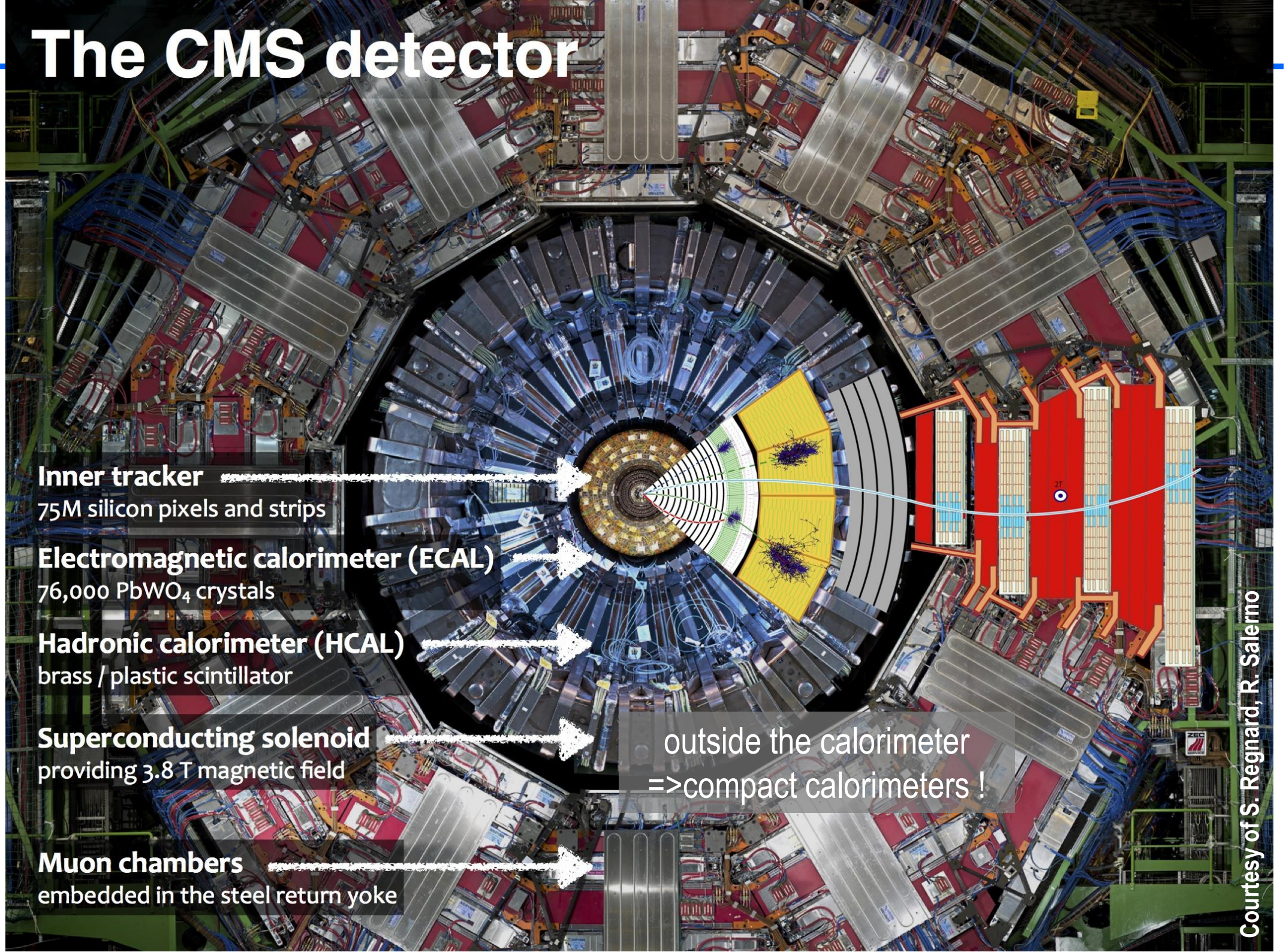
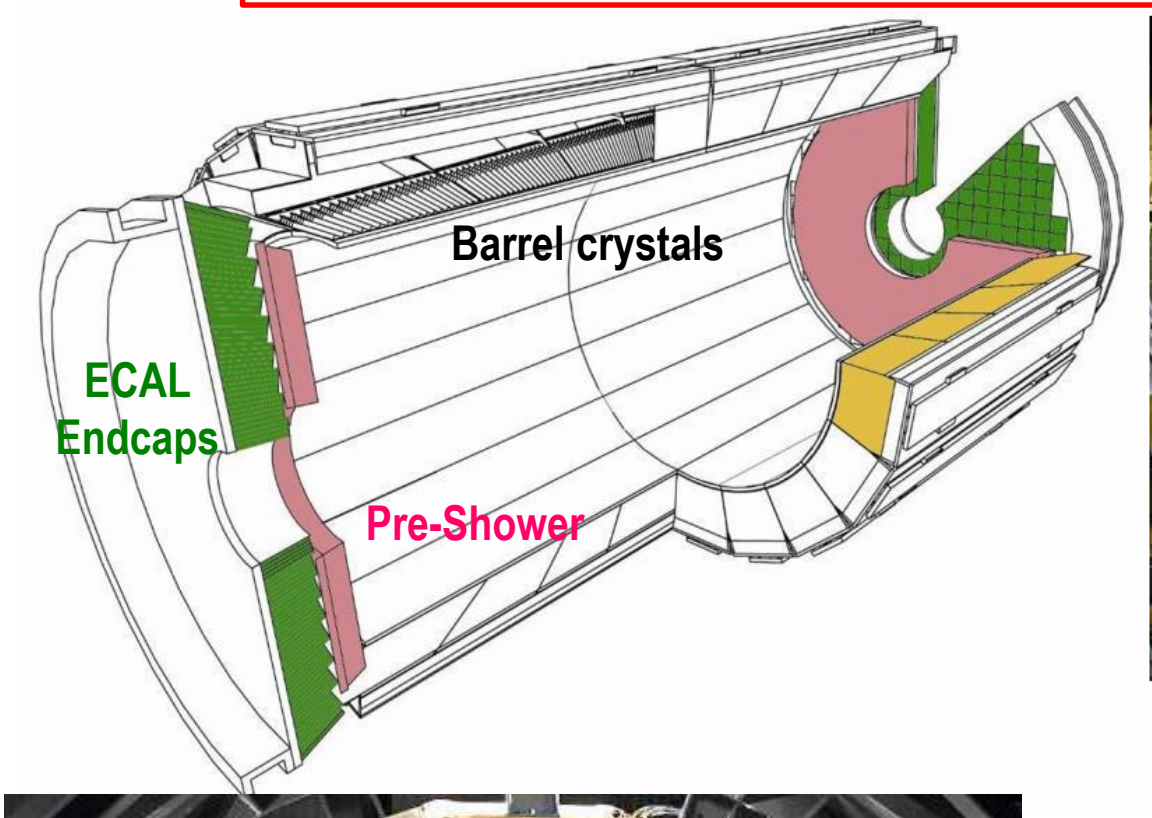
ATLAS & CMS Calorimeters examples

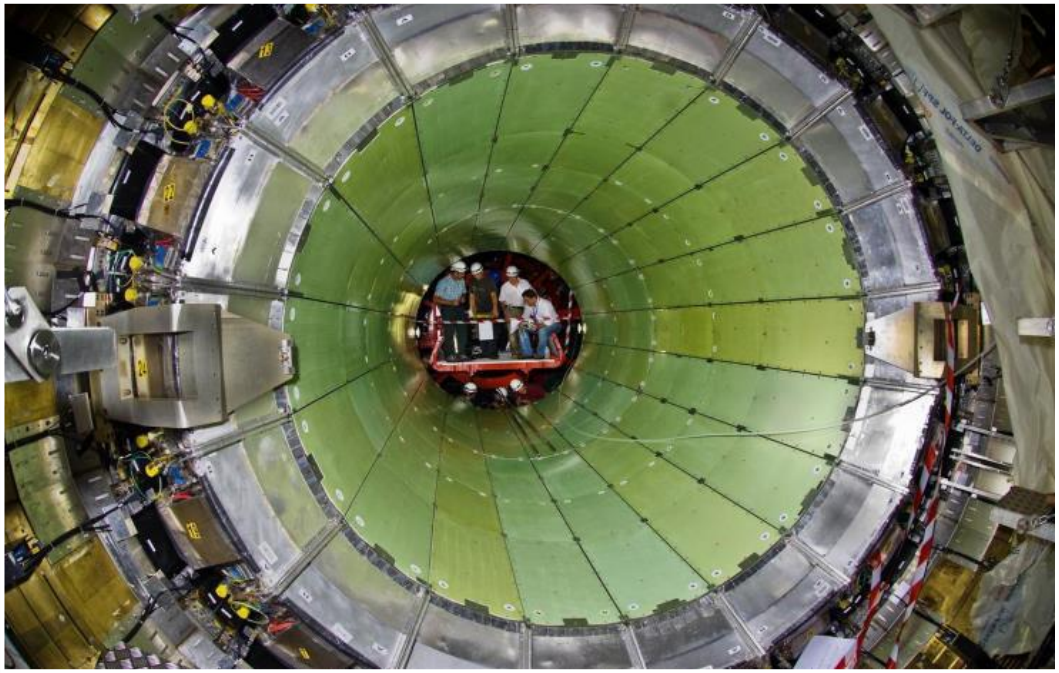
The CMS detector



CMS ECAL

Homogenous calorimeter made from 75848 $PbWO_4$ scintillating crystals

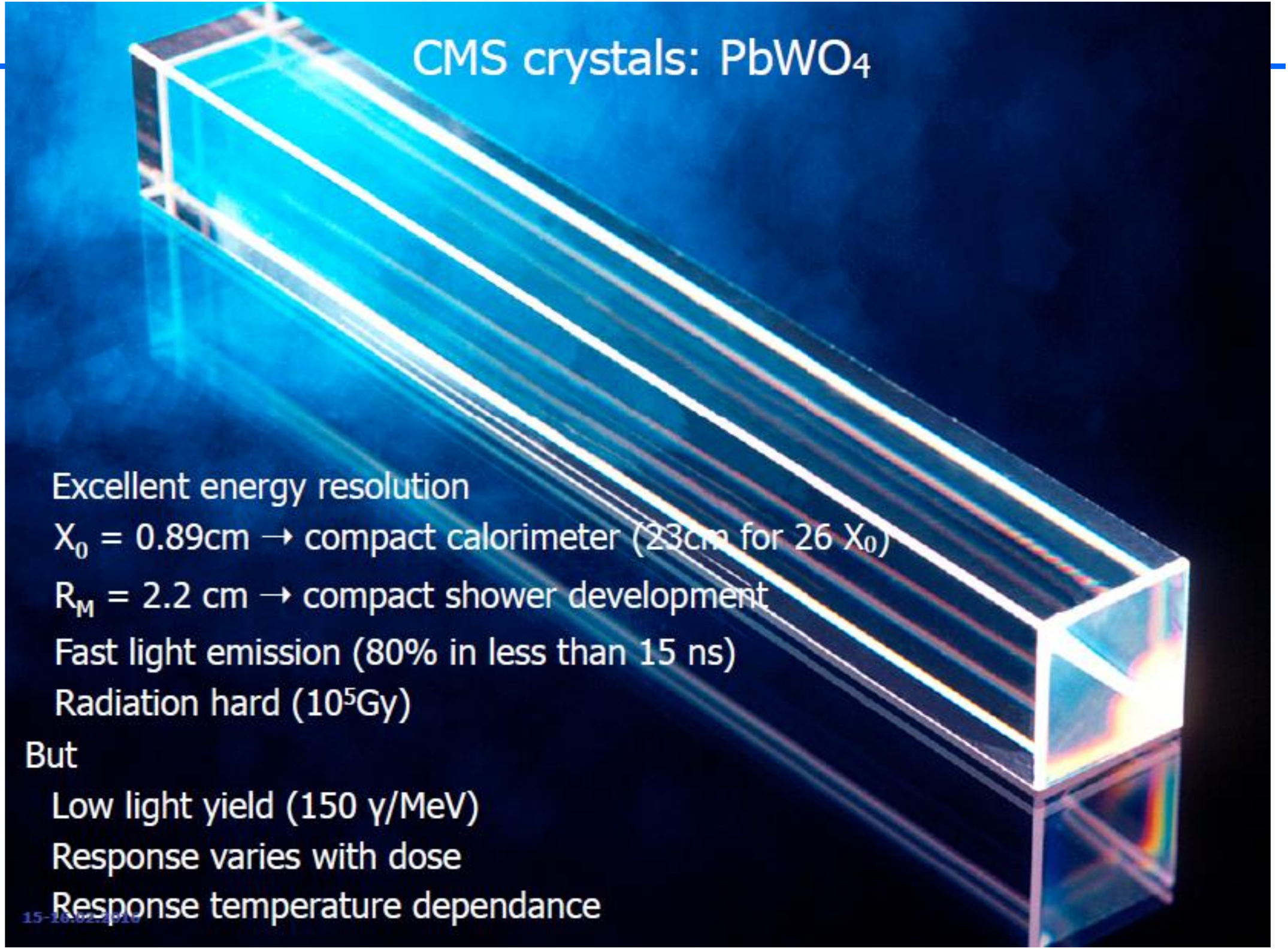




- Barrel ($|\eta|<1.48$), ~67 t
- 61200 crystals over 36 super-modules

- Endcaps ($1.48<|\eta|<3$), ~23 t
- 14648 crystals over 4 Dees (2 per endcap)
- Preceded by Pb/Si Pre-Shower

CMS crystals: $PbWO_4$



Excellent energy resolution

X_0 = 0.89cm → compact calorimeter (23cm for 26 X_0)

R_M = 2.2 cm → compact shower development

Fast light emission (80% in less than 15 ns)

Radiation hard (10^5Gy)

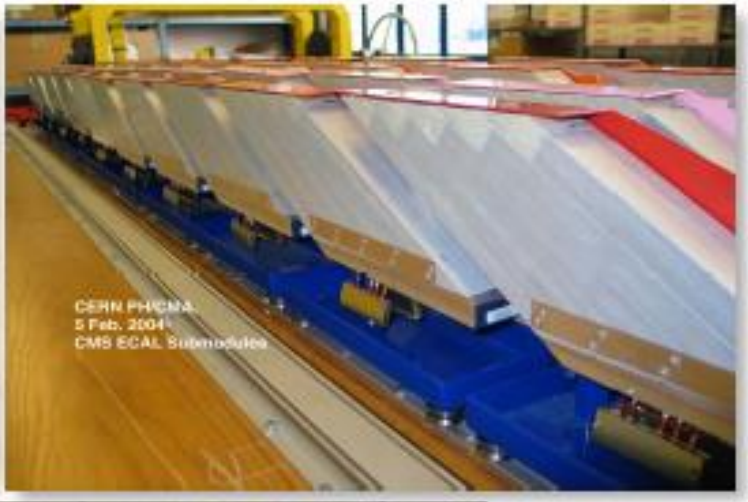
But

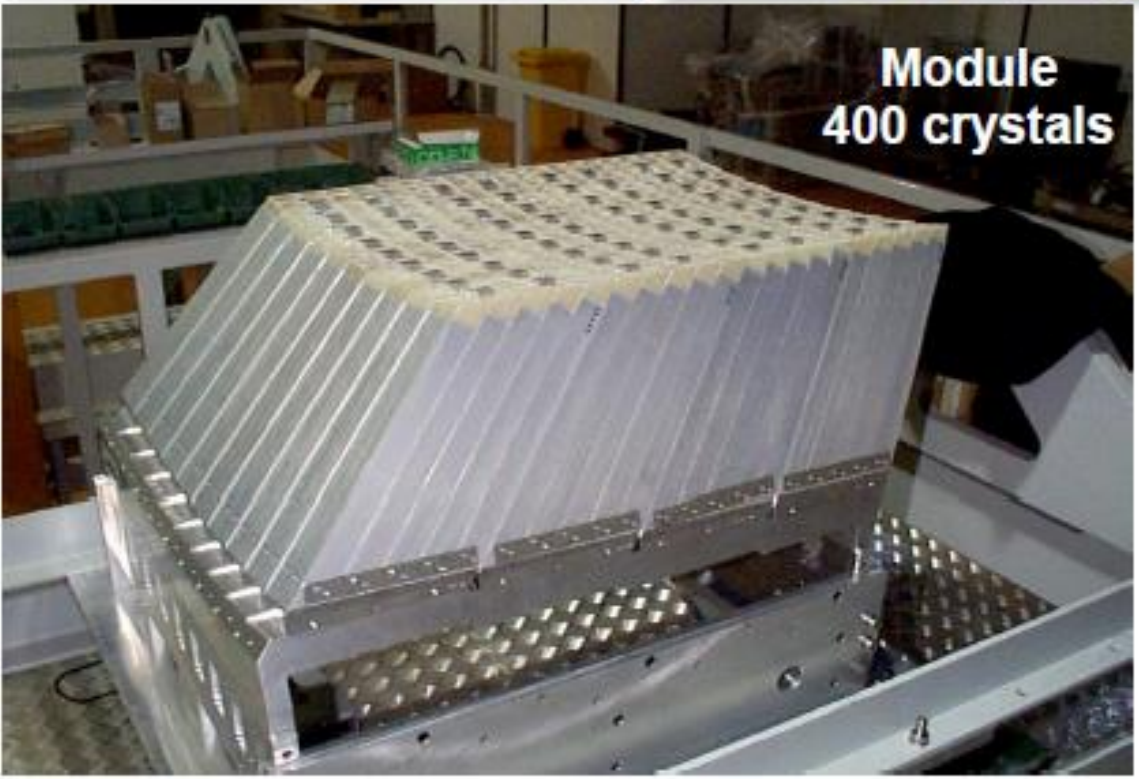
Low light yield (150 γ/MeV)

Response varies with dose

Response temperature dependance

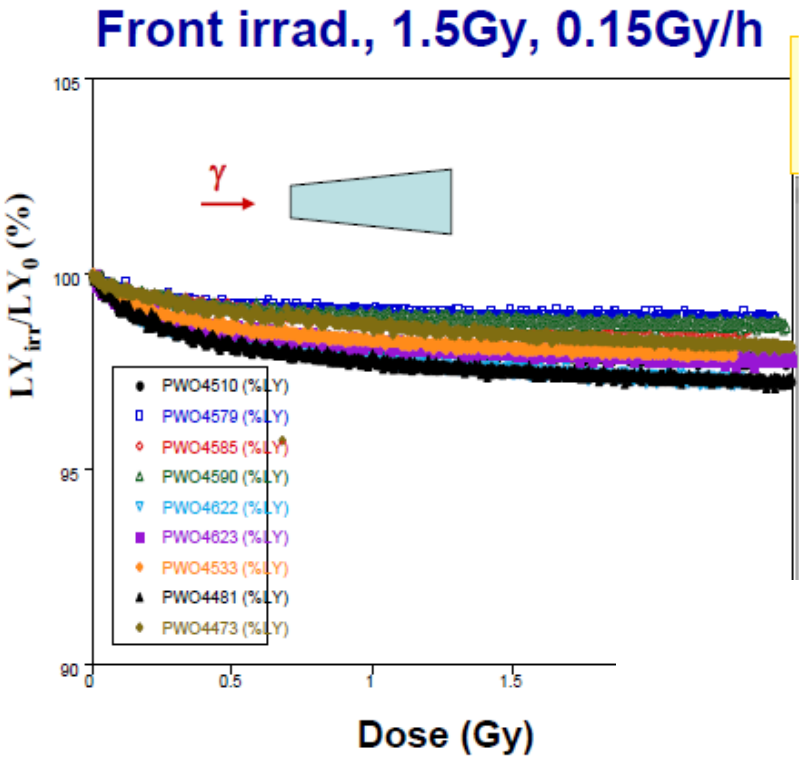
CMS ECAL Construction



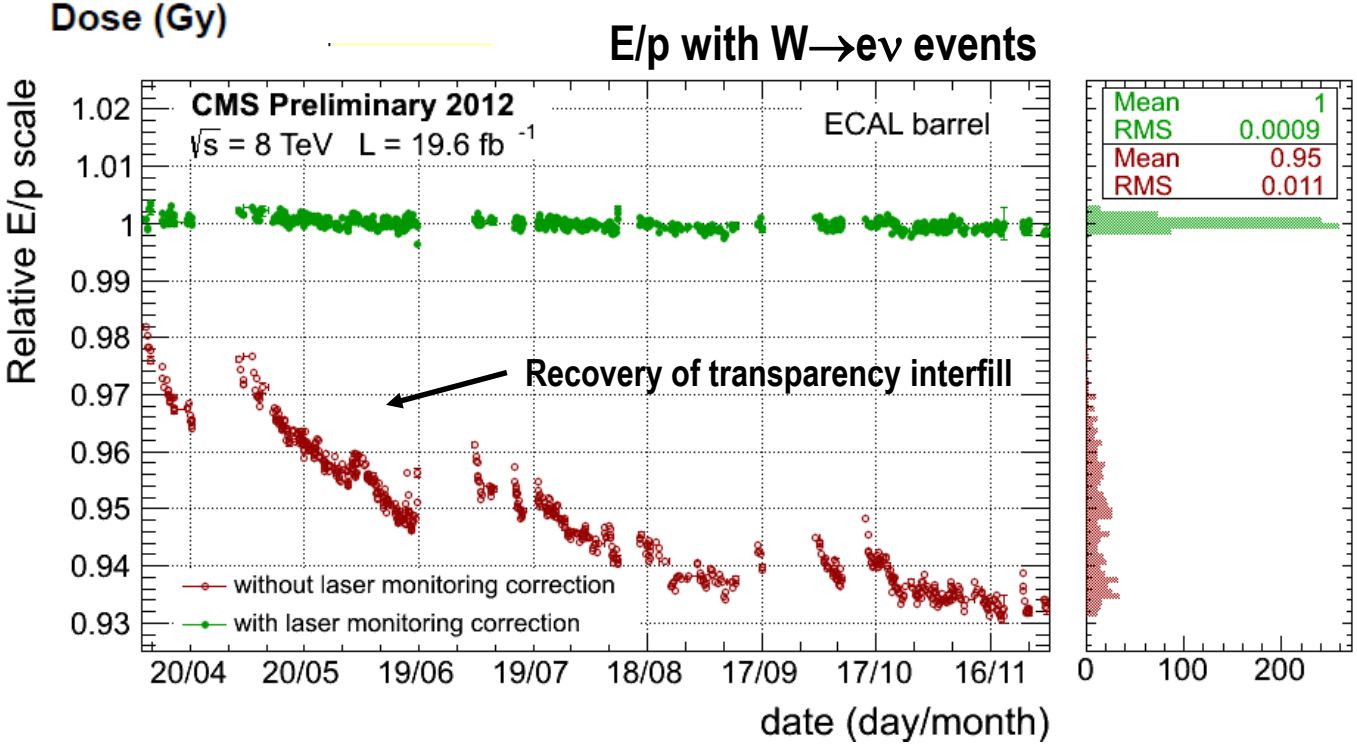


Total 36 Supermodules

CMS ECAL: monitoring



- Response of PbWO4 crystal change with irradiation
  - Loss of transparency
- Damage and recovery during LHC cycles tracked with a laser monitoring system

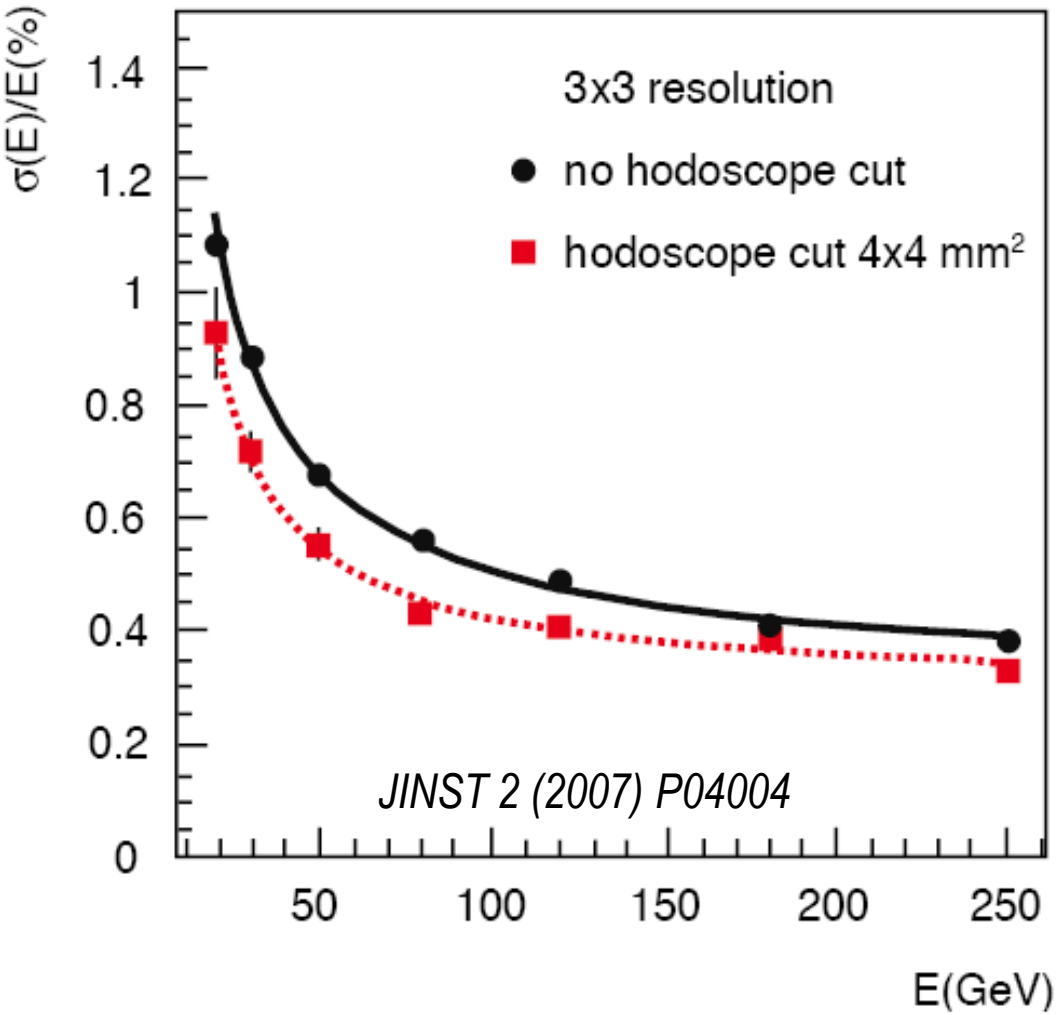


After laser correction

Before laser correction

CMS ECAL: performance

Stand-alone performance assessed during extensive test Beam campaigns at CERN...

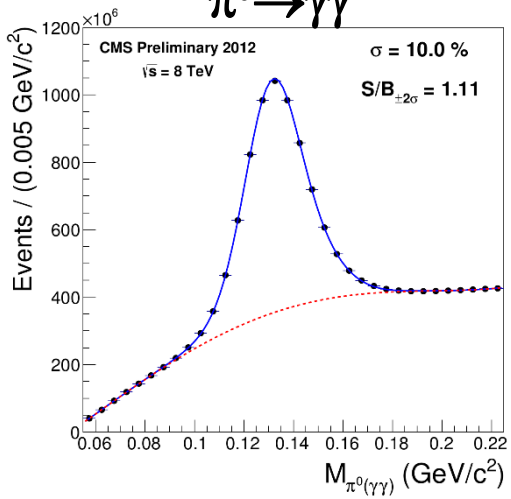


$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

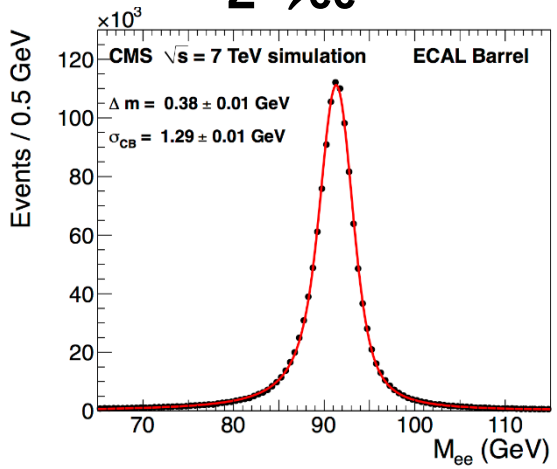
(test beam)

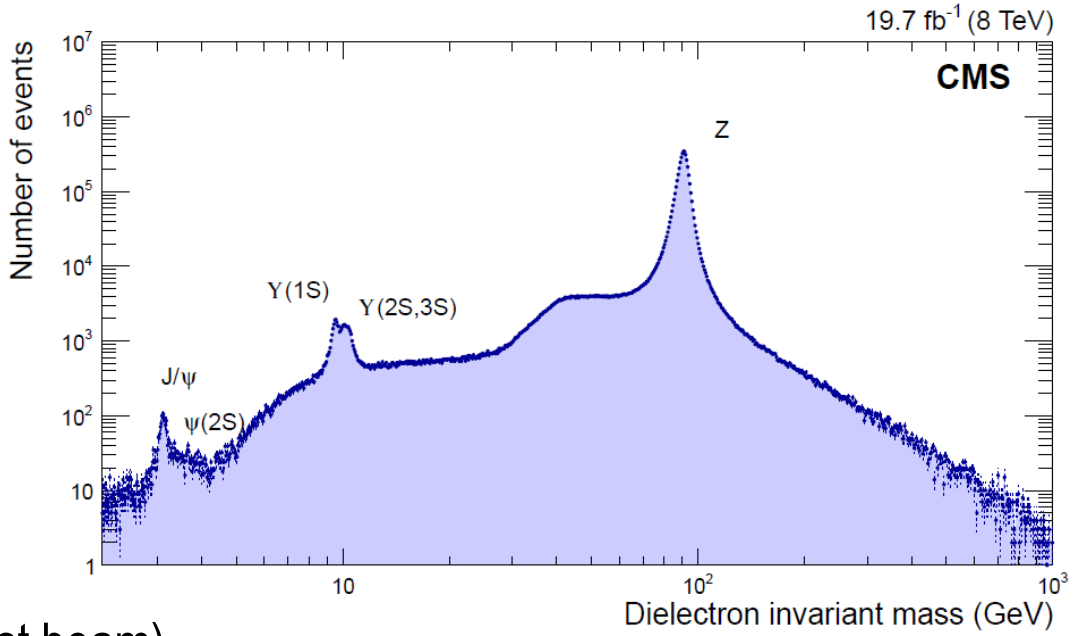
Combined performance measured in-situ

$\pi^0 \rightarrow \gamma\gamma$



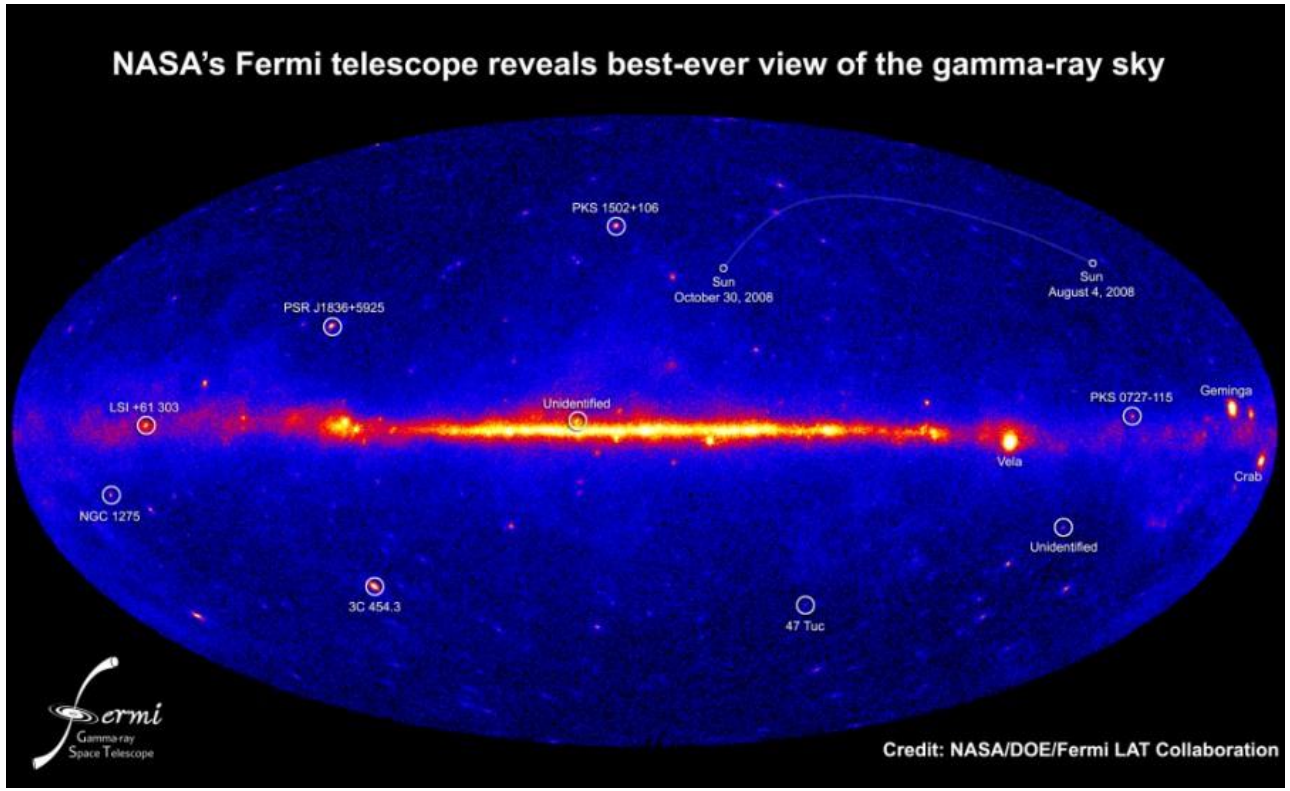
$Z \rightarrow ee$





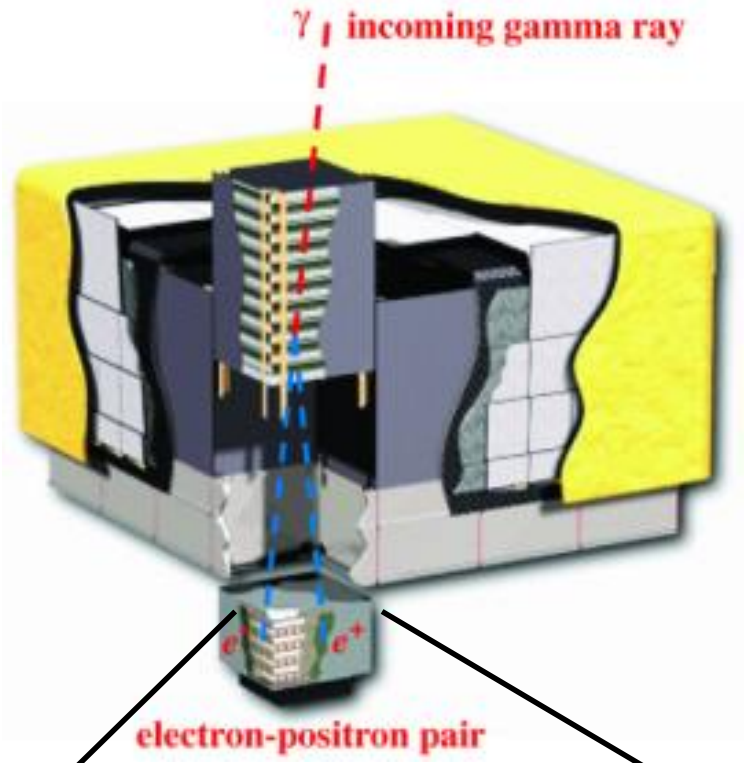
Calorimeters in space: FERMI/LAT

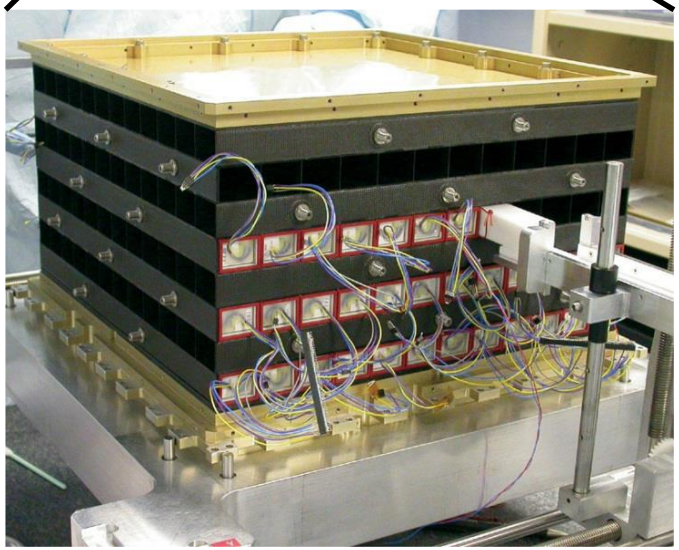
- **Fermi Satellite with Large Area Telescope (LAT) instrument.**
- **Gamma-Ray Telescope**
  - (200 MeV < γ < 300 GeV)
- Launched June 11 2008
- Consists of:
  - Tracker: Pb foils + Si strips
  - Calorimeter (**see next slide**)
  - Anticoincidence Detector : plastic scintillator tiles



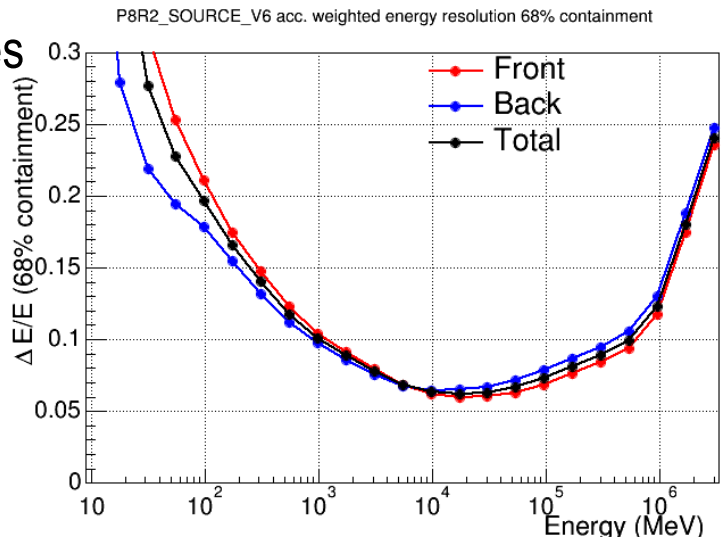
Calorimeters in space: FERMI ECAL

Homogenous calorimeter made from 1728 CsI(Tl) scintillating crystals





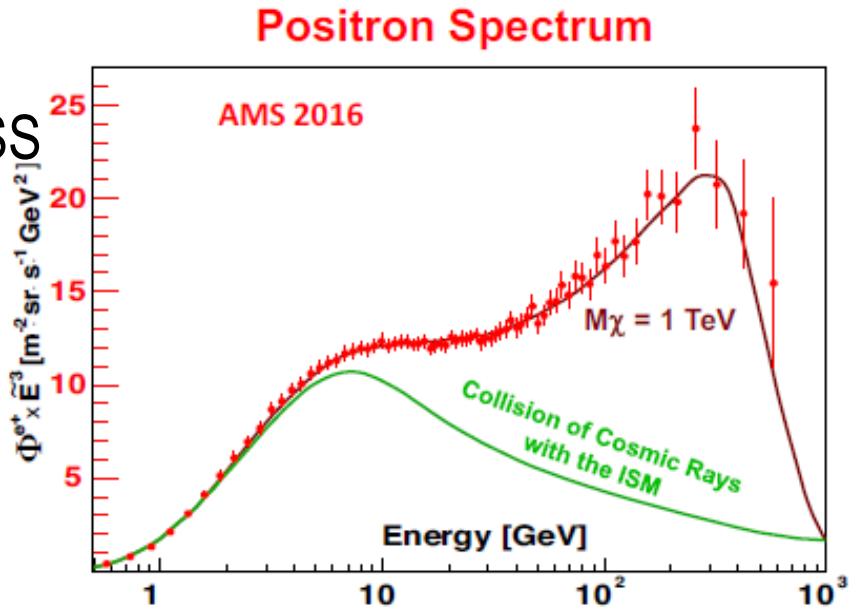
- 18 modules (400mmx400mmx250mm) ~100 kg each
- 1 module:
  - carbon-fiber alveolar structure +
  - **96 CsI(Tl) crystals (2.7 cm x 2.0 cm x 32.6 cm)**
  - arranged in 8 layers of 12 crystals each
- Each module aligned 90° wrt its neighbors, forming x,y (hodoscopic) array
- **Depth**: 8.6 X_0 (10.1 including tracker)
  ⇒ **Need shower leakage correction**
- Light read by 2 photo-diodes

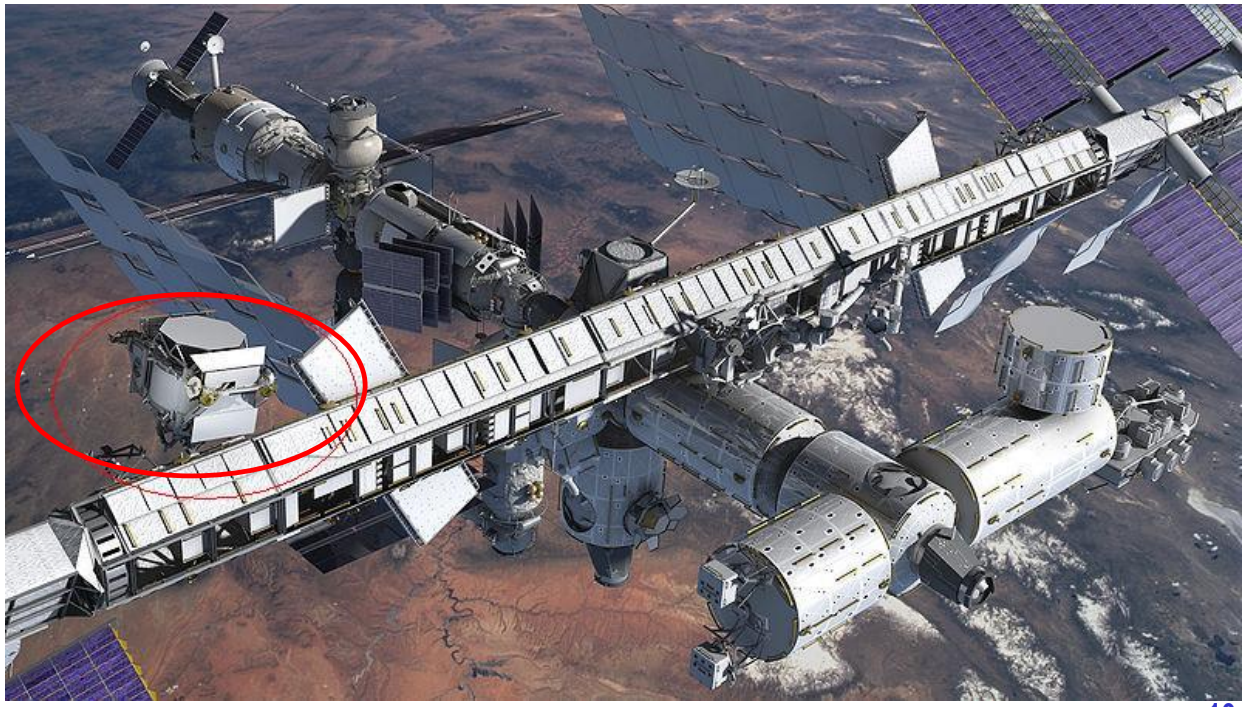


Calorimeters in space: AMS-02

- **Alpha Magnetic Spectrometer (AMS):**
  - HEP-like detector operating as external module on ISS
  - Launched in 2011

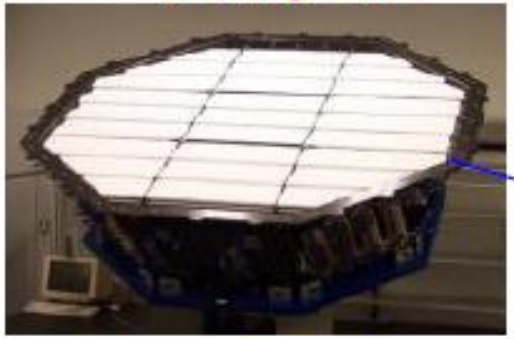
- Search for Dark Matter, anti-matter, precise study of high energy cosmic ray (flux, composition), gamma rays.



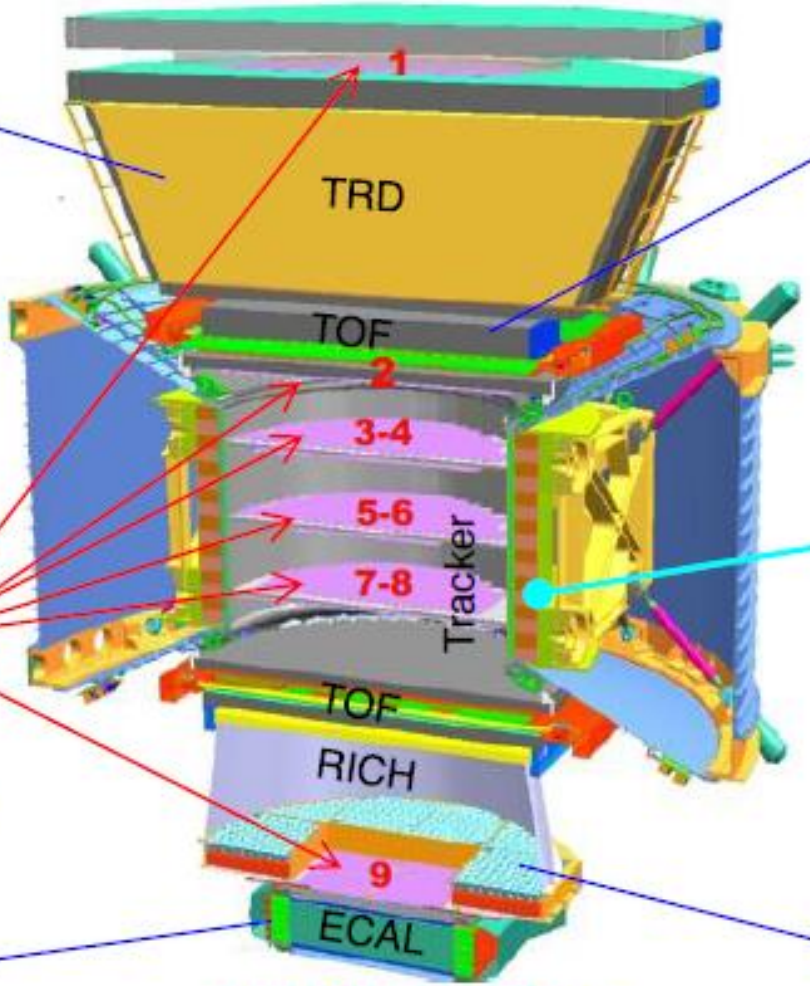


AMS: A TeV precision, multipurpose, magnetic spectrometer

Transition Radiation Detector
(TRD)
Identify e^+, e^-

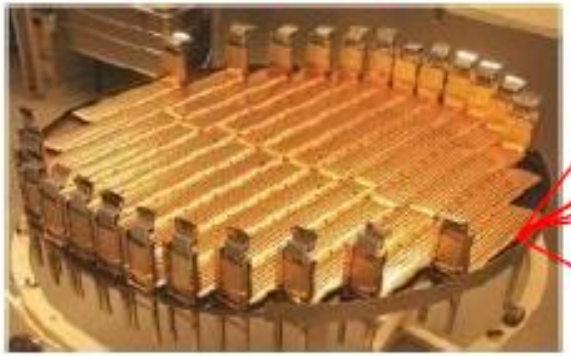


Time of Flight
(TOF)
Z, E



Magnet
±Z

Silicon Tracker
Z, P or R=P/Z



Ring Imaging Cherenkov
(RICH)
Z, E

Electromagnetic Calorimeter
(ECAL)
E of e^+, e^-

Z and P, E or R are

measured independently by Tracker,

ECAL, TOF and RICH

The AMS-02 ECAL

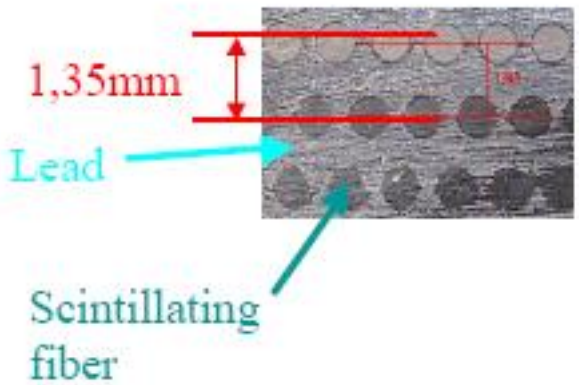
Sampling calorimeter made from Lead + Scintillating fibers

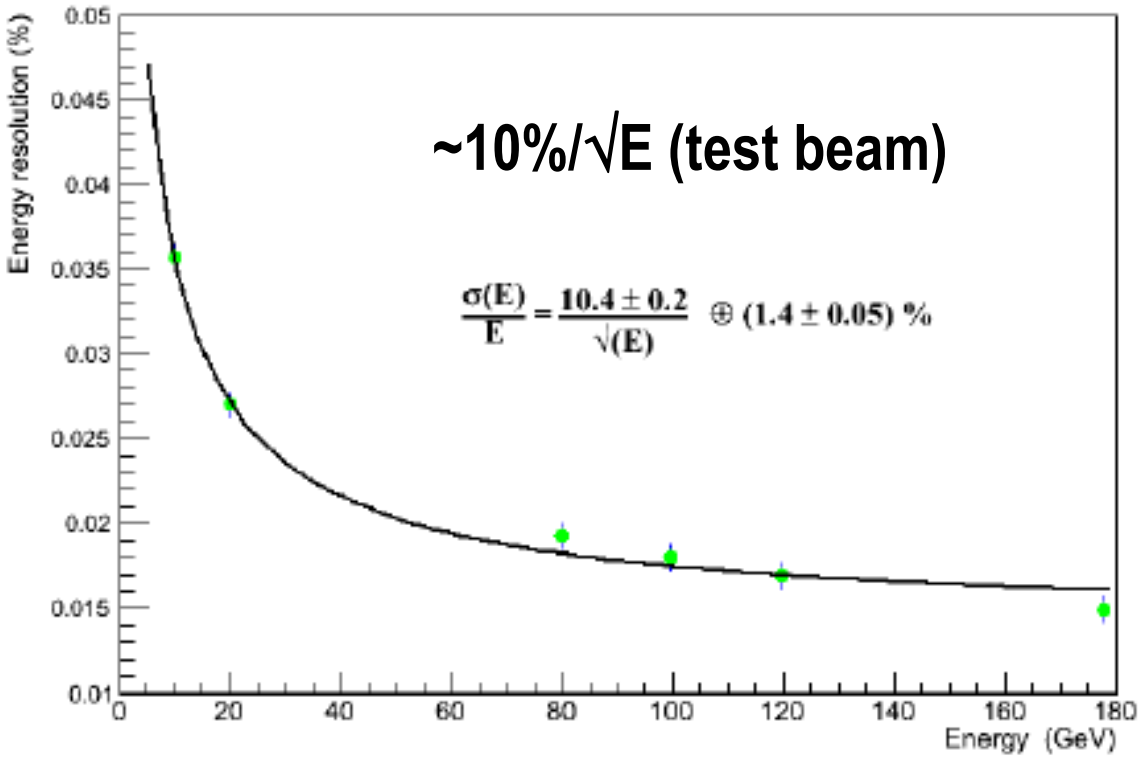
- **3-D imaging of shower development**
  - 9 Super-Layers (SL) alternatively oriented along X and Y axis (5 SL along X, 4 long Y)

- 1 Super-Layer (~18.5mm):
  - 11 grooved, Pb foils (1mm thick) interleaved with 10 layers of scintillating fibers (Ø~1mm) glued by epoxy-resin

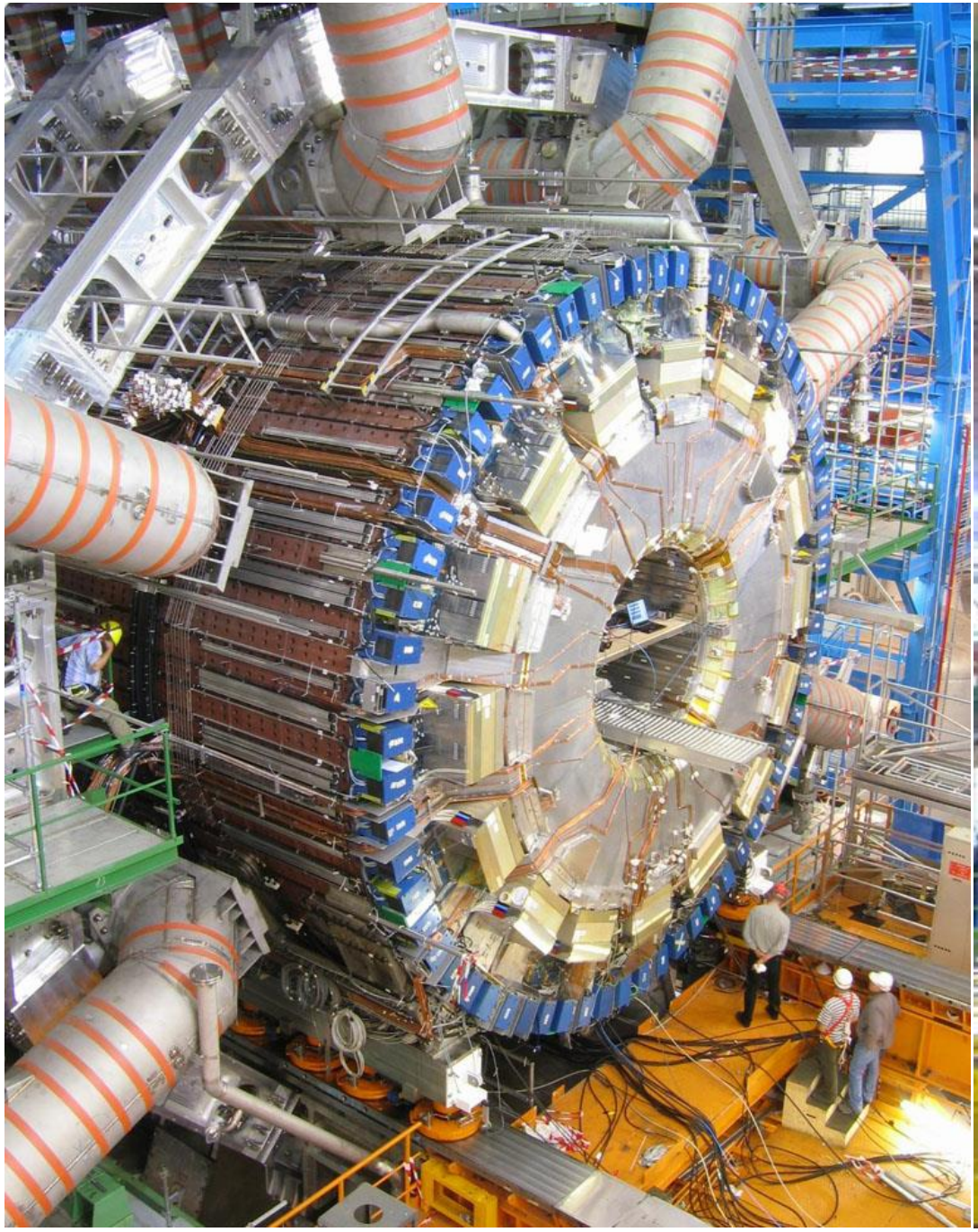
- **Depth:** ~17 X0
- Fibers read by PMT

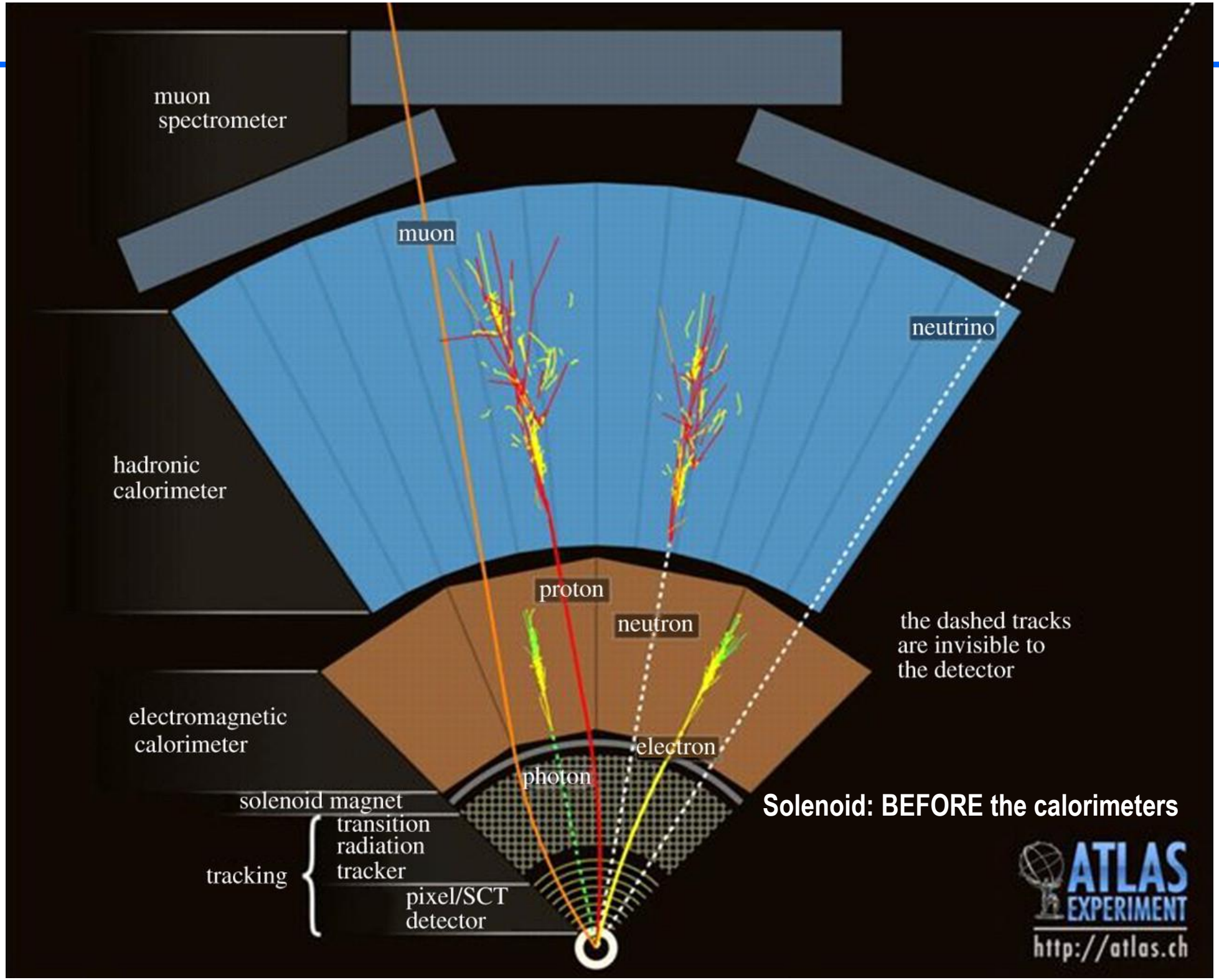
ECAL support structure





ATLAS & CMS calorimeters




muon
spectrometer
muon
neutrino
hadronic
calorimeter
proton
neutron
the dashed tracks
are invisible to
the detector
electromagnetic
calorimeter
electron
photon
solenoid magnet
transition
radiation
tracker
tracking
pixel/SCT
detector
Solenoid: BEFORE the calorimeters
ATLAS
EXPERIMENT
http://atlas.ch

The ATLAS ECAL

Sampling Pb/LAr calorimeter with innovative "accordion" geometry

- Longitudinal dimension ~25 X0, 47 cm (vs 22 cm for CMS)

  3 layers up to $|\eta|=2.5$ + presampler $|\eta|<1.8$

  2 layers $2.5<|\eta|<3.2$

  Layer 1 (γ/π^0 rej. + angular meas.)

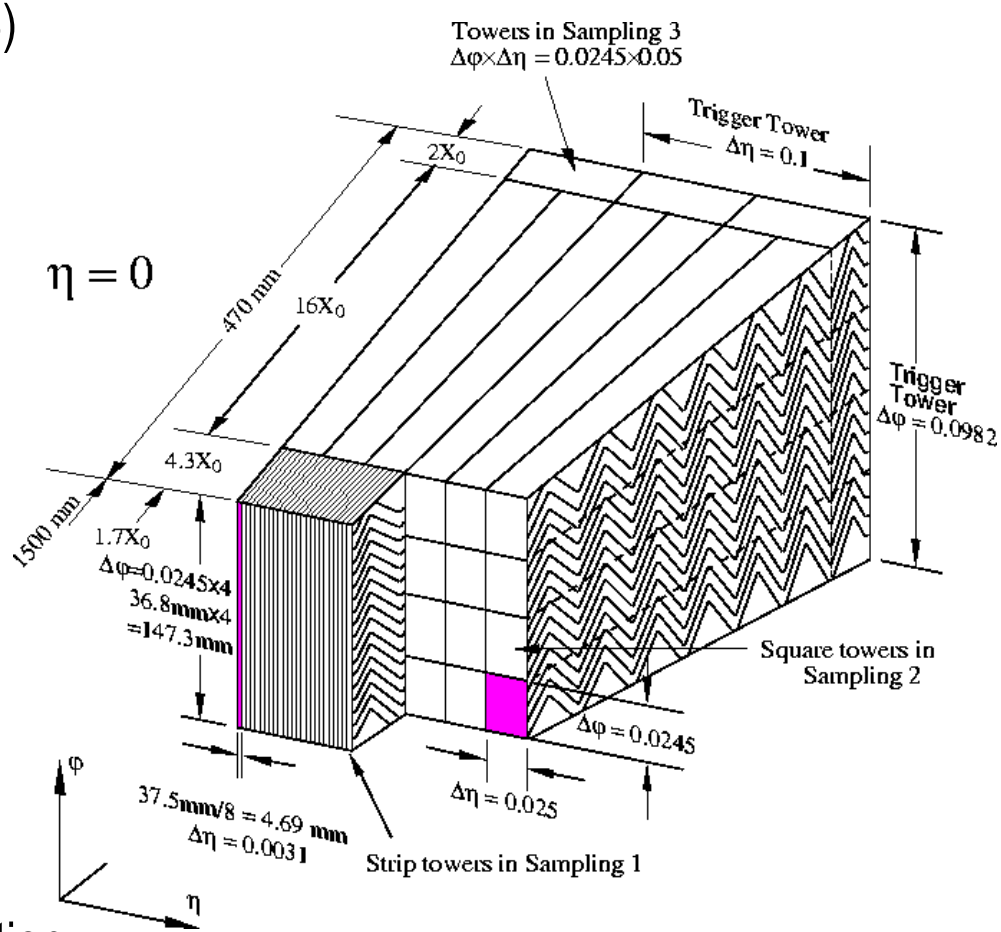
  $\Delta\eta.\Delta\varphi = 0.003 \times 0.1$

  Layer 2 (shower max)

  $\Delta\eta.\Delta\varphi = 0.025 \times 0.0.25$

  Layer 3 (Hadronic leakage)

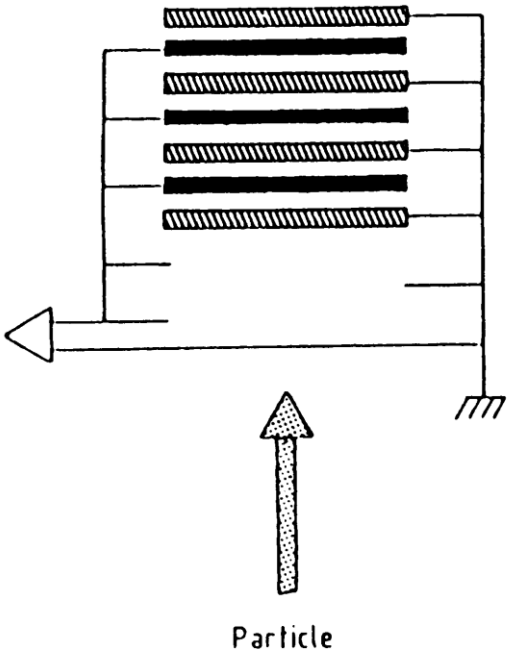
  $\Delta\eta.\Delta\varphi = 0.05 \times 0.0.025$



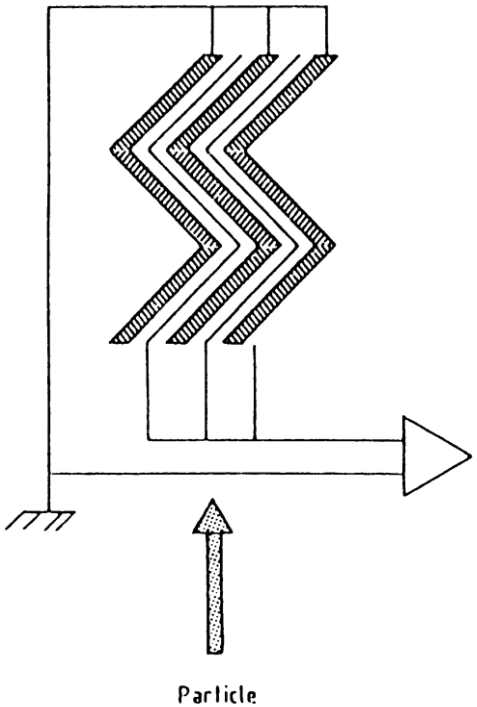
- ~170 000 channels
- **Usage of Liquid Argon**
  - Radiation Hard
  - High number of electron-ion pair produced by ionization (1 GeV deposit -> 5.10^6 e-)
  - Stable vs time
  - **BUT:**
    - Need a cryostat (90K)
    - Slow time response (400 ns vs 25 ns LHC bunch crossing)

ATLAS ECAL: accordion geometry (1)

Standard Liquid Argon



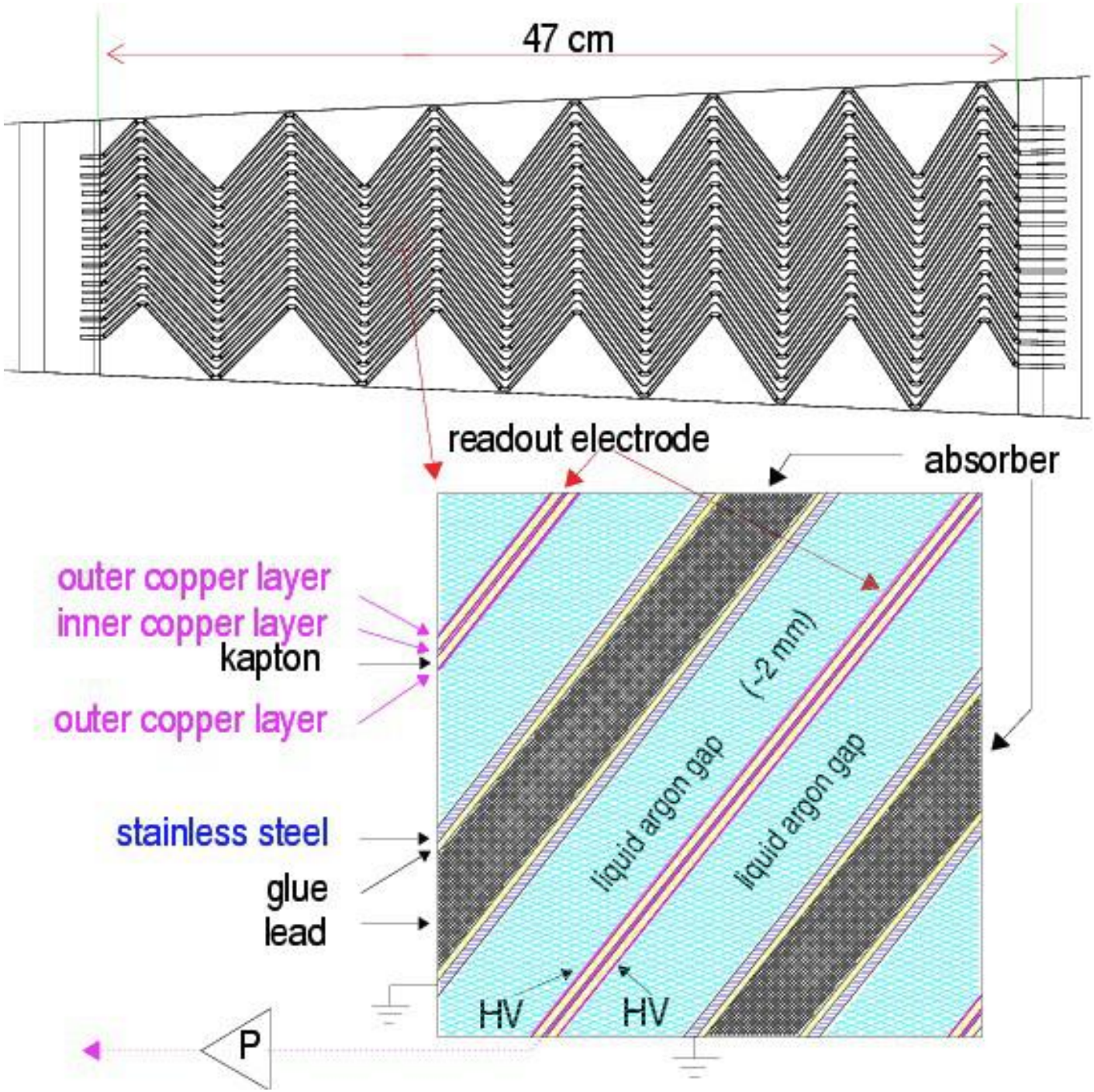
Accordion Liquid Argon

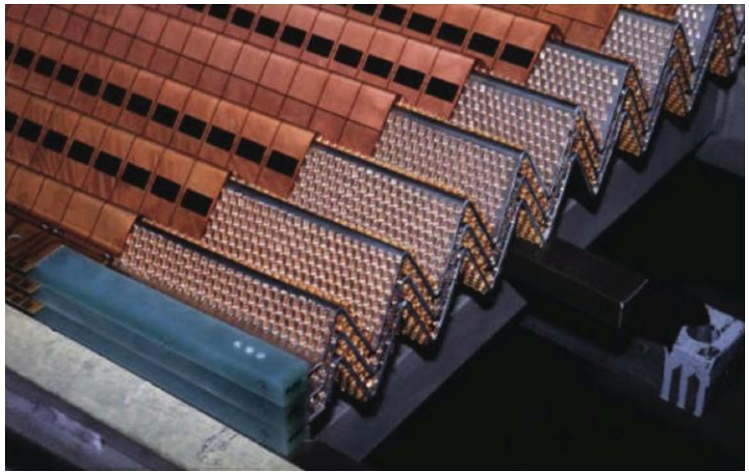


- Slow response (long integration time)
- Electrodes ⊥ particles
- Long cables
  - To bring signal to pre-amplifiers
  - Regroup gaps
- Dead zones due to cables

- Accordion geometry: **fast**
- Electrodes // to incident particles
  - Signal read out forward & backward
  - No long connection
- **No cracks (in azimuth)**

ATLAS ECAL: accordion geometry (2)

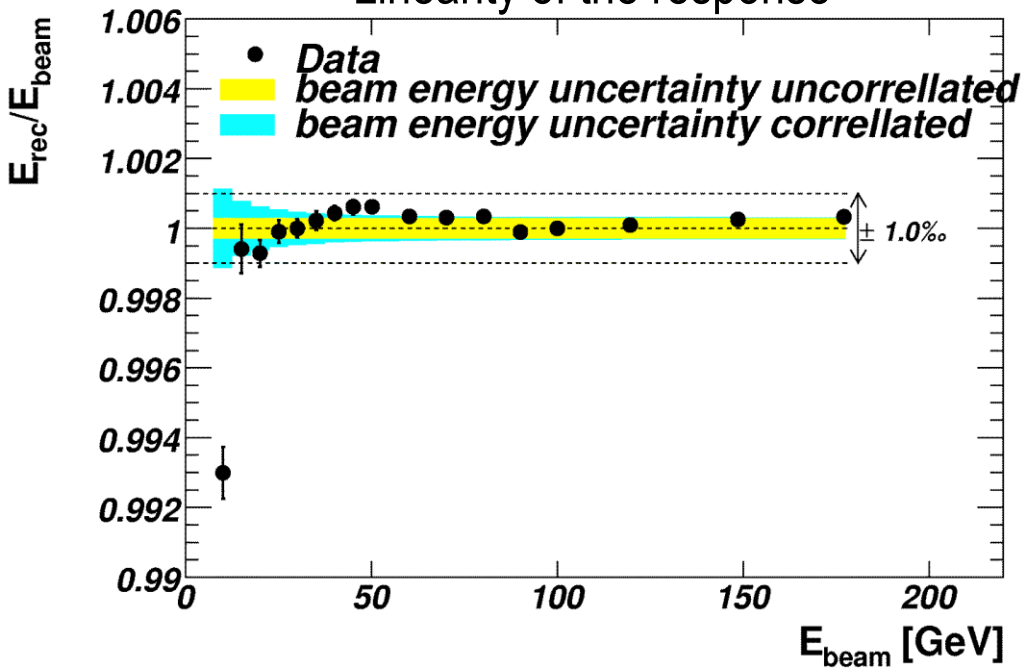




ATLAS ECAL: Performance

Stand-alone performance assessed during extensive test Beam campaigns at CERN...

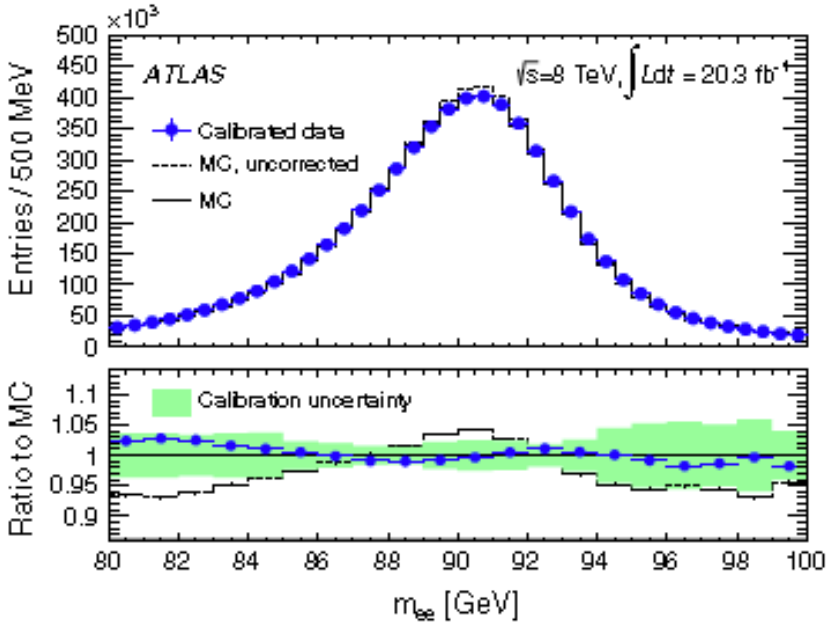
Linearity of the response

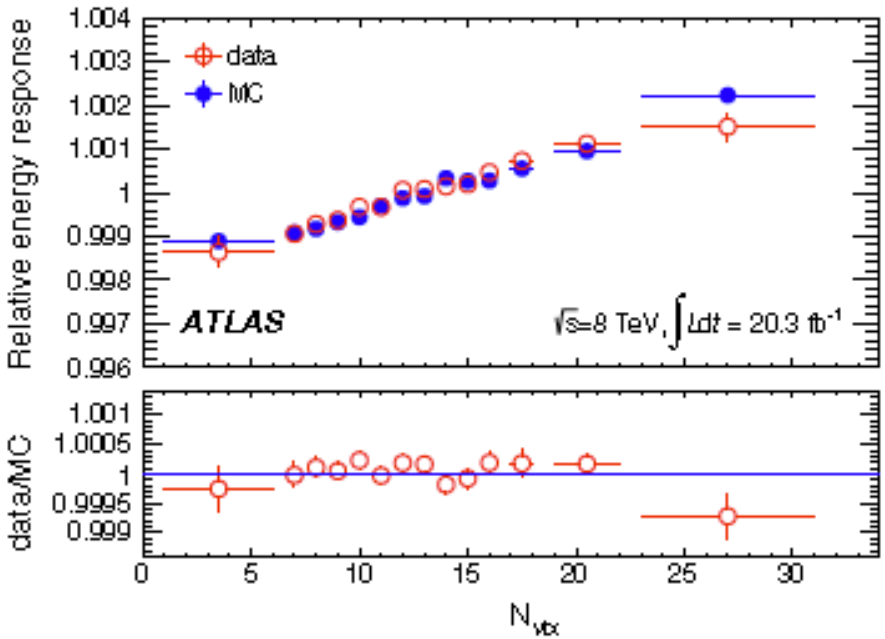


$$\frac{\sigma}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.3}{E} \oplus 0.7\%$$

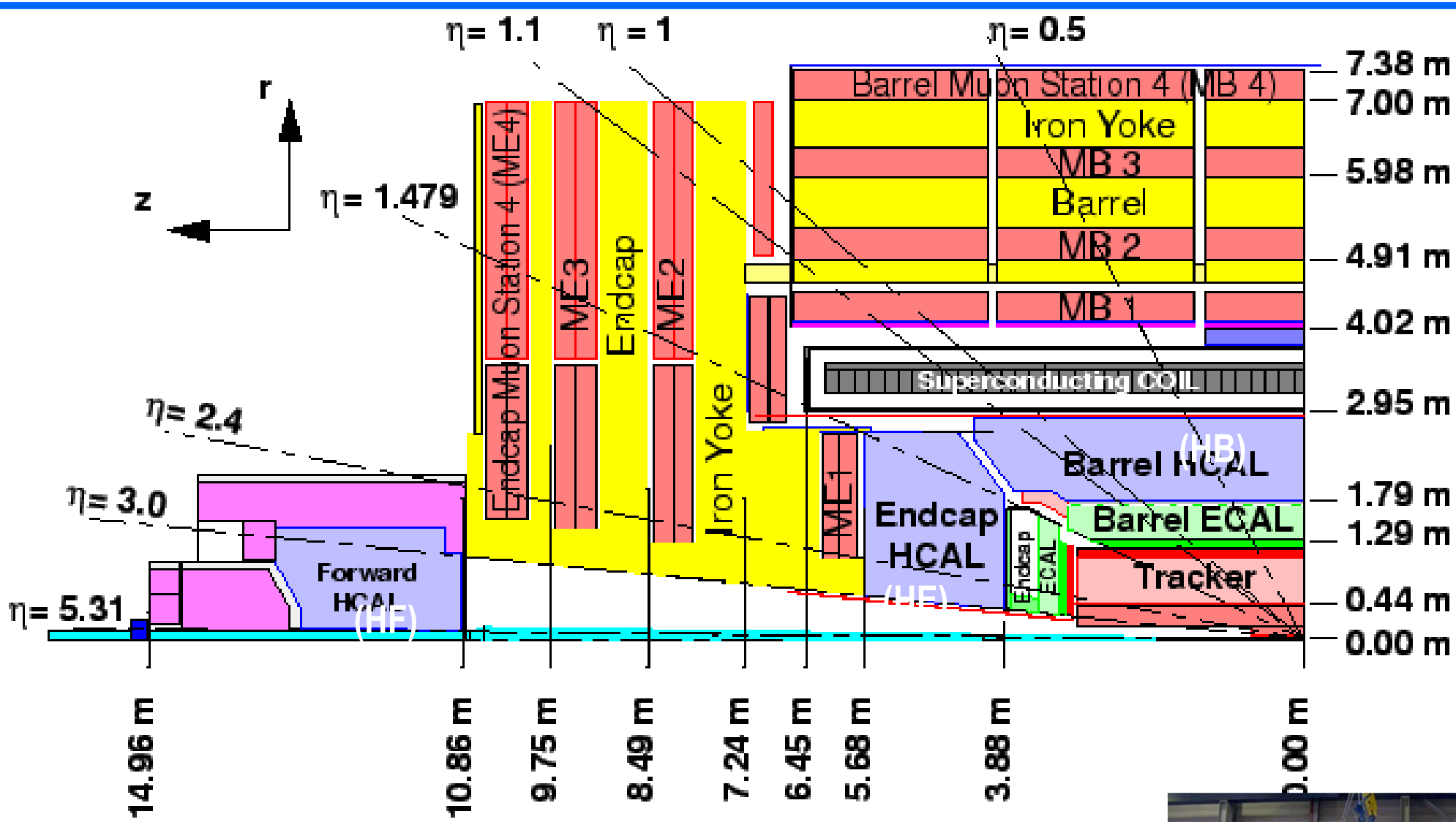
(test beam)

Combined performance measured in-situ





CMS HCAL



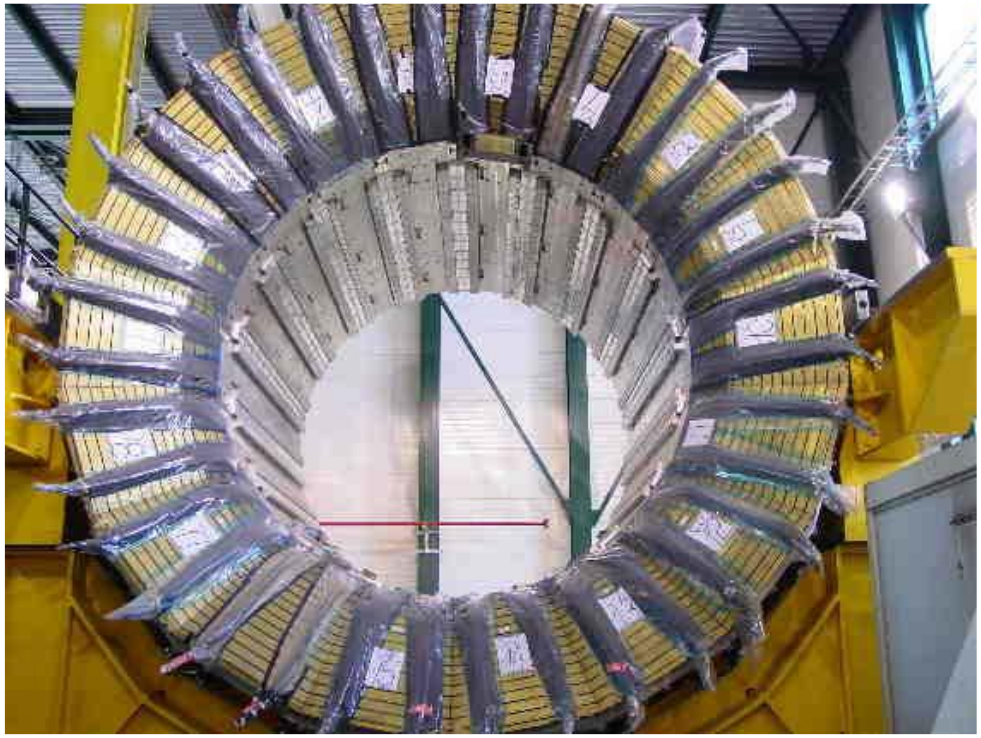
- HCAL Barrel (HB): $|\eta|<1.3$
- HCAL Endcap (HE): $1.3<|\eta|<3$
- Forward HCAL (HF): $3<|\eta|<5$, Fe+Quartz Fiber

See next

CMS HCAL

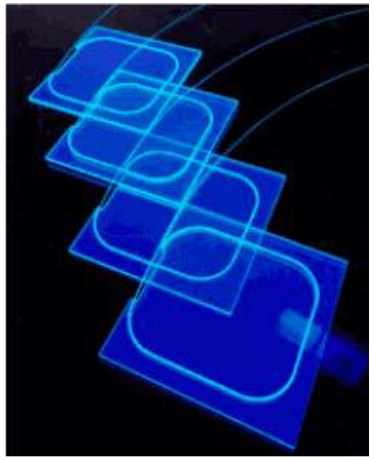
HB/HE: Sampling Brass/plastic scintillator calorimeter

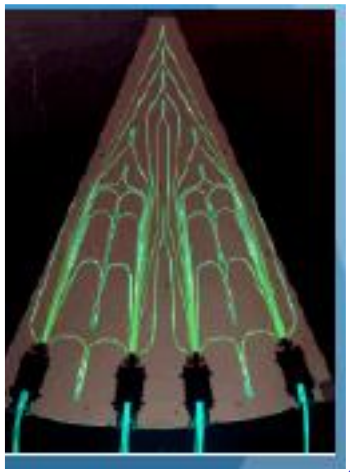
HB (17 longitudinal layers)



HE (19 longitudinal layers)

- Segmentation: $\Delta\eta x \Delta\phi$=0.087x0.087 (larger at high η)
- 18x20° "wedges" with alternate brass plates (5-8 cm) and "tiles" embedded with Wave Length Shifter (WLS).
  - Light from scintillator: blue-violet
  - WLS: absorb light then fluorescence in green
  - Green light read by Hybrid Photo Diode (HPD)





CMS HCAL: Brass absorber preparation

Workers in Murmansk sitting on brass casings of **decommissioned shells of the Russian Northern Fleet**

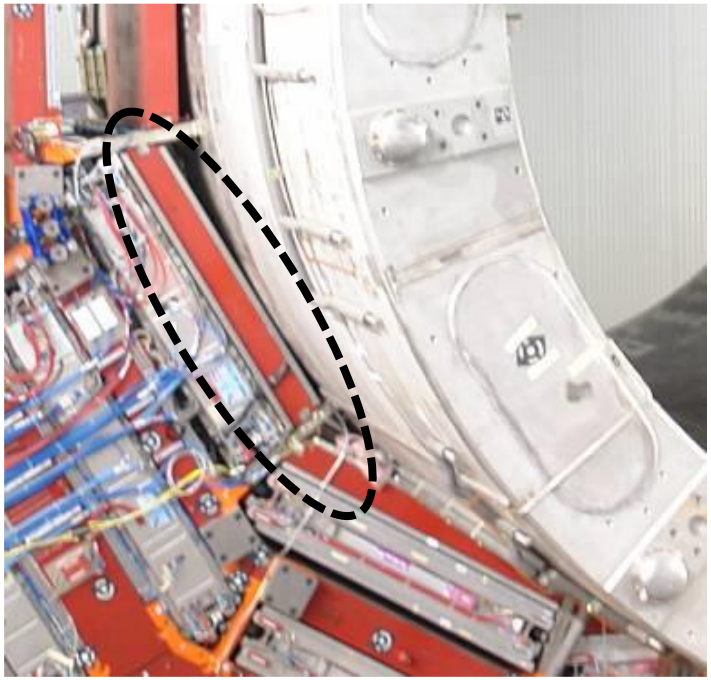
Explosives previously removed!

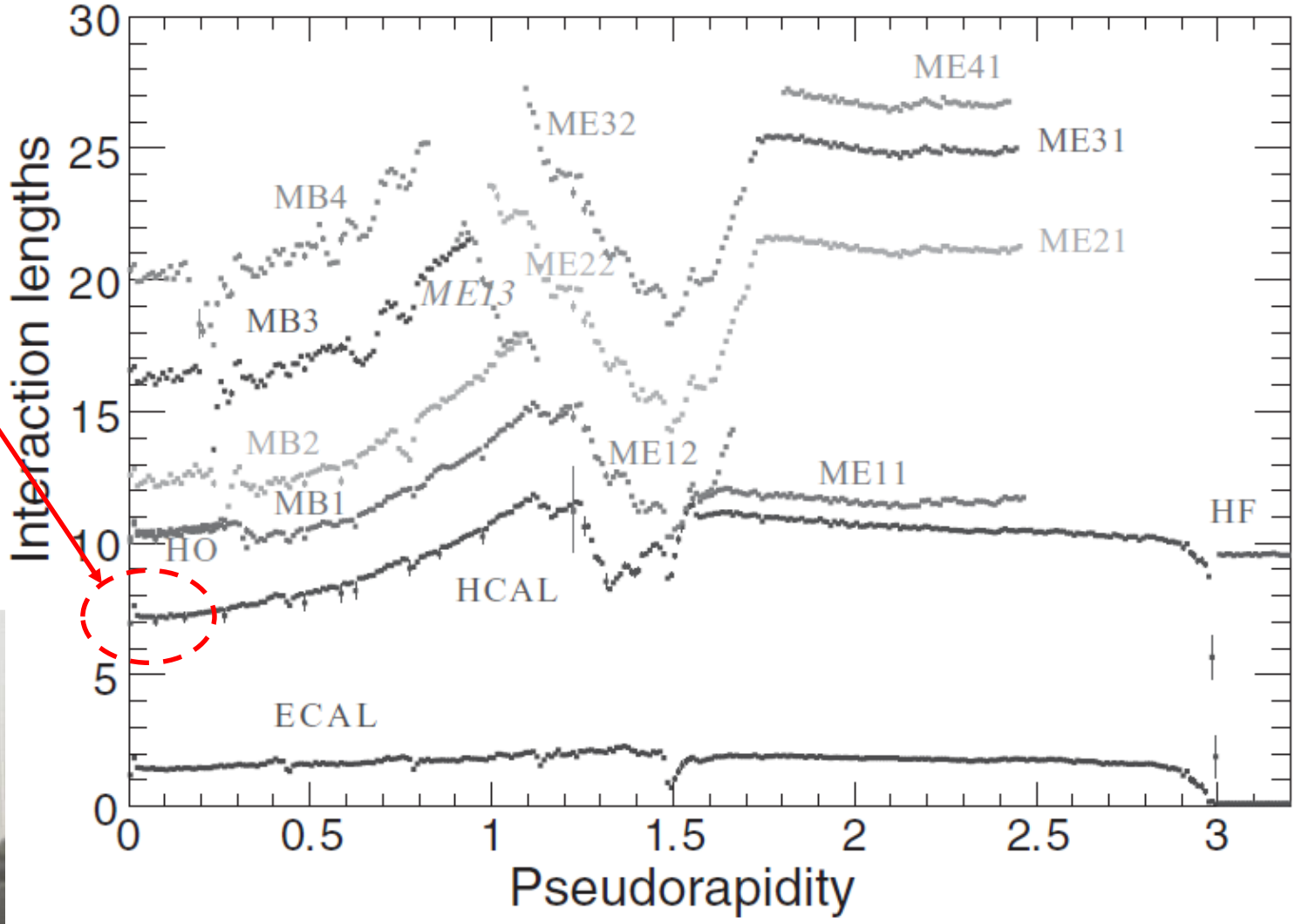
Casings melted in St Petersburg and turned into raw brass plates

Machined in Minsk and mounted to become absorber plates for the CMS Endcap Hadron Calorimeter

CMS HCAL: Containment

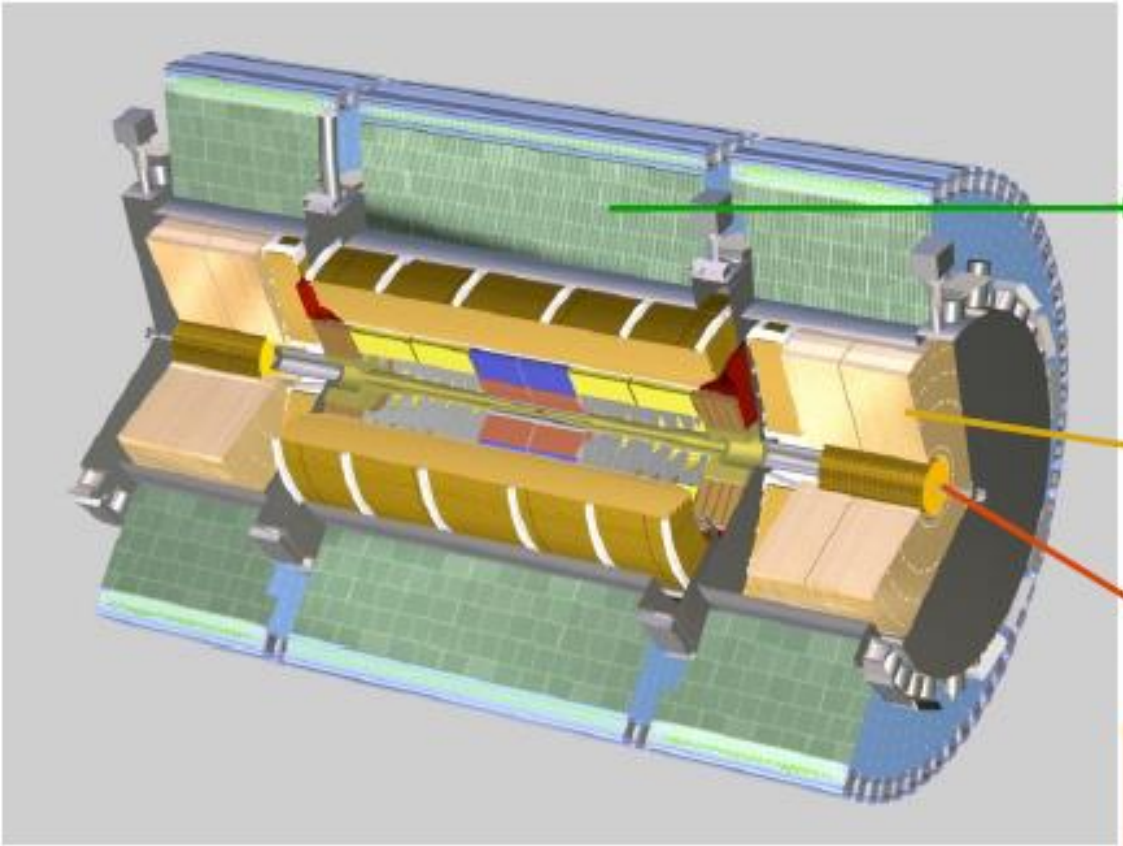
- At $|\eta|=0$, λ_{int} from HB =5.8 ! (7.2 with ECAL)
  - Large leakage…
- CMS adds HCAL Outer (HO):
  - Scintillator + WLS outside coil acting as "tail catcher".





Poor Resolution: ~100% / √E

ATLAS HCAL



Tiles Calorimeter $|\eta| < 1.7$

Fe / Scintillator

3 layers in depth

LAr/Cu $1.7 < |\eta| < 3.2$

4 layers in depth

Forward: 1 layer EM, 2 HAD

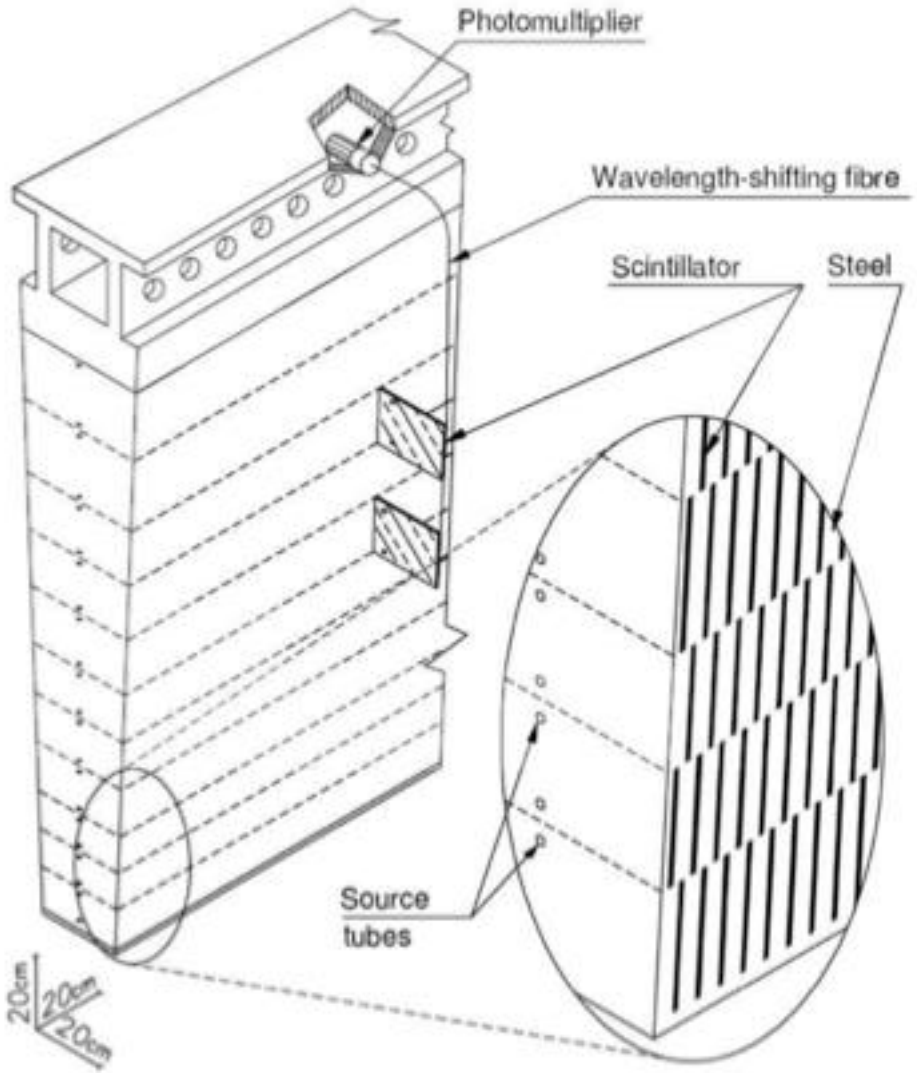
LAr/Cu or W $3.2 < |\eta| < 4.9$

Total thickness: ~ 8 -10 λ

Use of different technics: cope with radiations in forward region

ATLAS TileCal

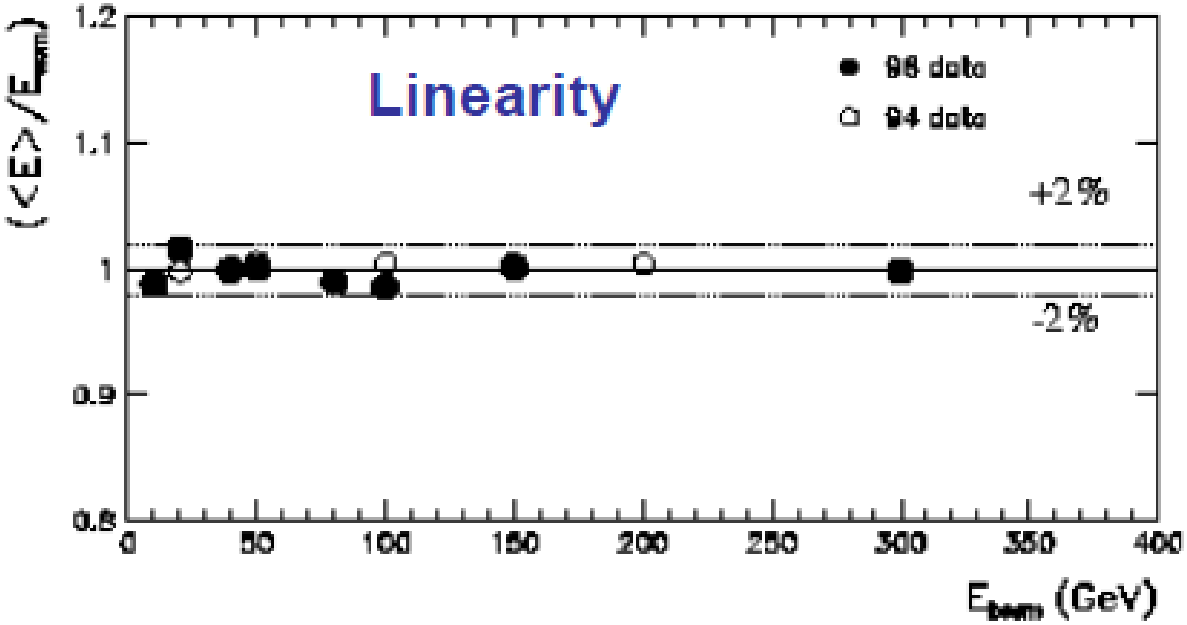
TileCal: Sampling Fe/plastic scintillator calorimeter

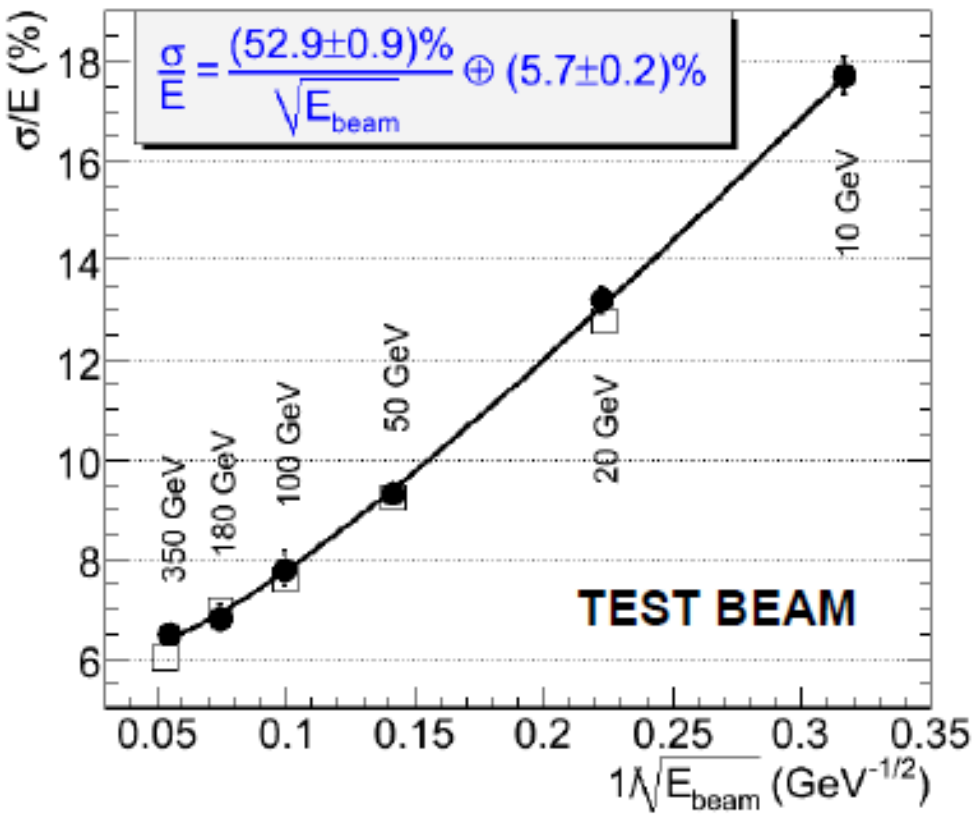


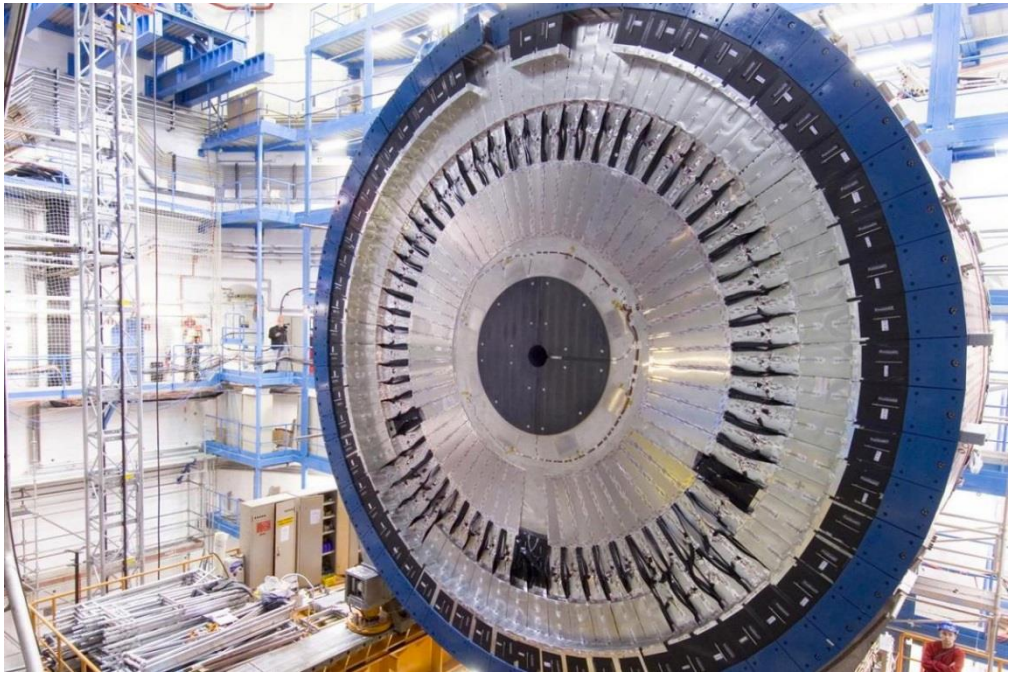
- Coverage: $|\eta|<1.7$
- 3 cylinders (1 barrel, 2 extended barrel)
- 3 longitudinal sampling
- Segmentation: $\Delta\eta x \Delta\phi$=0.1 (0.2) x0.1
- ~10 000 channels

- Key element: Tile
  - Perpendicular to beam axis
  - WLS carry light to PMT

ATLAS TileCal: Performance







Resolution: ~50% / √E

ATLAS/CMS ECAL Resolution

TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025×0.1	0.025×0.1		
Strips/ Si-preshower	0.003×0.1	0.003×0.1 to 0.006×0.1		32×32 Si-strips per 4 crystals
Main sampling	0.025×0.025	0.025×0.025	0.017×0.017	0.018×0.003 to 0.088×0.015
Back	0.05×0.025	0.05×0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2×2 mm		
Strips/ Si-preshower	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Main sampling	$\approx 16\ X_0$	$\approx 20\ X_0$	$26\ X_0$	$25\ X_0$
Back	$\approx 2\ X_0$	$\approx 2\ X_0$		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term a	10%	10 to 12%	3%	5.5%
Local constant term b	0.2%	0.35%	0.5%	0.5%

Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of $29 \times 29\ mm^2$. The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS EM barrel and end-cap calorimeters and for the CMS barrel crystals, the numbers quoted are based on stand-alone test-beam measurements.

ATLAS/CMS HCAL Resolution

TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS				CMS	
	Barrel LAr/Tile		End-cap LAr			
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

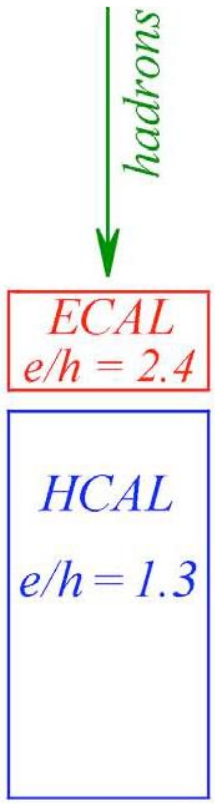
The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

How can CMS can compete with ATLAS on the jet physics given these numbers ?
=> **Particle Flow** (**see next lecture**)

Last note on ATLAS / CMS Calorimeters

ATLAS and CMS are NON-compensating calorimeters

- **Numbers** (*):
  - ATLAS Tile Barrel e/h ~ 1.4
  - CMS ECAL: e/h ~ 2.4
  - CMS HCAL: e/h ~ 1.3
  - CMS HF: e/h ~ 4.7



- Ex: CMS calibrates:
  - ECAL for electrons/photons
  - HCAL with pions non-interacting in ECAL
  - But pions DO interact with ECAL. And thus get wrong calibration.
  - Degrades the resolution.

Again, **Particle Flow technics will help there** (by separating charged and neutral pions). **See Lecture 3.**

(*) to be verified…