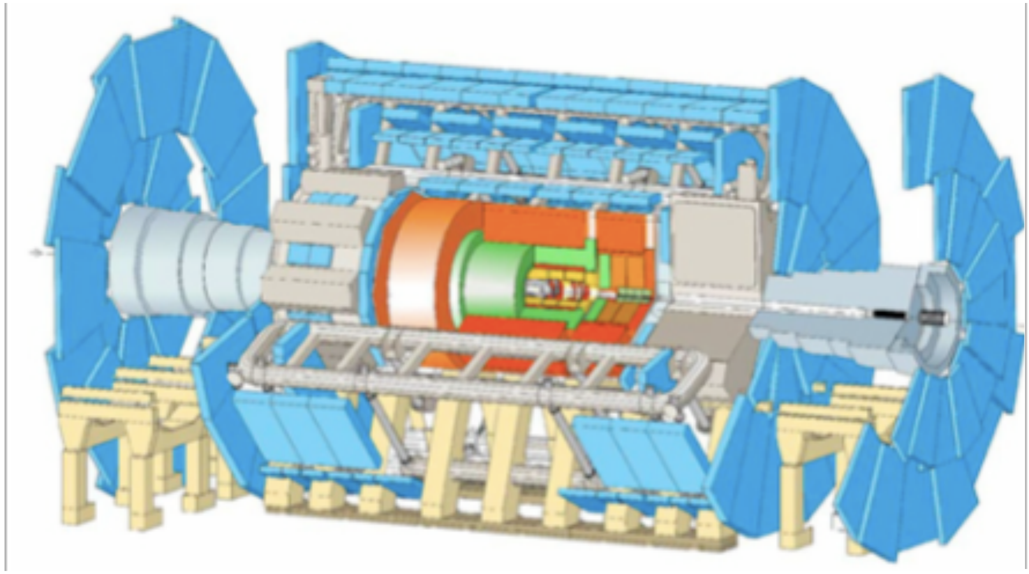
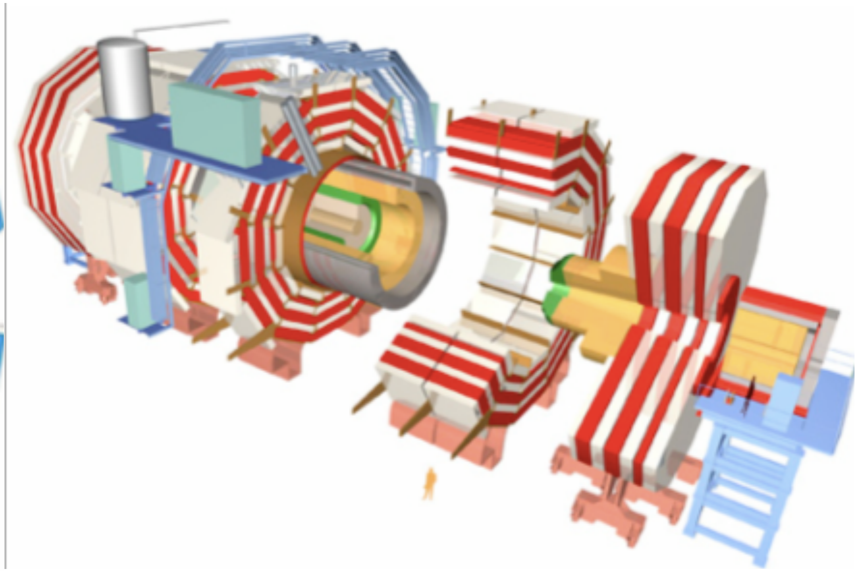
ATLAS and CMS: the LHC giants!

- Proton-proton collisions at the energy frontier $\sqrt{s}$ = 14 TeV with huge luminosity (L = 10^{34} $cm^{-2}s^{-1}$ ➔ μ = 25 evts / bunch crossing): $\mu = L\, \sigma_{tot} / f n_b = 10^{34} \times 100\ \text{mb} \times 25\ 10^{-9}$ s
- General purpose detector not devoted to a single measurement: detect all what you imagine can come out (with momenta from hundreds of MeV up to few TeV):
  - Leptons (electrons, muons)
  - Tau leptons (through their decays, either leptonic or hadronic)
  - Photons
  - Neutrinos (not directly but using the method of the "Missing Energy")
  - Quark/Gluons (not directly but through the so called "Jets")
- Need of data reduction at trigger level: most events are not interesting and you have to choose in a very short time: DAQ rate limited to O(1 kHz)
- Need to discriminate between simultaneous events (pile-up)

The Giants: ATLAS & CMS



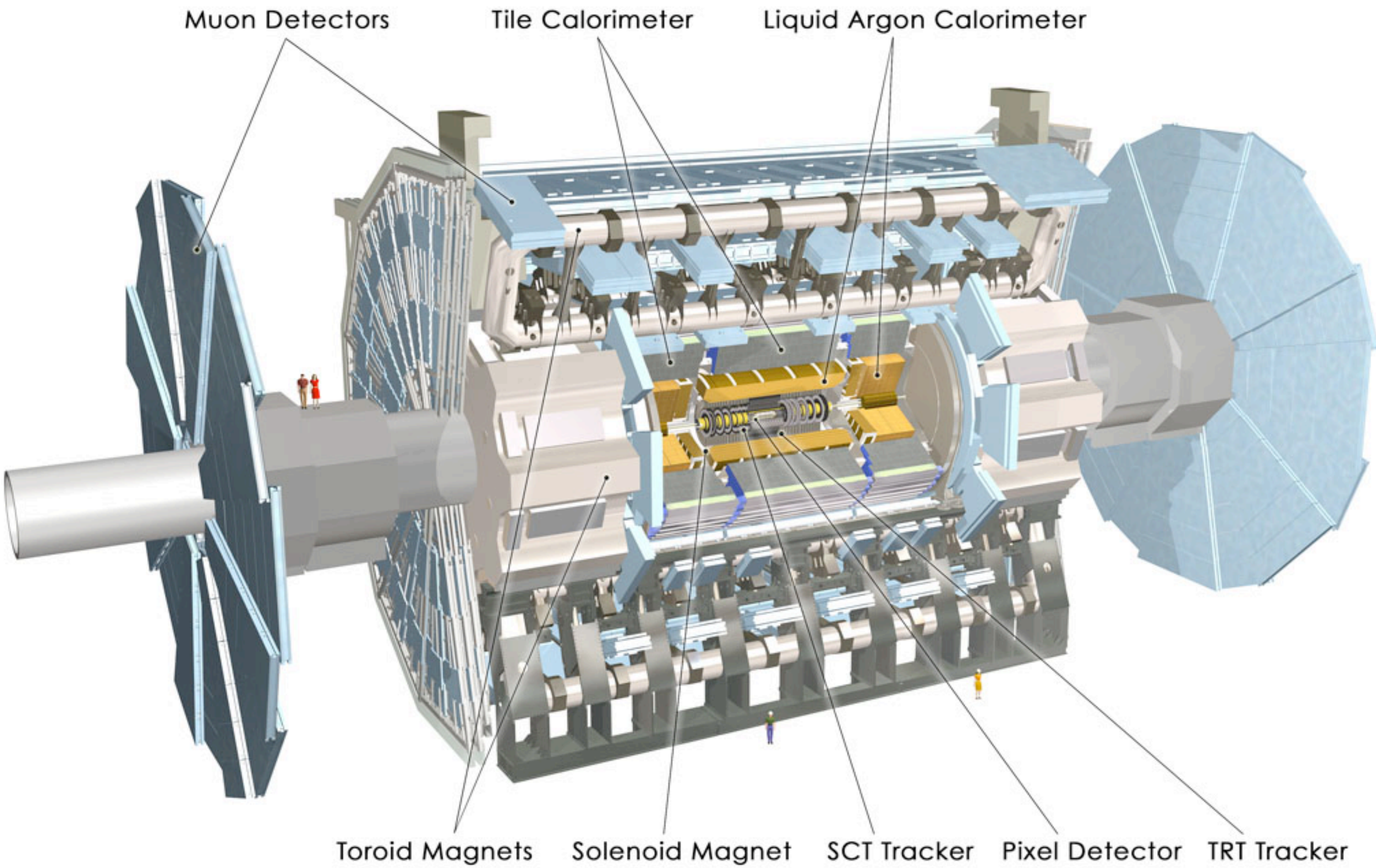
ATLAS (the largest): 46 x 25 m



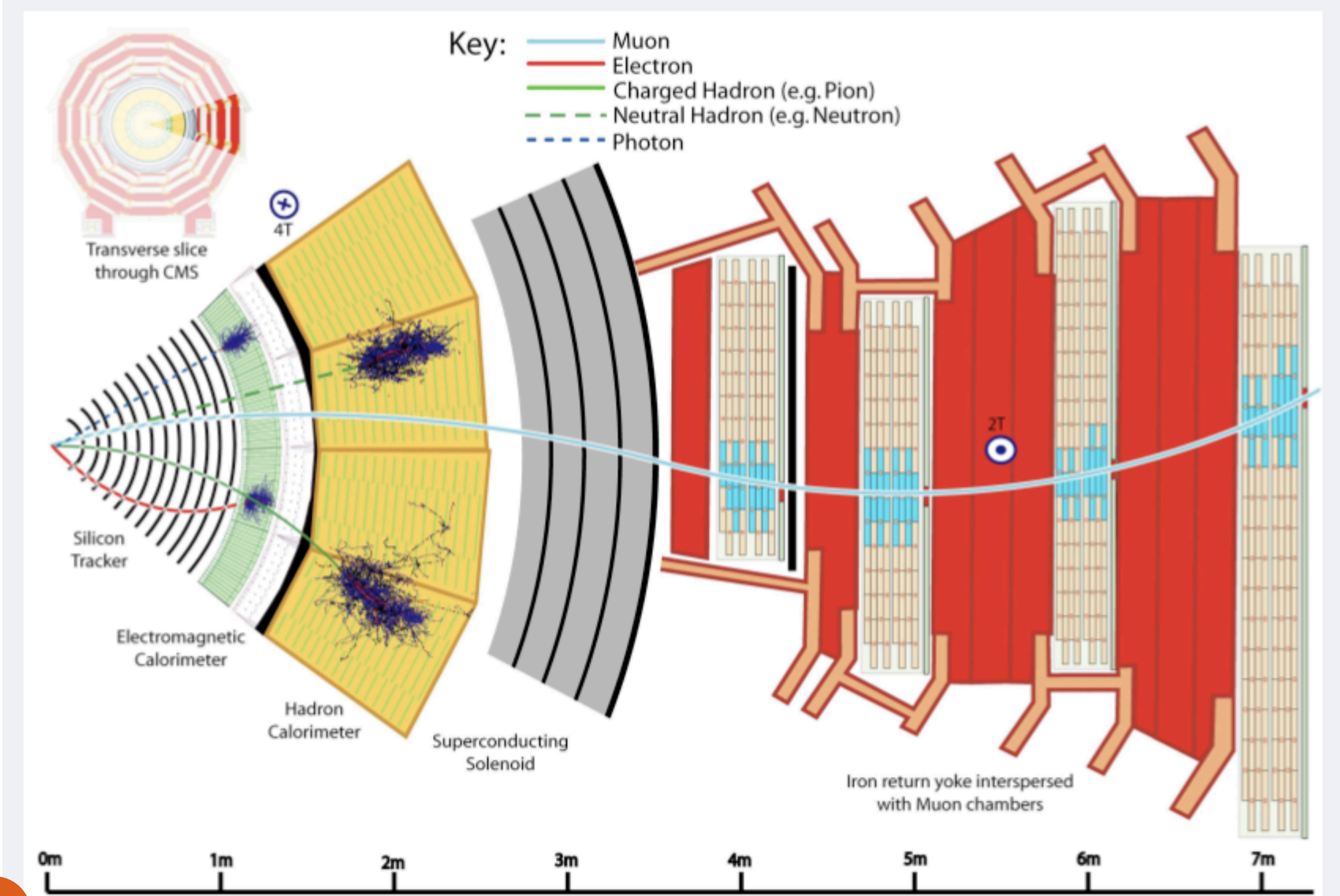
CMS (the heaviest): 12500 tonn

Common structure:	e	μ	Jet	γ	$\not{E}_T$
→ Magnetic Field system	✗	✗			
→ Inner Detector	✗	✗			
→ Electromagnetic Calorimeter	✗		✗	✗	✗
→ Hadronic Calorimeter			✗		✗
→ Muon Spectrometer		✗			

ATLAS


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

Example: overall structure of the CMS detector



Subdetectors

- Inner Tracker: high space resolution, high resistance to radiation, very high granularity
  - semi-conductor detectors (pixels, silicon strips);
  - gas detectors (ATLAS only) provide electron-hadron separation
- EM calorimetry: good energy resolution, photon identification, high granularity for isolation
- Hadron calorimeter: high eta coverage (for missing mass measurement), moderate granularity to recognize jets
- Muon spectrometer: tagging of muons and standalone trigger. Good momentum resolution (ATLAS only)

ATLAS-CMS: general

TABLE 2 Main design parameters of the ATLAS and CMS detectors

Parameter	**ATLAS**	**CMS**
Total weight (tons)	7000	12,500
Overall diameter (m)	22	15
Overall length (m)	46	20
Magnetic field for tracking (T)	2	4
Solid angle for precision measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 5.0$	$2\pi \times 5.0$
Solid angle for energy measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 9.6$	$2\pi \times 9.6$
Total cost (million Swiss francs)	550	550

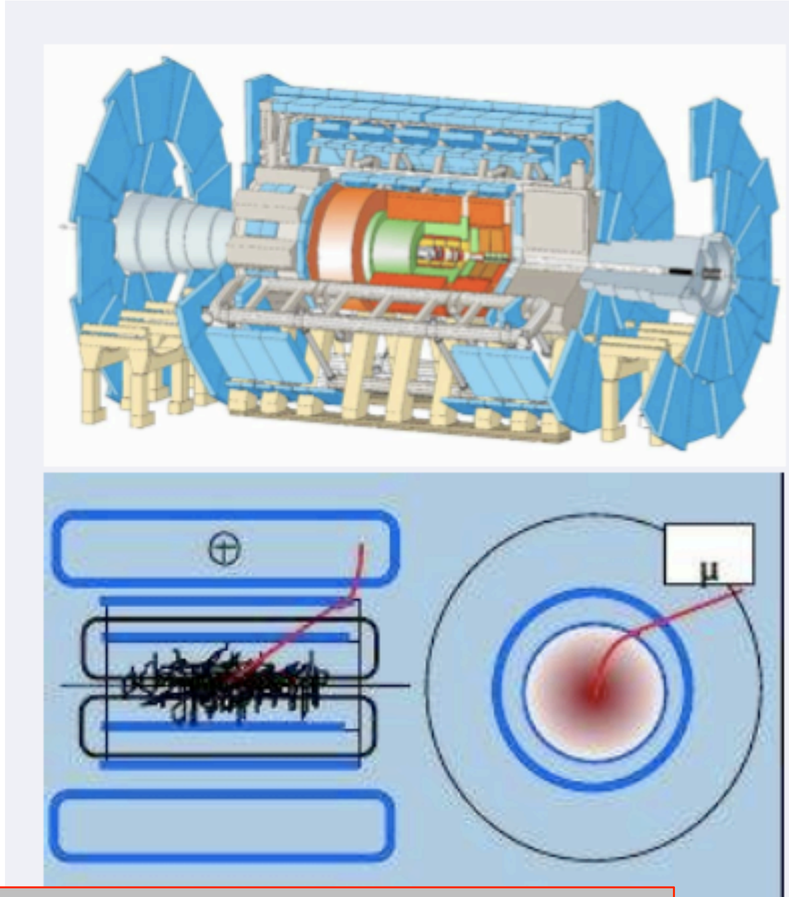
ATLAS-CMS: magnets

TABLE 3 Main parameters of the CMS and ATLAS magnet systems

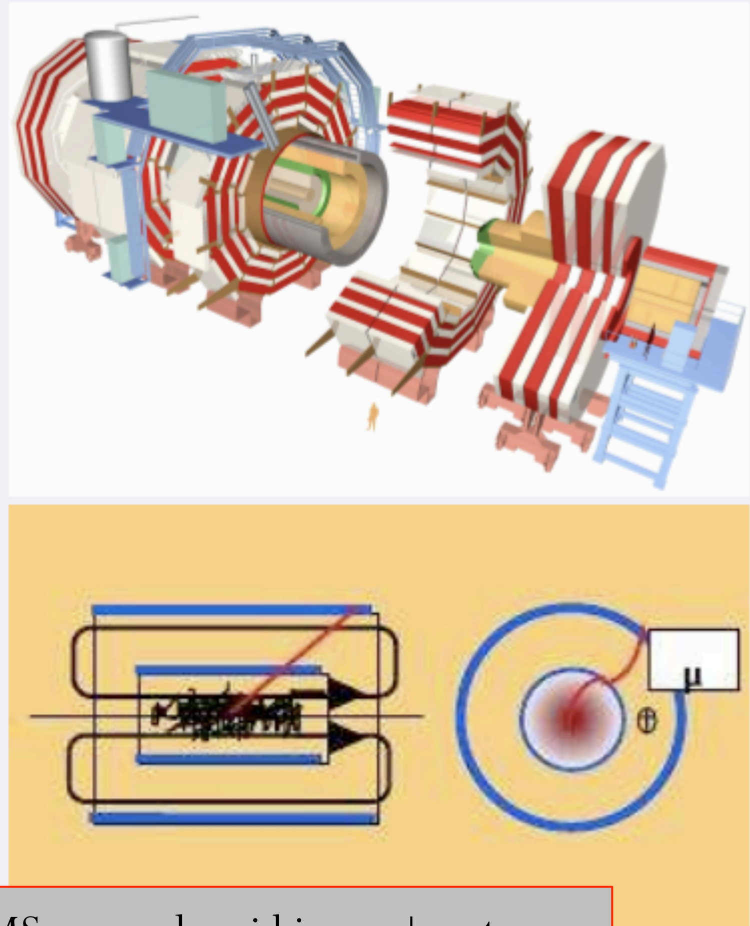
	CMS	ATLAS		
Parameter	**Solenoid**	**Solenoid**	**Barrel toroid**	**End-cap toroids**
Inner diameter	5.9 m	2.4 m	9.4 m	1.7 m
Outer diameter	6.5 m	2.6 m	20.1 m	10.7 m
Axial length	12.9 m	5.3 m	25.3 m	5.0 m
Number of coils	1	1	8	8
Number of turns per coil	2168	1173	120	116
Conductor size (mm^2)	64×22	30×4.25	57×12	41×12
Bending power	$4\ T \cdot m$	$2\ T \cdot m$	$3\ T \cdot m$	$6\ T \cdot m$
Current	19.5 kA	7.7 kA	20.5 kA	20.0 kA
Stored energy	2700 MJ	38 MJ	1080 MJ	206 MJ

How muons are detected at LHC

→ The calorimeters provide a “natural” muon filter;
→ The magnetic field system. ATLAS and CMS have different approaches



ATLAS: inner solenoid + outer toroids



CMS: one solenoid inner + outer (reversed direction)

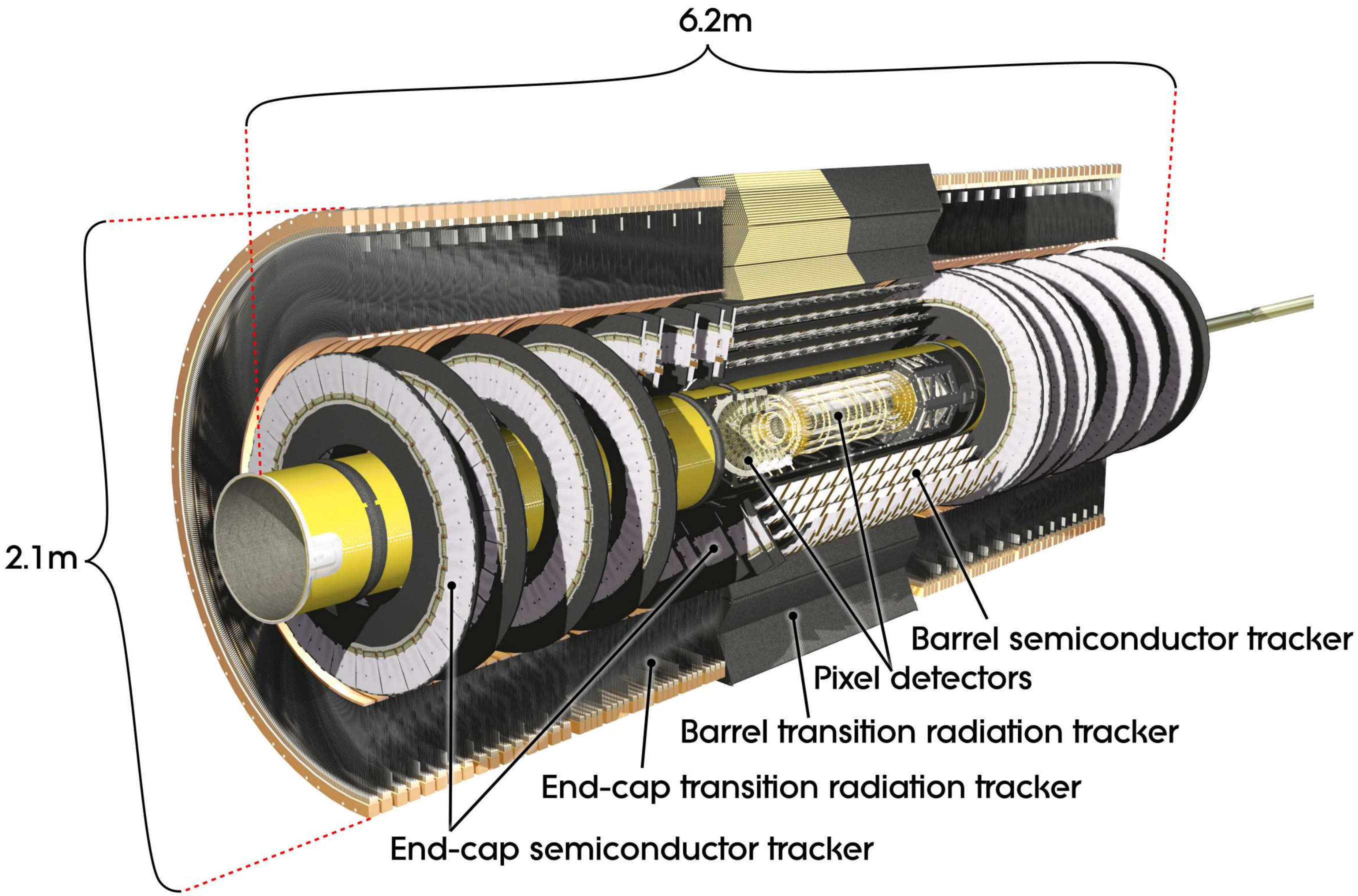
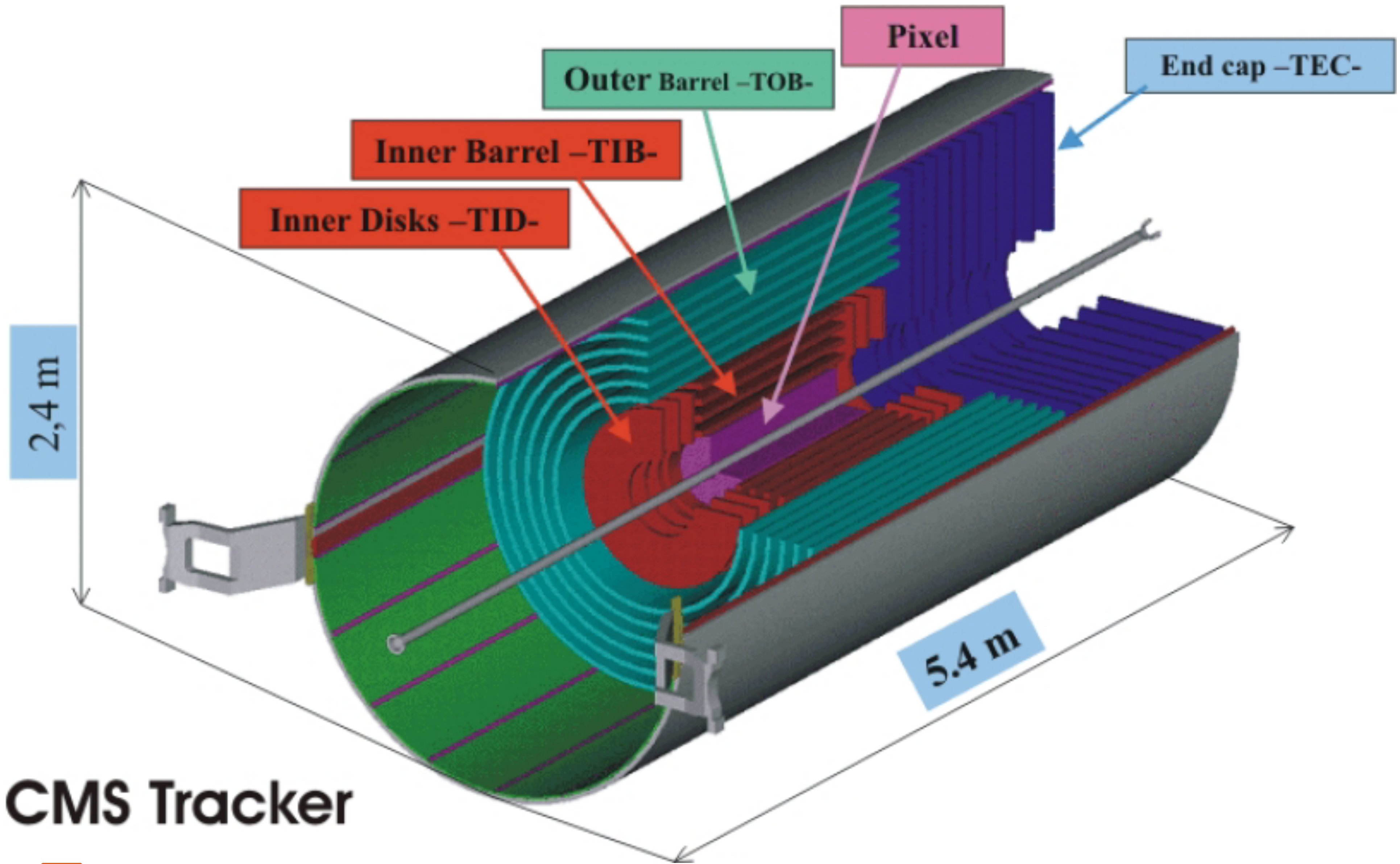


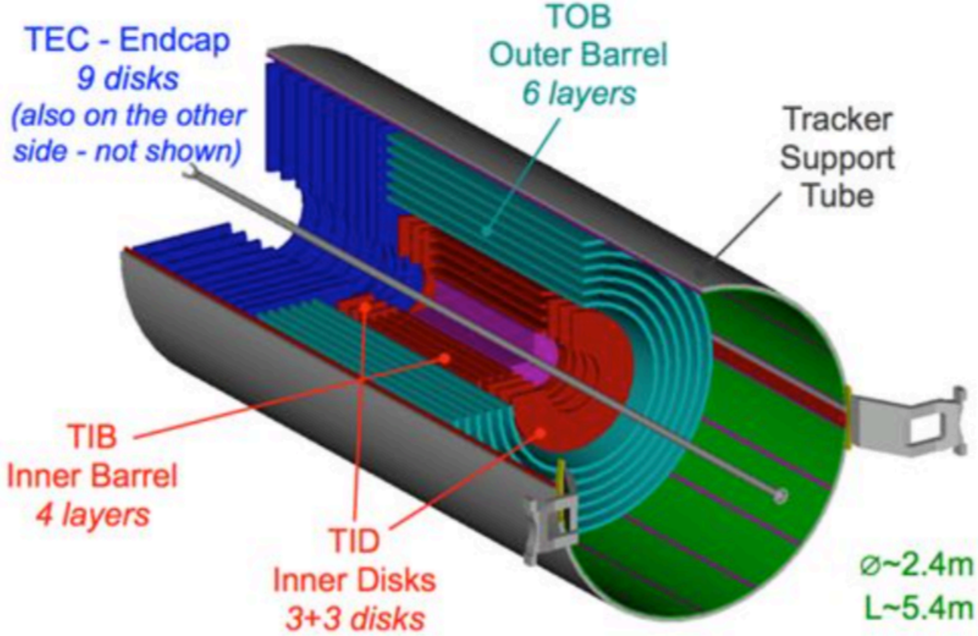
Figure 1.2: Cut-away view of the ATLAS inner detector.

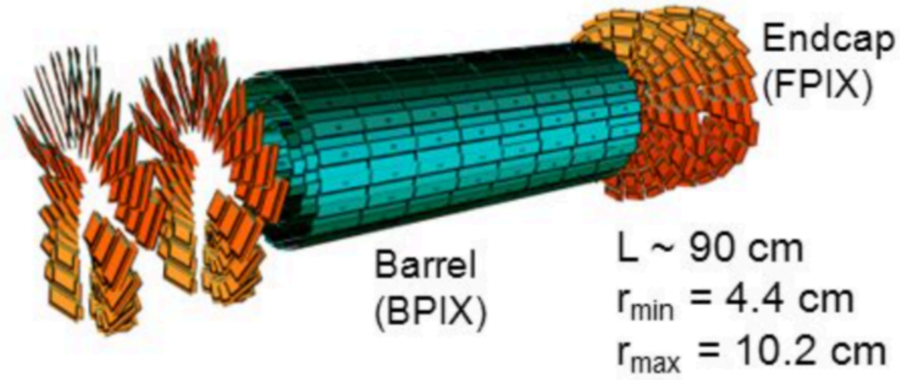


Pixel
End cap –TEC-
Outer Barrel –TOB-
Inner Barrel –TIB-
Inner Disks –TID-
2,4 m
5.4 m
CMS Tracker

CMS Silicon Strip Tracker

- Largest silicon tracker built
- Active area of 198 m^2
  - 5.4 m long, 2.4 m diameter
- Components:
  - Pixel detector (not covered in this talk)
  - TIB (Inner barrel): 4 layers
  - TID: 3 Inner Disks
  - TOB: (Outer Barrel): 6 layers
  - TEC (Endcaps): 9 disks on each side
- Key features:
  - 9.6 Million readout channels
  - Analog readout





ATLAS-CMS: inner tracker

TABLE 4 Main parameters of the ATLAS and CMS tracking systems (see Table 6 for details of the pixel systems)

Parameter	ATLAS	CMS
Dimensions (cm)		
-radius of outermost measurement	101–107	107–110
-radius of innermost measurement	5.0	4.4
-total active length	560	540
Magnetic field B (T)	2	4
BR^2 ($T \cdot m^2$)	2.0 to 2.3	4.6 to 4.8
Total power on detector (kW)	70	60
Total weight in tracker volume (kg)	≈4500	≈3700
Total material (X/X_0)		
-at $\eta \approx 0$ (minimum material)	0.3	0.4
-at $\eta \approx 1.7$ (maximum material)	1.2	1.5
-at $\eta \approx 2.5$ (edge of acceptance)	0.5	0.8
Total material (λ/λ_0 at max)	0.35	0.42
Silicon microstrip detectors		
-number of hits per track	8	14
-radius of innermost meas. (cm)	30	20
-total active area of silicon (m^2)	60	200
-wafer thickness (microns)	280	320/500
-total number of channels	6.2×10^6	9.6×10^6
-cell size (μm in $R\phi$ × cm in z/R)	80×12	$80/120 \times 10$
-cell size (μm in $R\phi$ × cm in z/R)		and $120/180 \times 25$
Straw drift tubes (ATLAS only)		
-number of hits per track ($\|\eta\| < 1.8$)	35	
-total number of channels	350,000	
-cell size (mm in $R\phi$ × cm in z)	4×70 (barrel)	
	4×40 (end caps)	

ATLAS-CMS: pixel

TABLE 6 Main parameters of the ATLAS and CMS pixel systems

	ATLAS	**CMS**
Number of hits per track	3	3
Total number of channels	80 10^6	66 10^6
Pixel size (μm in $R\phi \times$ μm in z/R)	50×400	100×150
Lorentz angle (degrees), initial to end	12 to 4	26 to 8
Tilt in $R\phi$ (degrees)	20 (only barrel)	20 (only end cap)
Total active area of silicon (m^2)	1.7 (n^+/n)	1.0 (n^+/n)
Sensor thickness (μm)	250	285
Total number of modules	1744 (288 in disks)	1440 (672 in disks)
Barrel layer radii (cm)	5.1, 8.9, 12.3	4.4, 7.3, 10.2
Disk layer min. to max. radii (cm)	8.9 to 15.0	6.0 to 15.0
Disk positions in z (cm)	49.5, 58.0, 65.0	34.5, 46.5
Signal-to-noise ratio for minimum ionizing particles (day 1)	120	130
Total fluence at L $= 10^{34}$ (n_{eq}/cm^2/year) at radius of 4–5 cm (innermost layer)	3×10^{14}	3×10^{14}
Signal-to-noise ratio (after 10^{15} n_{eq}/cm^2)	80	80
Resolution in $R\phi$ (μm)	≈10	≈10
Resolution in z/R (μm)	≈100	≈20

ATLAS-CMS: ECAL

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%

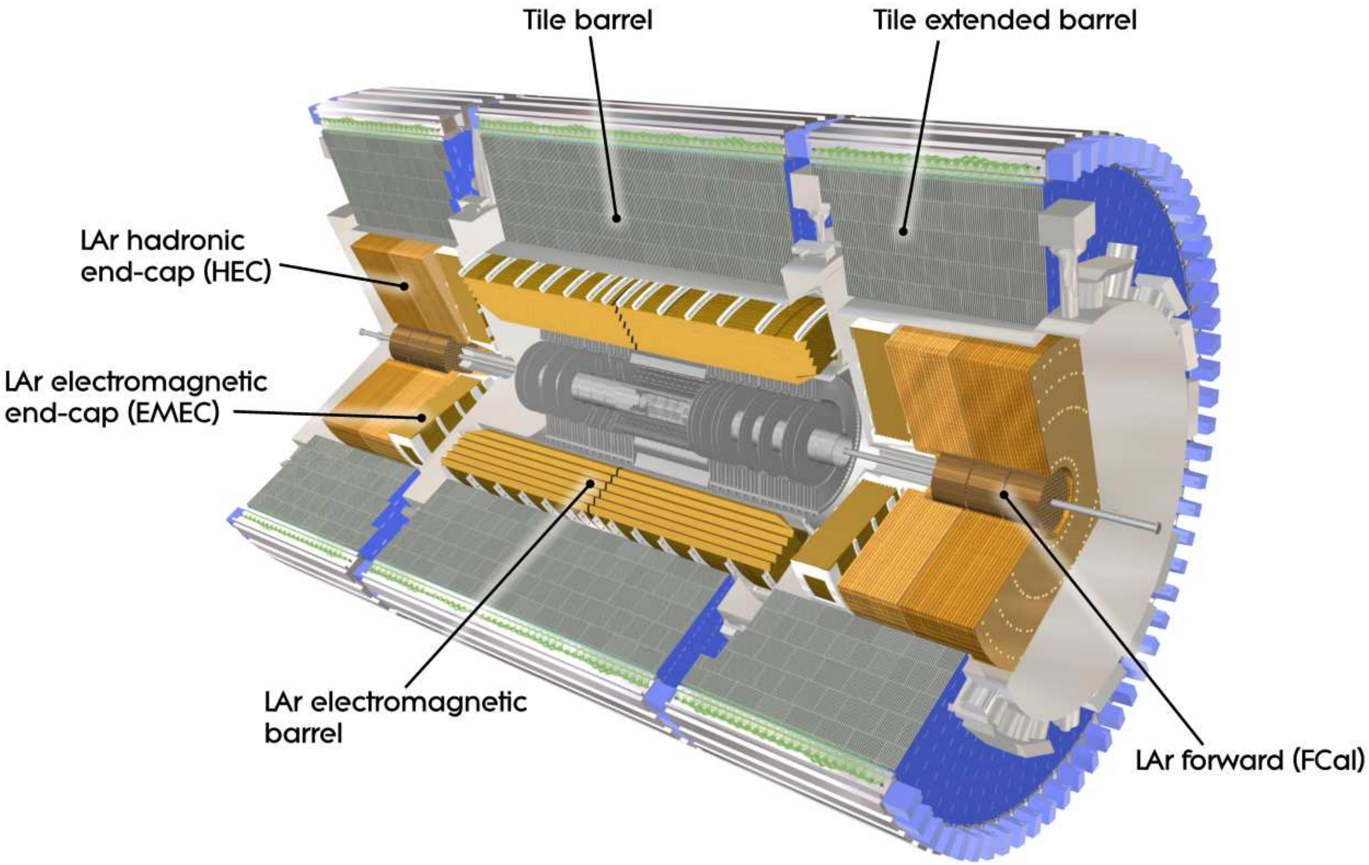
Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of 29×29 mm^2. The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS 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

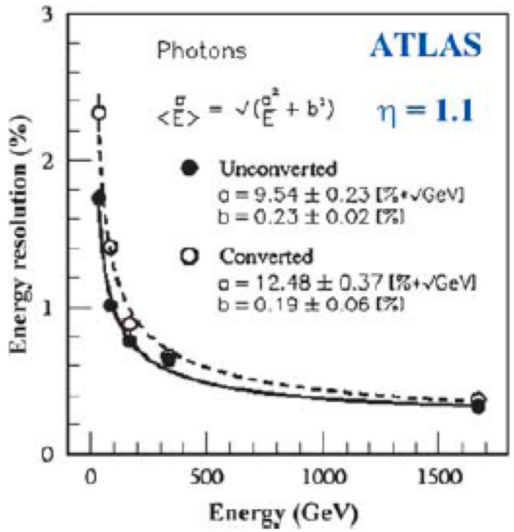
TABLE 9 Main parameters of the ATLAS and CMS hadronic calorimeters

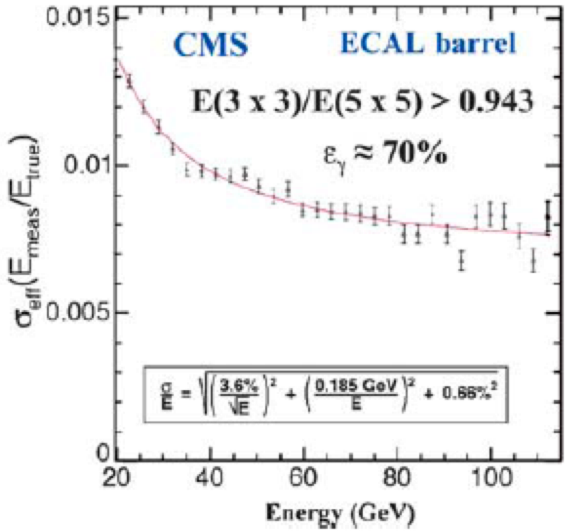
	ATLAS	CMS
Technology		
Barrel/Ext. barrel	14 mm iron/3 mm scint.	50 mm brass/3.7 mm scint.
End caps	25–50 mm copper/8.5 mm LAr	78 mm brass/3.7 mm scint.
Forward	Copper (front) - Tungsten (back)/0.25–0.50 mm LAr	Steel/0.6 mm quartz
Channels		
Barrel/Ext. barrel	9852	2592
End caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	0.1×0.1 to 0.2×0.1	0.087×0.087
End caps	0.1×0.1 to 0.2×0.2	0.087×0.087 to 0.18×0.175
Forward	0.2×0.2	0.175×0.175
Samplings ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	3	1
End caps	4	2
Forward	3	2
Abs. lengths (min.-max.)		
Barrel/Ext. barrel	9.7–13.0	7.2–11.0 10–14 (with coil/HO)
End caps	9.7–12.5	9.0–10.0
Forward	9.5–10.5	9.8

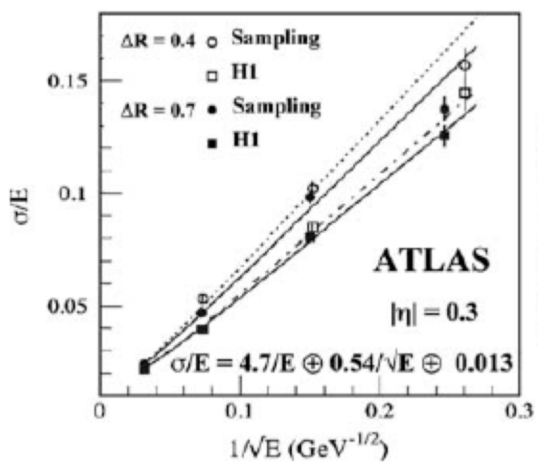
Note that the CMS barrel calorimeter (HB) is complemented by a tail catcher behind the coil (HO) to minimize problems with longitudinal leakage of high-energy particles in jets.

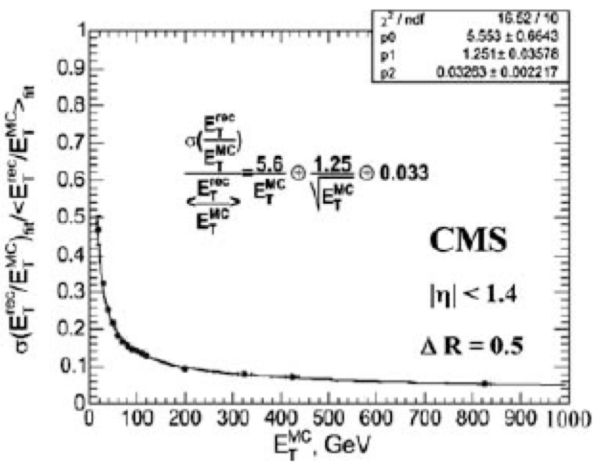

Tile barrel
Tile extended barrel
LAr hadronic end-cap (HEC)
LAr electromagnetic end-cap (EMEC)
LAr electromagnetic barrel
LAr forward (FCal)

ATLAS-CMS: calorimeters









ATLAS-CMS: muons

TABLE 11 Main parameters of the ATLAS and CMS muon chambers

	ATLAS	**CMS**
Drift Tubes	MDTs	DTs
-Coverage	$\|\eta\| < 2.0$	$\eta\| < 1.2$
-Number of chambers	1170	250
-Number of channels	354,000	172,000
-Function	Precision measurement	Precision measurement, triggering
Cathode Strip Chambers		
-Coverage	$2.0 < \|\eta\| < 2.7$	$1.2 < \|\eta\| < 2.4$
-Number of chambers	32	468
-Number of channels	31,000	500,000
-Function	Precision measurement	Precision measurement, triggering
Resistive Plate Chambers		
-Coverage	$\|\eta\| < 1.05$	$\|\eta\| < 2.1$
-Number of chambers	1112	912
-Number of channels	374,000	160,000
-Function	Triggering, second coordinate	Triggering
Thin Gap Chambers		
-Coverage	$1.05 < \|\eta\| < 2.4$	—
-Number of chambers	1578	—
-Number of channels	322,000	—
-Function	Triggering, second coordinate	—

ATLAS-CMS: muon momentum resolutions

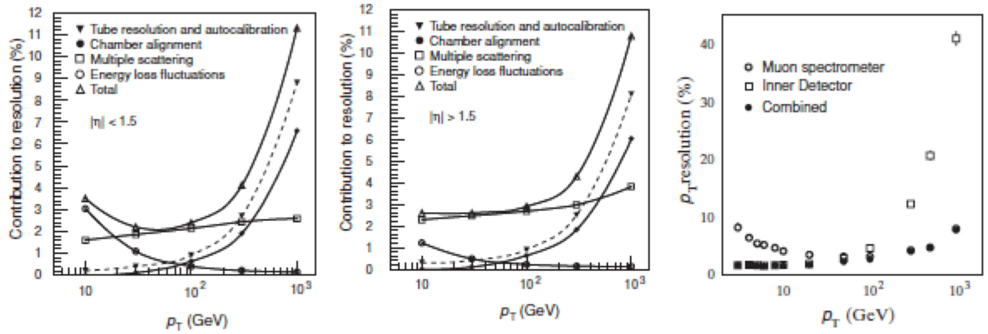


Figure 24 Expected performance of the ATLAS muon measurement. Contributions to the momentum resolution in the muon spectrometer averaged over $|\eta| < 1.5$ (*left*) and $1.5 < |\eta| < 2.7$ (*center*). (*Right*) Muon momentum resolution expected from muon spectrometer, Inner Detector, and their combination together as a function of muon transverse momentum.

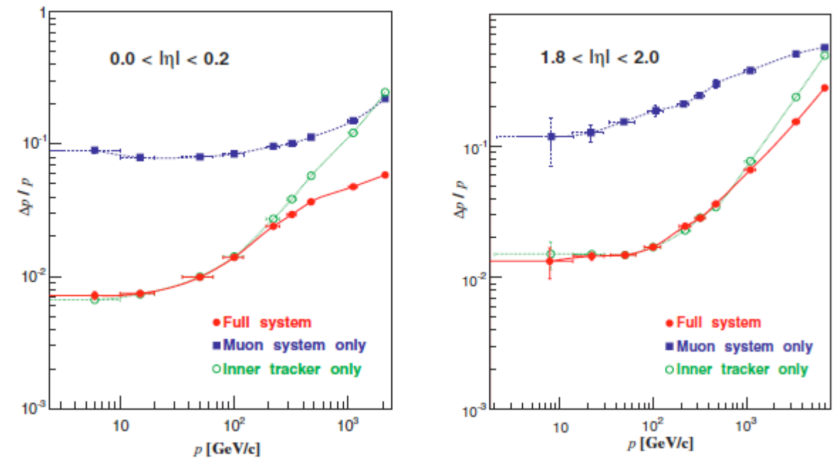
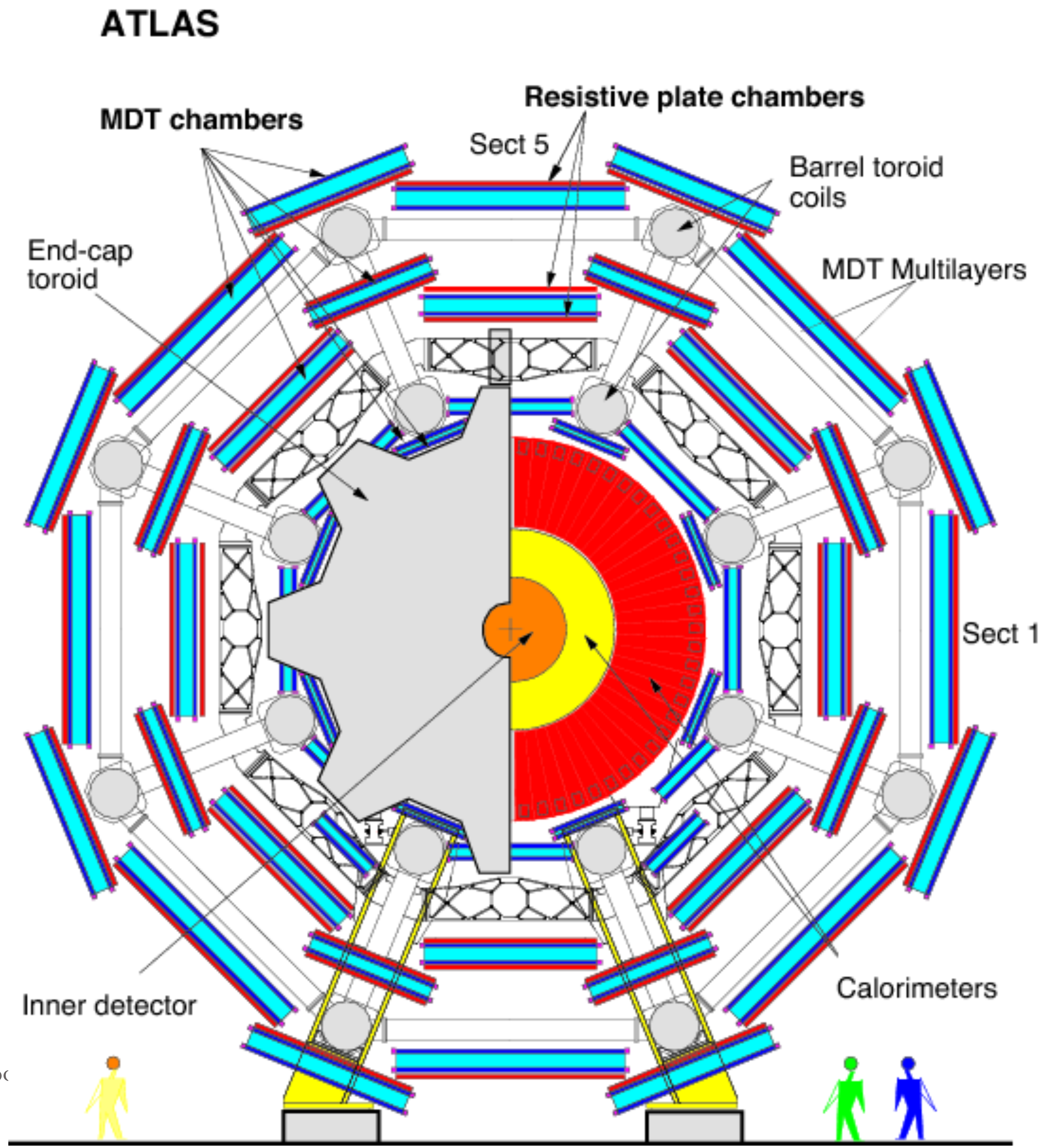
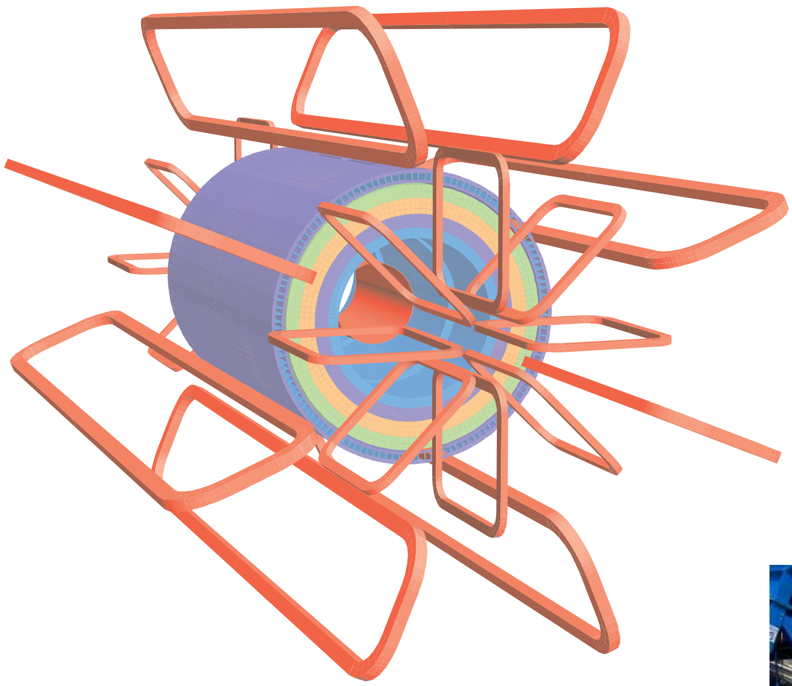
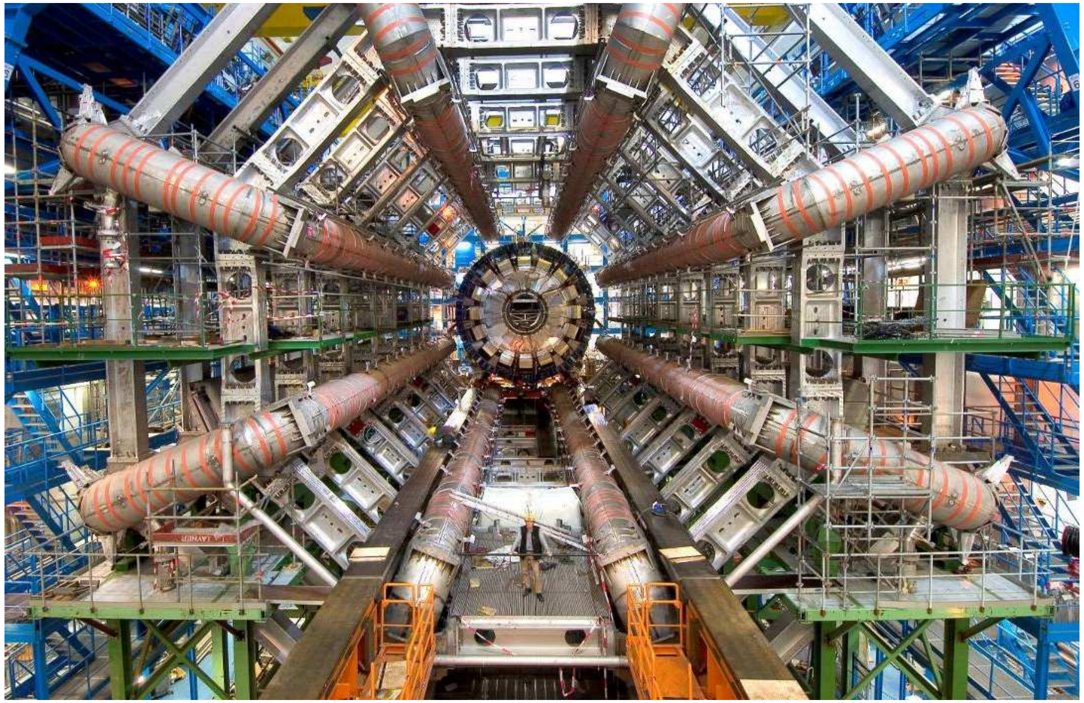


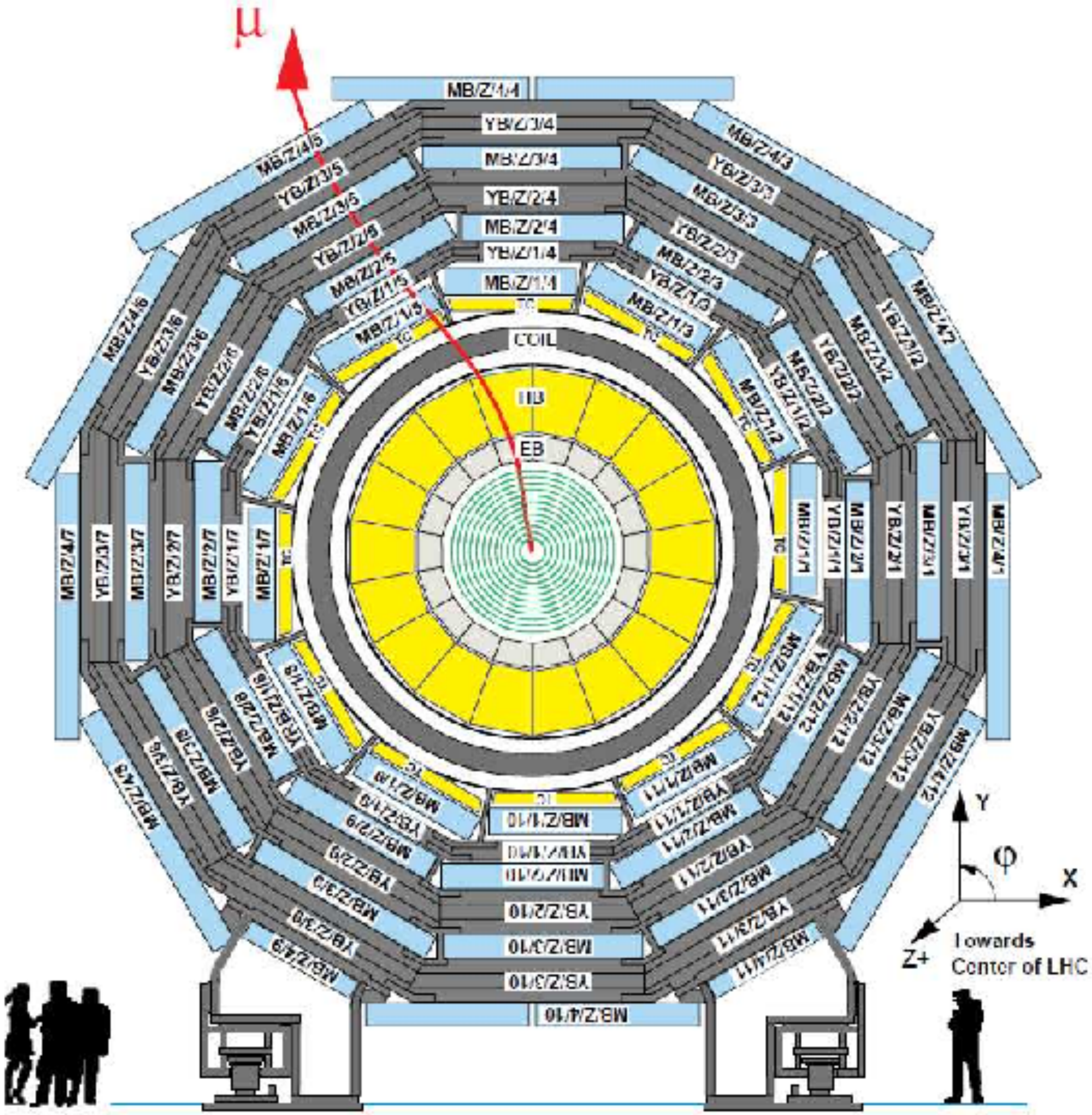
Figure 25 Expected performance of the CMS muon measurement. The muon momentum resolution is plotted versus momentum using the muon system only, the inner tracker only, or their combination (full system). (*Left*) Barrel, with $|\eta| < 0.2$. (*Right*) End cap, with $1.8 < |\eta| < 2.0$.


ATLAS
MDT chambers
Resistive plate chambers
Sect 5
Barrel toroid
coils
End-cap
toroid
MDT Multilayers
Sect 1
Inner detector
Calorimeters





CMS



ATLAS vs. CMS

- Driven by the goal to achieve a high-precision stand-alone momentum measurement of muons "achieved using an arrangement of a small-radius thin-walled solenoid integrated into the cryostat of the barrel ECAL, surrounded by a system of three large air-core toroids, situated outside the ATLAS calorimeter systems, and generating the magnetic field for the muon spectrometer."
- Electrons
  - ECAL, and matching between the E,p measured by ECAL and tracker
  - Also enhenced by ATLAS TRT's ability to separate electrons from charged pions
- ATLAS solenoid is located just in front of the barrel ECAL, resulting in significant energy loss by electrons and photons in the material in front of the active ECAL
- HCAL is thick enough: good jet and missing E_T measurement

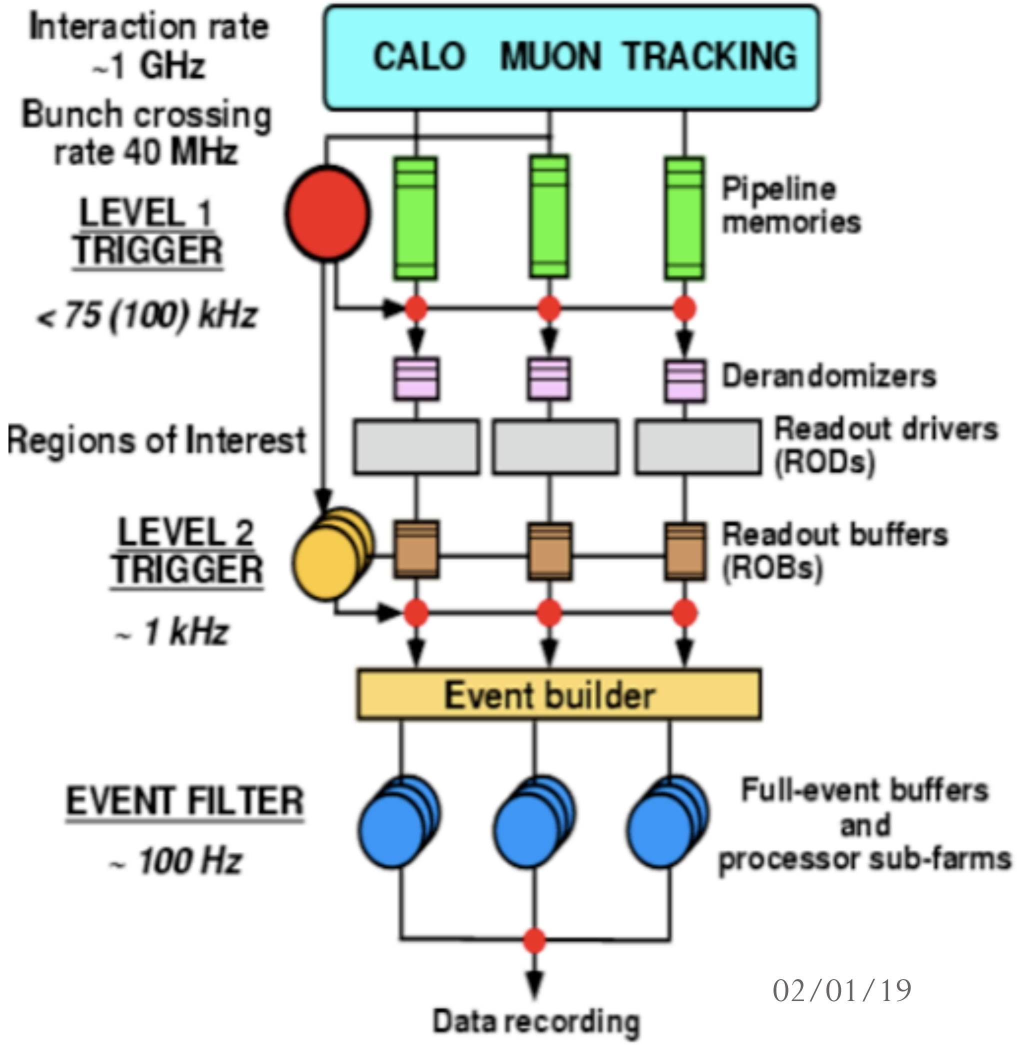
- A single magnet with "a high magnetic field in the tracker volume for all precision momentum measurements, and a high enough return flux in the iron outside the magnet to provide a muon trigger and a second muon momentum measurement."
- Invested in highest possible magnetic filed: 4T → better tracking resolution than ATLAS
  - Inner tracker consisting of all silicon detectors
- γ/Electrons → High resolution crystals, better than ATLAS
- The full EM calorimetry and most of its hadronic alorimetry are situated inside the solenoid coil and therefore bathed in the strong 4T magnetic field
- HCAL. The strong constraints imposed by the CMS solenoid have resulted in a barrel hadronic calorimeter with insufficient absorption (~ 7 absorption lengths). So a tail catcher (HO) has been added around the coil to complement the HB. But still, over-all, CMS jet resolution is worse than ATLAS.

An important quest for pp experiments: the ***Trigger***

$$\dot{N} = \sigma_{tot} L \approx 10^{-25} cm^2 \times 10^{32\div34} cm^{-2} s^{-1} = 10\,MHz \div 1GHz$$

bunch crossing rate = 40 MHz
➔ every b.c. contains at least
an interaction (25/b.c. at max L)

- Technically impossible and physically not interesting to register all b.c.s
- Retain only "interesting" b.c.
  ➔ TRIGGER = online decision:
  take or reject the b.c.
- *Decision has to be fast;*
- *Criteria have to be flexible and scalable;*
- *Thresholds have to be defined.*



Let's design an experiment - V

Momentum measurement

Assume a uniform magnetic field ***B*** in a region of dimension ***L*** and a particle of trasverse momentum ***p***

$$p_T(GeV) = 0.3\rho(m)B(T)$$

We define the "sagitta" ***s*** and suppose to measure it through 3 points x_1, x_2 and x_3: $s = x_2 - (x_1 + x_3)/2$

$$s = \frac{0.3BL^2}{8p_T}$$

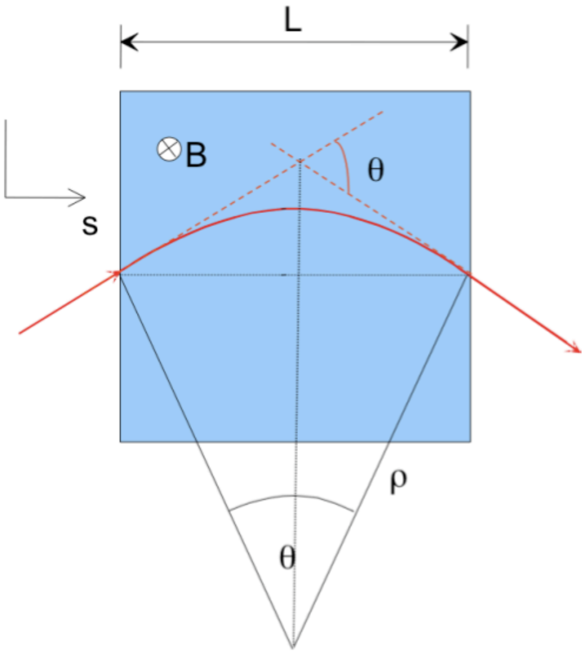
From ***s*** we get the transverse momentum, given the field ***B*** and the distance ***L*** between detectors 1 and 3

The resolution on p_T is:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{3}{2}}\sigma_X \frac{8p_T}{0.3BL^2}$$

In case of N points rather than 3, the resolution is:

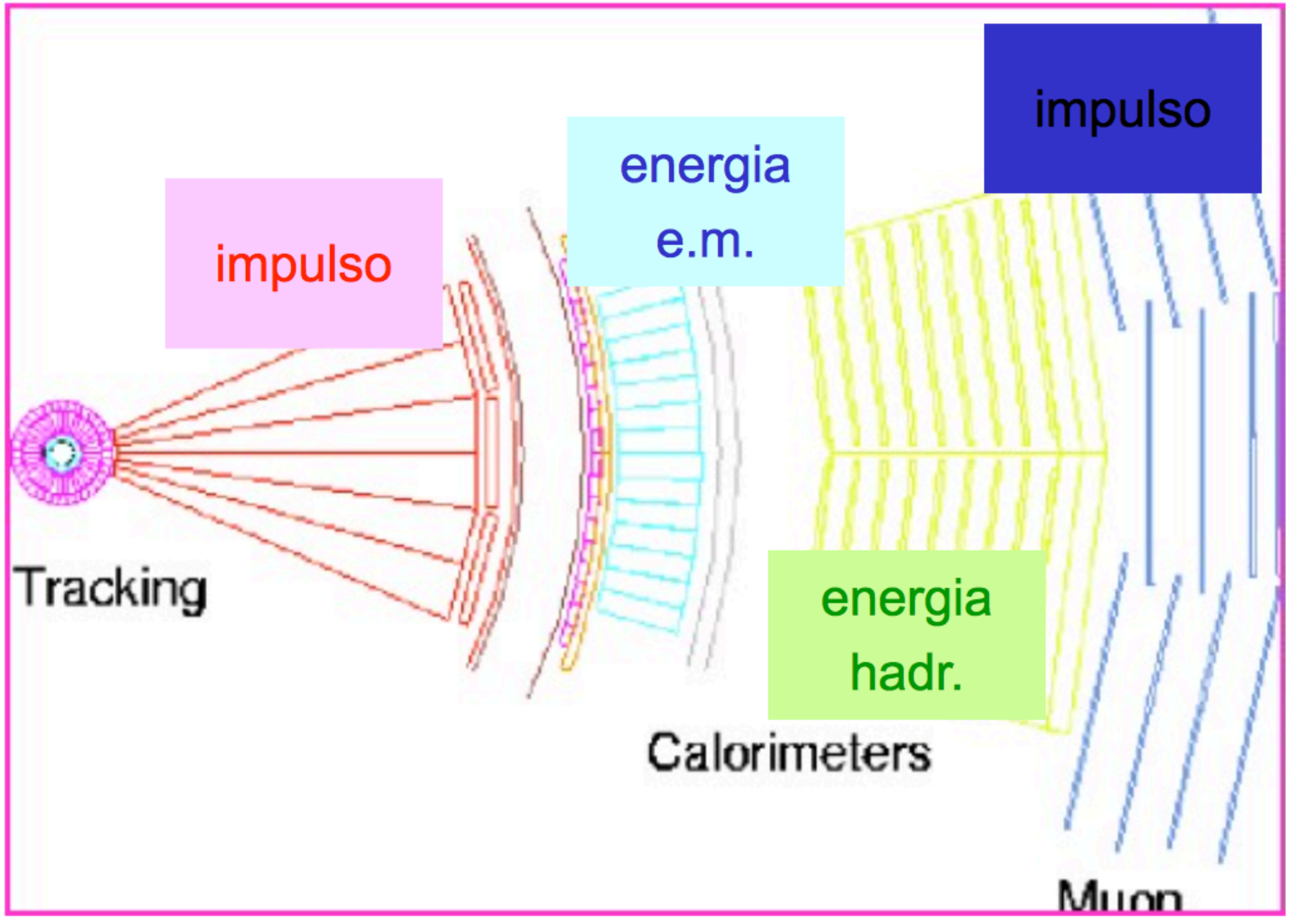
$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{720}{N+4}}\sigma_X \frac{p_T}{0.3BL^2}$$



Spare slides

	p_c	E_{em}	E_h	p_μ
• $e^\pm$:	si	si	no	no;
• γ :	no	si	no	no;
• $\pi^\pm$:	si	mip	si	no;
• n :	no	mip	si	no;
• $\mu^\pm$:	si	mip	mip	si;
• ν :	no	no	no	no;

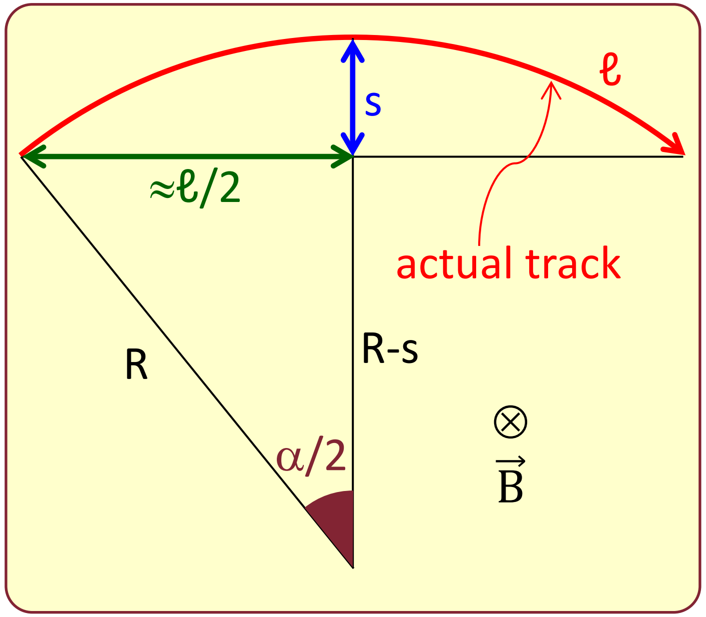
- ν da apparente sbilanciamento dell'evento (ermeticità).



particle measurement : spectrometers

The Lorentz force bends a charged particle in a magnetic field ⇒ the particle momentum is computed from the measurement of a trajectory ℓ. Simple case:

- track $\perp \vec{B}$ (or ℓ = projected trajectory);
- $\vec{B}$ = constant;
- ℓ ≪ R (i.e. α small, s ≪ R, arc ≈ chord);
- then (p in GeV, B in T, ℓ R s in m) :



$$R^2 = (R-s)^2 + \ell^2/4 \rightarrow (R, \ell \gg s)$$

$$0 = \cancel{s^2} - 2Rs + \ell^2/4 \rightarrow$$

$$s = \frac{\ell^2}{8R} \simeq \frac{R\alpha^2}{8};$$

$$p = 0.3BR = 0.3B\frac{\ell^2}{8s};$$

$$\frac{\Delta p}{p} = \left|\frac{\partial p}{\partial s}\right|\frac{\Delta s}{p} = \frac{\cancel{p}}{s}\frac{\Delta s}{\cancel{p}} = \frac{\Delta s}{s} = \left(\frac{8\Delta s}{0.3B\ell^2}\right)p.$$

- e.g. B = 1 T, ℓ = 1.7 m, Δs = 200 μm →

  Δp/p =1.6 × 10^{-3} p (GeV);

- in general, from N points at equal distance along ℓ, each with error ε :

$$\frac{\Delta p}{p} \simeq \frac{\varepsilon p}{0.3B\ell^2}\sqrt{\frac{720}{N+4}}$$

(Gluckstern formula [PDG]).

Resolution of energy measurements through e.m. calorimetry

- In general the energy resolution of an e.m. calorimeter is given in terms of $\sigma(E)/E$.
- Main contributions:
  - $a/\sqrt{E}$ ➔ due to statistics: sampling fluctuations and/or number of photoelectrons fluctuations;
  - b/E ➔ tipically due to the fluctuations of a constant contribution to the energy (e.g. pedestal, electronic noise,…)
  - c ➔ constant term: due to systematics, calibration, containment.
- All three terms contribute. Normally c dominates at high energies, and a at low/intermediate energies. b is present only in specific cases.

Electromagnetic calorimetry

Table 31.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$\mathrm{Bi_4Ge_3O_{12}}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$\mathrm{PbWO_4}$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20–30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20–30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996