Calorimetry at the LHC

CALOR06
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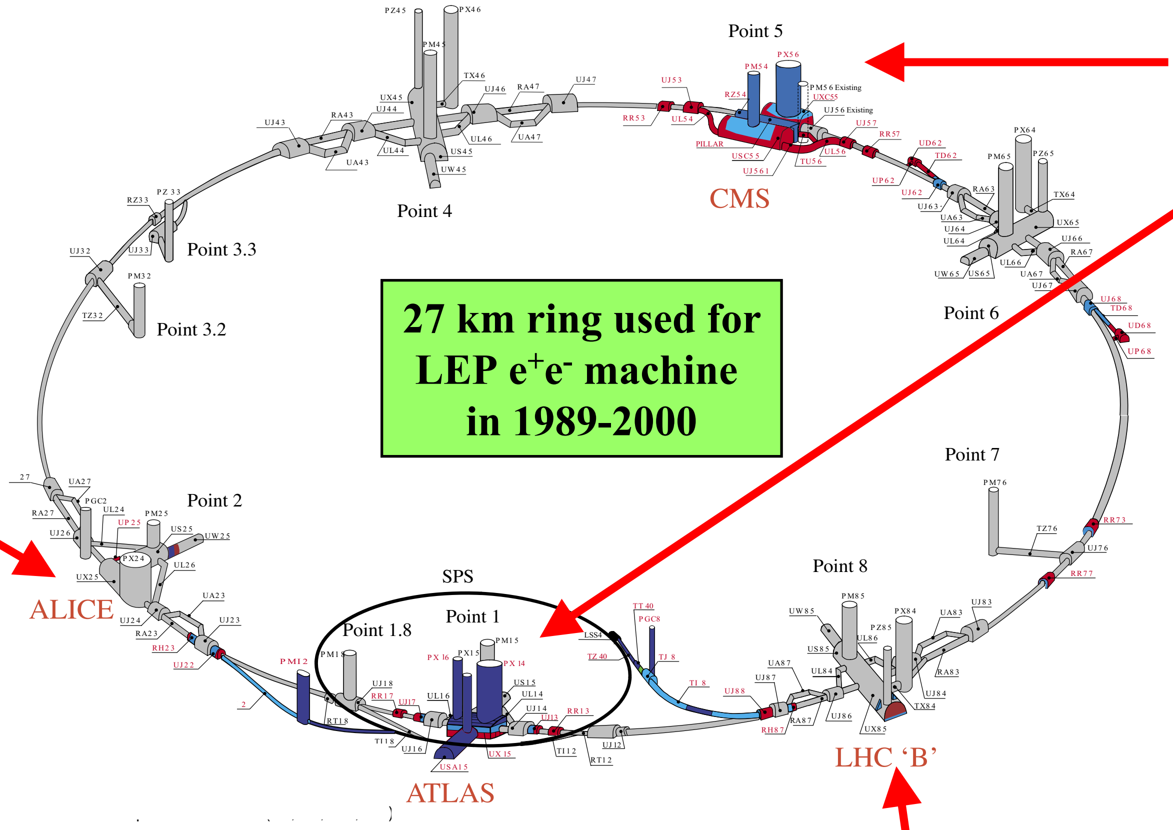
CONTENT

- LHC Project
- Calorimetry in LHC 4π pp Detectors
  - Physics requirements
  - CMS Calorimetry
  - ATLAS calorimetry
  - Expected performance of ATLAS / CMS
- ALICE & LHCb Calorimetry
- Conclusions

- $\sqrt{s} = 14$ TeV (7 times higher than Tevatron/Fermilab)
  → Search for new massive particles up to m ~ 5 TeV

- $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (>10^2 higher than Tevatron/Fermilab)
  → Search for rare processes with small σ ($N = L\ \sigma$)



ATLAS and CMS :
pp, general purpose

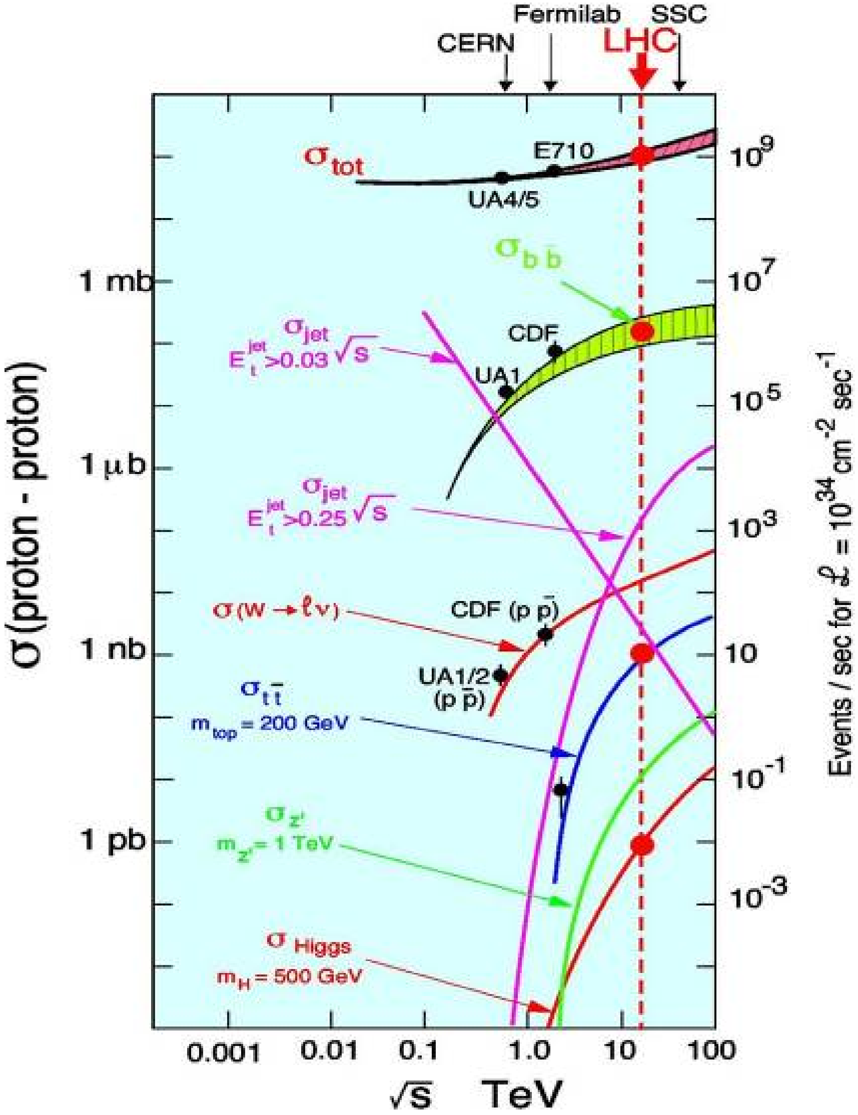
27 km ring used for LEP e^+e^- machine in 1989-2000

ALICE :
heavy ions

LHCb :
pp, B-physics

LHC pp Start 2007

Cross Sections and Production Rates



Rates for L = 10^{34} cm^{-2} s^{-1} at LHC

• Inelastic proton-proton reactions	10^9 / s
• bb pairs	5 10^6 / s
• t t pairs	8 / s
• W → e ν	150 / s
• Z → e e	15 / s
• Higgs (150 GeV)	0.2 / s
• Gluino, Squarks (1 TeV)	0.03 / s

LHC is a factory for:
top-quarks, b-quarks, W, Z, Higgs, …

Requirements E.m. Calorimeters

- Most of the requirements come from the $H \rightarrow \gamma\gamma$ and the $H \rightarrow 4e$ channels and have driven the calorimeter design.

  Here e.g. the ATLAS choice, CMS optimized differently.
- Large acceptance: $|\eta|<3.2$ (precision physics $|\eta|<2.5$)
- Energy resolution : → mechanics / electronics calibration
  - Stochastic term: $a \leq 10\%\ \mathrm{GeV}^{1/2}$
  - Noise term: $b \leq 300$ MeV
  - Global constant term: $c = 0.7\%$

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Linearity: 0.1% or better: → presampler for dead material
  - 0.02% for high precision measurement, e.g. M_W
- Angular resolution: $\sigma(\theta) \approx 50\ \mathrm{mrad}/\sqrt{E}$: → lateral / longitudinal segmentation
- Particle identification capabilities:
  - e / jet,
  - γ / jet (in particular γ/π^0 separation for isolated hi-p_T $\pi^0 > 3$)
- Time resolution: 100 ps
- Large dynamic range : 20 MeV->2TeV → electronic read-out

ATLAS / CMS EM Calors: Main Parameters

	ATLAS		CMS	
	Barrel	**End-caps**	**Barrel**	**End-caps**
Technology	Lead / LAr accordion		PbWO$_4$ scintillating crystals	
# Channels	110208	63744	61200	14648
Granularity ($\Delta\eta$ x $\Delta\phi$)				
Presampler	0.025 x 0.1	0.025 x 0.1		
Strips / Si-preshower	0.003 x 0.1	1.5-1.8: 0.003 x 0.1 1.8-2.0: 0.004 x 0.1 2.0-2.4: 0.006 x 0.1		32 x 32 Si-strips per 4 crystals
Main sampling / Crystals	0.025 x 0.025	0.025 x 0.025	0.017 x 0.017	0.018 x 0.003 to 0.088 x 0.015
Back	0.05 x 0.025	0.05 x 0.025		
Depth				
Presampler	10 mm LAr	2 x 2 mm LAr		
Strips / Si-preshower	~ 4.3 X_0	~ 4 X_0		3 X_0
Main sampling / Crystals	~ 16 X_0	~ 20 X_0	26 X_0	25 X_0
Back	~ 2 X_0	~ 2 X_0		
Resolution				
Noise per cluster	250 MeV	250 MeV	200 MeV (*)	600 MeV (**)
Intrinsic resolution				
Stochastic term a	10%	10 - 12% (***)	3%	5.5%
Local constant term b	0.2%	0.35%	0.3%	0.5%

Requirements Hadronic Calorimeters

- Hadronic calorimeters play essential role in identification and measurement of quarks, gluons, and neutrinos by measuring energy and direction of jets and of missing transverse energy (MET) flow in events.
- Granularity is determined by requirements for W-> jet-jet at high PT. $\Delta\eta * \Delta\phi = 0.1 * 0.1$ for $|\eta|<3$.
- Missing energy forms a crucial signature of new particles. For good missing energy resolution, a hermetic calorimetry coverage to $|\eta|=5$ is required.

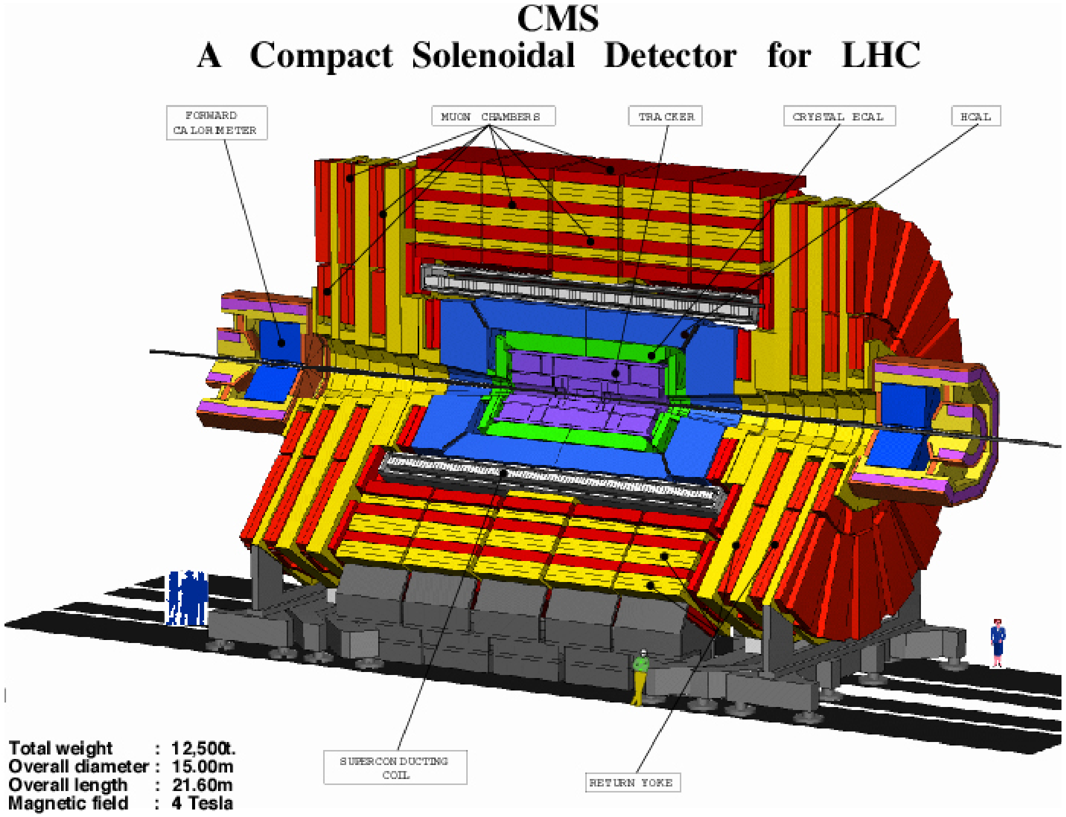
- Linearity of jet energy scale of 2% for jets up to 4 TeV.
- Jet energy resolution: Stochastic term ~50%, constant term ~3%.
- Total calorimeter thickness of 10 λ to achieve required energy resolution and MET performance.

- Hadronic calorimeters will aid in the identification of electrons, photons and muons in conjunction with the tracker, e.m. calorimeter, and muon systems.

ATLAS / CMS HAD Calors: Main Parameters

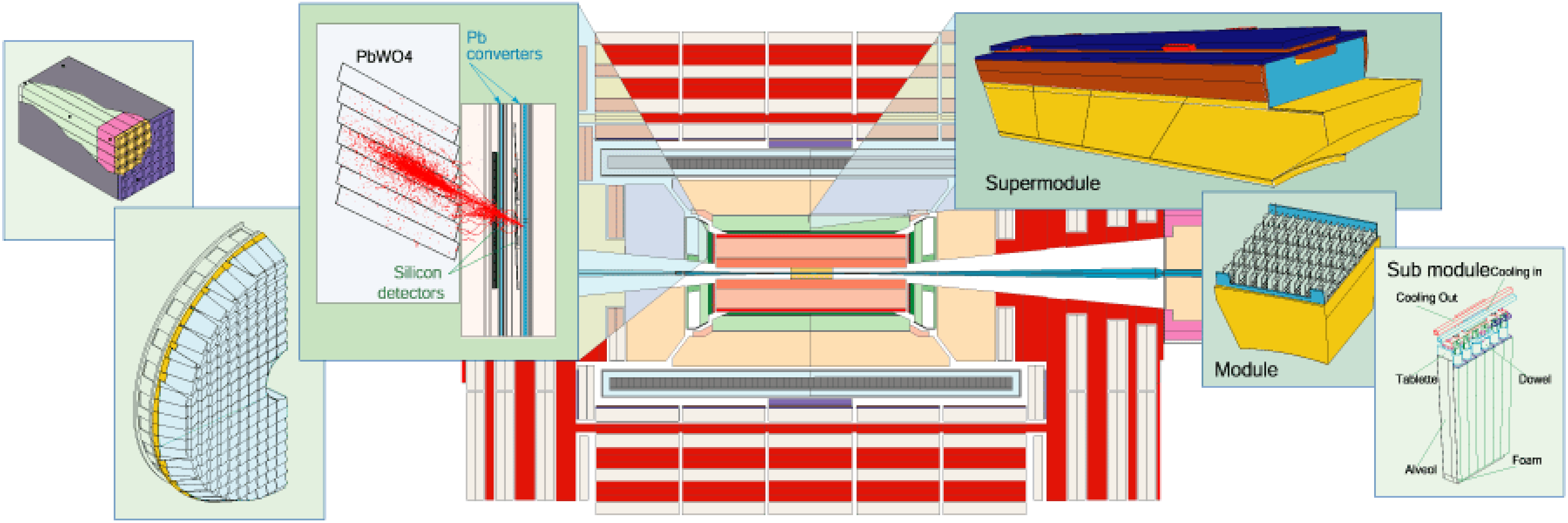
	ATLAS	CMS
Technology		
Barrel / Ext. Barrel	14 mm iron / 3 mm scint.	50 mm brass / 4 mm scint.
End-caps	25 mm (front) - 50 mm (back) copper / 8.5 mm LAr	80 mm brass / 4 mm scint.
Forward	Copper (front) - Tungsten (back) 0.25 - 0.50 mm LAr	4.4 mm steel / 0.6 mm quartz
# Channels		
Barrel / Ext. Barrel	9852	2592
End-caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta$ x $\Delta\phi$)		
Barrel / Ext. Barrel	0.1 x 0.1 to 0.2 x 0.1	0.087 x 0.087
End-caps	0.1 x 0.1 to 0.2 x 0.2	0.087 x 0.087 to 0.35 x 0.028
Forward	0.2 x 0.2	0.175 x 0.175
# Longitudinal Samplings		
Barrel / Ext. Barrel	Three	One
End-caps	Four	Two
Forward	Three	Two
Absorption lengths		
Barrel / Ext. Barrel	9.7 - 13.0	5.8 - 10.3 10 - 14 (with Coil / HO)
End-caps	9.7 - 12.5	9.0 - 10.0
Forward	9.5 - 10.5	9.8

CMS Detector



- Solenoidal magnetic field (4T) in inner tracking detector and in calorimeters.
  - Momentum measurement in ID
  - Muon measurement
- ID: High resolution semiconductor detectors: 9.7 Mio. channels, 210 m^2
- ECAL: Energy measurement in Lead – tungstate crystals (excellent E-resolution for Photons)
- HCAL: Hermetic coverage to $|\eta|=5$

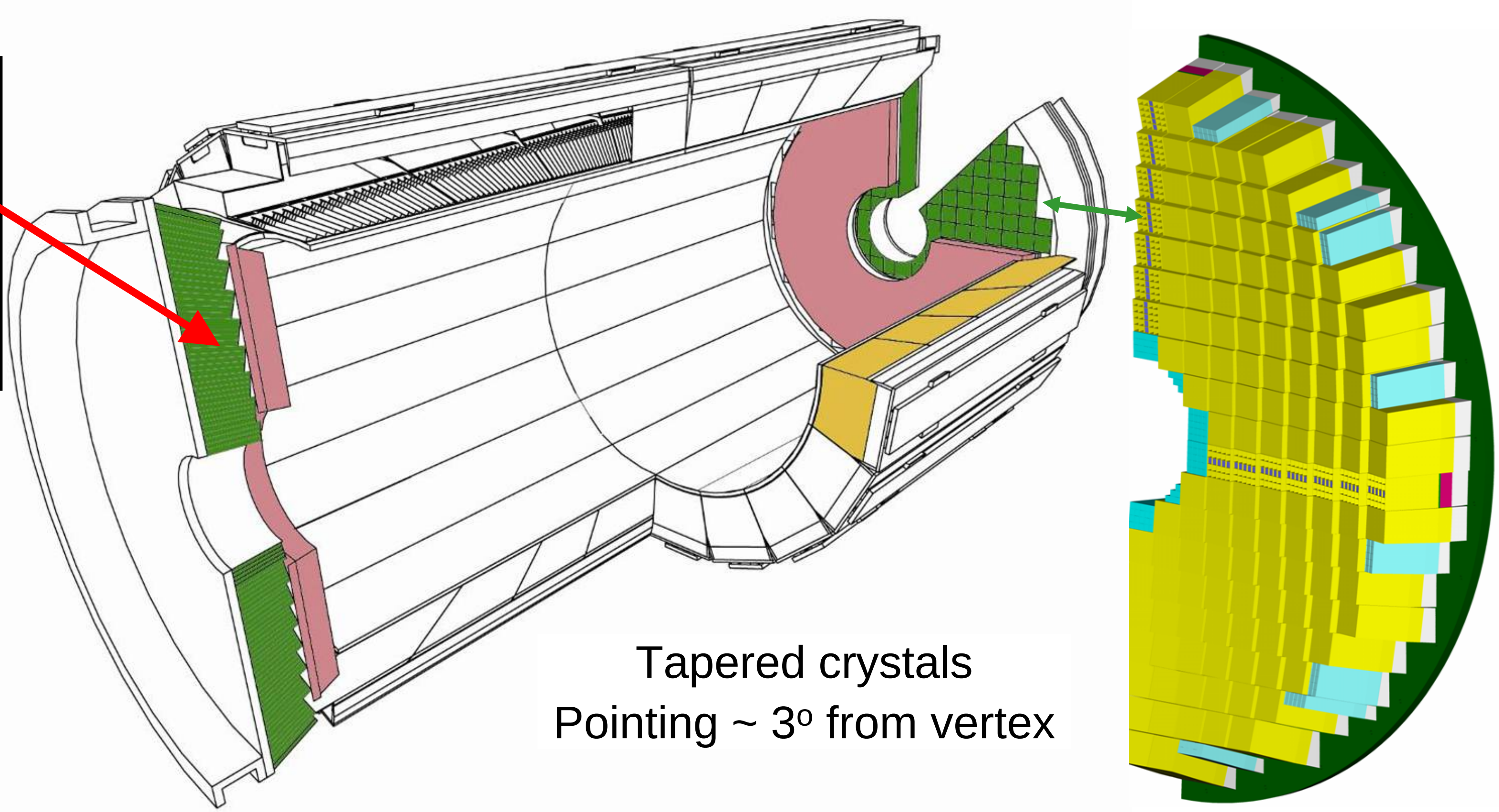
CMS E.m. Calorimeter: ECAL



- **Principal design objective: Construct a very high performance e.m. calorimeter of scintillating crystal calorimeter ($PbWO_4$ lead tungstate)**
- **Offers excellent energy resolution since almost all of the energy of electrons and photons is deposited within the crystal volume.**
- **Lead tungstate crystals: high density, small Moliere radius, low X_0.**
- **High-resolution crystal calorimeter to enhance the $H \rightarrow \gamma\gamma$ discovery potential at the initially lower luminosities at the LHC**

CMS ECAL Layout

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



Tapered crystals
Pointing ~ 3° from vertex

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)

$\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175$

End-caps:

4 Dees (2 per end cap)

14648 Crystals (1 type),total mass 22.9 t

Dimensions:~ 30 x 30 x 220 mm^3 (24.7 X^0

$\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175 \leftrightarrow 0.05 \times 0.05$

CMS ECAL Crystal Production

Crystal delivery determines ECAL Critical Path

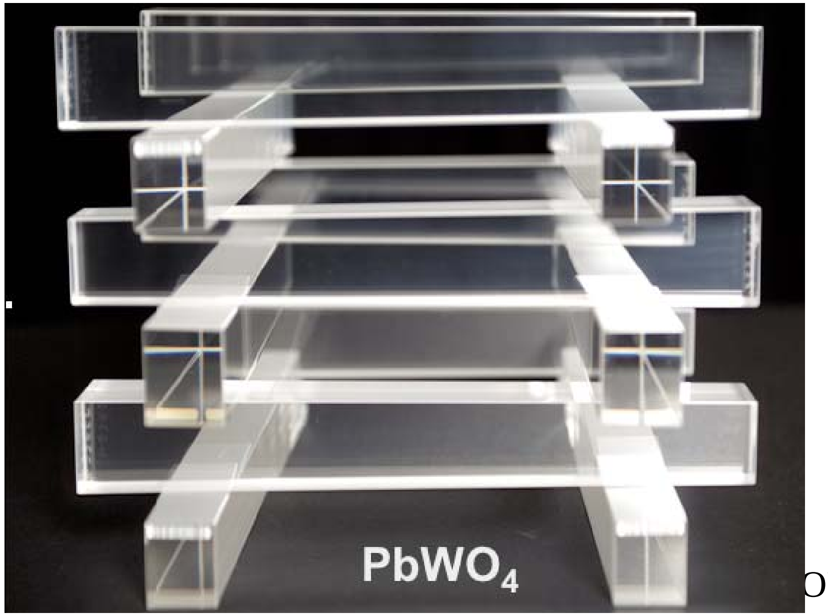
Suppliers:

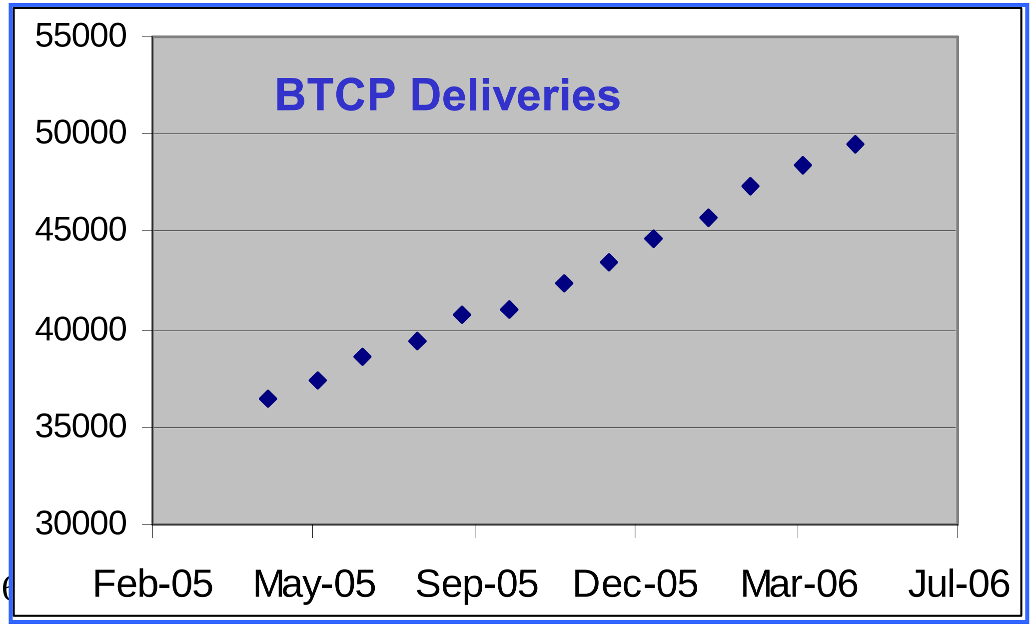
BTCP (Bogoroditsk, Russia)	~ 1100/month
SIC (Shanghai, China)	~ 130/month

~ 80% of Barrel crystals already delivered (48 950/61 200)

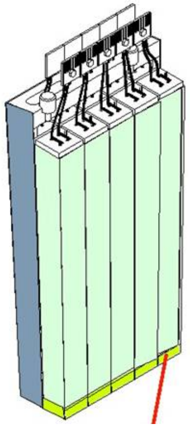
Preseries of Endcap crystals: 100 BTCP, 300 SIC

- **Last Barrel crystal delivery Feb 2007**
- **Last End-cap crystal delivery Jan 2008**

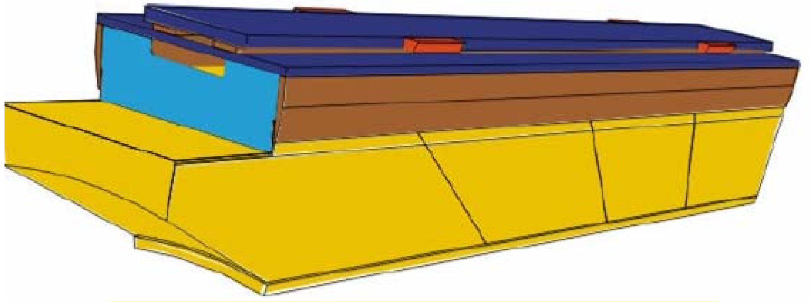




CMS ECAL Barrel Construction



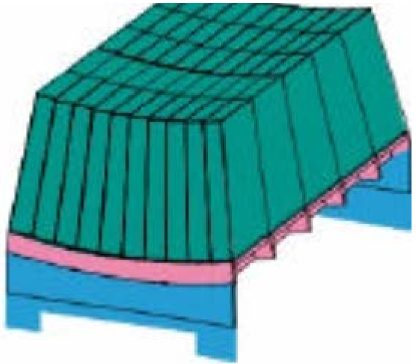
Sub-module: 10 crystals

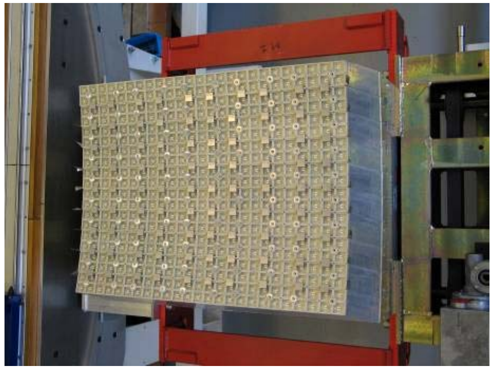


Super-module: 1700 crystals

Assembly status:
27/36 bare SMs assembled
18/36 SMs completed
Production rate 1 / week

2 Regional Centres: CERN and Rome

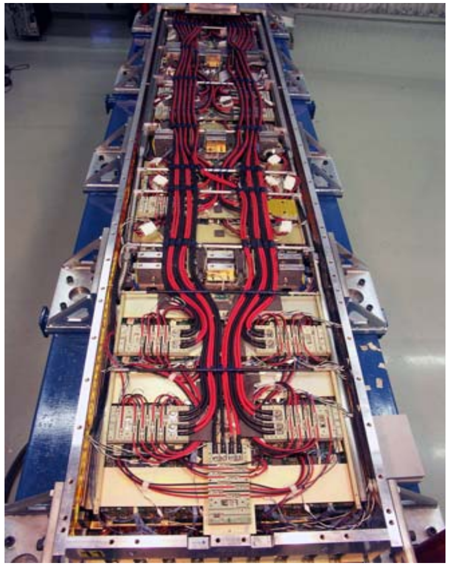




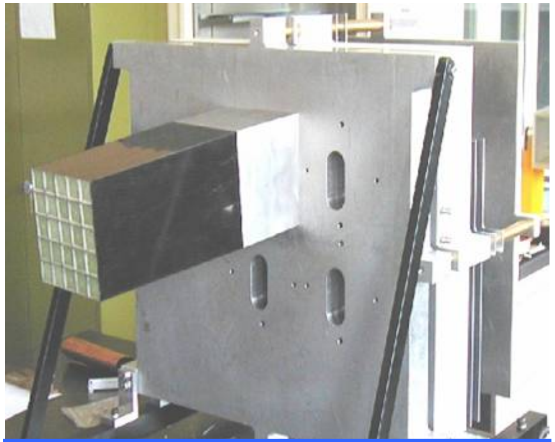
Module: 400/500 crystals

Bare SM

'Dressed' SM

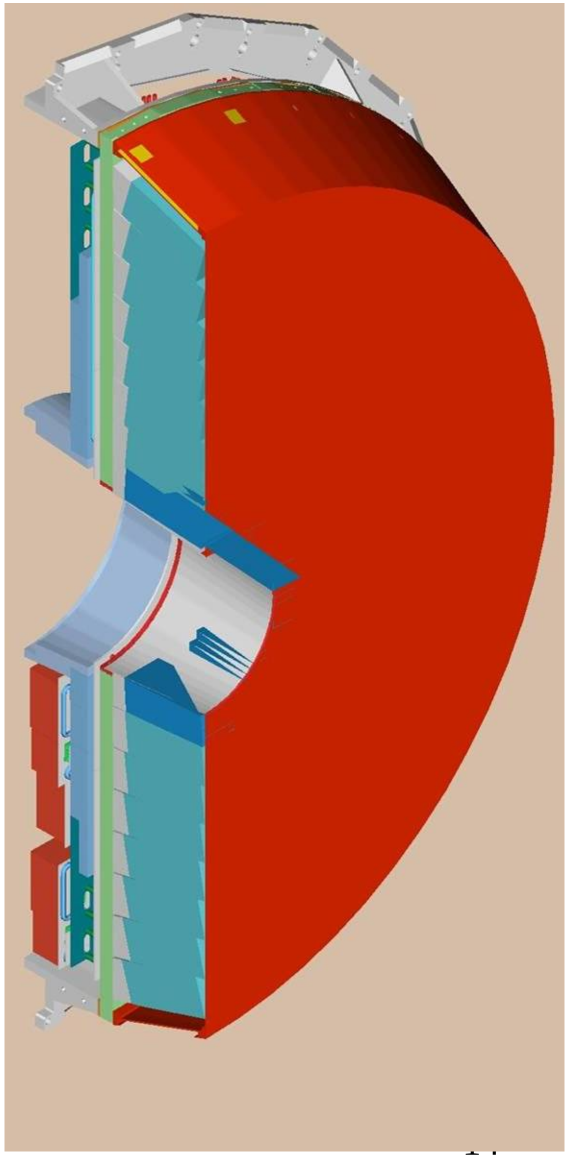


CMS ECAL End-cap Construction



Supercrystal: 25 crystals

Dee (½ end-cap): 3662 crystals

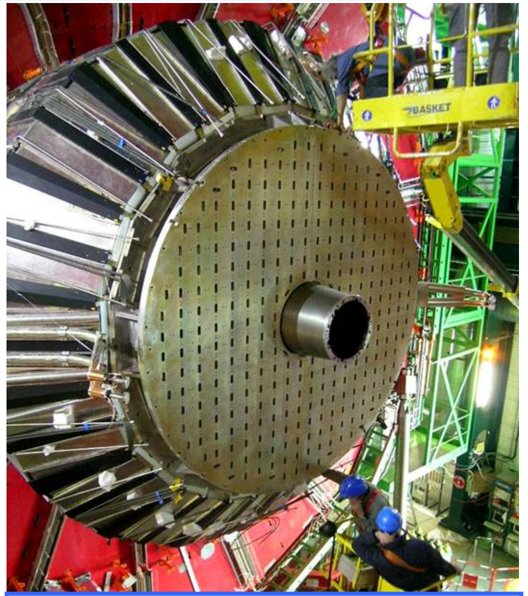


Production status:

- All mechanical parts delivered
- End-cap crystal production starts in summer 2006

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



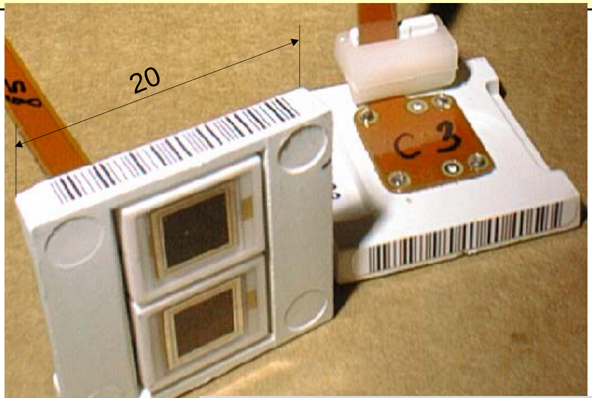
Backplates successfully test mounted on HCAL

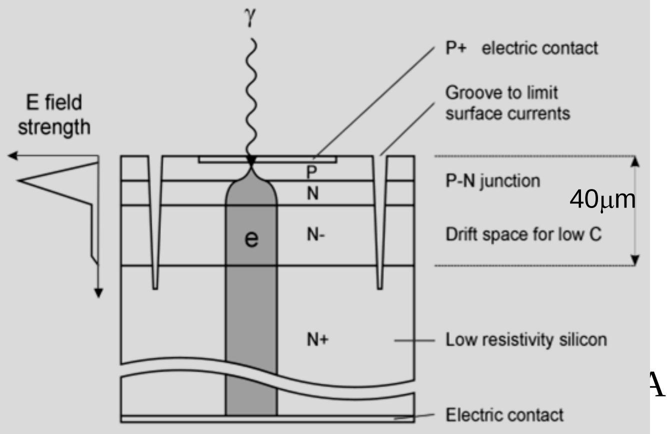
CMS ECAL Photodetectors

Barrel: Avalanche photodiodes (APD)

Two 5x5 mm^2 APDs/crystal

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

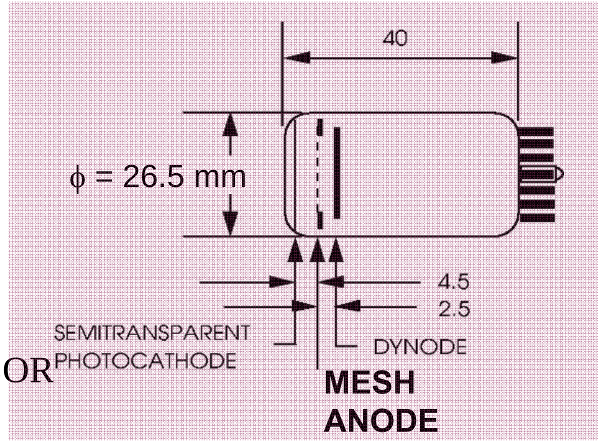


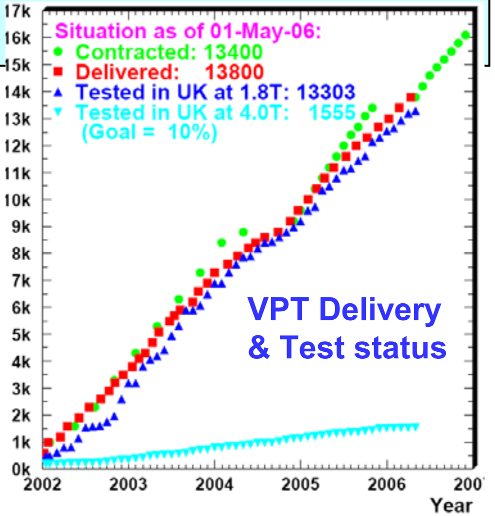


End-caps: Vacuum phototriodes (VPT)

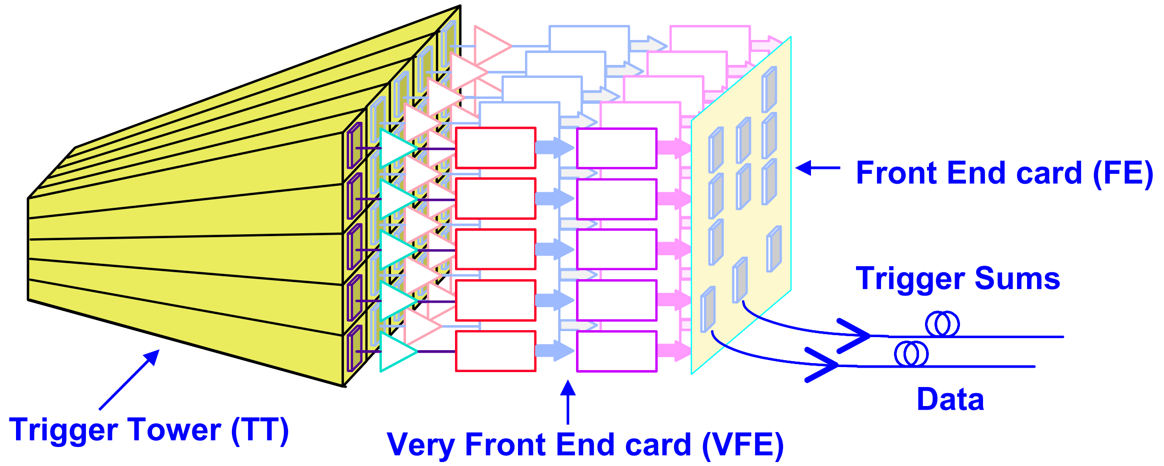
More radiation resistant than Si diodes (with UV glass window)

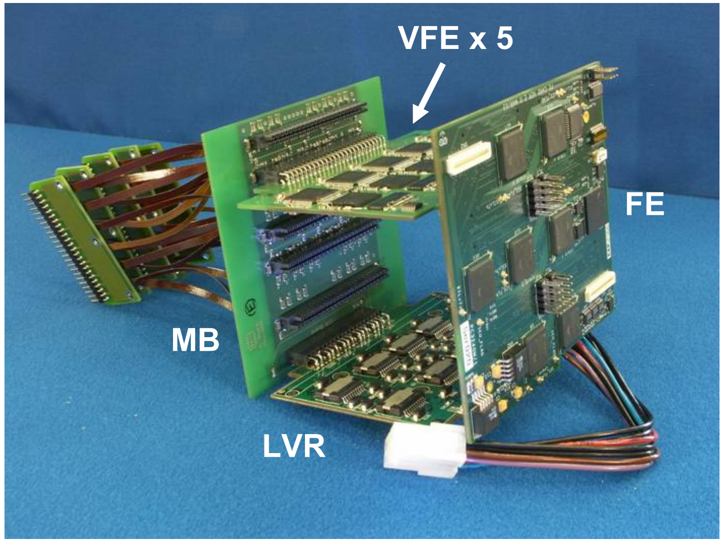
- Active area ~ 280 mm^2/crystal
- Gain 8 -10 (B=4T)   Q.E.~20% at 420nm
- **Delivery ~80%**

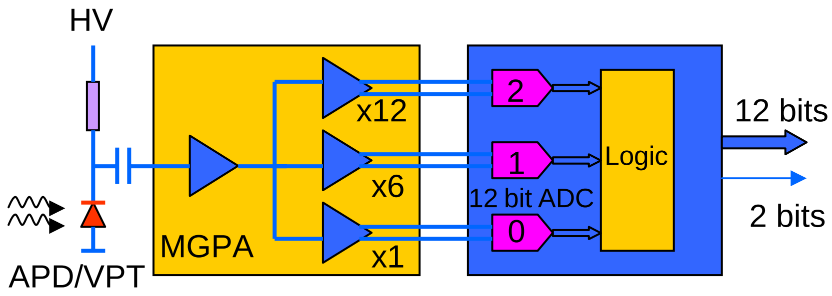




CMS ECAL On-detector Electronics







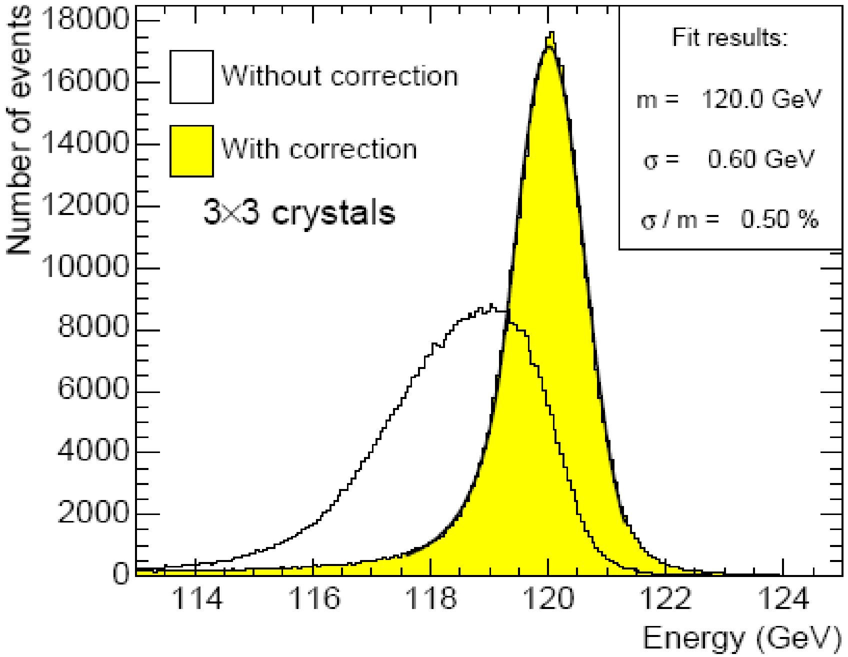
VFE architecture for single channel

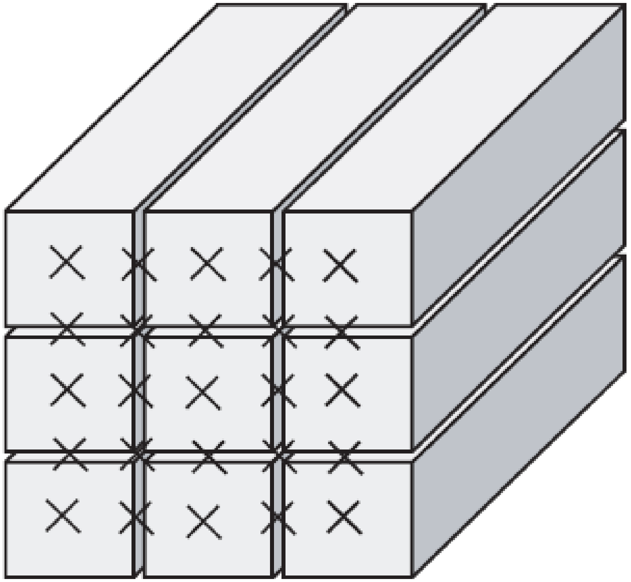
- Radical change of FE electronics in 2002
- TB 2004: It works !

- Trigger primitives computed on the detector
- Command & control via token ring
- Modularity: Trigger Tower (25 chan. in Barrel)
  - 1 Low Voltage Regulation Board (LVR)
  - 5 VFE Boards (5 channels each)
  - 1 FE Board
  - 1 Fibre sending trig primitives (every BC)
  - 1 Fibre sending data (on Level1 accept)

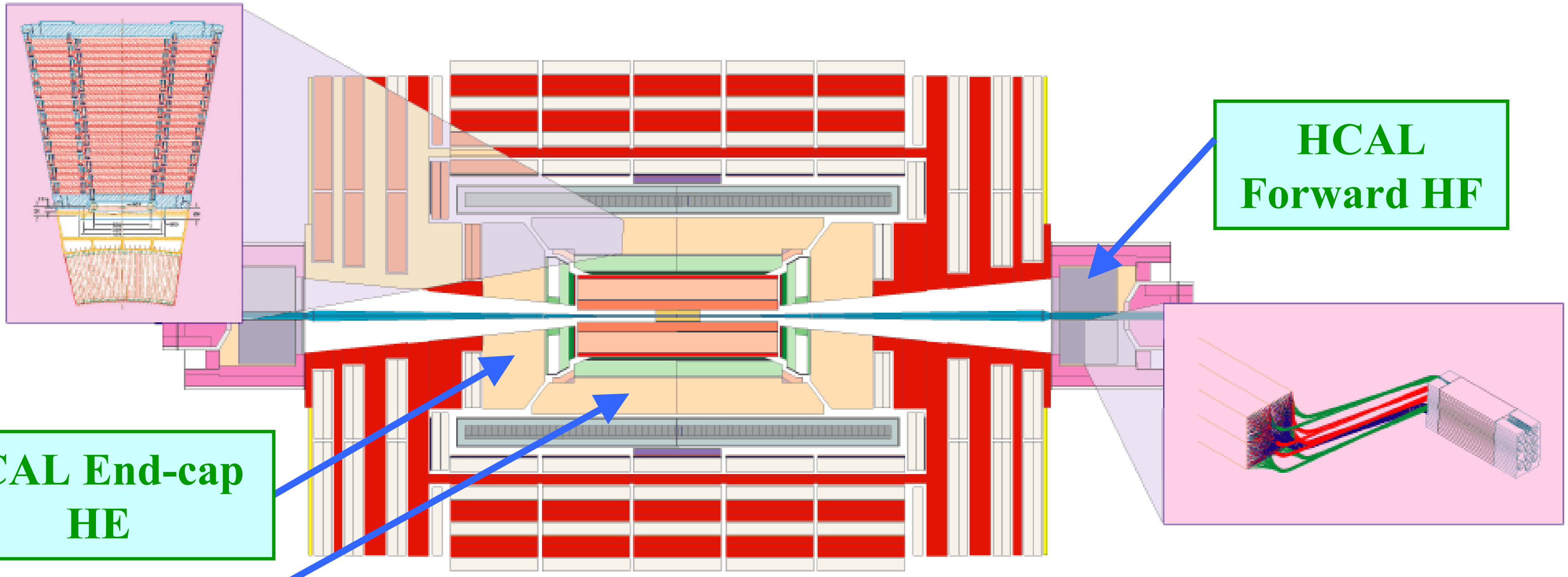
CMS ECAL: Energy Resolution over Large Areas

- Test beam position scan with 120 GeV electrons
- Corrections for "local containment" work as well as previous results and Monte-Carlo studies suggest
- Also corrections for losses close to 6 mm inter-module voids work well.





CMS Hadronic Calorimeter System HCAL



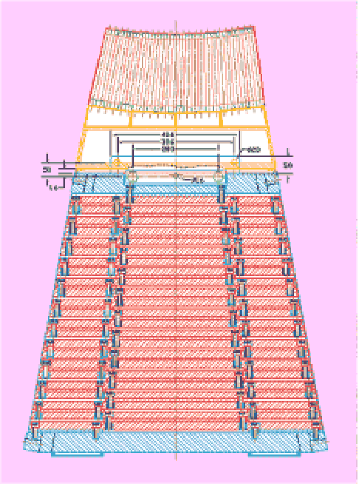
HCAL Forward HF

HCAL End-cap HE

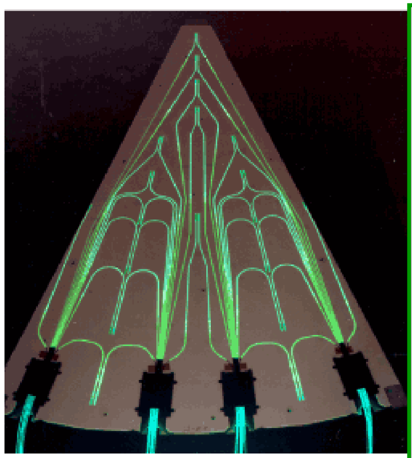
HCAL Barrel HB

- Hadronic Barrel and End-cap calorimeters are sampling calorimeters with 50 mm thick copper absorber plates interleaved with 4 mm thick scintillator sheets.
- Hadronic Forward calorimeters are sampling calorimeters with steel absorbers and quartz fibers for read-out oriented ~parallel to the beam axis.

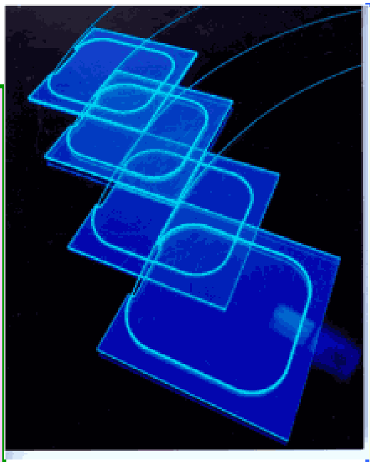
CMS HCAL Barrel / End-cap



- Copper as absorber material because of density.
- HB constructed of two half-barrels each of 4.3 m length.
- HE consists of two large structures at each end of the barrel within the region of high magnetic field.
- HB inside the coil not sufficiently thick, additional scintillation layers placed just outside the magnet coil.
- Full depth of the combined barrel detectors ~10 λ.



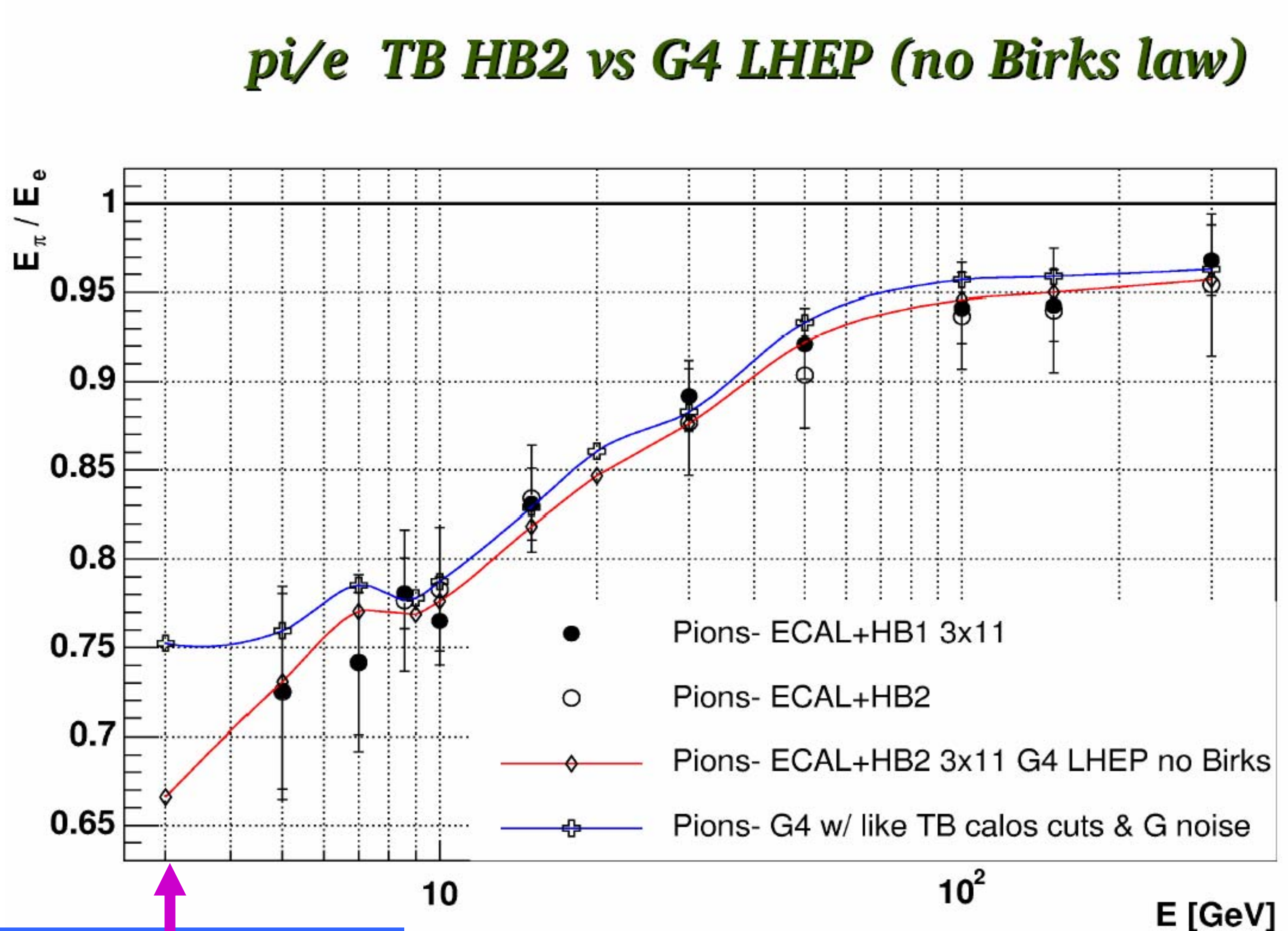
- Megatiles large sheets of plastic scintillator
- Subdivided into tiles of size $\Delta\eta$ x $\Delta\phi$ = 0.87 x 0.87
- Scintillation signals from megatiles detected using waveshifting fibers.
- Fiber diameter ~1 mm.



- Light emission from tiles in the blue-violet (410-425 nm).
- Light wavelength shifted via fibers to green (490 nm).
- Green light transported via clear fiber waveguides to connectors at the ends of the megatiles.

CMS Barrel HCAL

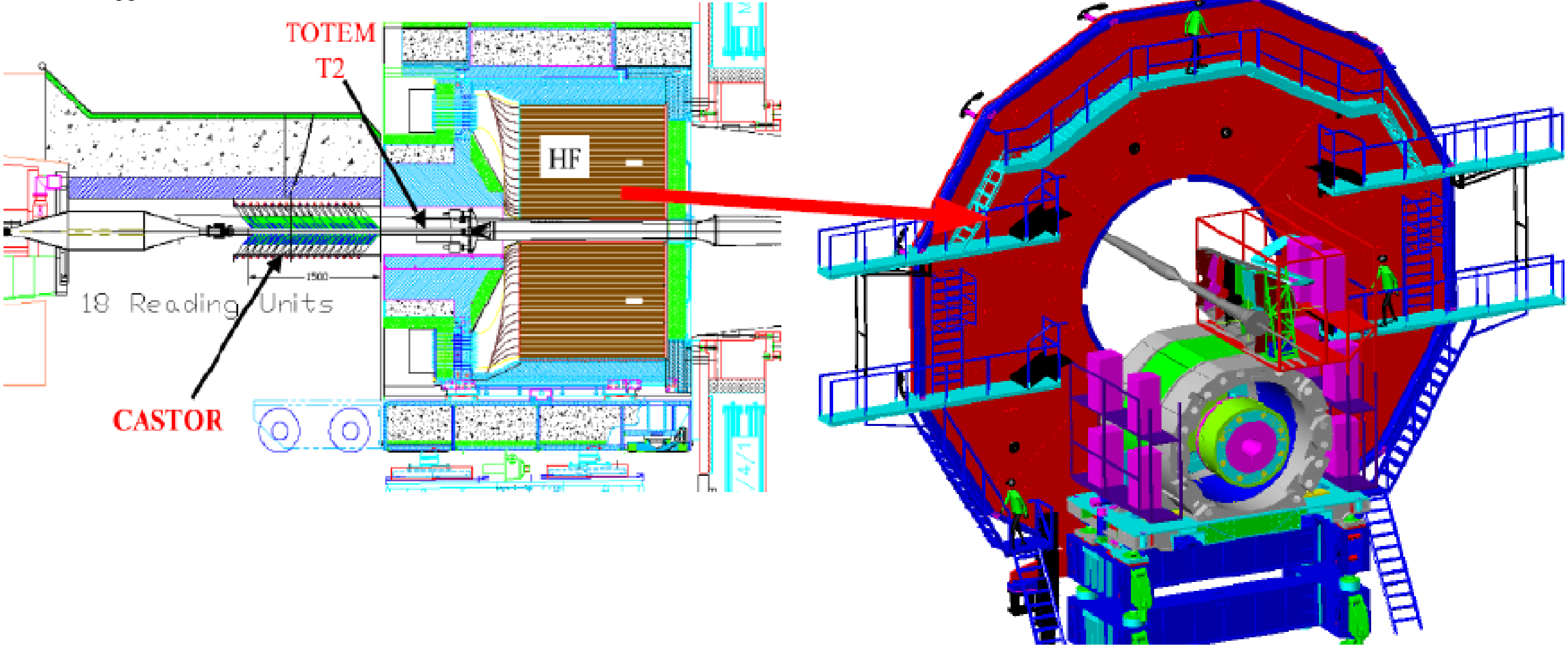
CMS Barrel HCAL Test Beam



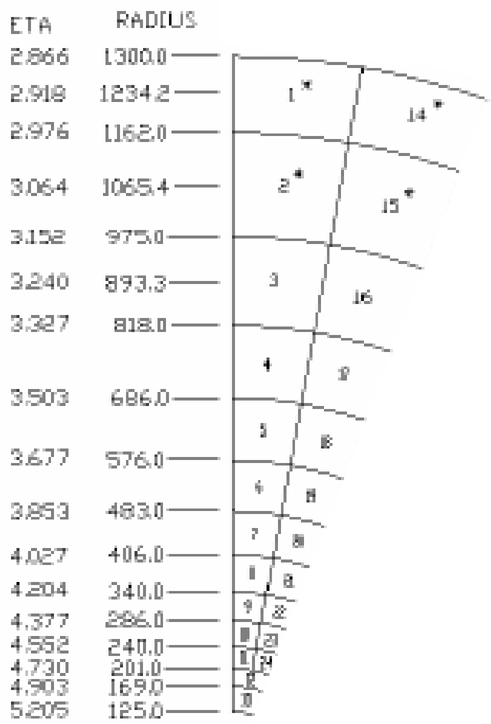
Low energy points require a lot of beam clean up.
(2,3 GeV points not shown)

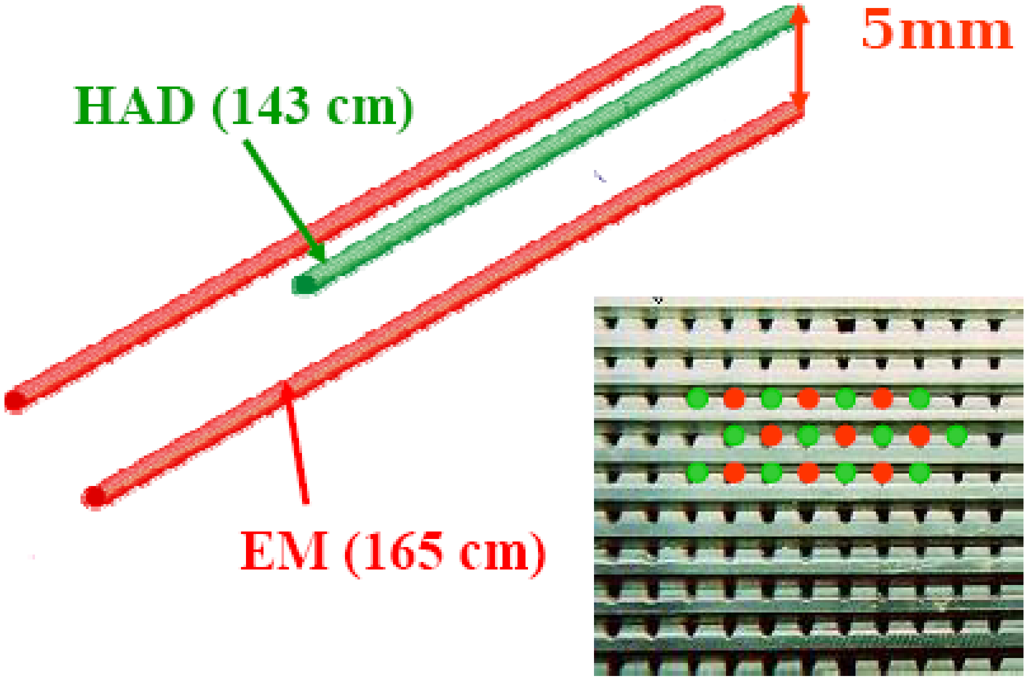
CMS Forward HCAL HF

- ..



CMS Forward HCAL HF





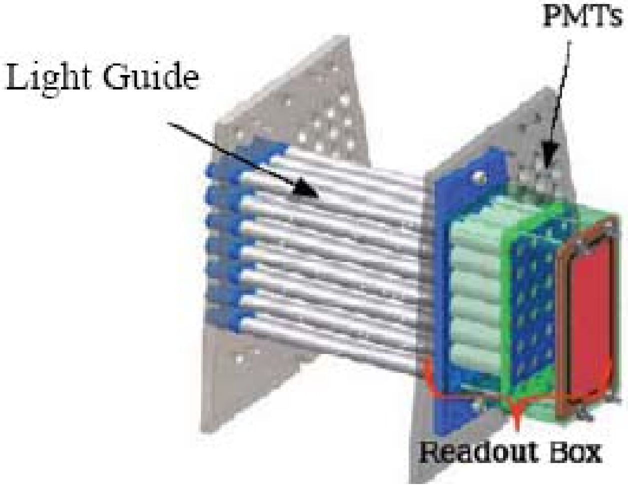
- Iron calorimeter, 20 deg wedges
- 3 < abs(η) < 5
- # Towers:
    - 2 * 432 for EM / HAD
    - Total 1728
- $\Delta\eta * \Delta\phi = 0.175 * 0.175$

Quartz fibers as active medium:

- Energy measured by Cerenkov light emitted by showering particles
- Radiation hard

CMS Forward HCAL HF

- Fibers inserted in all 36 wedges

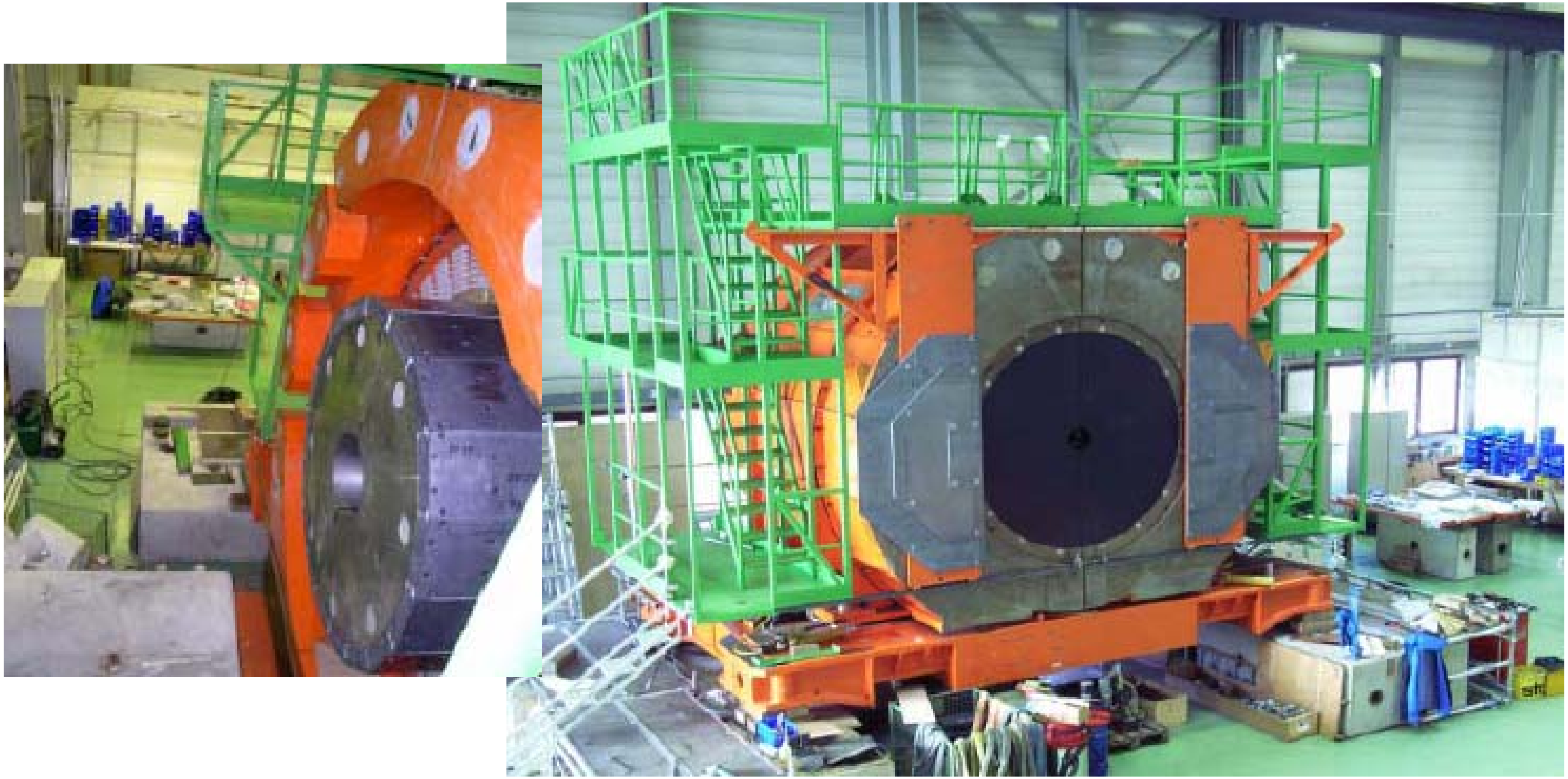


- HF are first Items to be lowered in July 2006

CMS HCAL Forward

HF in Bat. 186

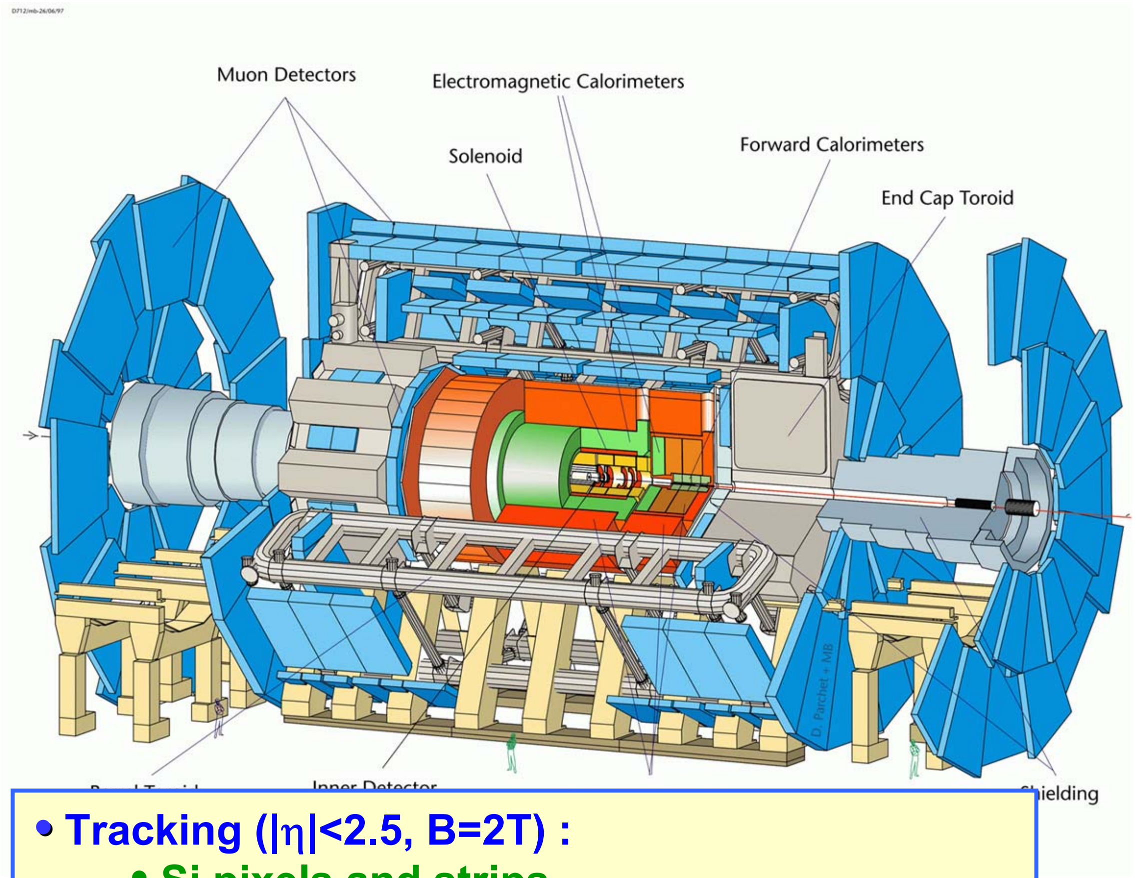
The two HF are the first elements to be lowered into UX in July 2006



CMS HCAL Status

- **Barrel HB**
  - HB+ Fully source calibrated to ~ 4 %. Ready for magnet insertion.
  - HB- ~ Fully calibrated
- **End-cap HE**
  - HE- Fully calibrated
  - HE+ Calibration ~complete.
- **Forward HF**
  - Source calibration of HF- completed in 10 days to ~ 5%.
  - Started HF+ source calibration.

ATLAS Detector

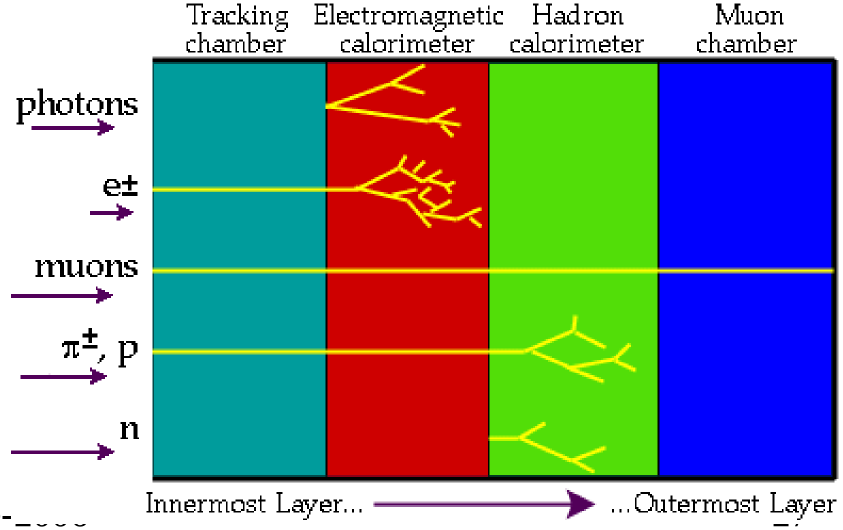


Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

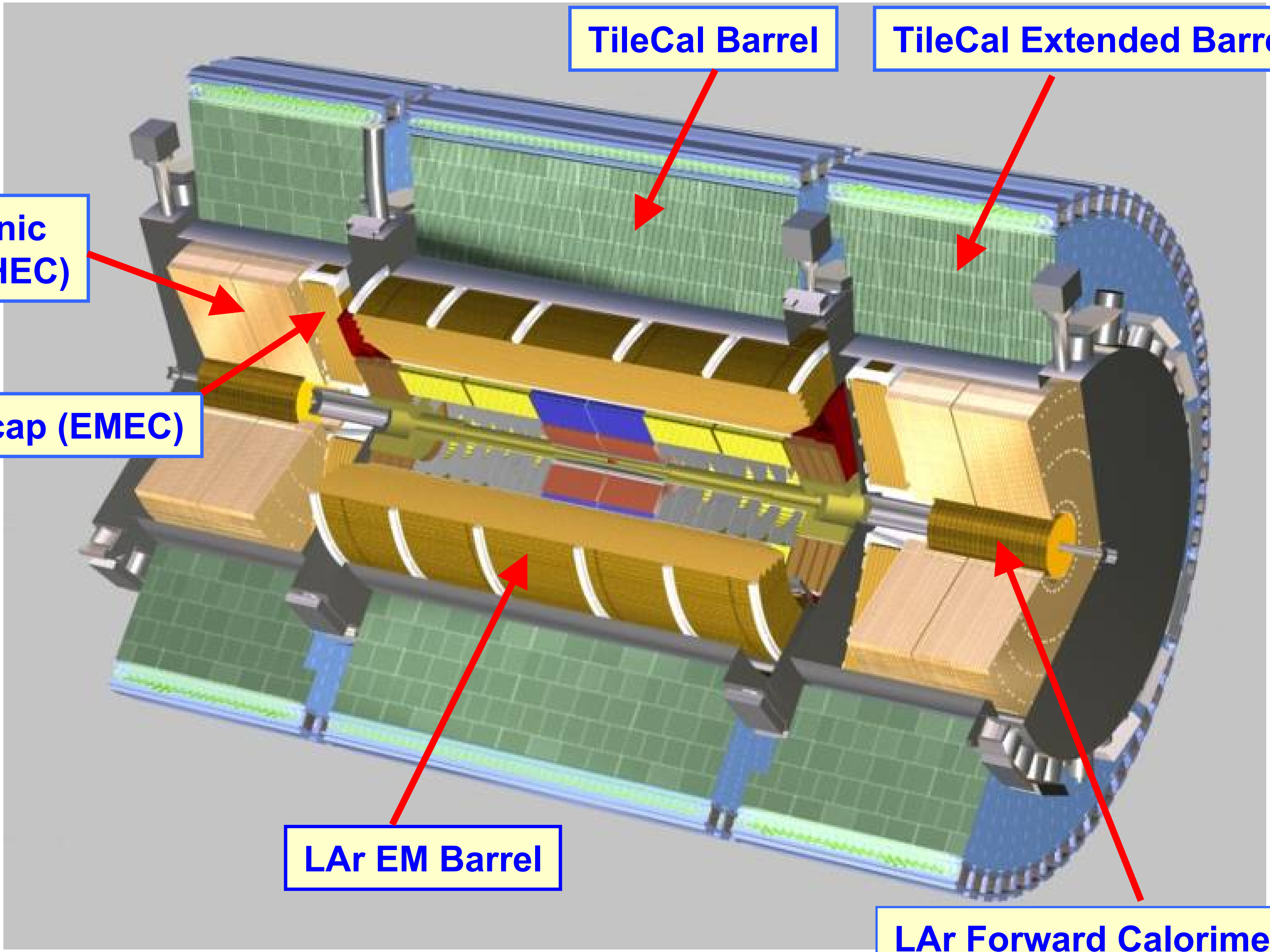
- **Tracking (|η|<2.5, B=2T) :**
  - **Si pixels and strips**
  - **Transition Radiation Detector (e/π separation)**

- **Calorimetry (|η|<5) :**
  - **EM : Pb / Liquid Argon (LAr)**
  - **HAD: Fe/scintillator (central), Cu/W-LAr (fwd)**

- **Muon Spectrometer (|η|<2.7) :**
  Air-core toroids with muon chambers



ATLAS LAr and Tile Calorimeters



TileCal Barrel

TileCal Extended Barrel

LAr Hadronic End-cap (HEC)

LAr EM End-cap (EMEC)

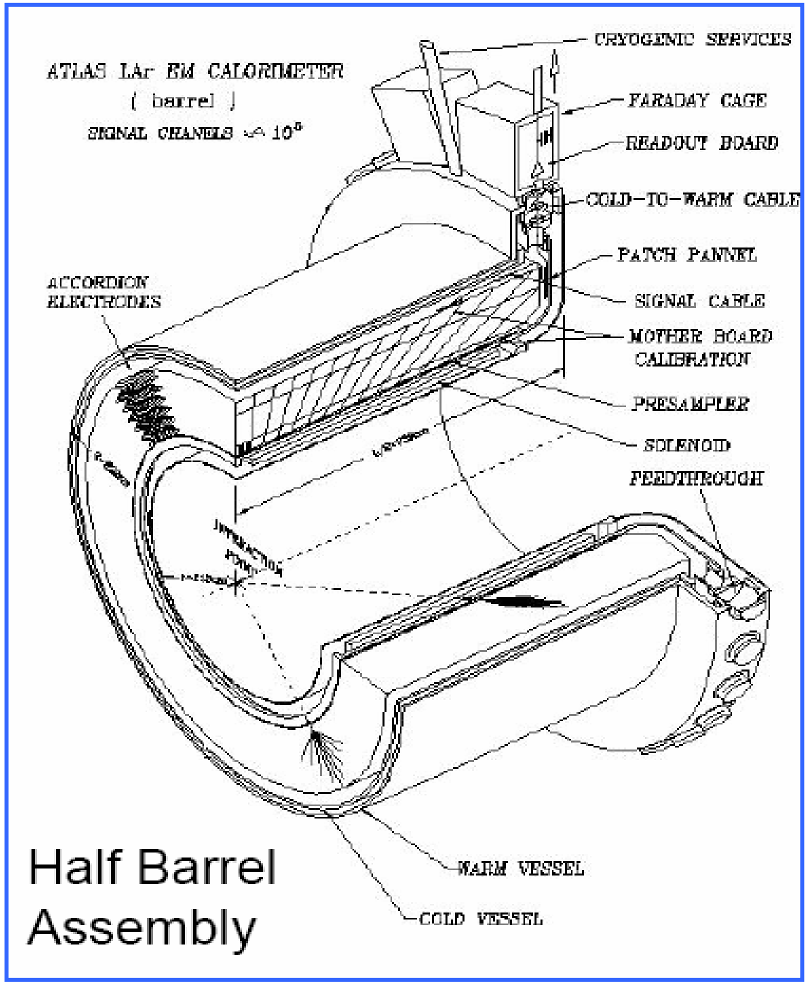
LAr EM Barrel

LAr Forward Calorimeter (FCAL)

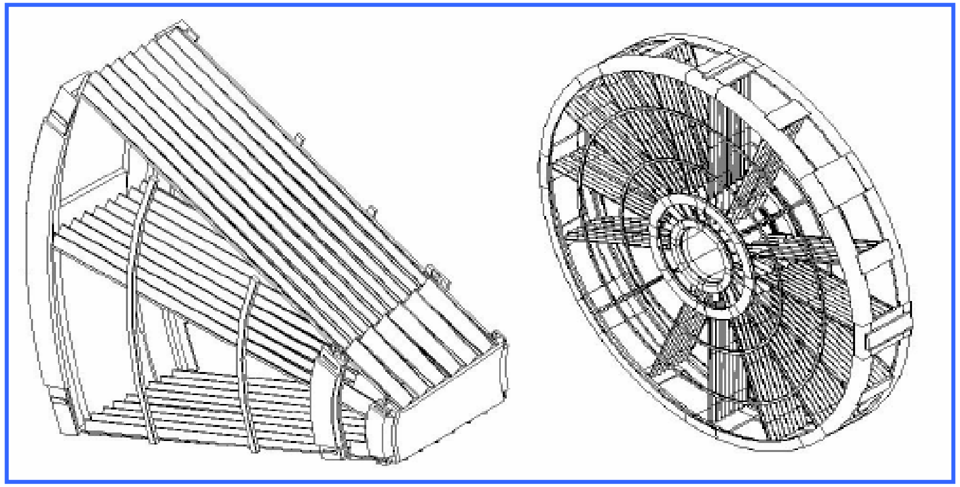
ATLAS E.m. Accordion Calorimeter

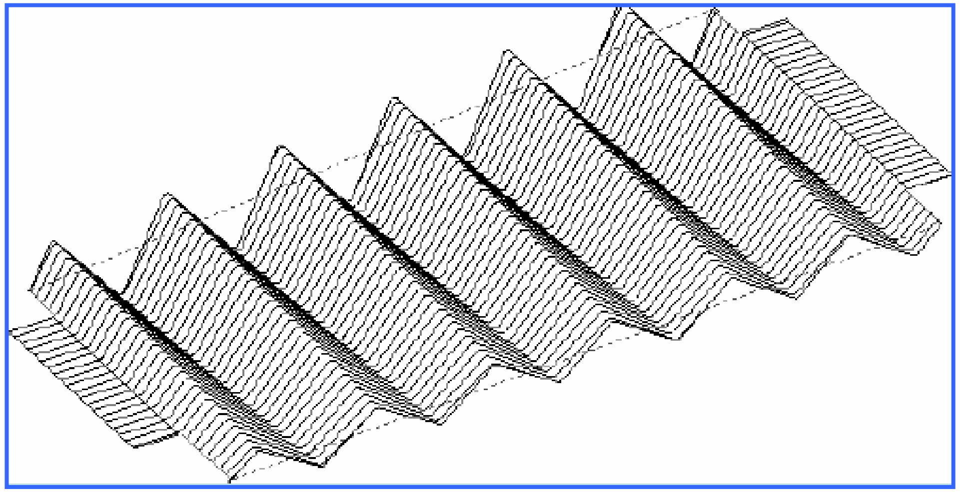
Electromagnetic Barrel EMB

Electromagnetic End-cap EMEC



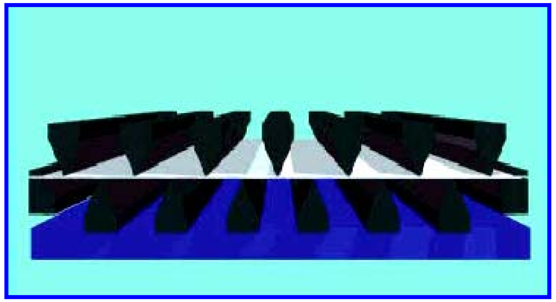
Half Barrel Assembly

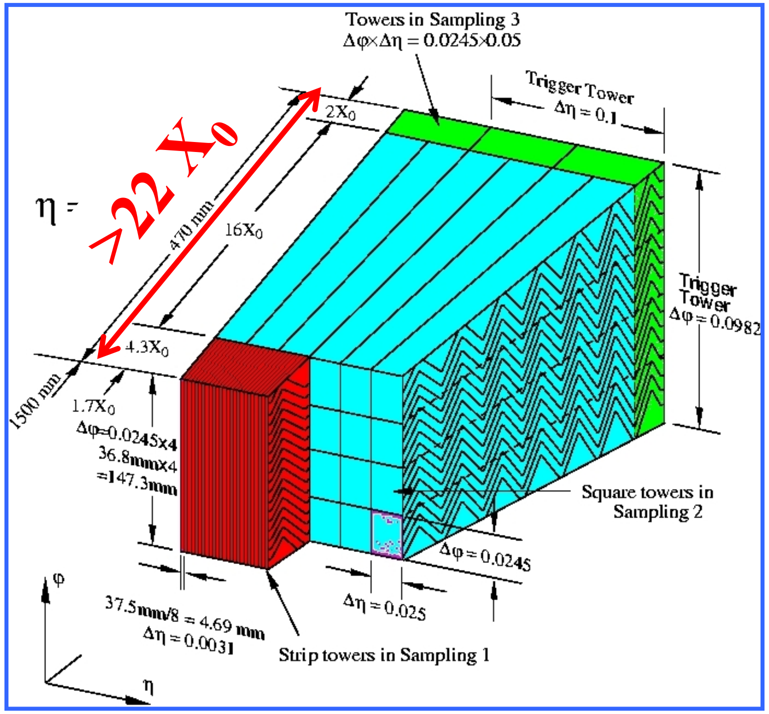




ATLAS EM Calorimeter

Lead/Liquid argon sampling calorimeter with accordion shape



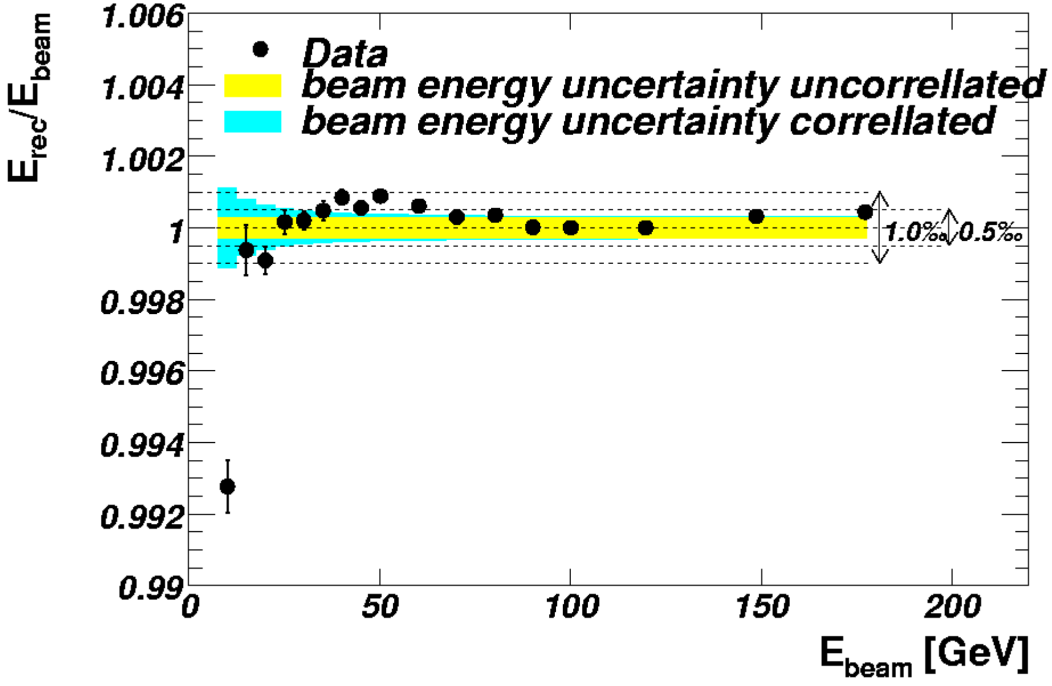


- Full azimuthal coverage
- Rapidity coverage up to 3.2
- High granularity (~180,000 channels)
- 3 Longitudinal segmentations
- Presampler for $\eta < 1.8$

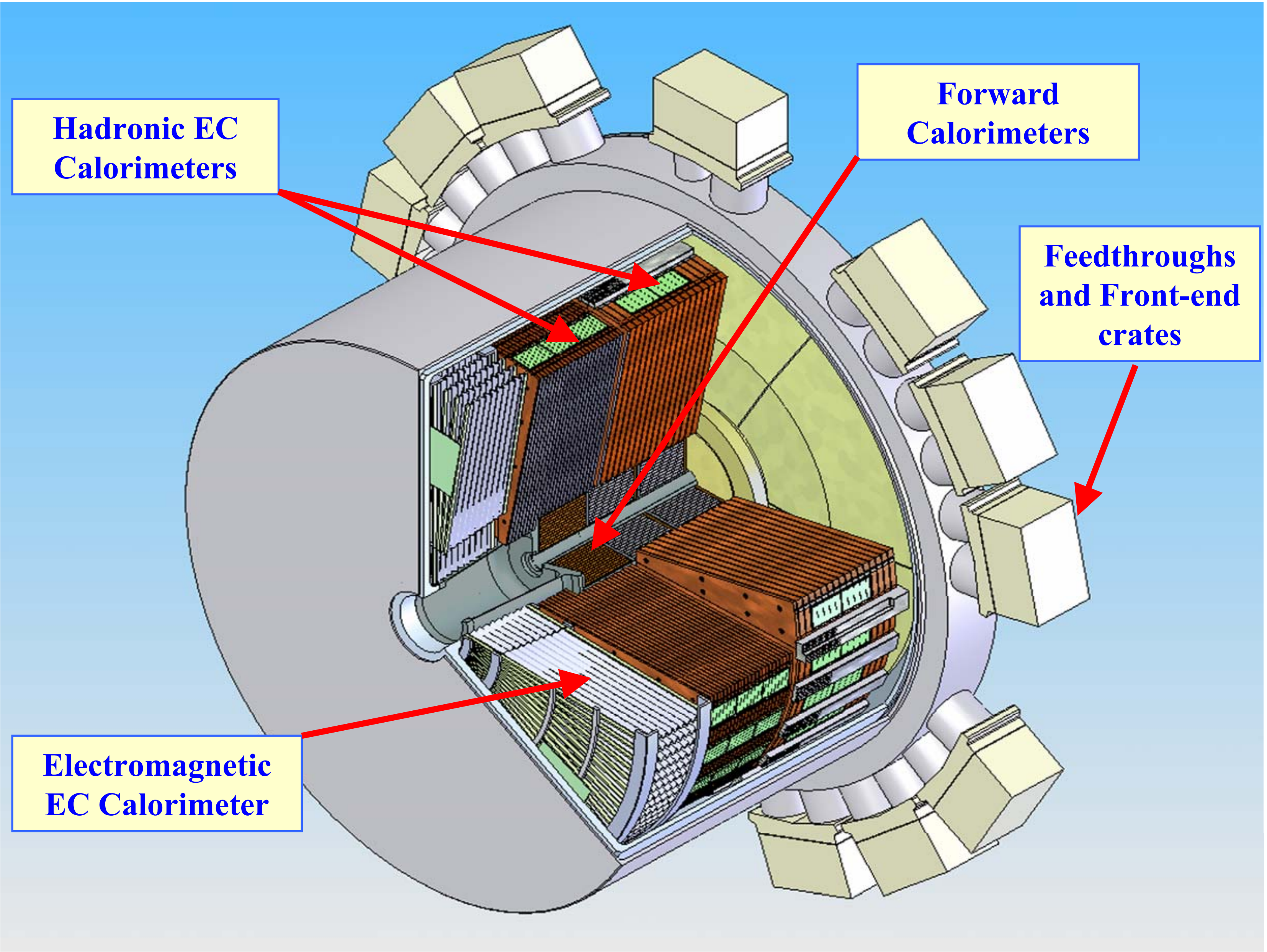
- Barrel : gap = 2.1mm @ 2000 V
  lead 1.5 (1.1) mm for $\eta < 0.8$ (>0.8)
- End-cap : gap varies with radius
  3.1->0.9 mm variable HV by steps

ATLAS EMB Linearity

- Needed a dedicated TB set-up in 2002 to measure the beam energy
- Linearity is better than 0.1% in the energy range 20-180 GeV
- A few caveats:
  - Check done at one η position
  - Less material than in ATLAS
- Performance adequate for most ATLAS measurements
- Exception: W mass
  - if one wants to improve over LEP+Tevatron, needs a ~0.02% energy scale
- Energy scale set by Z→ee
  - Will need combination with tracking detector to extrapolate from Z to W with such precision



ATLAS LAr End-Cap Calorimeters

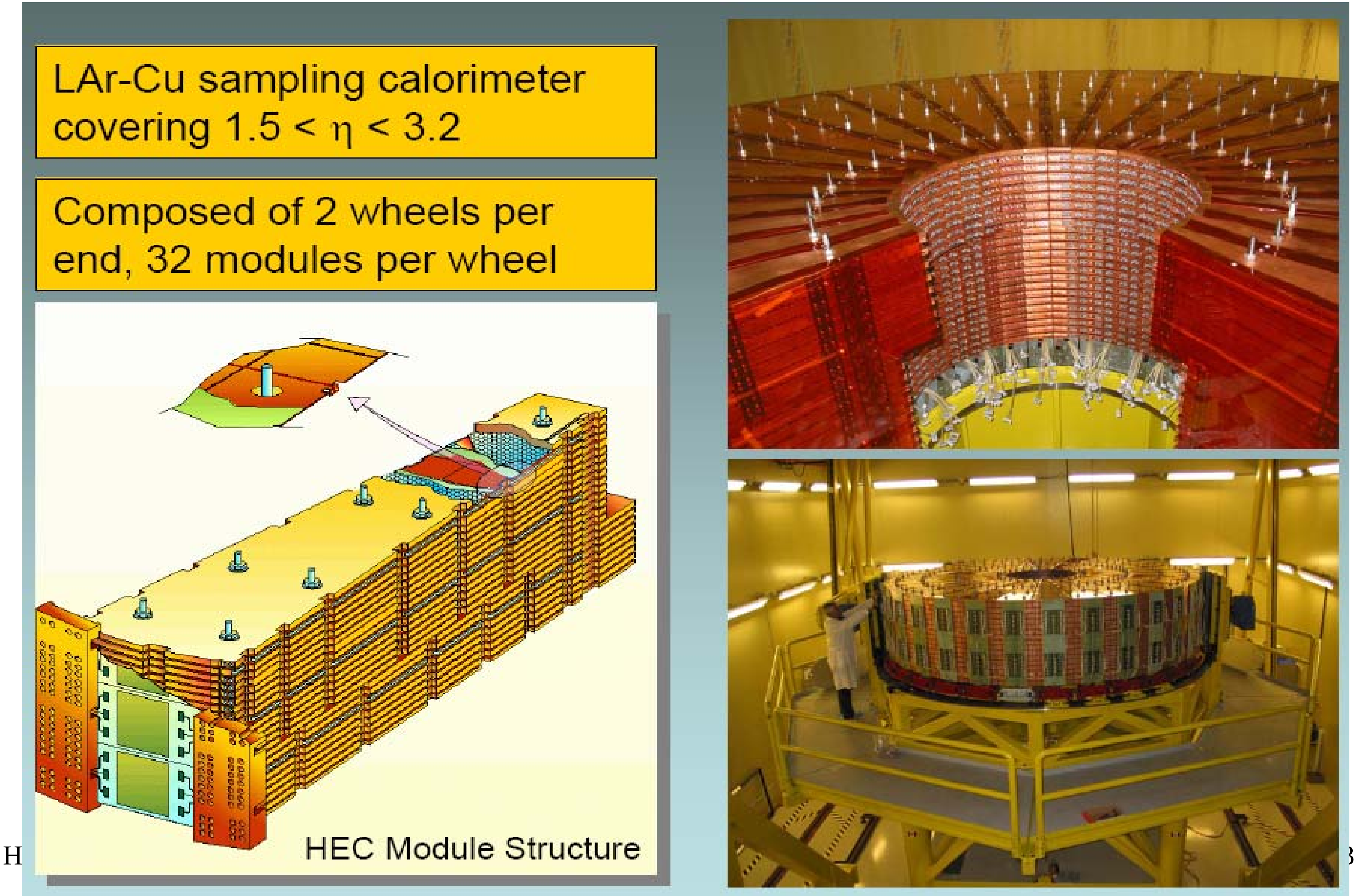

Hadronic EC Calorimeters

Forward Calorimeters

Feedthroughs and Front-end crates

Electromagnetic EC Calorimeter

ATLAS Hadronic End-Cap Calorimeter HEC



LAr-Cu sampling calorimeter covering $1.5 < \eta < 3.2$

Composed of 2 wheels per end, 32 modules per wheel

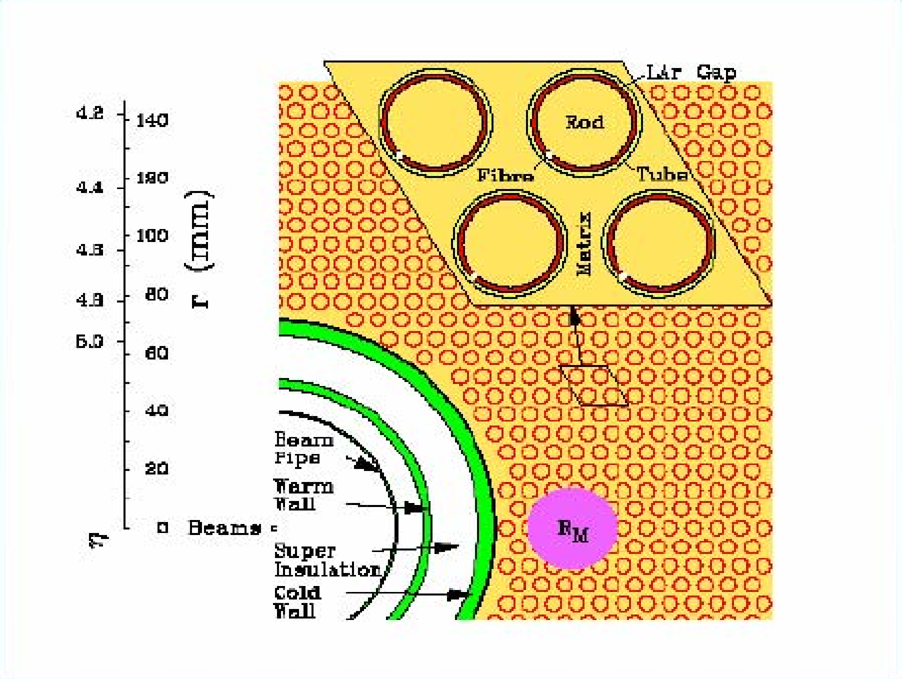
HEC Module Structure

ATLAS Forward Calorimeter FCal

Novel electrode structure → thin annular gaps formed by an tubes in an absorber matrix, which are filled with anode rods of slightly smaller radius

Gap maintained by helically-wound radiation hard plastic fibre (PEEK)

Three modules: 1 EM, 2Hadronic (ease of construction, depth segmentation)



	Type	Absorber	Gap (μm)	Number of Electrodes
FCal1	EM	copper	250	12000
FCal2	HAD	tungsten	375	10000
FCal3	HAD	tungsten	500	8000

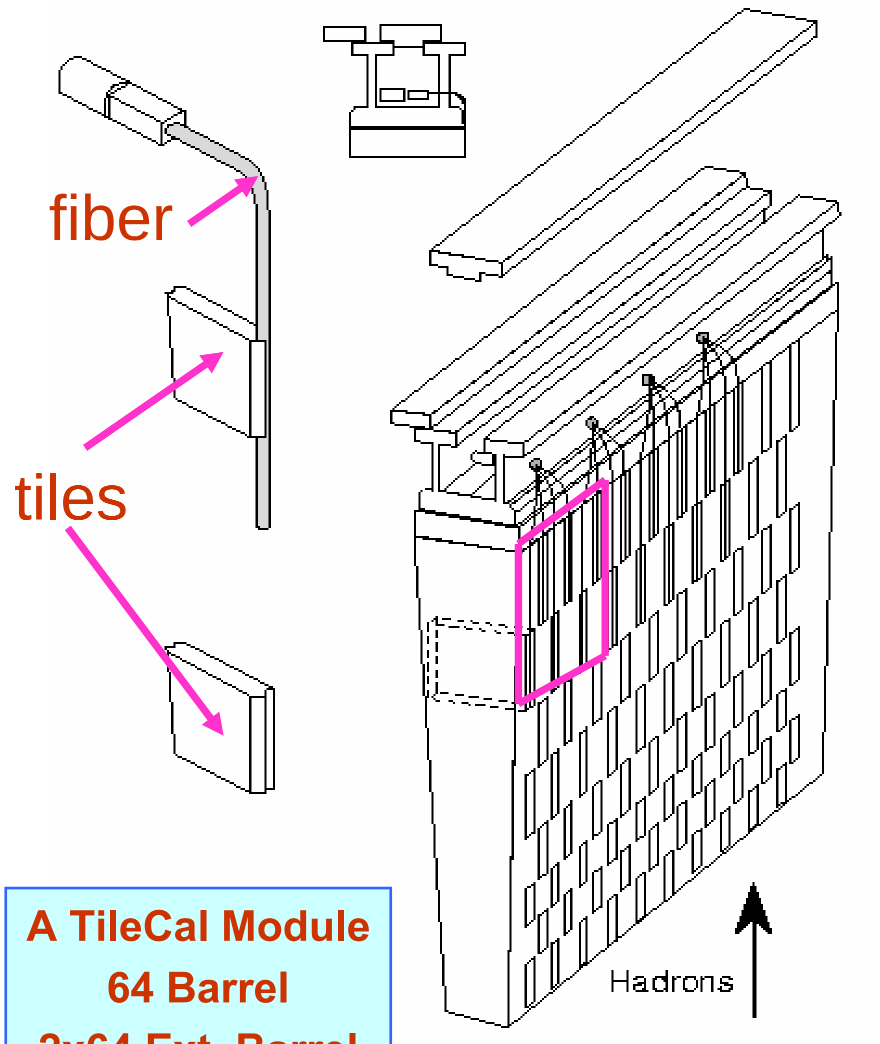
↓

matrix and rods are part of the detector 'absorber' and are composed of the same material

ATLAS LAr Commissioning Plans

- Cold testing at the surface after detector integration (complete)
- Testing (warm) in the ATLAS cavern
- Cold testing in the ATLAS cavern
- Electronic calibration, noise studies including magnet operation
- Commissioning / integration of trigger / DAQ system
- Data taking with cosmic rays begins 2006
  - LAr Barrel ~July 2006
  - LAr End-cap ~Dec 2006
- Commissioning with single beams in summer 2007 (?)
- Commissioning with colliding beams in fall 2007 (?)

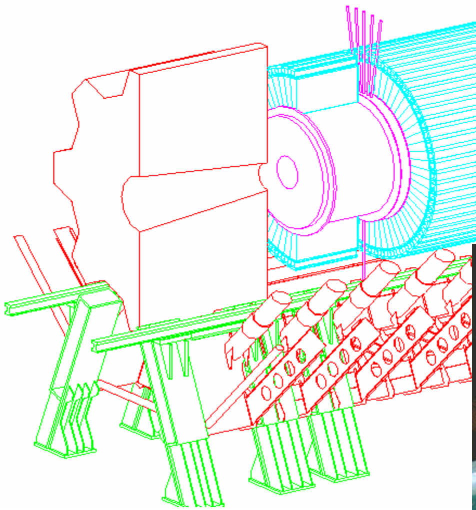
ATLAS TileCal Detector



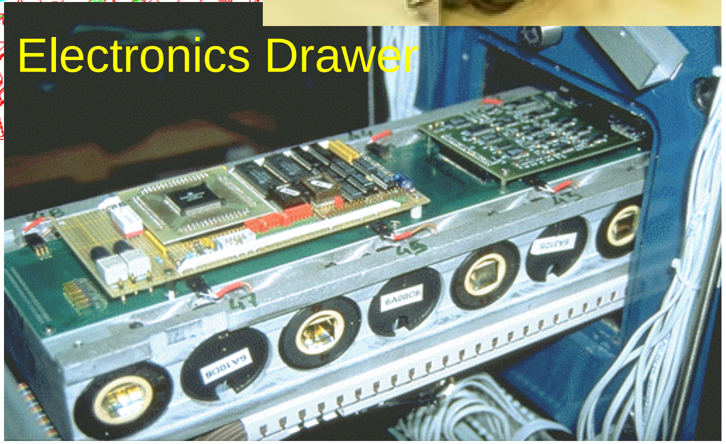
A TileCal Module

64 Barrel

2x64 Ext. Barrel

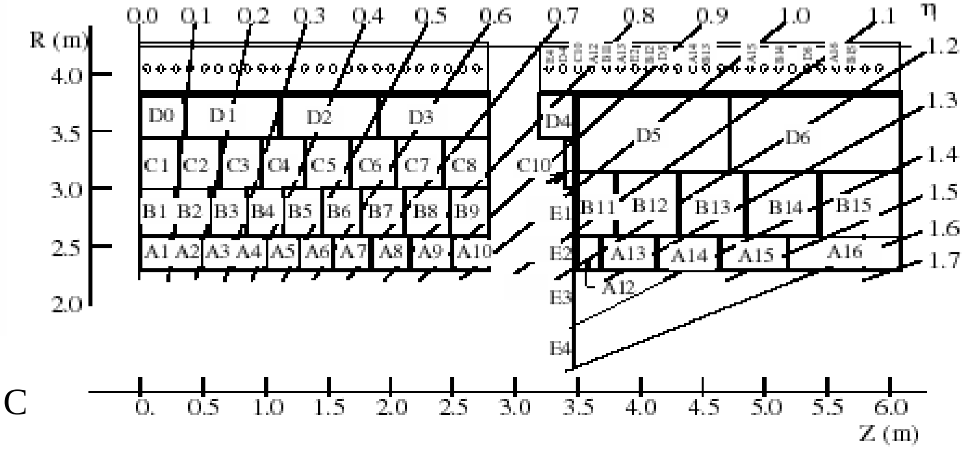


Finger LVPS



Electronics Drawer

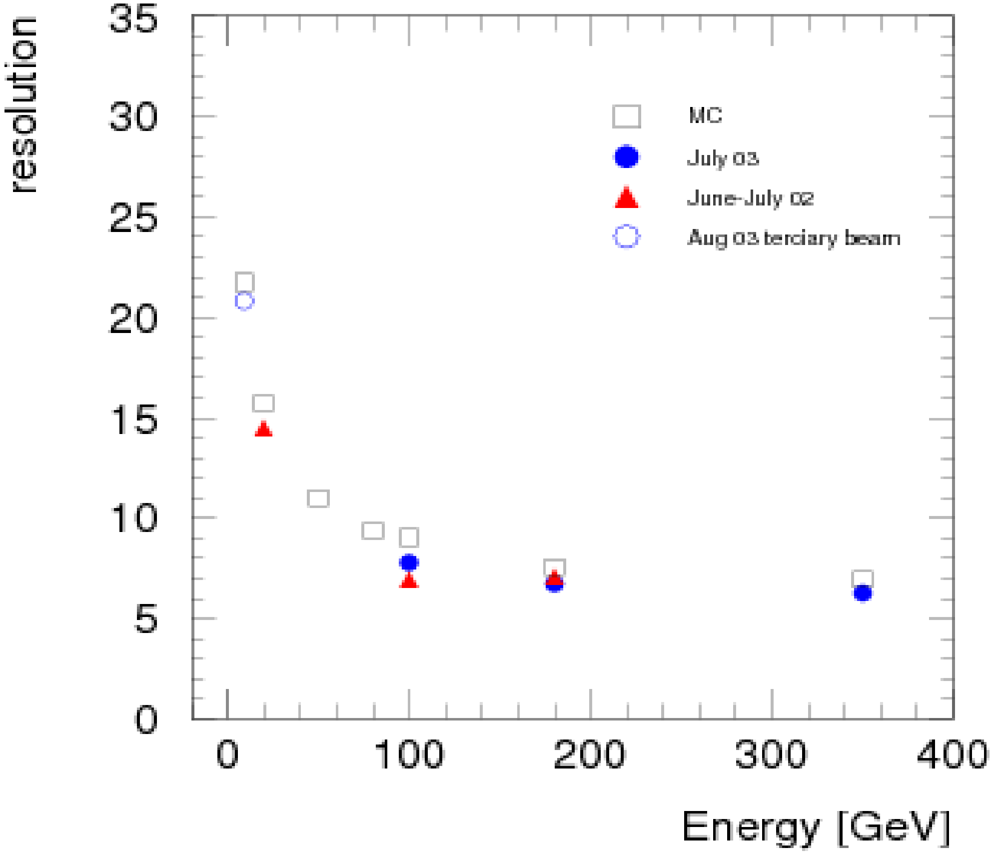
TILECAL CELLS



ATLAS TileCal Performance for Pions

Testbeam results:

- linearity studies show e/h=1.36
- uniformity of response over several modules at the level of 1.5%

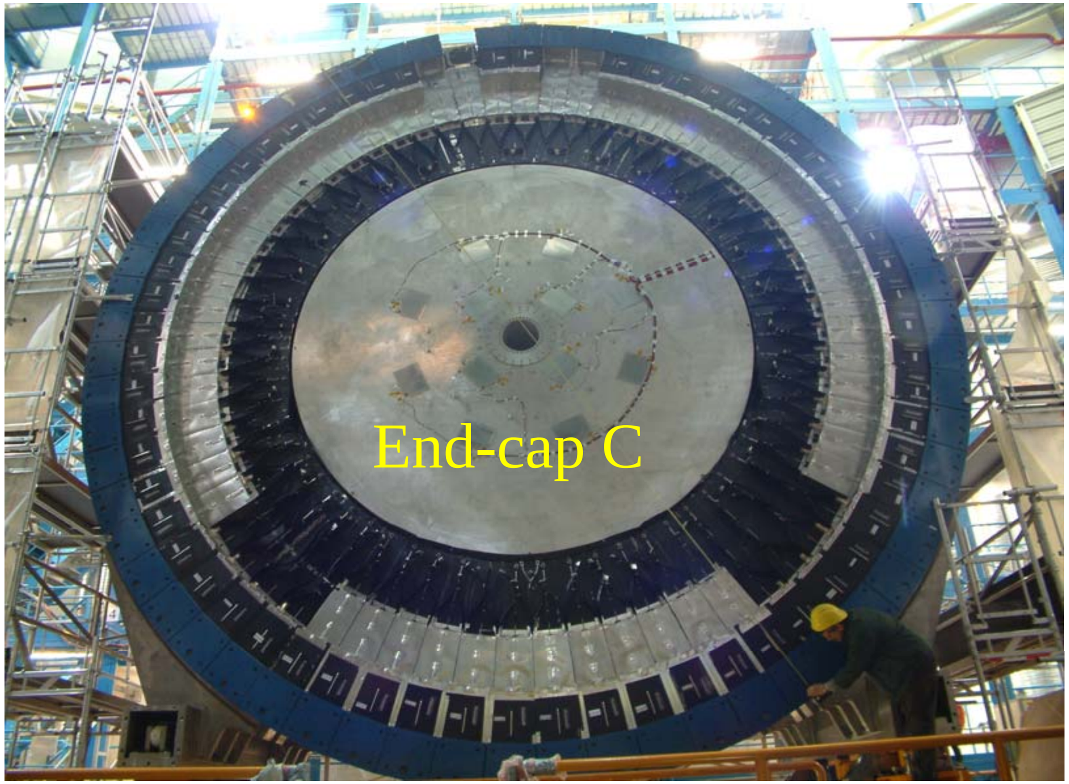


Good agreement with latest G4 MC (4.7.1 QGSP)

ATLAS Calorimeter Installation Status

- **Barrel** part of the calorimeter (Tile + LAr) is at its final position.
- LAr Barrel is cold and filled with LAr as of today !
  - Tile FE electronics in the modules certified.
  - LAr FE electronics installed, being commissioned.

- **End-cap C**
  (Tile with gap Scintillators + LAr) in open position within toroid
  - Tile FE electronics certified.
  - LAr FE electronics being installed
- **End-cap A**
  (Tile with gap Scintillators + LAr) in garage position
  - Tile + LAr FE electronics being installed.



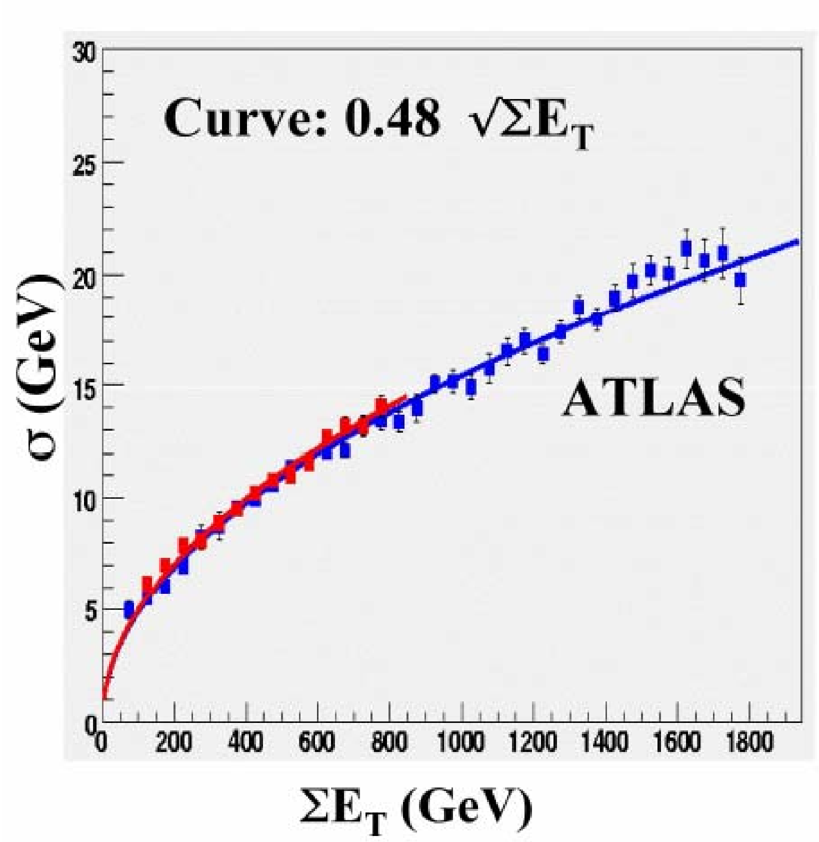
ATLAS / CMS: Hadronic Performance

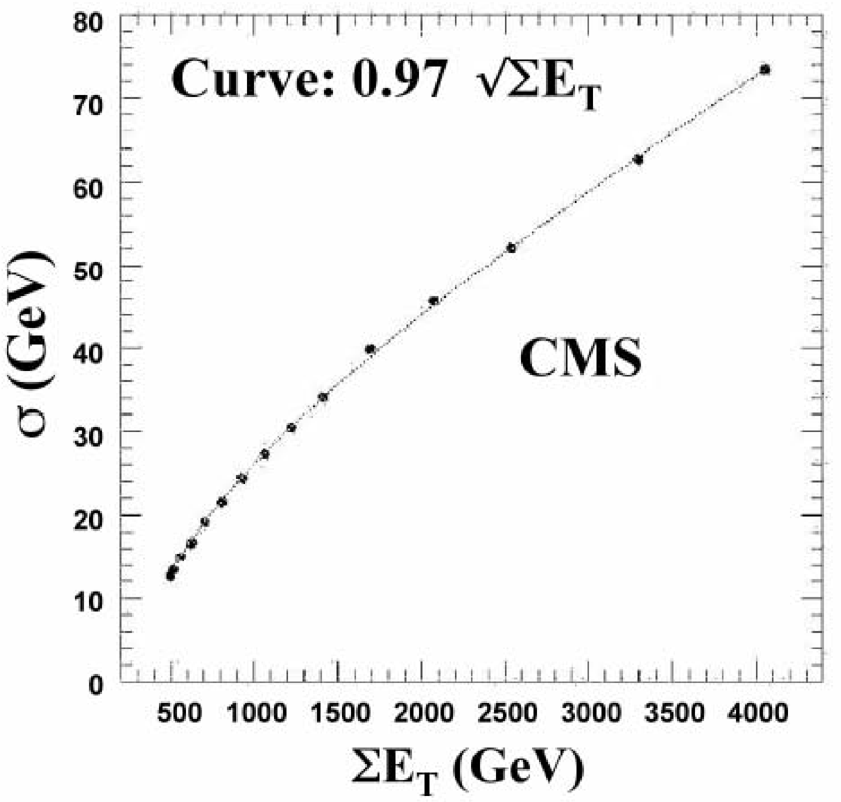
Main hadronic performance parameters of the different calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions.

	ATLAS				CMS	
	Barrel LAr / TileCal		End-cap LAr EMEC / HEC		Barrel ECAL / HCAL	
	TileCal	Combined	HEC	Combined	Hadronic Barrel	Combined
e/h Ratio	1.36	1.37	1.49			
Stochastic term	45 %	55 %	75 %	85 %	100 %	70 %
Constant term	1.3 % (*)	2.3 % (*)	5.8 %	< 1 %		8 %
Noise	Small	3.2 GeV	5.8 GeV	1.2 GeV	Small	1 GeV

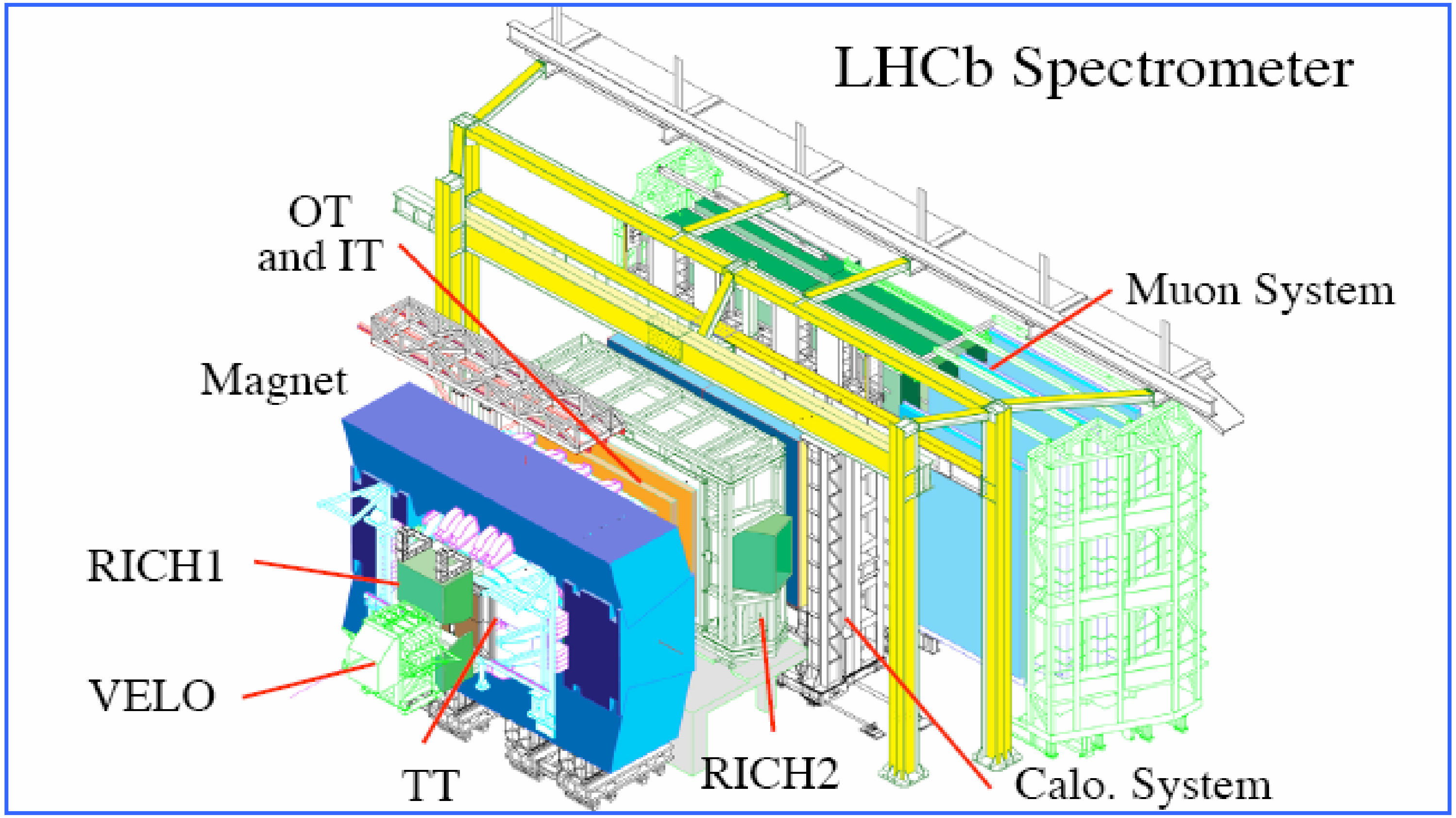
ATLAS / CMS: Missing ET

Expected precision of measurement of missing ET as function of ET measured per event.





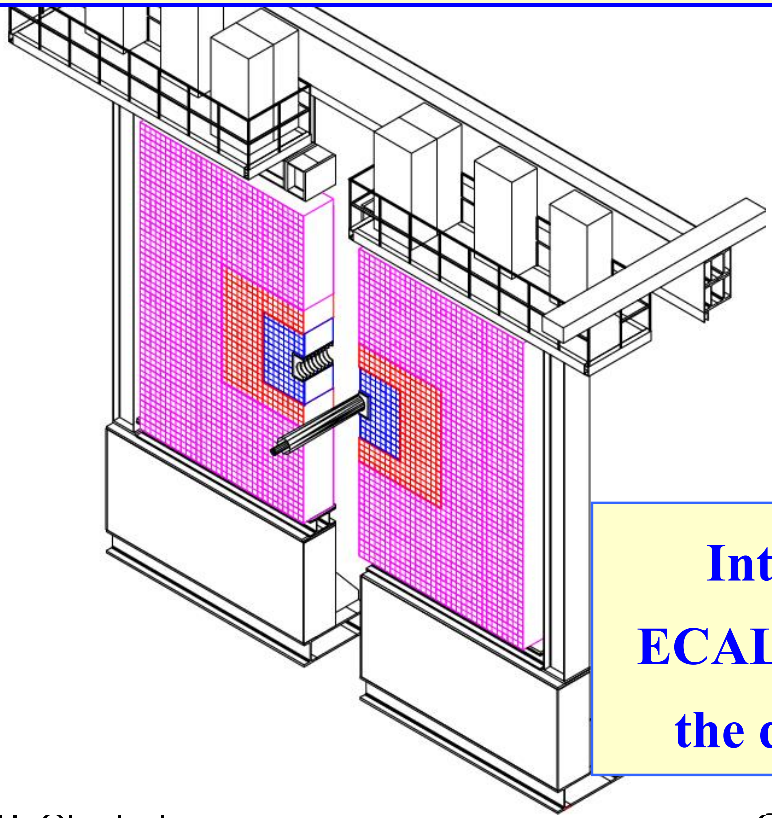
LHCb

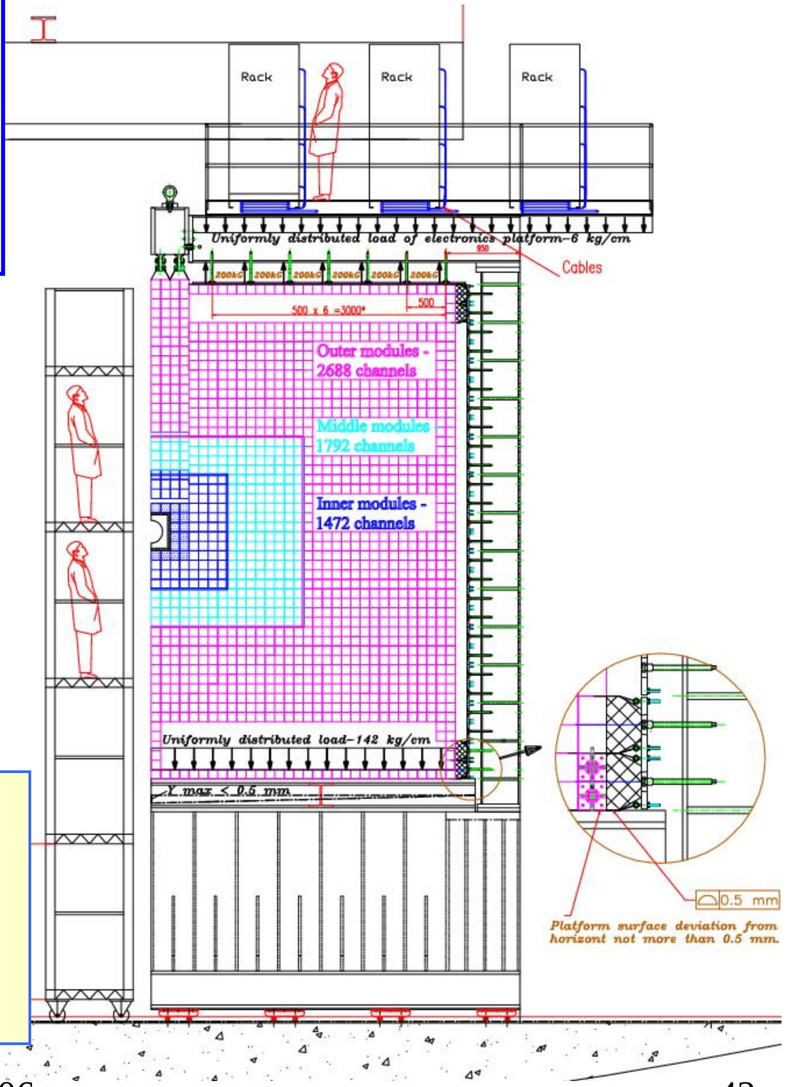


- **Experiment to investigate**
  CP-violation in B-Meson system
- **Important precision measurements**
- **High event rates expected:**
  10^{12} bb-pairs / year @ L =1032

LHCb ECAL

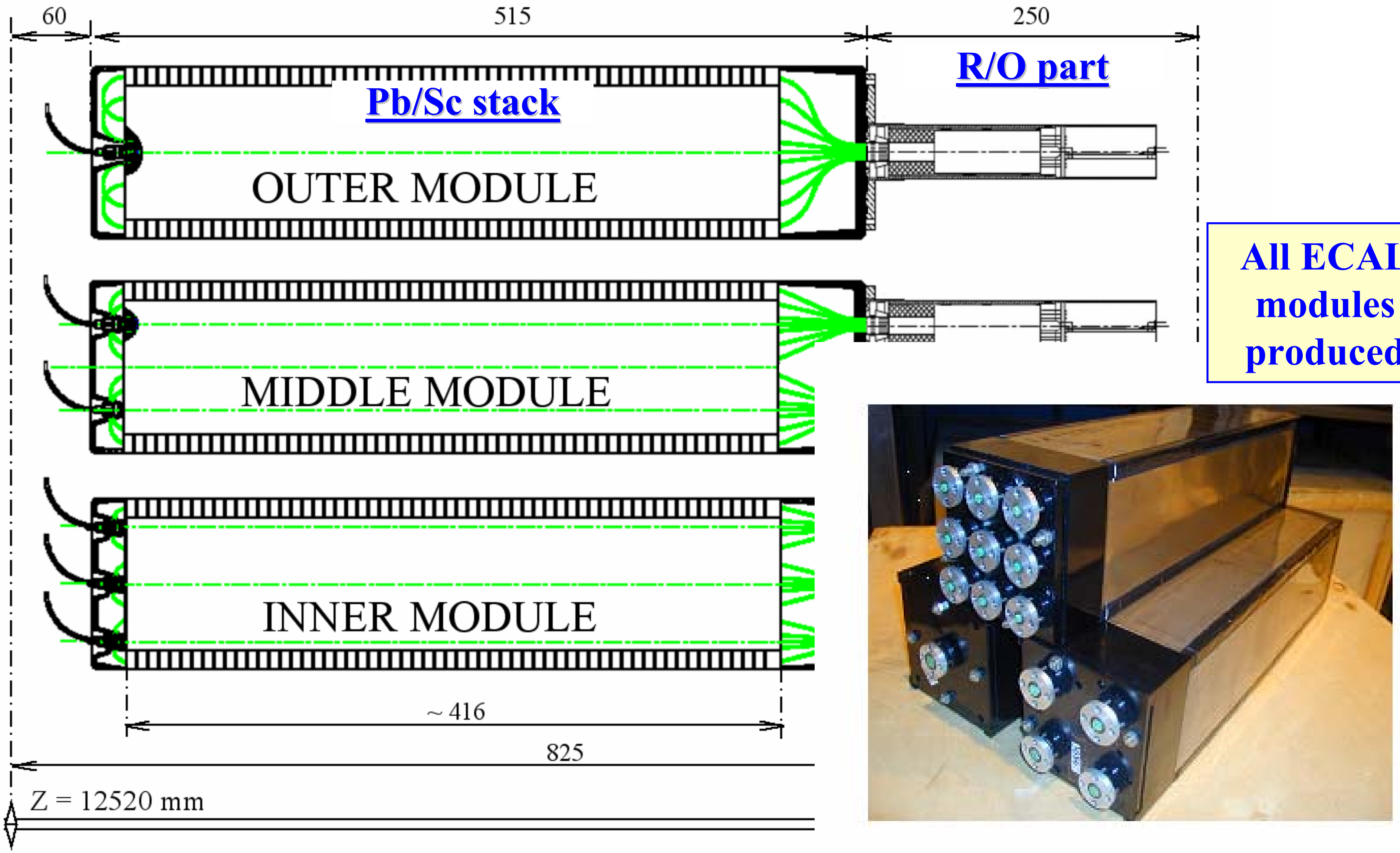
- Shashlik type technology
- 3 regions with different cell size
- 3.3 k modules, 6.0 k electronics channels





Integration of ECAL modules into the detector wall

LHCb ECAL Module



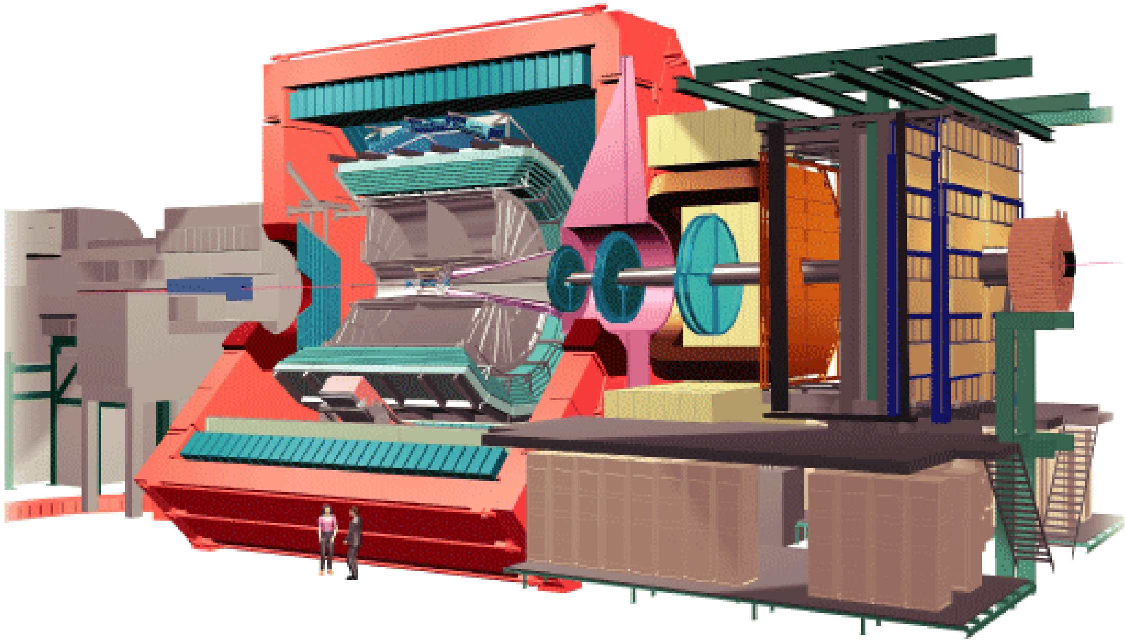
All ECAL modules produced

LHCb Calorimeter Installation in IP8


E-cal


H-cal

ALICE

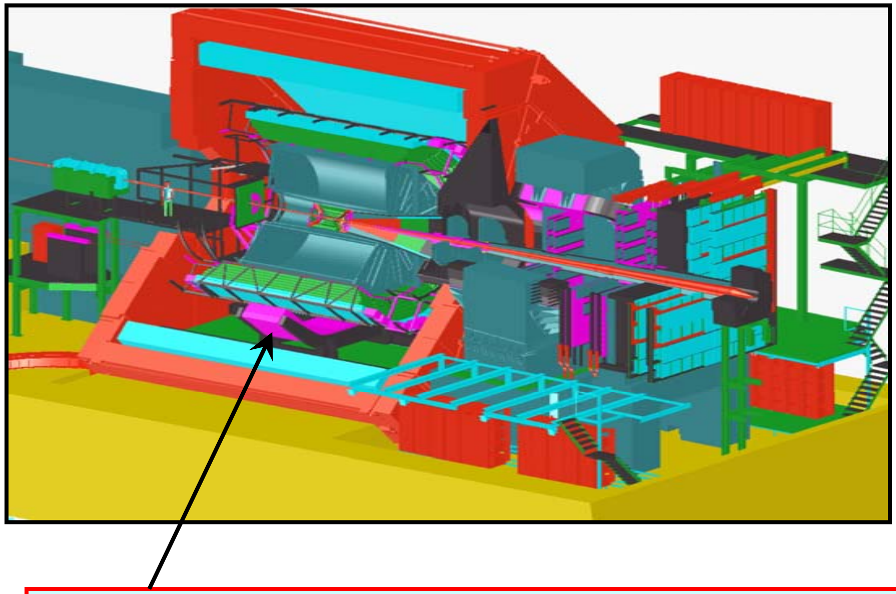


- The ALICE Collaboration is building a dedicated heavy-ion detector to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies.
- Aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected.

ALICE PHOS

PHOS investigates

- **initial phase of the collision of heavy nuclei via direct single photons and diphotons,**
- **jet-quenching as a probe of deconfinement, studied via high pT γ and π0,**
- **signals of chiral-symmetry restoration.**

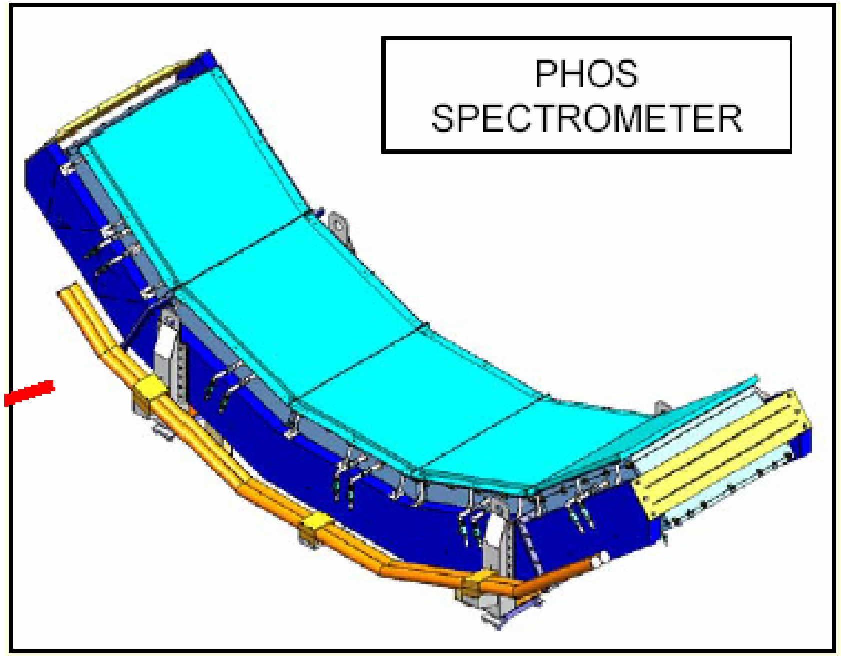


PHOS (PHOton Spectrometer) is a high resolution electromagnetic calorimeter consisting of 17920 detection channels based on lead-tungstate crystals.

PHOS parameters:

Distance to IP	**4400 mm**
Coverage in pseudorapidity	**-0.12 / +0.12**
Coverage in azimuthal angle	**100^o**
# Modules	**5**
Total area	**$8\ m^2$**
# Lead-tungstate crystals	**17920**
Crystal size	**$22x22x180\ mm^3$**
Depth (X0)	**20**
Total crystal weight	**12.5 t**
Operating temperature	**$-25\ ^oC$**
Photo readout	**APD**

ALICE PHOS

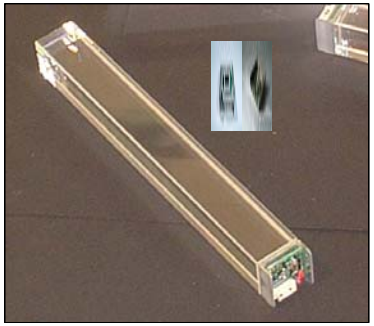


Module structure

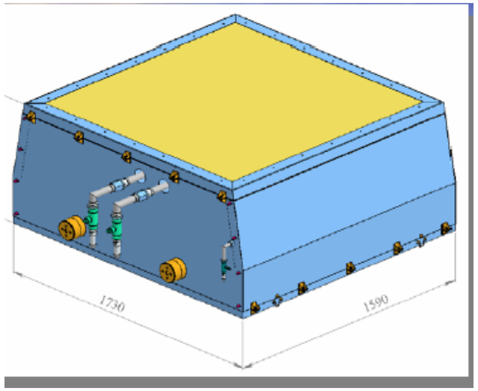
5 independent modules each of

3584 *crystal detector units:*

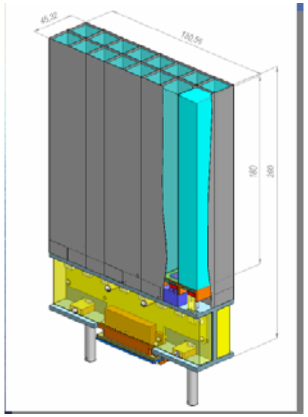
PWO crystal + APD + preamp.



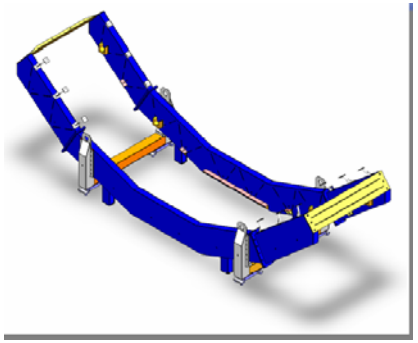
Crystal detector unit



PHOS module

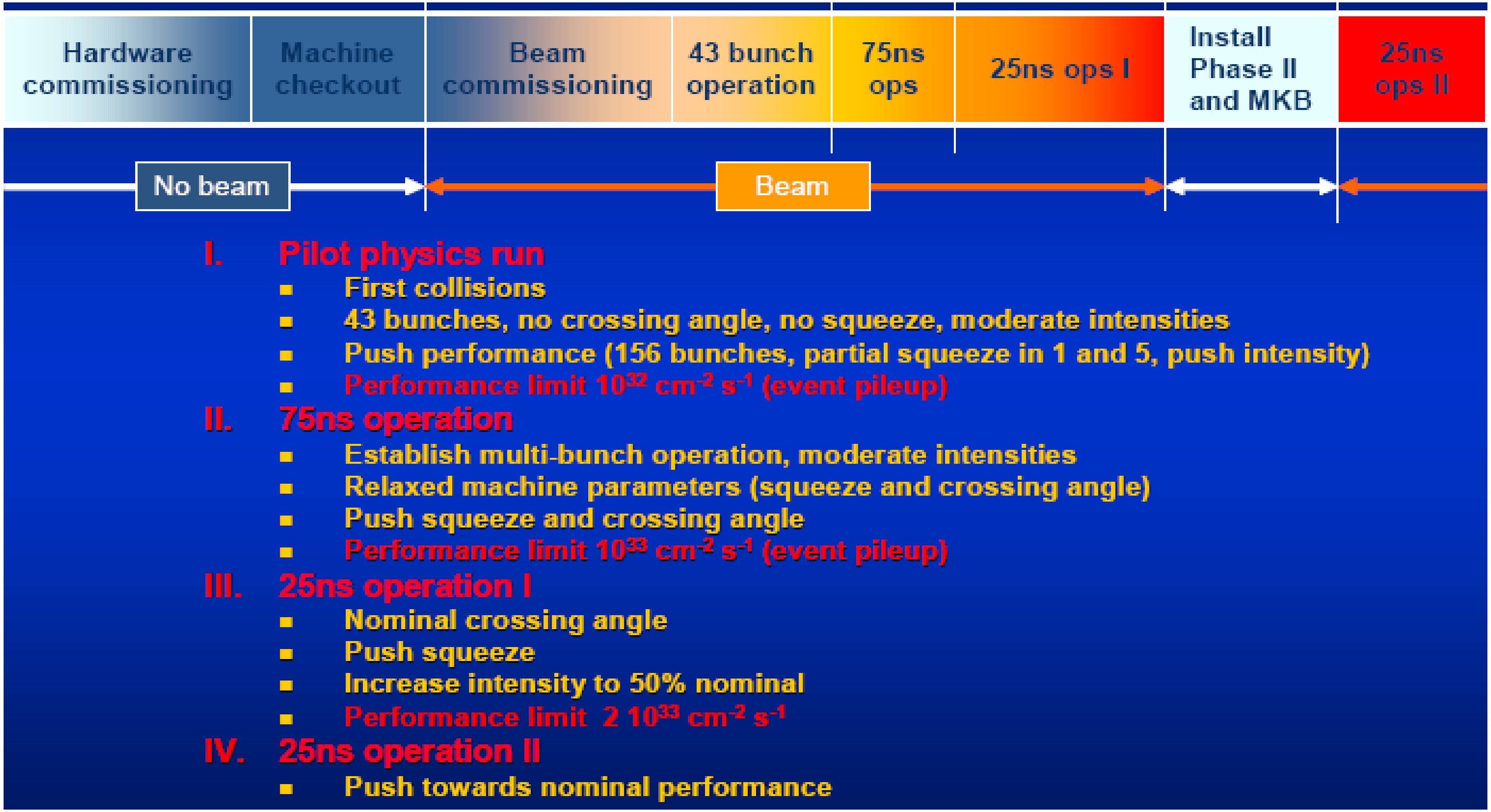


Strip unit
(16 detector units)



PHOS Cradle

LHC Start-up for Physics



Hardware commissioning | Machine checkout | Beam commissioning | 43 bunch operation | 75ns ops | 25ns ops I | Install Phase II and MKB | 25ns ops II

No beam | Beam

I. Pilot physics run

- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. 75ns operation

- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

III. 25ns operation I

- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

IV. 25ns operation II

- Push towards nominal performance

CONCLUSIONS

- The LHC calorimeters cover a wide range of novel physics searches.
- They employ sophisticated, mature as well as novel techniques.
- In some cases not enough attention has been devoted to ‘low tech‘ applications.
- Radiation hardness sets challenging requirements, which have been met in most cases.
- Severe quality control during production is a must and has rigorously been implemented in most cases.
- The LHC calorimeters try to be ready for the start-up of the machine in 2007.
- In some cases the efforts will have to be increased to cope with this deadline.