ATLAS and CMS: the LHC giants!

- Proton-proton collisions at the energy frontier $\sqrt{s} = 14\,\text{TeV}$ with huge luminosity (L = 10^{34} cm^{-2}s^{-1} ➜ μ = 25 evts / bunch crossing): $\boldsymbol{\mu}$ = L σ_{tot} /fn$_b$ = 10^{34} × 100 mb × 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)
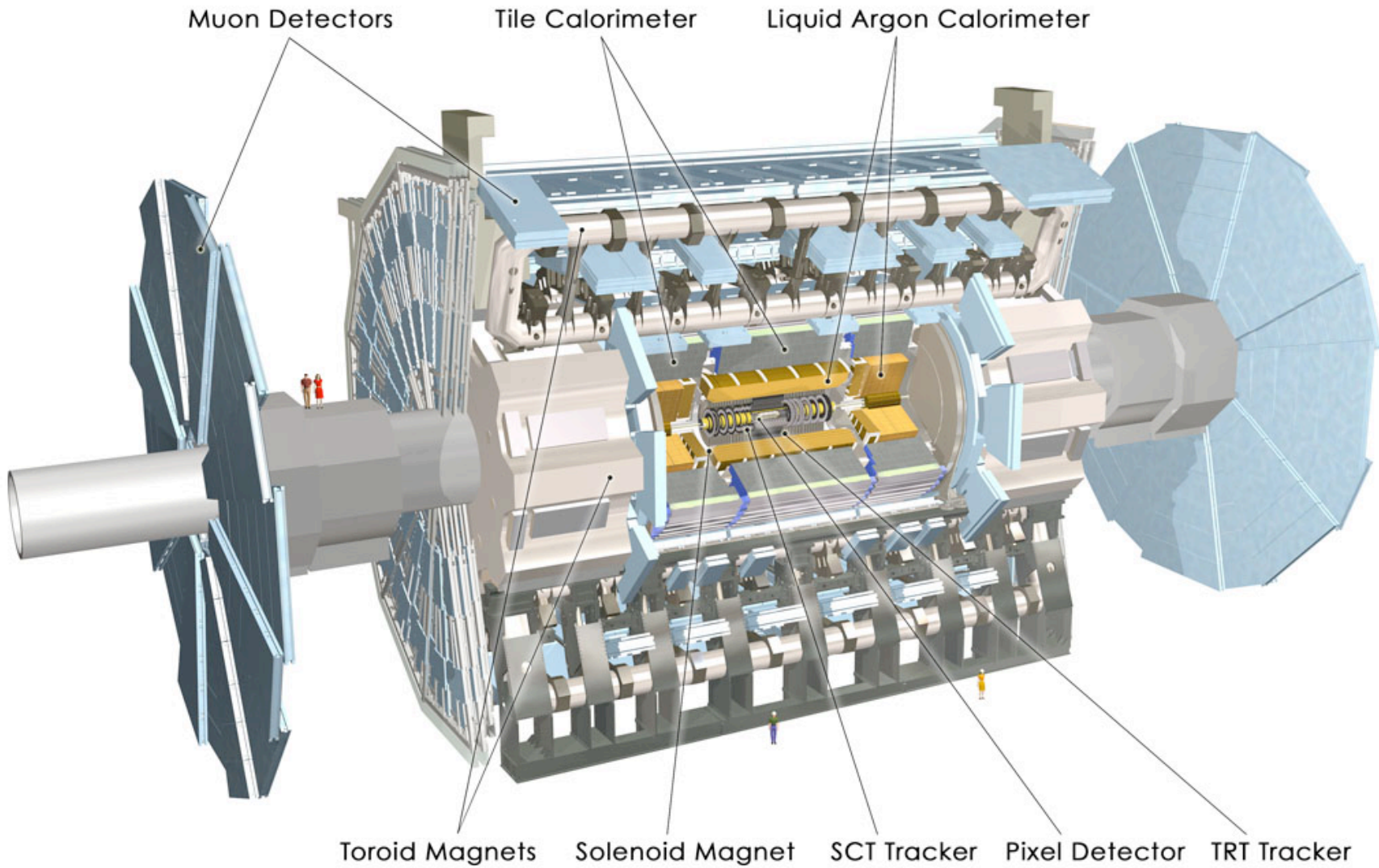
The Giants: ATLAS & CMS
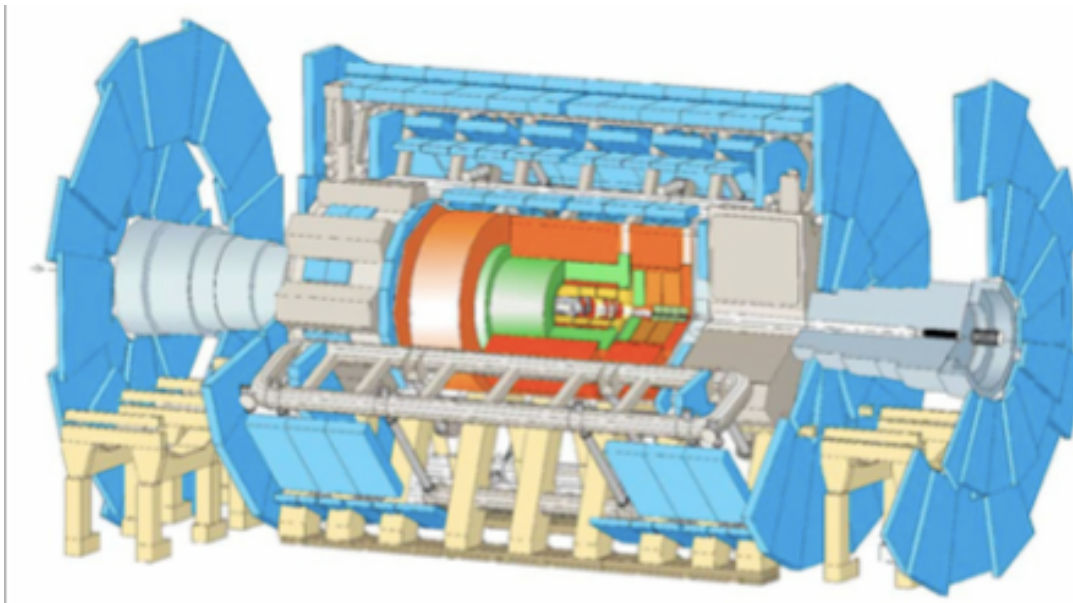
ATLAS (the largest): 46 x 25 m
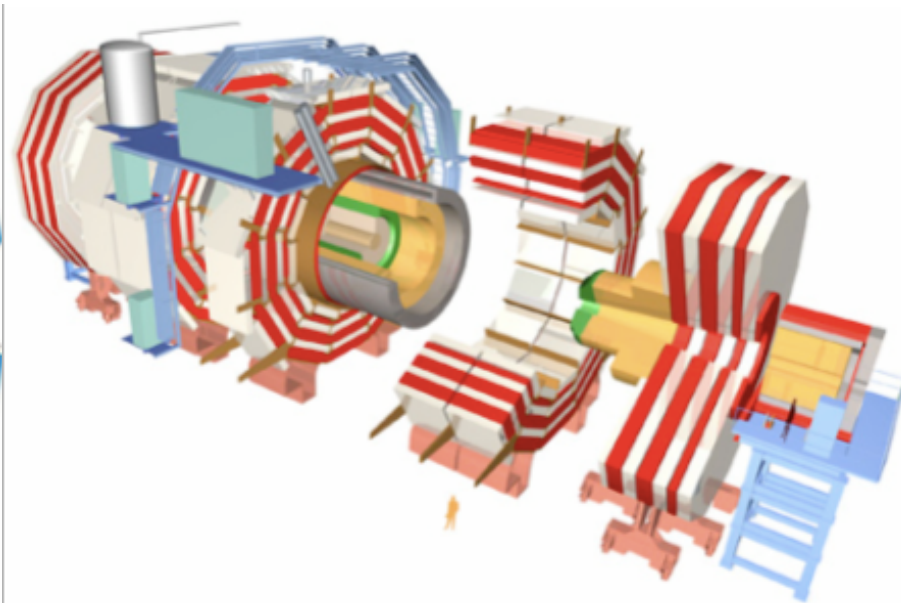
CMS (the heaviest): 12500 tonn

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

ATLAS

Muon Detectors   Tile Calorimeter   Liquid Argon Calorimeter

Toroid Magnets   Solenoid Magnet   SCT Tracker   Pixel Detector   TRT Tracker

Methods in Experimental Particle Physics

Example: overall structure of the CMS detector
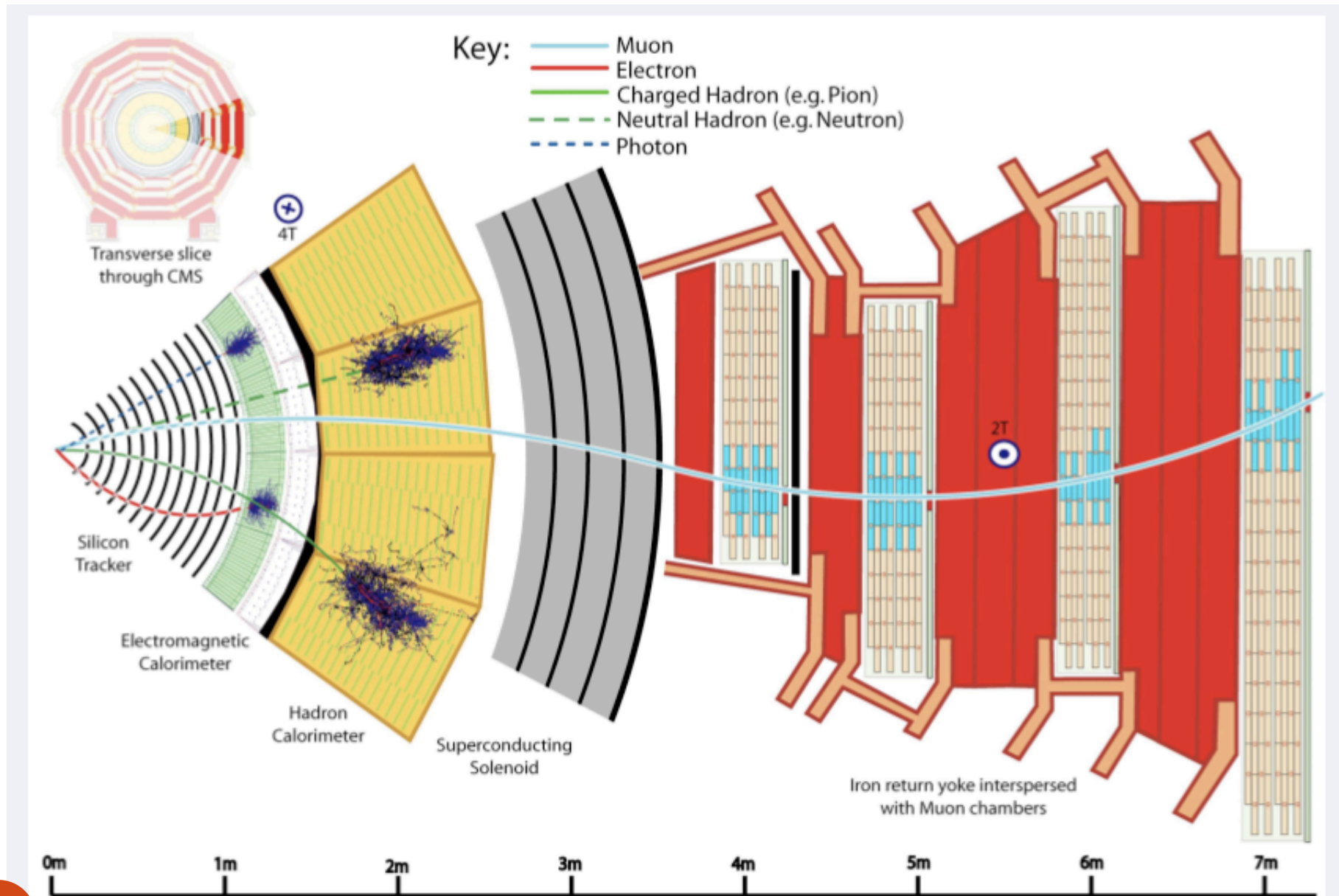
Subdetectors

- 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

Methods in Experimental Particle Physics

ATLAS-CMS: magnets

TABLE 3 Main parameters of the CMS and ATLAS magnet systems

| Parameter	CMS Solenoid	ATLAS Solenoid	ATLAS Barrel toroid	ATLAS 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

Methods in Experimental Particle Physics

How muons are detected at LHC

→ The calorimeters provide a "natural" muon filter;
→ The magnetic field system. ATLAS and CMS have different approaches
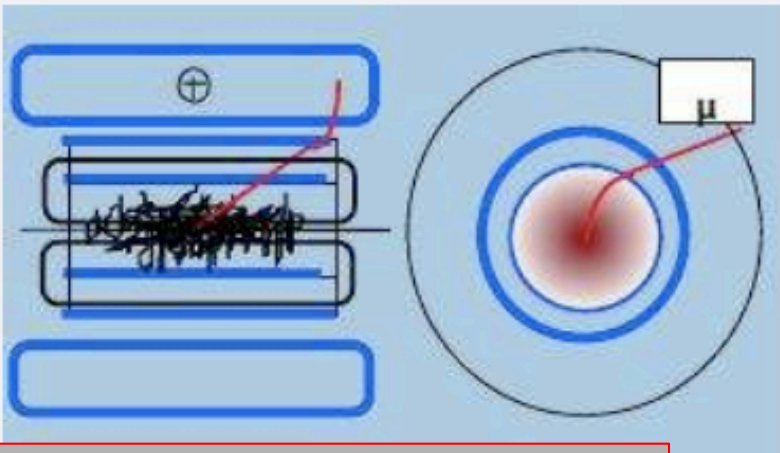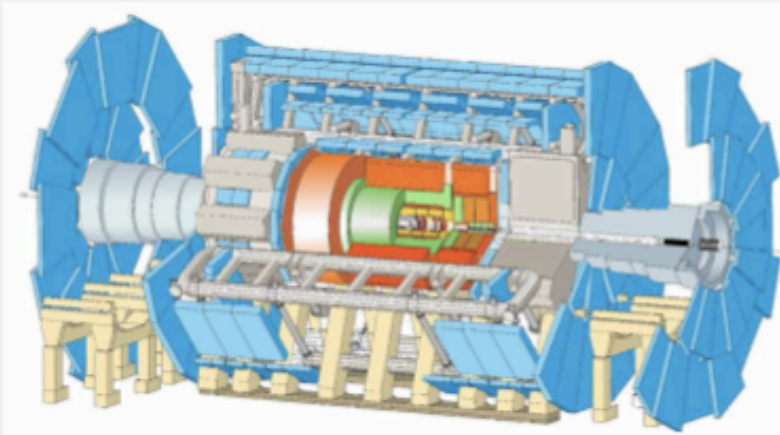
ATLAS: inner solenoid + outer toroids
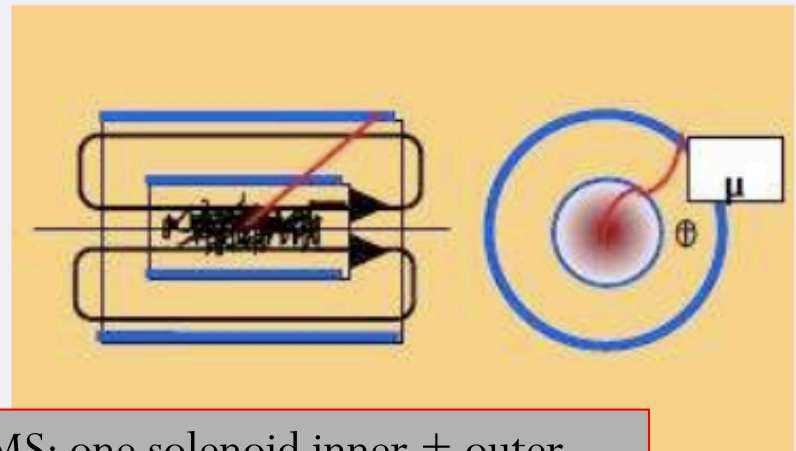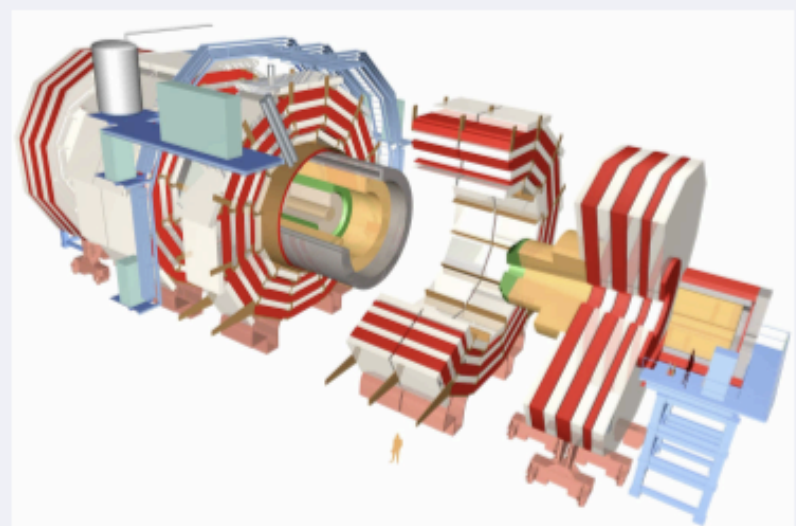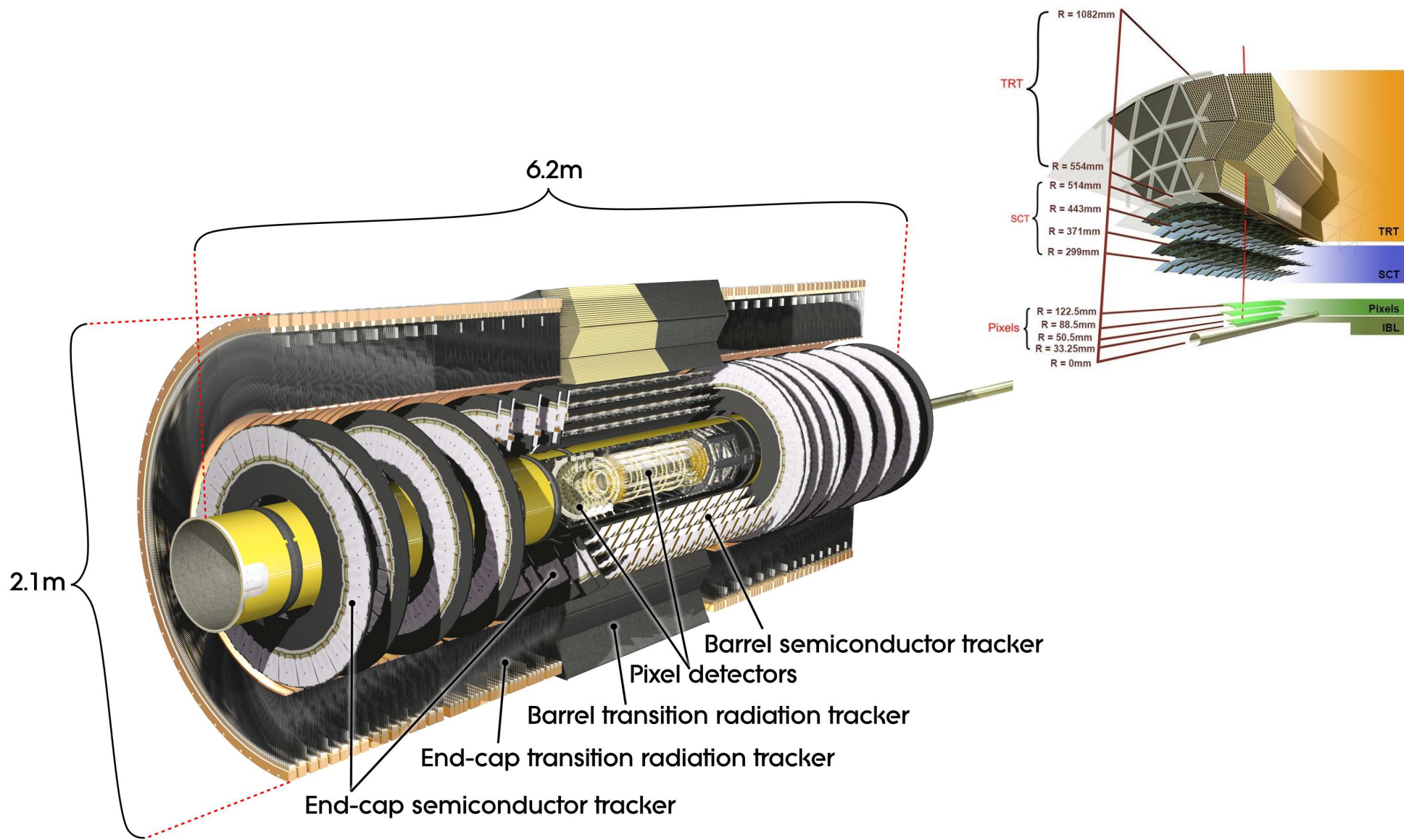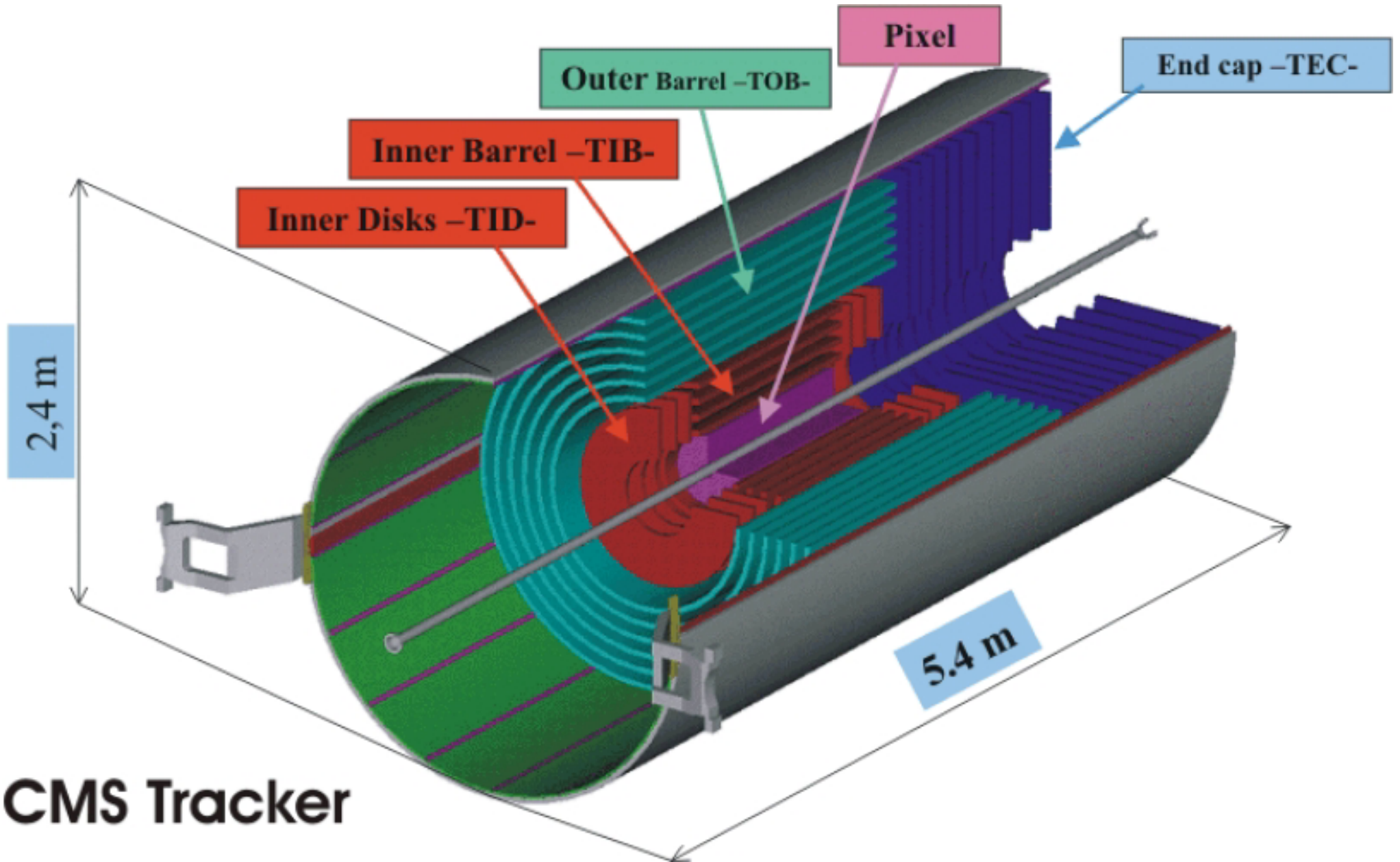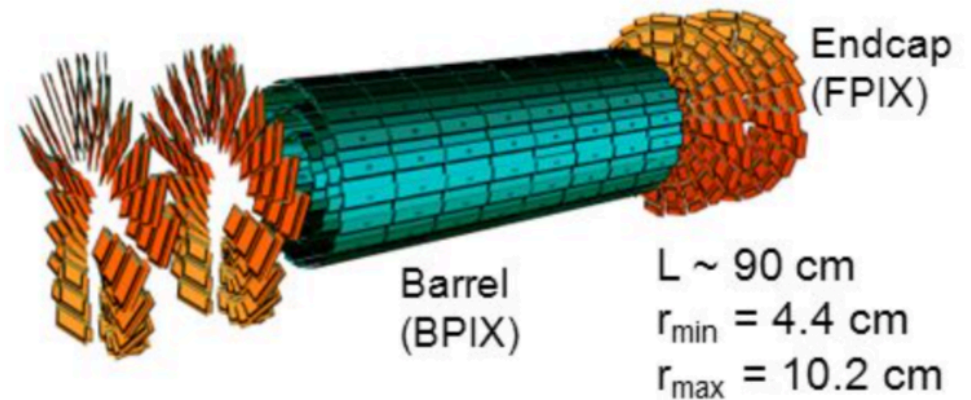
CMS: one solenoid inner + outer (reversed direction)

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

Pixel

Outer Barrel –TOB–

Inner Barrel –TIB–

Inner Disks –TID–

End cap –TEC–

2,4 m

5.4 m

CMS Tracker

CMS Silicon Strip Tracker

- Largest silicon tracker built
- Active area of 198 m²
  - 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

TEC - Endcap
9 disks
(also on the other side - not shown)

TOB
Outer Barrel
6 layers

Tracker Support Tube

TIB
Inner Barrel
4 layers

TID
Inner Disks
3+3 disks

ø~2.4m
L~5.4m

Endcap (FPIX)

Barrel (BPIX)

$L \sim 90$ cm
$r_{min} = 4.4$ cm
$r_{max} = 10.2$ cm
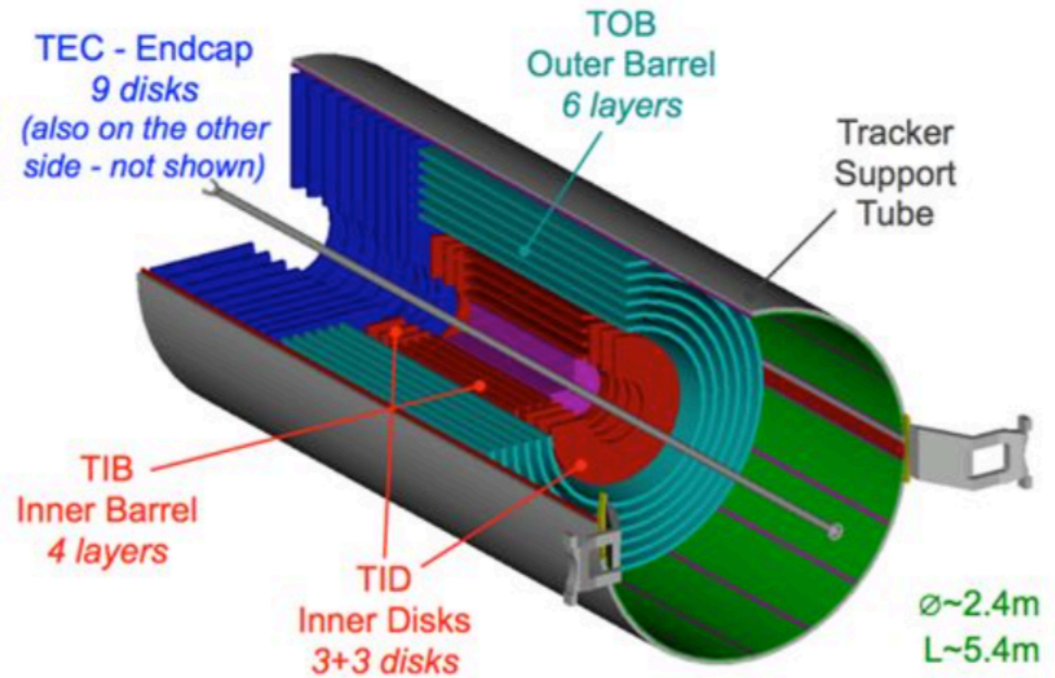
ATLAS-CMS: inner tracker

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·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 $R\phi \times$ cm in z/R)	80×12	$80/120 \times 10$
-cell size (μm in $R\phi \times$ 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 $R\phi \times$ cm in z)	4×70 (barrel)	
	4×40 (end caps)	

Methods in Experimental Particle Physics

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ATLAS-CMS: pixel

TABLE 6 Main parameters of the ATLAS and CMS pixel systems
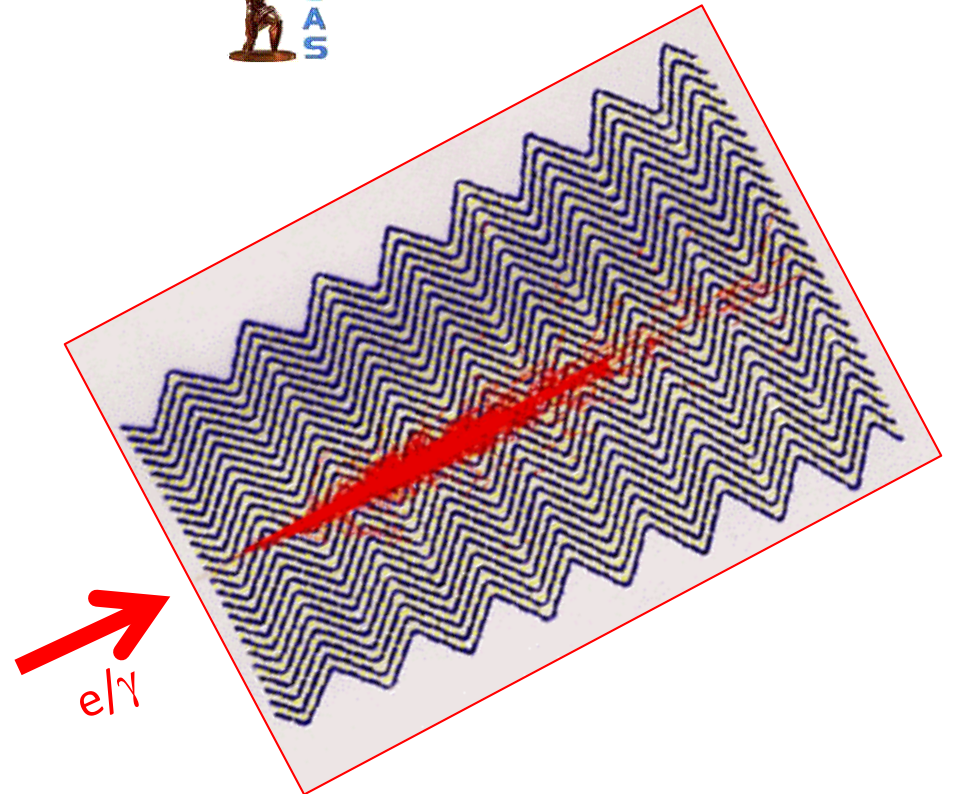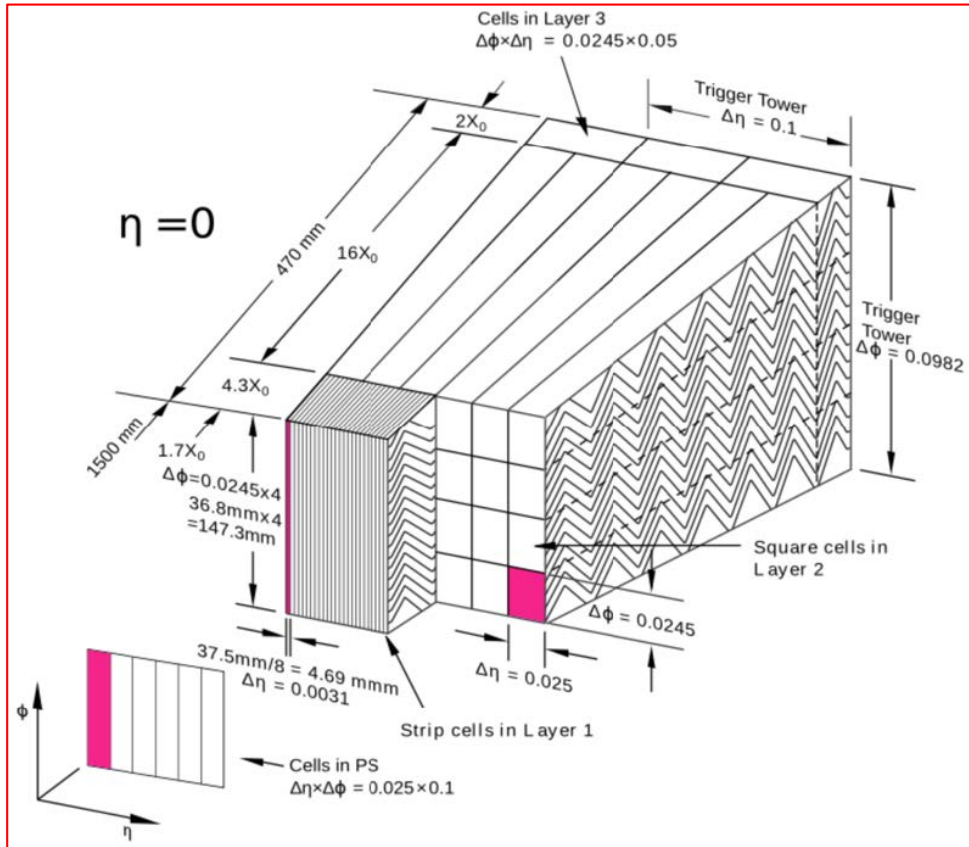
	ATLAS	CMS
Number of hits per track	3	3
Total number of channels	$80 \cdot 10^6$	$66 \cdot 10^6$
Pixel size (μm in $R\phi \times \mu$m in z/R)	50×400	100×150
Lorentz angle (degrees), initial to end	12 to 4	26 to 8
Tilt in $R\phi$ (degrees)	20 (only barrel)	20 (only end cap)
Total active area of silicon (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

Methods in Experimental Particle Physics

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/	0.003×0.1	0.003×0.1 to		32×32 Si-strips
Si-preshower		0.006×0.1		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/	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Si-preshower				
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.

Cells in Layer 3
$\Delta\phi \times \Delta\eta = 0.0245 \times 0.05$

Trigger Tower
$\Delta\eta = 0.1$

$\eta = 0$

470 mm

$16X_0$

$2X_0$

$4.3X_0$

1500 mm

$1.7X_0$

$\Delta\phi = 0.0245 \times 4$
36.8mm×4
=147.3mm

Trigger Tower
$\Delta\phi = 0.0982$

Square cells in Layer 2

$\Delta\phi = 0.0245$

$\Delta\eta = 0.025$

37.5mm/8 = 4.69 mmm
$\Delta\eta = 0.0031$

Strip cells in Layer 1

Cells in PS
$\Delta\eta \times \Delta\phi = 0.025 \times 0.1$

ϕ

η

e/γ

- "accordion" LAr – Pb
- cryogenic
- hermetic
- longitudinal + radial segmentation

Methods in Experimental Particle Physics
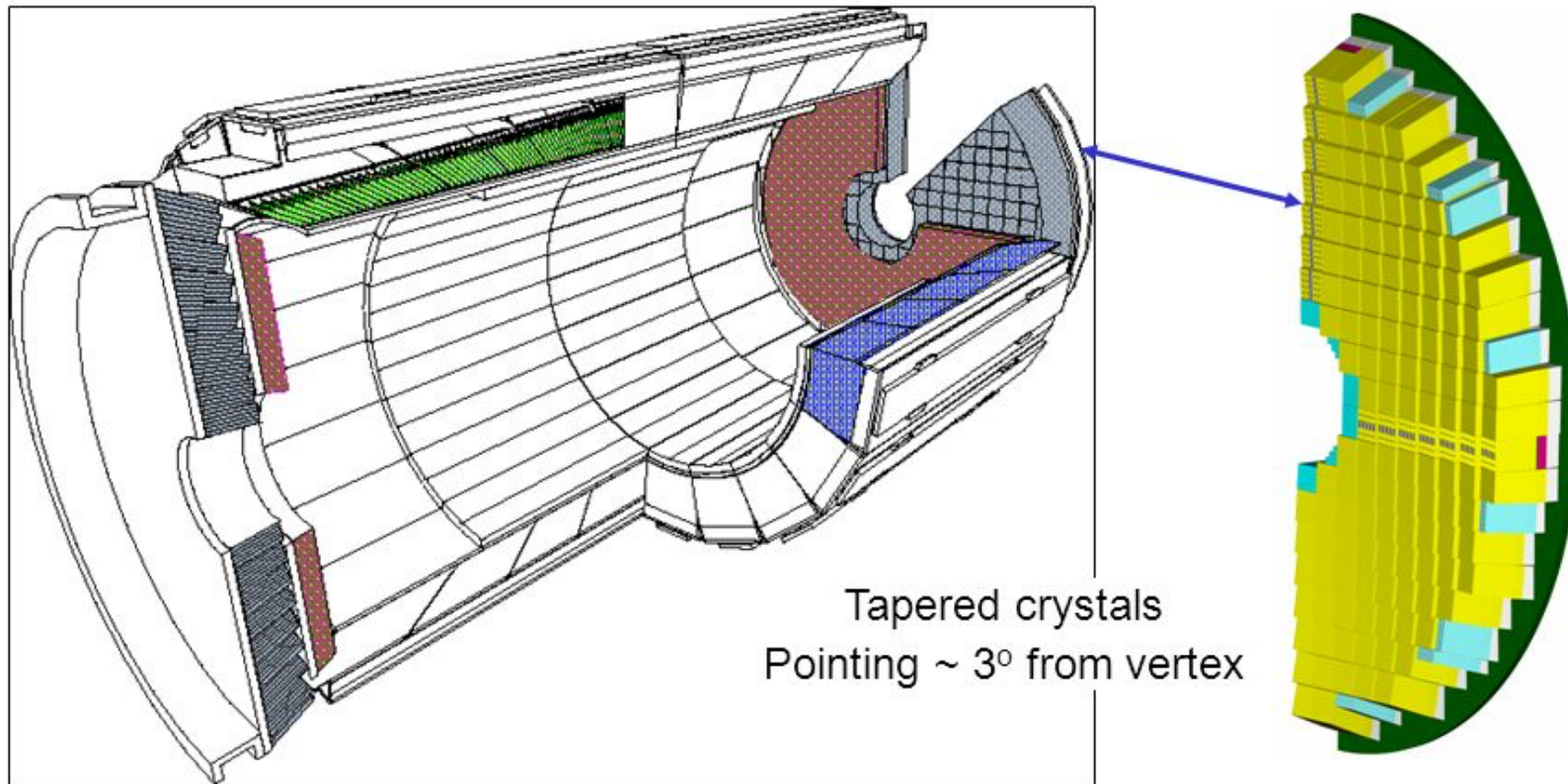
Tapered crystals
Pointing ~ 3° from vertex

Barrel:
36 Supermodules (18 per half-barrel)
61200 Crystals
Total mass 67.4 t

Endcaps:
4 Dees (2 per endcap)
14648 Crystals
Total mass 22.9 t

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.

ATLAS-CMS: HCAL

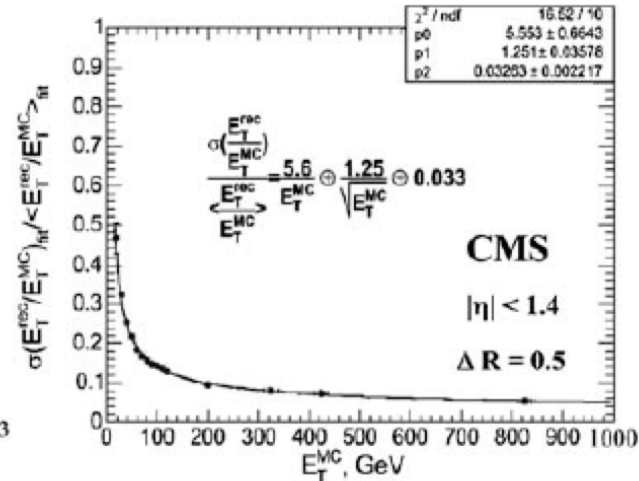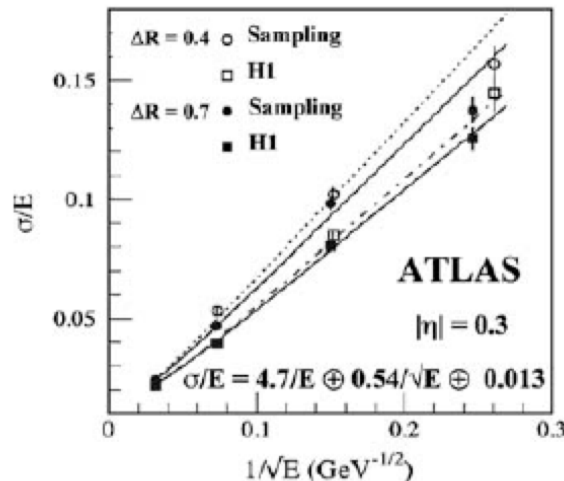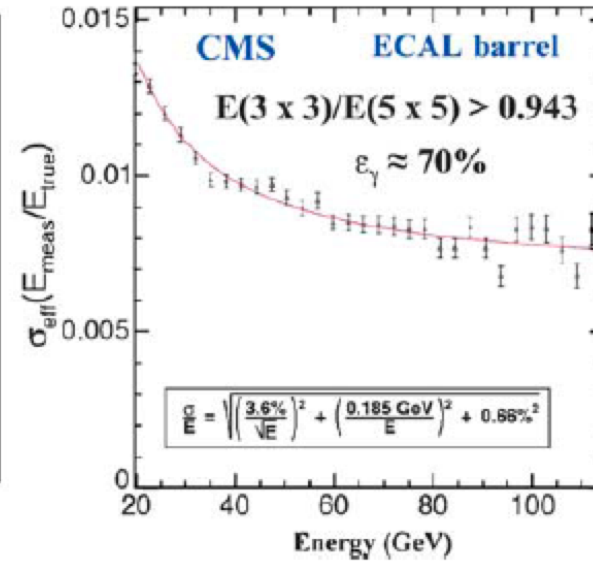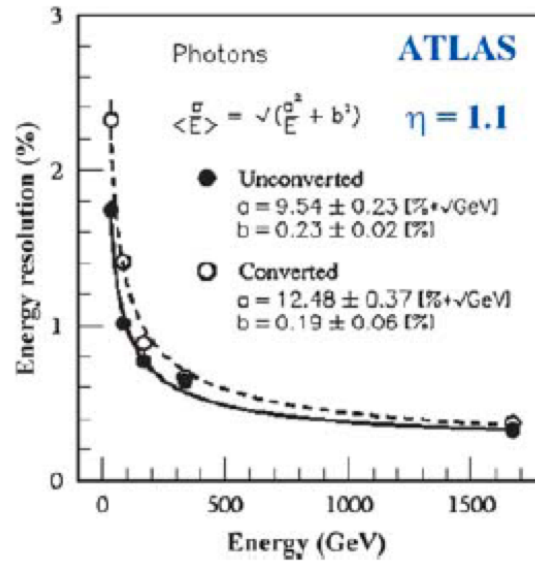**TABLE 9** Main parameters of the ATLAS and CMS hadronic calorimeters

	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.

ATLAS

Tile barrel

Tile extended barrel

LAr hadronic end-cap (HEC)

LAr electromagnetic end-cap (EMEC)

LAr electromagnetic barrel

LAr forward (FCal)

hadron calorimeter as return yoke

Central Solenoid 2 T in centre

Methods in Experimental Particle Physics

ATLAS-CMS: calorimeters

Methods in Experimental Particle Physics

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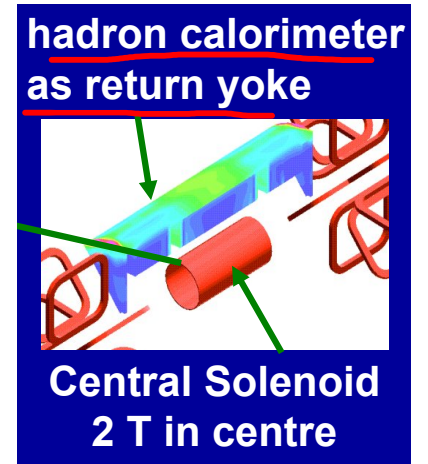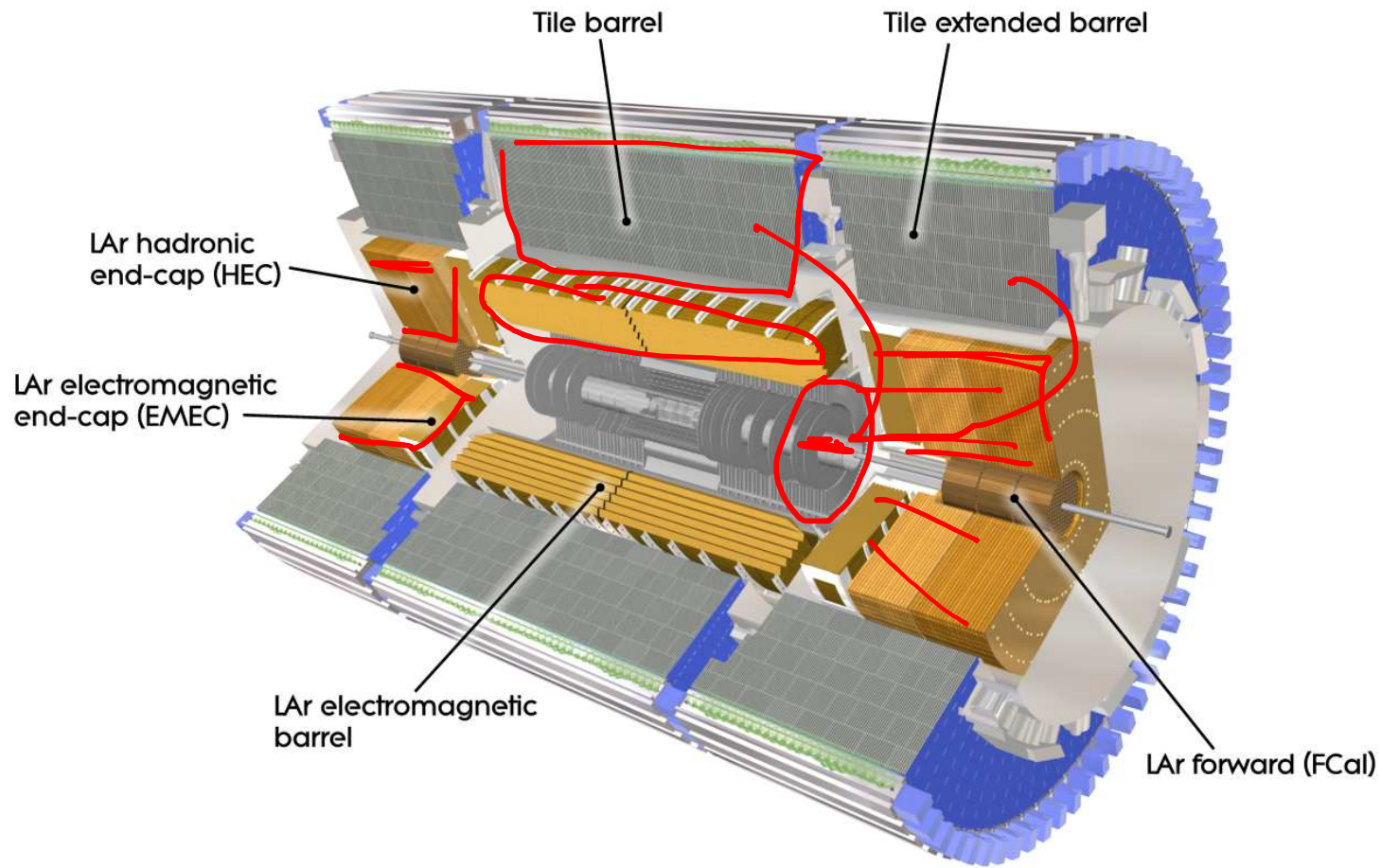
ATLAS-CMS: muons

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	—

Momentum measurement

Momentum measurement

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

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

We define the "sagitta" **s** and suppose to measure it through 3 points x_1, x_2 and x_3: $s = x_2 - (x_1 + x_3)/2$
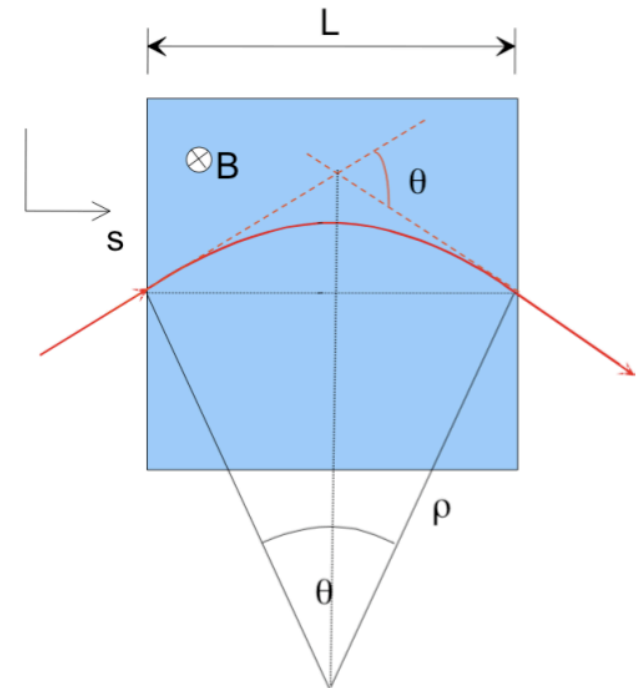
$$s = \frac{0.3BL^2}{8p_T}$$

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:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{720}{N+4}}\sigma_X \frac{p_T}{0.3BL^2}$$
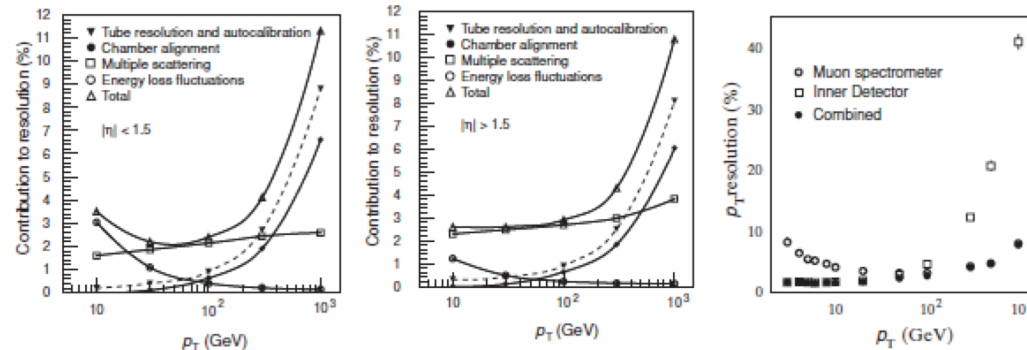
ATLAS-CMS: muon momentum resolutions

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.
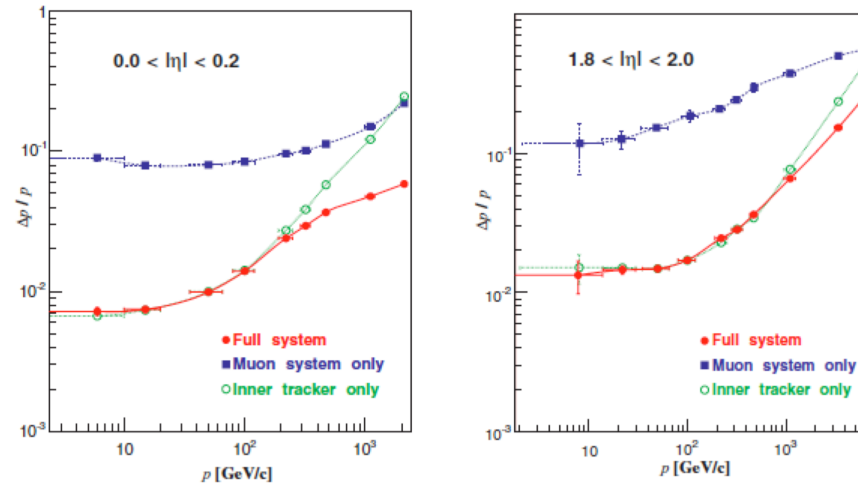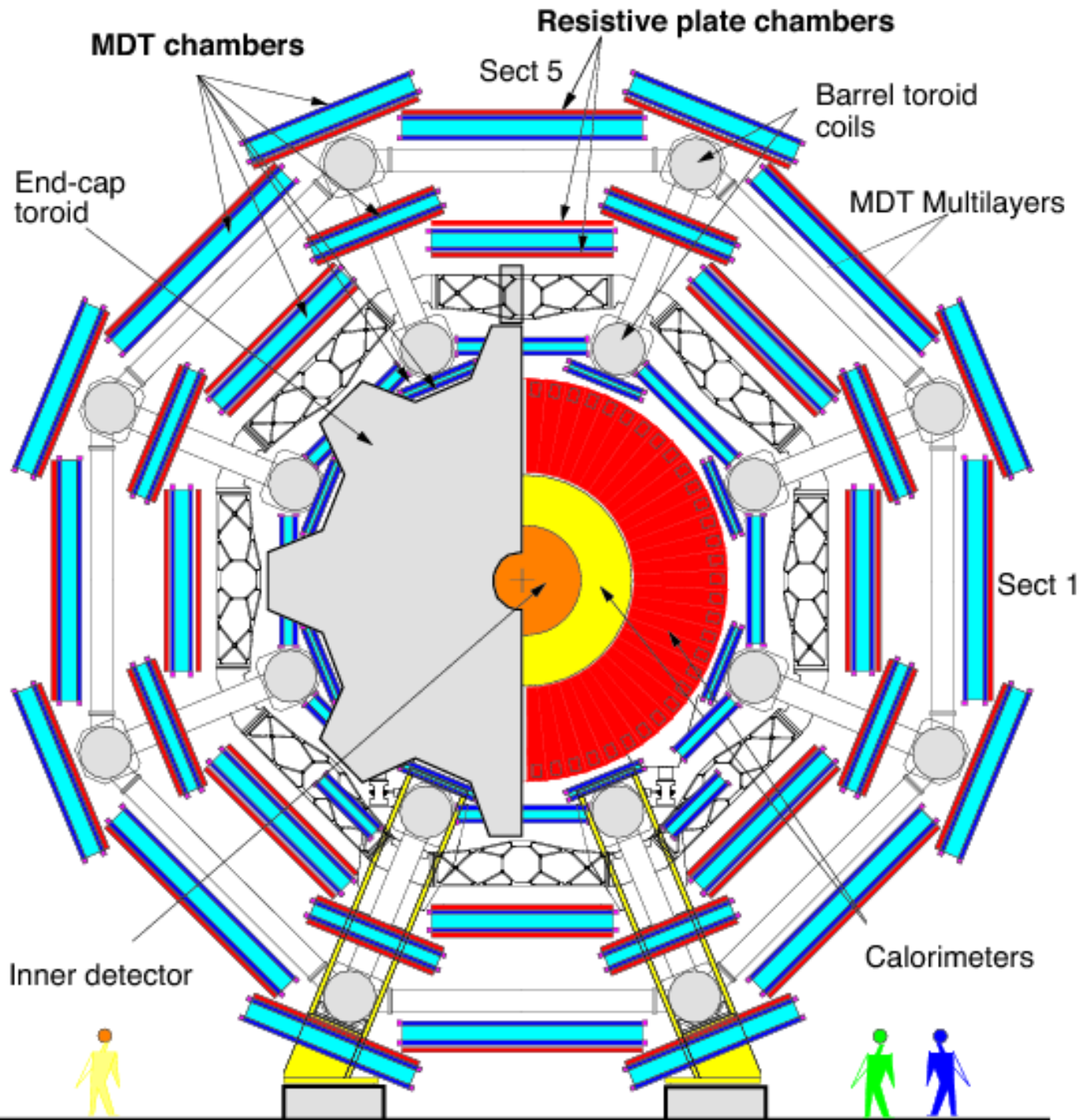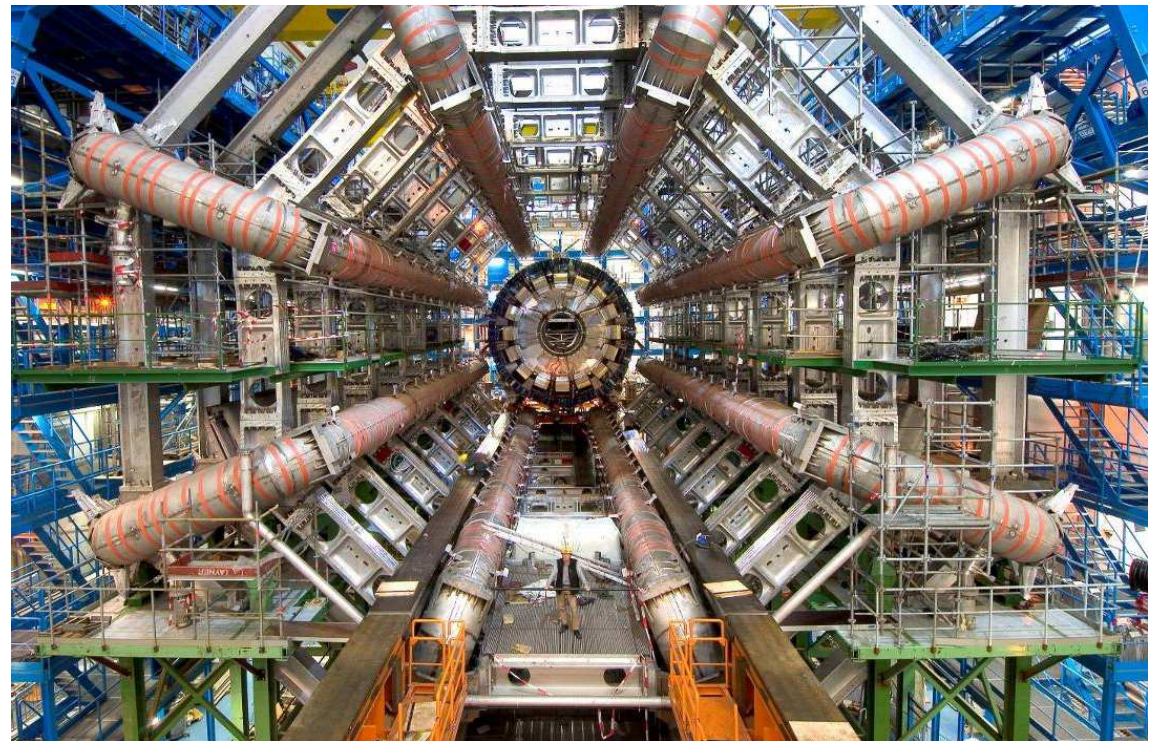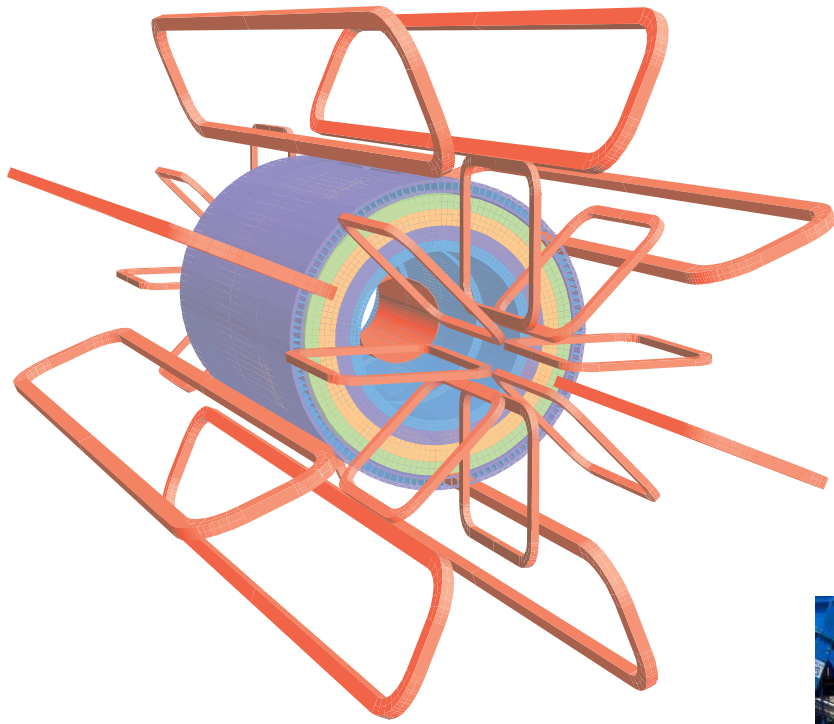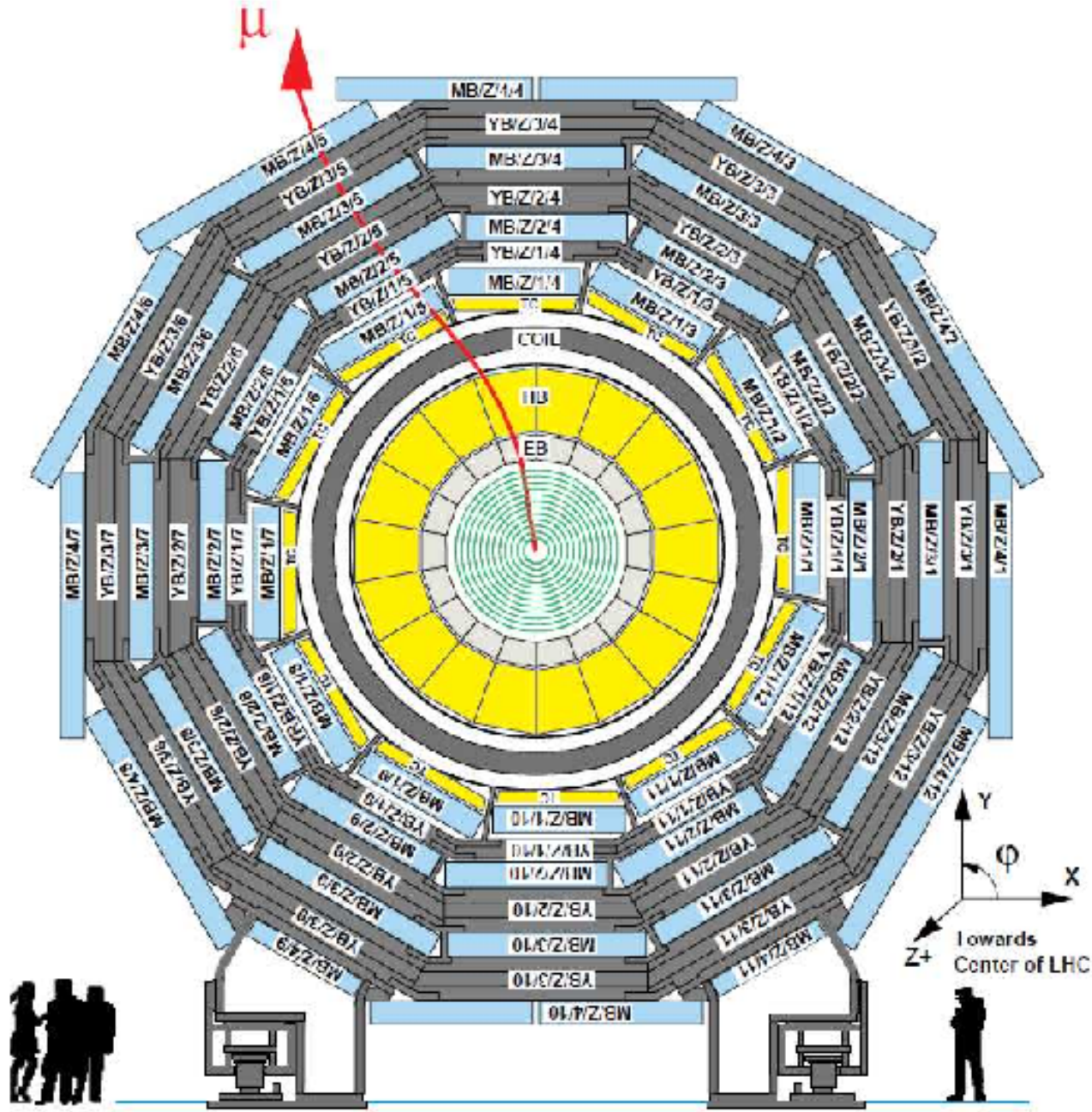

Figure 25 Expected performance of the CMS muon measurement. The muon momentum resolution is plotted versus momentum using the muon system only, the inner tracker only, or their combination (full system). (*Left*) Barrel, with $|\eta| < 0.2$. (*Right*) End cap, with $1.8 < |\eta| < 2.0$.

Methods in Experiment

ATLAS

MDT chambers

Resistive plate chambers

Sect 5

Barrel toroid coils

End-cap toroid

MDT Multilayers

Sect 1

Inner detector

Calorimeters

Method

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Methods in Experimental Particle Physics

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 calorimetry are situated inside the solenoid coil and therefore bathed in the strong 4 T 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.
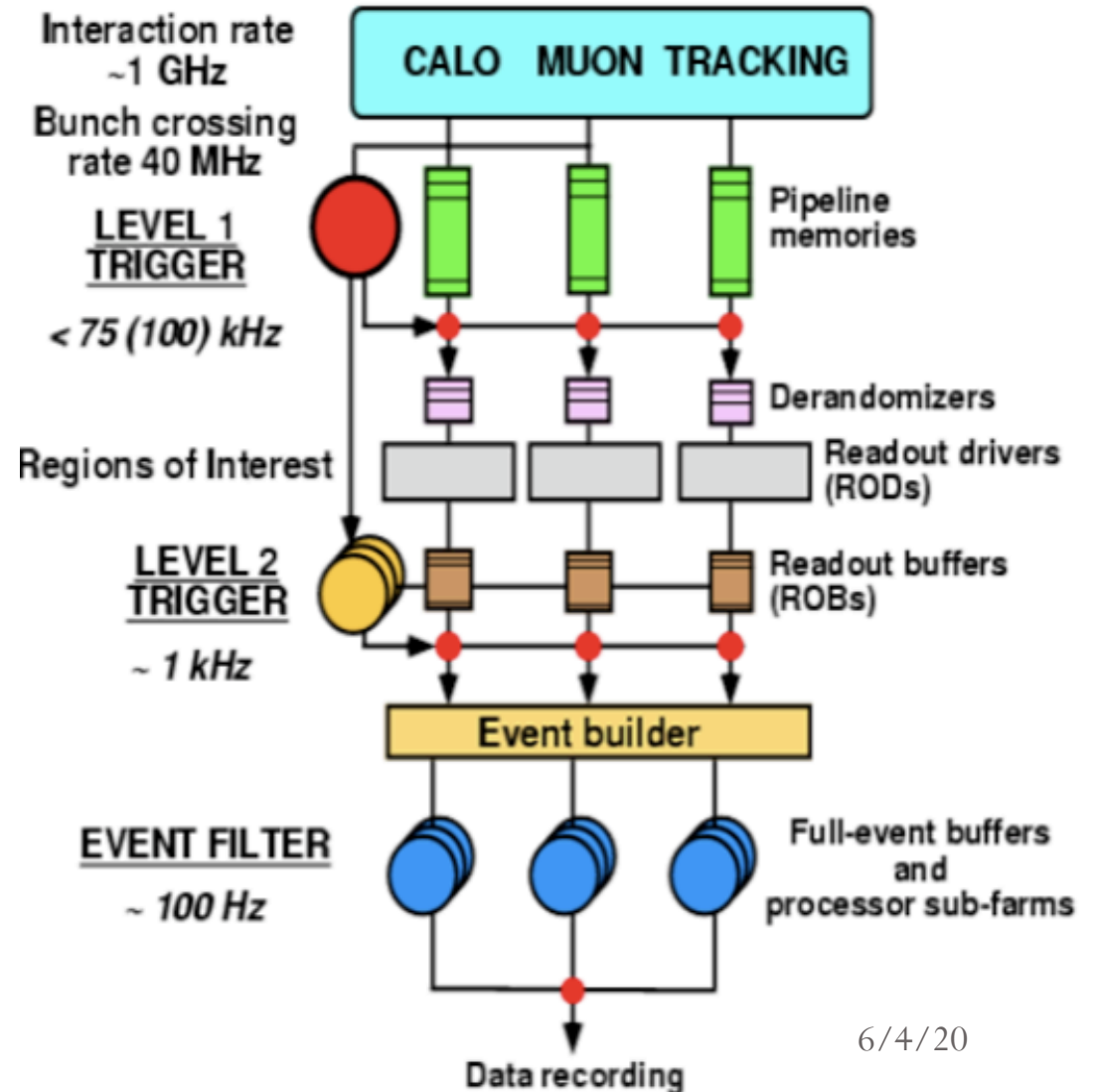
An important quest for pp experiments: the *Trigger*

$$\dot{N} = \sigma_{tot} L \approx 10^{-25} cm^2 \times 10^{32 \div 34} cm^{-2} s^{-1} = 10 MHz \div 1 GHz$$
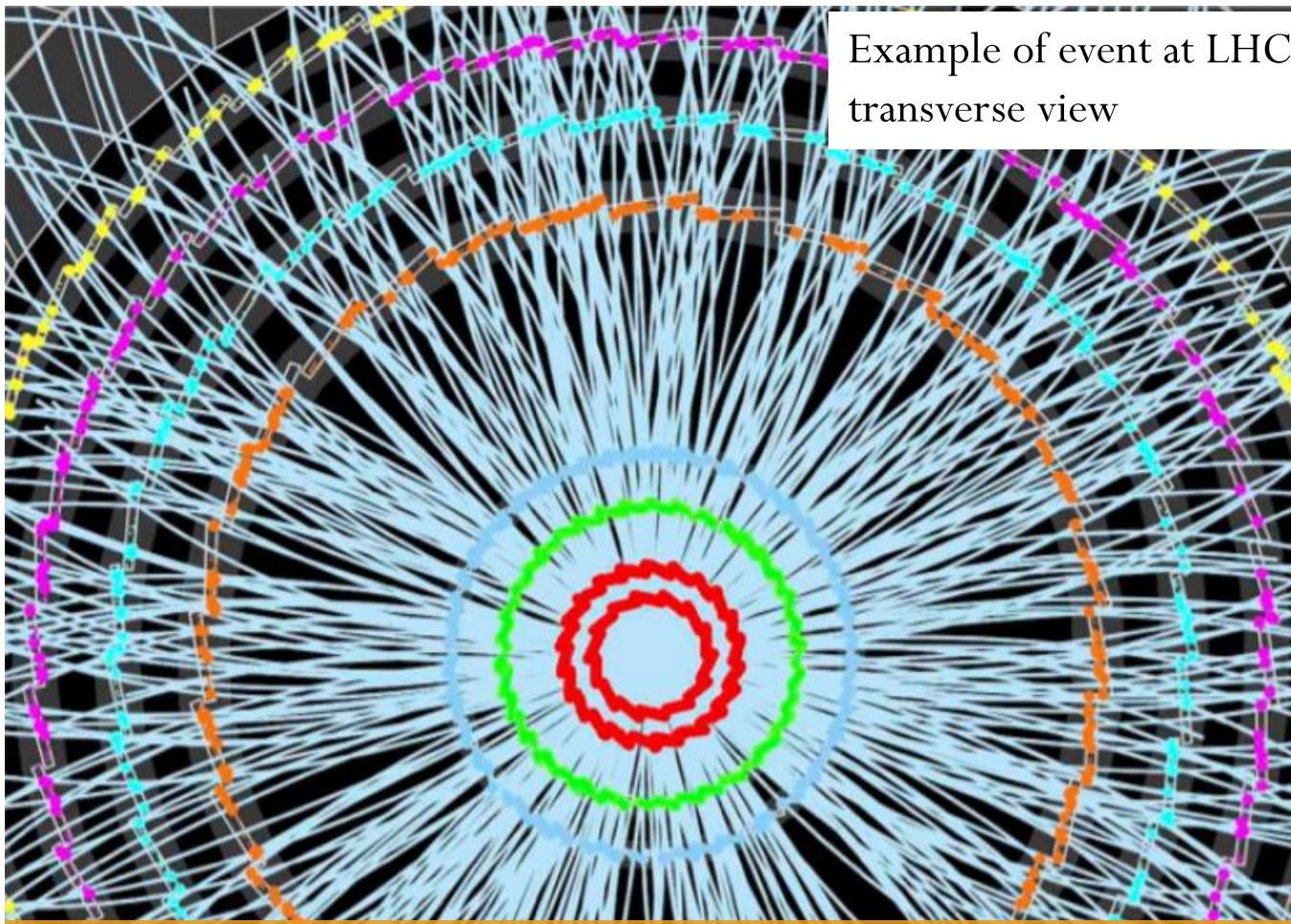
bunch crossing rate = 40 MHz
➔ every b.c. contains at least
an interaction (25/b.c. at max L)

- 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.*

Interaction rate ~1 GHz
Bunch crossing rate 40 MHz
LEVEL 1 TRIGGER
< 75 (100) kHz
Regions of Interest
LEVEL 2 TRIGGER
~ 1 kHz
EVENT FILTER
~ 100 Hz

CALO   MUON   TRACKING
Pipeline memories
Derandomizers
Readout drivers (RODs)
Readout buffers (ROBs)
Event builder
Full-event buffers and processor sub-farms
Data recording

Methods in Experimental Particle Physics

Example of event at LHC transverse view

17 reconstructed vertices

ATLAS EXPERIMENT
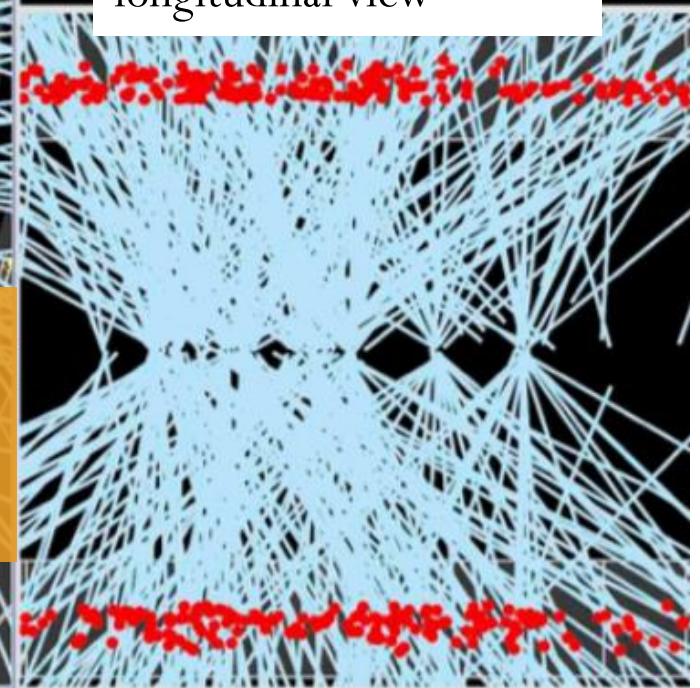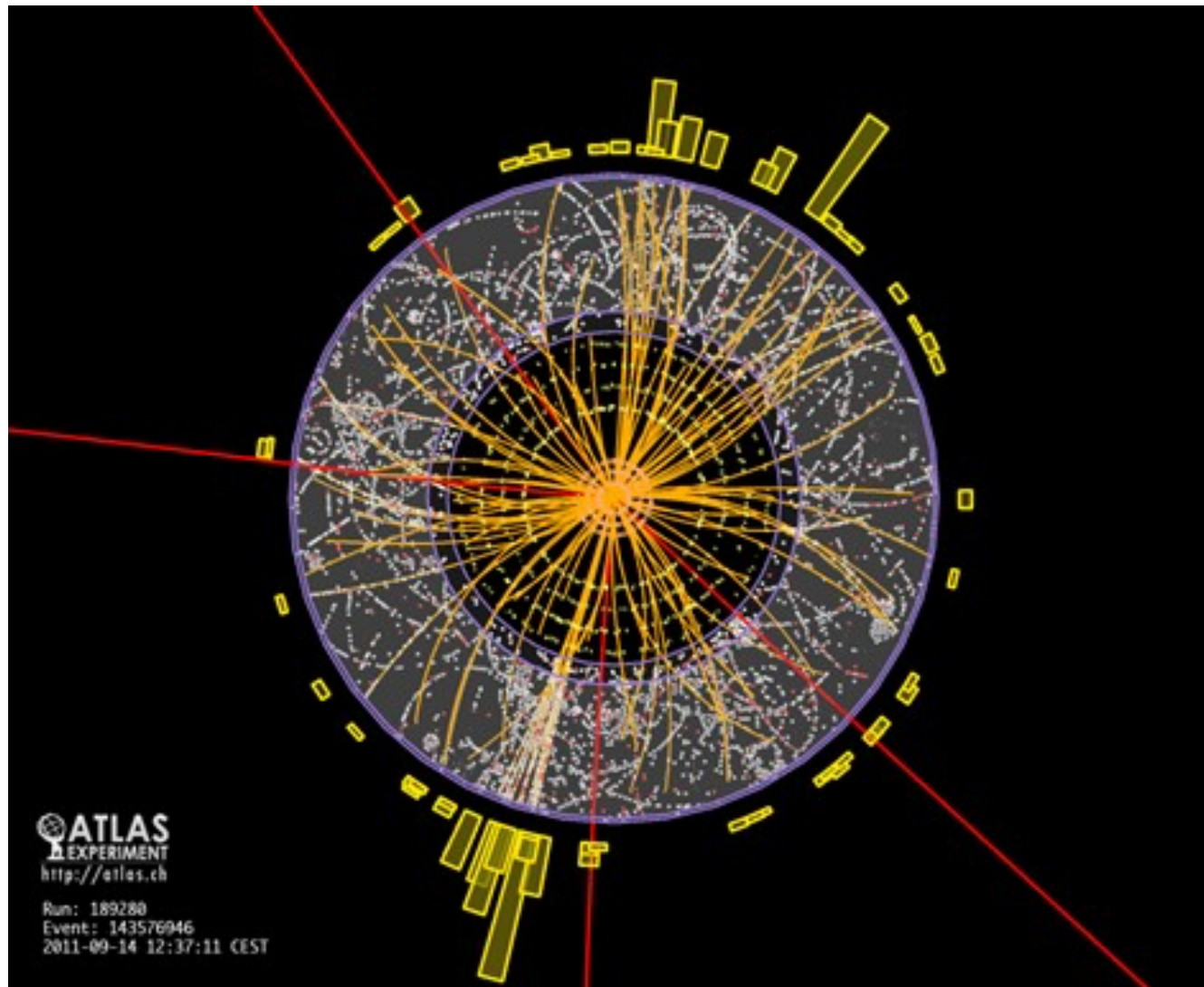
Run Number: 266904, Event Number: 25884805

Date: 2015-06-03 13:41:54 CEST

Example of event at LHC longitudinal view

Up to ~ 10k charged particles per event. Need to reconstruct every one efficiently, precisely and quickly

Methods in Experimental Particle Physics

Run Number: 190300,
Event Number: 60554334
Date: 2011-10-04, 05:25:26 CET

EtCut>0.3 GeV
PtCut>3.0 GeV
Vertex Cuts:
Z direction <1cm
Rphi <1cm

Muon: blue
Cells:Tiles, EMC

Persint