Calorimetry Lecture 2
Building a Calorimeter

Thanks to Dan Green, Chris Tully, Ursula Bassler, Beate Heinemann, Yasar Onel, Ugur Akgun

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Outline of Lecture 2 – Building a calorimeter

- Brief review of Lecture 1
- Design – based on Physics Goals
- Technology
- Calorimeters at the Tevatron and LHC

Lecture 1, summarized

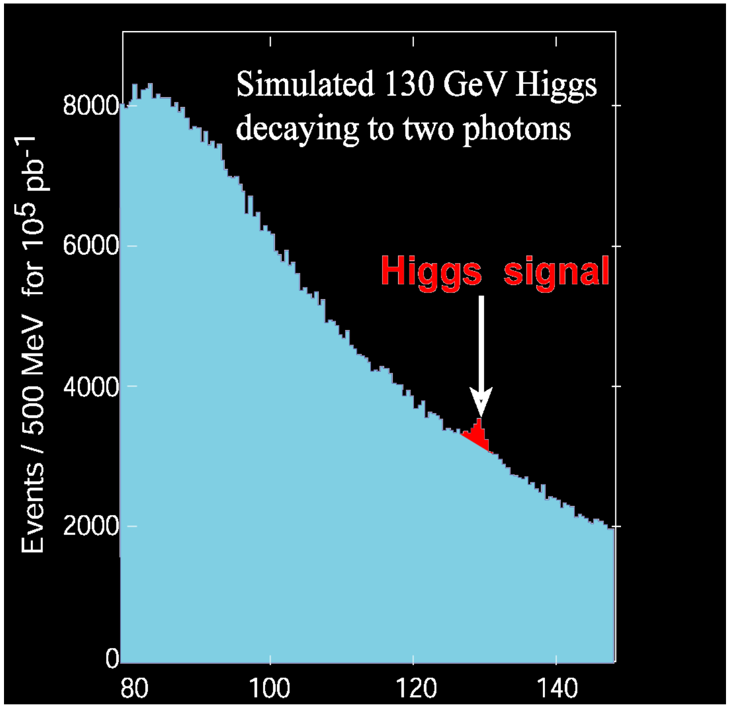
- Calorimetry in HEP – accurate, precise measurement of energy
  - Electromagnetic (EM)
    - Ionization, bremsstrahlung, pair production, cherenkov
  - Hadronic (HAD)
    - Nuclear processes, $\pi^0 \rightarrow \gamma\gamma$, ionization
  - Design calorimeters to use these processes to collect energy
  - Detection chain
  - Technology choices

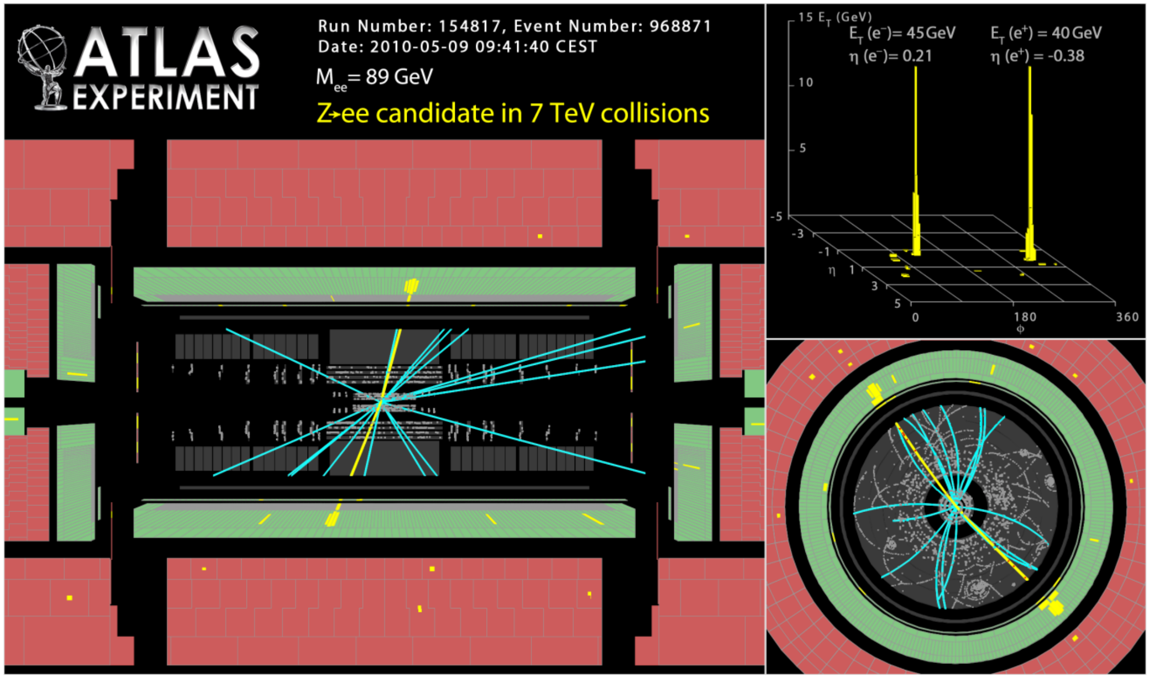
Considerations for Detectors

- When designing a calorimeter, take into account physics goals, environmental constraints, cost:
  - What is being measured?
  - What energy resolution is needed?
  - What spatial resolution is needed?
  - What is the event rate (time needed for signal production)?
  - What is your environment (radiation)?
  - What are the size constraints?
  - How much money do you have?
- Compromise…best physics is over-arching goal

Physics Goals

- Use CMS/Atlas Physics Goals as example
  - Detection of H→γγ
    - Precise electron/photon reconstruction
    - Known Standard Model processes used as “standard candles”

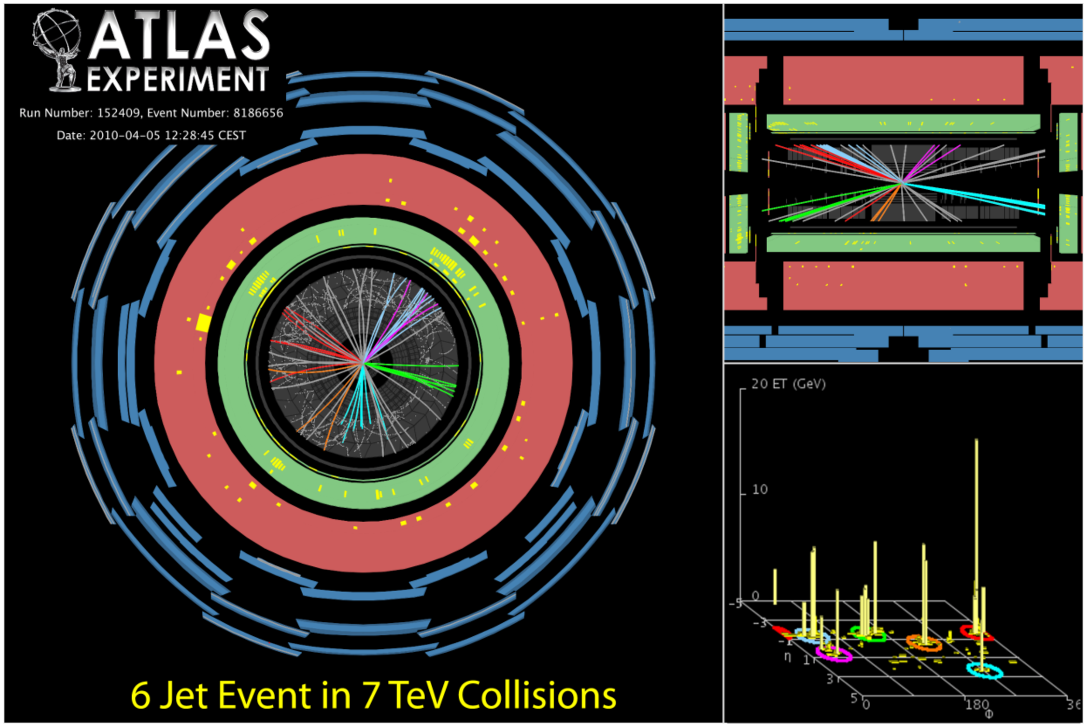




Candidate for Z→ee decay, collected on 9 May 2010.
Event properties: $E_T(e^+)$ = 40 GeV
$\eta(e^+)$ = -0.38
$E_T(e^-)$ = 45 GeV
$\eta(e^-)$ = 0.21
m_{ee} = 89 GeV

Physics Goals

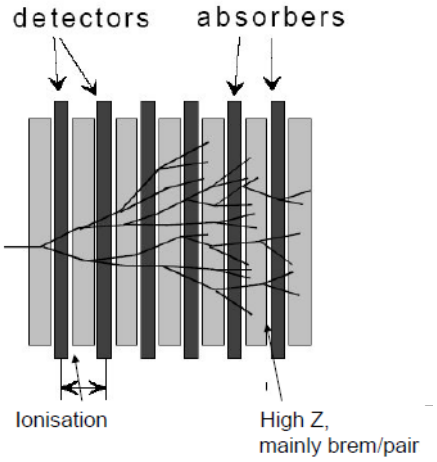
- Supersymmetry
  - Hallmark of many processes is Missing Transverse Energy (MET) carried away by the lightest SUSY particle (LSP)
  - Need 4π coverage (as close as you can get), electromagnetic and hadronic shower containment



An event with 6 jets taken on April 4th, 2010. The jets have calibrated transverse momenta between 30 GeV and 70 GeV and are well separated in the detector. Note that the energies given in the lego plot are yet uncalibrated, that is, they are lower than the calibrated energies.

Technology Choices

- Types of Calorimeters
  - Total absorption – homogeneous – creates and detects shower
  - Sampling – interleave active/passive
- Active material choice
  - Noble liquids
  - Scintillating crystals
- Passive material choices
- Photodetection devices



Crystals used in Homogeneous Calorimeters (EM)

Belle/ Babar

L3

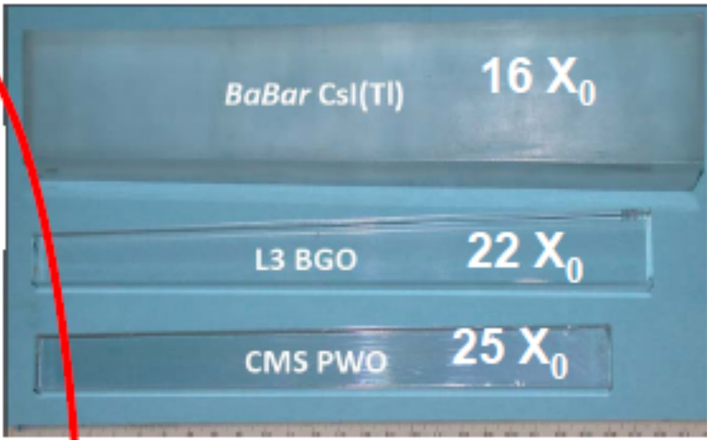
CMS/ Alice

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF$_2$	BGO	CeF$_3$	PbWO$_4$
Density g.cm^{-2}	3.67	4.51	4.51	4.89	7.13	6.16	8.28
Rad. length cm	2.59	1.85	1.85	2.06	1.12	1.68	0.89
Moliére radius cm	4.5	3.8	3.8	3.4	2.4	2.6	2.2
Int. length cm	41.4	36.5	36.5	29.9	22.0	25.9	22.4
Decay Time ns	250	1000	35 6	630 0.9	300	10-30	<20>
Peak emission nm	410	565	420 310	300 220	480	310- 340	425
Rel. Light Yield %	100	45	5.6 2.3	21 2.7	9	10	0.7
d(LY)/dT %/^{0}C	≈ 0	0.3	- 0.6	- 2 ≈ 0	- 1.6	0.15	-1.9
Refractive Index	1.85	1.80	1.80	1.56	2.20	1.68	2.16

10ms interaction rate, good light yield, good S/N

25μs bunch crossing, low radiation dose

25ns bunch crossing, high radiation dose



Need to match crystal with photo-detector

- Crystal advantages:
  - Dense
  - Compact
  - Fast
  - Good photon yield
  - Stable

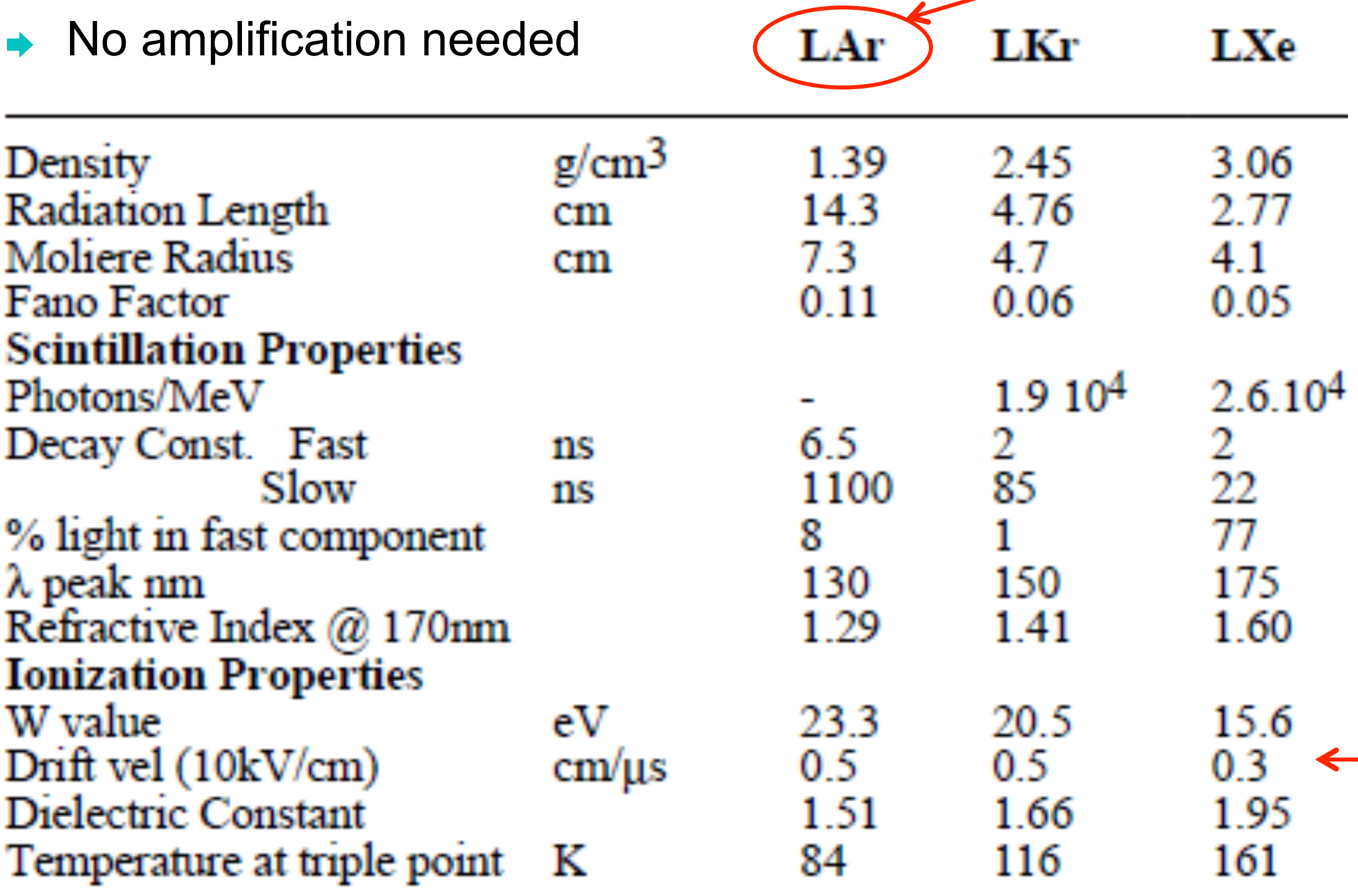
Active Layers

- Detection of ionization
  - Gas (example L3's Uranium/gas hadron cal)
    - Amplification of signal using proportional tubes
    - But slow (too slow for today's hadron collider experiments)
  - Noble liquid (eg LAr, LKr)
    - Planar geometry
    - High density of liquid means no amplification needed
    - Radiation hard…but not very fast
    - Must be cryogenically cooled, and high purity sample
  - Scintillators (fibers, tile)
    - Bring light out for photodetector readout
    - Flexible, fast → common choice
    - But not radiation-hard
  - Cherenkov radiating fibers
    - Also fast, and radiation-hard.

Noble Liquids for Calorimeters

- Ionization in noble liquids
  - Typically parallel-plate geometry → ionization chamber
  - Requires long mean-free path of electron (noble liquid)
  - No amplification needed

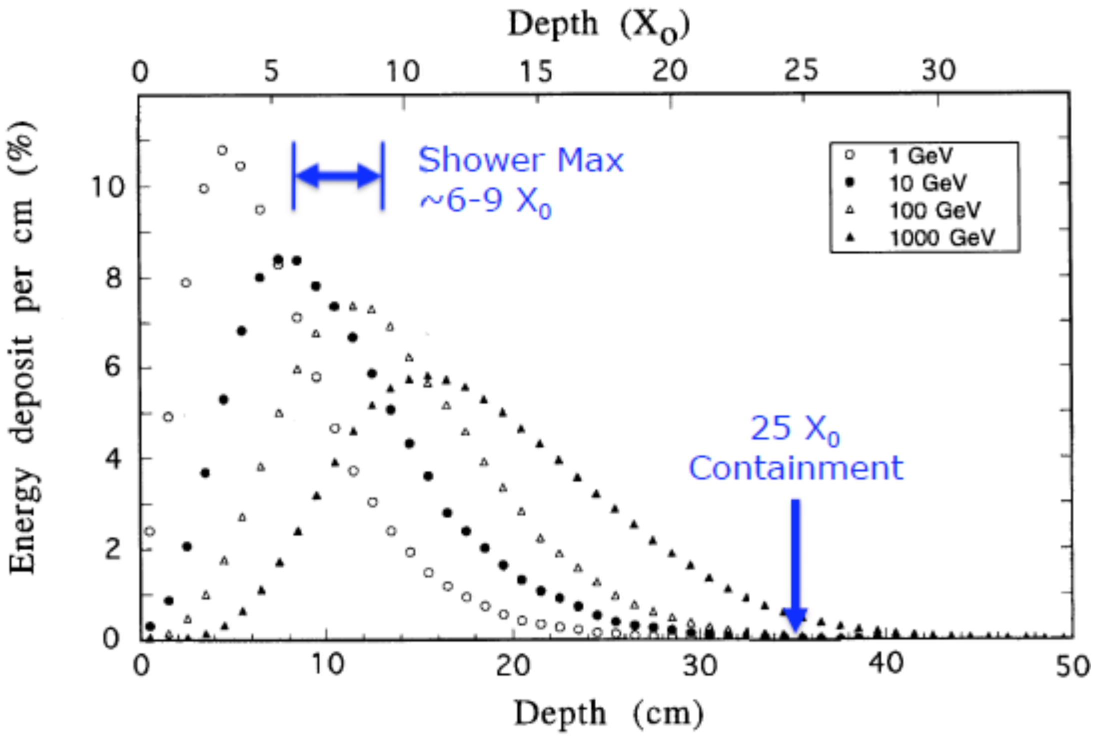
D0, Atlas



		LAr	LKr	LXe
Density	g/cm^3	1.39	2.45	3.06
Radiation Length	cm	14.3	4.76	2.77
Moliere Radius	cm	7.3	4.7	4.1
Fano Factor		0.11	0.06	0.05
Scintillation Properties				
Photons/MeV		-	$1.9\ 10^4$	$2.6.10^4$
Decay Const. Fast	ns	6.5	2	2
Slow	ns	1100	85	22
% light in fast component		8	1	77
λ peak nm		130	150	175
Refractive Index @ 170nm		1.29	1.41	1.60
Ionization Properties				
W value	eV	23.3	20.5	15.6
Drift vel (10kV/cm)	cm/μs	0.5	0.5	0.3
Dielectric Constant		1.51	1.66	1.95
Temperature at triple point	K	84	116	161

Charge collection time is defined by the drift velocity

Leakage Energy and Depth

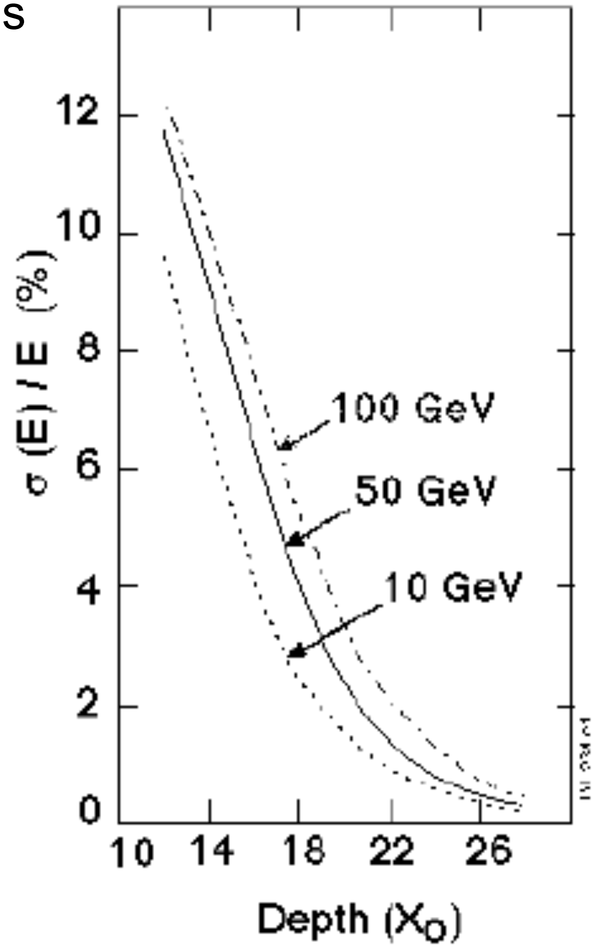


Shower Max ~6-9 X_0

25 X_0 Containment

(Courtesy of R. Wigmans)

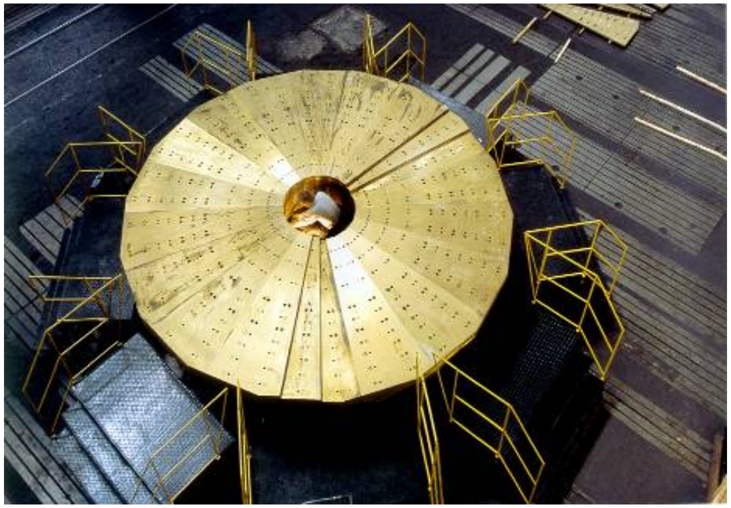
As we saw in Lecture 1, depth needed for shower containment depends on the energy of the particles



- Fluctuations hurt resolution because the energy lost in leakage fluctuates
- Also depends on energy
- If your calorimeter has 20 X_0, your energy resolution would be 2% at 50 GeV from leakage alone!

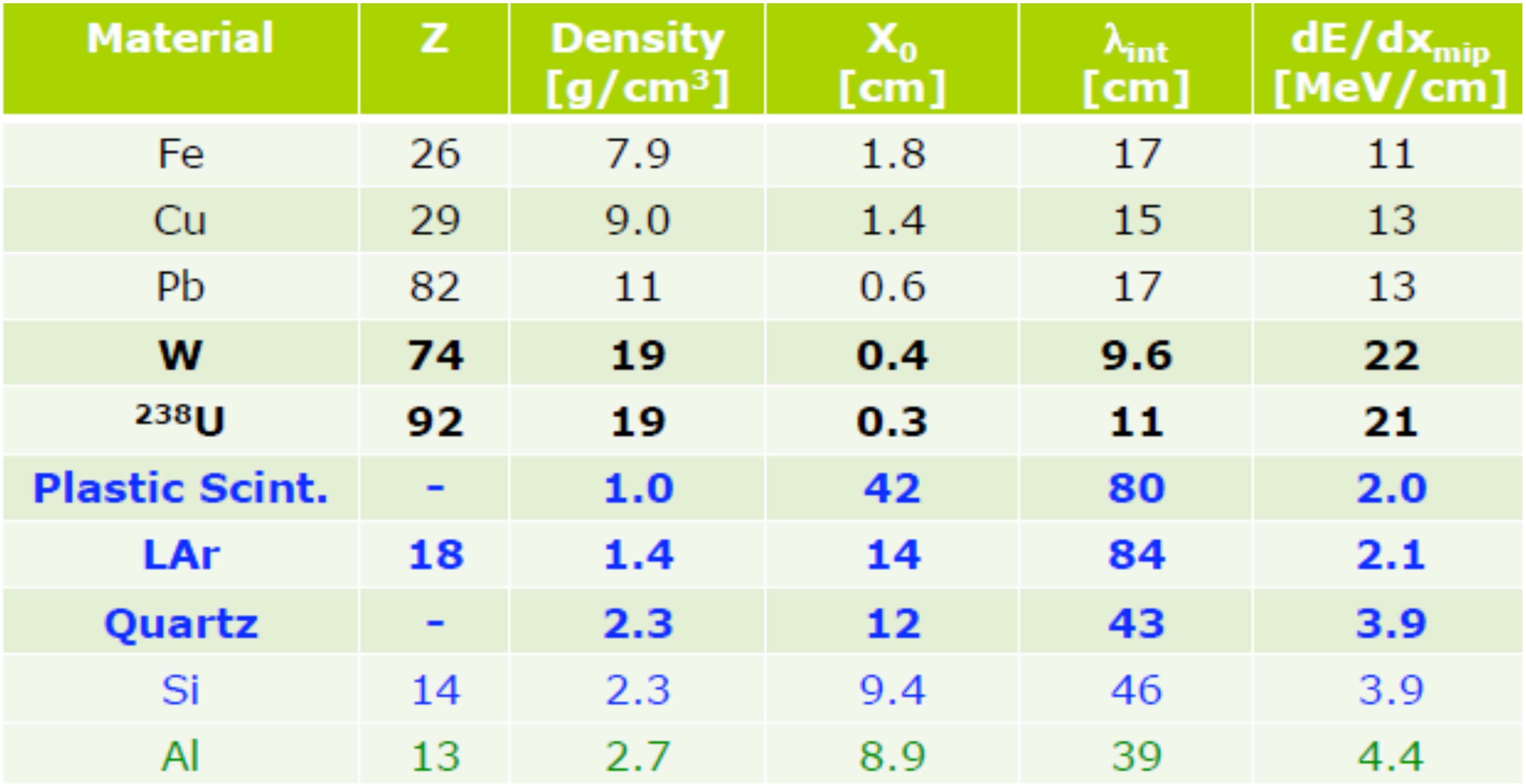
Passive Medium

- Want high Z material
  - Quickly induce EM showers
  - Feasibly build thick enough to contain hadronic showers (size, cost)



CMS uses old Russian shell casings for brass in HCAL

Comparison of materials



Material	Z	Density [g/cm³]	X_0 [cm]	λ_{int} [cm]	dE/dx_{mip} [MeV/cm]
Fe	26	7.9	1.8	17	11
Cu	29	9.0	1.4	15	13
Pb	82	11	0.6	17	13
W	**74**	**19**	**0.4**	**9.6**	**22**
^{238}U	**92**	**19**	**0.3**	**11**	**21**
Plastic Scint.	**-**	**1.0**	**42**	**80**	**2.0**
LAr	**18**	**1.4**	**14**	**84**	**2.1**
Quartz	**-**	**2.3**	**12**	**43**	**3.9**
Si	14	2.3	9.4	46	3.9
Al	13	2.7	8.9	39	4.4

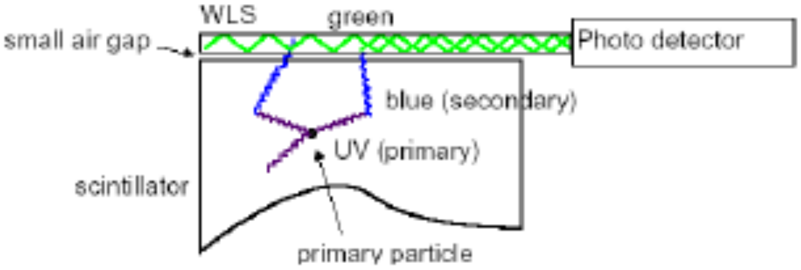
absorber

active

support

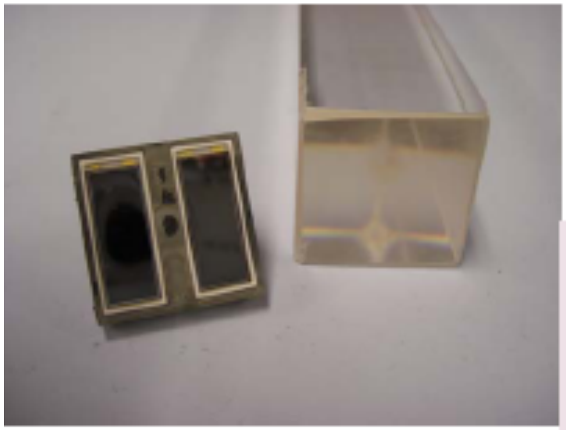
Photodetection devices

- Scintillating crystals, quartz fibers produce light in proportion to the energy lost by incoming particle
- Light converted to analog signal with photodetector
- Must meet physics, design constraints
  - Quantum efficiency (probability to convert an incoming photon into a photoelectron) meshes with light output
  - Environment – magnetic field, radiation
  - Readout requirements – single or multi-anode PhotoMultipler
  - Sensitive to wavelength of light from active detector
    - Or else use WaveLength Shifter to collect light

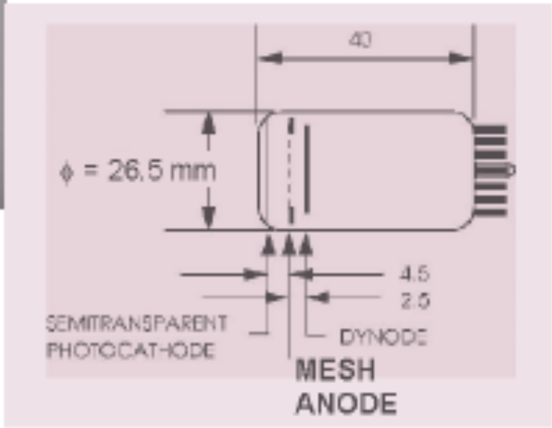


Photodetectors that operate in a magnetic field

PIN Diodes
Unity Gain

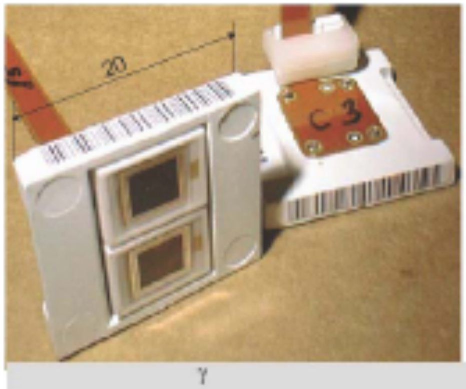


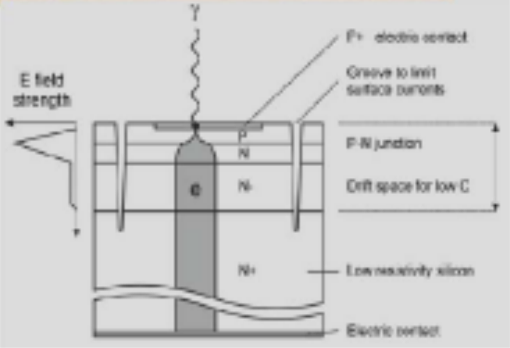
Vacuum PhotoTriode (VPT)
Gain ~x10



CMS ECAL Endcap
Copper mesh anode for operation in 4T B field

Avalanche PhotoDiode (APD)
Gain ~x50

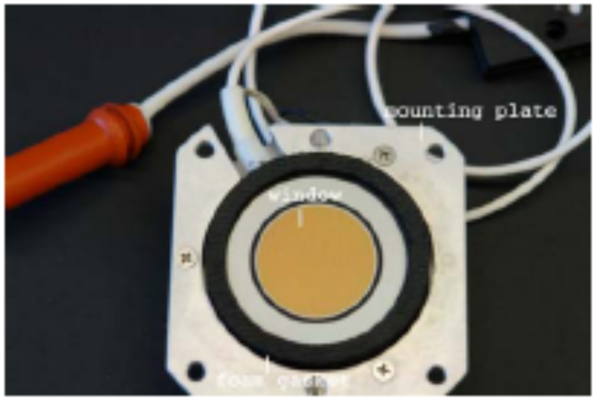


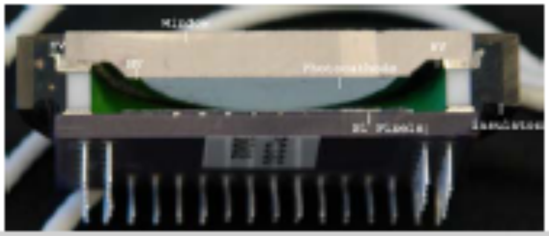


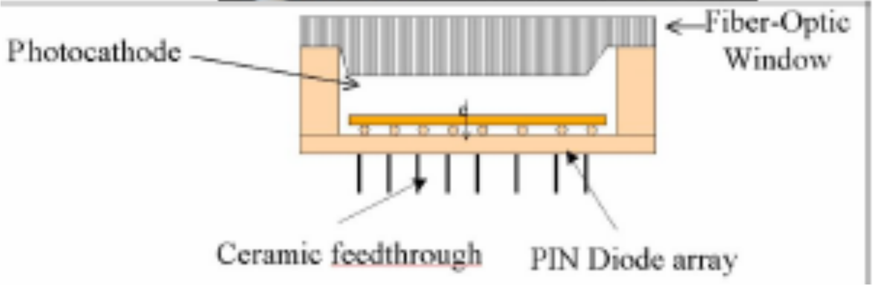
CMS ECAL Barrel
Can survive 10 years in LHC conditions

Photodetectors that operate in a magnetic field

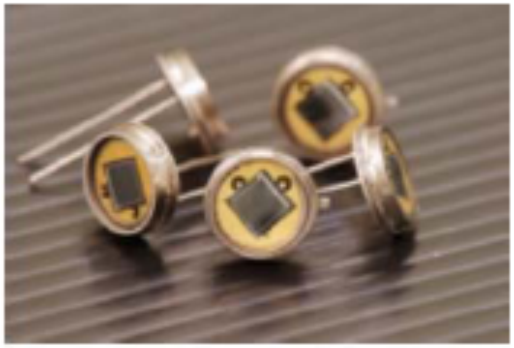
Hybrid PhotoDiode (HPD)
Gain ~x2000







Silicon PhotoMultipliers (SiPM)
Micro-pixel Avalanche PhotoDiodes (MAPD)
Multi-Pixel Photon Counters (MPPC)
Gain ~x60,000-1,000,000



Environment -- radiation

- Damage caused by ionizing radiation
  - caused by energy deposited by particles in the detector material: ≈ 2 MeV g^{-1} cm^{-2} for a min. ion. particle
  - also caused by photons from EM showers
  - damage proportional to the deposited energy per unit mass, or dose -- measured in Gy (Gray):
    - 1 Gy = 1 Joule / kg = 100 rads
    - 1 Gy = 3 $\times 10^9$ particles per cm^2 of material with unit density
- At LHC design luminosity, the ionizing dose is: $\sim 2 \times 10^6$ Gy / r_T^2 / year,
  - r_T (cm) is the transverse distance to the beam

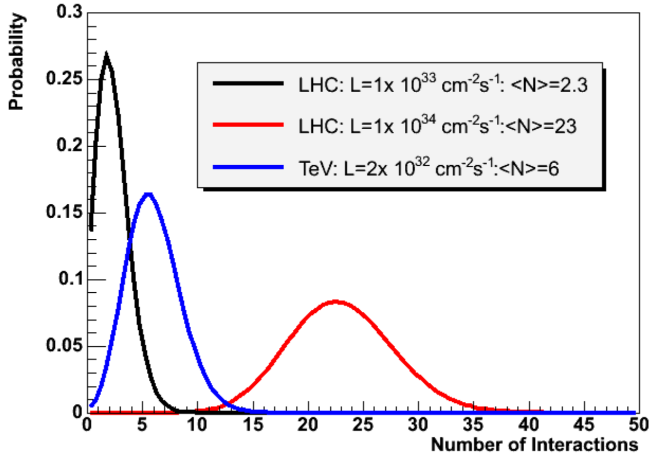
Environment -- Neutrons

- Damage caused by neutrons
  - neutrons created in HAD shower, also in the forward shielding of the detectors and in beam collimators
  - neutrons (energies in the 0.1 -- 20 MeV range) bounce back and forth (like gas molecules) on the various nuclei --can fill up the whole detector
- expected neutron fluence ~ 3 x10^{13} per cm^2 per year in the innermost part of the detectors (inner tracking systems)
  - these fluences are moderated by the presence of Hydrogen (eg in scintillator):
    - σ(n,H) ~ 2 barns with elastic collisions
    - mean free path of neutrons is ~ 5 cm at this energy
    - at each collision, neutron loses 50% of its energy (this number would be e.g. only 2% for iron)

More on neutrons

- the neutrons cause trouble in semiconductors-- modify the crystalline structure
  - Independent of deposited energy
- need radiation-hard electronics
  - off-the-shelf electronics usually dies out for doses above 100 Gy and fluences above 10^{13} neutrons/cm^2
  - rad-hard electronics (especially deep-submicron) can survive up to 10^5-10^6 Gy and 10^{15} neutrons/cm^2

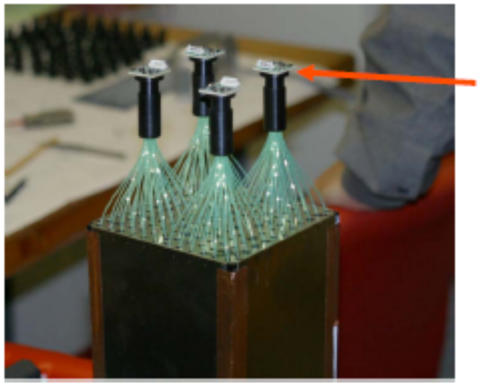
Environment – multiple interactions

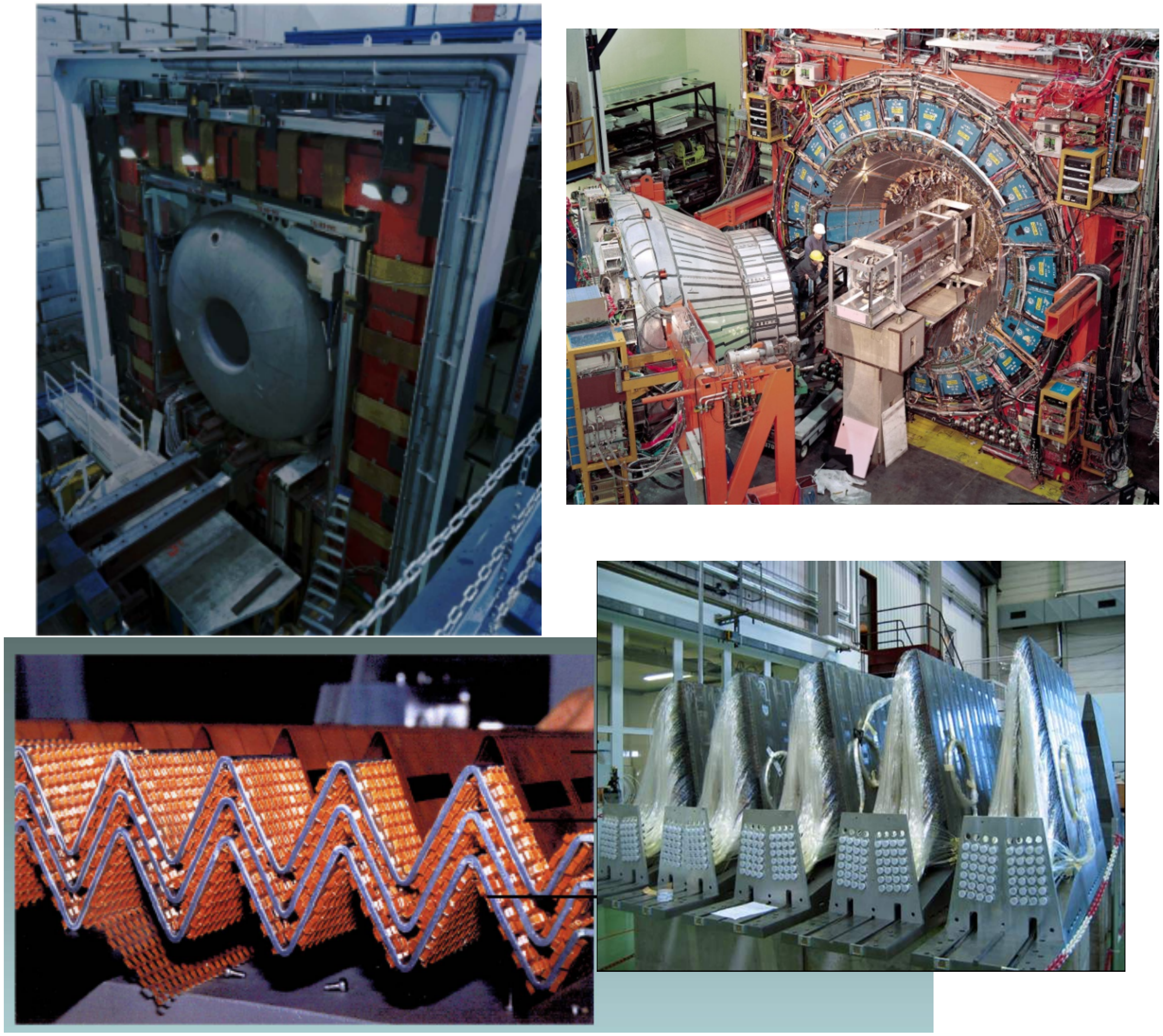


- Pile-up -- impact of the many (20 at LHC design luminosity) uninteresting (usually) interactions occurring in the same bunch crossing as the interesting hard-scattering process
- Detector design to minimize impact of pileup
  - a precise (and if possible fast) detector response minimizes pile-up in time (20-50 ns)
  - a highly granular detector minimizes pile-up in space → large number of channels (100 million pixels, 200,000 cells in electromagnetic calorimeter)

Calorimeters in today’s hadron colliders

- Tevatron
  - CDF
  - D0
- LHC
  - Atlas
  - CMS
  - LHCb
  - ALICE



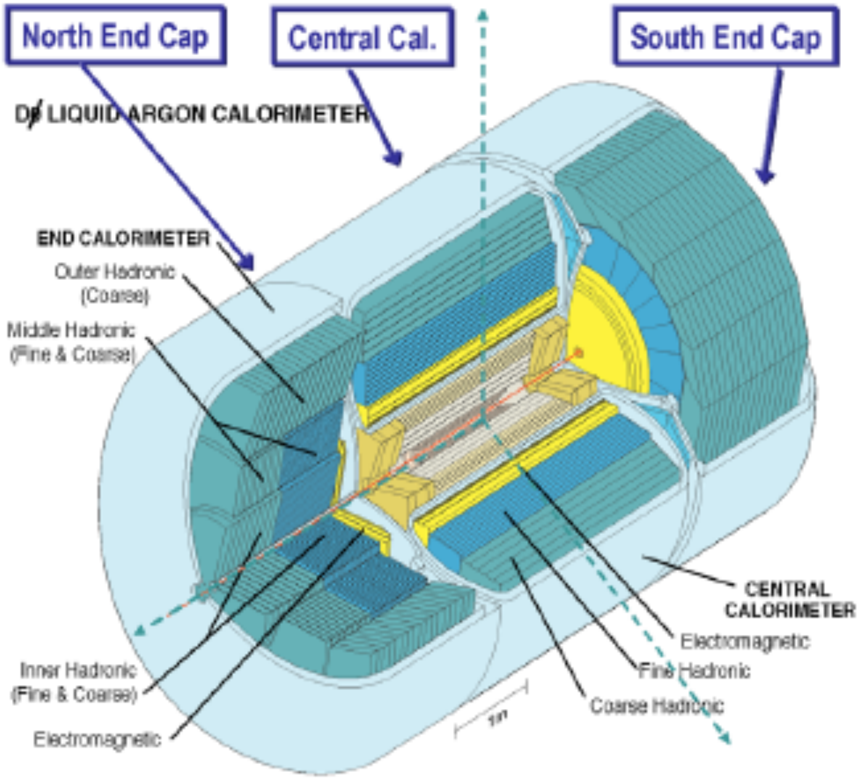


Tevatron Calorimeters

- CDF and D0 detectors were designed >25 years ago for Run 1 (1992-96), optimized for Standard Model physics (top discovery)
- upgraded for Run 2 (2001 -- 2011)
  - Upgrade of readout, trigger needed for Run 2 (Tevatron bunch-crossing time decreased from 3.4us in Run 1 to 396ns for Run 2
  - CDF and D0 built new tracking, D0 added solenoid
  - CDF upgraded plug calorimeter (same technology used for CMS HCAL), added preshower and timing readout to Central EM calorimeter
- Compared to LHC, Tevatron calorimeters have more time between crossings, no radiation hardness requirements, somewhat smaller dynamic range
  - Well understood, producing excellent physics results !

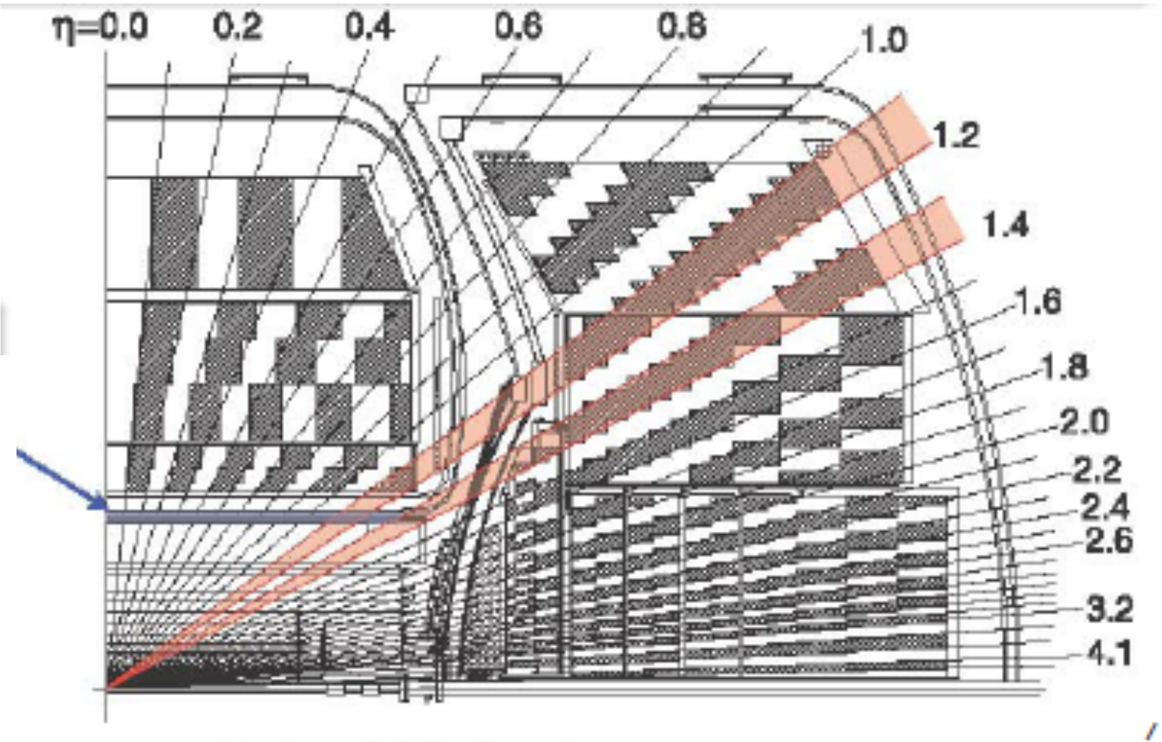
D0 Calorimeters

- Uranium/Liquid Argon EM cal
  - 4 layers (2,2,7,10 X_0)
- Copper/Steel hadronic cal
  - 4-5 hadronic layers
  - l > 7.2 (total)
- Numbers
  - 55,000 readout cells
  - 5000 semi-projective trigger towe
    - $\delta\eta \times \delta\phi = 0.1 \mathrm{x} 0.1$
  - Coverage |h|<4.2
- Performance
  - Compensating: e/h ~ 1 (with 3.4μ integration time)
  - Single particle resolution (testbeam)
    - e: $\sigma_E/E = 15\% /\sqrt{E} + 0.3\%$
    - π: $\sigma_E/E = 45\% /\sqrt{E} + 4\%$



D0 Calorimeter

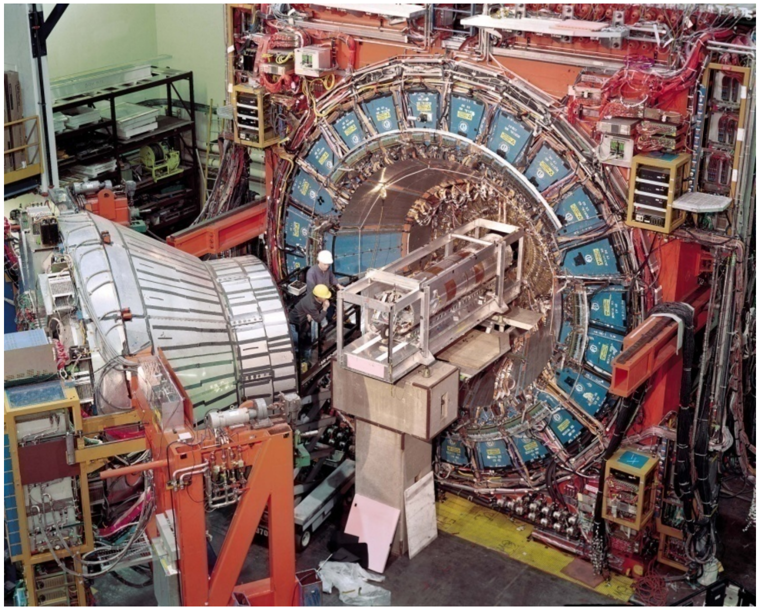
- Pseudo-projective towers
- Hadronic segmentation : 3 central, 7.2 λ; 4 endcap layers, 8.0 λ
- Significant material in front of calorimeter: $4X_0$ (solenoid, preshowers, trackers)

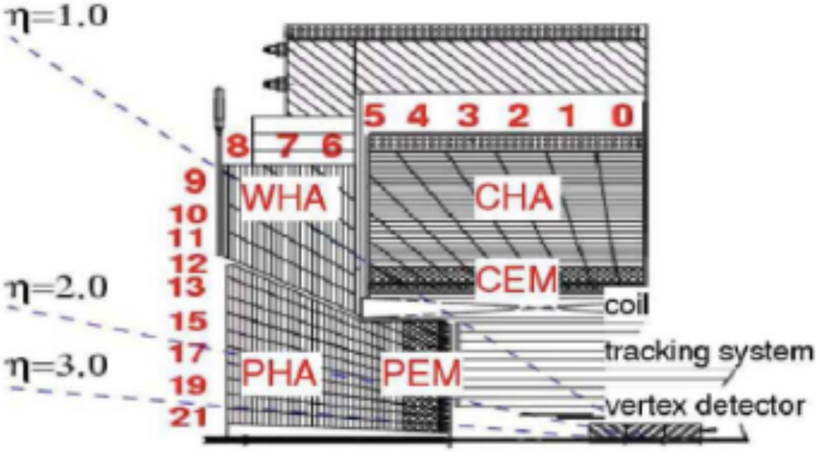


Preshower detector
•scintillating fibers
•Improve γ detection

Note, ICD Region

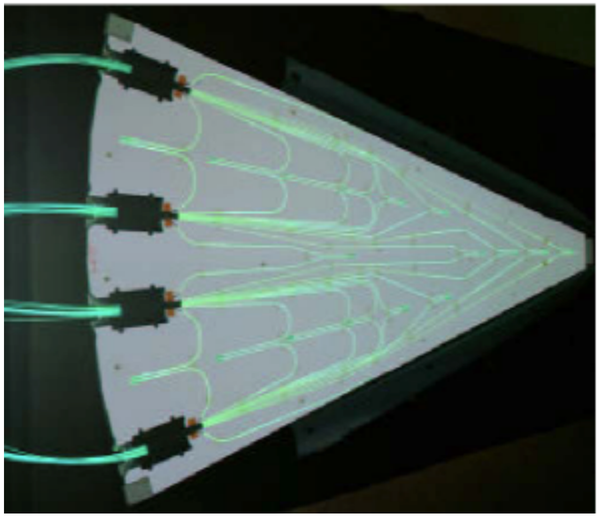
CDF Calorimeters





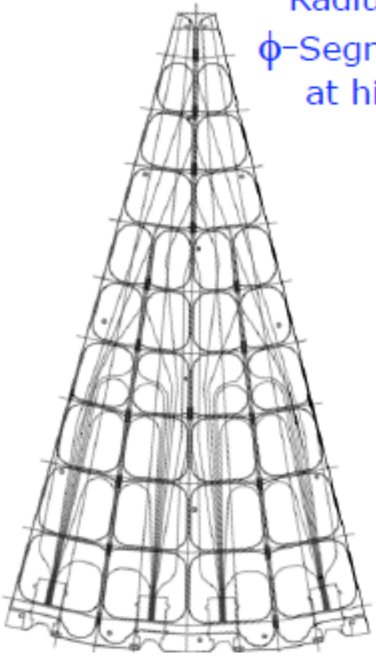
Sampling cal's	ECAL	HCAL
material	Pb-Scintillator	Fe-Scintillator
Resolution Central	$13.5\%/\sqrt{E\sin\theta} + 2\%$	$50\% /\sqrt{E}$
Resolution endcap	$16\%/\sqrt{E} + 1\%$	$80\%/\sqrt{E} + 5\%$
depth	$21X_0$, 1λ (SMX $6X_0$)	7λ

CDF Plug Calorimeter



30° Megatiles

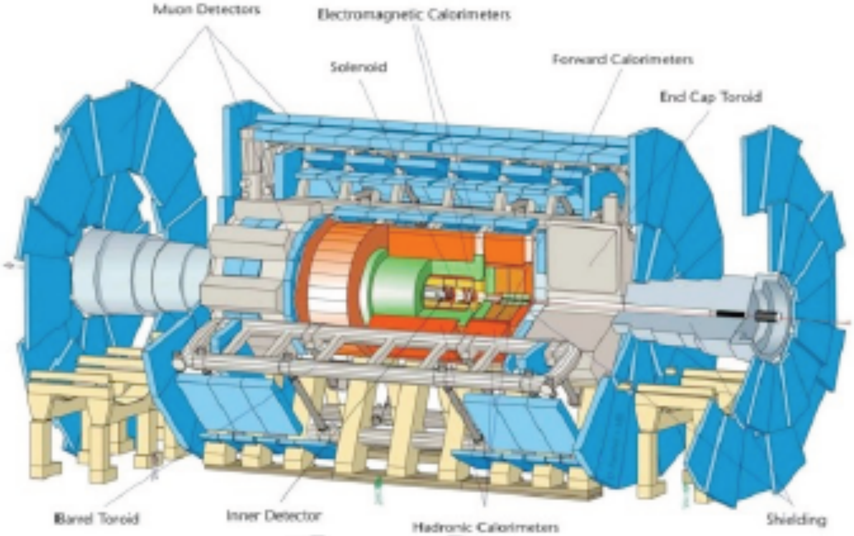
	EM	HAD
Segmentation	$\sim 8 \times 8 cm^2$	$\sim 24 \times 24 cm^2$
Total Channels	960	864
Thickness	$21\ X_0,\ 1\ \lambda_0$	$7\ \lambda_0$
Density	$0.36\rho_{Pb}$	$0.75\rho_{Fe}$
Samples	22 + Preshower	23
Active	4 mm Scint	6 mm Scint
Passive	4.5 mm Pb	2 inch Fe
Light Yield (pe/MIP/tile)	$\geq$3.5	$\geq$2
Resolution	$16\%/\sqrt{E} \oplus 1\%$	$80\%/\sqrt{E} \oplus 5\%$



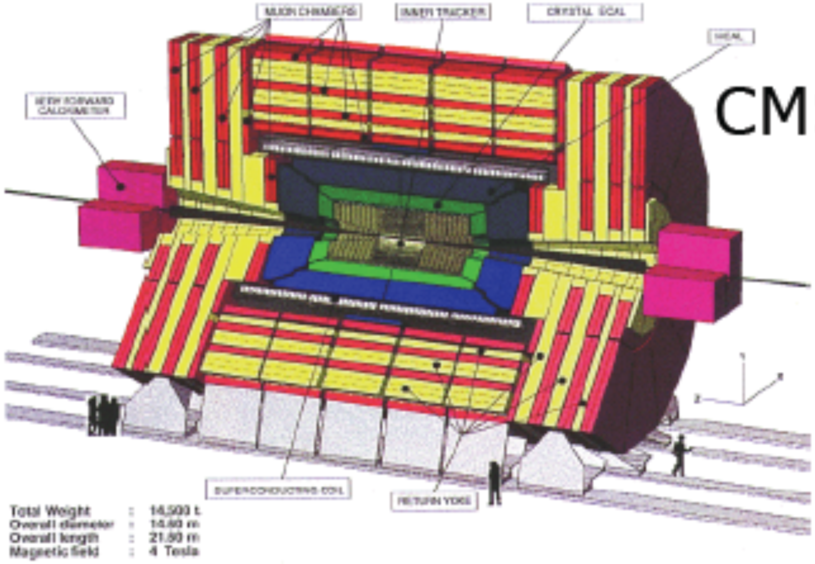
Fiber bending
Radius limits
ϕ-Segmentation
at high eta

LHC Experiments

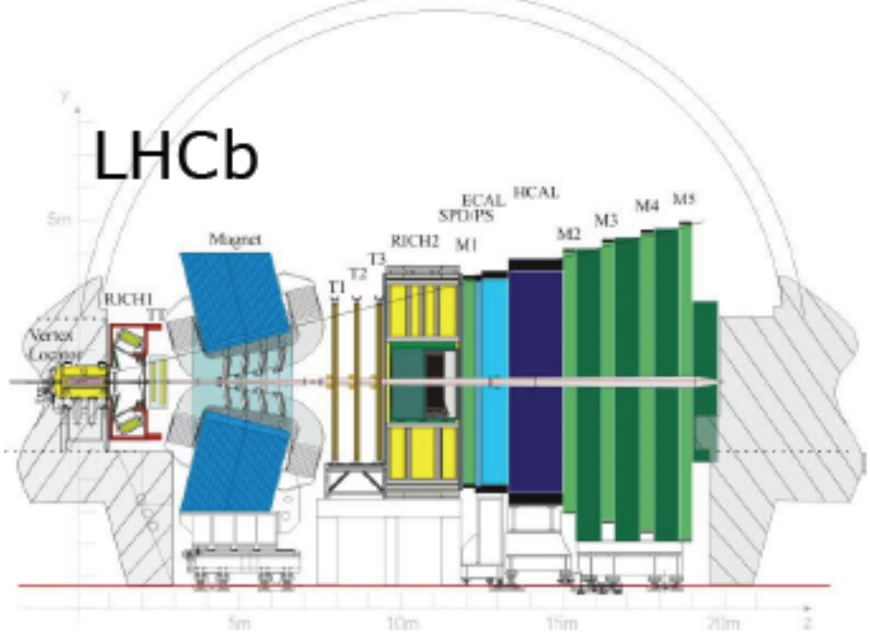
ATLAS

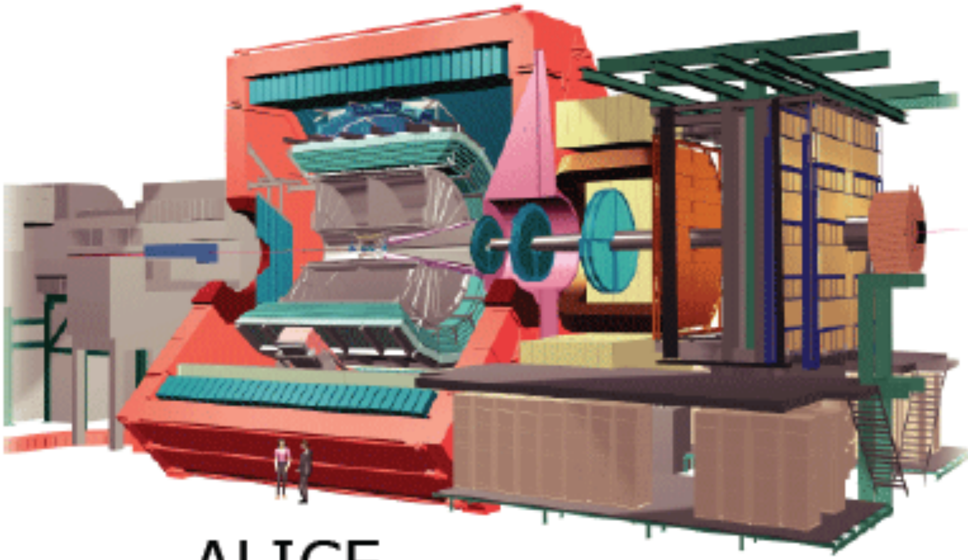


CMS



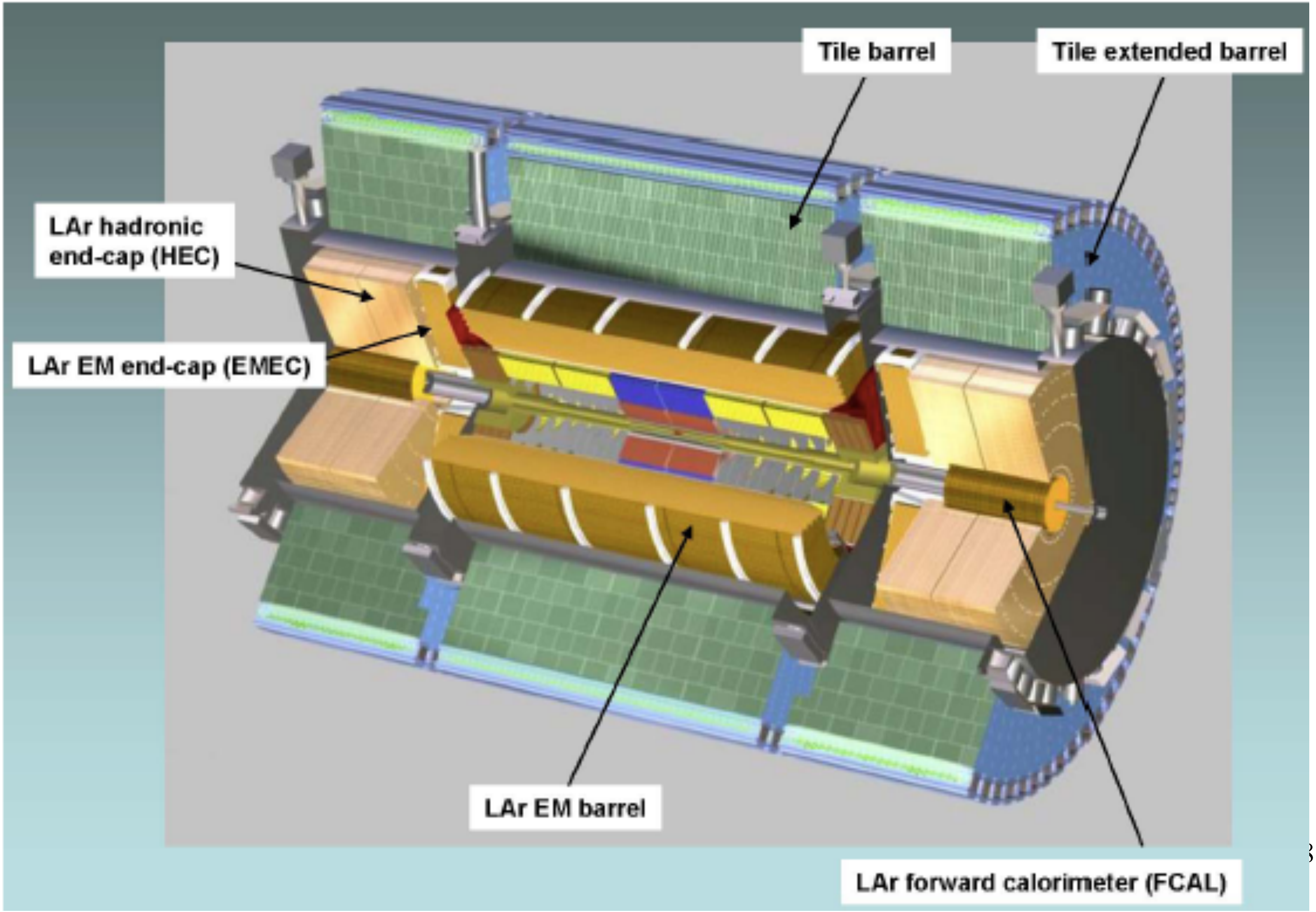
LHCb





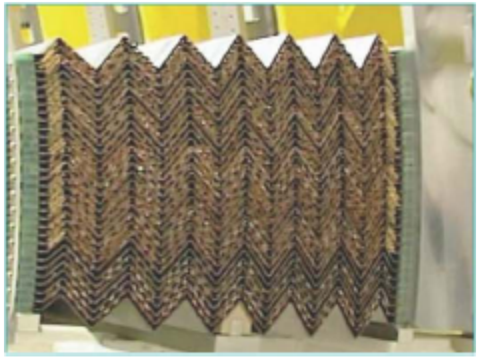
ALICE

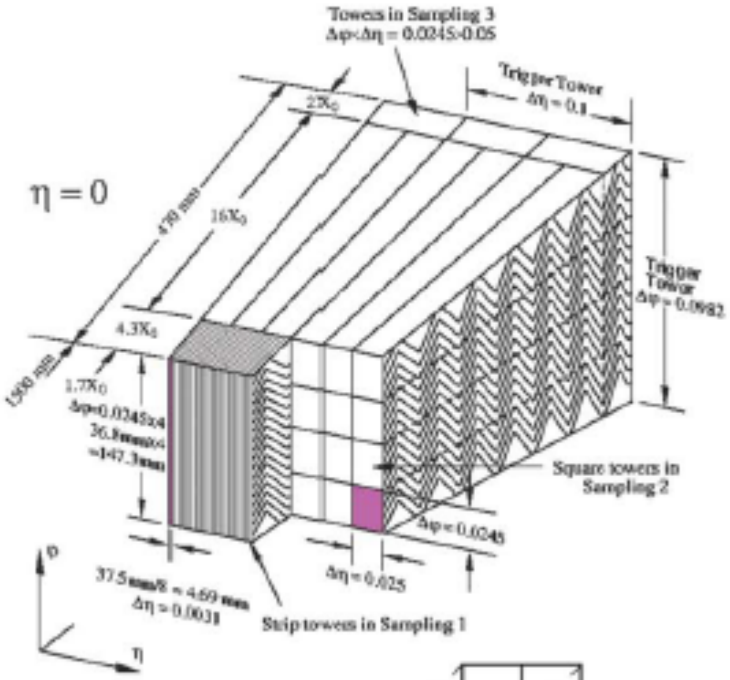
Atlas Calorimeters



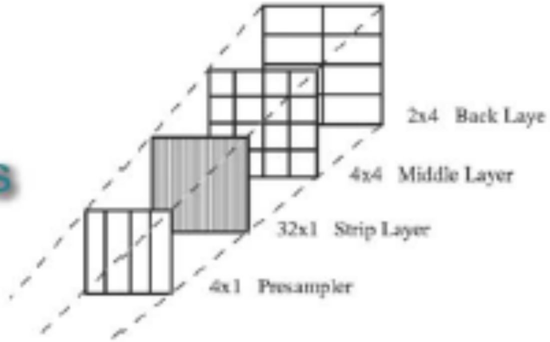
Atlas Lead-Liquid Argon EM Calorimeter

- $22X_0$ (47cm) barrel, $24X_0$ endcap
- Pb thickness optimized as a function of η for energy resolution
  - Central region ($|\eta|<2.5$) : 3 longitudinal layers (+ presampler $|\eta|<1.8$) for precision physics
    - 4 X_0 : fine gran.strip layer – reject $\pi^0 \rightarrow \gamma\gamma$
    - 16 X_0 : middle – shower core
    - 2 X_0: back – late showers
  - Endcap ($|\eta|$ 2.5 – 3.2) : 2 long. segments, coarser granularity



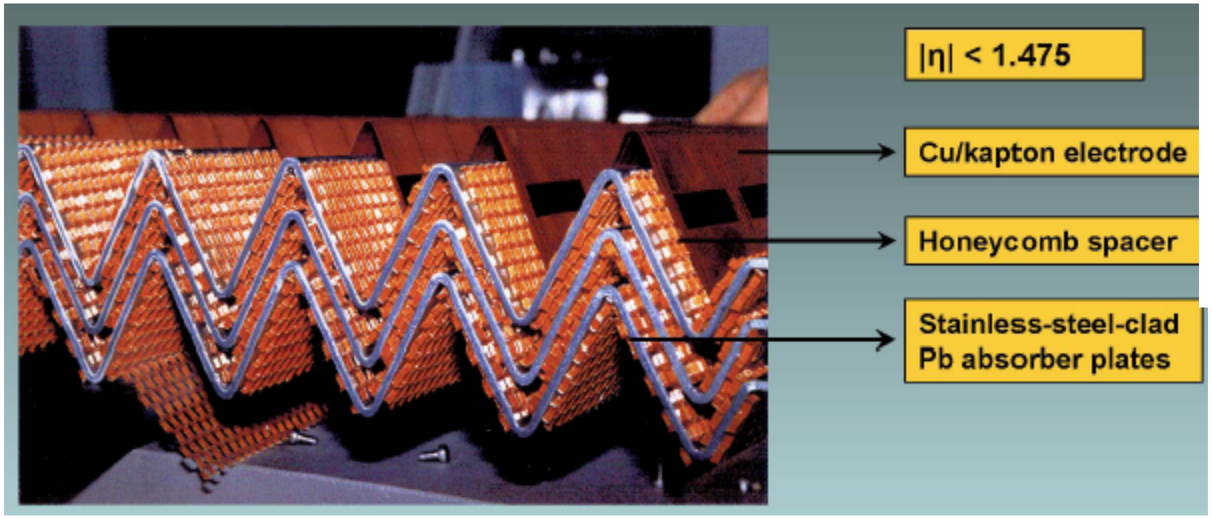


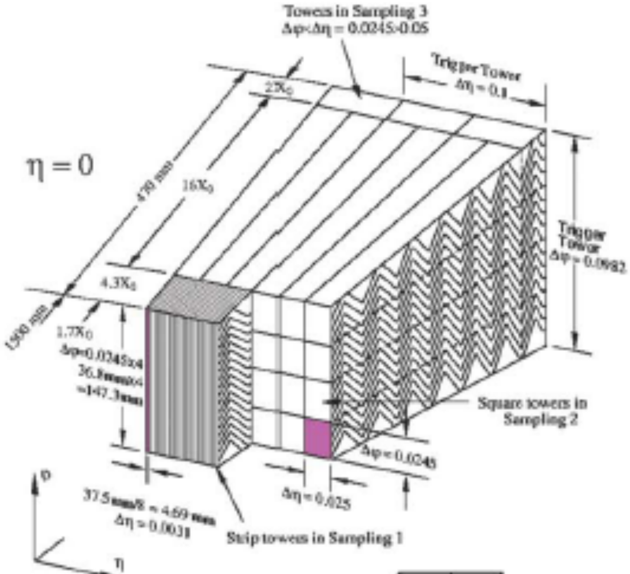
170000 channels



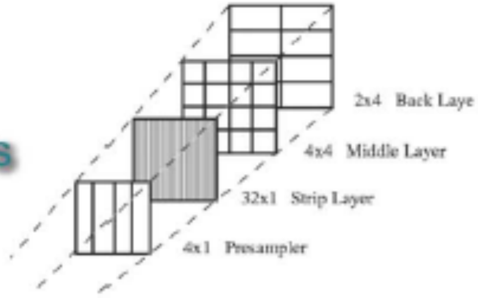
Atlas Lead - Liquid Argon EM calorimeter

- Accordion-shaped capton electrodes and lead absorber plates
  - Complete ϕ symmetry without azimuthal cracks
- Spacing held with honeycomb structure

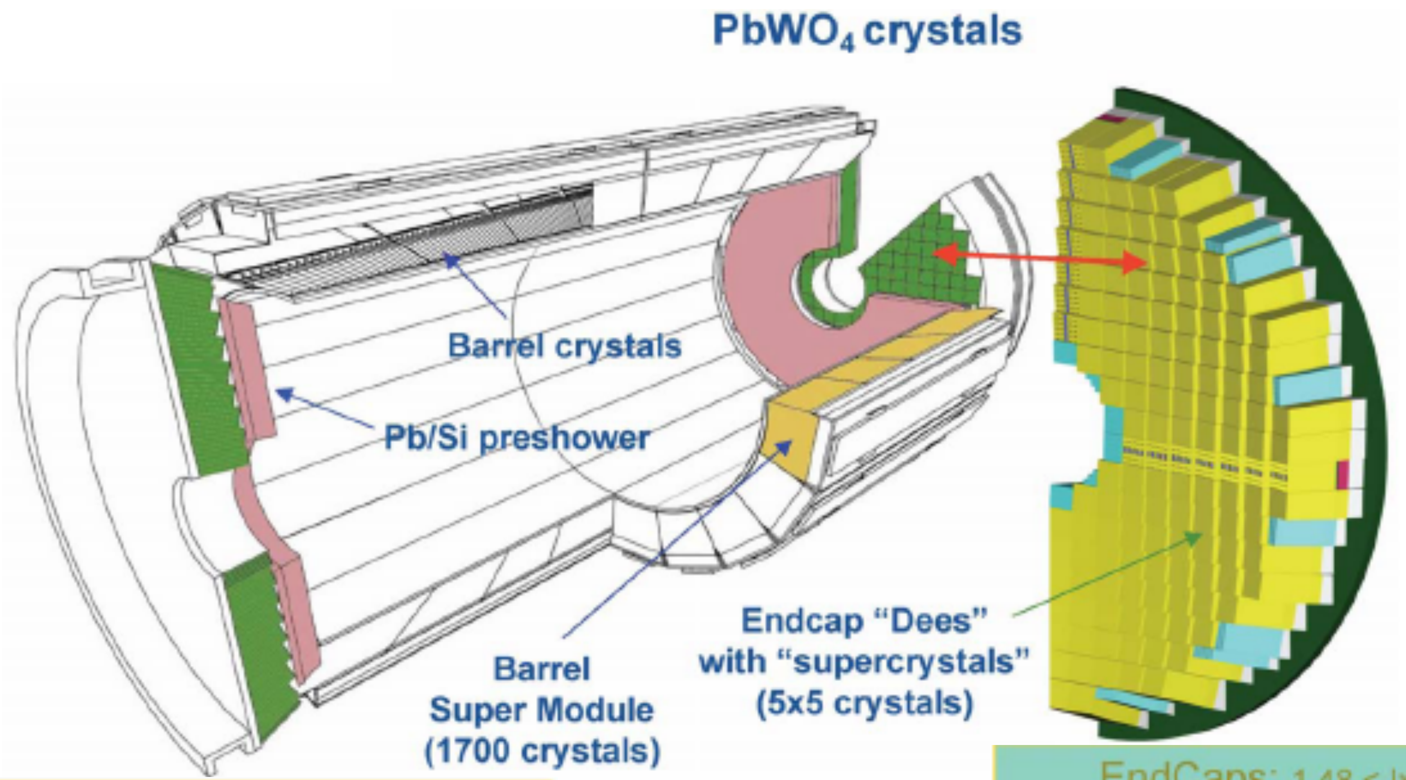




170000 channels



CMS Electromagnetic Calorimeter

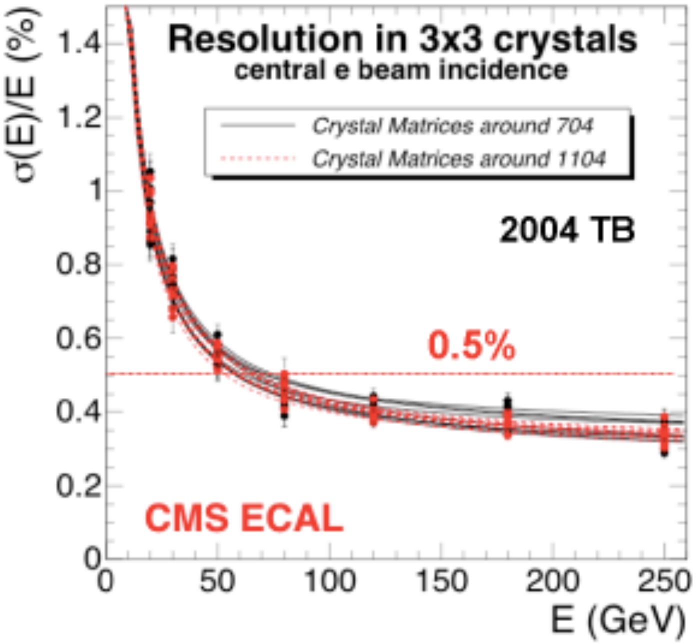


Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2 \times 2 \times 23 cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3 \times 3 \times 22 cm^3$)

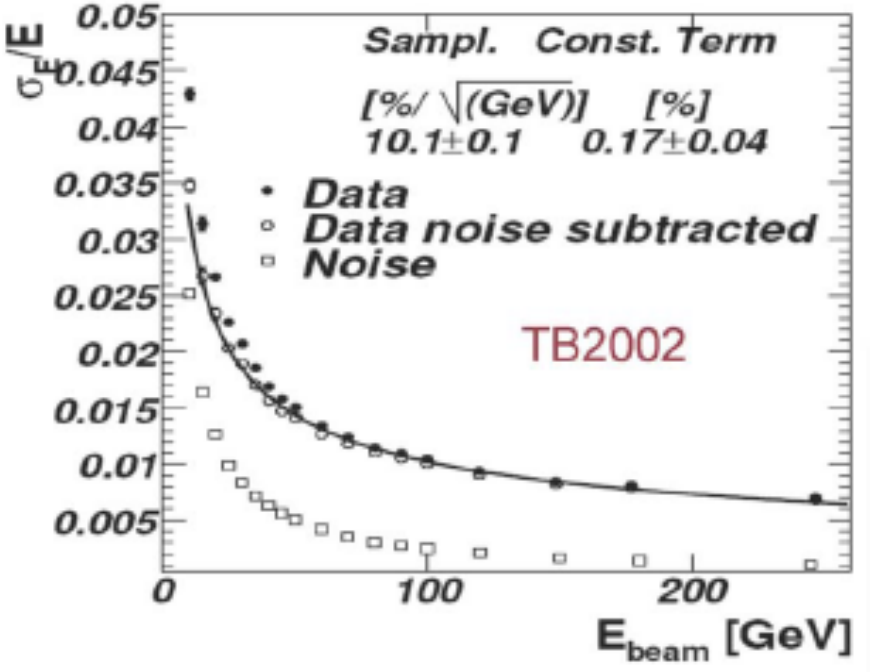
- Crystals give excellent stochastic resolution
- Challenge: uniformity, stability

Compare CMS and Atlas EM cal resolution



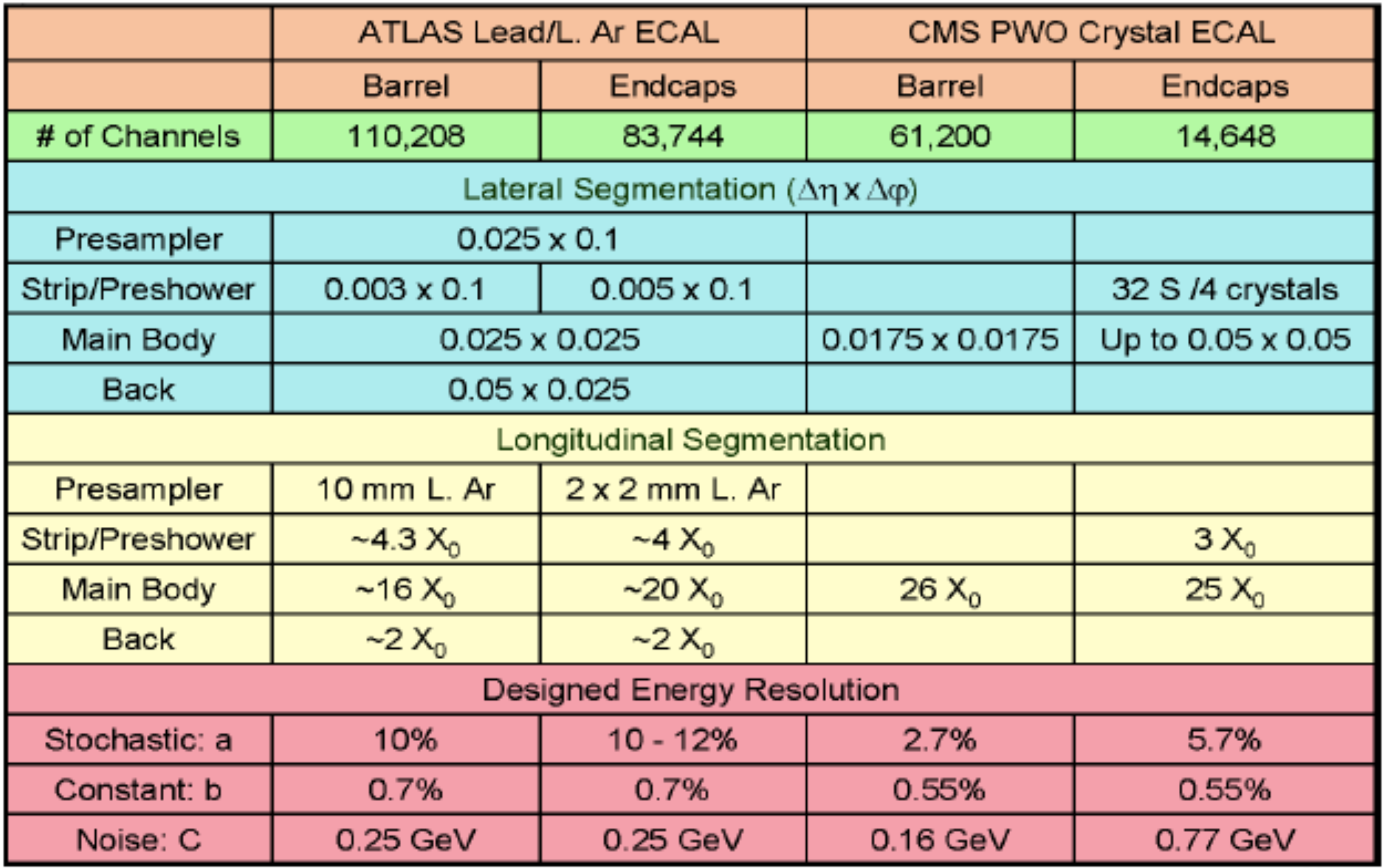
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

Atlas EM Resolution



- Global constant term CMS: <0.5%; Atlas: 0.6 – 0.7%

Parameters of CMS/Atlas EM calorimeters



	ATLAS Lead/L. Ar ECAL		CMS PWO Crystal ECAL	
	Barrel	Endcaps	Barrel	Endcaps
# of Channels	110,208	83,744	61,200	14,648
Lateral Segmentation $(\Delta\eta \times \Delta\varphi)$				
Presampler	0.025 x 0.1			
Strip/Preshower	0.003 x 0.1	0.005 x 0.1		32 S /4 crystals
Main Body	0.025 x 0.025		0.0175 x 0.0175	Up to 0.05 x 0.05
Back	0.05 x 0.025			
Longitudinal Segmentation				
Presampler	10 mm L. Ar	2 x 2 mm L. Ar		
Strip/Preshower	~4.3 X_0	~4 X_0		3 X_0
Main Body	~16 X_0	~20 X_0	26 X_0	25 X_0
Back	~2 X_0	~2 X_0		
Designed Energy Resolution				
Stochastic: a	10%	10 - 12%	2.7%	5.7%
Constant: b	0.7%	0.7%	0.55%	0.55%
Noise: C	0.25 GeV	0.25 GeV	0.16 GeV	0.77 GeV

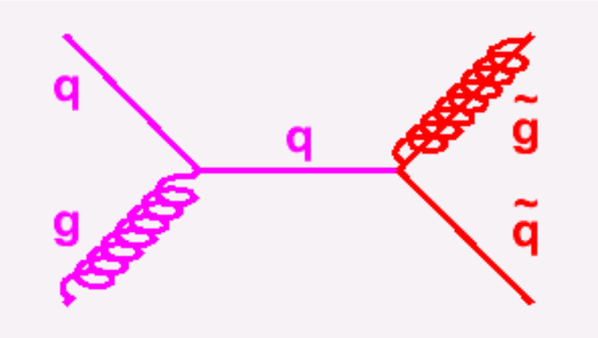
Some physics considerations for Atlas/CMS EM cal

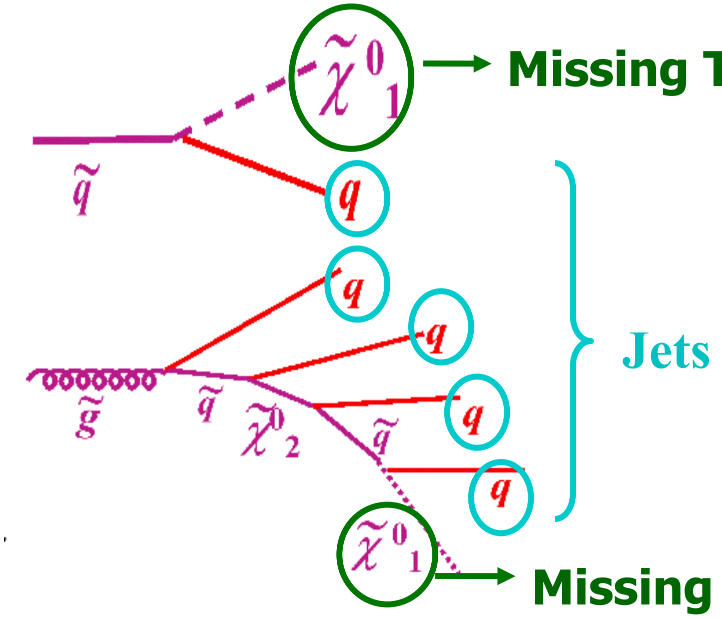
- ATLAS uses LAr sampling calorimeter with good energy resolution and excellent lateral and longitudinal segmentation (e/γ identification)
- CMS use $PbWO_4$ scintillating crystals with excellent energy resolution and lateral segmentation but no longitudinal segmentation
- Signals from $H \rightarrow \gamma\gamma$ or $H \rightarrow ZZ^* \rightarrow 4e$ should appear as narrow peaks above essentially pure background from same final state
  - intrinsically much narrower in CMS
  - intrinsically background from fakes smaller in ATLAS

Physics Goals for Hadronic Calorimeter

- Physics goal – jet, Missing ET measurements for eg, SUSY searches.

Supersymmetric squark and gluino production





Missing Transverse Energy

Jets

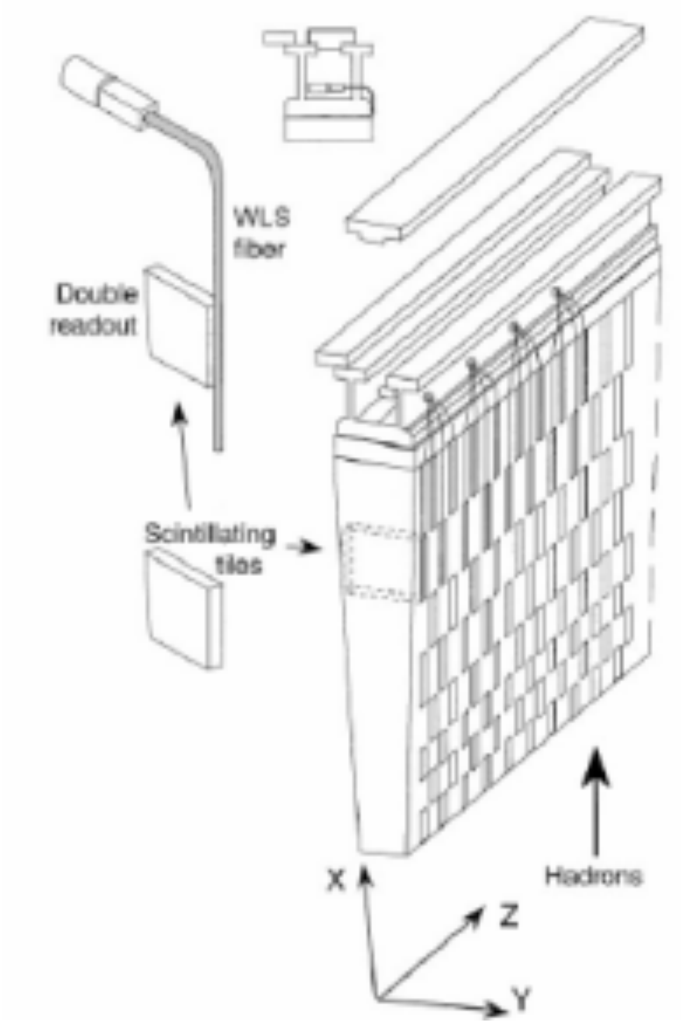
Missing Transverse Energy

Leads to events with jets and Missing transverse energy

Need good energy measurement and angular coverage from the hadronic calorimeter

Atlas Tile Calorimeter

- Fe/Scintillator, WLS fiber readout via PMT



Cell geometry in barrel. Open circles are PMT's

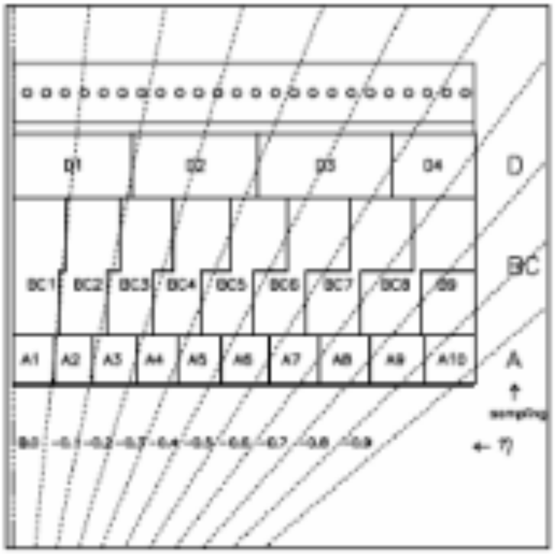
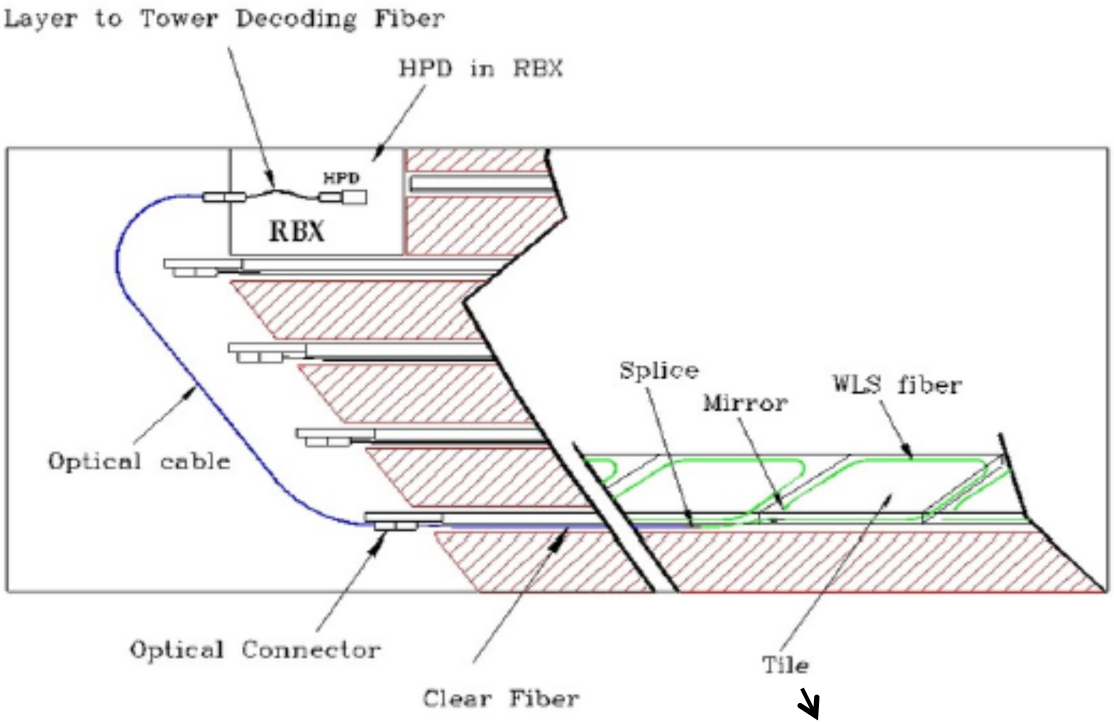


Figure 5-15 Cell geometry of half of a barrel module. The fibres of each cell are routed to one PMT.

CMS HCAL -- Barrel

Common technology used for HCAL Barrel and Endcap

Insertion of tiles into wedge



Tile and WLS fiber

Brass from old Russian warships used for CMS HCAL

CMS HCAL Endcap

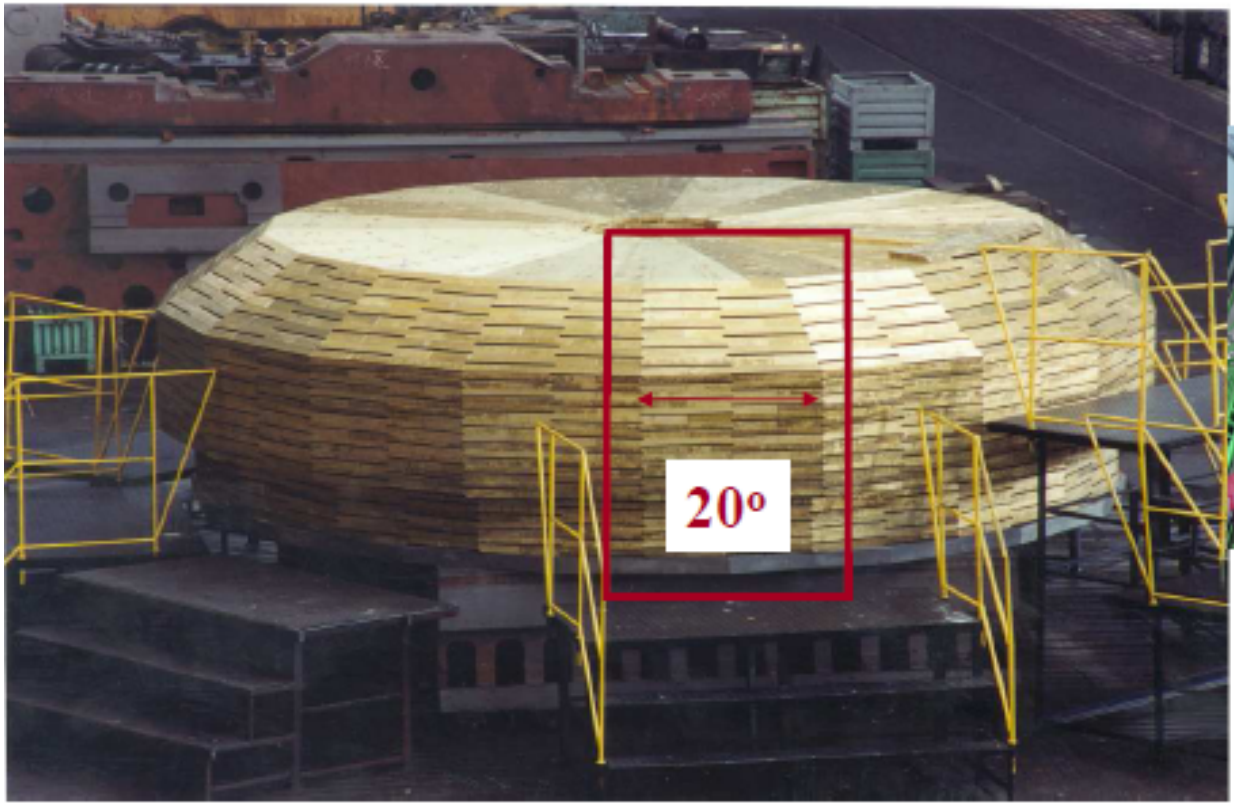
Sampling calorimeter: brass (passive) & scintillator (active)

Coverage: $1.3<|\eta|<3$

Depth: $10\ \lambda_{int}$

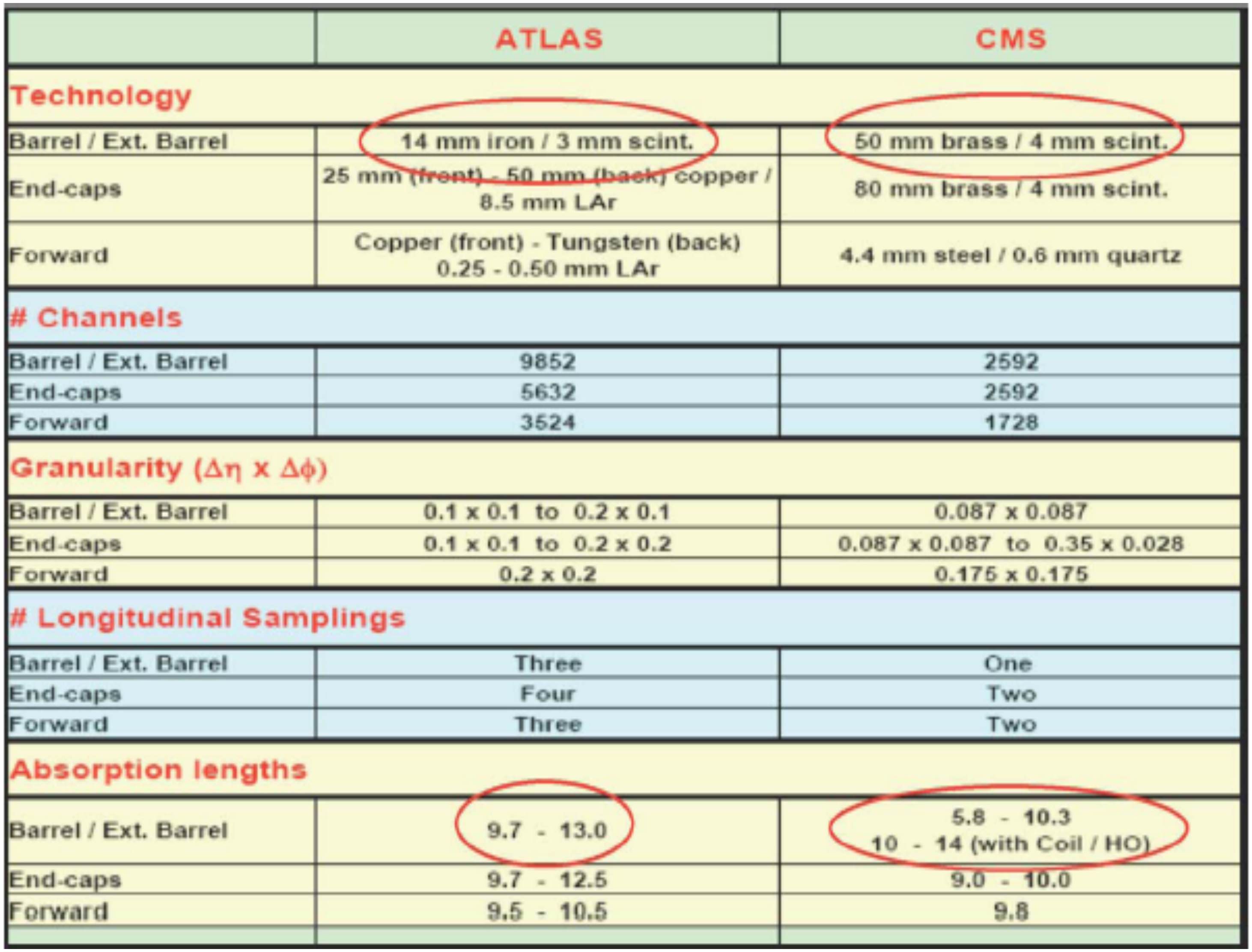
π resolution: $\sim 120\%/\sqrt{E}$

segmentation: $\phi \times \eta = 0.087 \times 0.087$



19 layers longitudinally

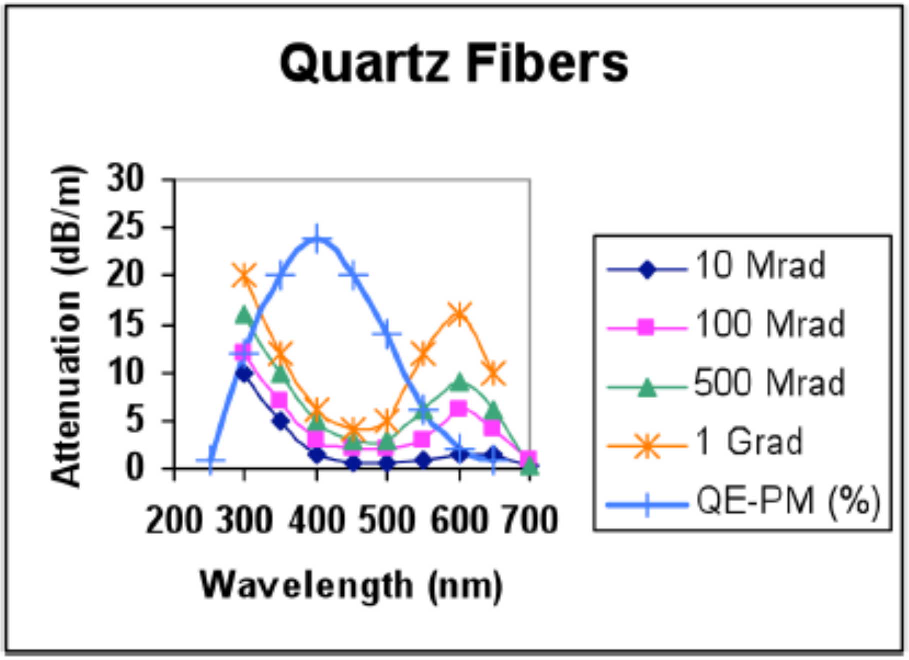
Compare CMS and Atlas Hadronic Cal



	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

Cherenkov Calorimeter – CMS HF

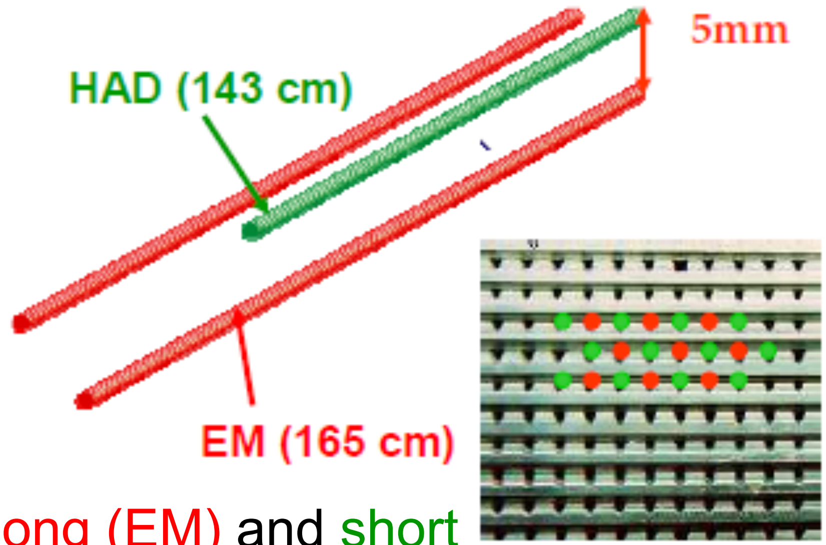
- Hadronic Forward --- Covers |η| 3-5
- |η| 4.5-5 will get 100Mrad/year (>1GRad in 10 years)
  - Quartz fibers can withstand radiation



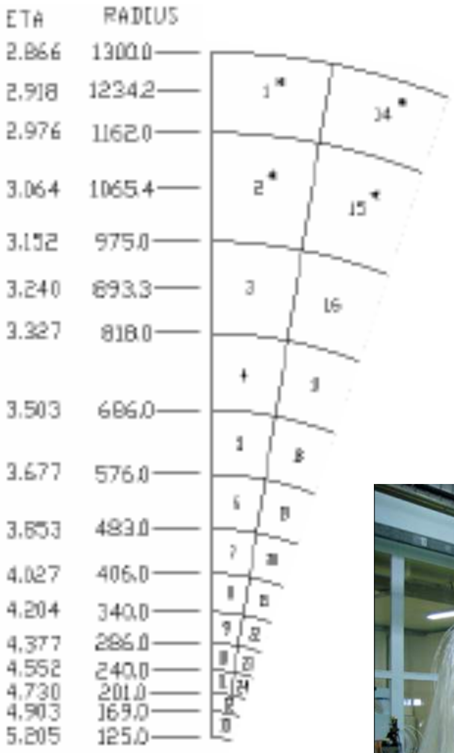
Typical spectral response of QF shows reduced radiation damage effects in the region around maximum (420 nm) of PMT sensitivity (Quantum Efficiency); this is an important asset of quartz-fiber calorimetry.

CMS HF

- Fe/QF (quartz fiber) calorimeter, measures energy through Cherenkov light generated by shower particles



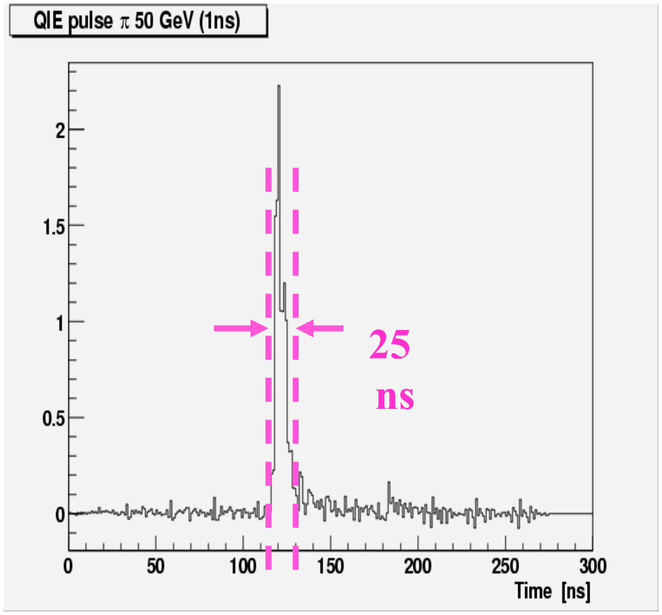
Long (EM) and short (HAD) fibers

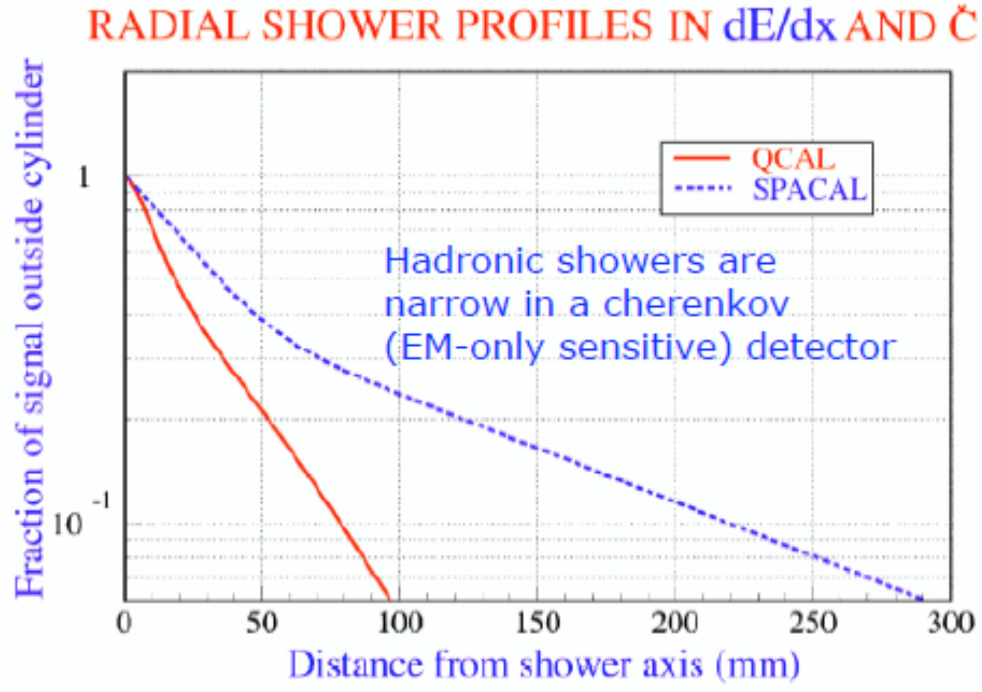


Iron calorimeter
Covers 5 > η > 3
Total of 1728 towers, i.e.
2 x 432 towers for EM and HAD
η x ϕ segmentation (0.175 x 0.175)

Properties of Cherenkov showers

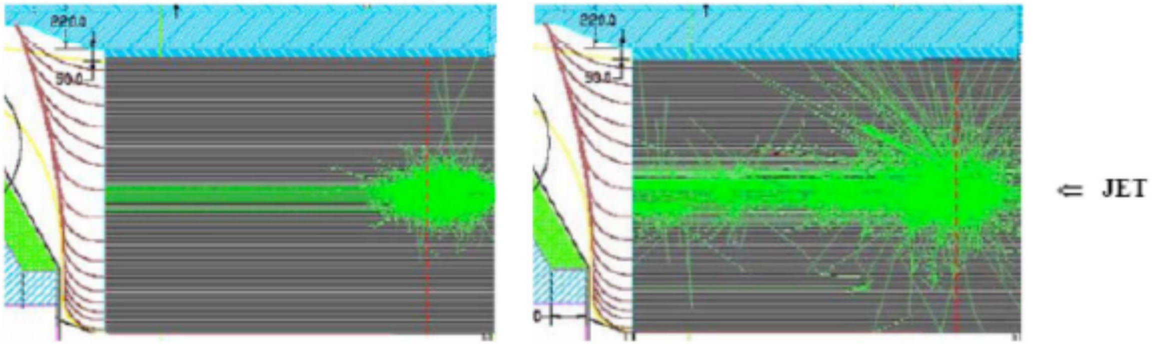
- pulse from Cherenkov light – very fast





- Hadronic showers are narrow in Cherenkov compared to ionization (scintillator) detectors

Resolution of CMS HF



100 GeV electron shower

100 GeV proton shower

100 GeV electron and proton in HF

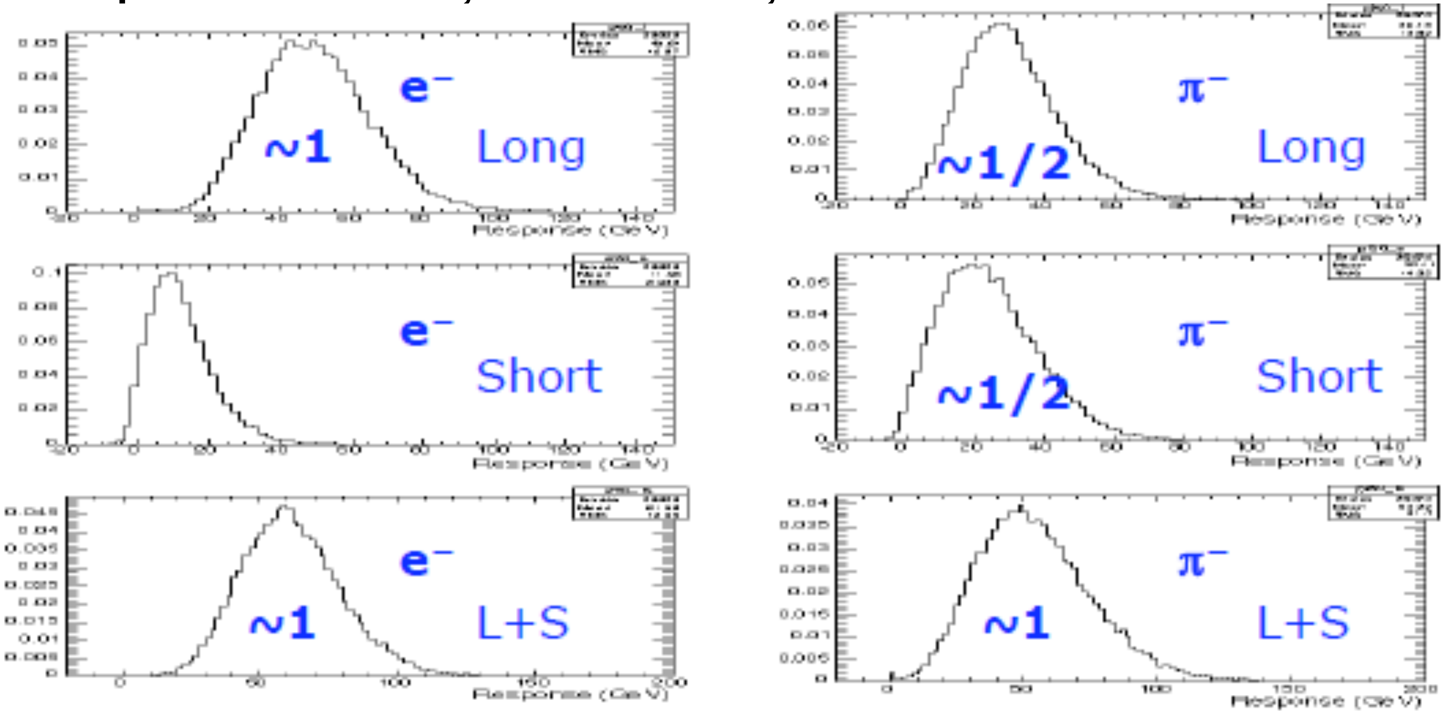
- Recall resolution expression:
  - a: intrinsic or stochastic term
  - b: noise
  - c: constant

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

- EM resolution dominated by photostatistics: a=198% , c=9%
- Hadronic resolution dominated by fluctuations of π^0 production: a = 280% and c = 11%
- Highly non-compensating e/h~5
- Light yield ~0.3 pe/GeV, Transverse uniformity +/- 10%
- Precision in η~0.03 and in ϕ~0.03rad

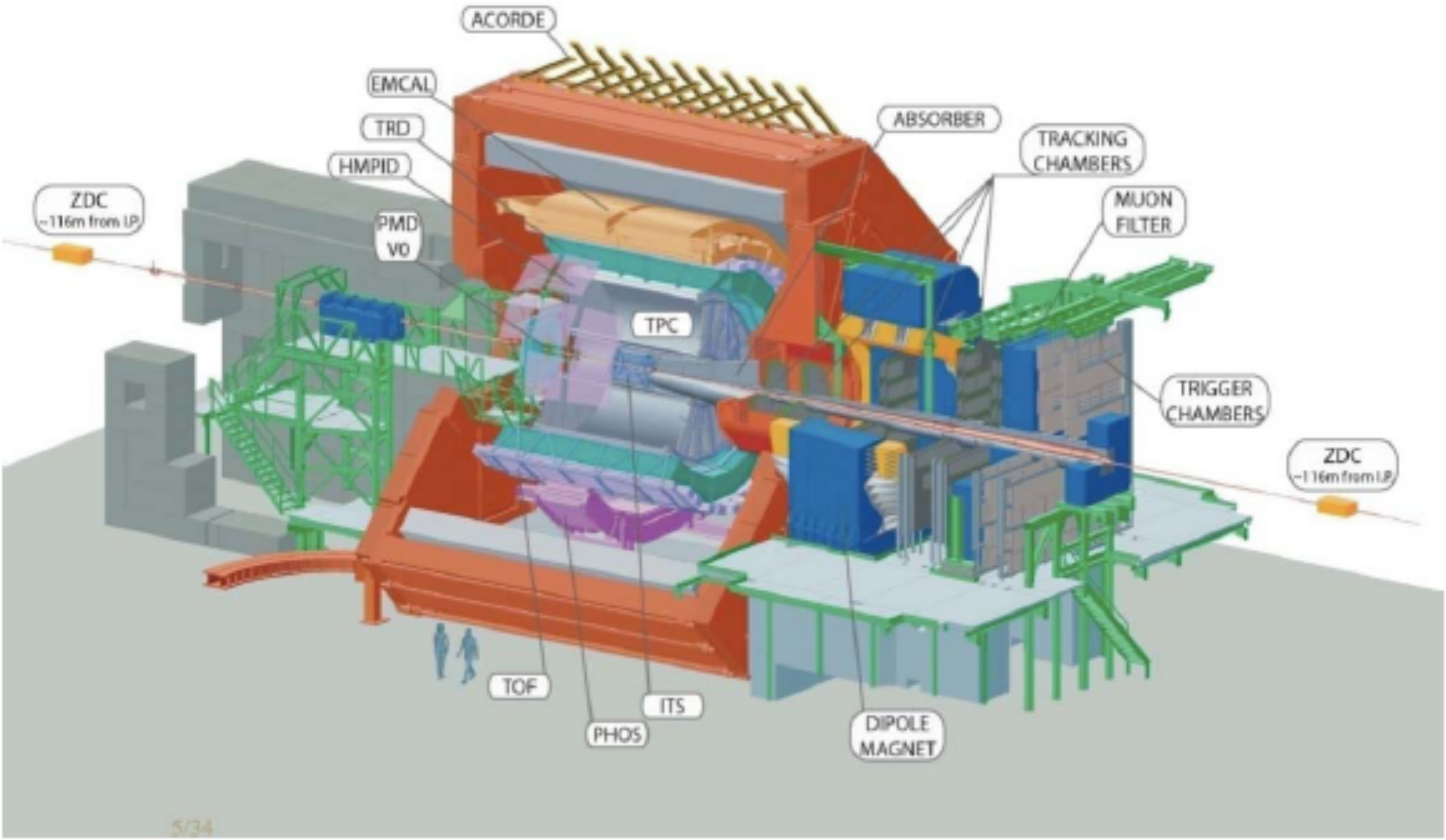
Hardware compensation

- HF Cherenkov cal has 2 lengths of Quartz Fibers, read out separately
  - Designed to compensate e/h for energies 50 -150 GeV
  - Total Response: L+S ; EM = L-S; HAD = 2S



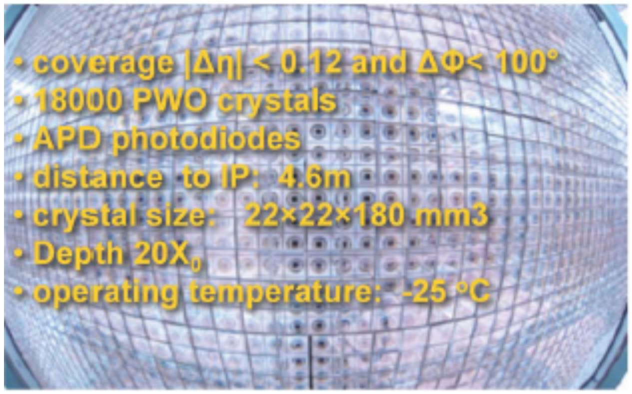
Response in L and S fibers for e and π of same energy

ALICE EMCAL and PHOS (PHOton Spectrometer



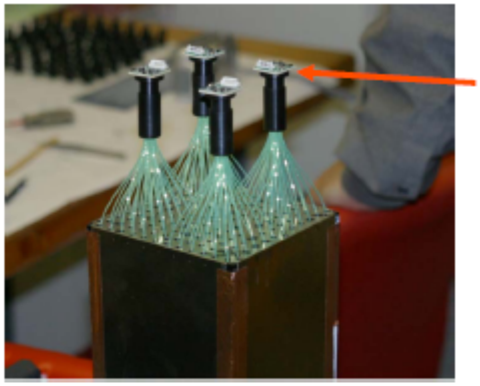
ALICE Calorimeters

- PHOS – $PbWO_4$ crystals
  - Goal – measure γ, π^o, η from 0.5 to 100 GeV
  - Energy resolution: $\frac{\sigma E}{E} = \frac{0.018}{E} + \frac{0.033}{\sqrt{E}} + 0.011$



- coverage $|\Delta\eta| < 0.12$ and $\Delta\Phi < 100°$
- 18000 PWO crystals
- APD photodiodes
- distance to IP: 4.6m
- crystal size: 22×22×180 mm3
- Depth $20X_0$
- operating temperature: -25 °C

- EMCAL – Pb-Scint. sampling
  - 4 6x6 cm2 towers/module
  - WLS fiber readout on 1cm grid
  - 5x5 mm2 Hammamatsu APD
  - ~4.5 pe/MeV
  - Full scale energy = 250 GeV
  - $\Delta\eta = \delta\phi = 0.014$; 20.1 X_0; Pb:Sc = 1.44: 1.76

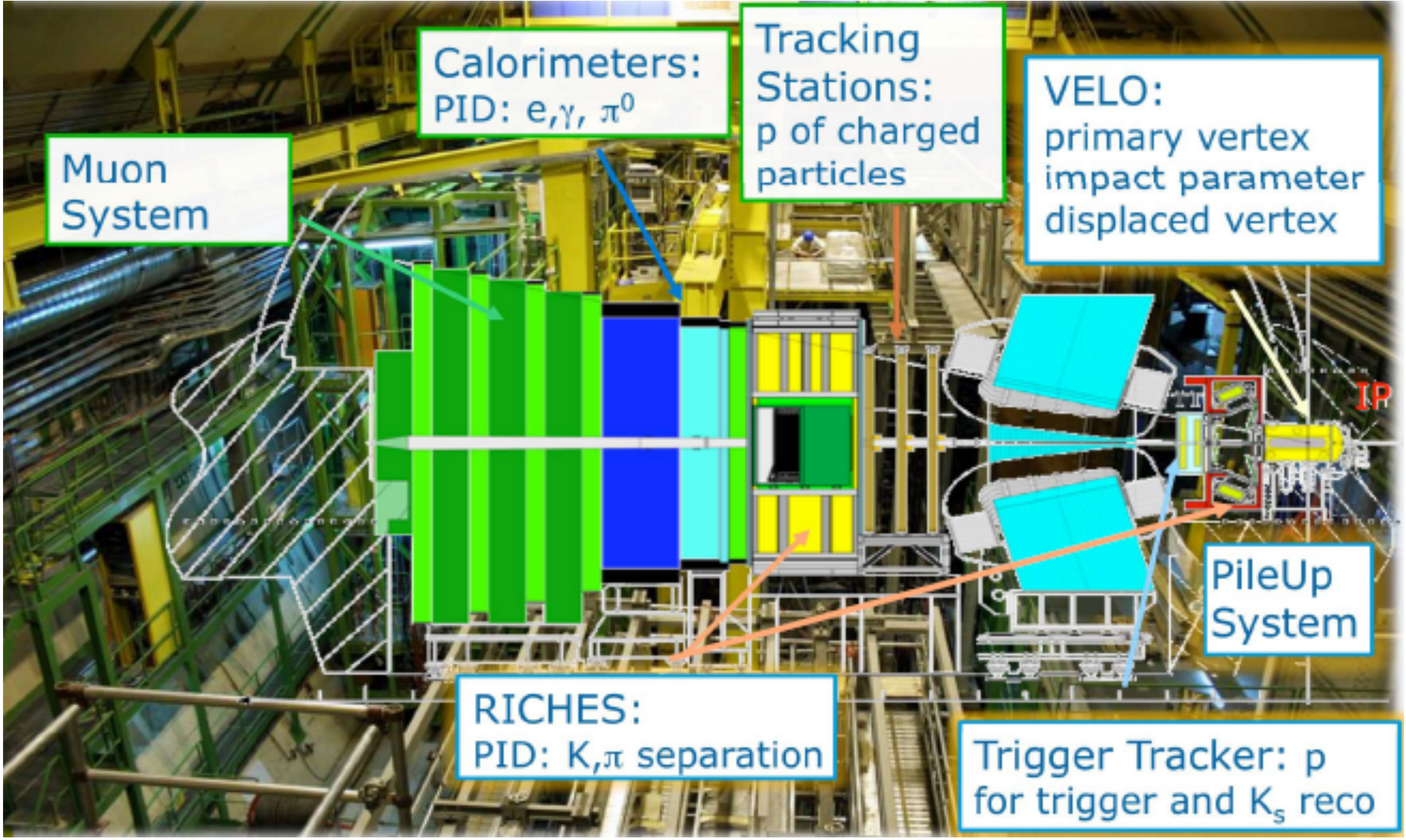


Summary

- Overview of basic technology choices for calorimeters
- Physics goals
- Environment
- Quick tour of Hadron Collider calorimeters

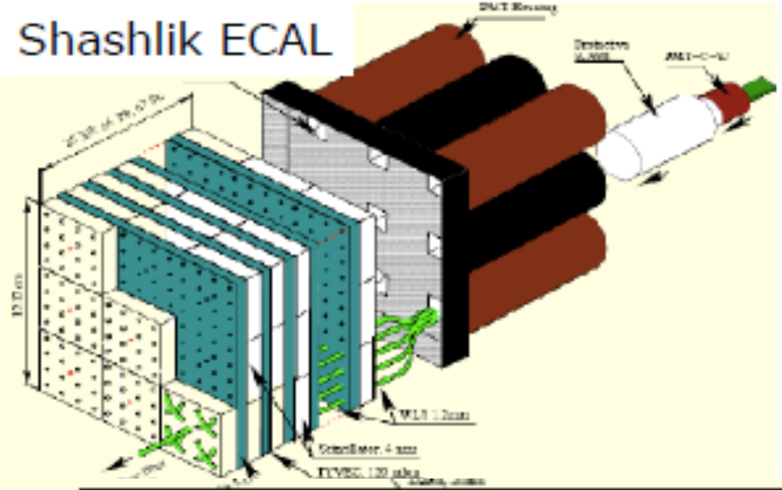
Extra slides

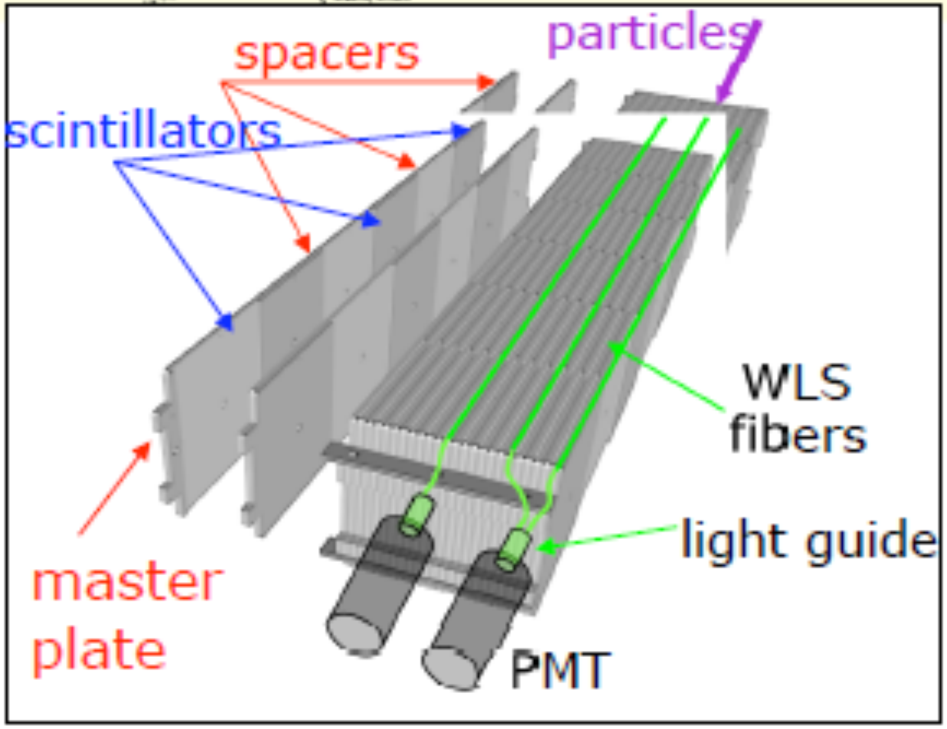
LHCb Calorimeters



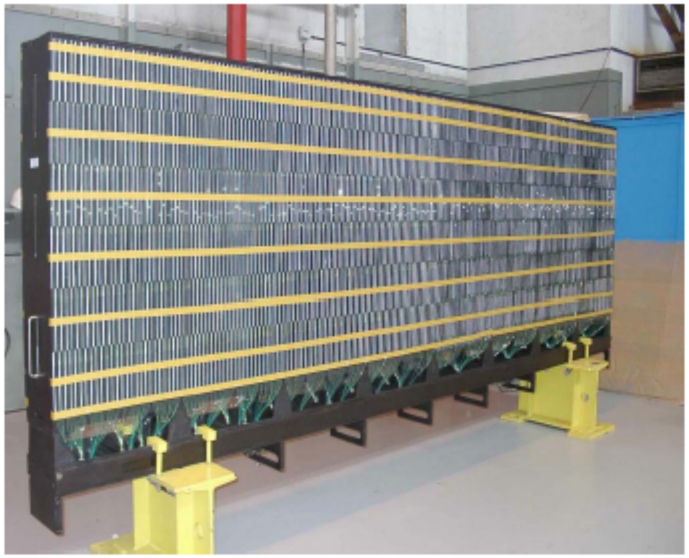
LHCb Calorimeters

Shashlik ECAL





LHCb HCAL



Module standing on end showing 6 longitudinal compartments

Master plates	6 mm
Spacers	4 mm
Scintillator	3 mm
Sampling:	
longitudinal	20 cm
lateral	2 cm

6 longitudinal sections (5.6 λ_I) (high energy showers not fully contained – but does not spoil the trigger operation)

HCAL Resolution:

$$\frac{\sigma}{E} = \frac{(69 \pm 5)\%}{\sqrt{E}} \oplus (9 \pm 2)\%$$

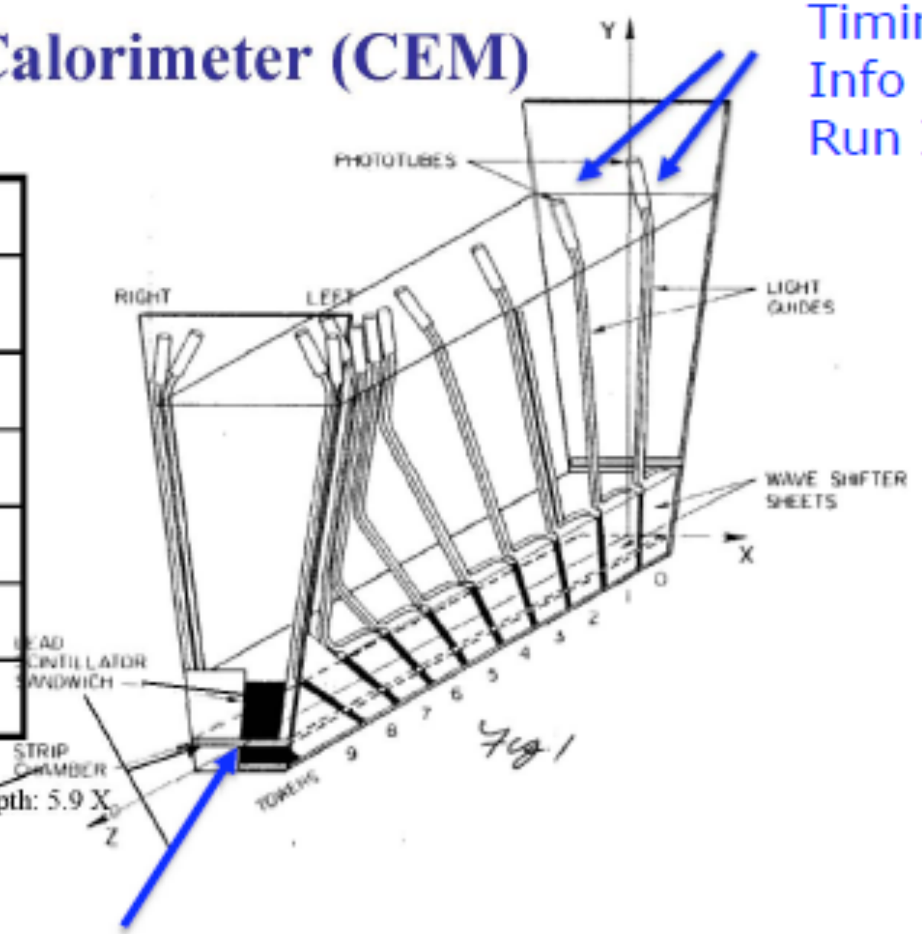
ECAL Resolution:

$$\frac{\sigma_E}{E} = \frac{(9.4 \pm 0.2)\%}{\sqrt{E}} \oplus (0.83 \pm 0.02)\% \oplus ((145 \pm 13)\ \mathrm{MeV})/E$$

CDF EM Calorimeter

Central Electromagnetic Calorimeter (CEM)

Thickness	$18X_0$, 11
Abs. (pb) layer	1/8" (4.2 mm,0.6 X_0)
Scint. layer	5 mm , polystyrene (SCSN-38)
w.l.s.	3mm Y7 acrylic sheet
PMT	Ham. R580 (1.5")
light yield	>100 p.e./GeV/pmt
resolution	$13.5/\sqrt{E_T}$



Added Timing Info in Run II

Shower Max Detector (Gas Strip Chamber) at EM Shower Max

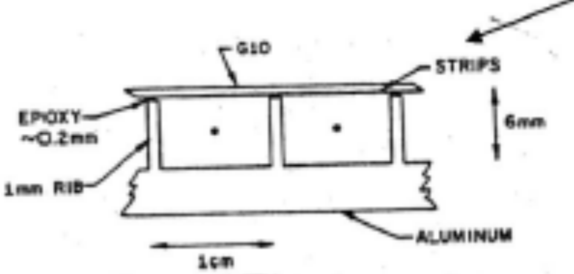


Fig. 3. Prototype strip chamber cross section.

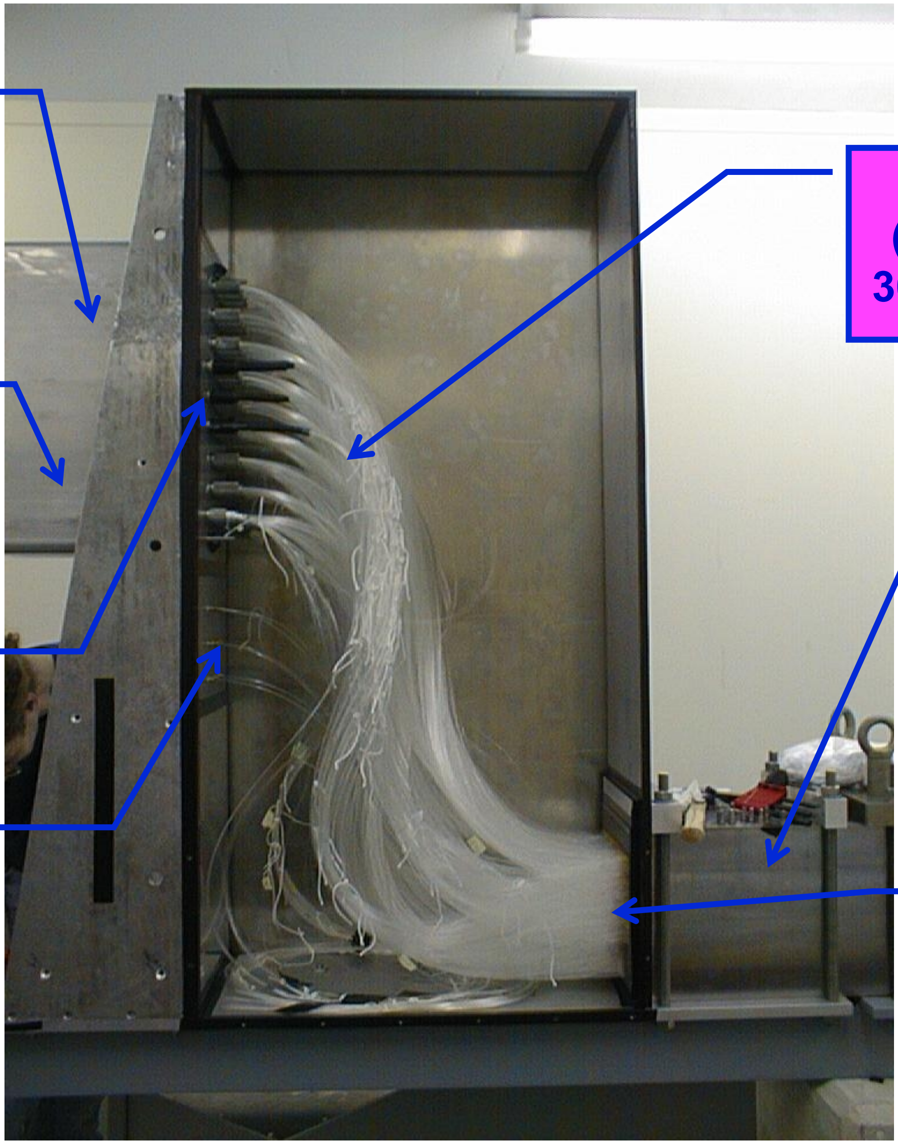
Total absorption calorimeters

- Resolution will depend on counting statistics – EM shower particles released bv the active material and recorded

$$\frac{\sigma}{E} = \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \approx \frac{a}{\sqrt{E}}$$

- Examples:
  - Solid-state detector (Si,Ge(Li)), liberate electron-hole pair with ~3.8 eV on average (bandgap is 1.1 eV) – most of the deposited energy goes into electron-hole pair creation
  - Scintillator – visible light with energies 2-3 eV can be emitted for a given amount of energy deposition in the crystal
    - E(eV) = 1240/λ[nm]
  - Cherenkov radiator (lead-glass or quartz) will emit in the UV (~3-6 eV) for relativistic charged particles

HF PPP1 Side View



ROBox (Light Guides) R6425 PMTs

LED, Laser and PIN PDs

Ferrules

Radioactive Source Tubes

Fiber Bundles (EM, HAD and TC) 300-micron core QP

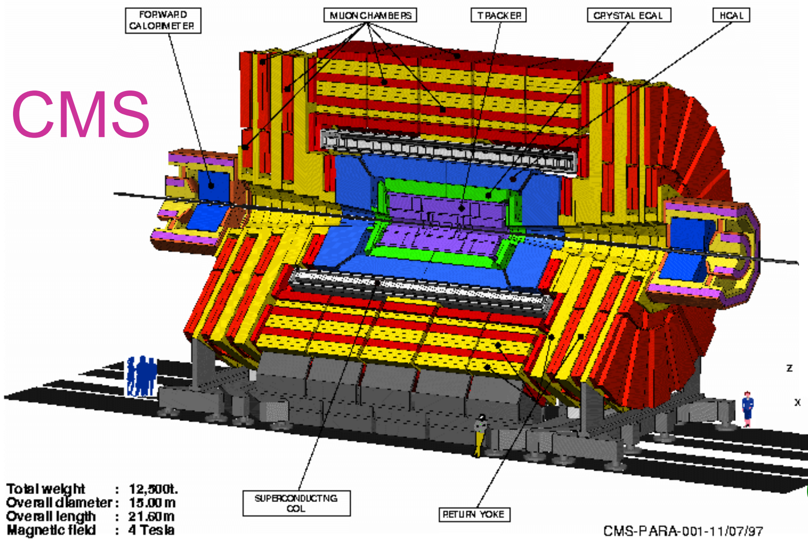
Iron Absorber (9.5 l_l)

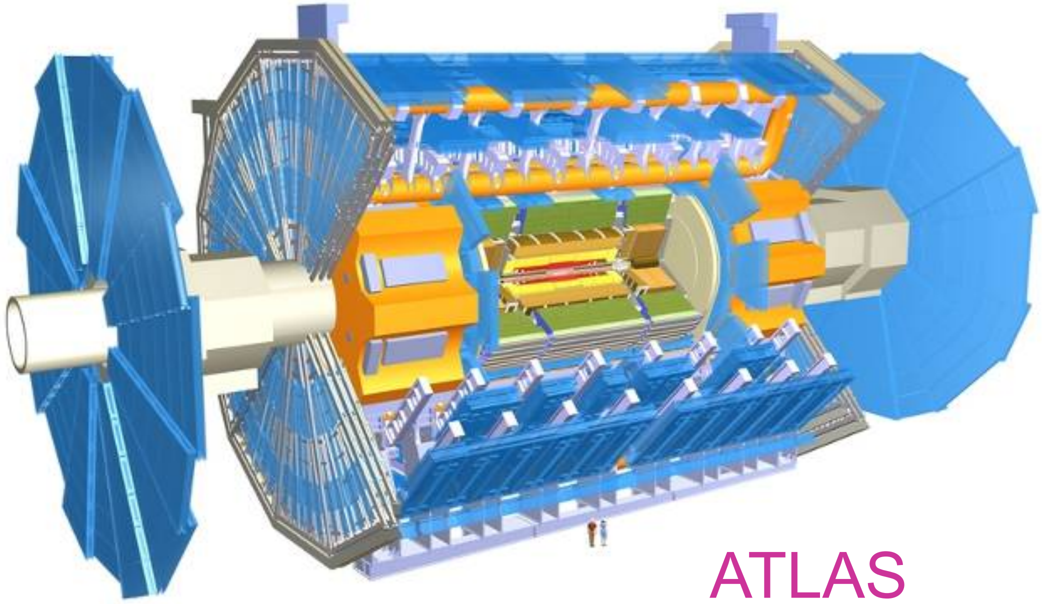
3 x 3 Tower structure (6 cm x 6 cm)

Atlas and CMS

ATLAS superimposed to the 5 floors of building 40

CMS





ATLAS

	ATLAS	CMS
Overall weight (tons)	*7000*	*12500*
Diameter	*22 m*	*15 m*
Length	*46 m*	*22 m*
Solenoid field	*2 T*	*4 T*

Compensation with cherenkov calorimetry

Basic Idea:
Cerenkov Light is most sensitive to electrons (photons)
Ionization sensitive to neutrons, hadrons, electrons
Use these 2 measurements to correct calorimeter energy – stochastic & constant terms

- Detect both Cerenkov Signal Ec and Ionization Ei on the same shower.
- For pure e-m showers, normalize the detected energies so that Ei = Ec = Eem.
- For hadrons, only when only π^0 are produced does Eh ~ Ei ~ Ec.
- As Eh fluctuates more into n, π^{+-}, etc., Ec decreases faster than Ei.
- On an Ec vs Ei scatter plot, the fluctuation is correlated/described by a straight line with slope a<1, from which the constant α is defined by $a = \alpha/(1+\alpha)$.
- The Ec vs Ei correlation yields an estimate of the compensated E as:

$$\text{Ecomps} = \text{Ei} + \alpha(\text{Ei}-\text{Ec}),$$

where the constant α is different for each calorimeter material/design.
For electrons, Ecomps = Ei = Ec, since (Ei-Ec) = 0
- No “suppression” needed for compensation, thus more active material can be used, up to 100%, thus reducing the stochastic term.
- Two independent measurements enable tuning the constant term to near zero.