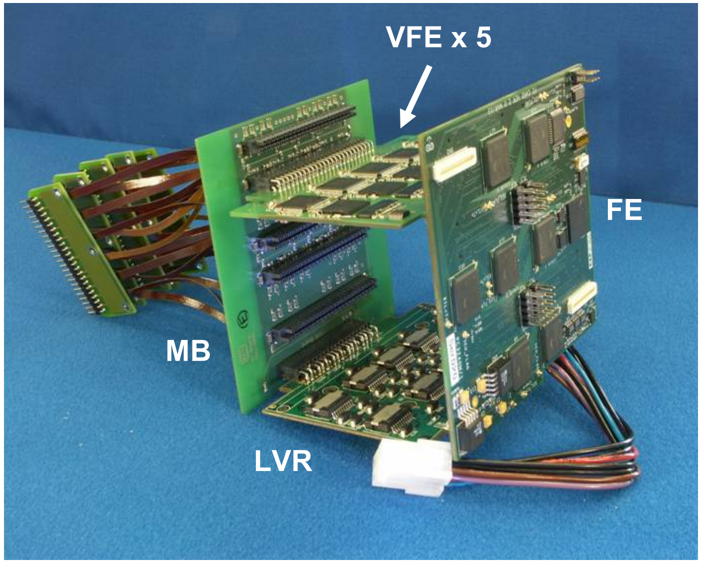


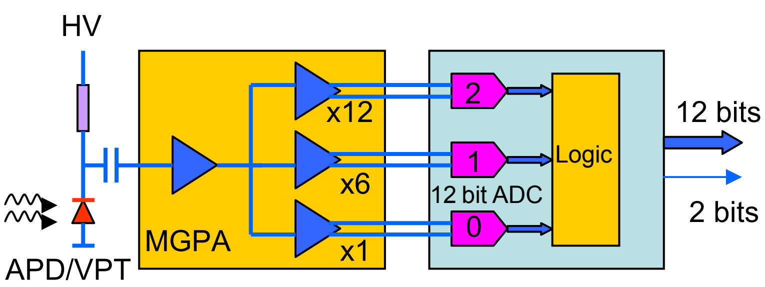




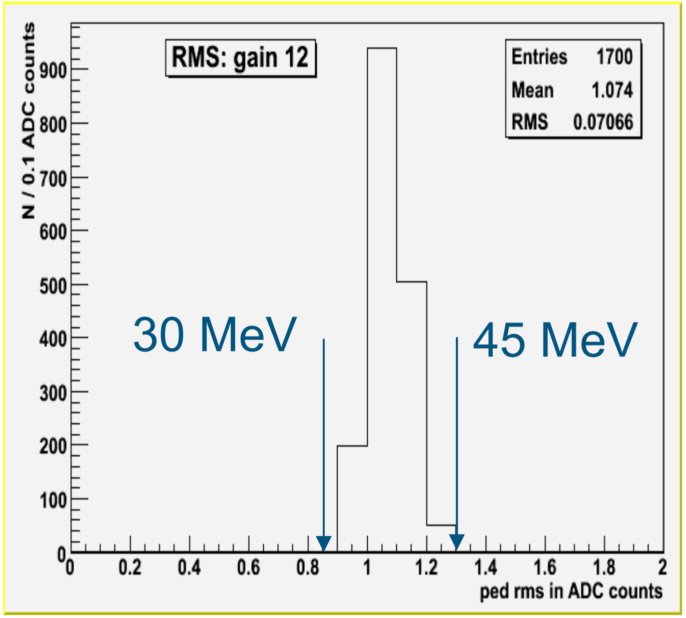
On-detector Electronics







VFE architecture for single channel



Noise distribution for 1,700 channels (one SM) measured in cosmic tests

Cooling and Temperature Stabilization

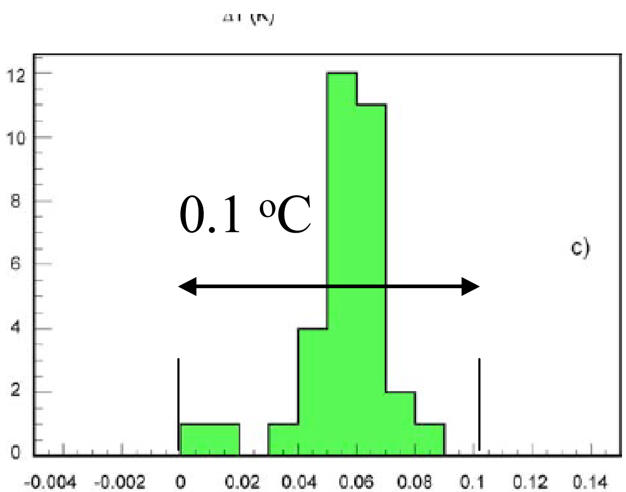
- Power dissipation of Barrel on-detector electronics ~160 kW
- Combined temperature sensitivity of (crystal + APD):

$$\left.\frac{dA}{dT}\right|_{APD+LY} \approx -4\% / {}^{o}C$$

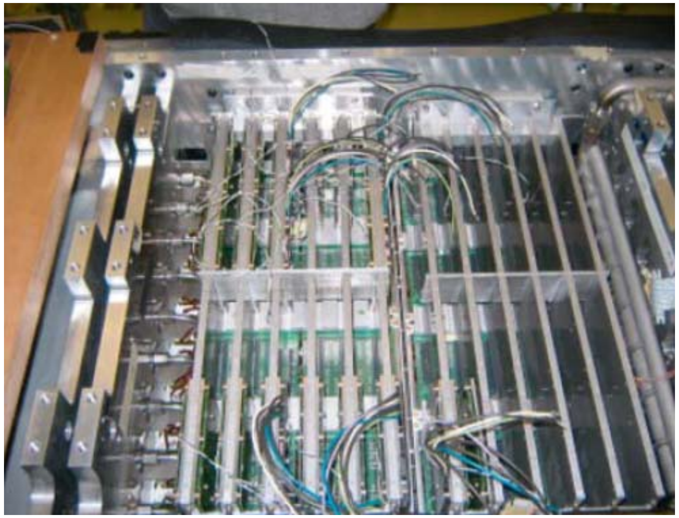
→ **Stabilise temperature to better than ± 0.05 ^{O}C**

- Chilled water at 50l/s

Water manifold and pipes on SM



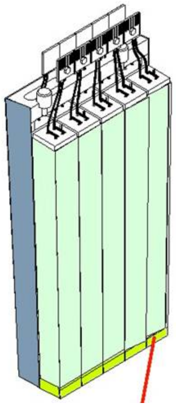
ΔT at APD when electronics is powered-up
(Worst case: Bottom Supermodule)



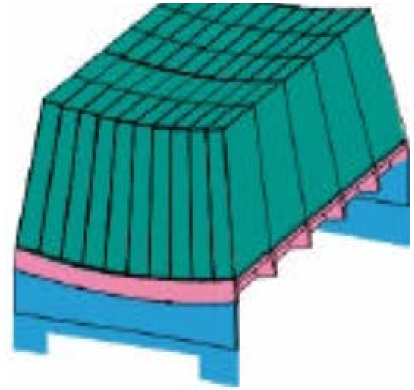
Cooling bars in direct contact with electronic cards

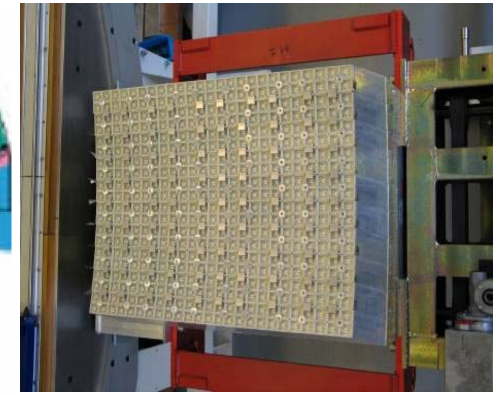
Construction: Barrel

2 Regional Centres: CERN and Rome

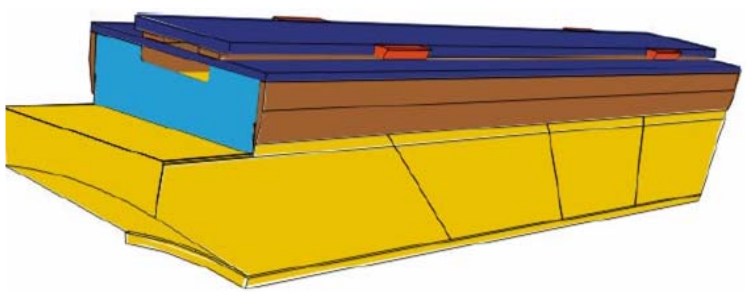


Sub-module: 10 crystals





Module: 400/500 crystals



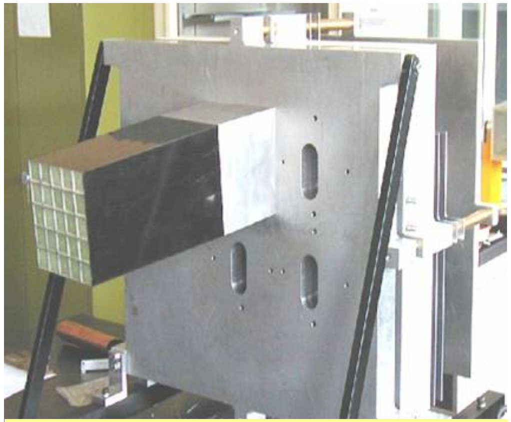
Super-module: 1700 crystals

Assembly status:
27/36 bare SMs assembled
21/36 SMs completed
Production rate 4/month

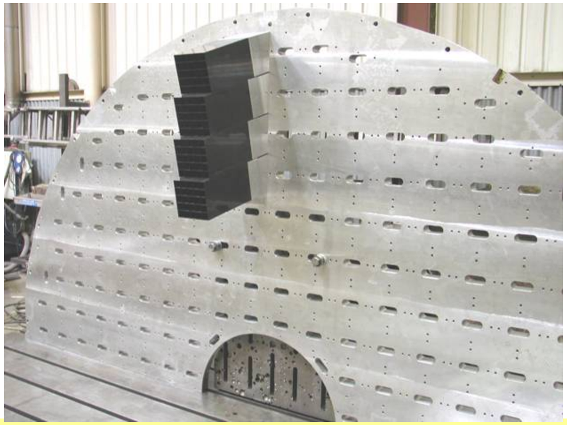
Bare SM

SM with cooling

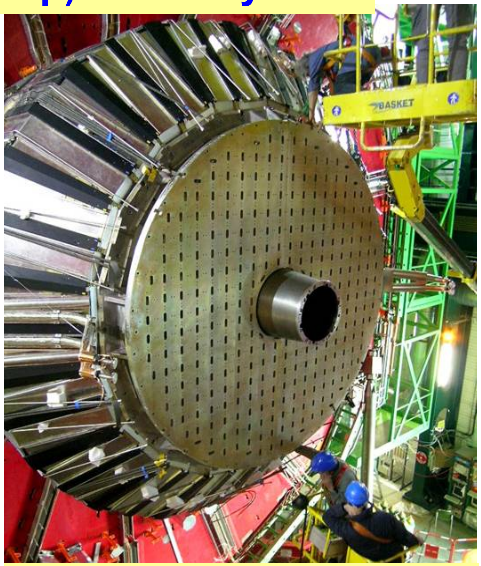
Construction: Endcaps



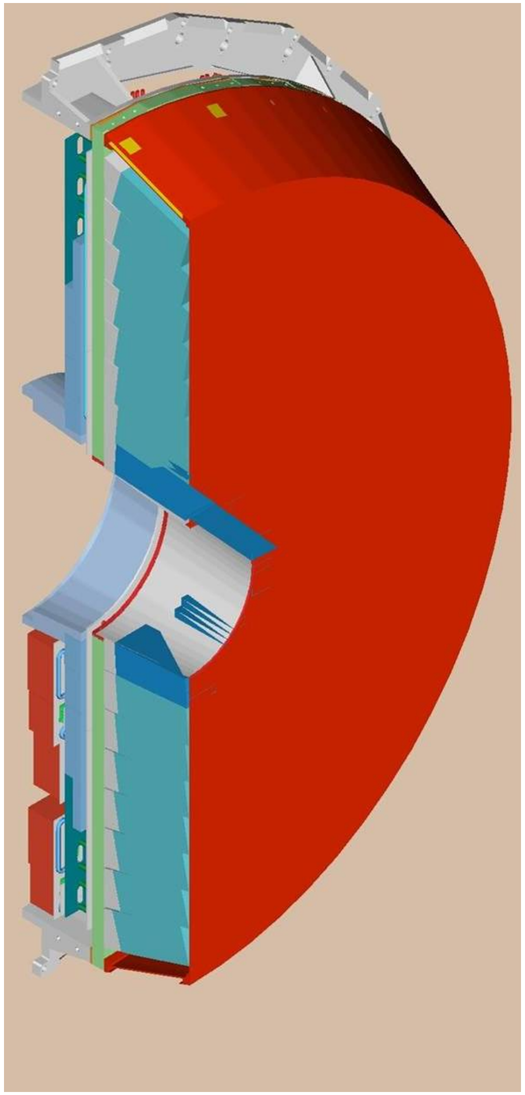
Supercrystal: 25 crystals



Dee (½ endcap): 3662 crystals



Backplates successfully test mounted on HCAL



Production status

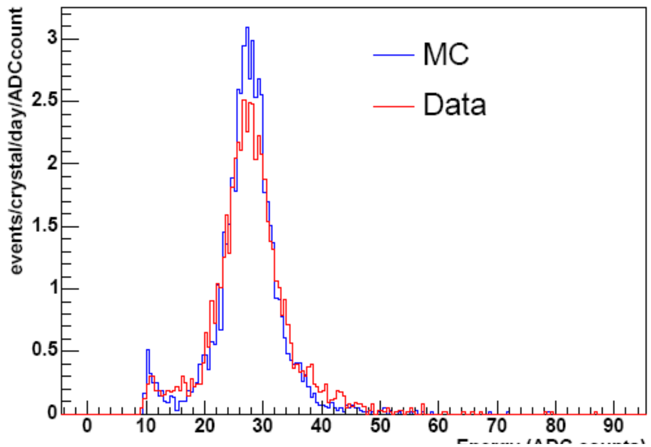
All mechanical parts delivered

Endcap crystal production starts in summer 2006

Cosmic Muon Test & Calibration

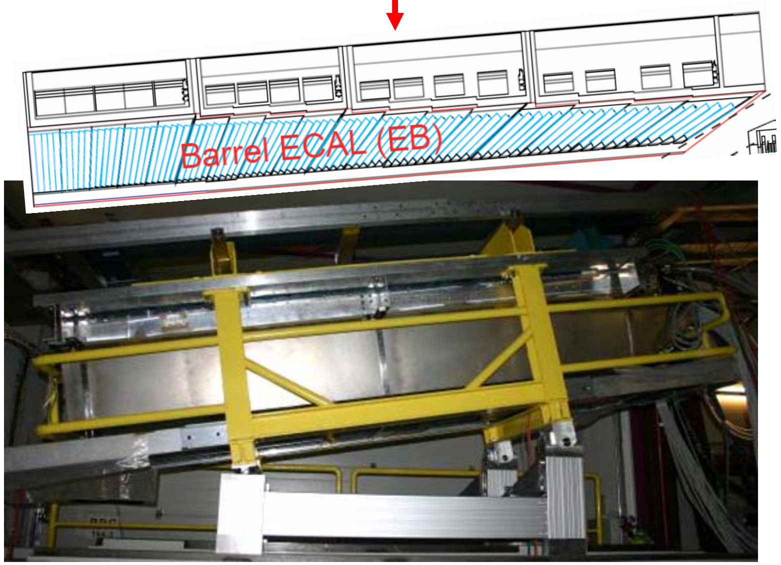
Each SM operated with cosmic rays for ~1 week

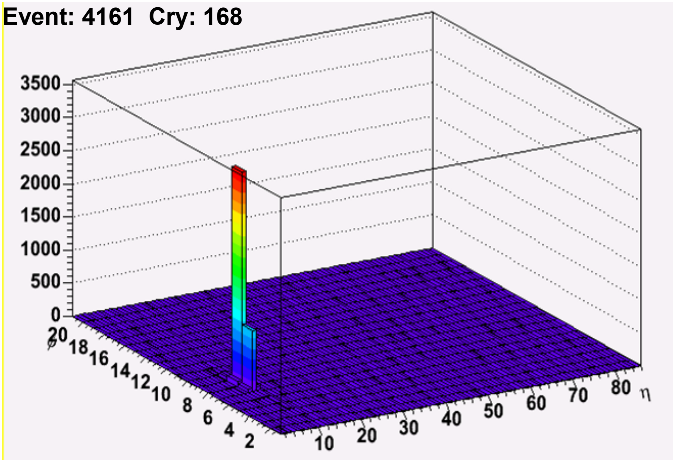
→ **Intercalibration: 1-3% (stat) depending on η**



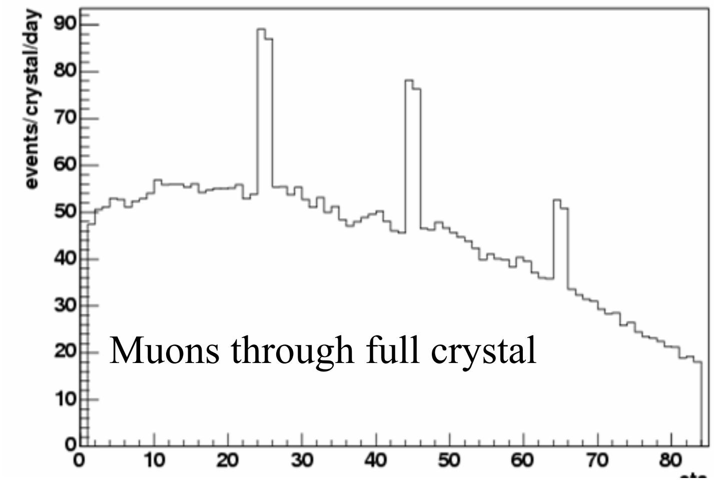
Mip deposits ~250MeV
(increase APD gain from 50 to 200)

Cosmic muons

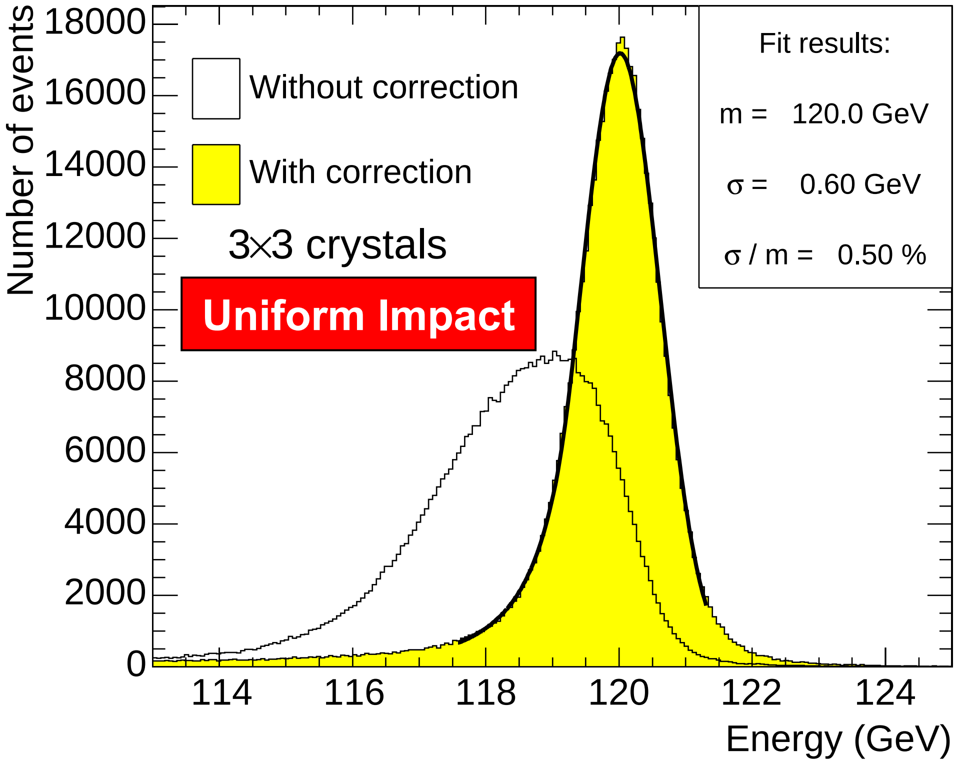


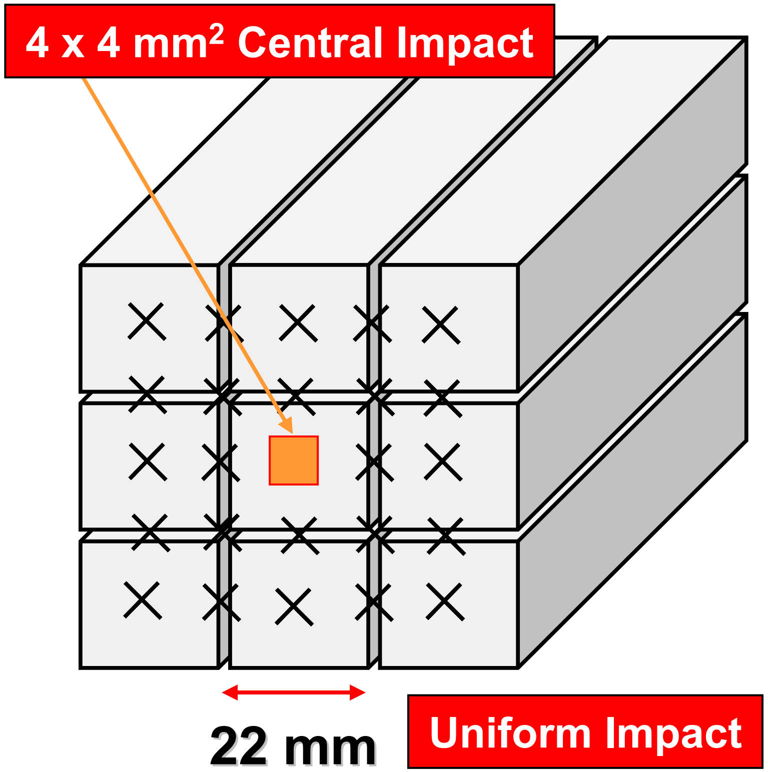


Status: 15 SM calibrated by cosmic rays



Test Beam: Containment Corrections



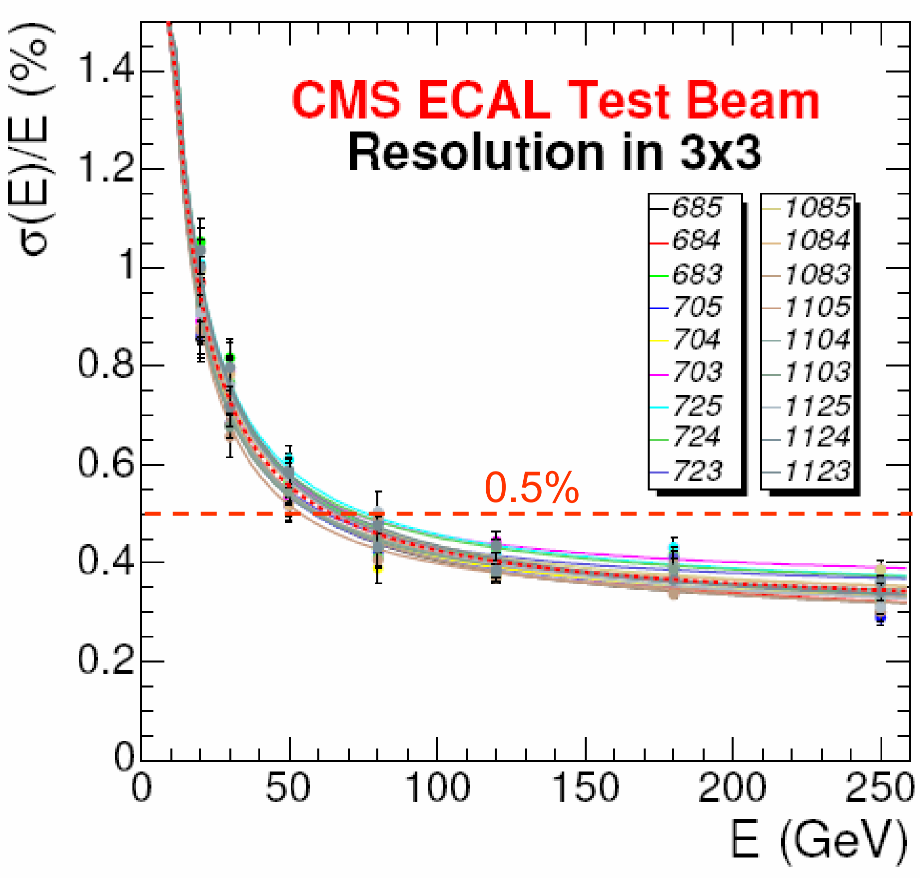


Two energy resolution curves are compared:

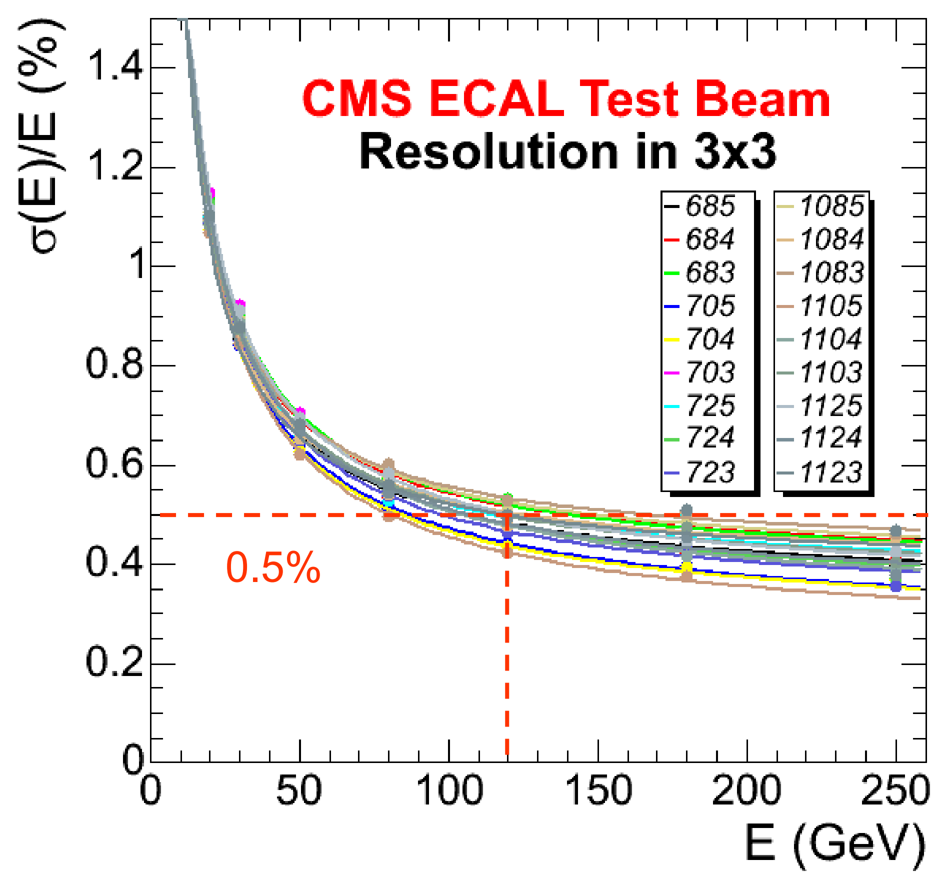
- Including cuts on electron position to select only electrons hitting crystal centre => central impact resolution
- Without any cuts, but including cluster corrections => uniform impact resolution

Test Beam Result: Energy Resolutions

Central Impact



Uniform Impact



Energy resolution: $\sigma E/E = 2.9/\sqrt{E} \oplus 0.3 \oplus 0.125/E$

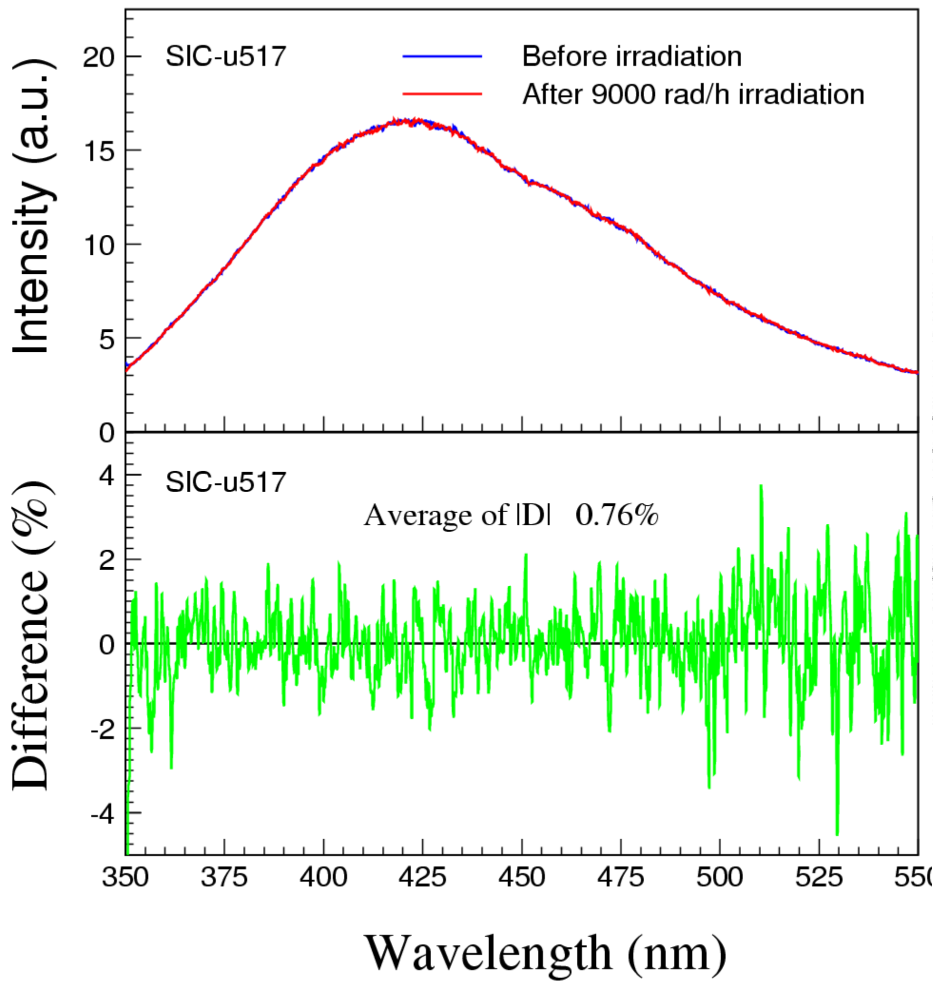
Effects of Crystal Radiation Damage

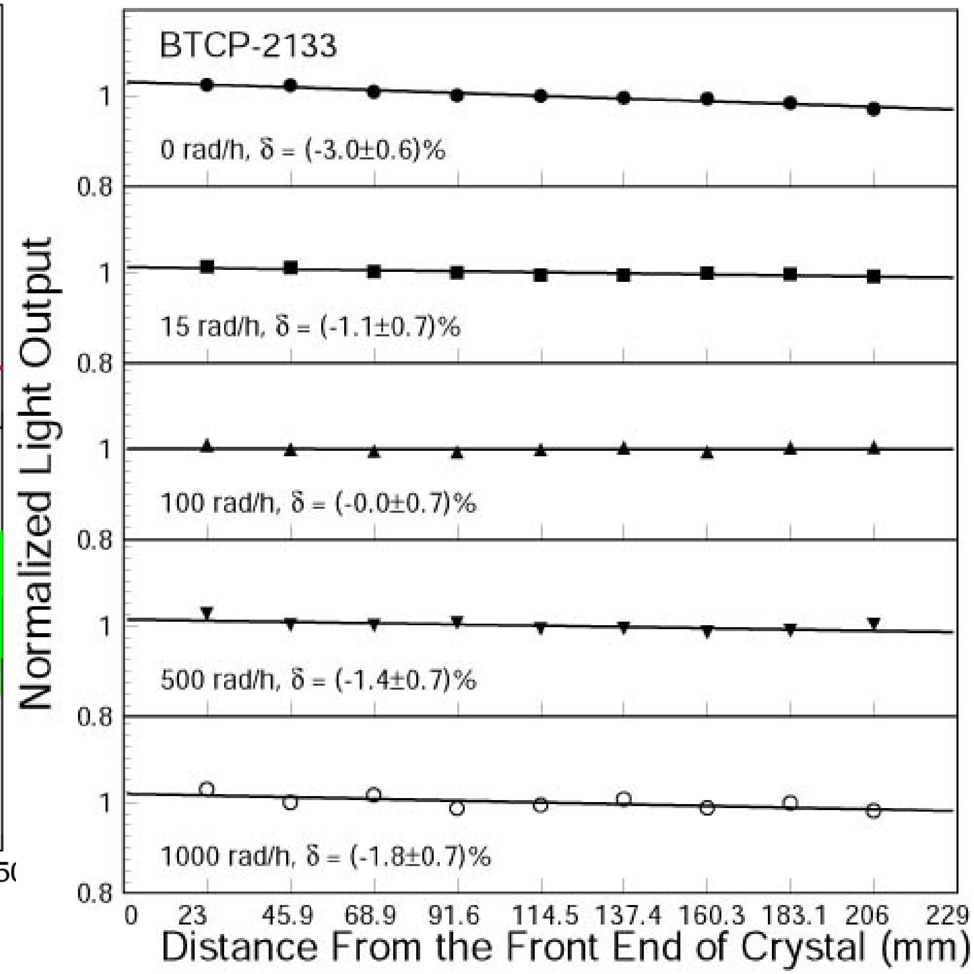
- Induced absorption caused by color center formation:
  - reduces light attenuation length and thus light output, and maybe
  - degrades light response uniformity (LRU)
- Induced phosphorescence:
  - increases readout noise
- Reduced scintillation light yield:
  - reduces light output and degrades light response uniformity

Item	CsI(Tl)	CsI	BaF_2	BGO	$PbWO_4$
Color Centers	Yes	Yes	Yes	Yes	Yes
Fluorescence	Yes	Yes	Yes	Yes	Yes
Scintillation	No	No	No	No	No
Recover @RT	Slow	Slow	No	Yes	Yes
Dose Rate Dependence	No	No	No	Yes	Yes
Thermall Annealing	No/Yes	No/Yes	Yes	Yes	Yes
Optical Bleaching	No/Yes	No/Yes	Yes	Yes	Yes

PWO: No Damage in Scintillation

No variation in emission and light response uniformity

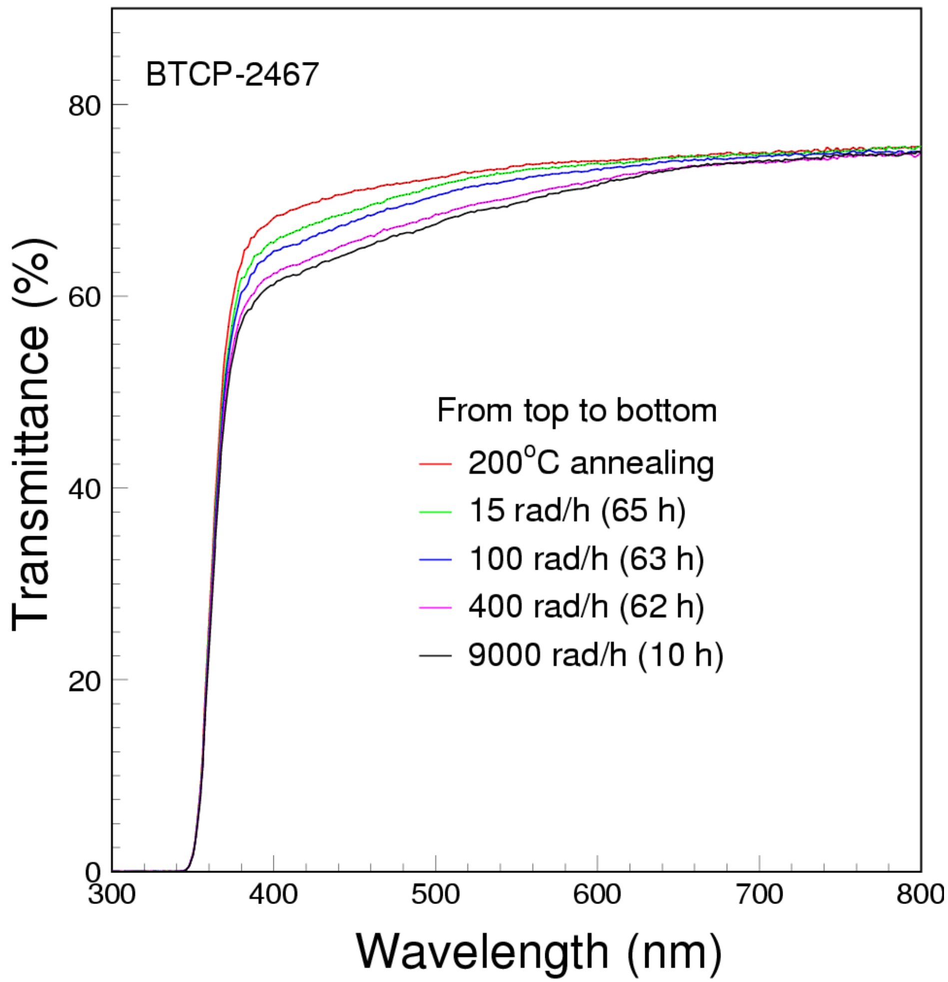


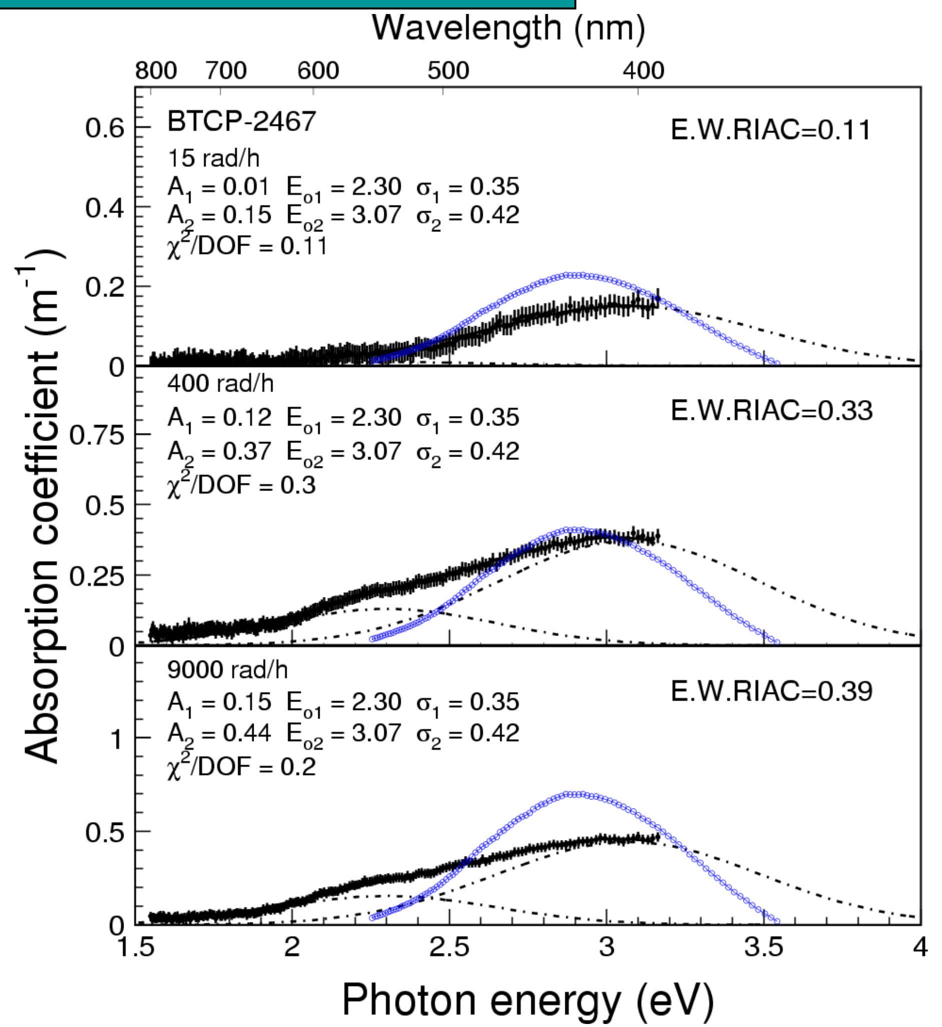


Calorimeter resolution would not be damaged even with light output loss

PWO: Radiation Induced Absorption

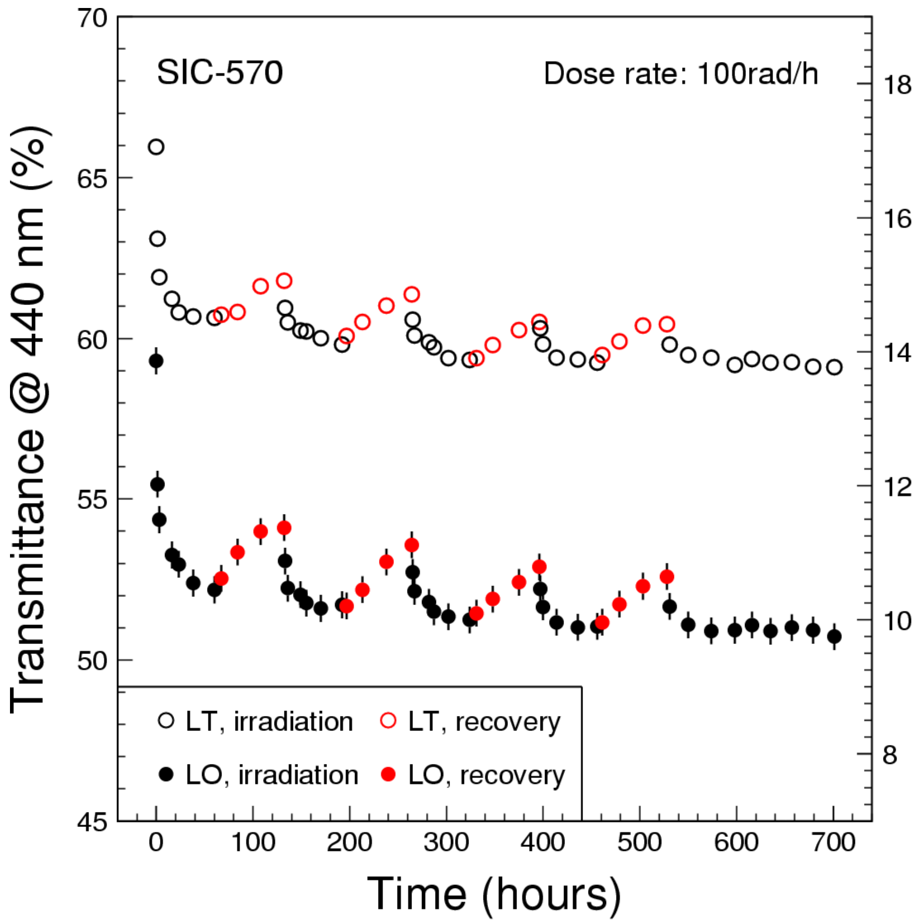
Radiation induces absorption caused by color center formation

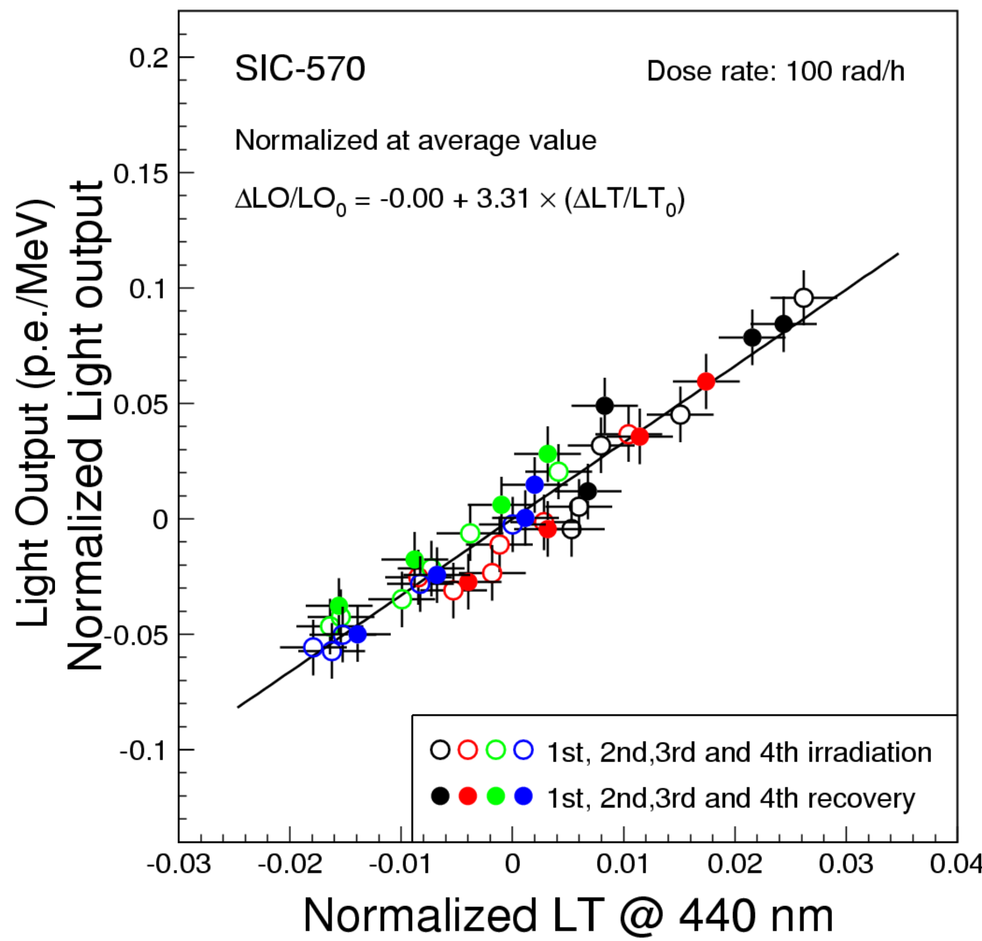




PWO: δLO/LO vs. δLT/LT @ 100 rad/h

Light output variations can be corrected by transmittance variations





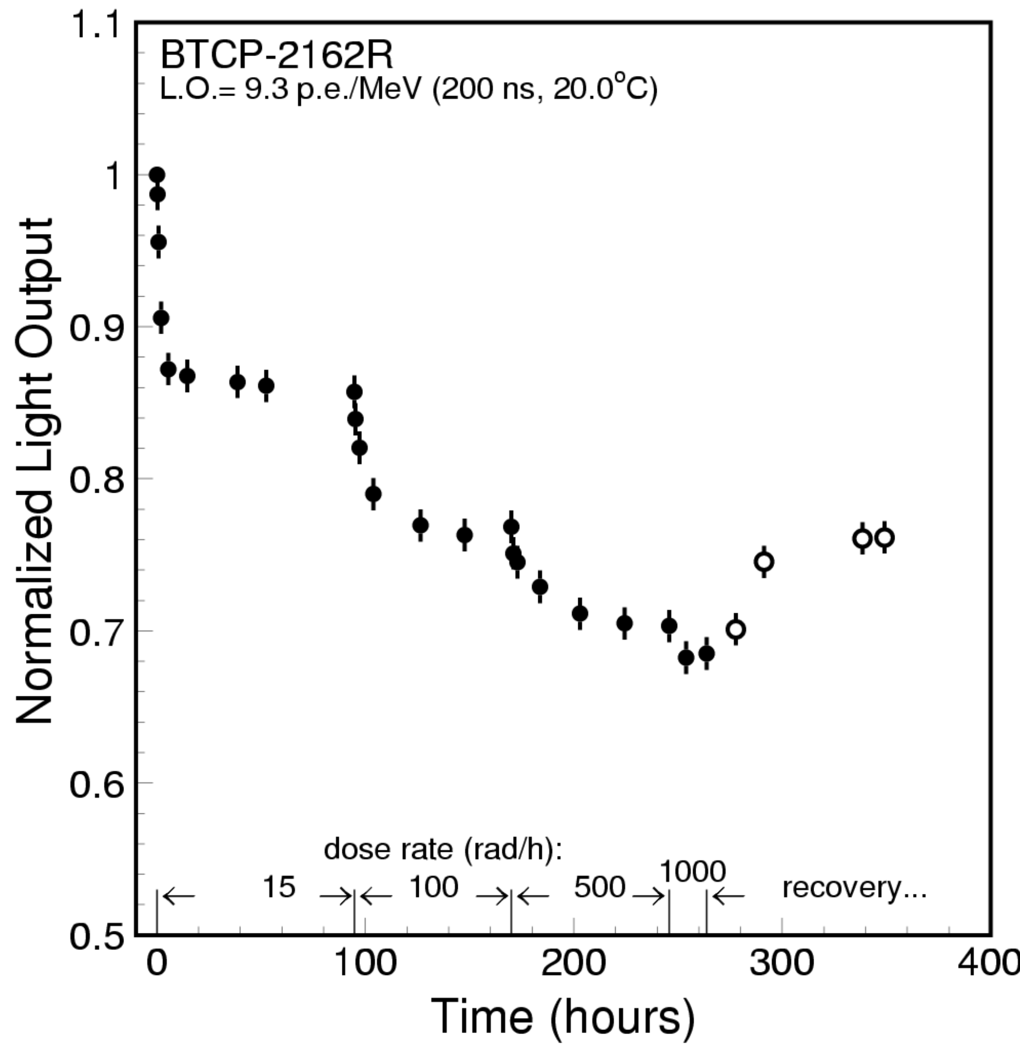
PWO: Damage is Dose Rate Dependent

$$dD = \sum_{i=1}^{n} \{-a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt\}$$

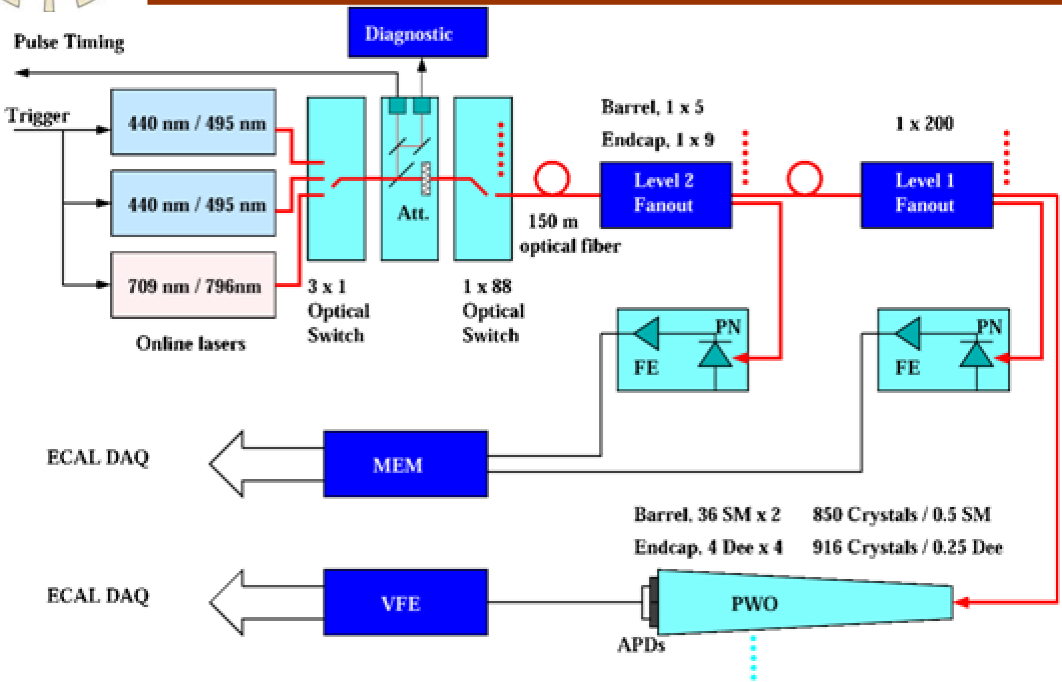
$$D = \sum_{i=1}^{n} \{\frac{b_i R D_i^{all}}{a_i + b_i R}\,[1 - e^{-(a_i+b_iR)t}] + D_i^0 e^{-(a_i+b_iR)t}\}$$

- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

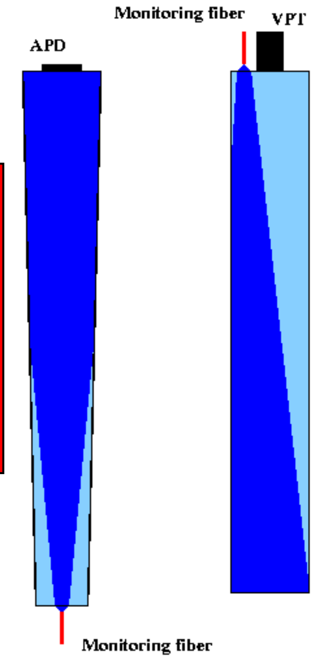
$$D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}$$



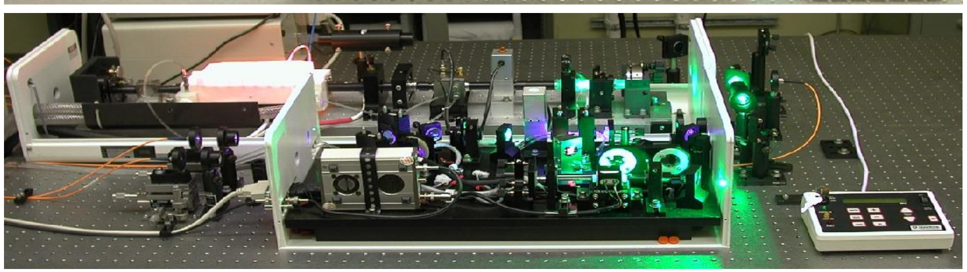
Laser Light Monitoring System

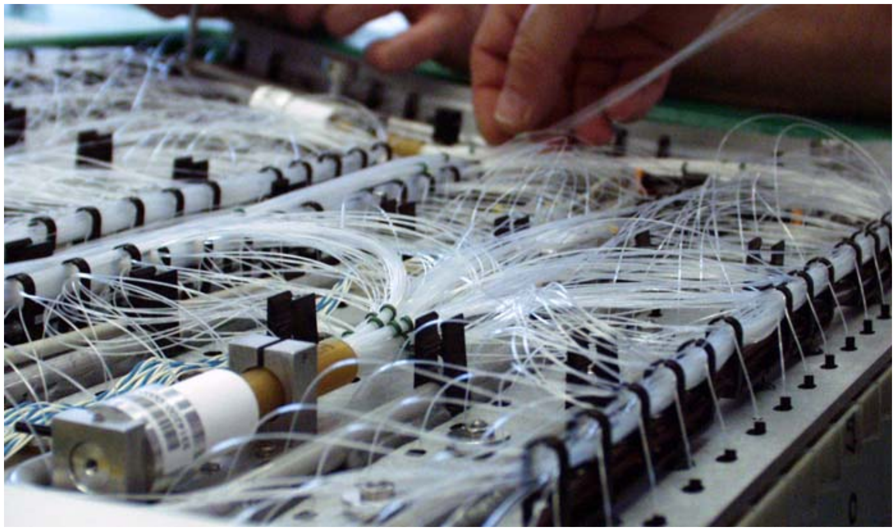


Fibers at front for barrel crystal



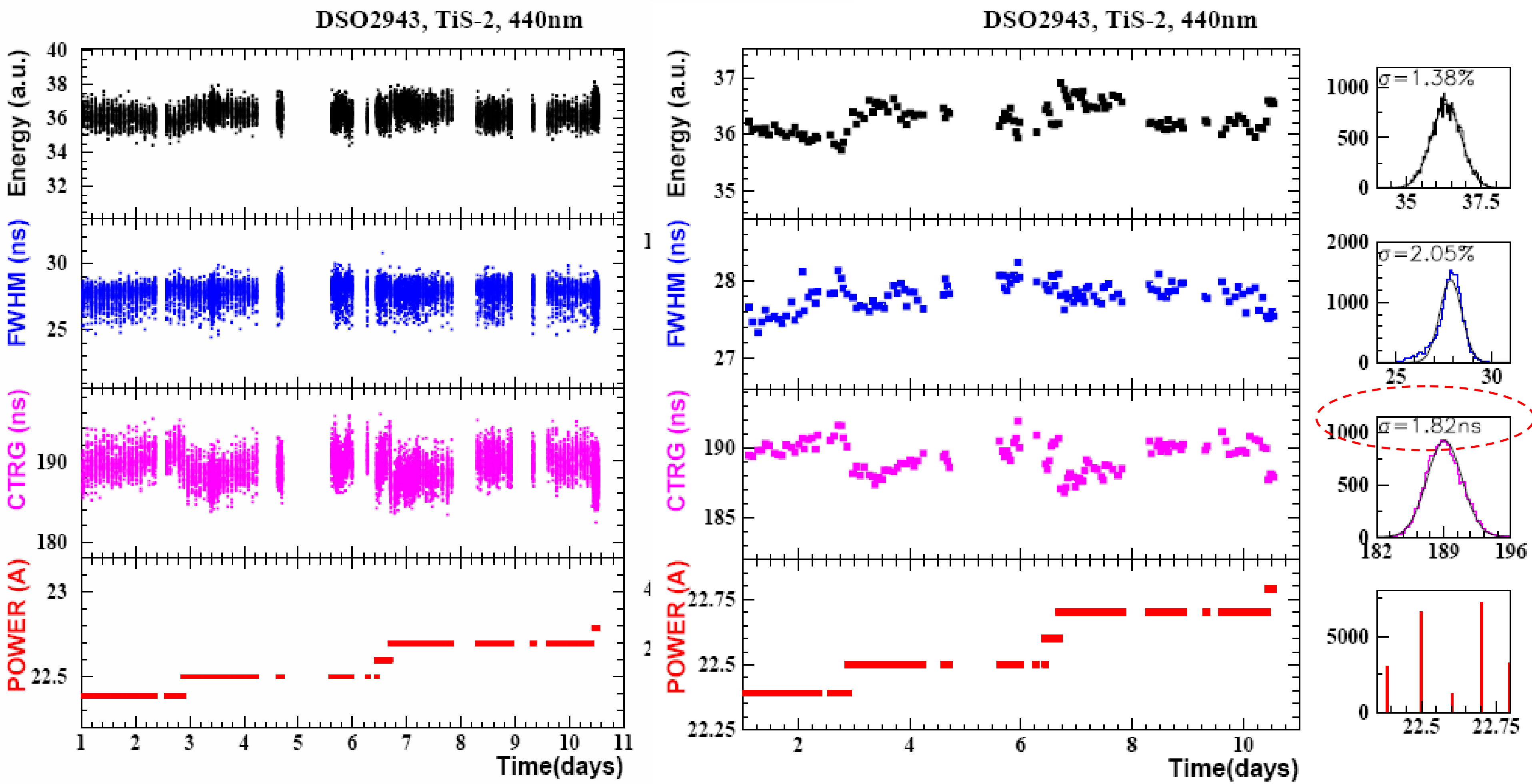
Fibers at back for endcap crystal



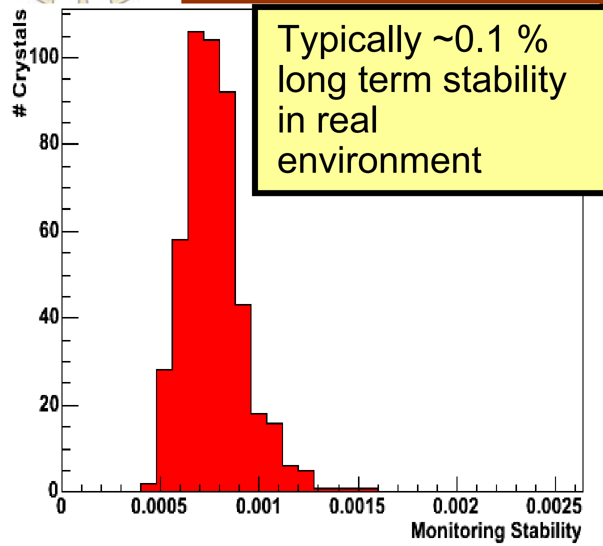


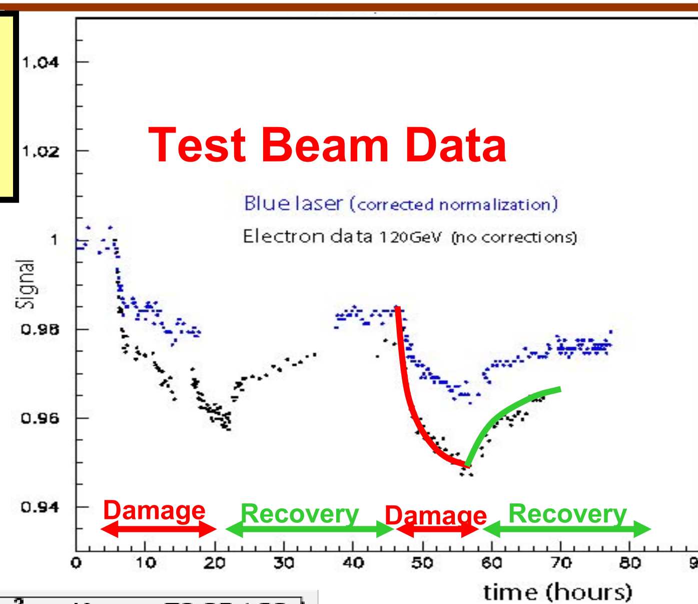
Laser Stability with Software Feedback

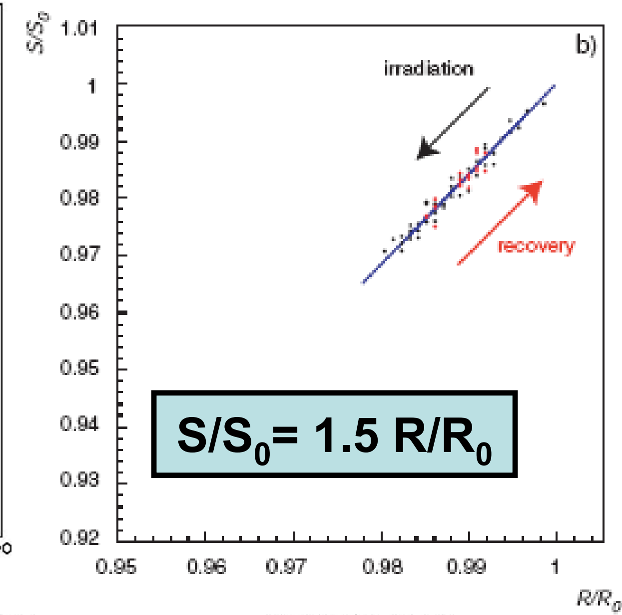
A factor of two better stability has been observed in a run of 10 days, using laser pulse timing as the feedback input, when YLF current increased by 0.5 A

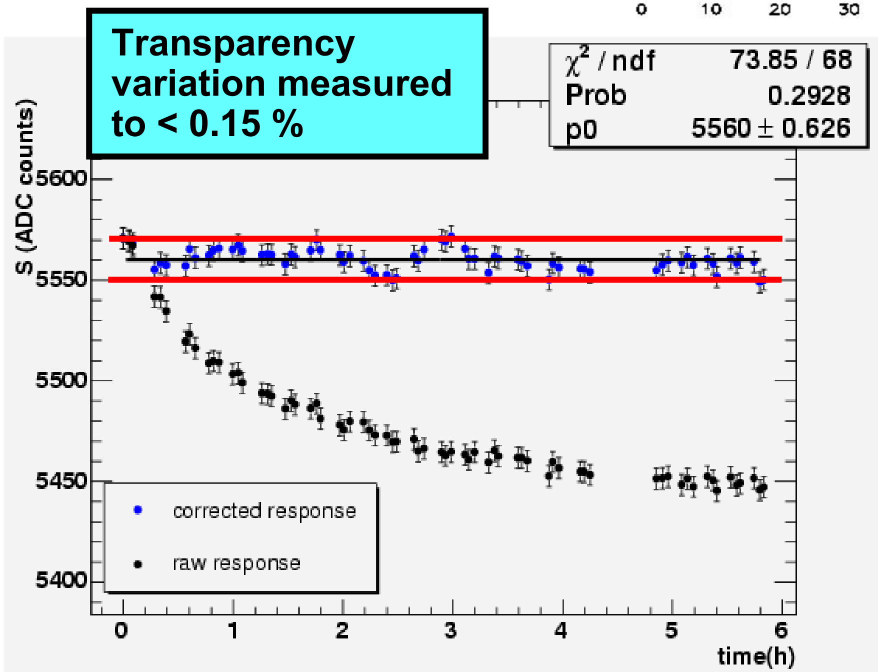


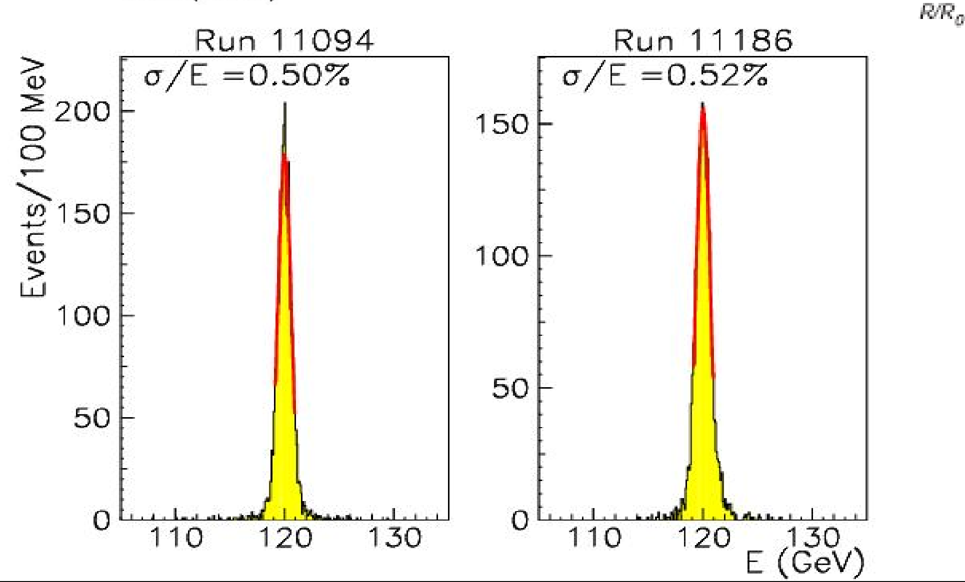
Laser Monitoring Performance







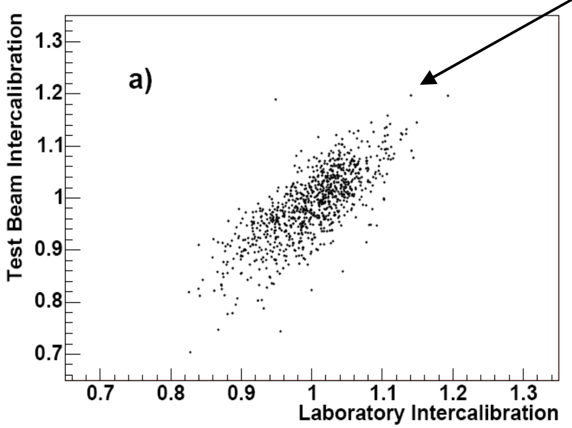




Resolution before/after irradiations & monitor corrections

In situ Calibration Strategy

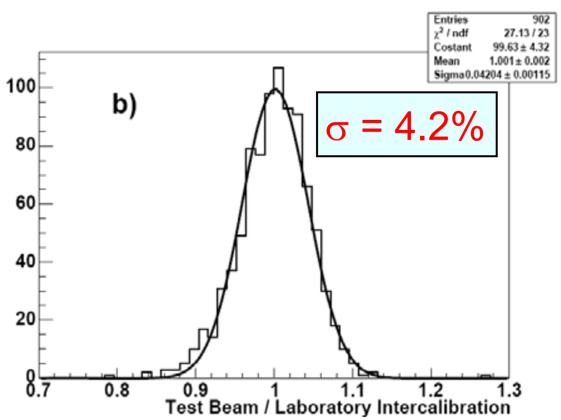
Lab measurements → Pre-calibration → In-situ calibration



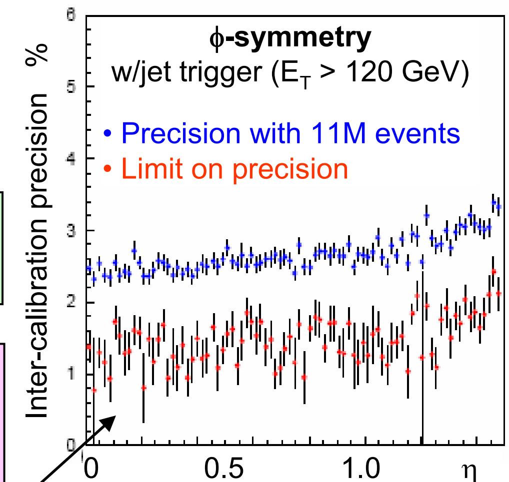
Pre-calibration based on lab Data (~4%)

Cosmit test beam data (1-3%)

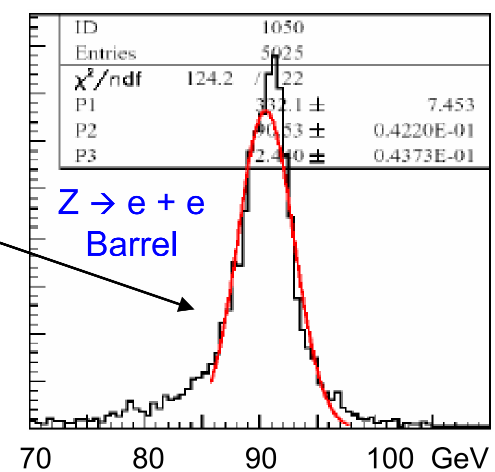
Calibration of few SM with 50/120 GeV electrons in test beam



Fast in-situ calibration based on the principle that mean energy deposited by jet triggers is independent of ϕ at fixed η (after correction for Tracker material) (~2-3% in few hours)

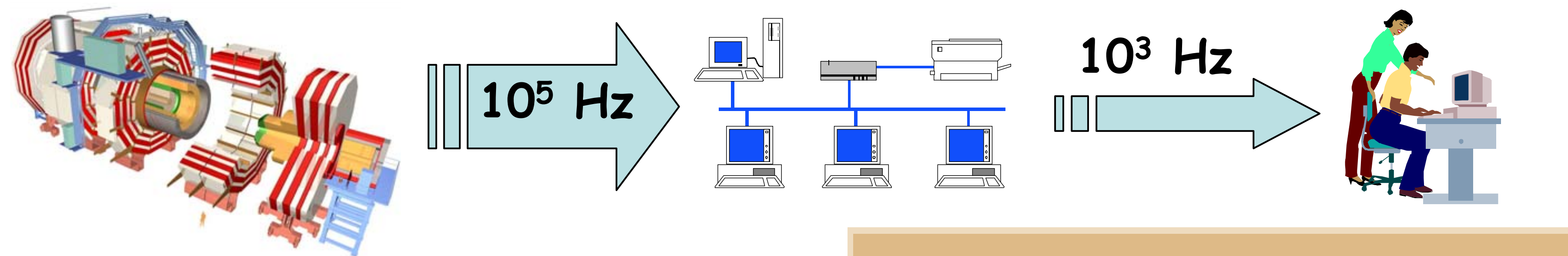


ϕ-ring inter-calibration with $Z \rightarrow e+e$ (~1% in 1 day)

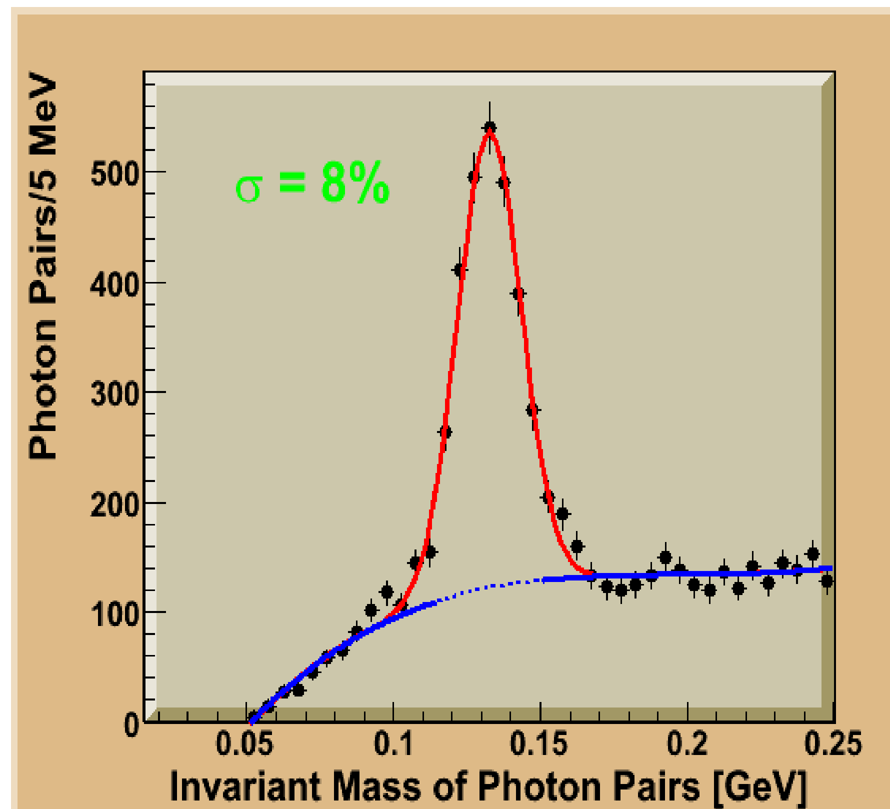


Calibration to < 0.5% with $W \rightarrow \nu + e$ and 5 fb^{-1} @ η =0

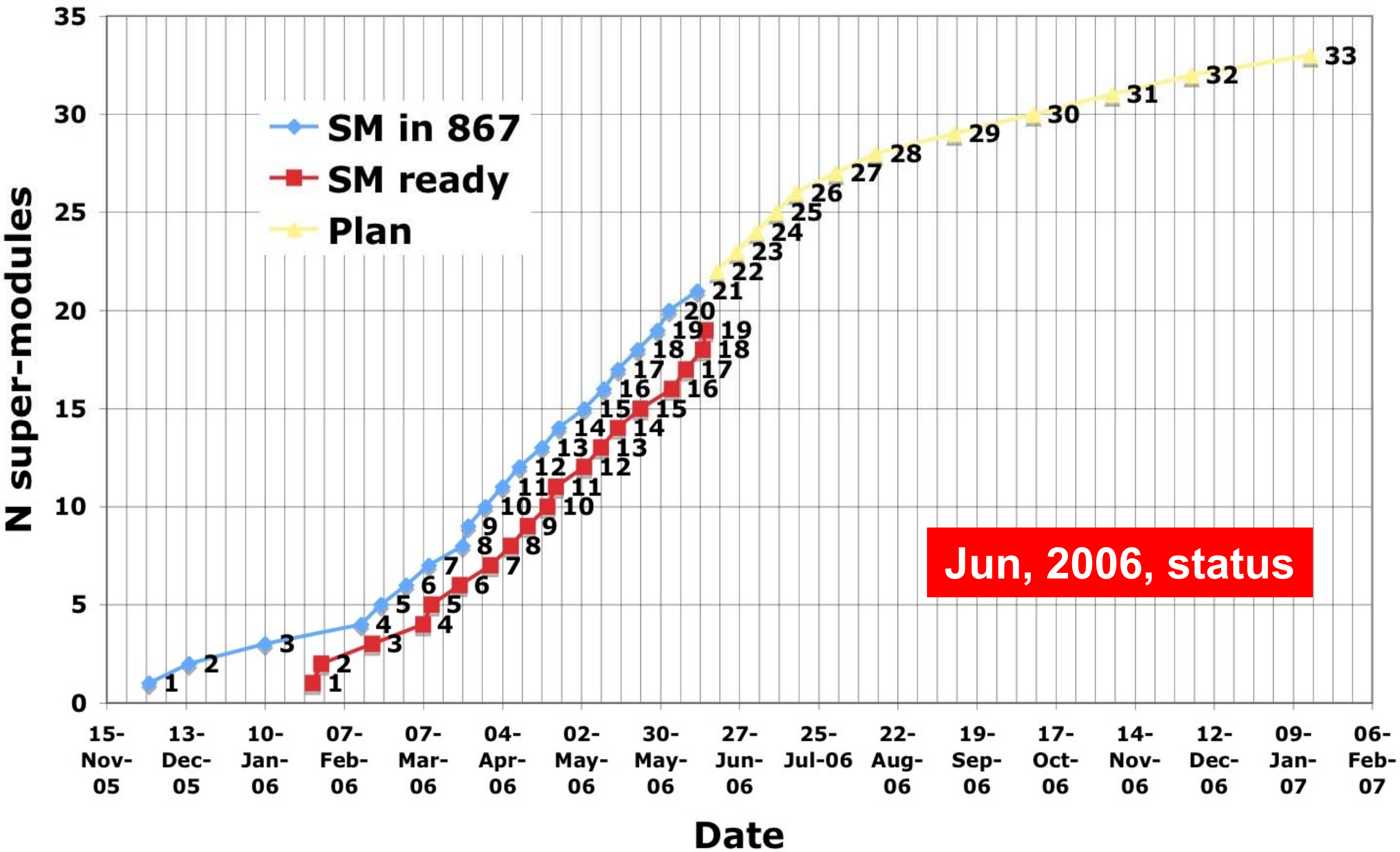
π^0 Calibration under Development



- Level 1 trigger rate dominated by QCD giving dozens of π^0's/event
- Useful $\pi^0 \rightarrow \gamma\gamma$ decays selected online giving ~10^3 Hz rate
- ~ 500 π^0/crystal/day expected skimmed event format: ~1 MB/sec
- Daily calibration runs would give a precision of ~ 1%



ECAL Barrel SM Integration



July, 2006, status:

27 bare SM

21 SM fully assembled

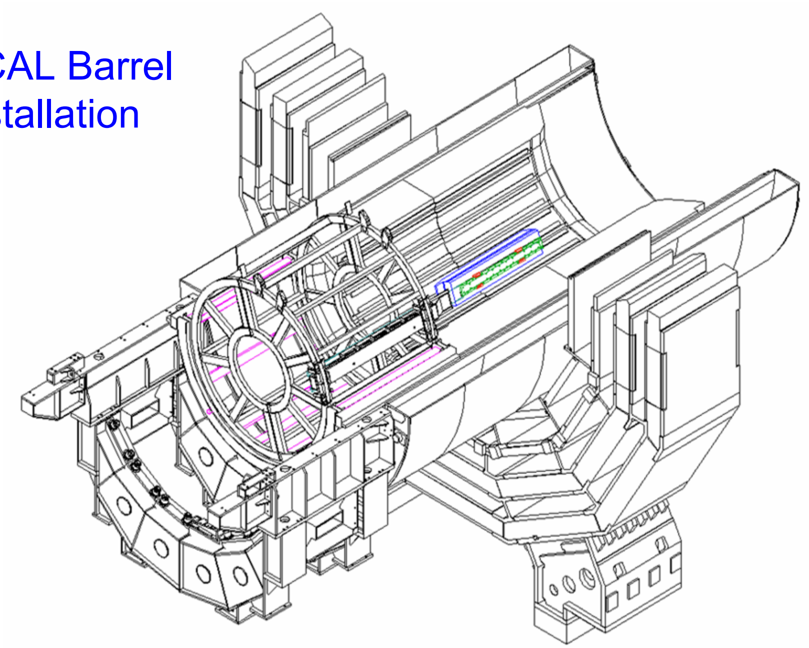
15 SM went through cosmic test

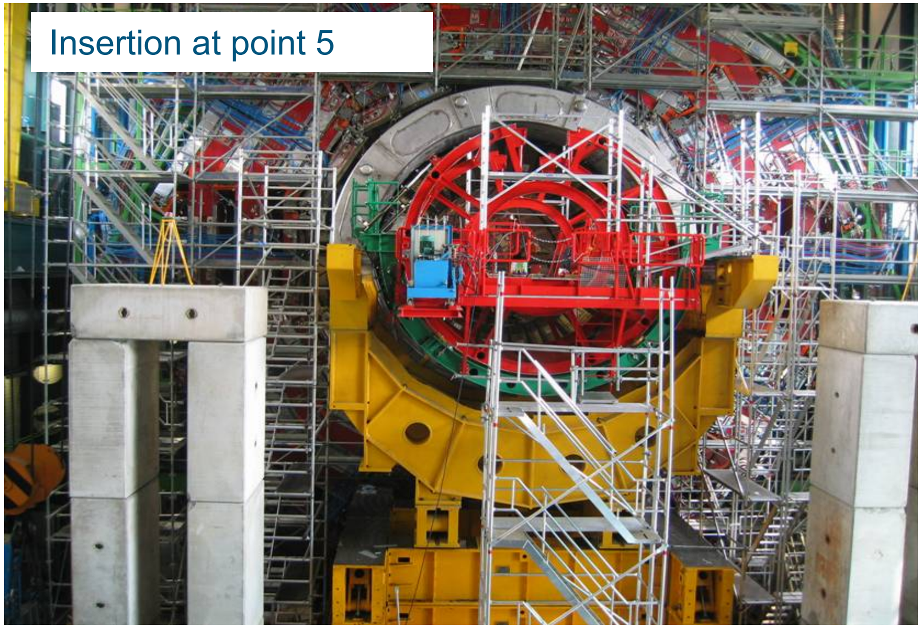
2 SM inserted in HCAL for magnet test

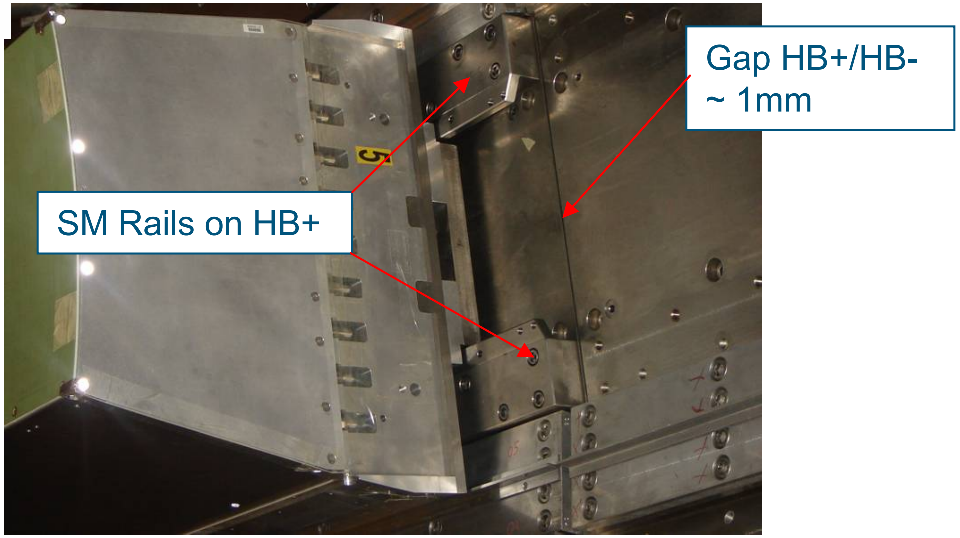
After commissioning and cosmic data taking of first ~10 super-modules (17,000 channels): ~ 15 channels are not working, ~ 15 channels are noisy

Supermodule Installation at SX5

ECAL Barrel
installation







CMS PWO ECAL Commission

- 18 SMs (EB+) will be inserted into HB+ at SX5 (surface).
- Maximum SMs (EB-) will be inserted into HB- at SX5 by mid-Jan..
- Remaining SMs will be commissioned at UXC (underground).

- Endcap Assembly plan assumes last EE crystal delivered end Jan 08
- Aim is to have Endcaps installed for 2008 Physics Run
- All cables and services are already installed
- Goal: D1 Sept07, D2 Nov07, D3 Jan08, D4 Apr08

Summary

- LHC physics requires precision ECAL
- LHC environment presents unprecedented technical challenge
- Design of ATLAS and CMS ECAL represent state of art development in calorimetric technology
- Construction of LHC ECAL runs smoothly
- Test beam results of LHC ECAL satisfy their design goals
- Commission of LHC ECAL is well under way
- Looking forward to wonderful physics at LHC