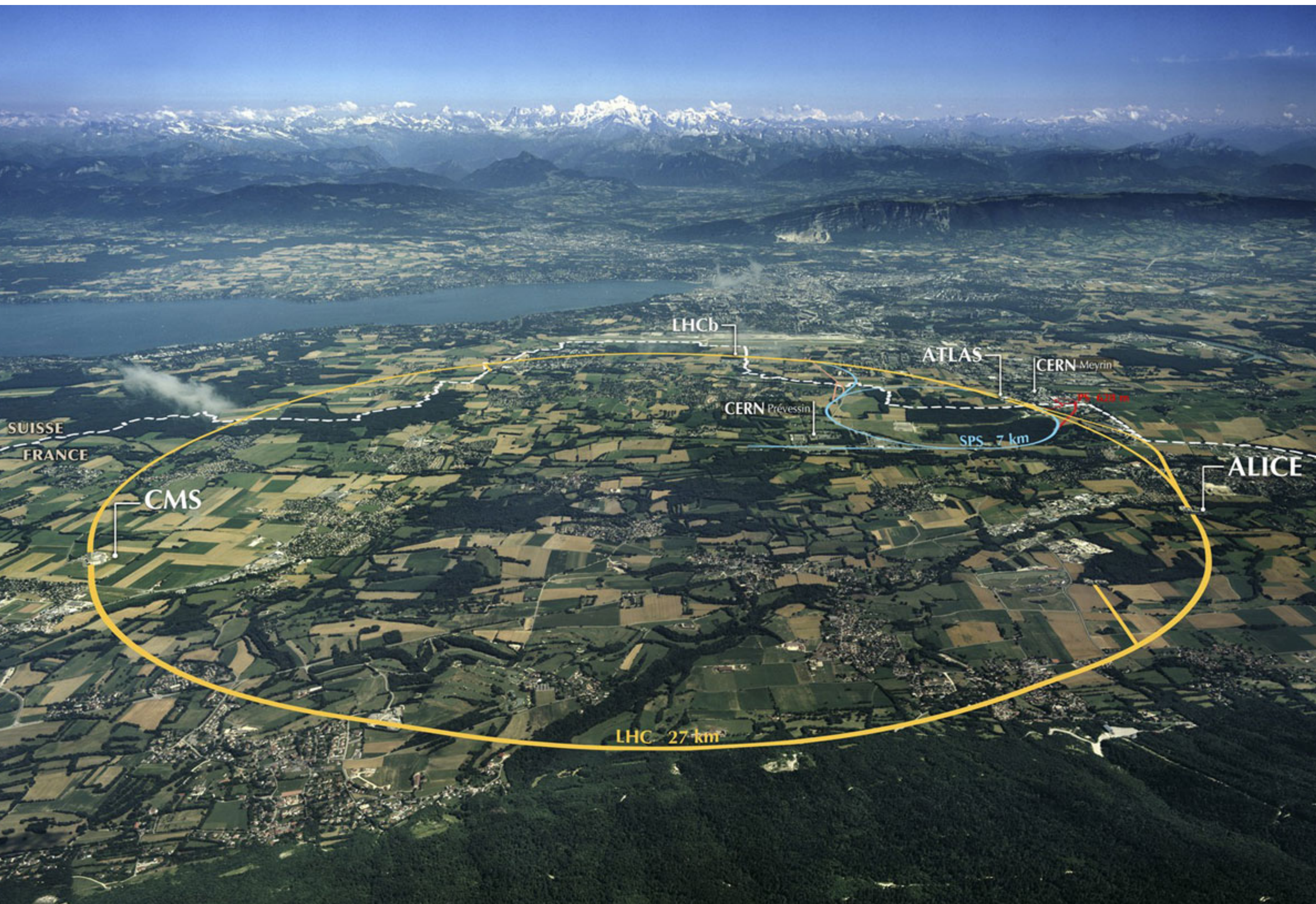
Experimental particle physics

5. particle experiment design (and a a few words on S/B optimization)

European School of Instrumentation in Particle & Astroparticle Physics

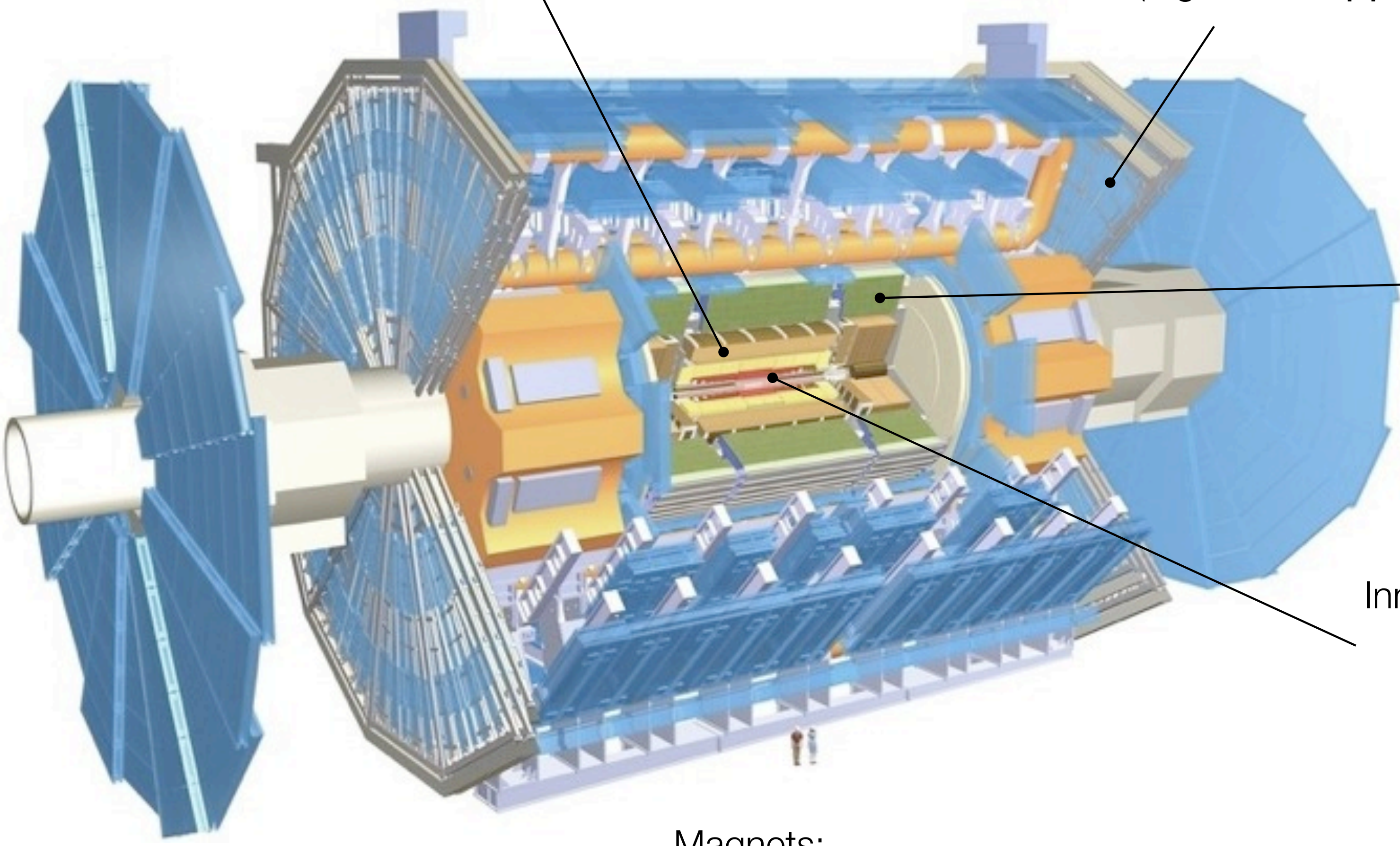

LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

The ATLAS detector

[expected perfomance]

EM Calorimeters: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$
- excellent e/γ identification
- good energy resolution (e.g. for $H \to \gamma\gamma$)

Precision Muon Spectrometer: $\sigma/p_t \approx 10\%$ @ 1 TeV
- fast trigger response
- good momentum resolution
- (e.g. $A/Z' \to \mu\mu$, $H \to 4\mu$)



Hadron Calorimeter:
- $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$
- good jet resolution
- good missing E_T resolution
- (e.g. $H \to \tau\tau$)

Inner Detector:
- Si Pixel & strips; TRT
- $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$
- good impact parameter res., i.e.
- $\sigma(d_0) \approx 15\ \mu m$ @ 20 GeV
- (e.g. $H \to bb$)

Magnets:
- Solenoid (inner detector): 2 T
- Toroid (muon spectrometer): 0.5 T

The CMS detector

[expected perfomance]

EM Calorimeters:

$\sigma/E \approx 3\%/\sqrt{E} \oplus 0.5\%$

[vs. ATLAS: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$]

Inner Detector:

$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$

[vs. ATLAS $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$]

Hadron Calorimeter:

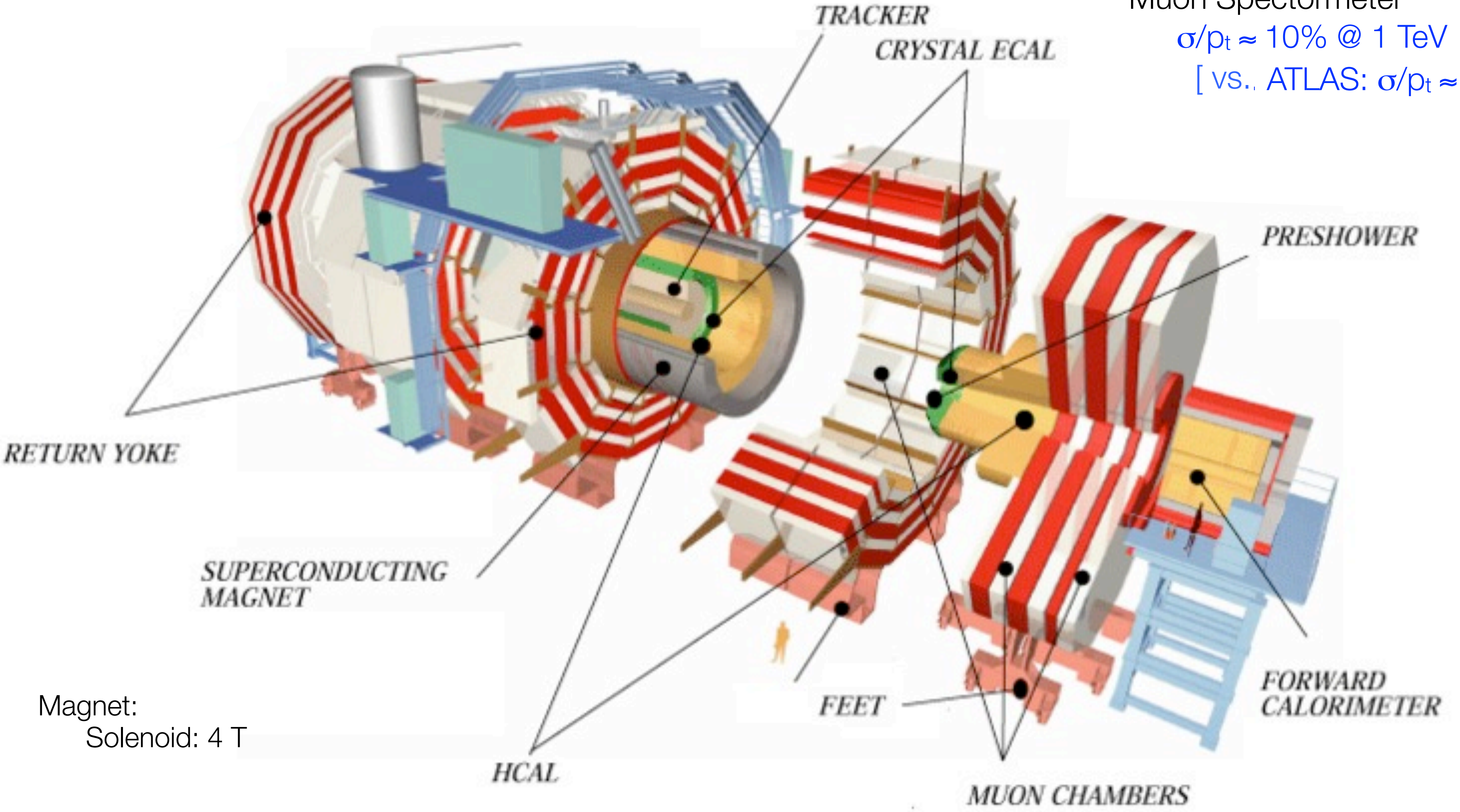
$\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$

[vs. ATLAS: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$]

Muon Spectormeter

$\sigma/p_t \approx 10\%$ @ 1 TeV

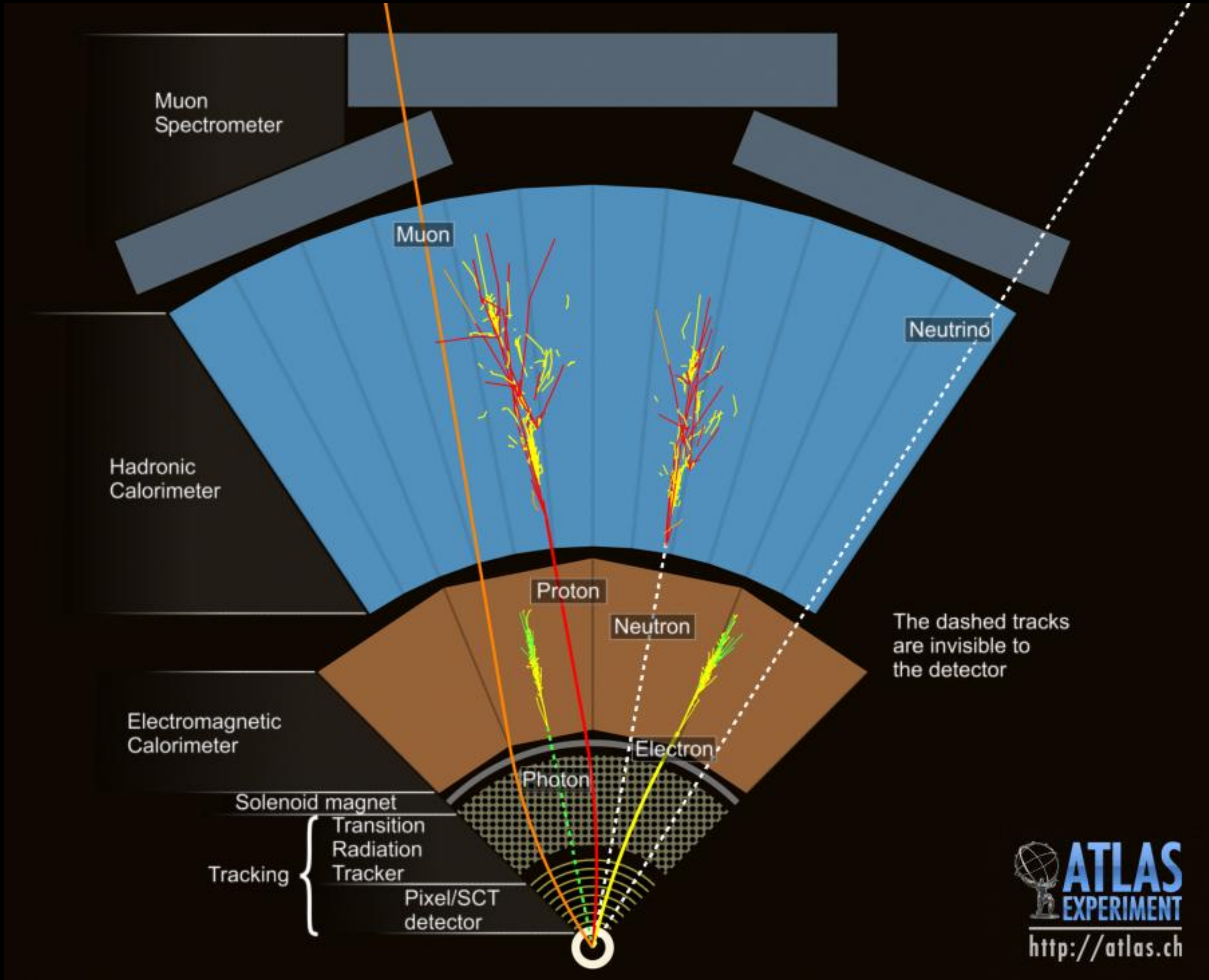
[vs., ATLAS: $\sigma/p_t \approx 10\%$ @ 1 TeV]



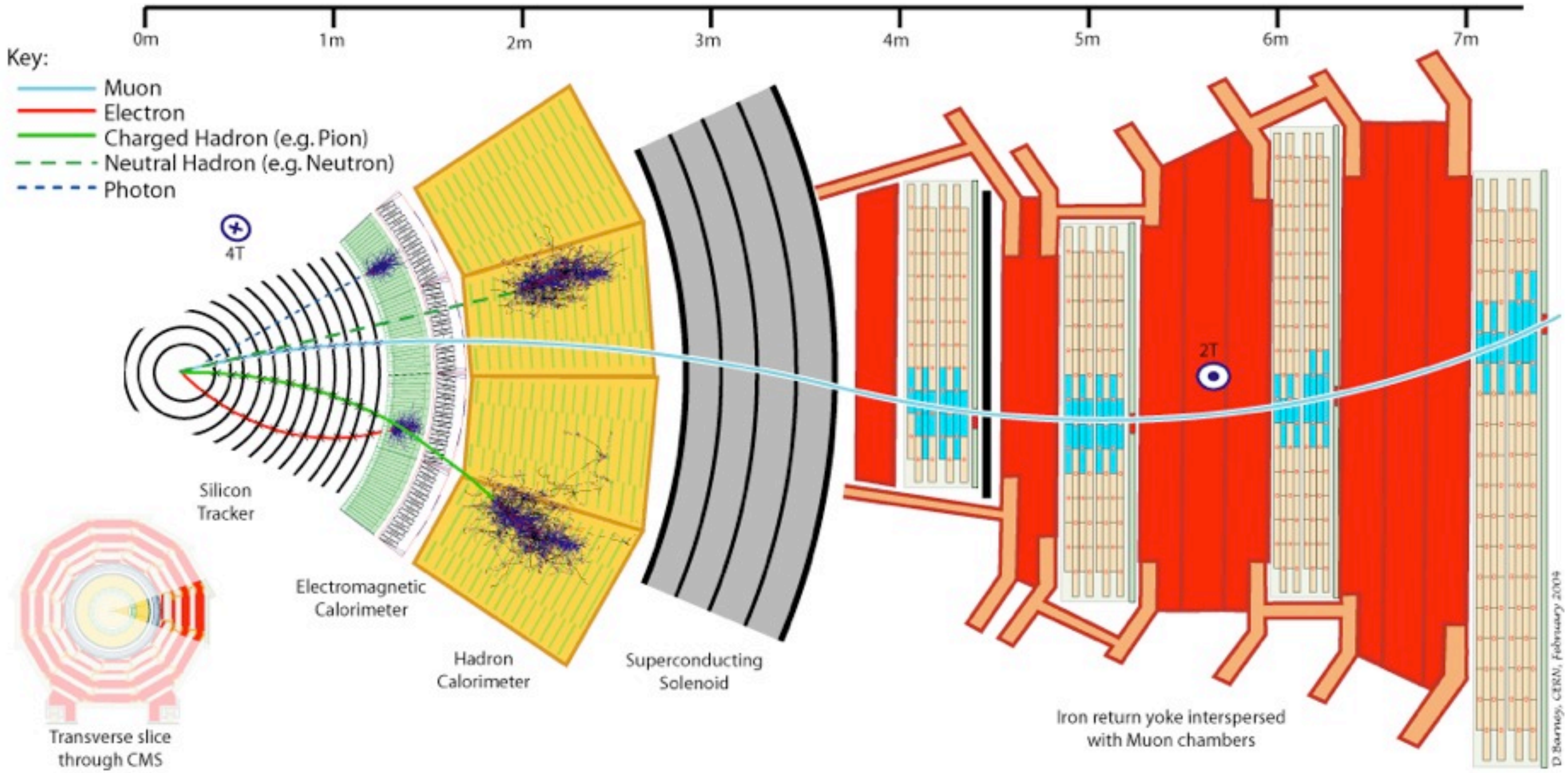
Magnet:

Solenoid: 4 T

The ATLAS detector



The CMS detector



Main Design Parameters Comparison

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

This table (and others) from:
Daniel Froidevaux and Paris Sphicas, "GENERAL-PURPOSE DETECTORS FOR THE LARGE HADRON COLLIDER",
Annu. Rev. Nucl. Part. Sci. 2006. 56:375–440

ATLAS vs. CMS

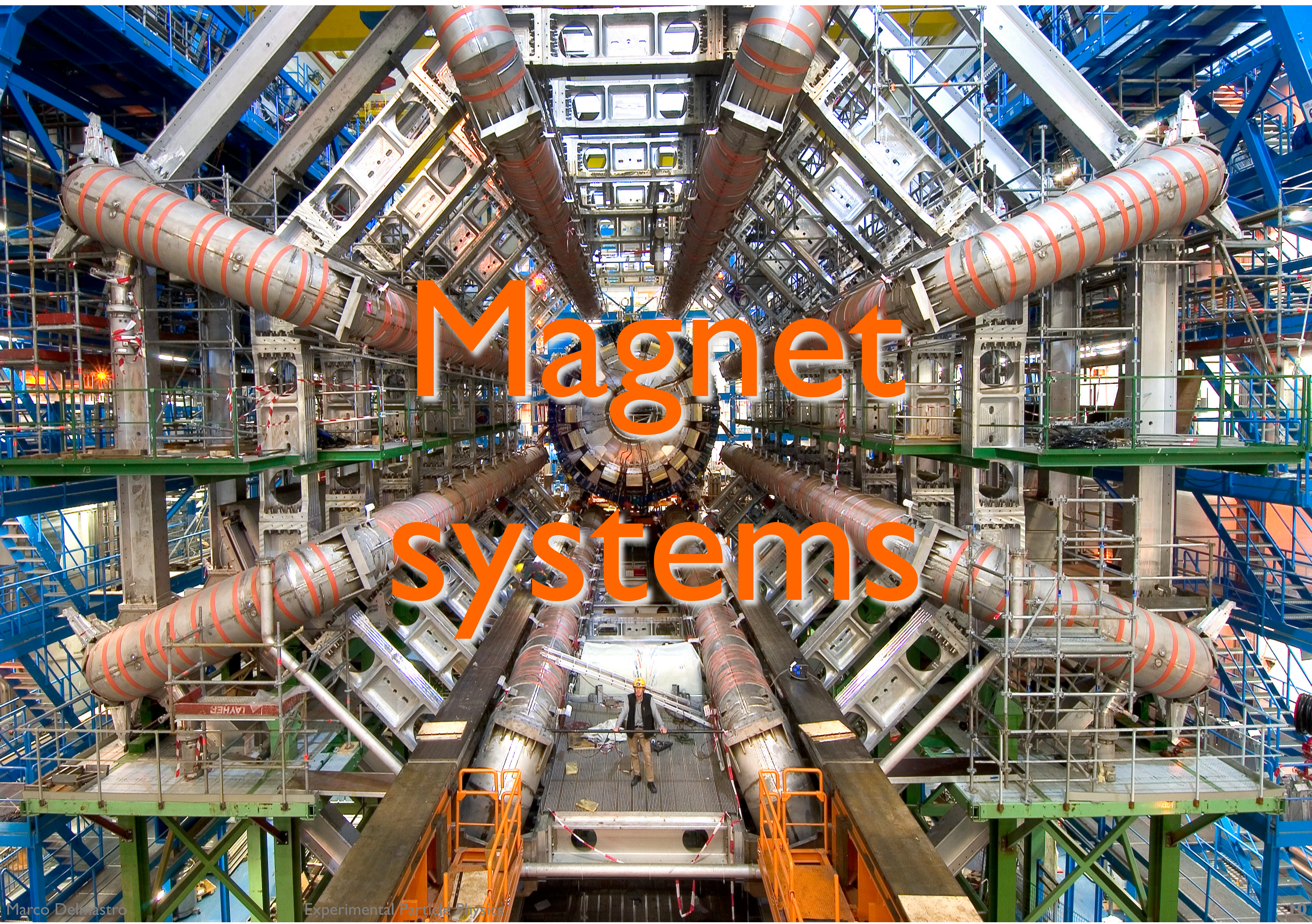
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel; 1 T end-cap)	4 T solenoid + return yoke
Tracker	Si pixels and strips + TRT $\sigma / p_T \approx 5 \times 10^{-4} p_T + 0.01$	Si pixels and strips $\sigma / p_T \approx 1.5 \times 10^{-4} p_T + 0.005$
EM calorimeter	LAr + Pb $\sigma / E \approx 10\%/\sqrt{E} \oplus 0.007$	$PbWO_4$ crystals $\sigma / E \approx 2\text{-}6\%/\sqrt{E} \oplus 0.005$
Hadronic calorimeter	Scint. + Fe / LAr + Cu (10 λ) $\sigma / E \approx 50\%/\sqrt{E} \oplus 0.03$ GeV	Scint. + Cu (5.8 λ + catcher) $\sigma / E \approx 100\%/\sqrt{E} \oplus 0.05$ GeV
Muon spectrometer	$\sigma / p_T \approx 2\%$ @ 50 GeV – 10% @ 1 TeV (ID + MS)	$\sigma / p_T \approx 1\%$ @ 50 GeV – 5% @ 1 TeV (ID + MS)
Trigger	L1 + RoI-based HLT (L2 + EF)	L1 + HLT (L2 + L3)
σ_m / m_H ($H \rightarrow \gamma\gamma$)	1.2 GeV @ m_H = 120 GeV	0.7 GeV @ m_H = 120 GeV

- G.Aad et al (ATLAS Collaboration). J. Instrum. 3. s08003 (2008)
- S.Chatrchysn (CMS Collaboration), J. Instrum. 3. s08004 (2008)

Main design choices

- **ATLAS**
  - ✓ Invested much in three superconducting toroid magnets and a set of precise muon chambers
    - "This system provides a stand-alone muon momentum measurement"
  - ✓ Transition detector in the tracking system (electron vs. pions)
  - ✓ Sampling calorimeter
    - Mediocre energy resolution, longitudinal segmentation, fine lateral segmentation
  - ✓ Good HAD calorimeter
- **CMS**
  - ✓ Invested in highest possible magnetic field (4T)
  - ✓ Inner tracker consisting of all silicon detectors
  - ✓ Homogeneous EM Calorimeter
    - Excellent energy resolution, no longitudinal segmentation, coarse lateral segmentation
  - ✓ Mediocre HAD calorimeter

Magnet systems

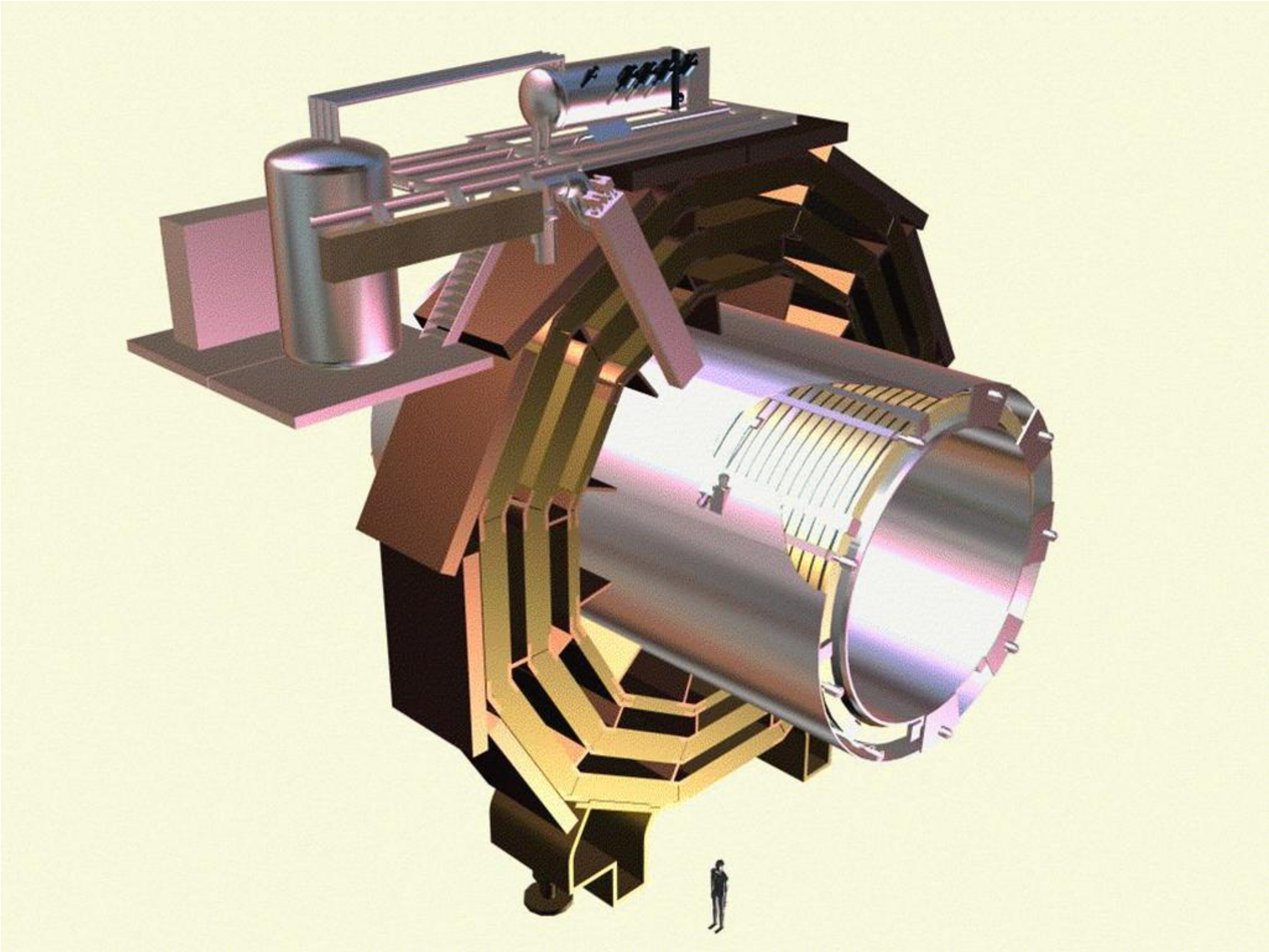


Magnet systems

- ATLAS
  - ✓ 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."*
- CMS
  - ✓ 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."*

ATLAS magnets

CMS magnet



Magnet systems

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

Inner tracker systems

Inner tracking systems

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 × 10
-cell size (μm in $R\phi$ × cm in z/R)		and 120/180 × 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)	

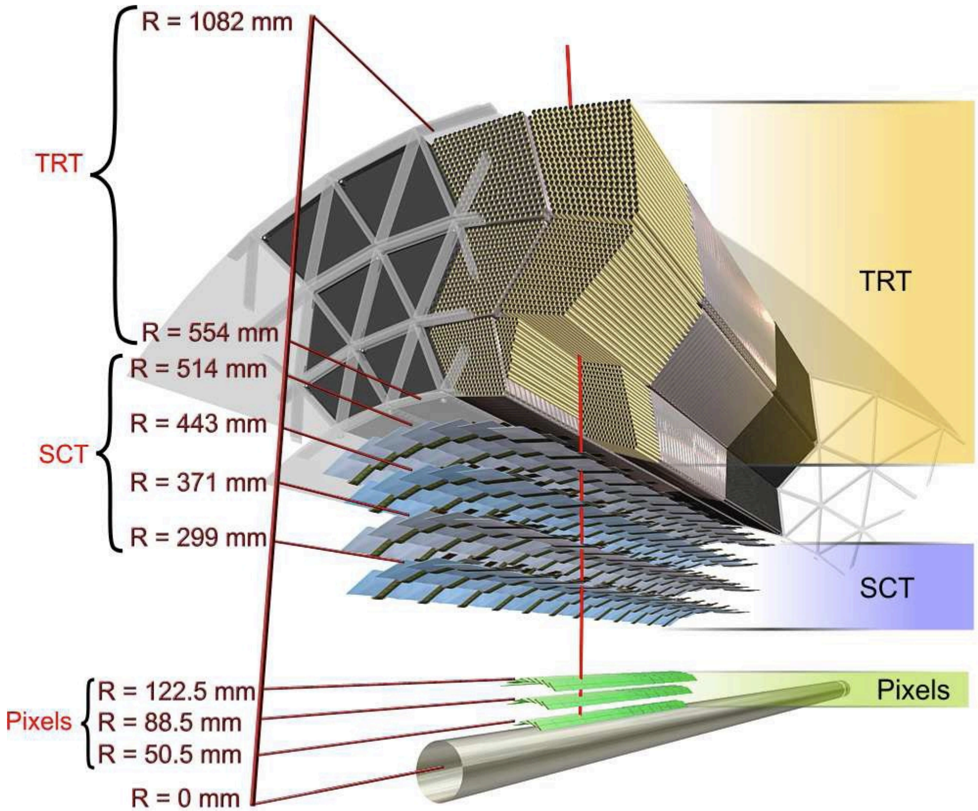
Pixel detectors

TABLE 6 Main parameters of the ATLAS and CMS pixel systems

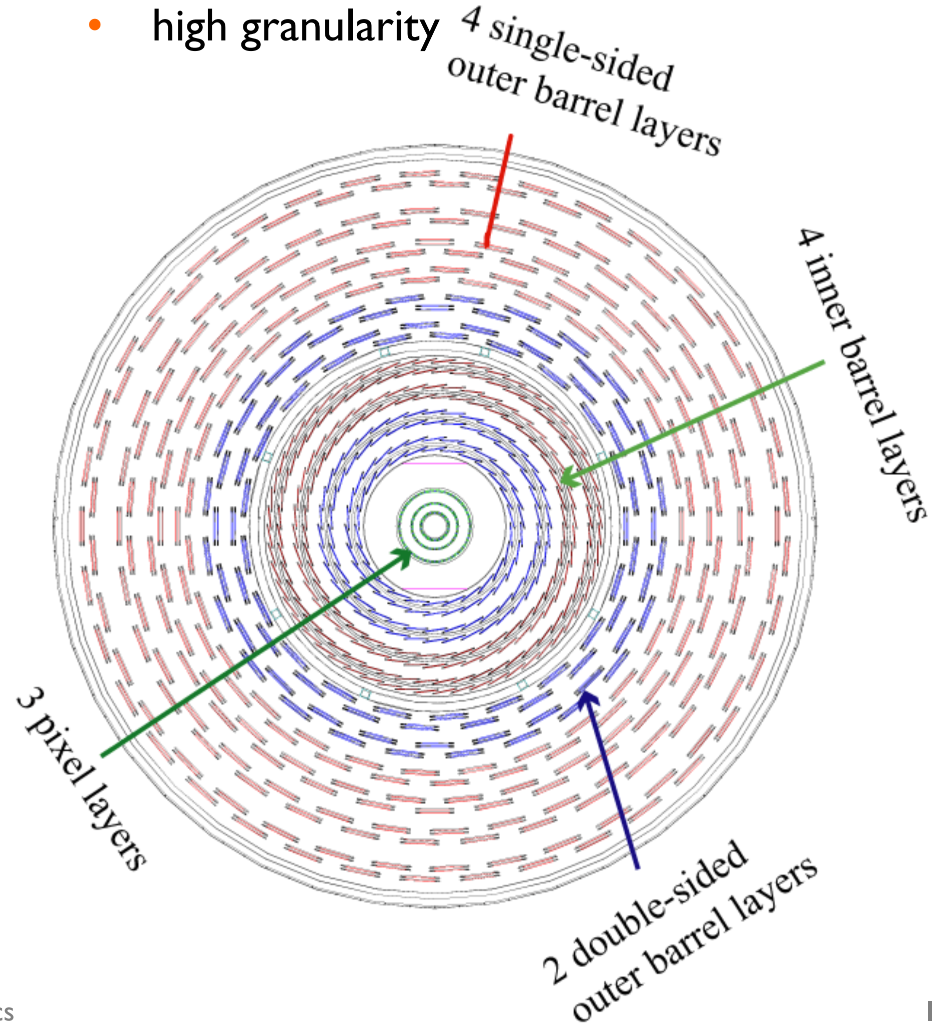
	ATLAS	**CMS**
Number of hits per track	3	3
Total number of channels	$80\ 10^6$	$66\ 10^6$
Pixel size (μm in $R\phi$ × μm in z/R)	50×400	100×150
Lorentz angle (degrees), initial to end	12 to 4	26 to 8
Tilt in $R\phi$ (degrees)	20 (only barrel)	20 (only end cap)
Total active area of silicon (m^2)	1.7 (n^+/n)	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 $10^{15}\ n_{eq}/\mathrm{cm}^2$)	80	80
Resolution in $R\phi$ (μm)	≈10	≈10
Resolution in z/R (μm)	≈100	≈20

Inner tracking systems

- **ATLAS**
  - ✓ Solenoidal field: 2 T
  - ✓ Silicon (strips and pixels) + TRT
    - high granularity and resolution close to interaction region
    - "continuous" tracking at large radii



- **CMS**
  - ✓ Solenoidal filed: 4 T
  - ✓ Full silicon strip and pixel detectors
    - high resolution
    - high granularity

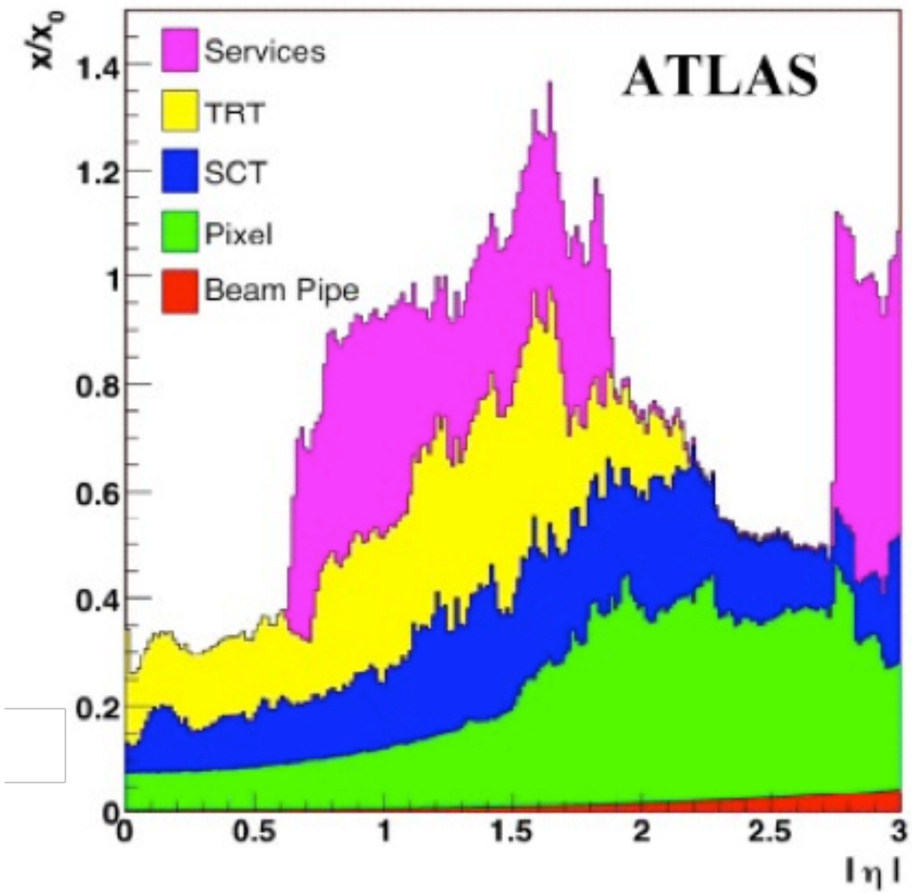


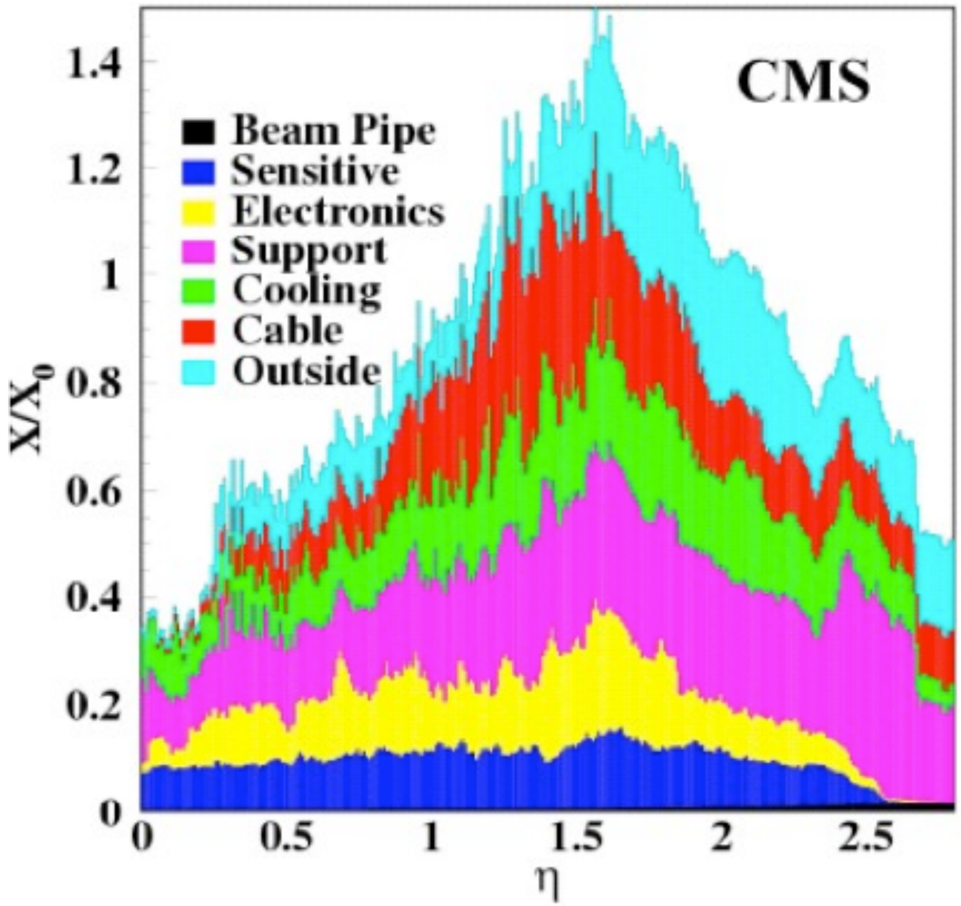
Main performance of tracking systems

	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	900	1060

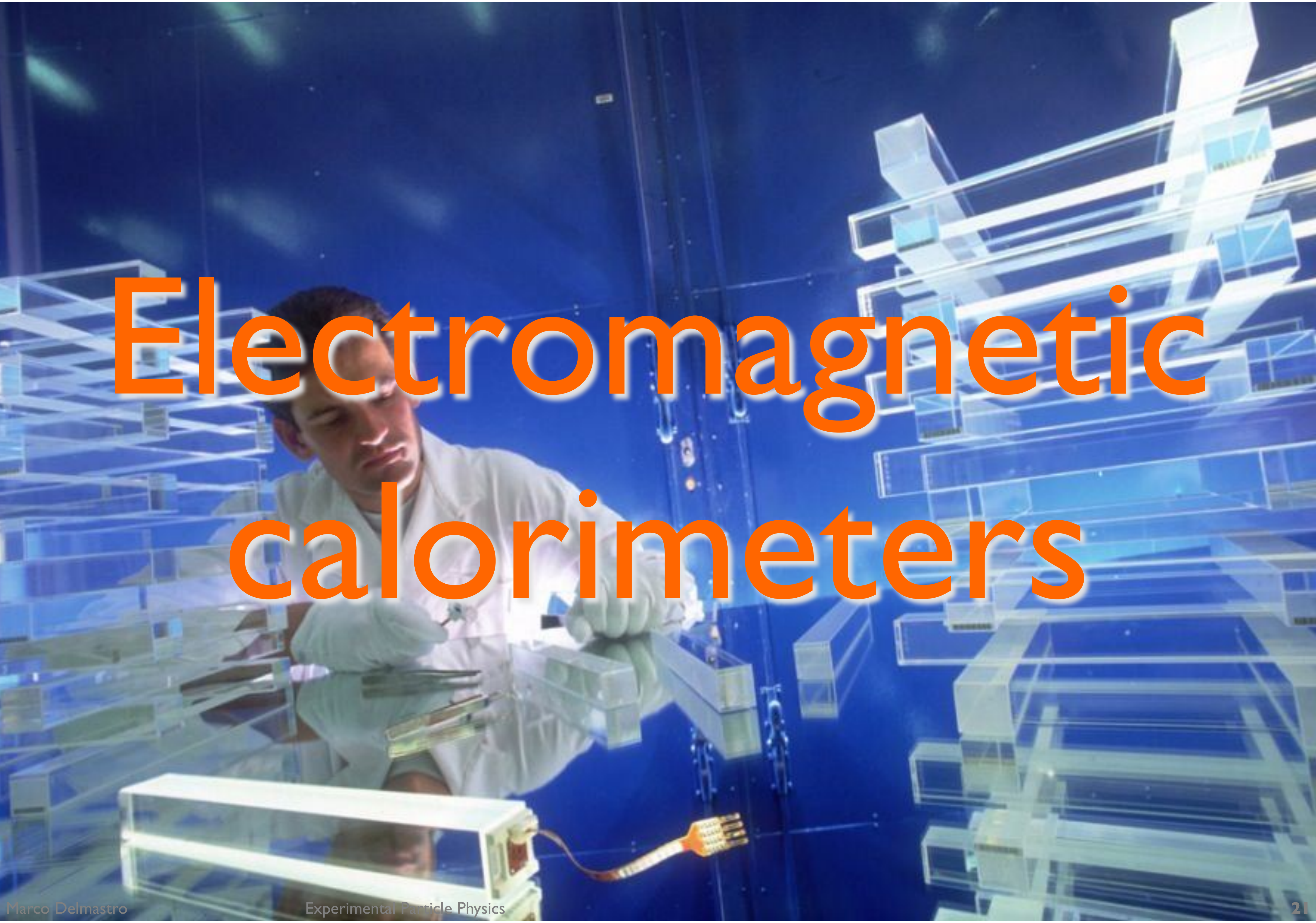
- Momentum resolution on average superior in CMS
- Similar vertexing and b-tagging performances are similar
- Impact of material and B-field already visible on efficiencies

Amount of material in inner trackers





- Active sensors and mechanics account each only for ~10% of material budget
- Need to bring ~70 kW power into tracker and to remove similar amount of heat
  - ✓ Very distributed set of heat sources and power-hungry electronics inside volume
  - ✓ Complex layout of services, most of which are difficult to properly implement in detector simulation (calorimeter calibration!)



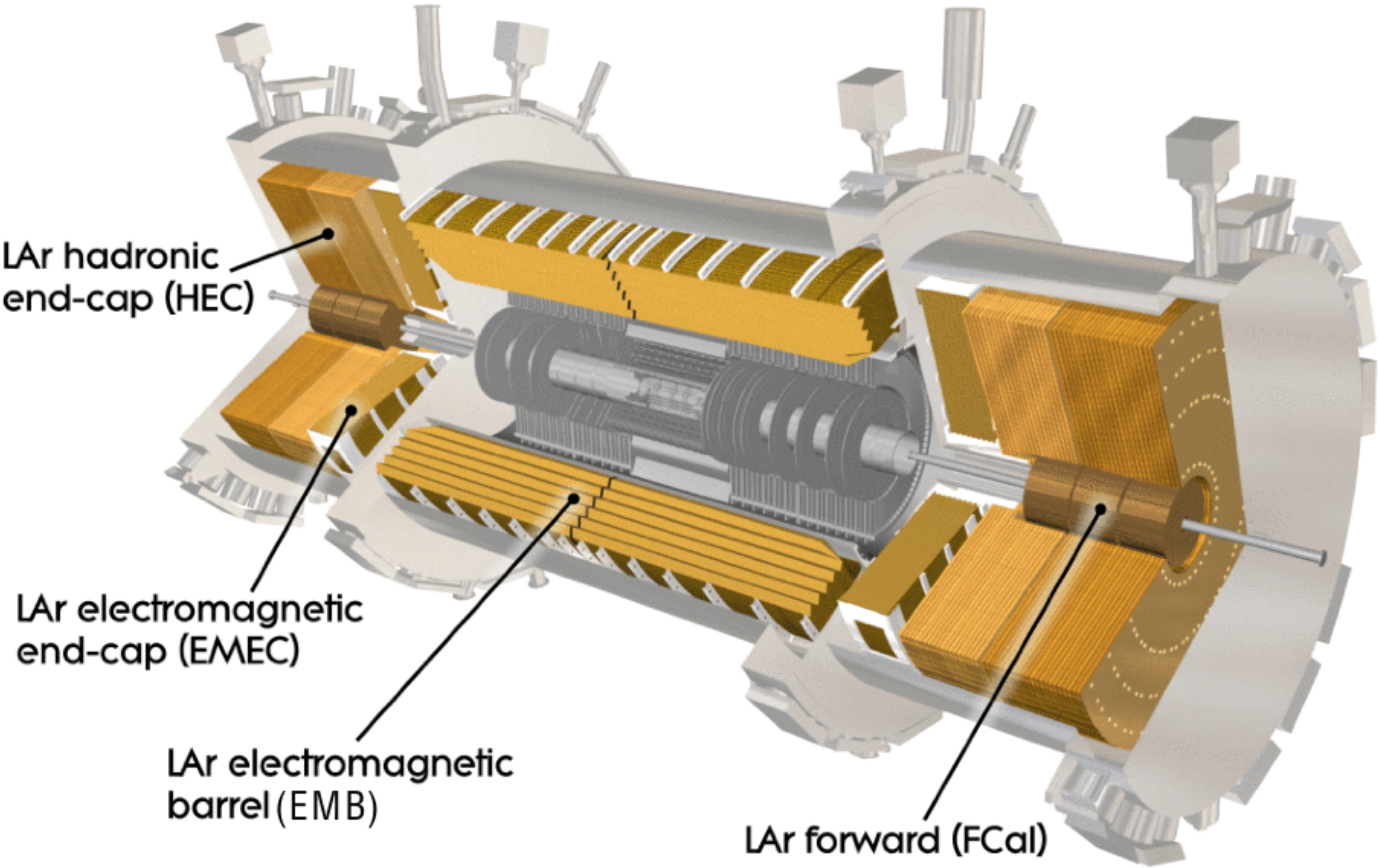
Electromagnetic calorimeters

Electromagnetic calorimeter

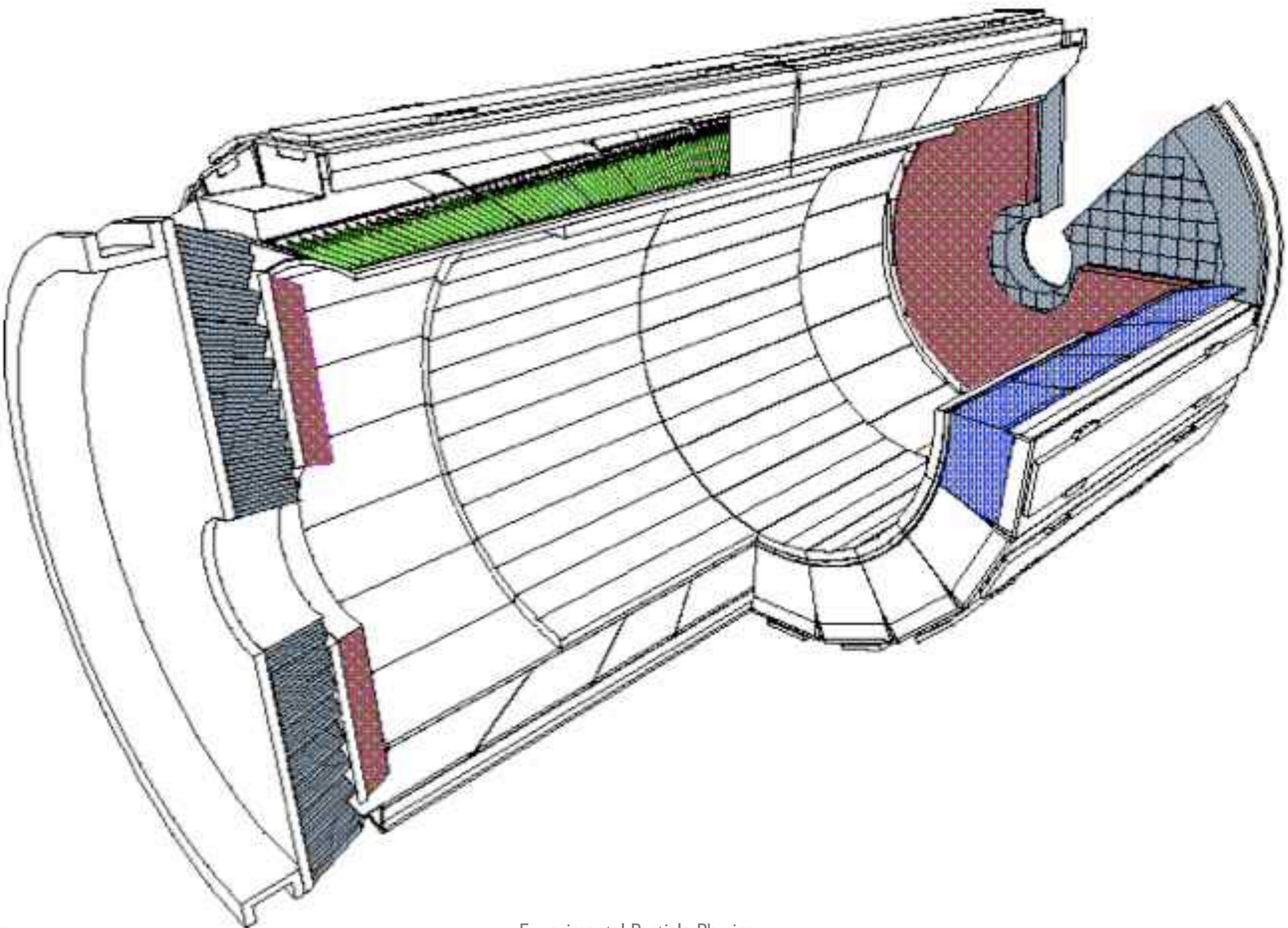
- **ATLAS**
  - ✓ EM calorimeter is outside inner solenoidal field
    - More material in front, energy losses, photon conversions
  - ✓ Sampling calorimeter
    - Liquid argon + Pb
    - Worse energy resolution
    - High granularity and segmentation (eta, phi, longitudinally)
      - better PID and rejection
      - position measurement for photons
  - ✓ Electrical signals
    - High stability in calibration and radiation resistant

- **CMS**
  - ✓ EM calorimeter is bathed in magnetic field
    - Shower shape distortion
  - ✓ Homogenous calorimeter
    - PbWO4 crystal calorimeter
    - Higher intrinsic resolution
    - Poorer segmentation
  - ✓ Light signals
    - Crystal light response vary with radiation, calibration vs. time complicated

ATLAS electromagnetic calorimeter



CMS electromagnetic calorimeter



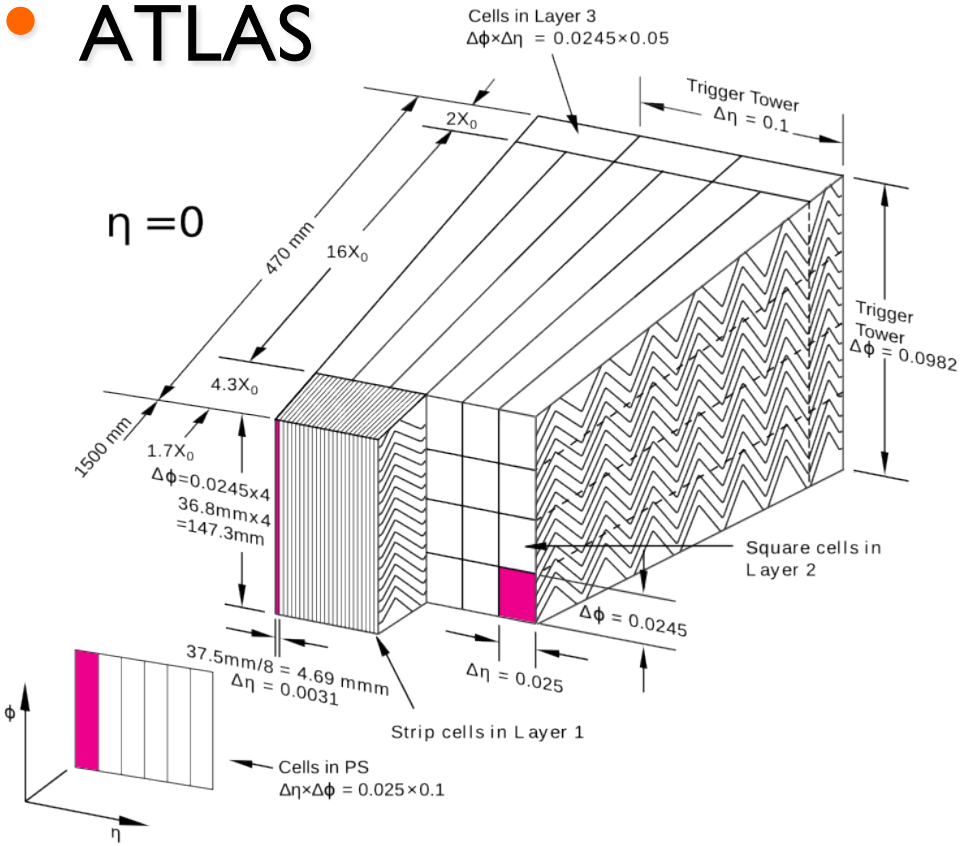
Electromagnetic calorimeters

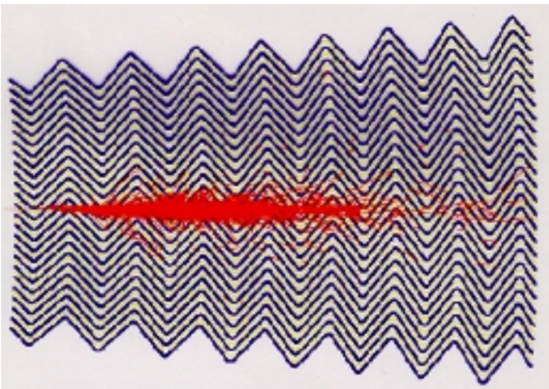
TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	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%

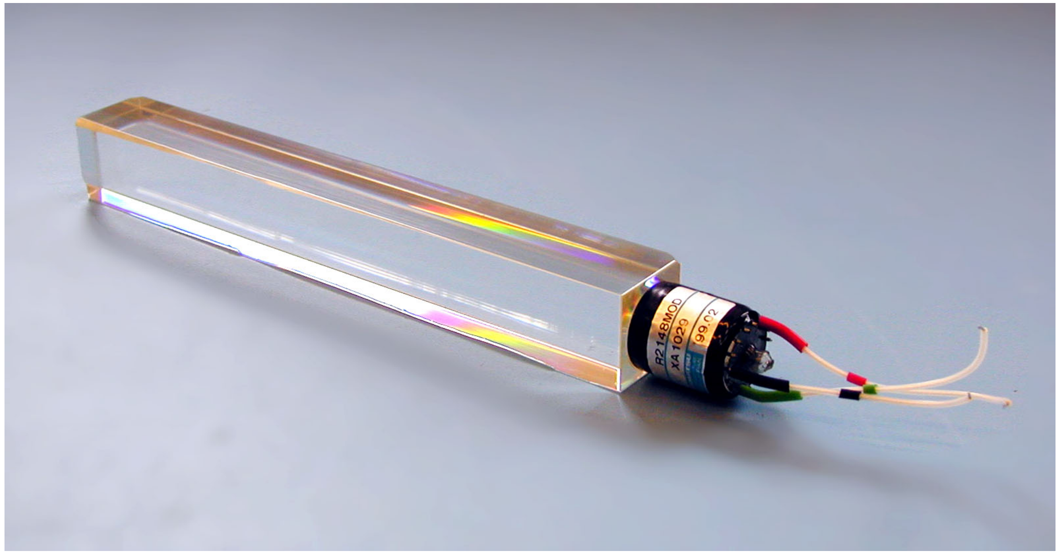
Electromagnetic calorimeters

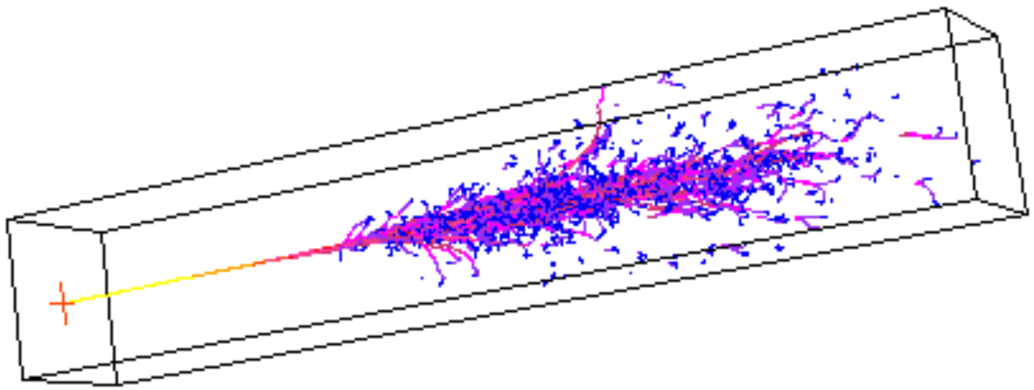
- ATLAS



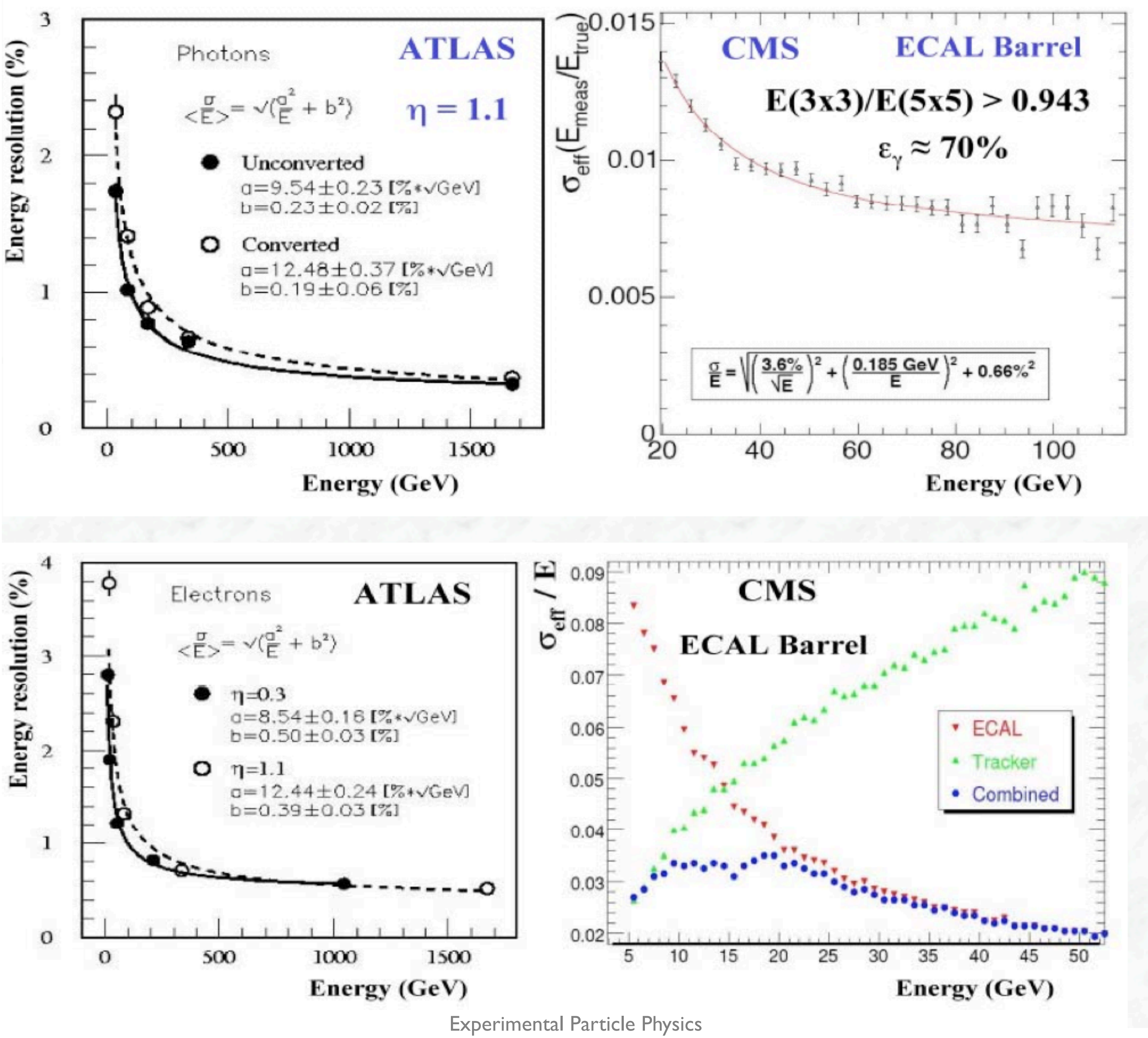


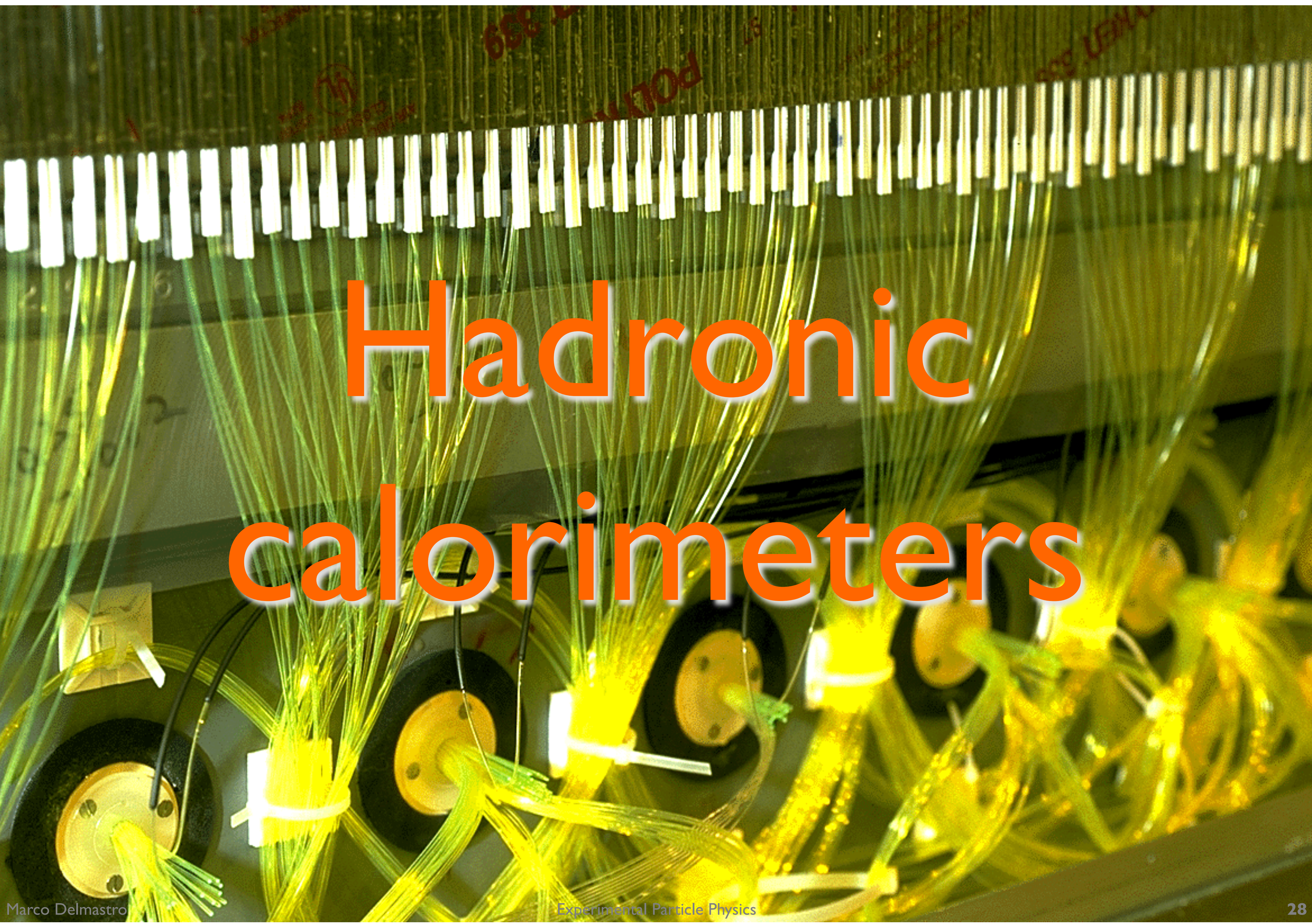
- CMS





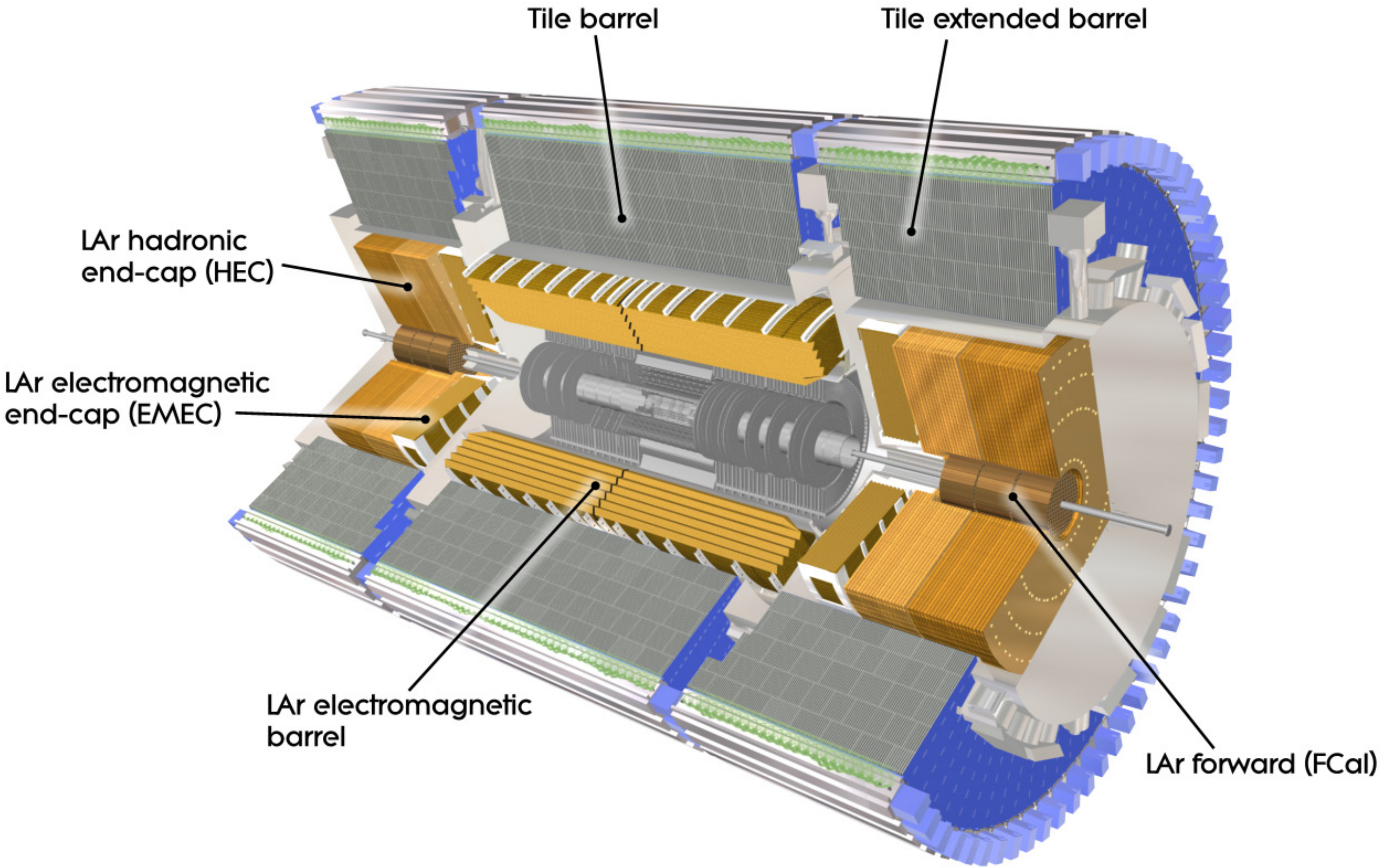
Performance of electromagnetic calorimeters



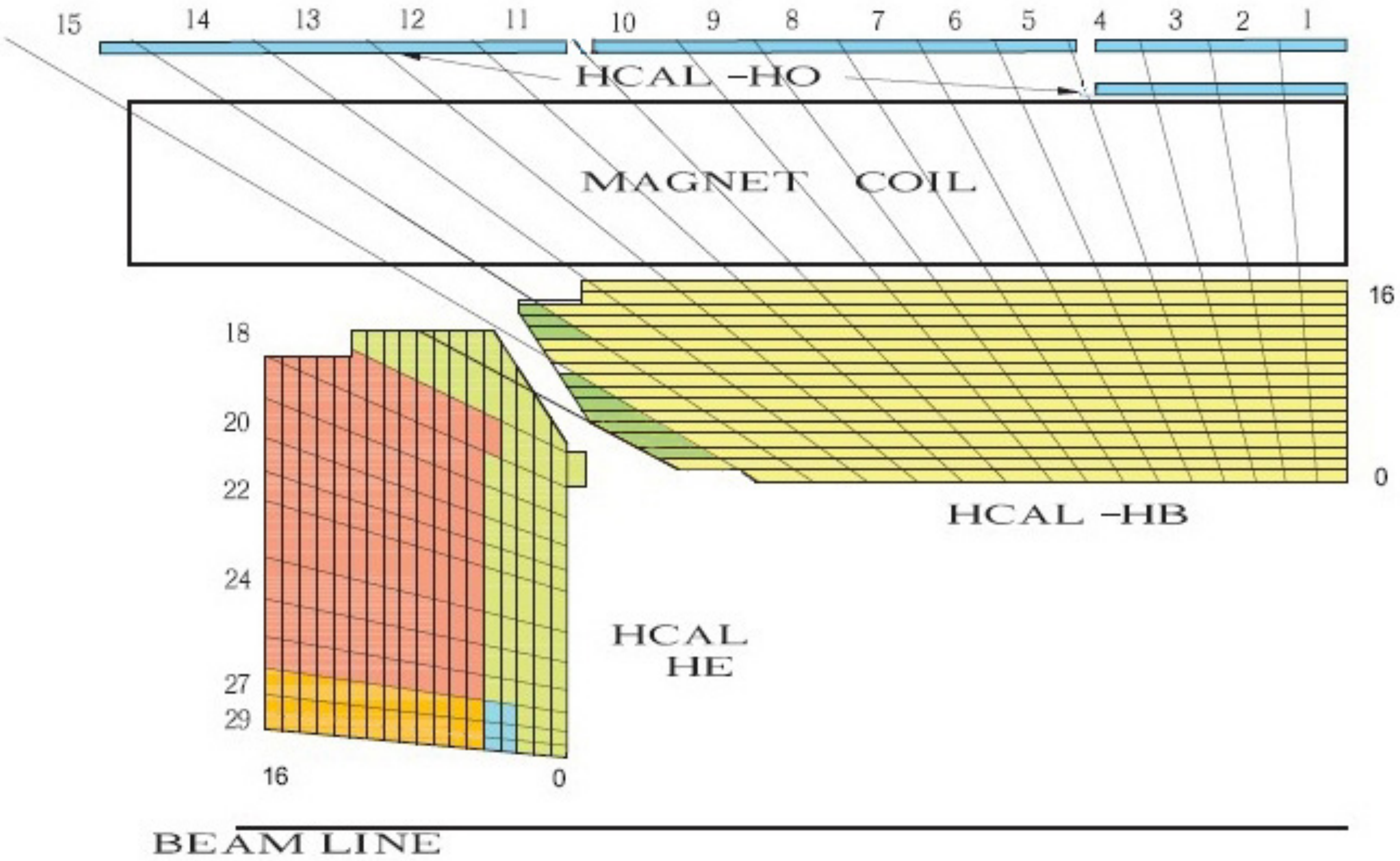


Hadronic calorimeters

ATLAS hadronic calorimeters



CMS hadronic calorimeter




http://cms.web.cern.ch/news/using-russian-navy-shells

Hadronic calorimeters

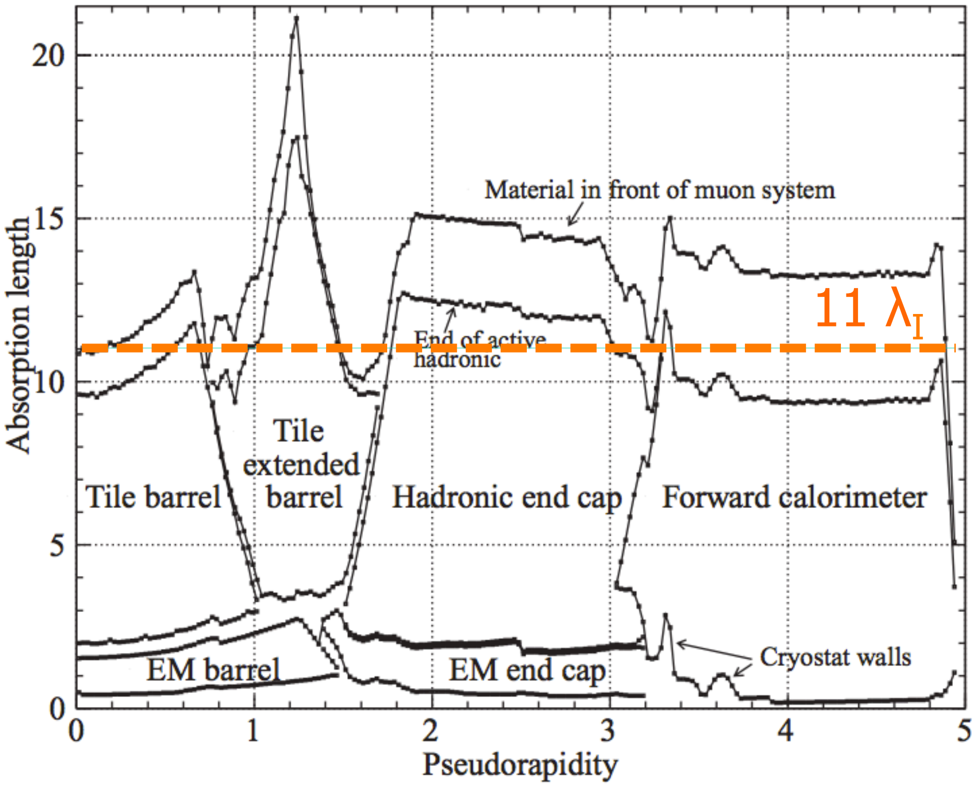
TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	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

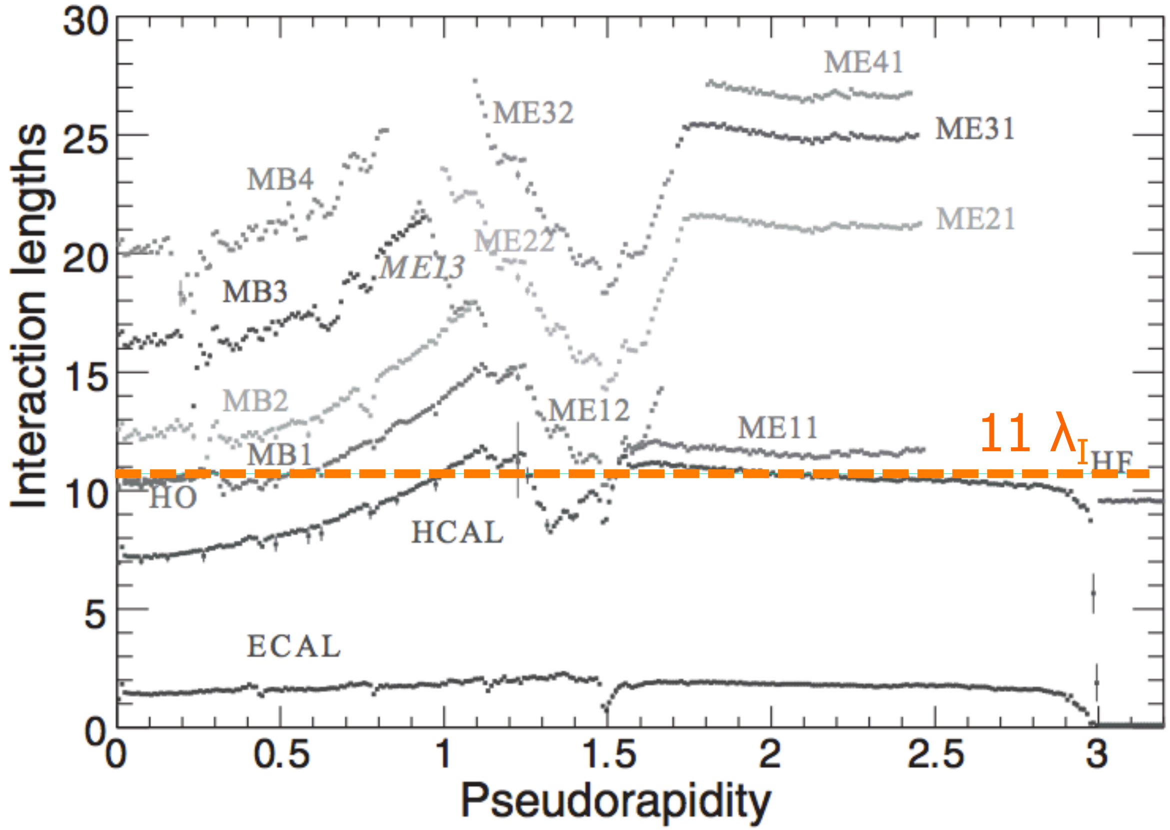
The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term,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

Hadronic absorption length

- ATLASs



- CMS



Performance of calorimeters: jets

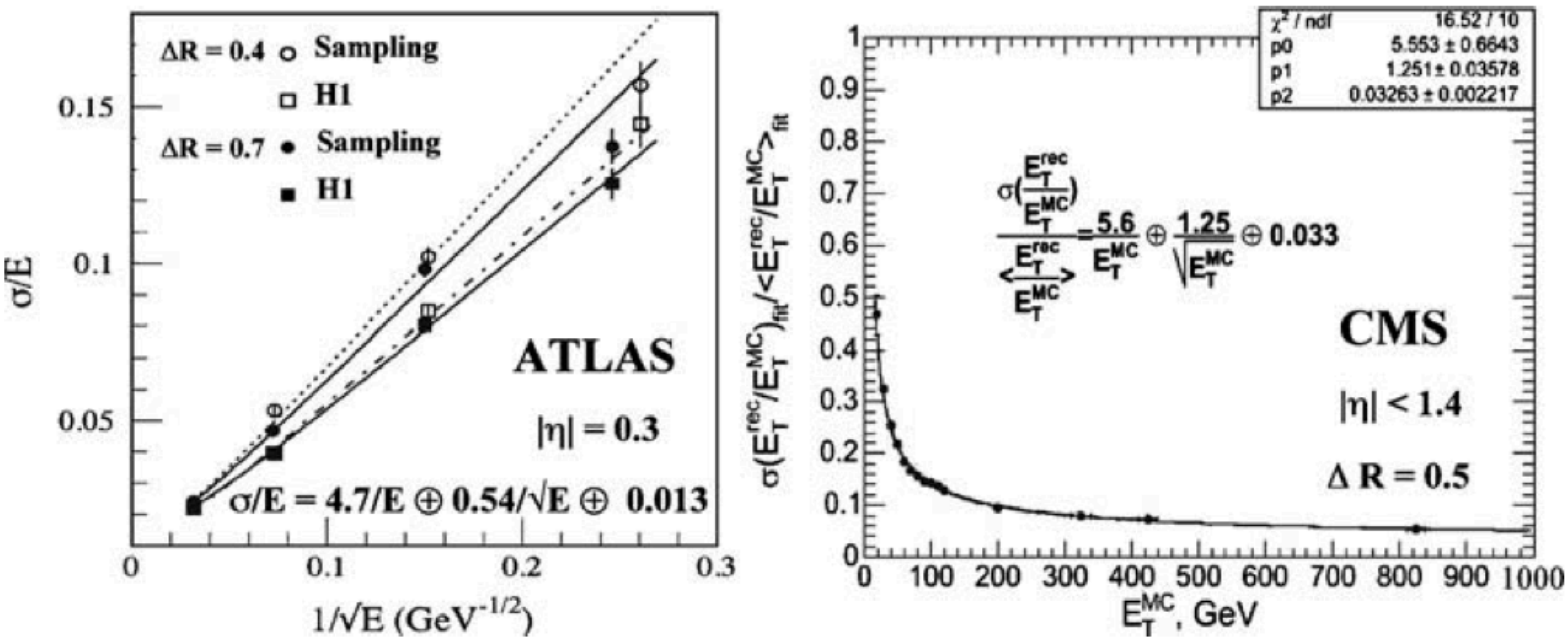


Figure 20 For ATLAS (*left*) and CMS (*right*), expected relative precision on the measurement of the energy of QCD jets reconstructed in the central region as a function of $1/\sqrt{E}$, where E is the jet energy for ATLAS, and as a function of E_T^{MC}, where E_T^{MC} is the jet transverse energy for CMS.

Performance of calorimeters: MET

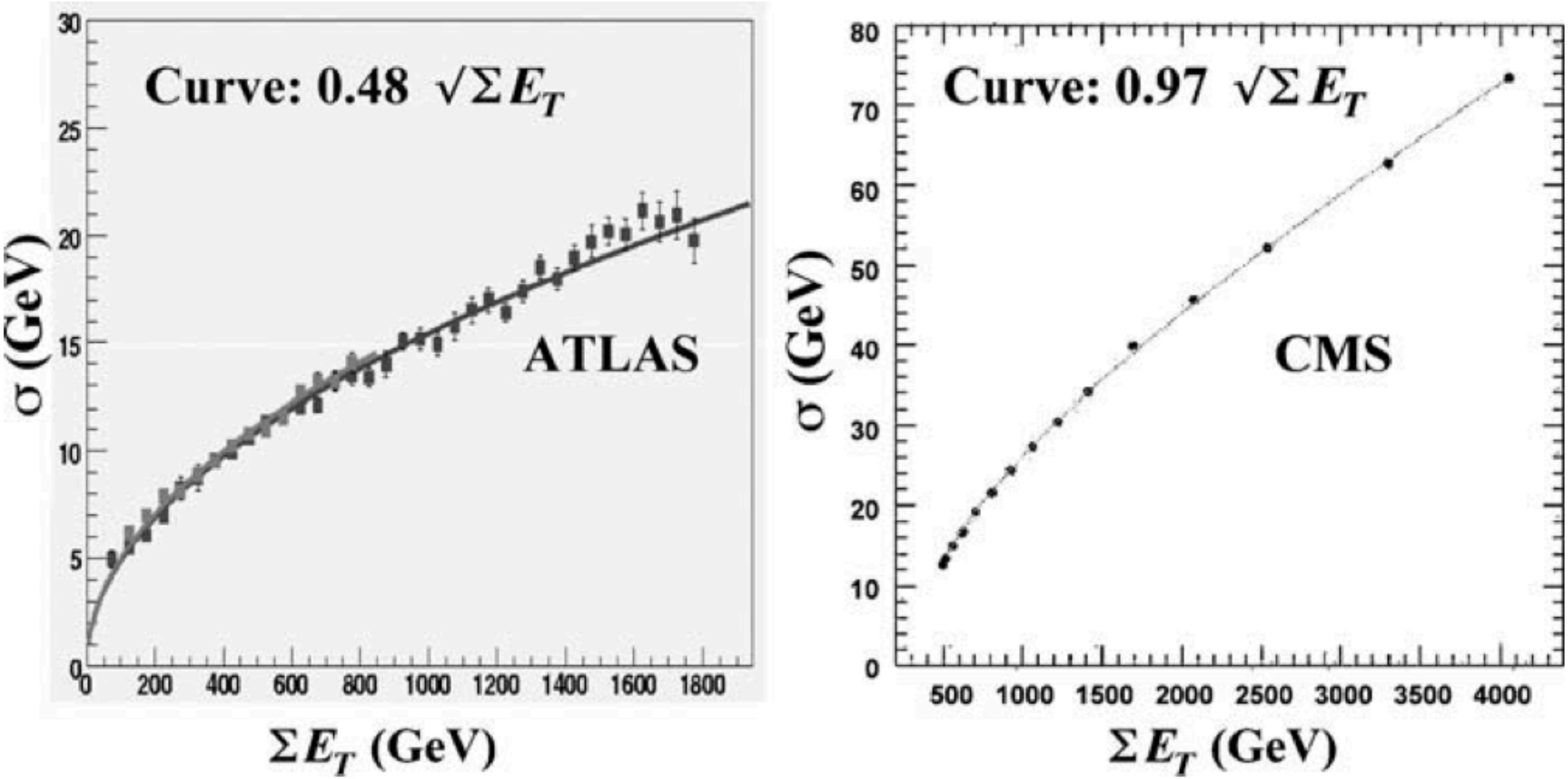
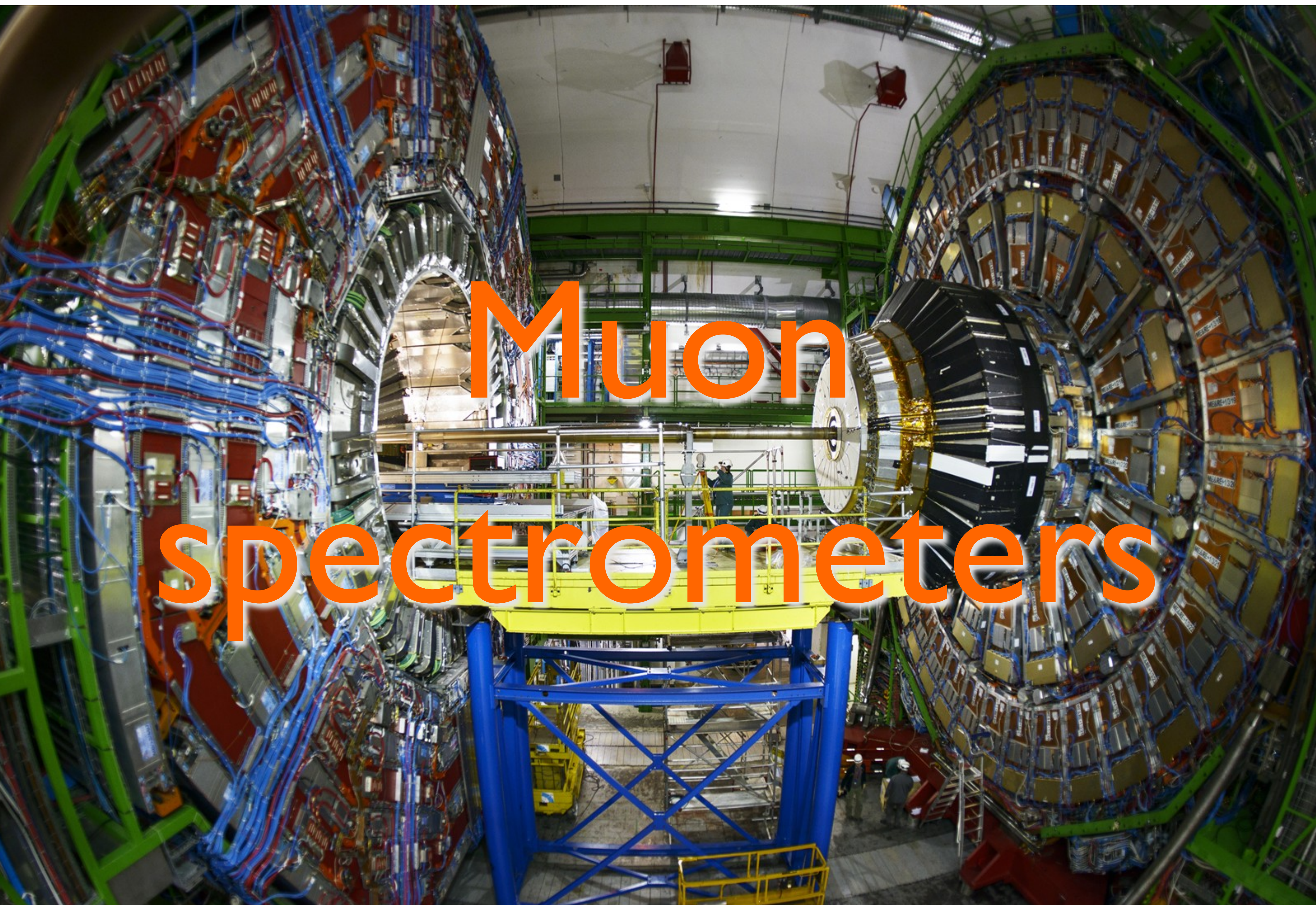


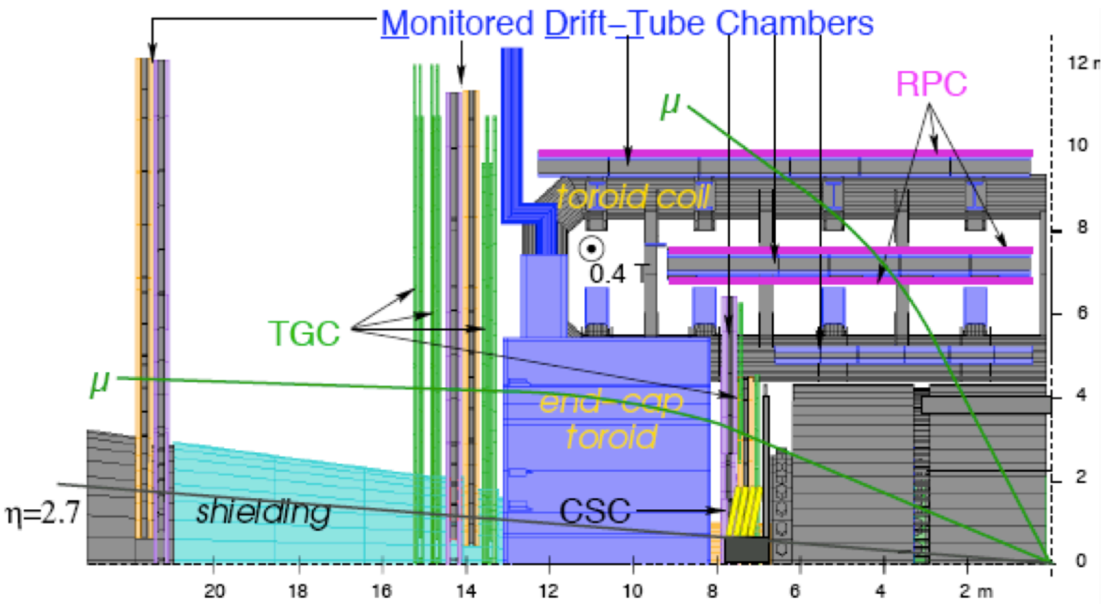
Figure 21 For ATLAS (*left*) and CMS (*right*), expected precision on the measurement of the missing transverse energy as a function of the total transverse energy, ΣE_T, measured in the event.

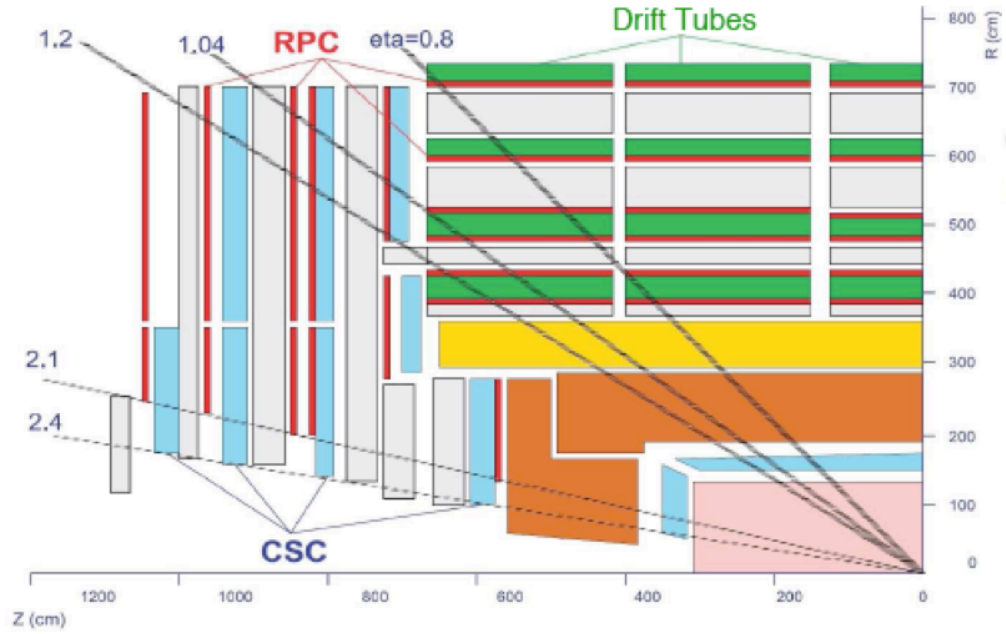
Muon spectrometers



Muon spectrometers

- ATLAS
  - ✓ independent muon spectrometer with excellent stand-alone capabilities
- CMS
  - ✓ superior combined momentum resolution in the central region;
  - ✓ limited stand-alone resolution and trigger capabilities
    - multiple scattering in the iron





Muon spectrometers

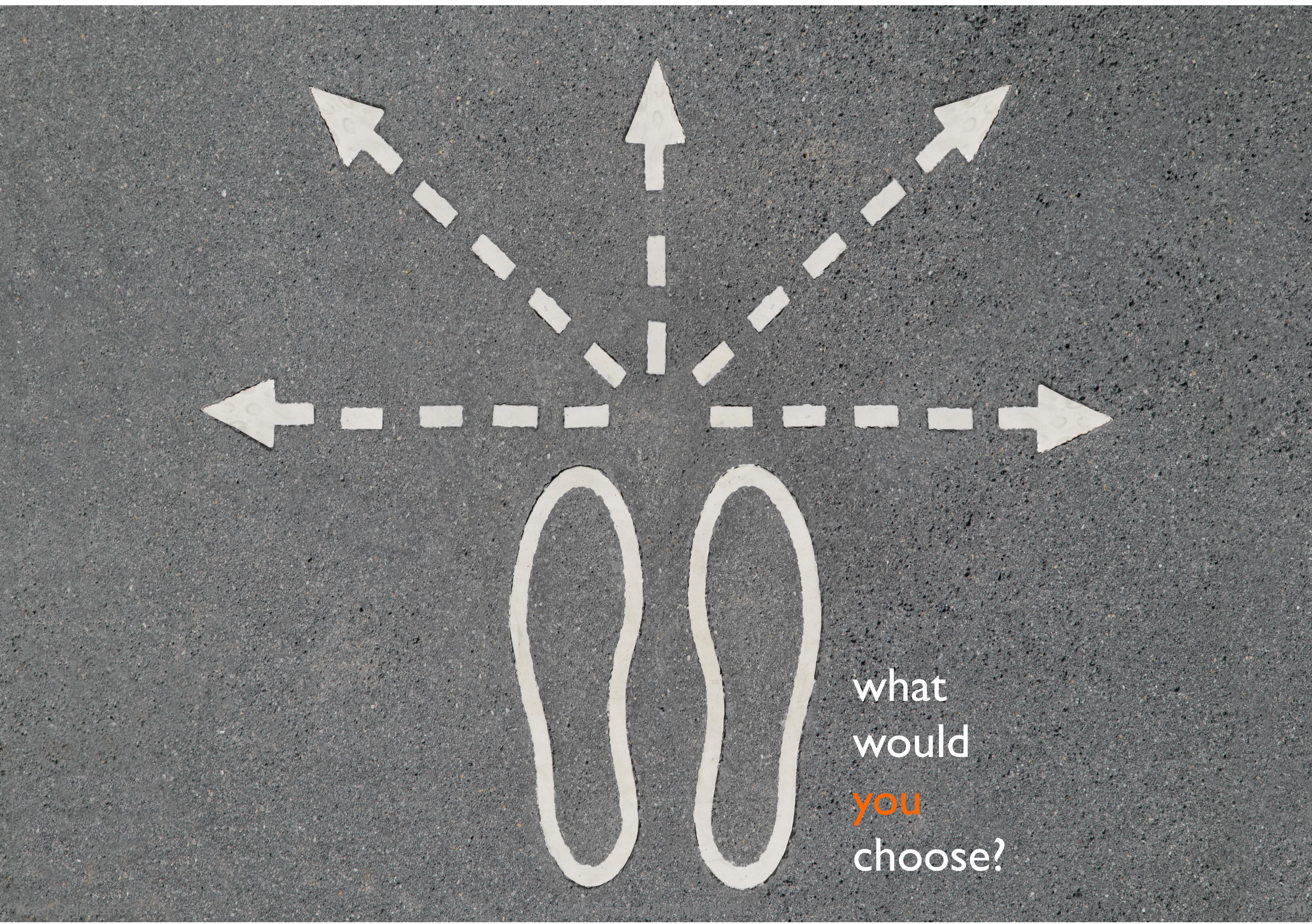
TABLE 11 Main parameters of the ATLAS and CMS muon chambers

	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	—

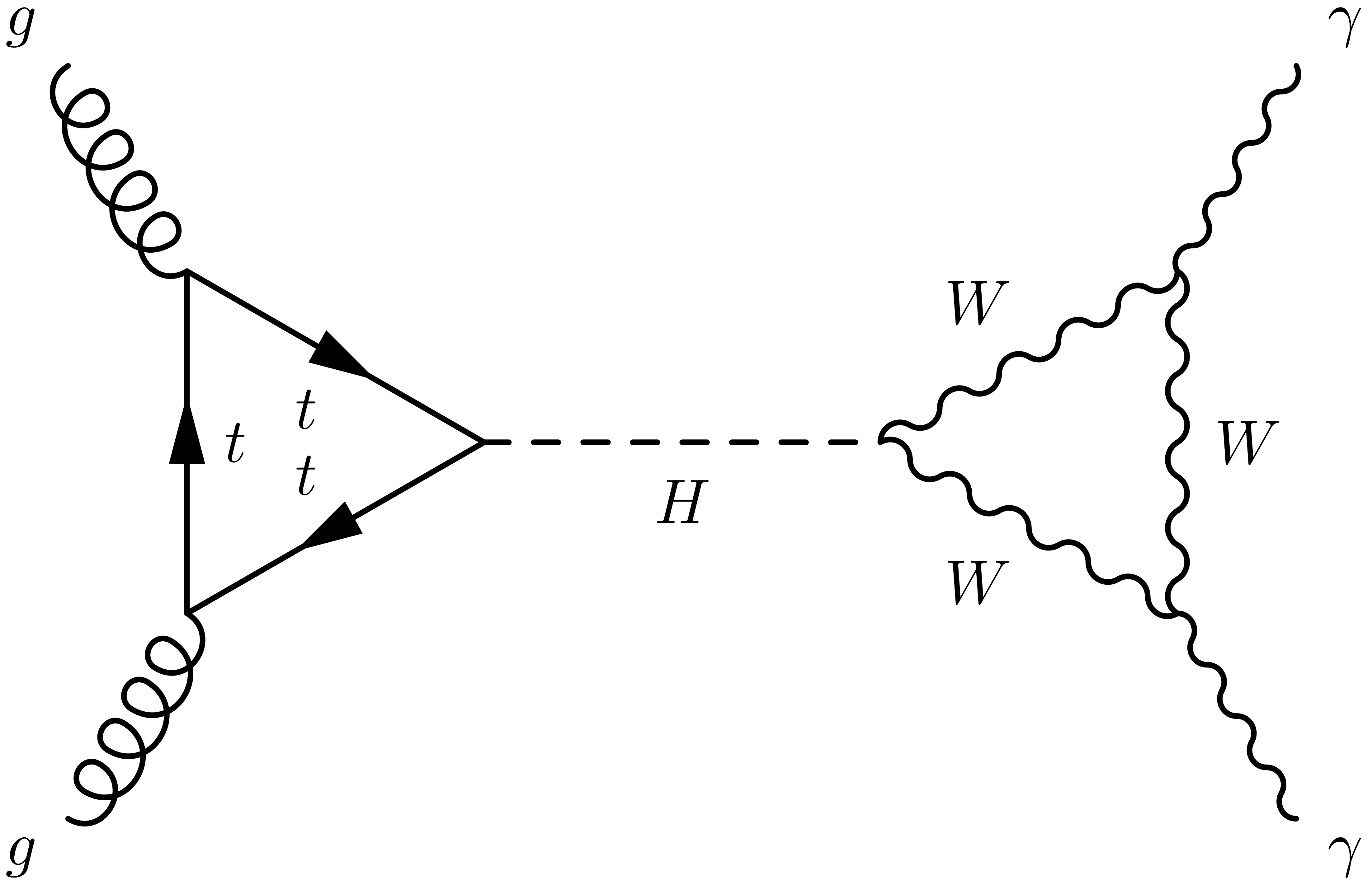
Muon spectrometers

TABLE 12 Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

Parameter	ATLAS	CMS
Pseudorapidity coverage		
-Muon measurement	$\|\eta\| < 2.7$	$\|\eta\| < 2.4$
-Triggering	$\|\eta\| < 2.4$	$\|\eta\| < 2.1$
Dimensions (m)		
-Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
-Innermost (outermost) disk (*z*-point)	7.0 (21–23)	6.0–7.0 (9–10)
Segments/superpoints per track for barrel (end caps)	3 (4)	4 (3–4)
Magnetic field B (T)	0.5	2
-Bending power (BL, in T· m) at $\|\eta\| \approx 0$	3	16
-Bending power (BL, in T· m) at $\|\eta\| \approx 2.5$	8	6
Combined (stand-alone) momentum resolution at		
-p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
-p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
-p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
-p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
-p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
-p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)


what
would
you
choose?

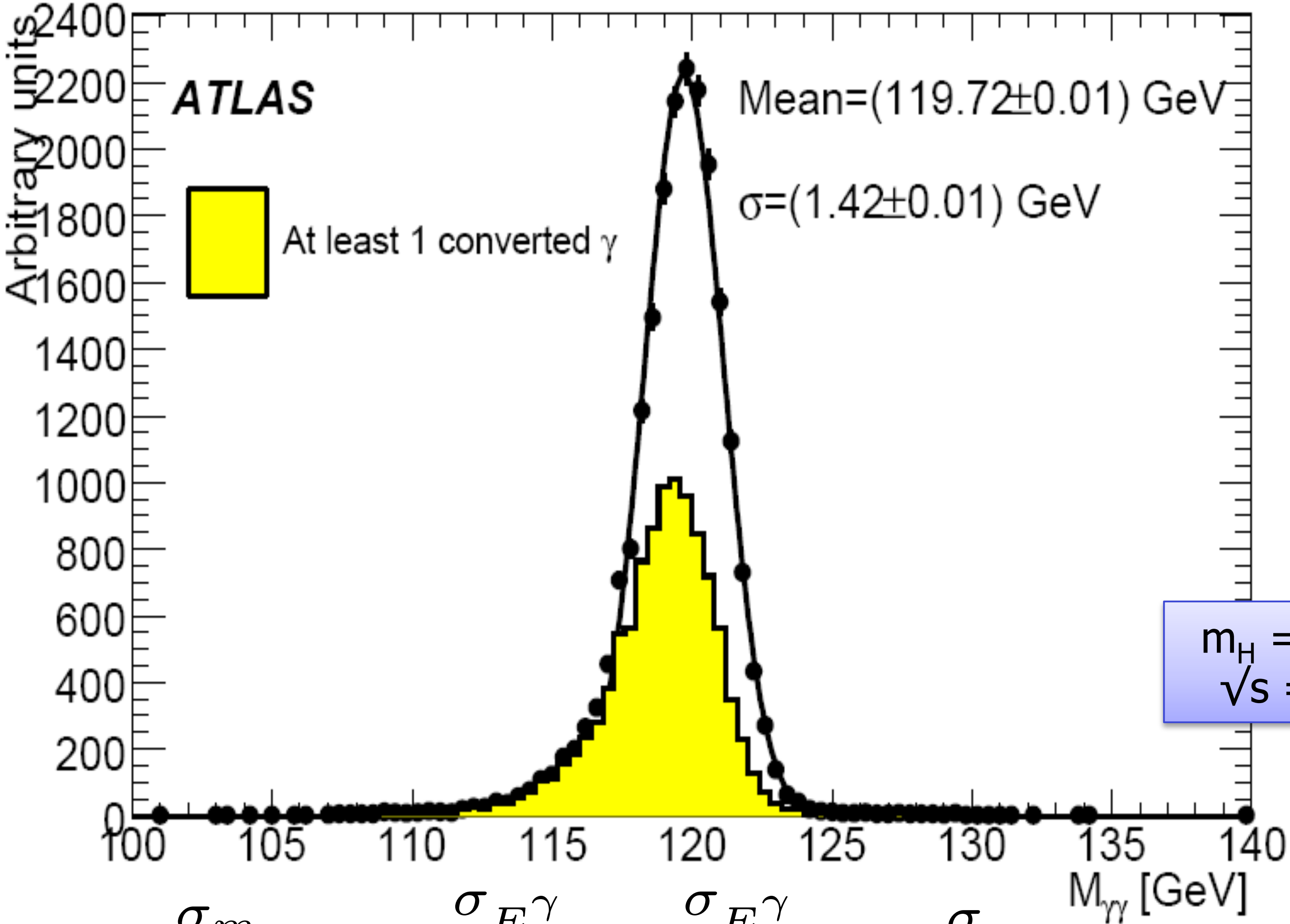
$$\frac{S}{\sqrt{B}}$$



g
g
t
t
t
H
W
W
W
γ
γ

A narrow mass peak…

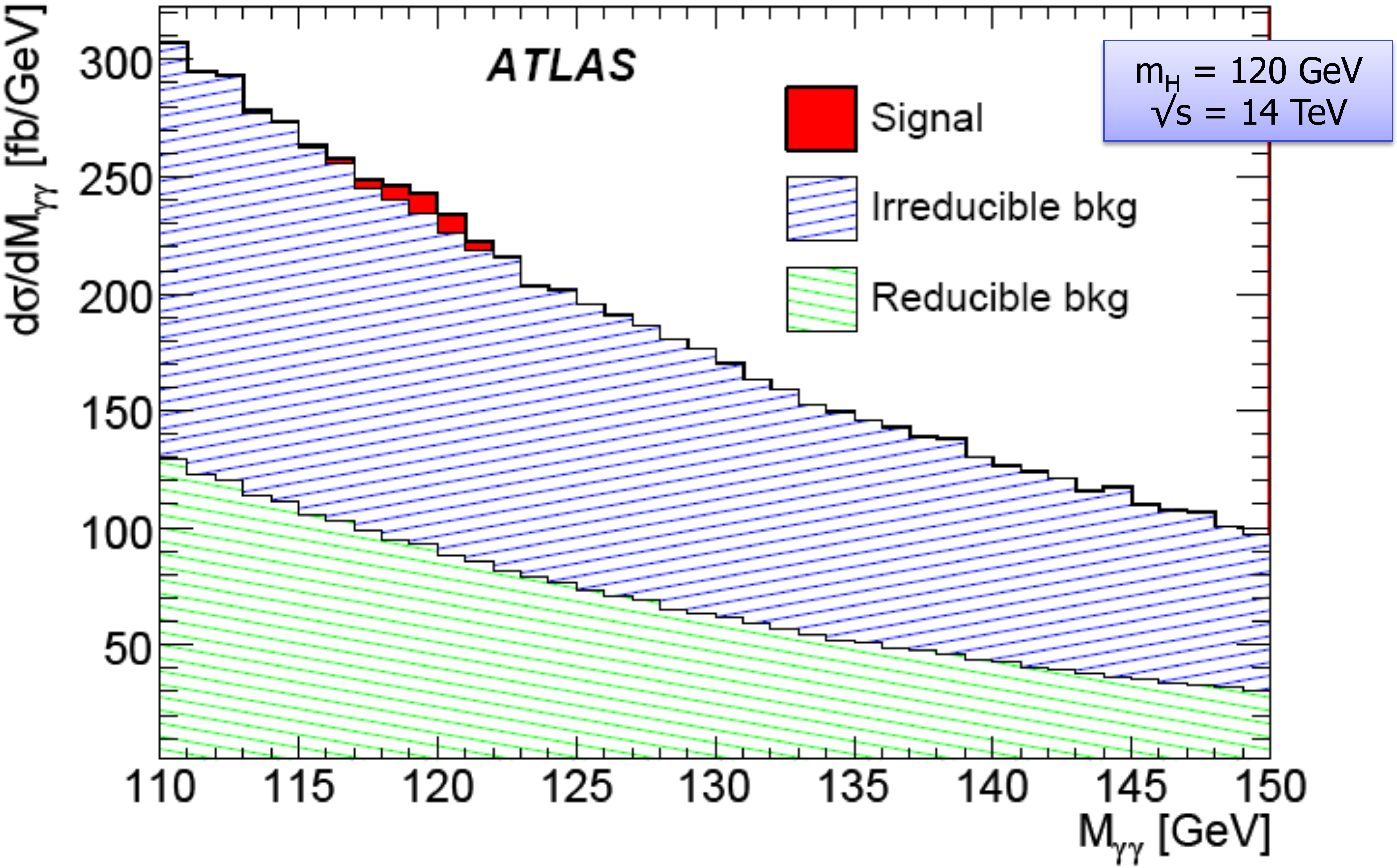
$$m_{\gamma\gamma} = \sqrt{E_1^\gamma E_2^\gamma (1 - \cos\alpha_{12})}$$



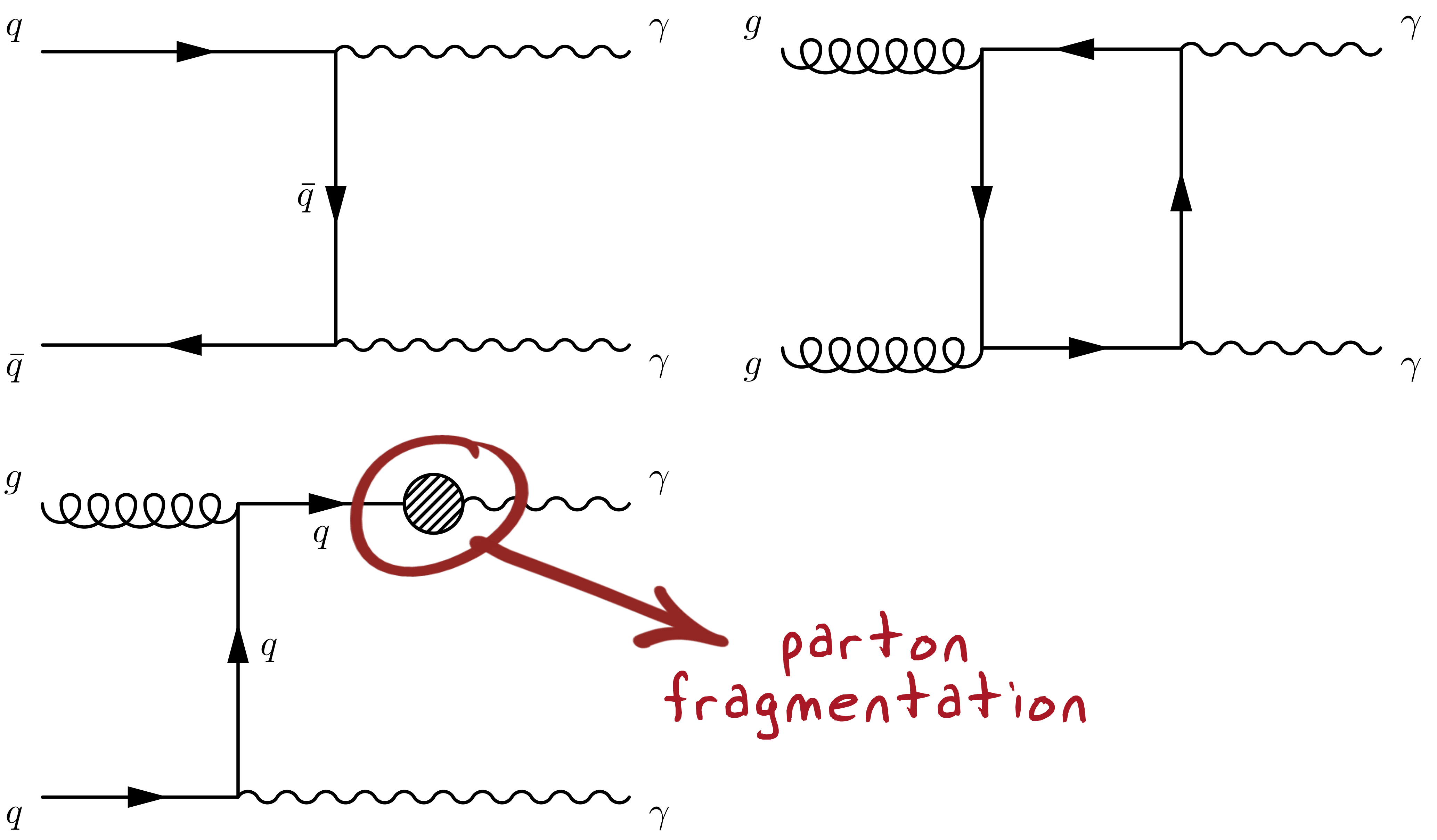
m_H = 120 GeV
$\sqrt{s}$ = 14 TeV

$$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{\sigma_{E_1^\gamma}}{E_1^\gamma} \oplus \frac{\sigma_{E_2^\gamma}}{E_2^\gamma} \oplus \frac{\sigma_{\alpha_{12}}}{\tan\alpha_{12}}$$

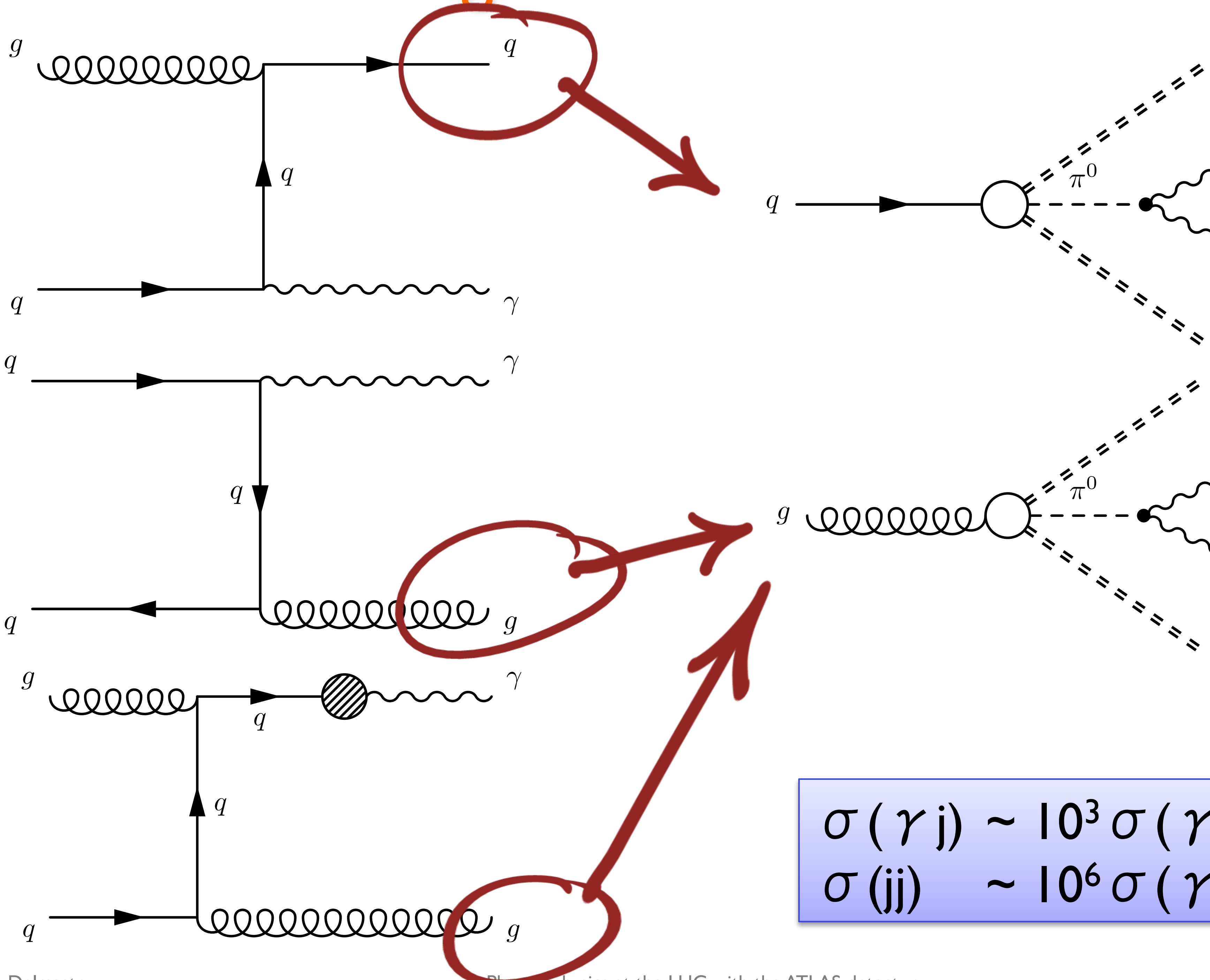
… on a large background!



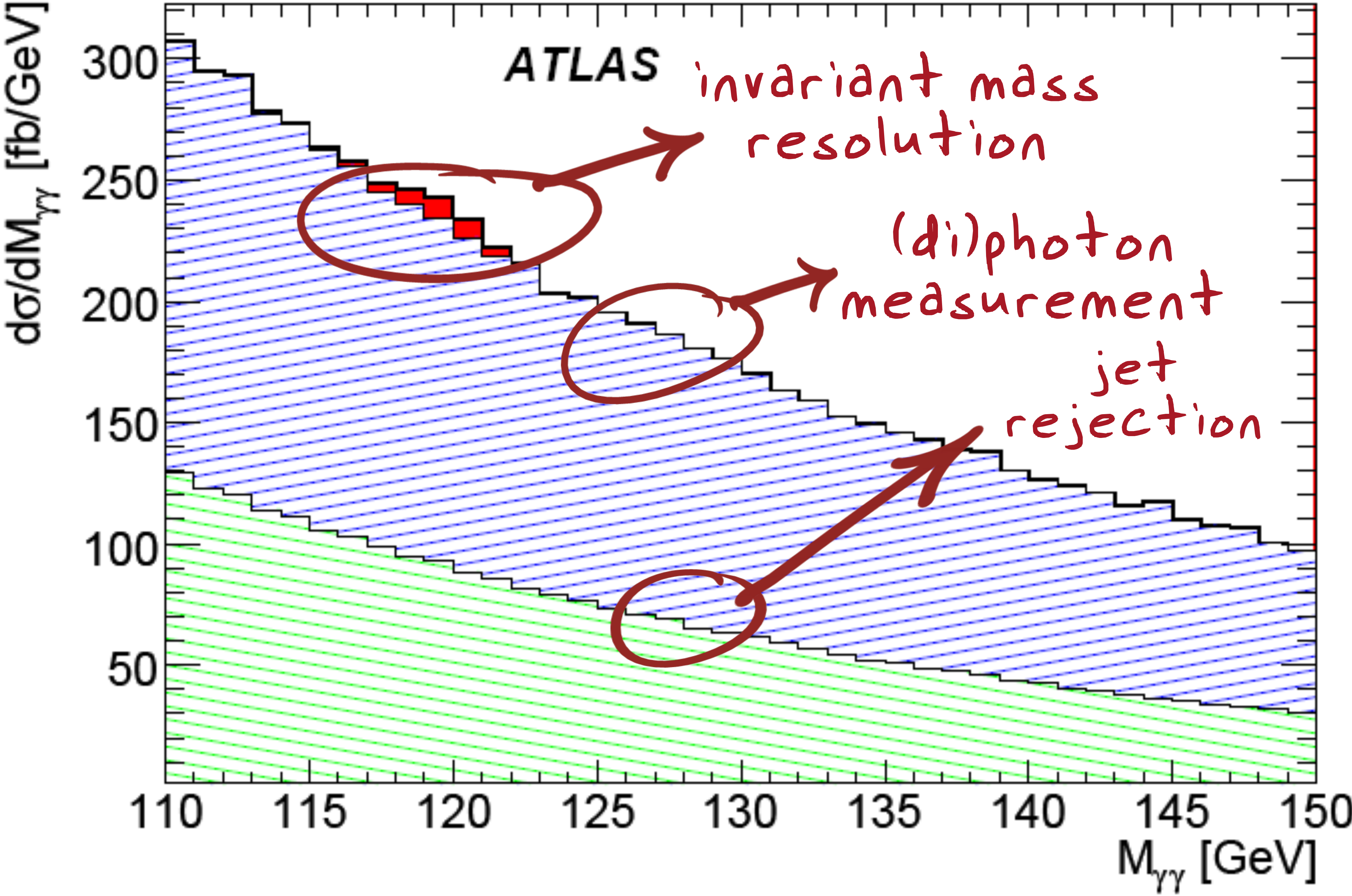
“Irreducible” background



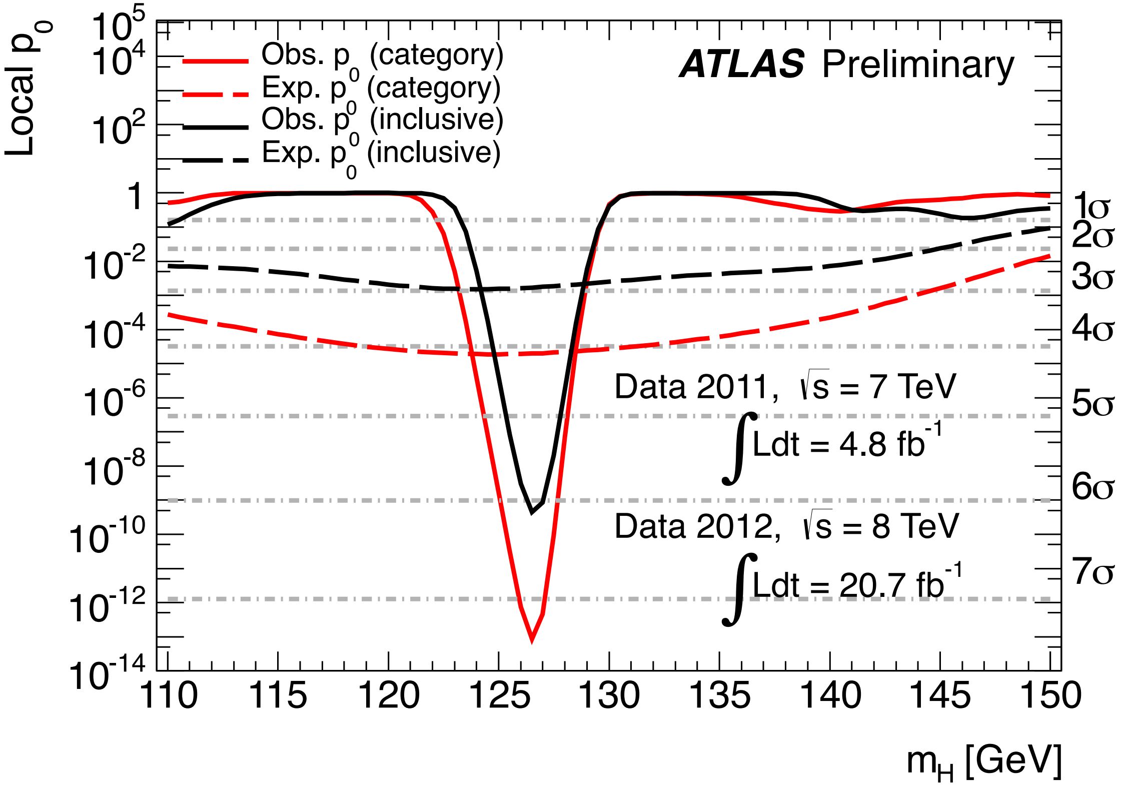
"Reducible" background

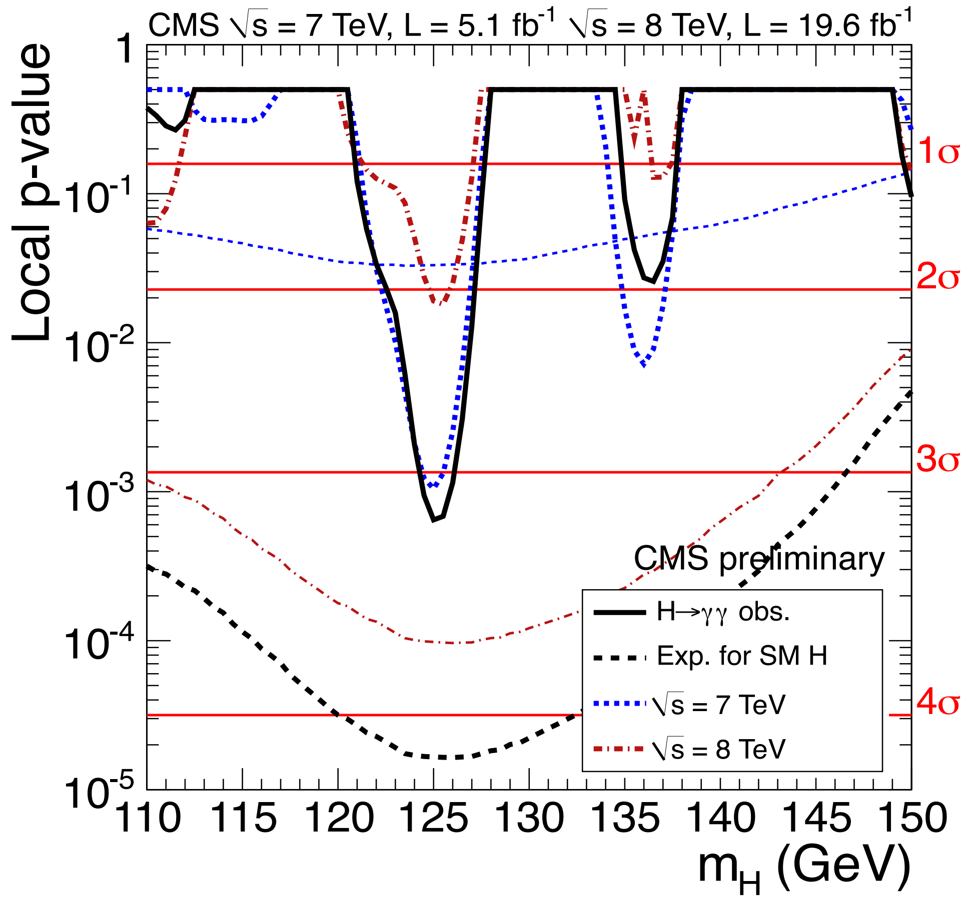


$$\sigma(\gamma j) \sim 10^3 \sigma(\gamma\gamma)$$
$$\sigma(jj) \sim 10^6 \sigma(\gamma\gamma)$$


ATLAS
invariant mass resolution
(di)photon measurement
jet rejection
$d\sigma/dM_{\gamma\gamma}$ [fb/GeV]
300
250
200
150
100
50
110
115
120
125
130
135
140
145
150
$M_{\gamma\gamma}$ [GeV]

H→γγ: ATLAS vs. CMS





- Significance at m_H = 126.5 GeV: 7.4 σ (expected 4.1)

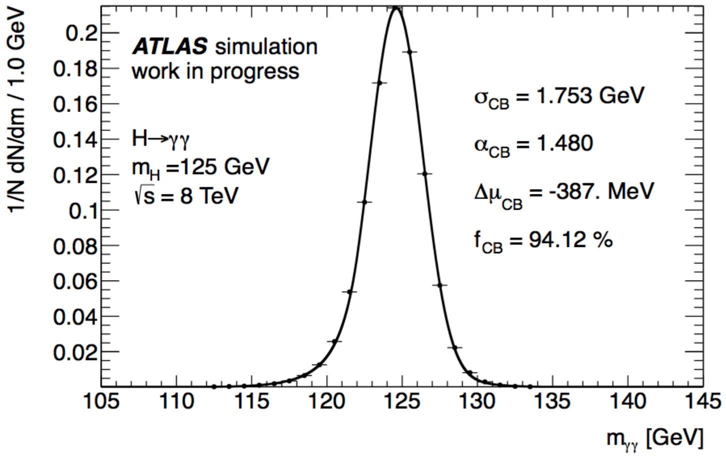
Significance @ 125.0 GeV: 3.2 σ (4.2 exp.)

With additional data and new analysis: significance decreased compared to the published results

Mass resolution

ATLAS

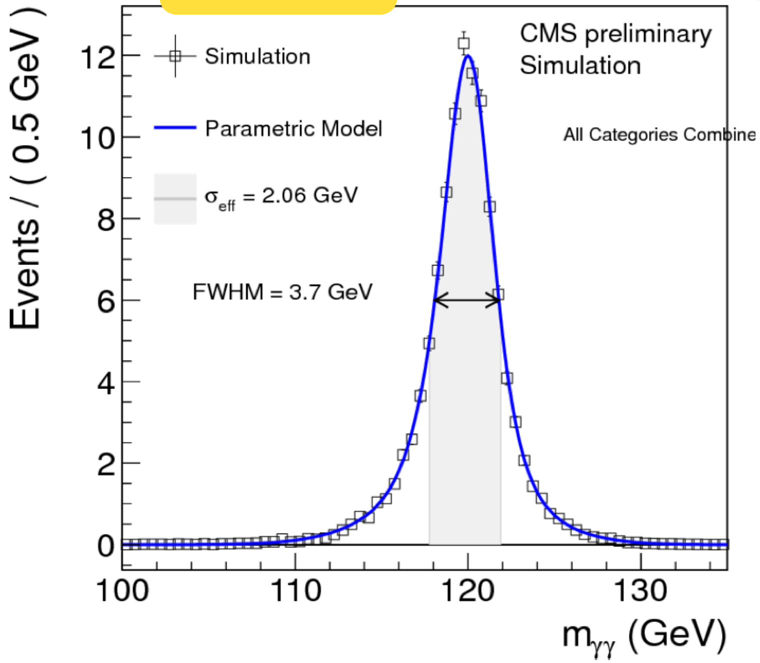
- Overall mass resolution very stable with time and pile-up
  - ✓ ~1.7 GeV



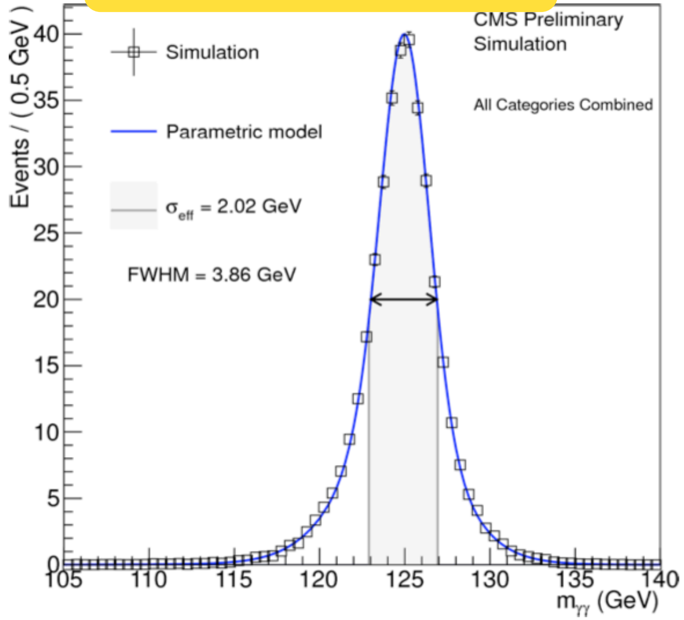
CMS

- Change of crystal calibration from ICHEP 2012 to Moriond/Aspen 2013, claim additional improvement

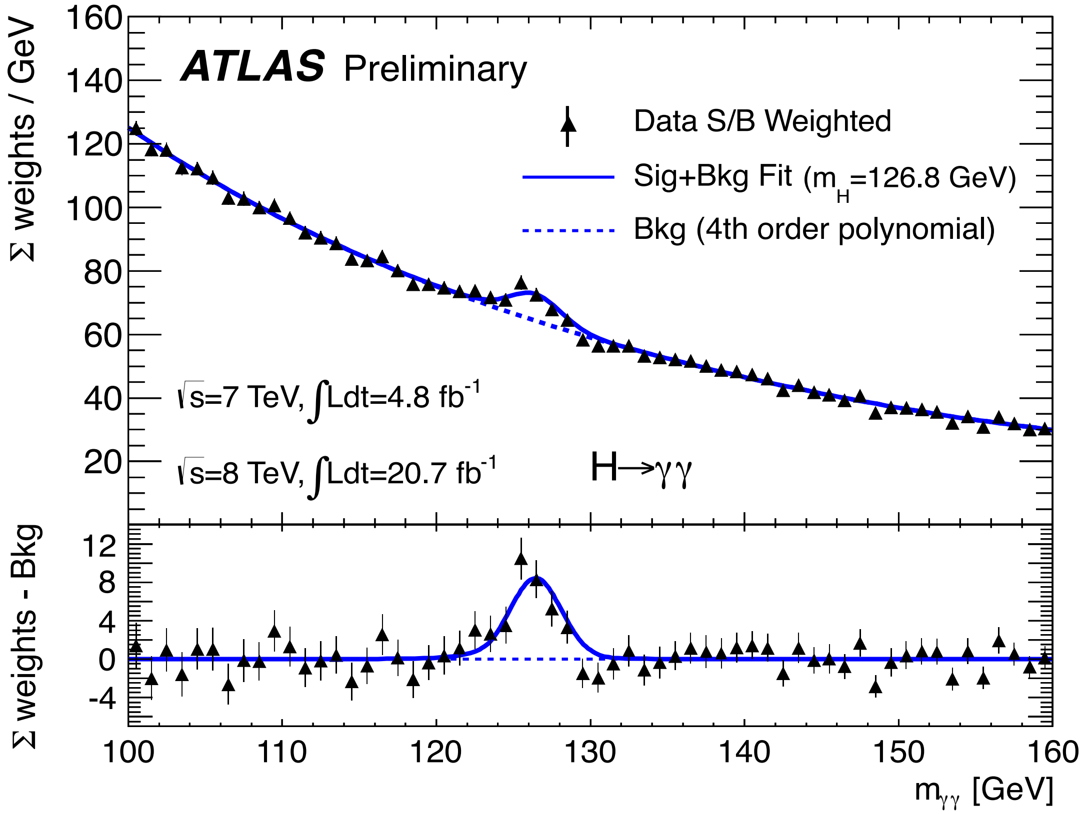
ICHEP

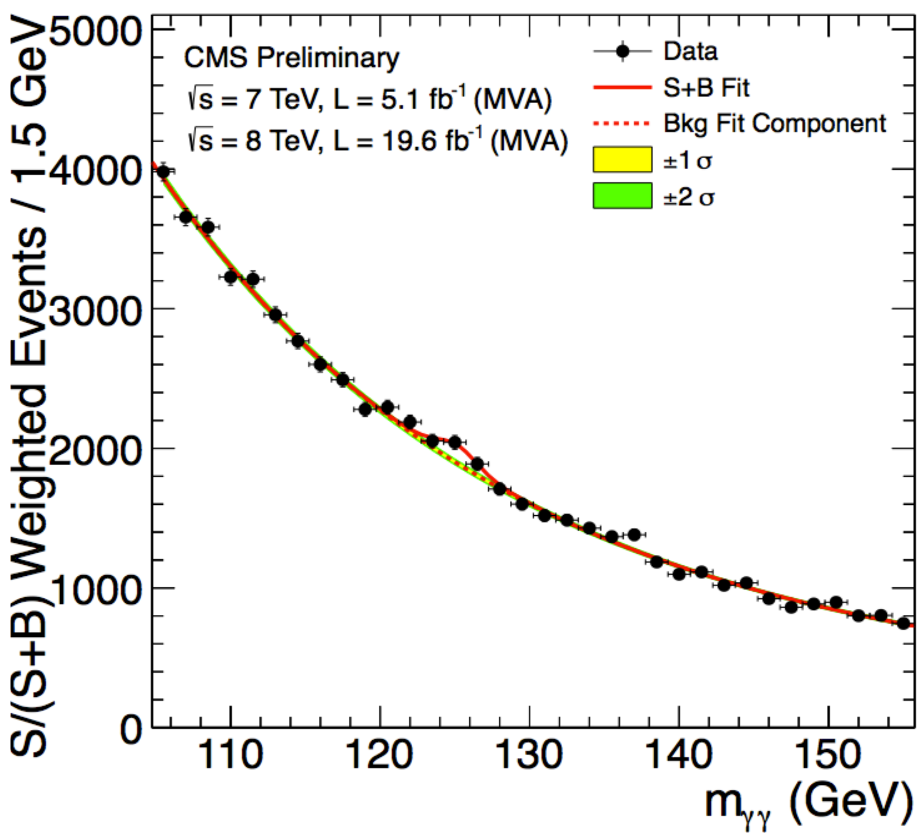


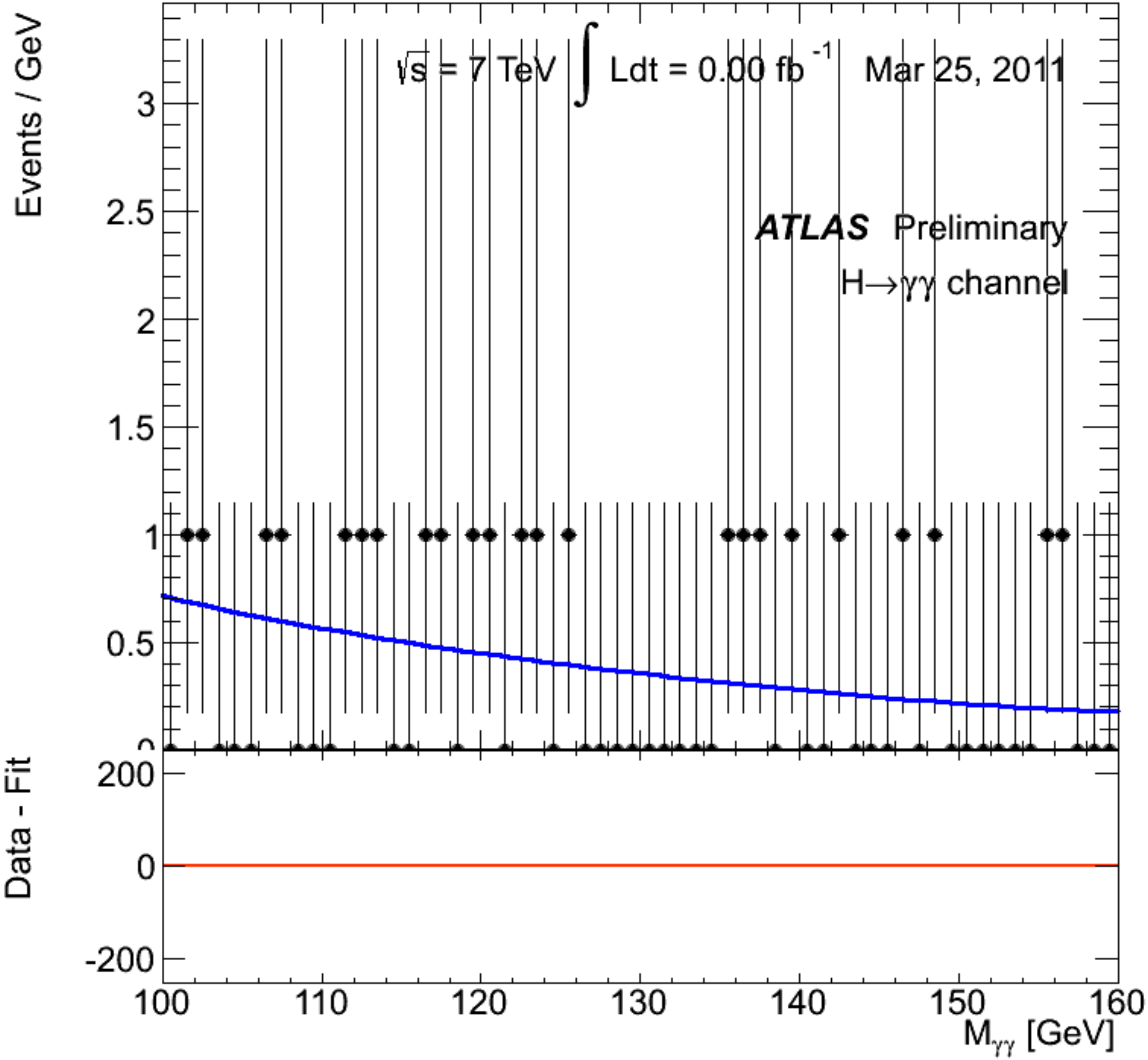
Moriond/Aspen



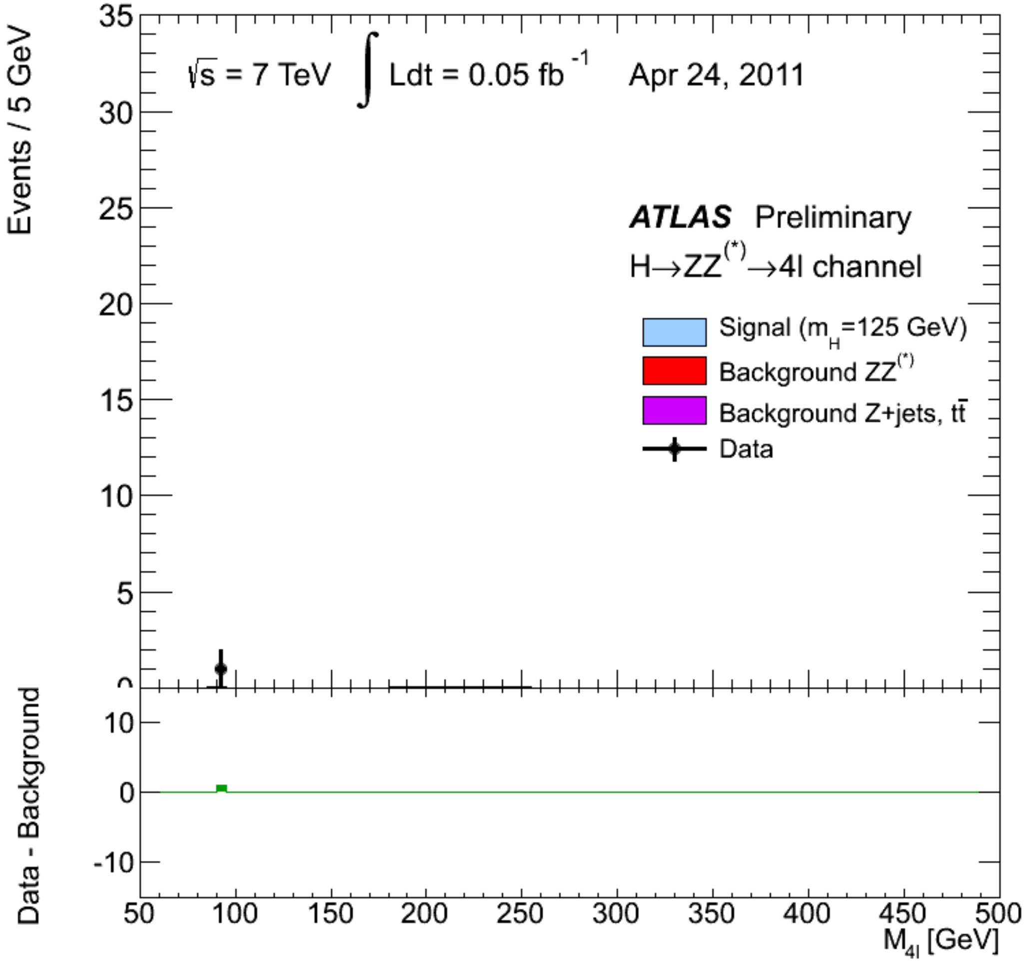
H→γγ weighted mass spectra



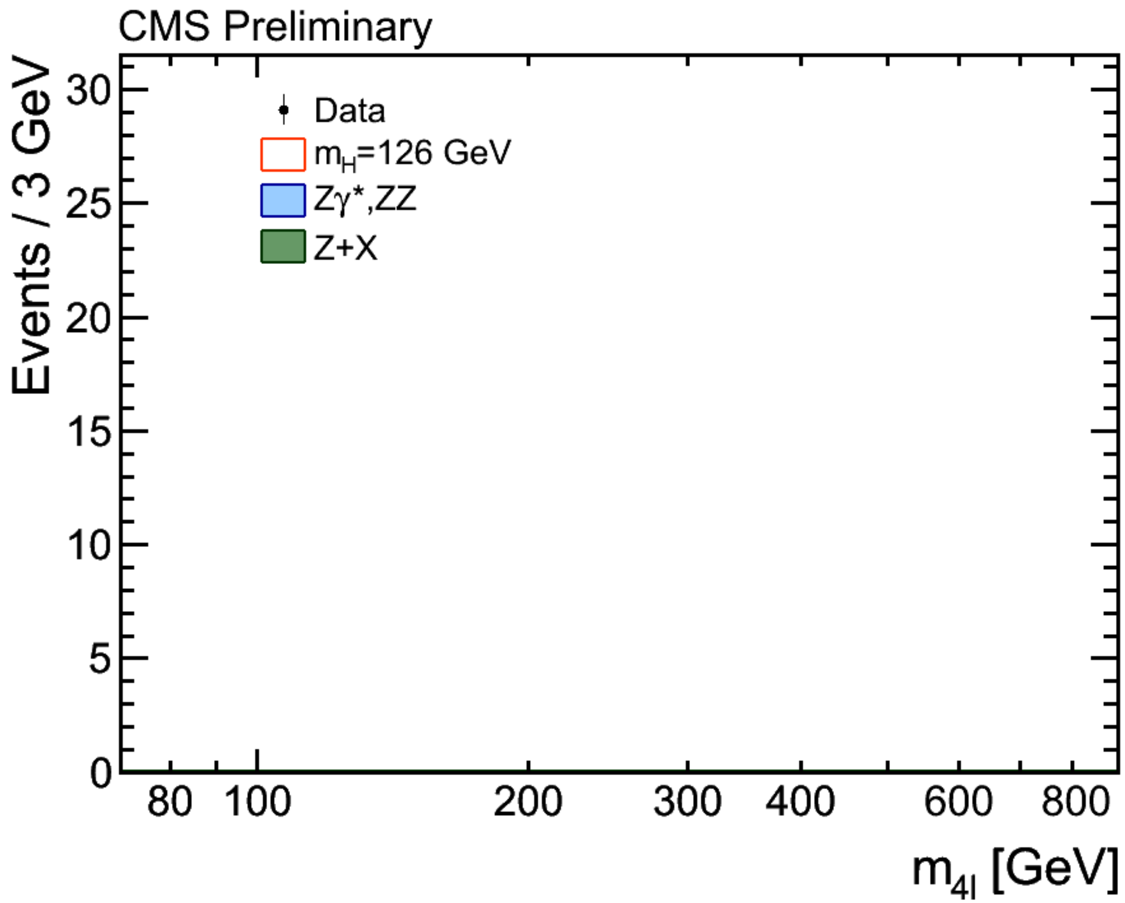




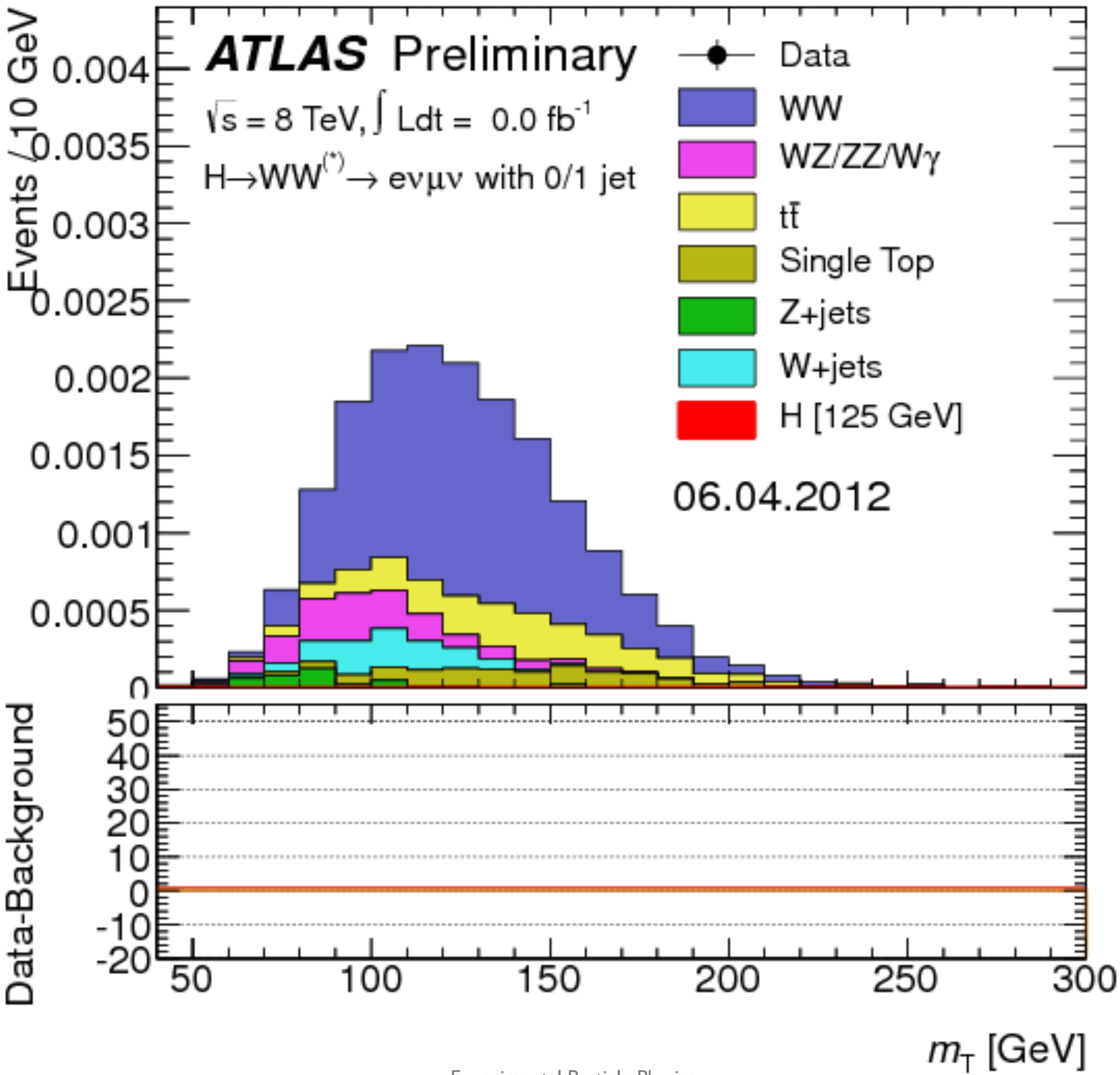
Events / GeV
√s = 7 TeV ∫ Ldt = 0.00 fb -1 Mar 25, 2011
ATLAS Preliminary
H→γγ channel
3
2.5
2
1.5
1
0.5
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]



Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb⁻¹ Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M4l [GeV]



CMS Preliminary
Events / 3 GeV
Data
mH=126 GeV
Zγ*,ZZ
Z+X
m4l [GeV]


ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 0.0 fb-1
H→WW(*)→ eνμν with 0/1 jet
Data
WW
WZ/ZZ/Wγ
tt̄
Single Top
Z+jets
W+jets
H [125 GeV]
06.04.2012
Events / 10 GeV
Data-Background
mT [GeV]