INFN
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Calorimetry
Modern HEP Calorimeter Systems

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Q1: What is modern?

Q2: What is calorimetry?

outline

- Lecture 1
  - Basics of calorimetry for High-Energy Physics
- Lecture 2
  - Modern HEP Calorimetry Systems
- Lecture 3
  - Particle-Flow Calorimeters
- Lecture 4
  - Dual-readout Calorimeters

- Examples of calorimetry systems
- Calorimeter @ hadron colliders
- Upgrades for Hi-Lumi LHC
- Intensity Frontier and Trends in HEP
- Outside Physics w/ Beams ?

Examples of calorimetry systems

Lecture recap

Examples of complex calorimetry system implementations

Importance of all boundary/environmental conditions

→ calorimeters are complex systems

→ calorimetric measurements depend on full “picture”

→ can NOT optimise all parameters at same time

Search compromises driven by physics goals

(unknown → choices may be wrong)

Few implementations @ LHC and for High-Lumi LHC

Evolution toward high granularity calorimetry

Calorimeter role @ non-accelerator/collider exp.s

past ...

LEP calorimeters:

ALEPH	em (Pb+PWC): $18\% / \sqrt{E} + 1.9\%$ (~ 4 mrad / $\sqrt{E}$) had (Fe+LST): $85\% / \sqrt{E}$
DELPHI	em (Pb+TPC): $23\% / \sqrt{E} + 4.3\%$ (~ 5 mrad) had (Fe+LST): $120\% / \sqrt{E}$
L3	em (BGO): $2.2\% / \sqrt{E} + 0.7\%$ (~ 10 mrad) had (U+PWC): $55\% / \sqrt{E}$
OPAL	em (lead glass): $6.3\% / \sqrt{E} + 0.2\%$ (~ 4.5 mrad) had (Fe+LST): $120\% / \sqrt{E}$

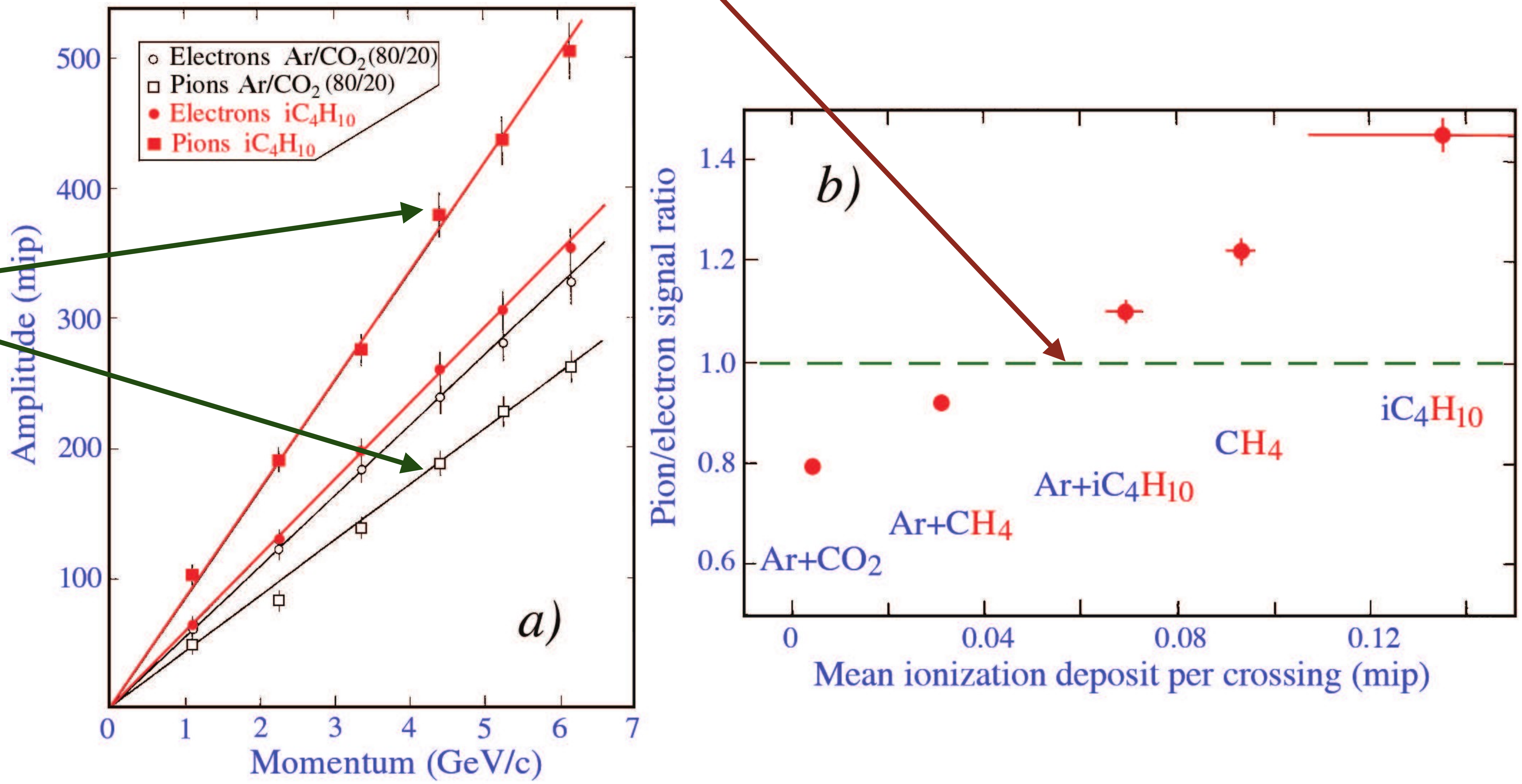
all sampling but L3 and OPAL ECALs

L3 HCAL

Could even be made compensating (e/h = 1)

Just by changing gas, pion response may ~double

Why ?



One way to compensation

(SAND : Signal Amplification through Neutron Detection)

Q: could be successfully exploited ?

Cons: slow response → integration of signal over large volume and long time

BGO also “slow” (decay time ~ 300 ns)

Invariant mass resolution?

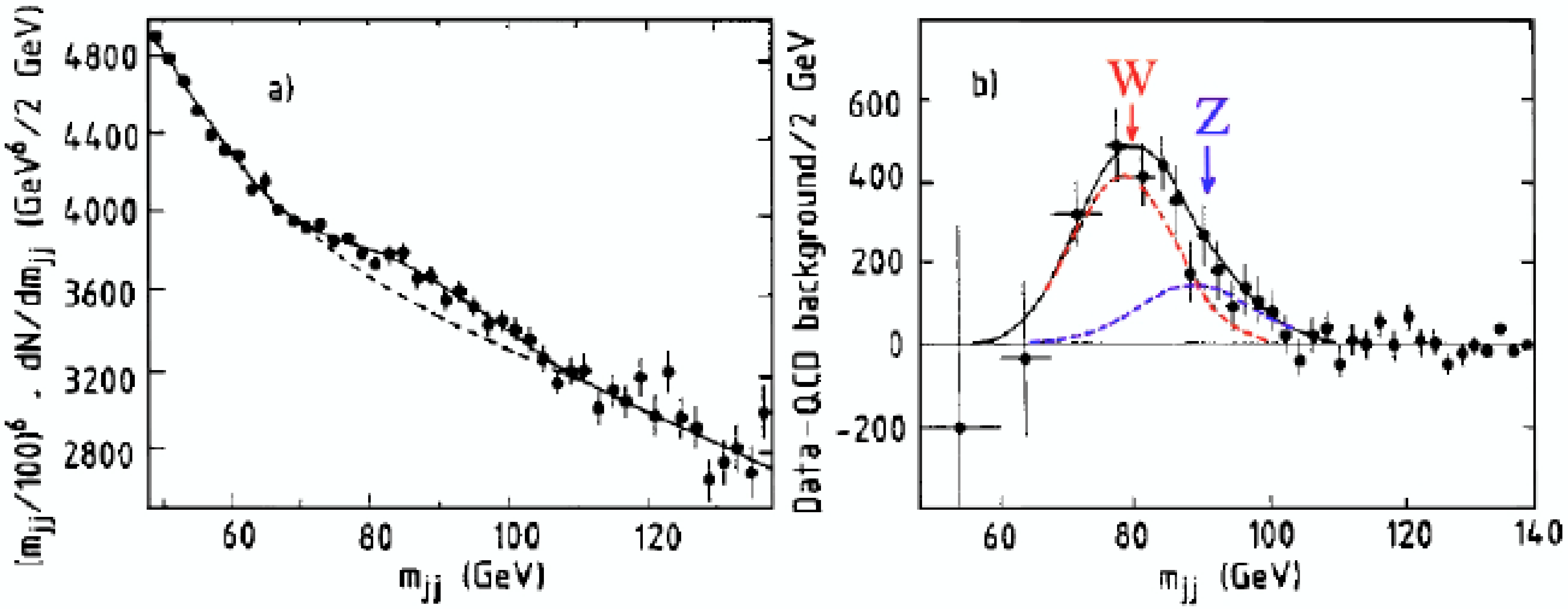


FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \to q\bar{q}$ decays. Diagram b) shows the same data after subtracting the QCD background. The data are compatible with peaks at m_W = 80 GeV and m_Z = 90 GeV. The measured width of the bump, or rather the standard deviation of the mass distribution, was 8 GeV, of which 5 GeV could be attributed to non-ideal calorimeter performance [Jen 88].

Invariant mass resolution?

needs both energy resolution and angular resolution
(for small separation angles, i.e. decays of boosted objects)

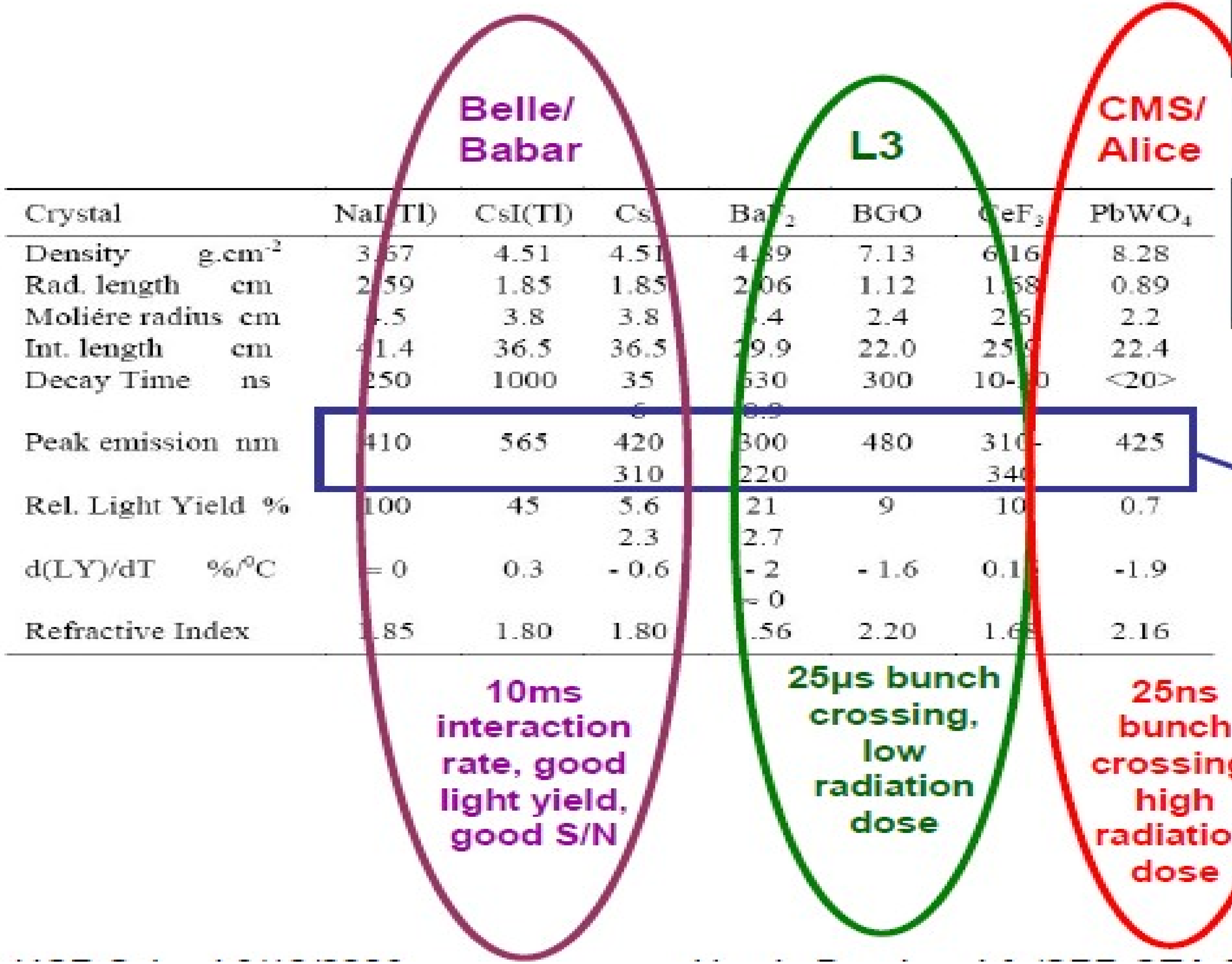
How to design your calorimeter?

Must match physics requirements, environmental constraints, … cost:

Objects (final states) to be identified and measured ?
Energy resolution ?
Spatial / angular resolution ?
Stability and linearity ?
Signal handling ?
Event rate (time needed for signal production) ?
Data size / throughput ?
Environment (radiation / pile-up) ?
Monitoring and calibration ?
Cost / funding ?

Compromise / optimise … target physics performance

Scintillating crystals used in EM calorimeters



Belle/ Babar

L3

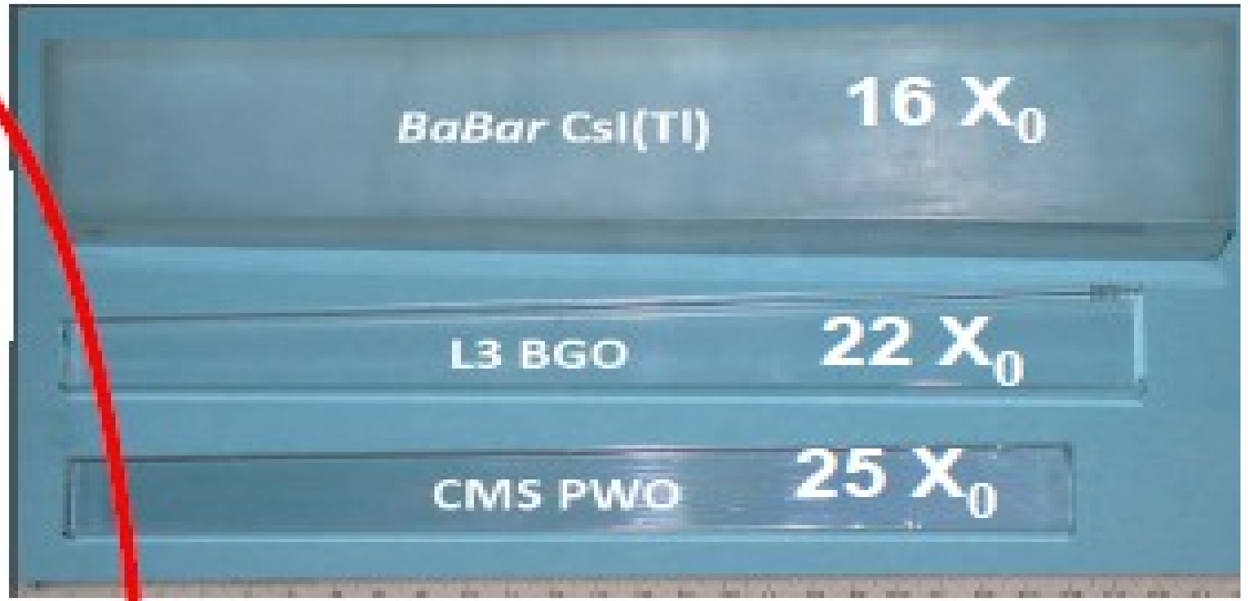
CMS/ Alice

Crystal	NaI(Tl)	CsI(Tl)	Cs	BaF$_2$	BGO	eF$_3$	PbWO$_4$
Density g.cm^{-2}	3.67	4.51	4.51	4. 9	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	.5	3.8	3.8	.4	2.4	2.6	2.2
Int. length cm	41.4	36.5	36.5	29.9	22.0	25.	22.4
Decay Time ns	250	1000	35 6	630 0.9	300	10-	<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 %/°C	≈ 0	0.3	- 0.6	- 2 ≈ 0	- 1.6	0.1	-1.9
Refractive Index	1.85	1.80	1.80	.56	2.20	1.6	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

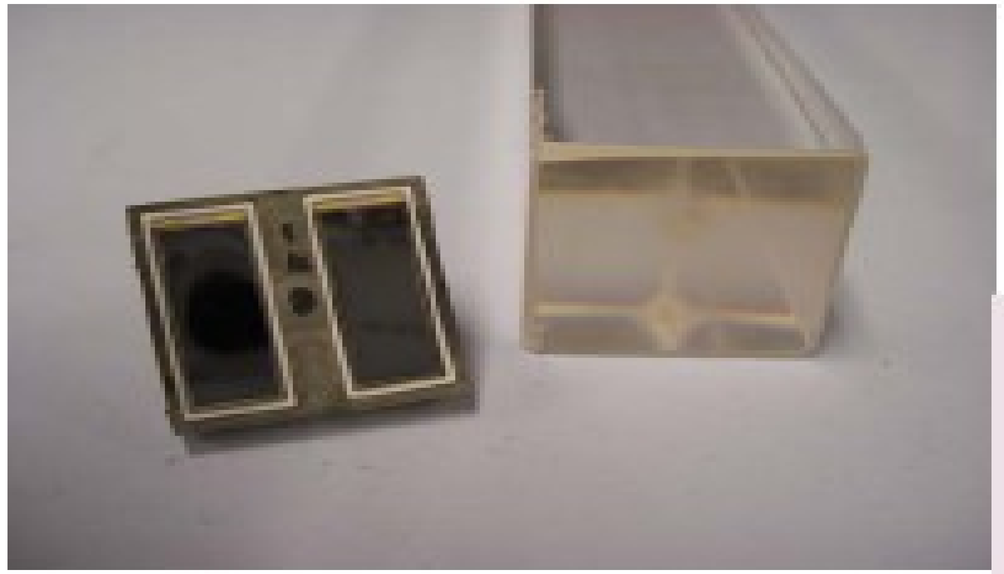
Environment ? Magnetic field ?

Photosensors behaviour in B field ?

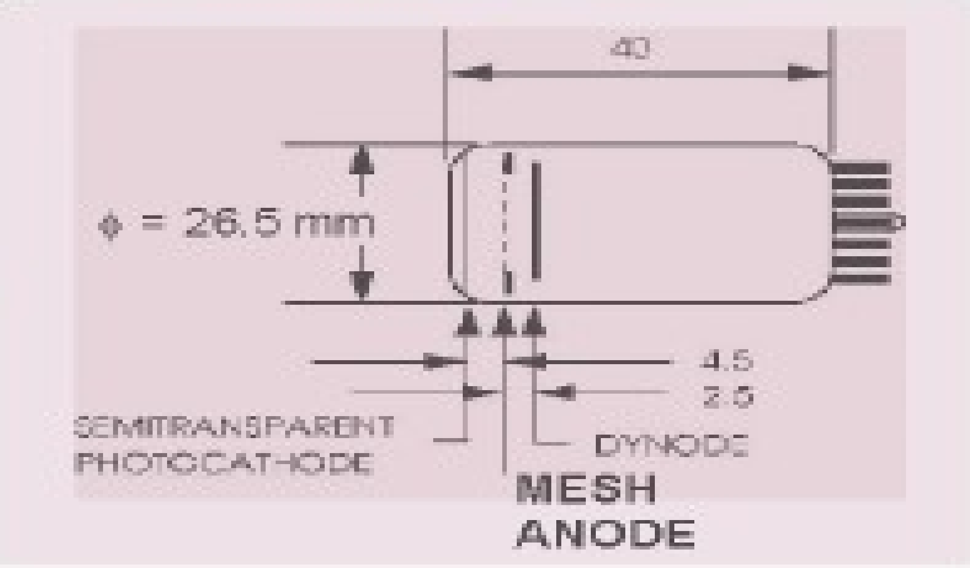
Photomultipliers do not work in magnetic field
→ need to bring light in some more confortable place

Photodetectors that can operate in B fields

PIN Diodes
Unity Gain

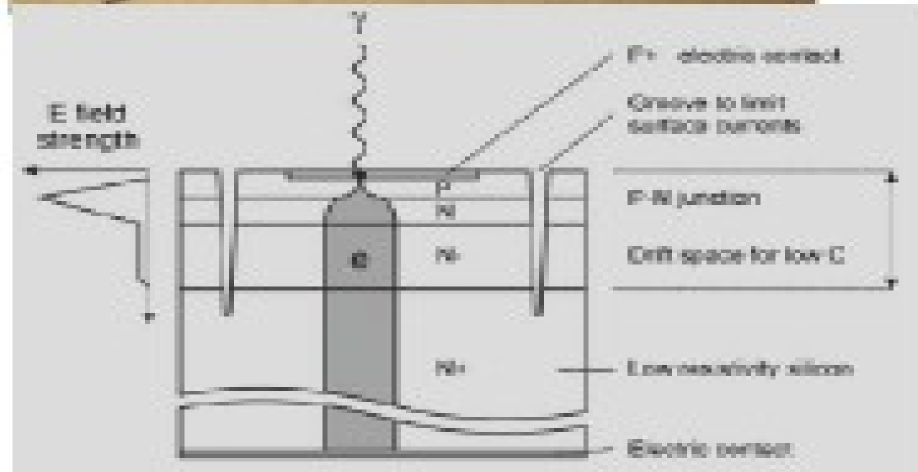


Vacuum PhotoTriodes (VPTs)
Gain ~10



CMS ECAL Endcap
copper mesh anode
4 T B field operation

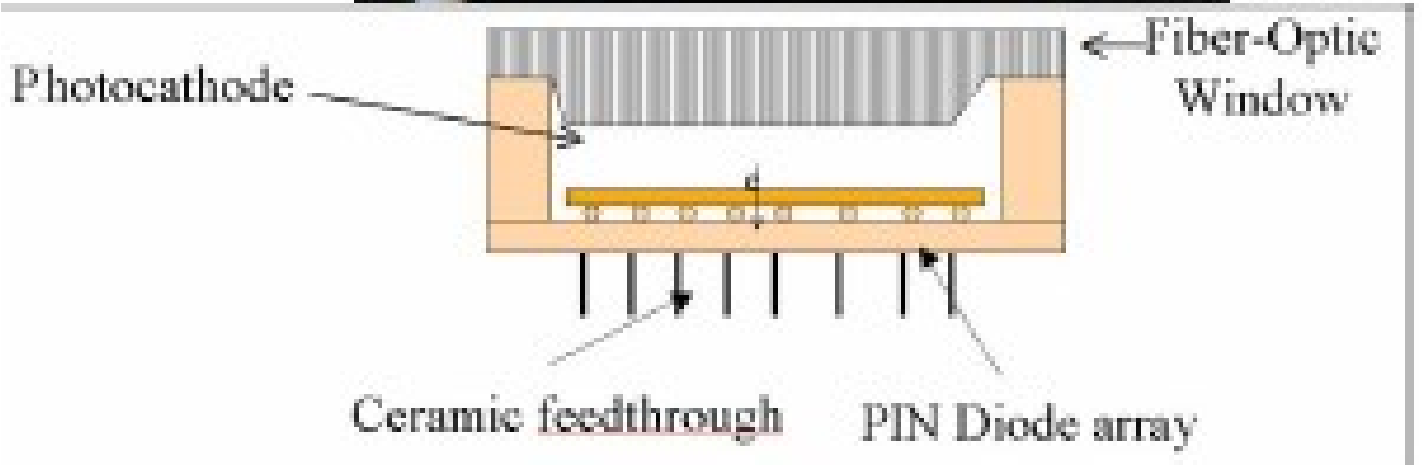
Avalanche PhotoDiodes (APDs)
Gain ~50



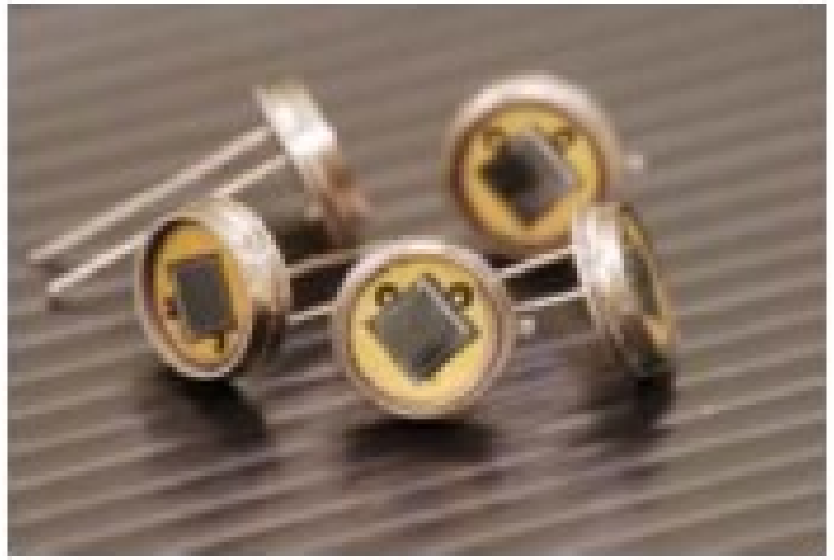
CMS ECAL Barrel
More cooling and new FE elx
needed for HL-LHC

Photodetectors that can operate in B fields

Hybrid PhotoDiodes (HPDs)
Gain ~2000



Silicon PhotoMultipliers (SiPMs)
Micro-pixel Avalanche PhotoDiodes (MAPDs)
Micro-Channel-Plate PhotoMulTipliers (MCP-PMTs)
Gain ~ 60000-10^6



Environment ? Radiation ?

Damage by ionising radiation

→ caused by energy deposited in detector material: ≈ 2 MeV / g / cm^2 for MIP
→ also caused by photons from EM and HAD showers
→ damage proportional to deposited energy per unit mass, or dose – unit Gy
1 Gy = 1 Joule / kg
1 Gy = 3×10^9 particles per cm^2 of material with unit density

At LHC design luminosity, in CMS Central Barrel, ionising dose is: ~ 7500 Gy / year

Environment ? Neutrons ?

Damage by neutrons

- → created in HAD showers, in detector material (also forward shielding and collimators)
- → bounce back and forth, energy in 0.1-20 MeV range
- → neutron “gas” can fill up whole detector

Expected fluence: ~ 3×10^{13} / cm^2 / year in innermost detector part (inner tracking system)

- → moderated by Hydrogen presence (e.g. in organic scintillators):
  - → $\sigma(n,H)$ ~ 2 barns with elastic collisions
  - → mean neutron free path ~ O(1-10 cm)
  - → at each collision, neutron loses ~ 50% of energy (~ 2% in iron)

More on neutrons

can modify crystalline structure of semiconductors (independently of deposited energy)

off-the-shelf elx usually dies out for doses > 100 Gy and fluences > 10^{13} n / cm^2

→ need rad-hard elx (especially deep-submicron)
→ can survive up to 10^5-10^6 Gy and 10^{15} n / cm^2

Environment ? Pile-up ?

Many (mostly uninteresting) interactions in same bunch crossing of hard-scattering process

Minimise impact in space and time:

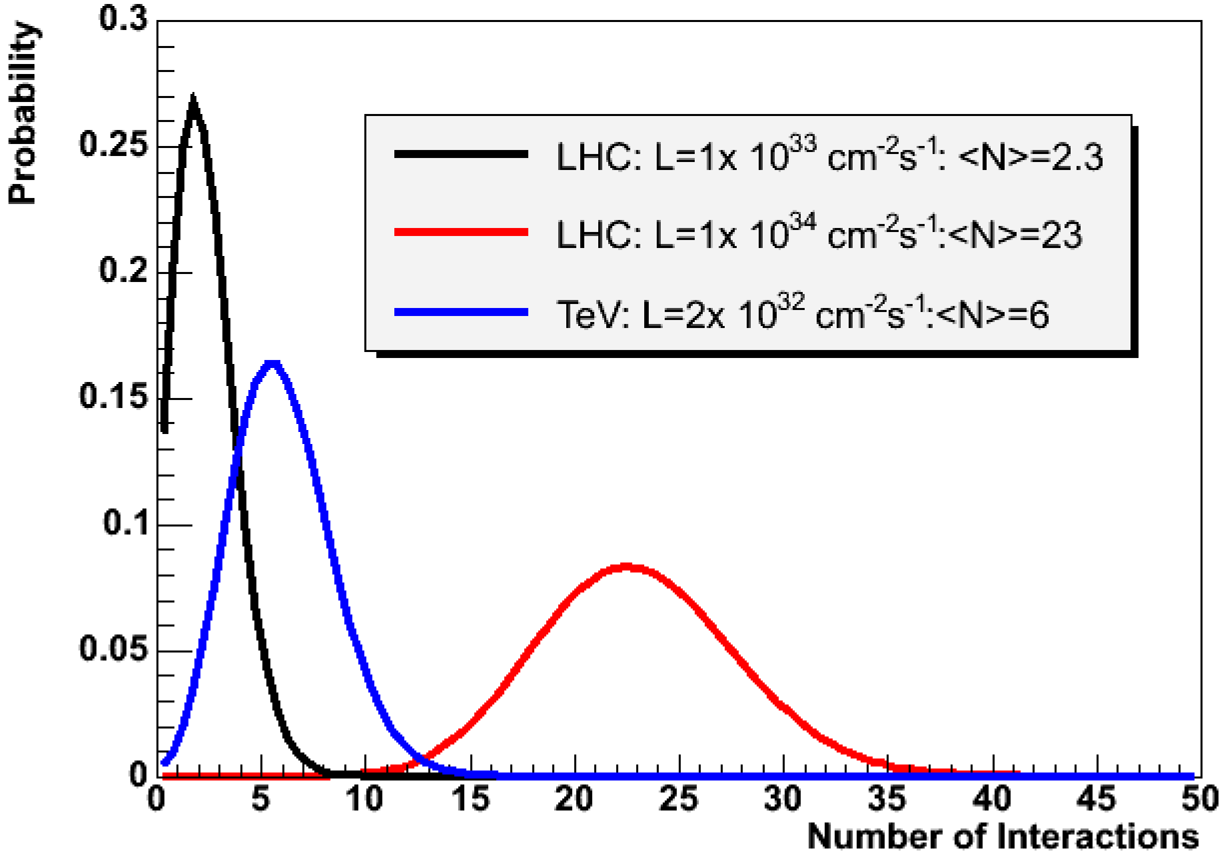
→ highly granular detector

→ precise and fast response

→ large number of channels

~10^8 pixels, O(10^5) EM calo readout cells

→ ~10^9 pixels for Hi-Lumi LHC

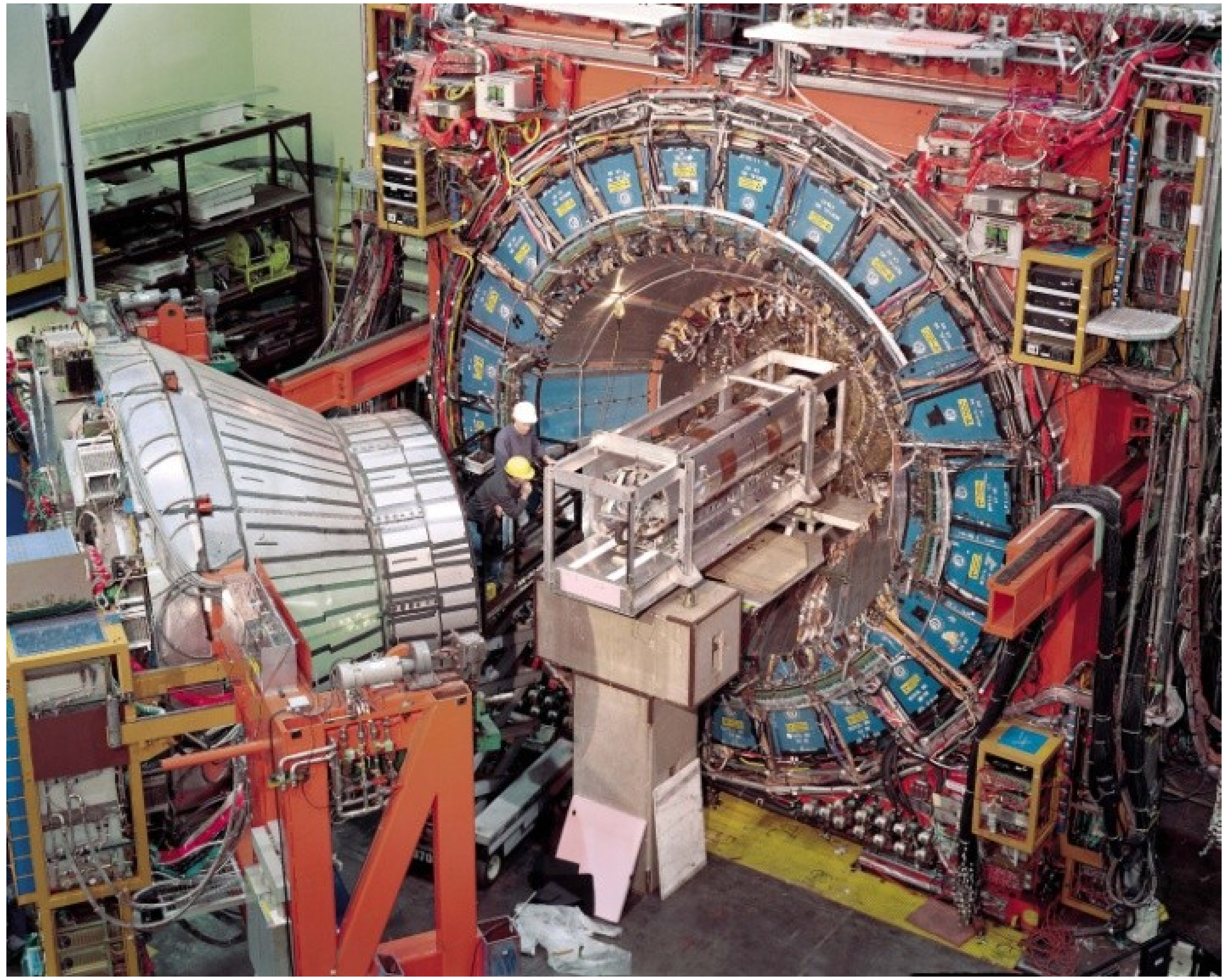


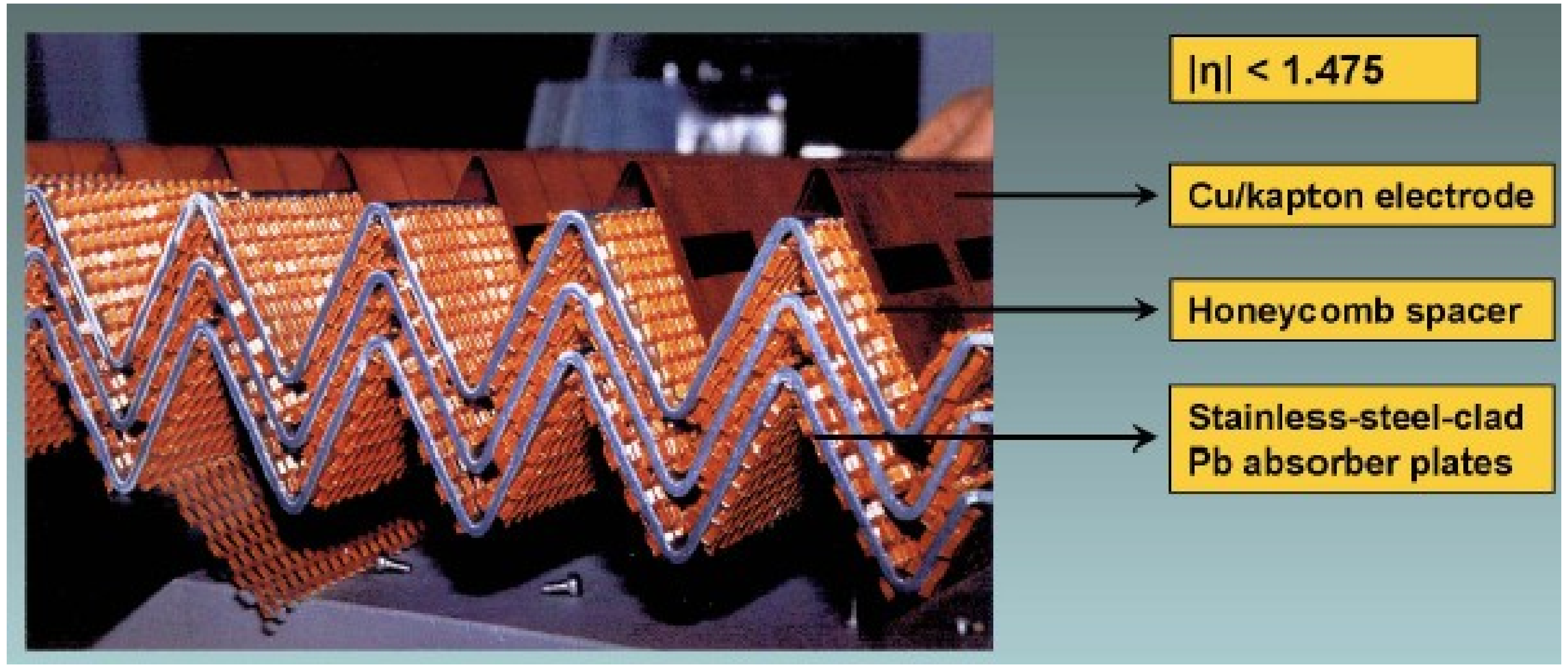
Calorimeters @ hadron colliders

Calorimeters @ hadron colliders

Tevatron: CDF, D0

LHC: Atlas, CMS, LHCb, ALICE





Tevatron calorimeters

Designed ~40 years ago for Run 1 (1992-96)
→ optimised for Standard Model physics (top discovery)

Upgraded for Run 2 (2001-2011)

Compared to LHC, more time between crossing, no rad-hard issues

D0 calorimeters

U/LAr EM cal (21 X_0)

Cu(Fe)/LAr HCAL (7.2 λ_I)

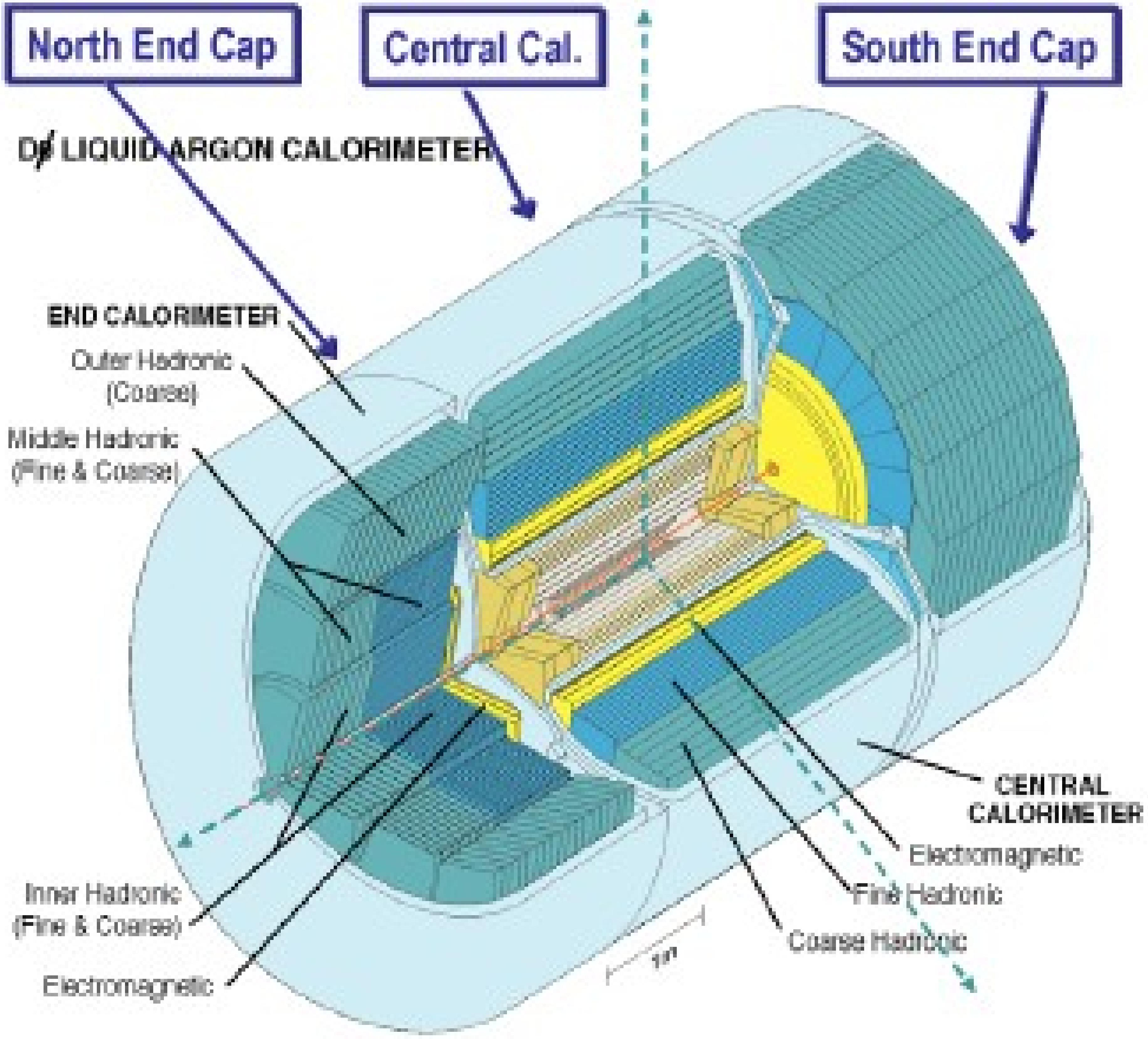
~ compensating: e/h ~1

→ ~ 3.4 μs integration time

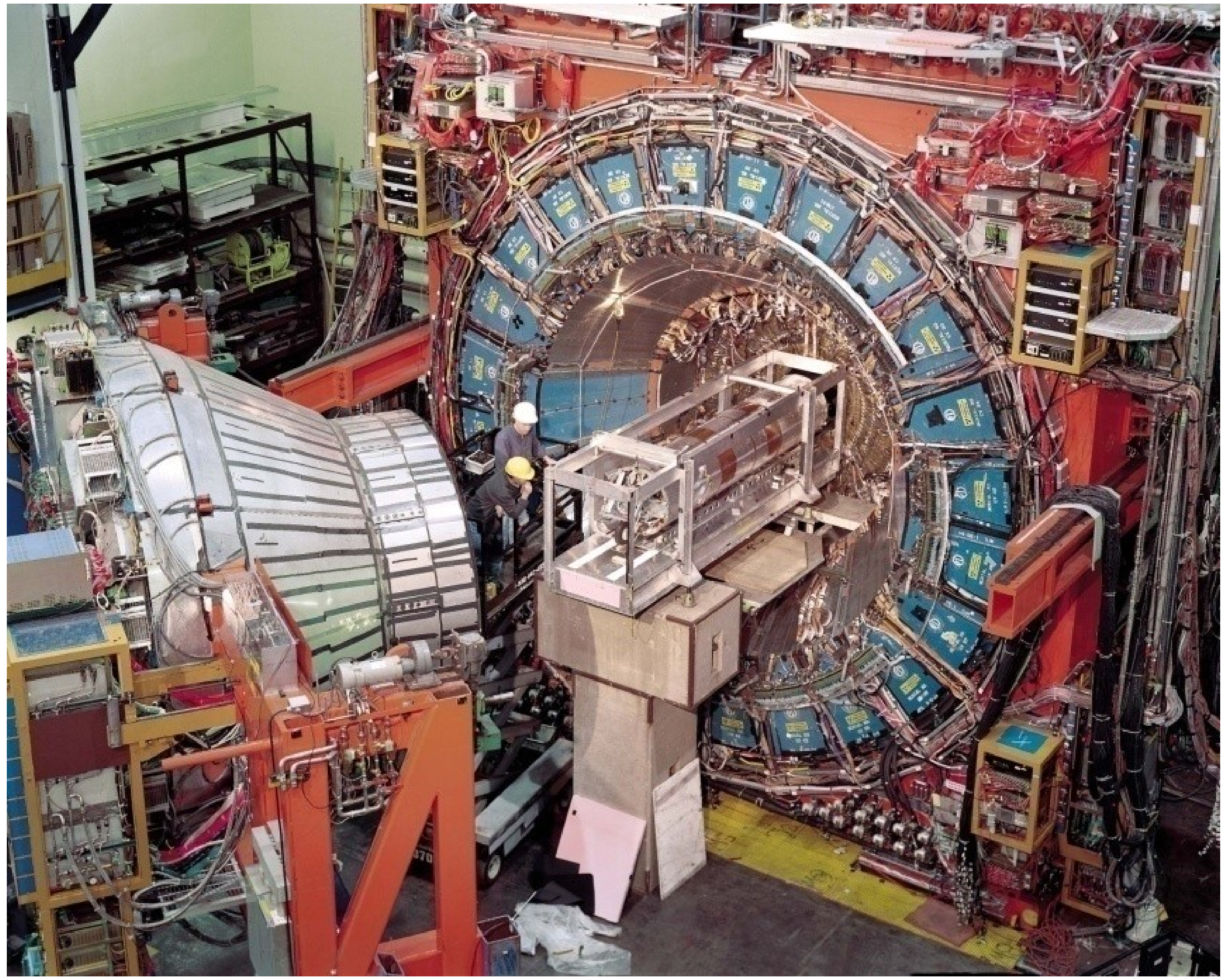
Single particle resolution (testbeam)

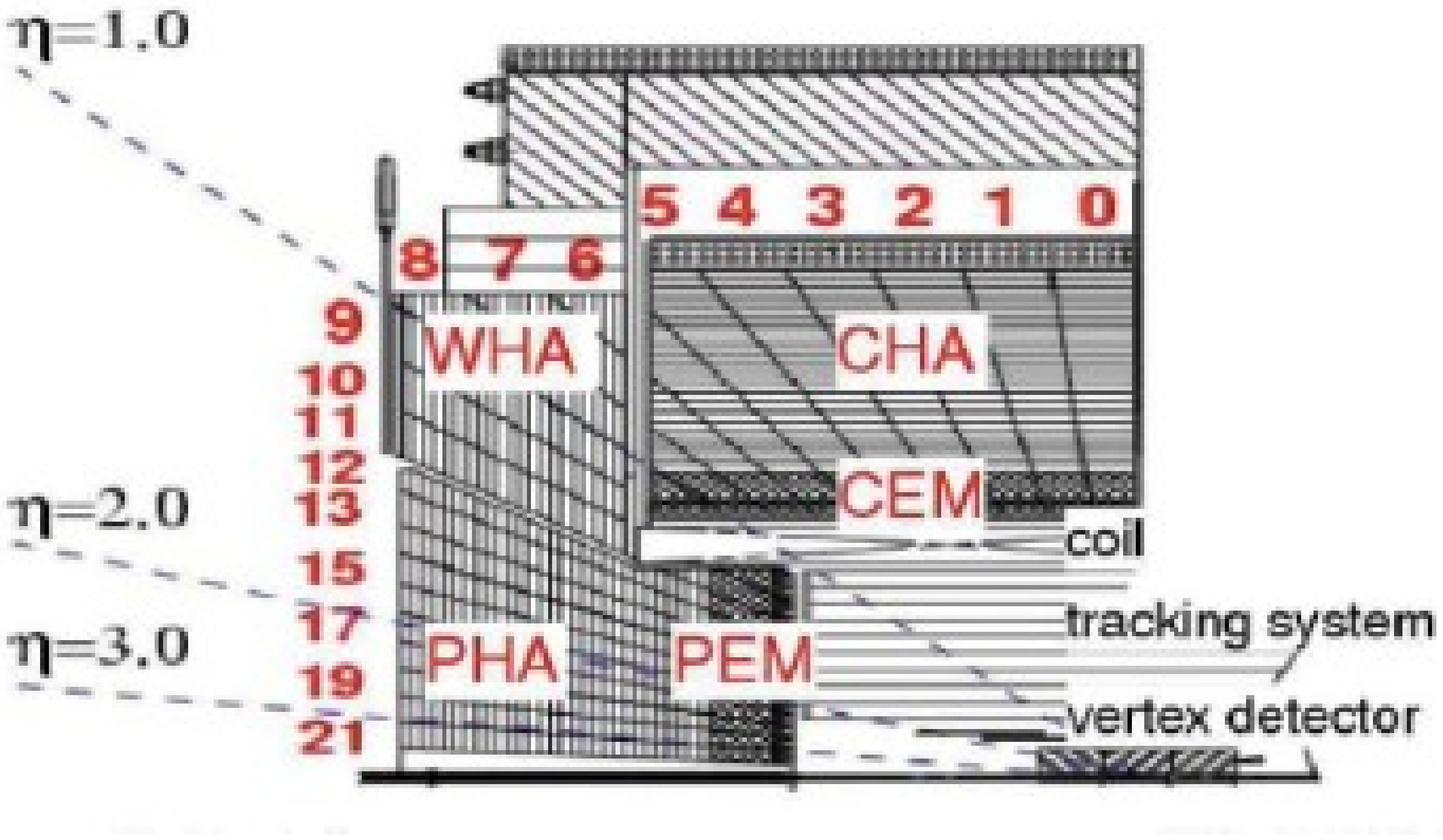
e: $\sigma_E/E = 15\% /\sqrt{E} + 0.3\%$

π: $\sigma_E/E = 45\% /\sqrt{E} + 4\%$



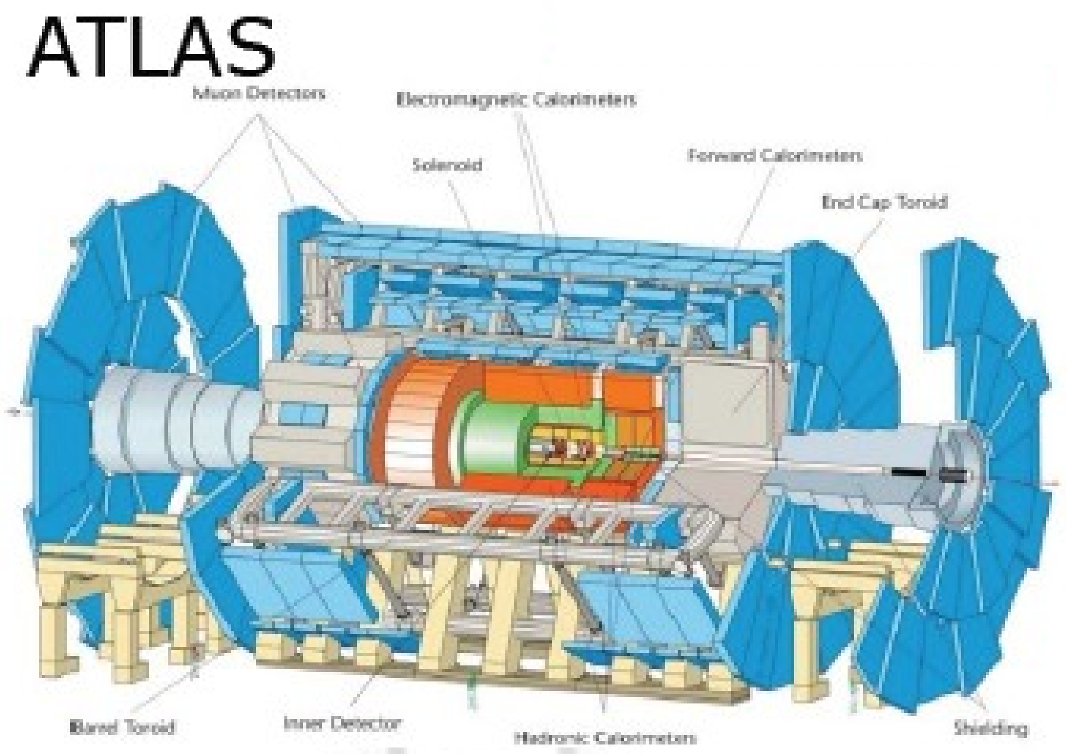
CDF calorimeters

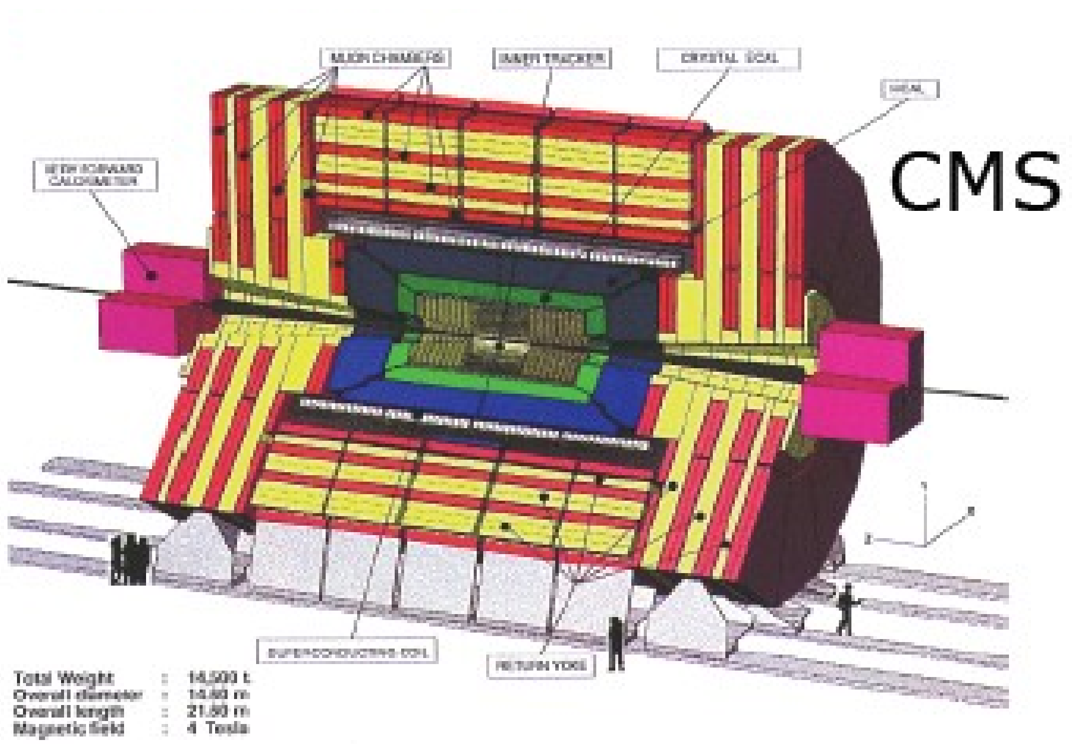


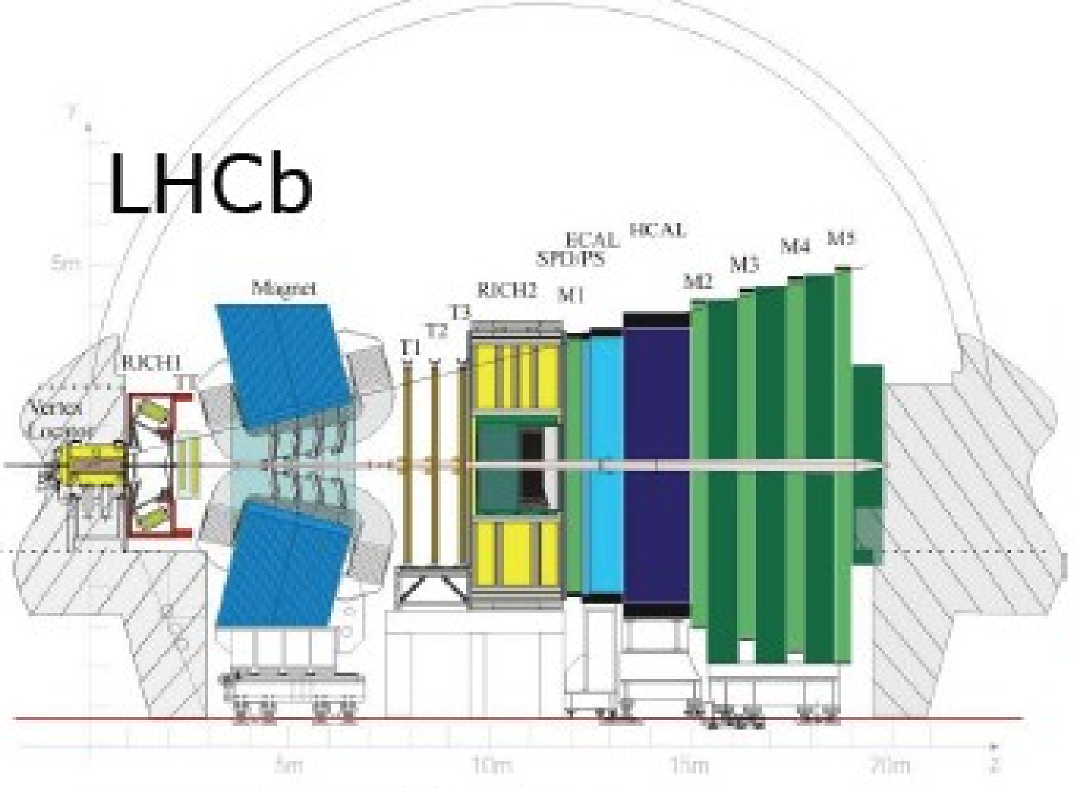


Sampling cal's	ECAL	HCAL
material	Pb-Scintillator	Fe-Scintillator
Resolution Central	$13.5\%/\sqrt{E\sin\theta} + 2\%$	$50\% /\sqrt{E}$
Resolution endcap	$16\%/\sqrt{E} + 1\%$	$80\%/\sqrt{E} + 5\%$
depth	$21X_0$, 1λ (SMX $6X_0$)	7λ

LHC (big) experiments

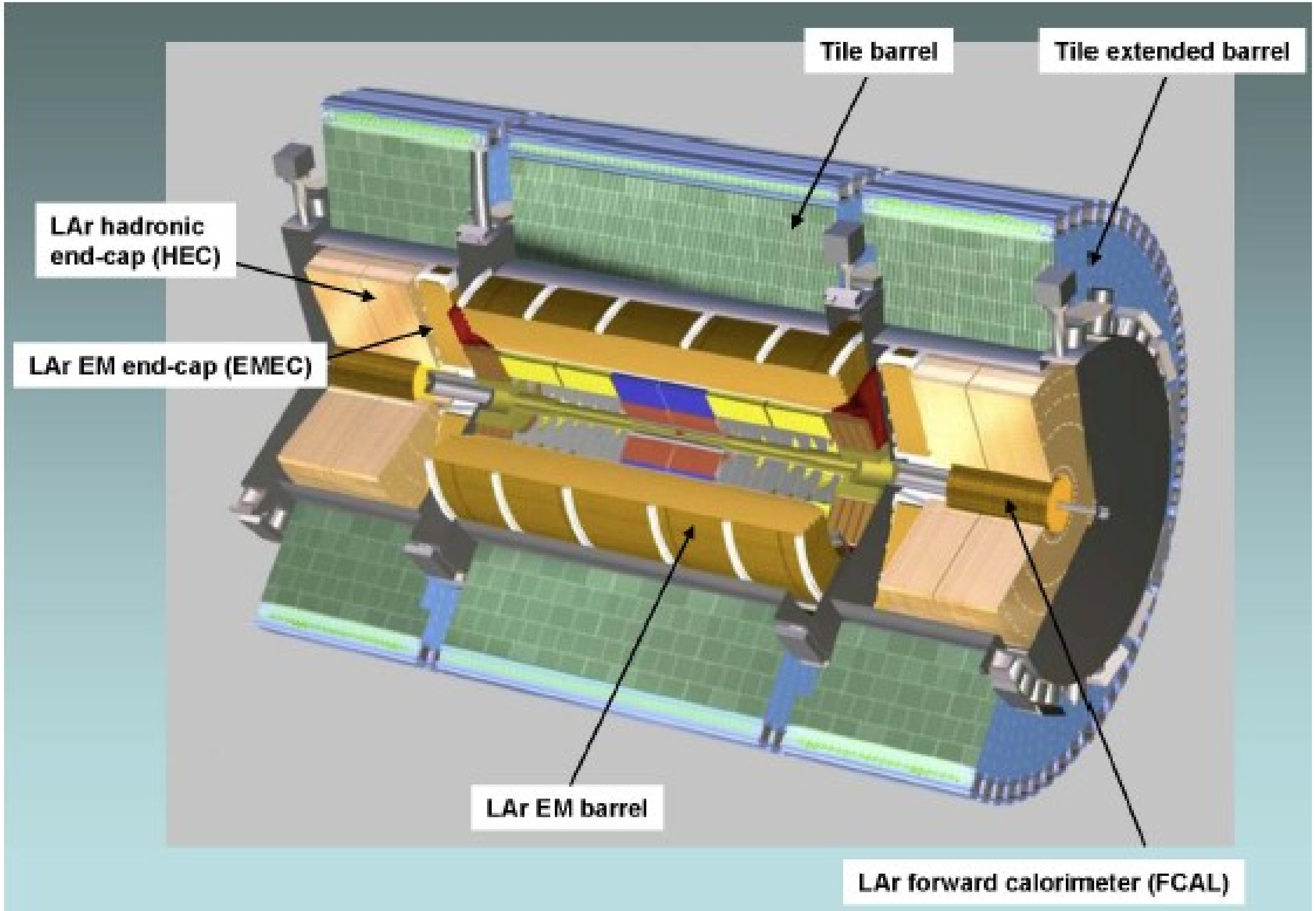

ATLAS


CMS


LHCb


ALICE

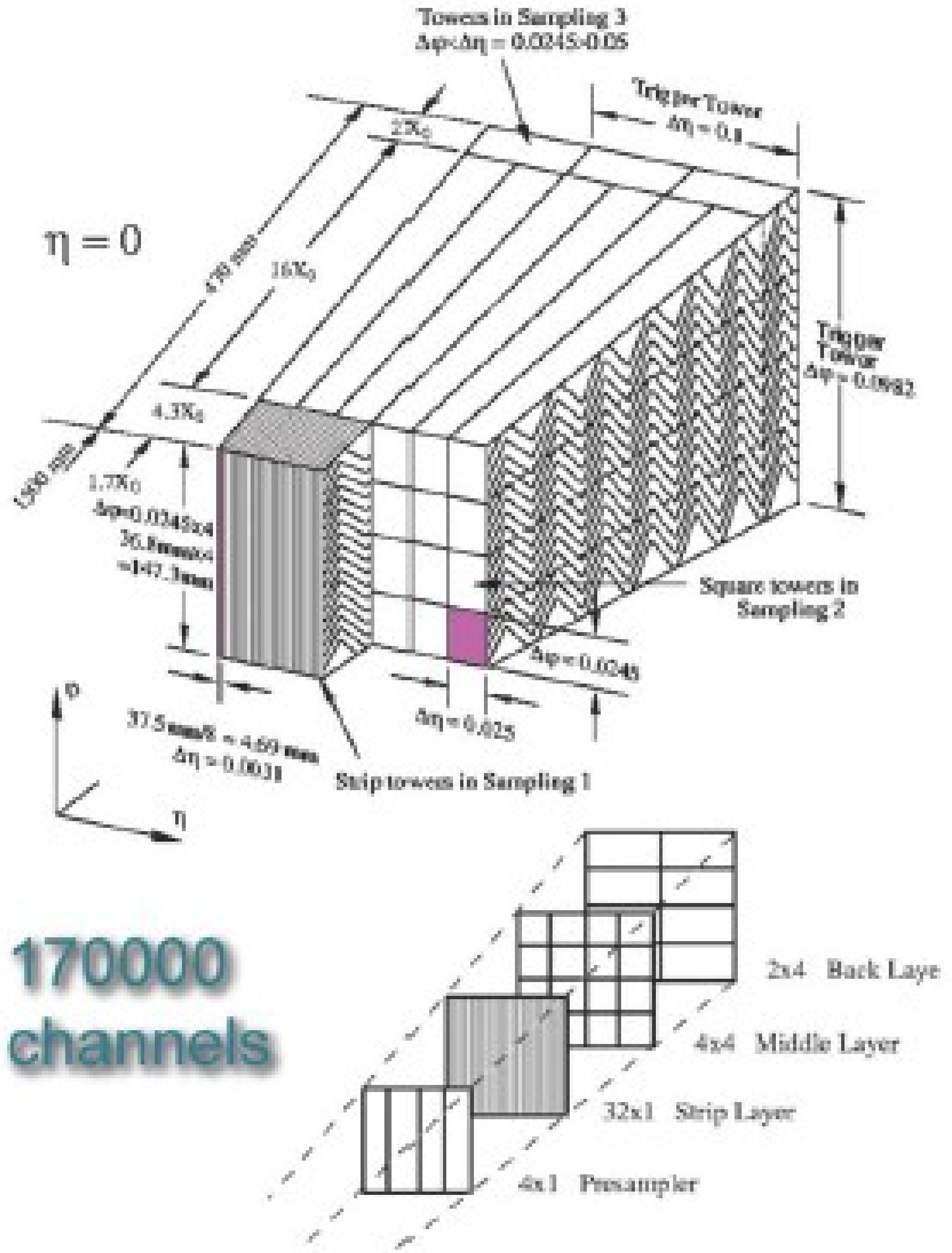
ATLAS calorimeters



ATLAS Pb/LAr EM calorimeter

22 X_0 (47 cm) barrel, 24 X_0 endcap

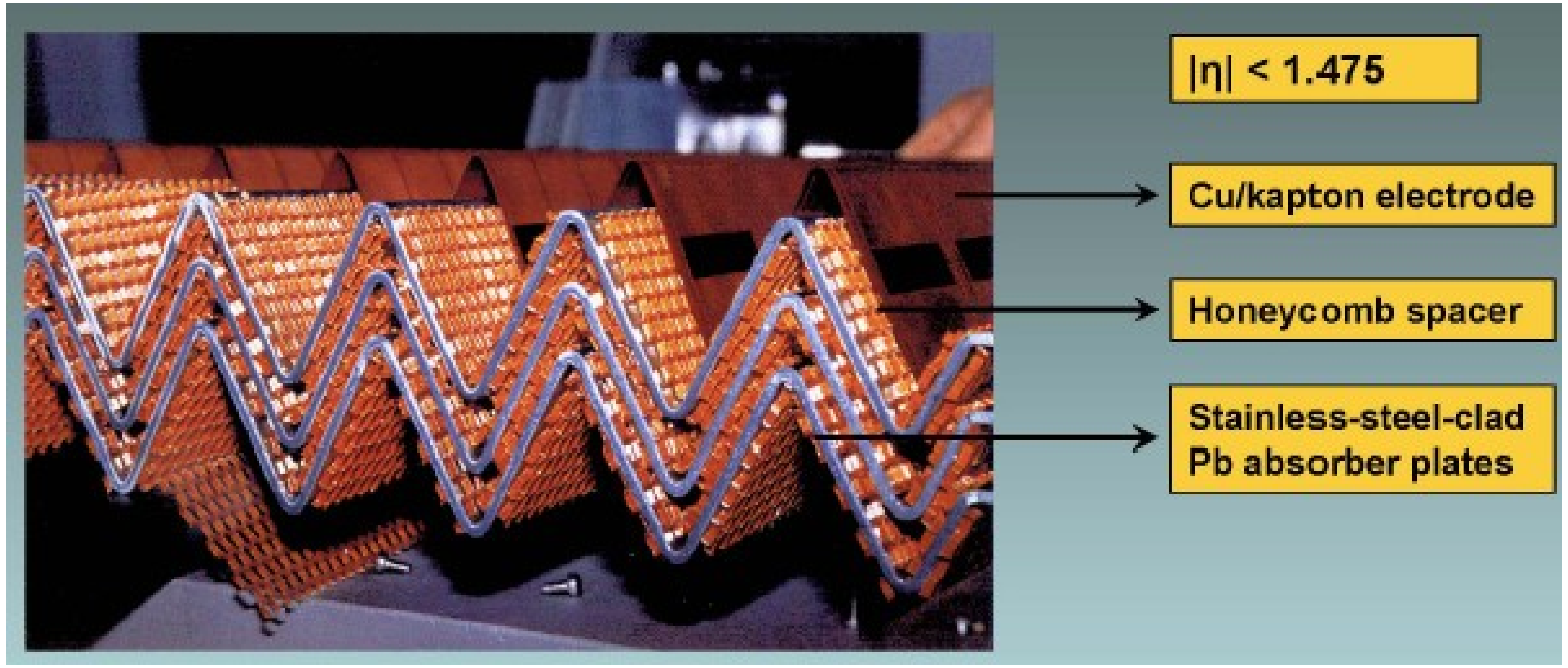
Pb thickness optimised over η for energy resolution

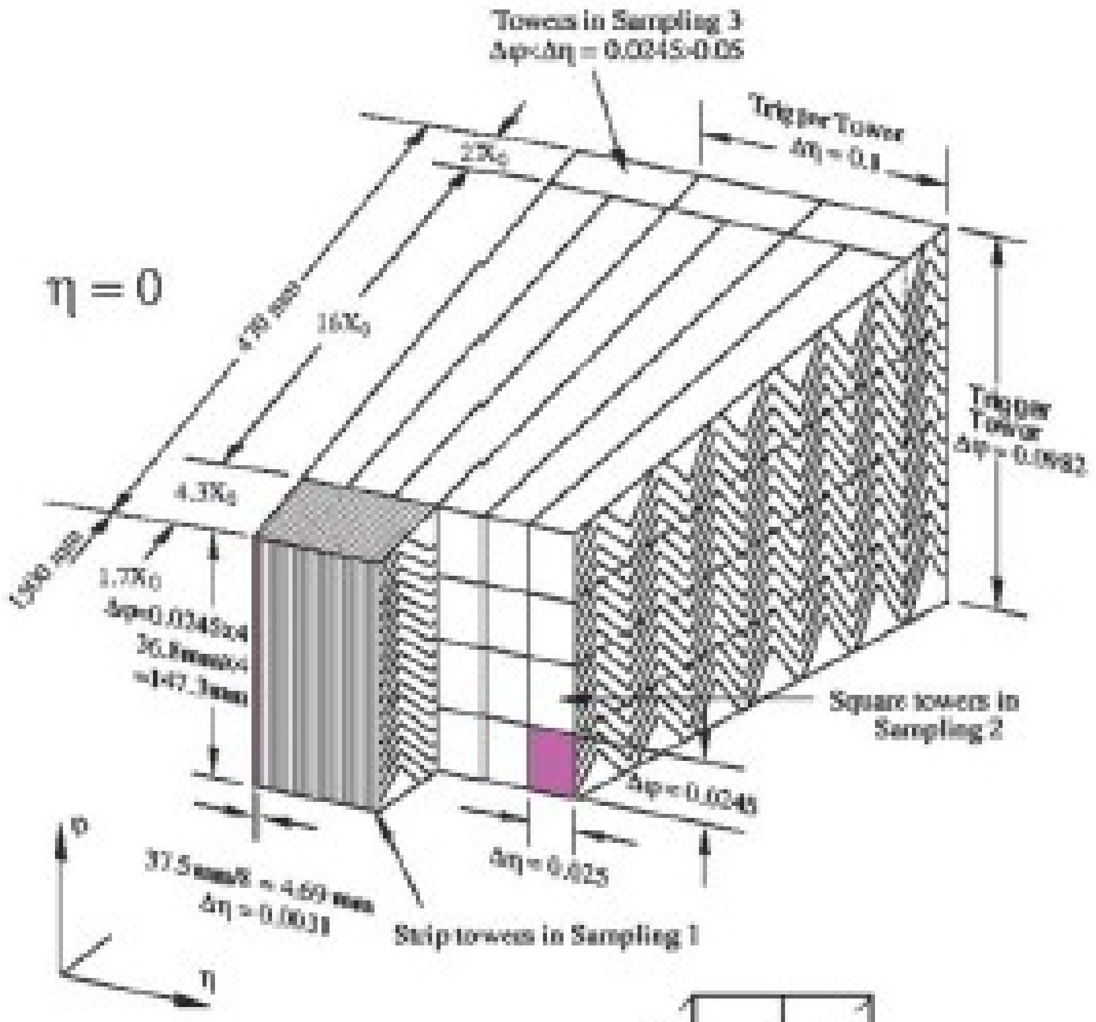


170000 channels

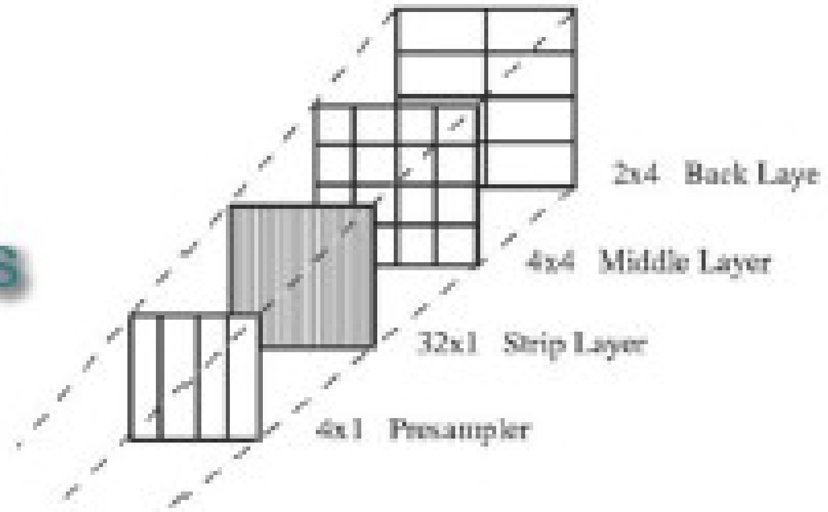
ATLAS Pb/LAr EM calorimeter

Accordion-shaped capton electrodes + Pb absorber
→ no azimuthal cracks

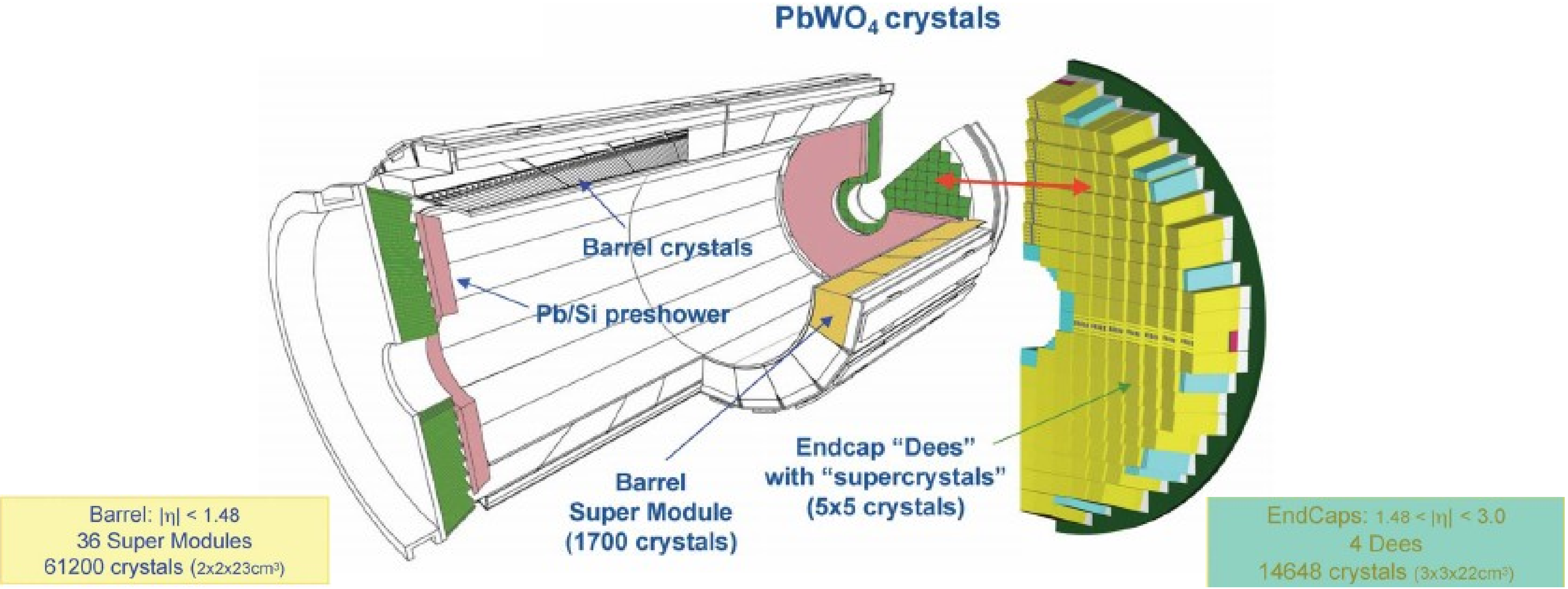




170000
channels



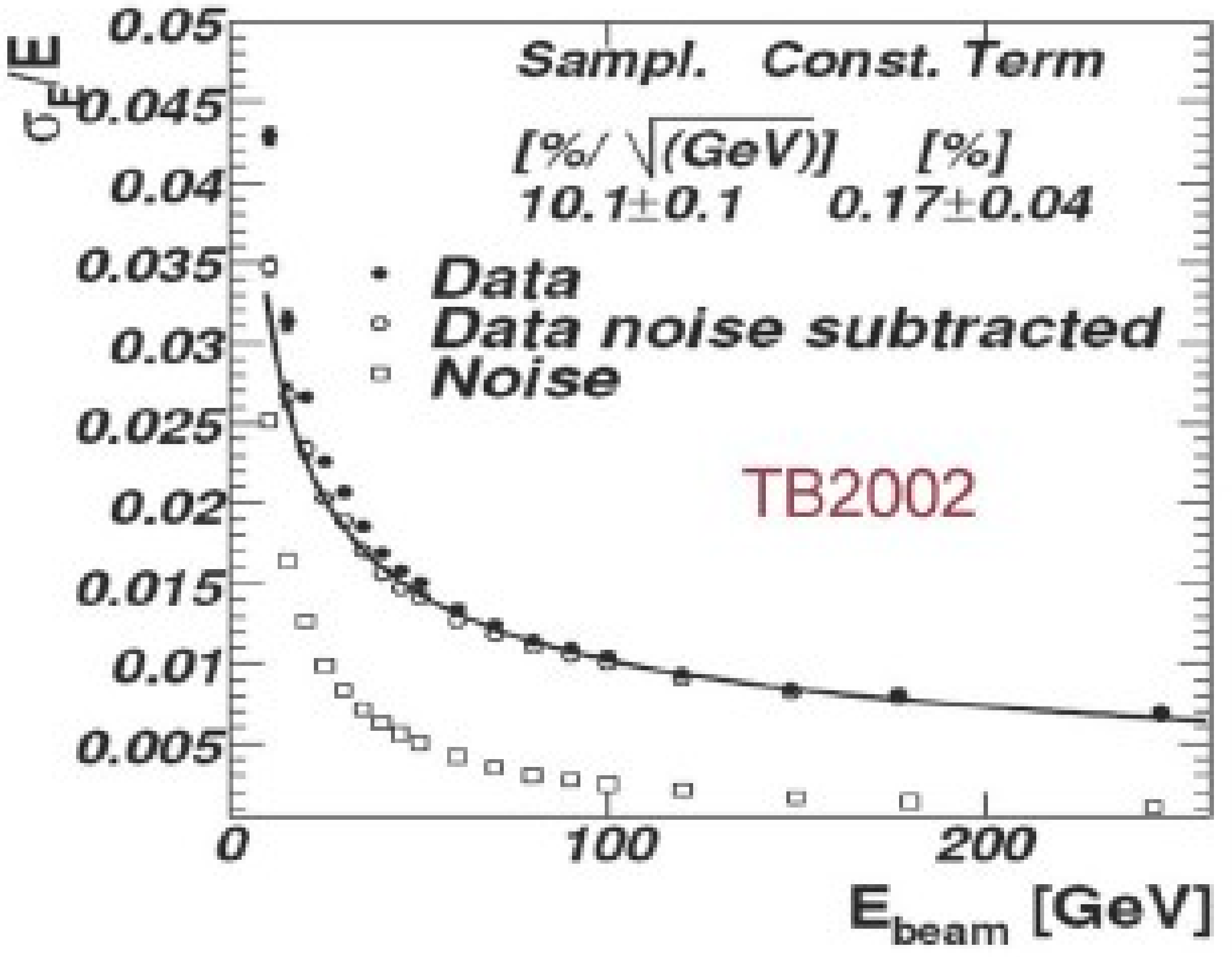
CMS EM calorimeter



Fast scintillator: O(10 ns) decay time
Excellent stochastic resolution
Challenge: uniformity, stability

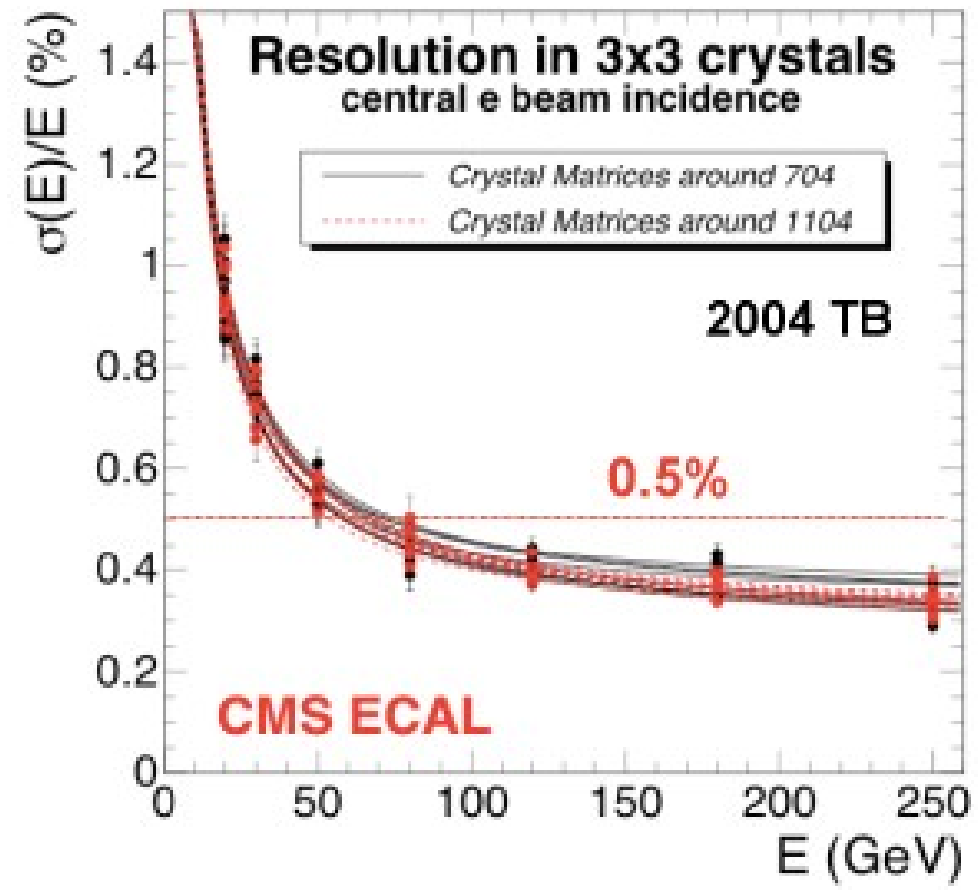
EM resolution(s)

Atlas EM Resolution



Global constant term 0.6-0.7%

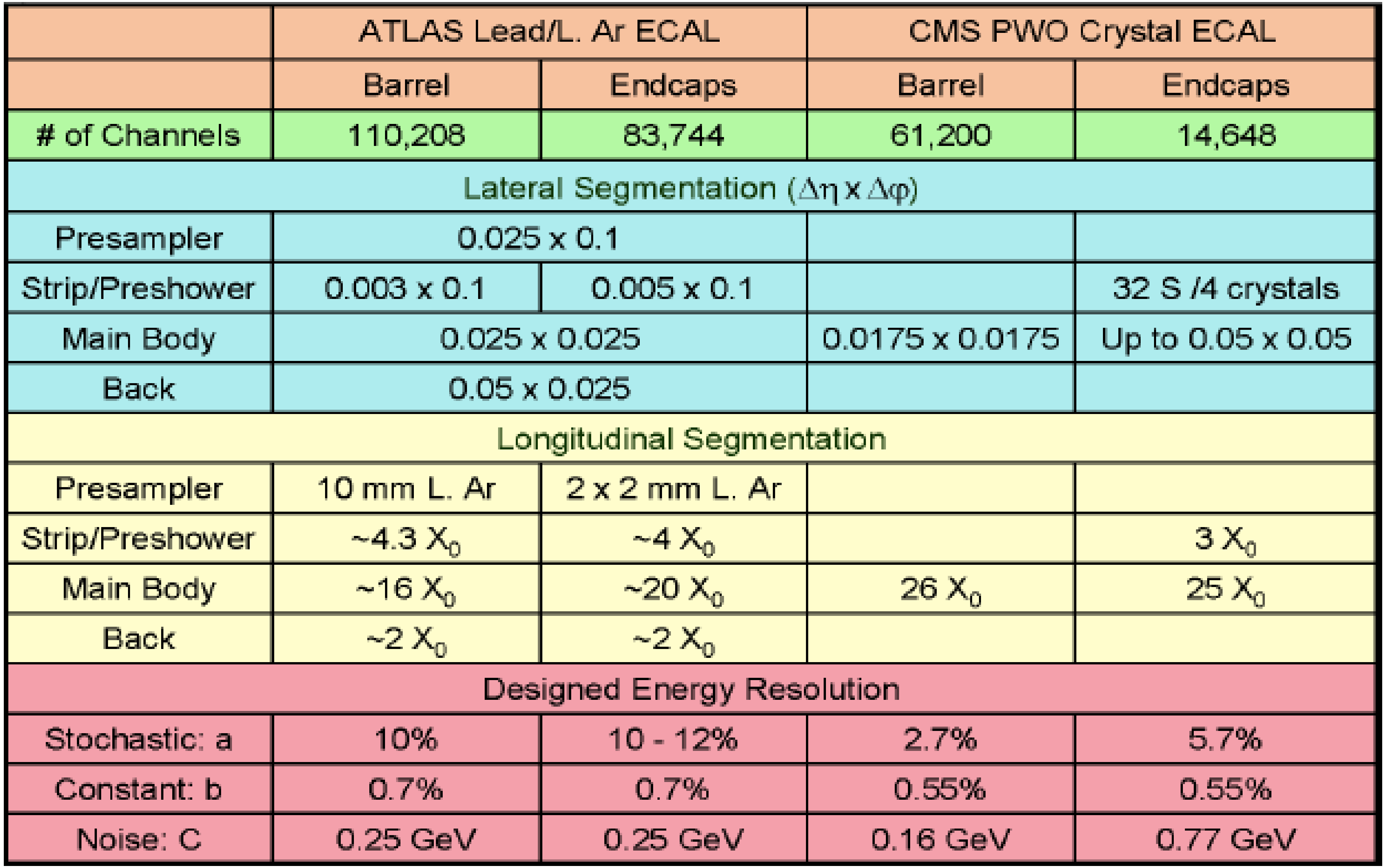
CMS EM ResolutionC



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

Global constant term < 0.5%

Atlas vs. CMS ECAL parameters



	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

ECAL summary

ATLAS: + (excellent) longitunal segmentation - (good) energy resolution

CMS: + (excellent) energy resolution - (no) longitudinal segmentation

Signals $H \rightarrow \gamma\gamma$ or $H \rightarrow ZZ^* \rightarrow 4e$ narrower peak in CMS

Intrinsic background from fakes smaller in ATLAS (better $e/\gamma/\pi^0$ separation)

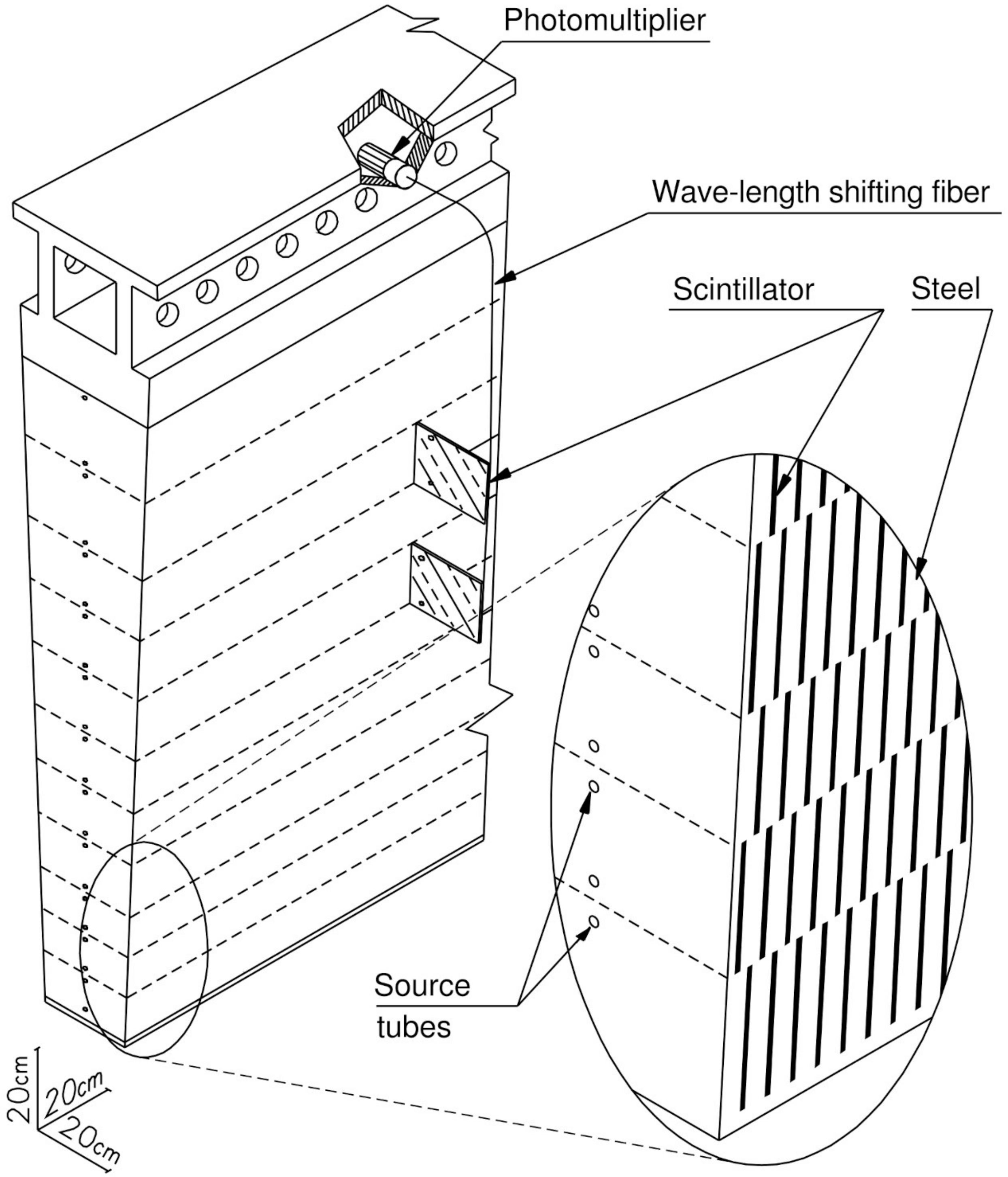
Hadron calorimetry

Main drivers: jet final states, Missing ET (BSM searches)

MET: needs both precision and angular (~ 4π) coverage

ATLAS Tile calorimeter (Barrel)

Fe/scintillator, WLS fibre readout via PMT



Cell geometry in barrel

Open circles are PMTs

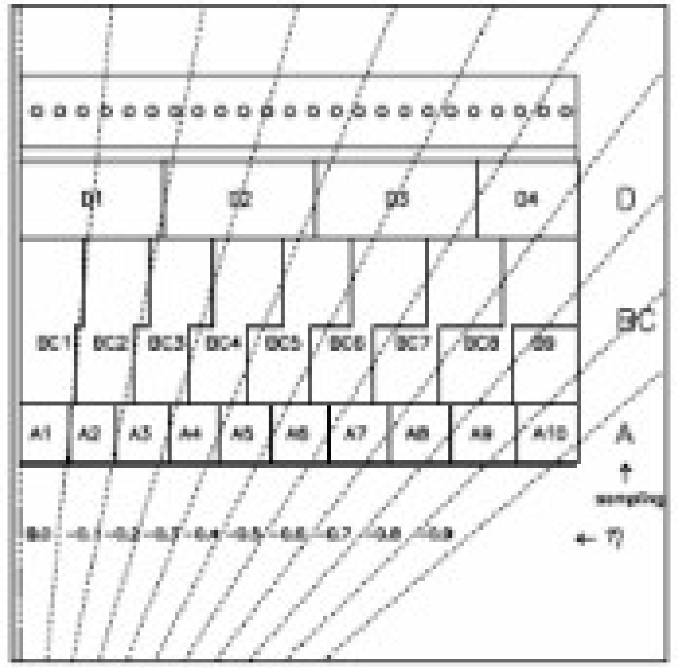
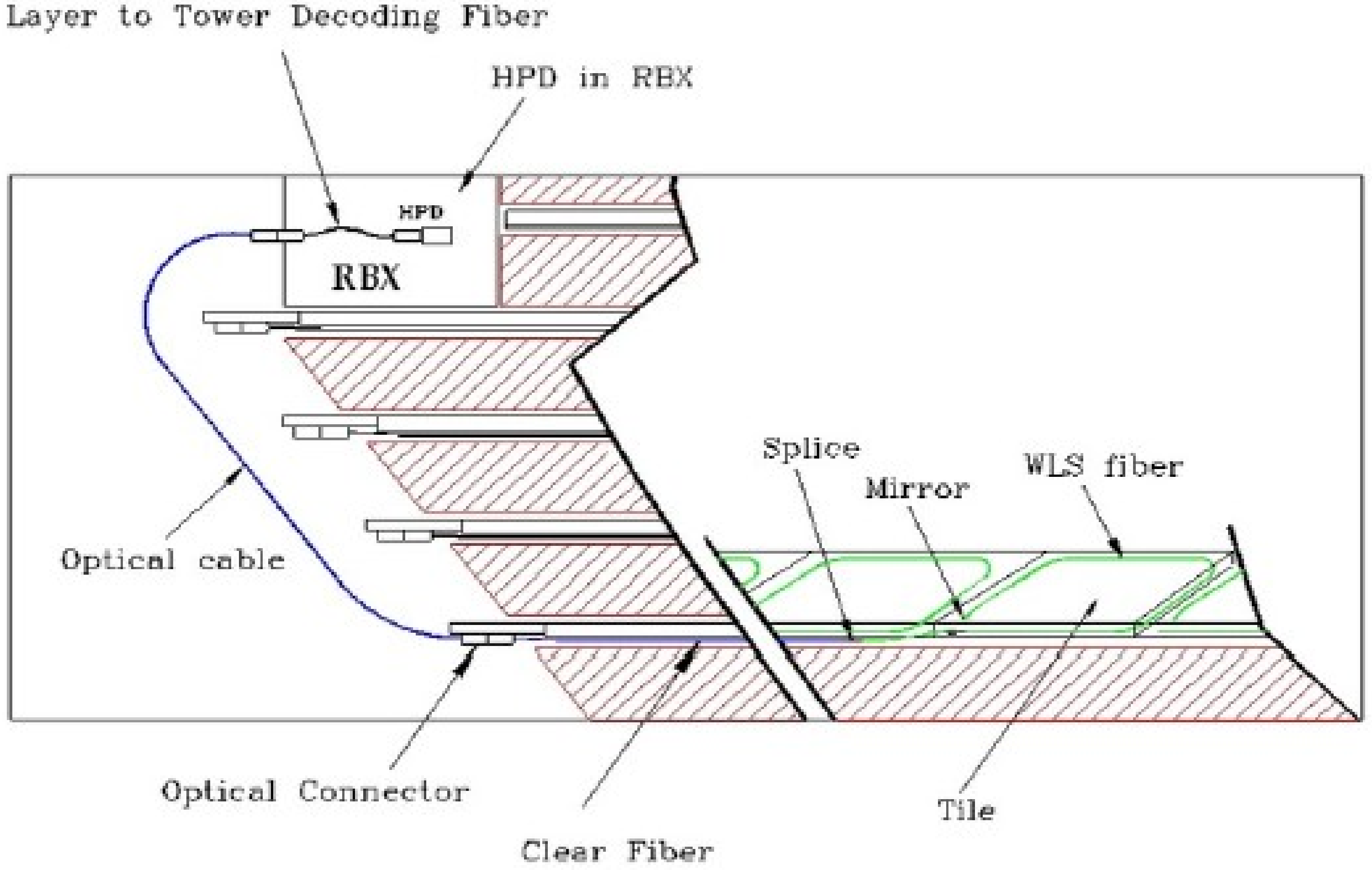


Figure 5-15 Cell geometry of half of a barrel module. The fibres of each cell are routed to one PMT. The PMTs are located in the open circles shown in the girder region.

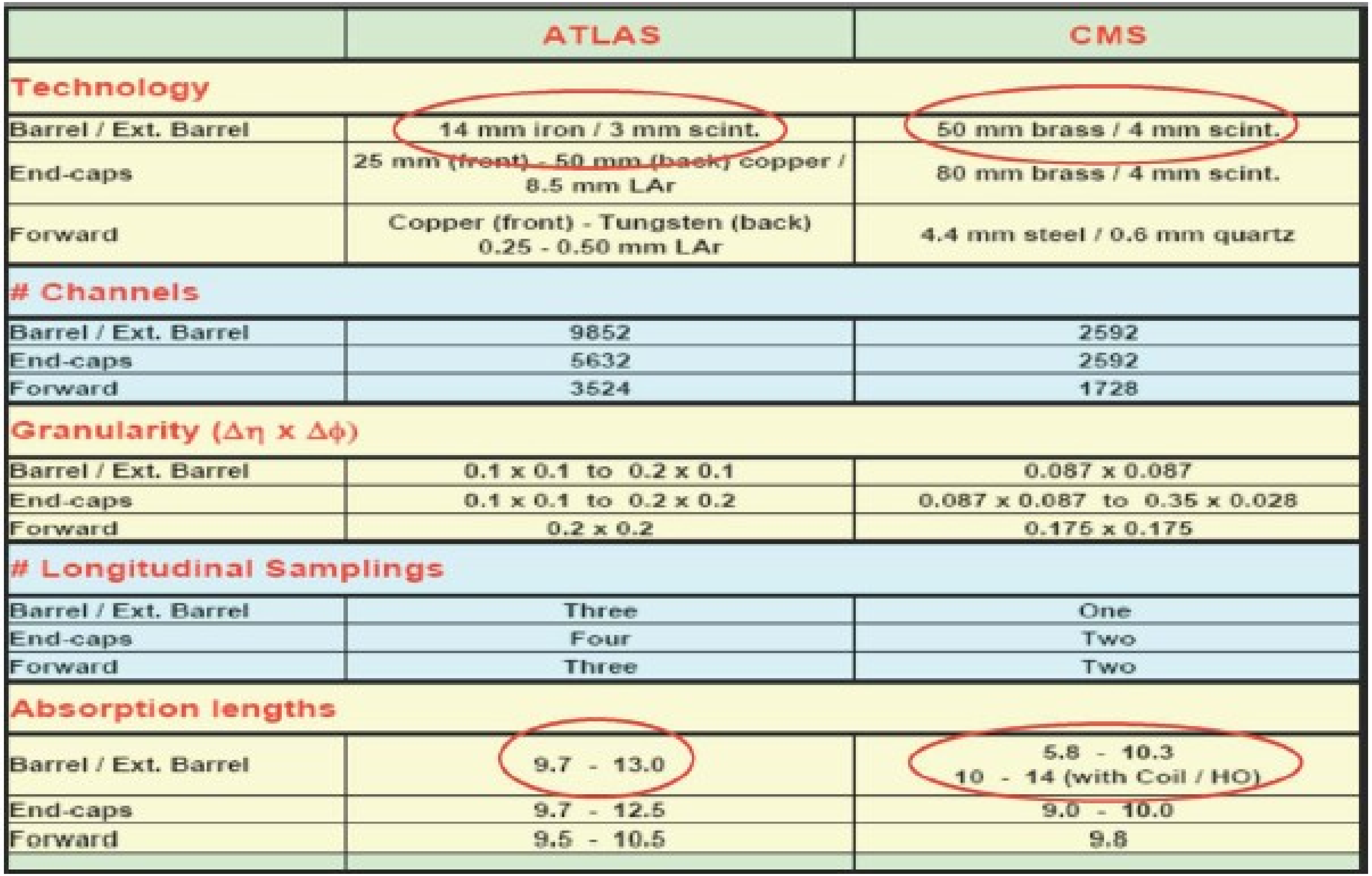
CMS HCAL

Brass/scintillator, WLS fibre readout via HPD



Common technology for Barrel (HB) and Endcap (HE)

Atlas vs. CMS HCAL parameters



	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 ($\Delta\eta \times \Delta\phi$)		
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

Hadronic resolution

Atlas: $\sigma_E/E \sim 50\% / \sqrt{E} \oplus 3\%$

CMS: $\sigma_E/E \sim 100\% / \sqrt{E} \oplus 5\%$

→ Missing E_T resolution:

Atlas: $\sigma_{ET}/E_T \sim 50\% / \sqrt{\sum E_T}$

CMS: $\sigma_{ET}/E_T \sim 100\% / \sqrt{\sum E_T}$

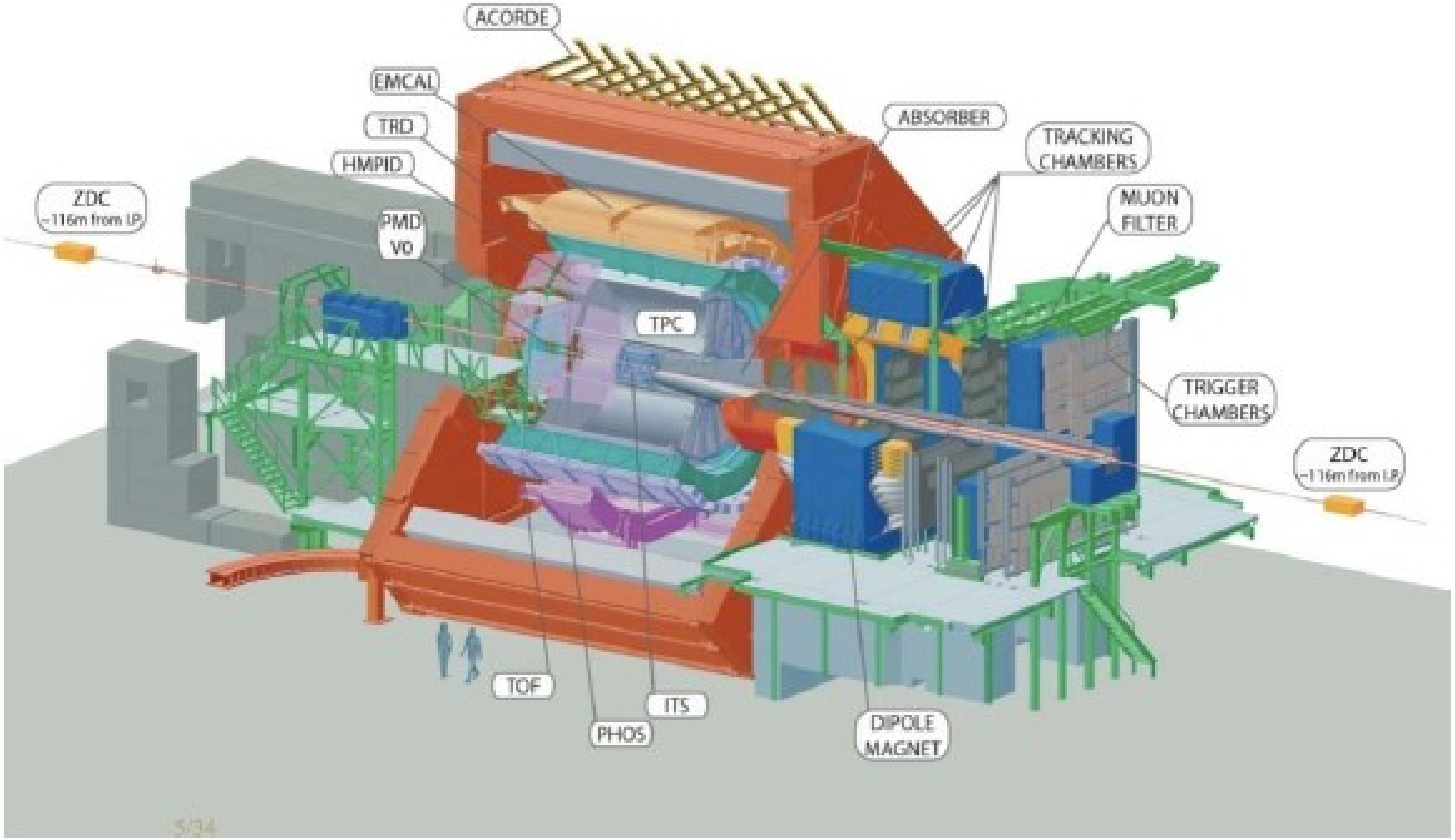
However, similar performance for BSM searches (e.g. better CMS detector hermeticity)

More limitating factors to (both EM and had) energy resolution @ LHC:

a) pile-up fluctuations

b) inner detector material (first X_0s before calorimeters)

ALICE EMCAL and PHOS (PHOton Spectrometer)



ALICE EMCAL and PHOS (PHOton Spectrometer)

PHOS: $PbWO_4$ crystals

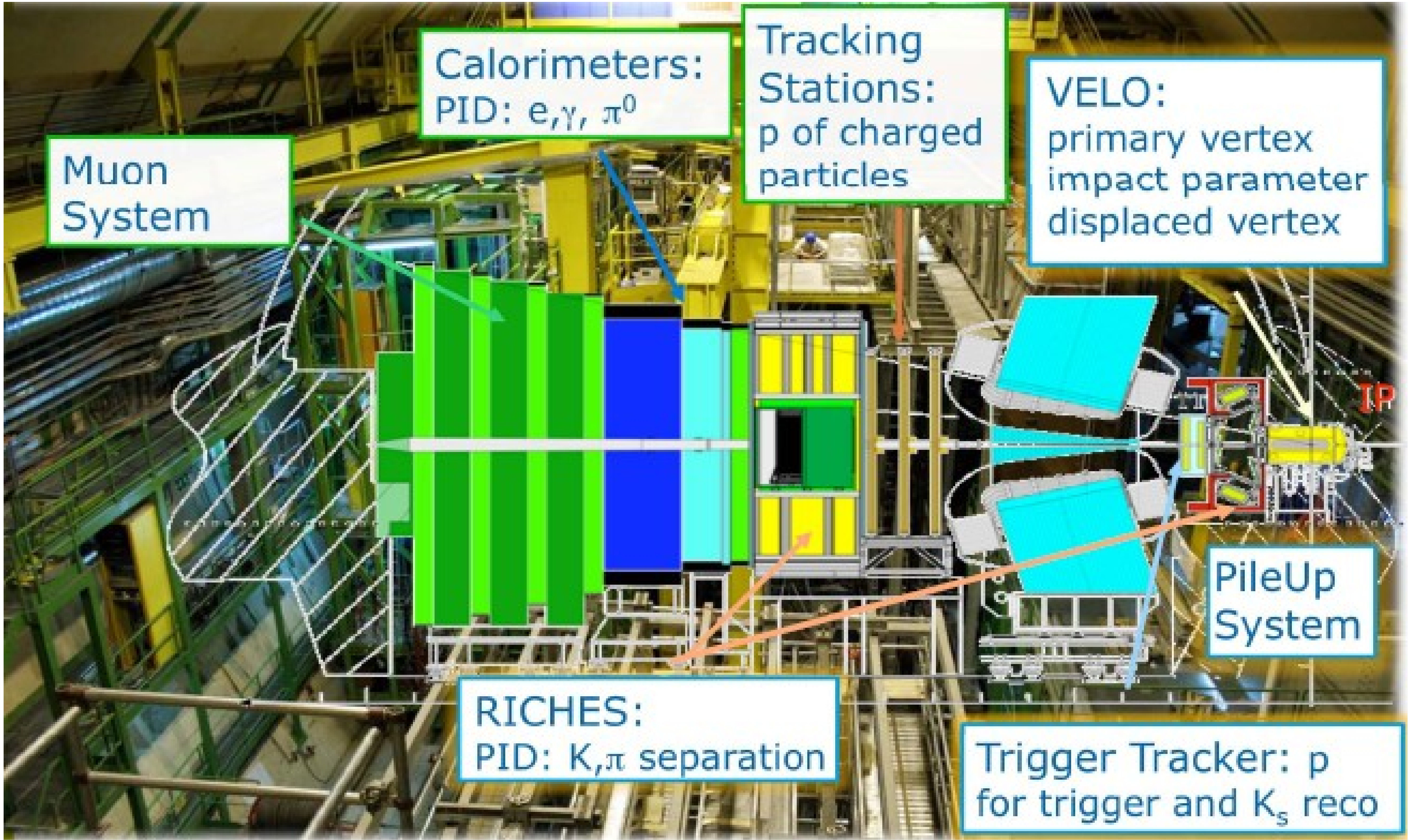
- Target: measure γ, π°, η from 0.5 to 100 GeV
- Energy resolution: $\sigma_E/E = 3.3\% / \sqrt{E} + 1.8\% / E + 1.1\%$

EMCAL(DCAL): Pb-scintillator (Shashlik)

- WLS fibre readout
- 5×5 mm^2 Hamamatsu APD
- Light yield: ~ 4.5 pe/MeV
- Full scale energy: 250 GeV
- Lateral segmentation: $\Delta\eta = \delta\varphi = 0.014$
- Depth: 20.1 X_0
- Volume ratio: Pb:Scint = 1.44:1.76
- Energy resolution: $\sigma_E/E = 9.5\% / \sqrt{E} + 2.9\% / E + 1.4\%$

→ EMCAL + DCAL: 2-arm electromagnetic calorimeter (di-jet studies)

LHCb calorimeters



Calorimeters:
PID: e,γ, π^0

Tracking Stations:
p of charged particles

VELO:
primary vertex
impact parameter
displaced vertex

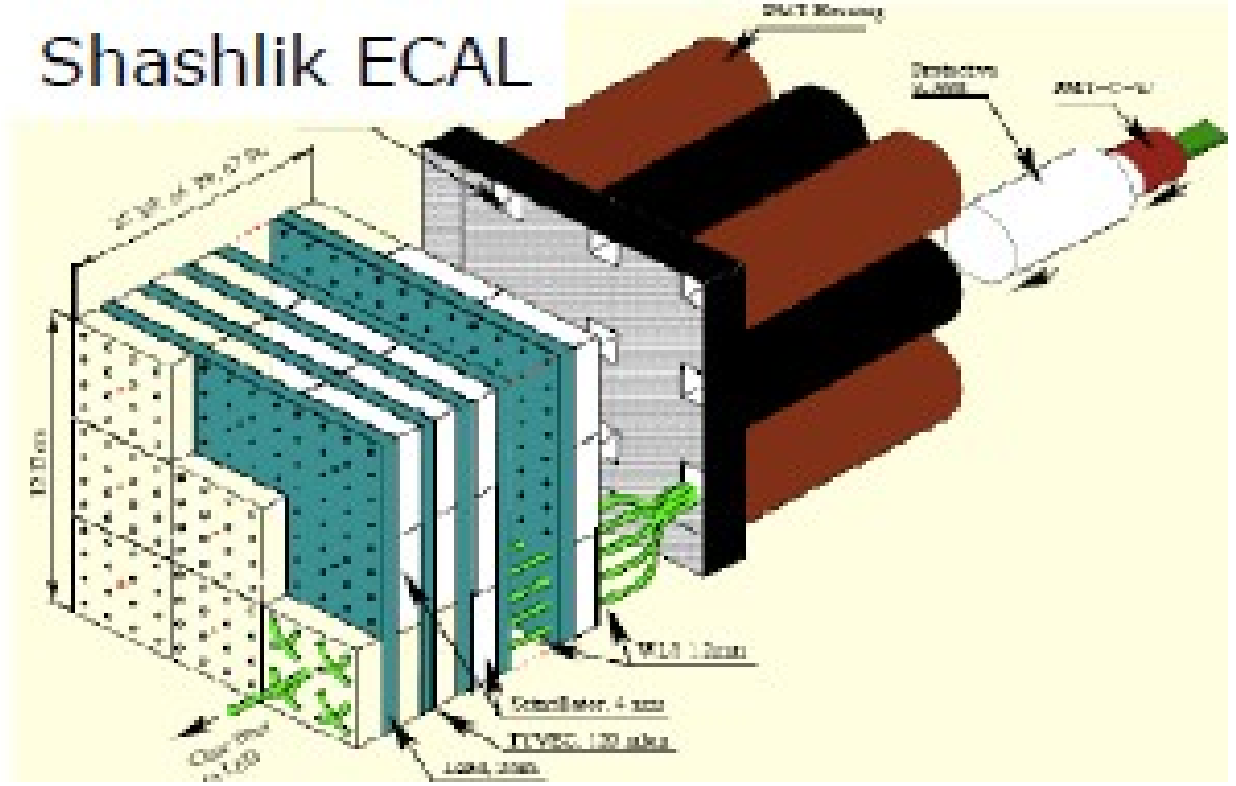
Muon System

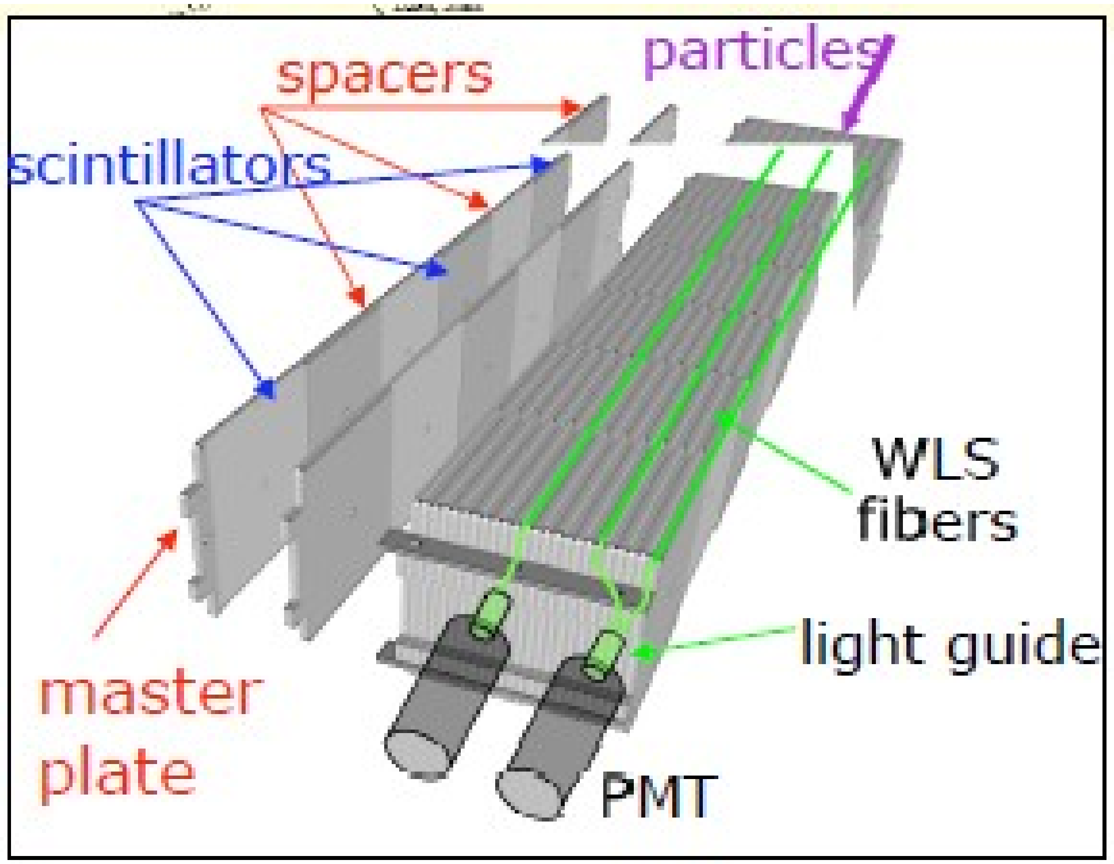
PileUp System

RICHES:
PID: K,π separation

Trigger Tracker: p for trigger and K_s reco

LHCb calorimeters





LHCb calorimeters

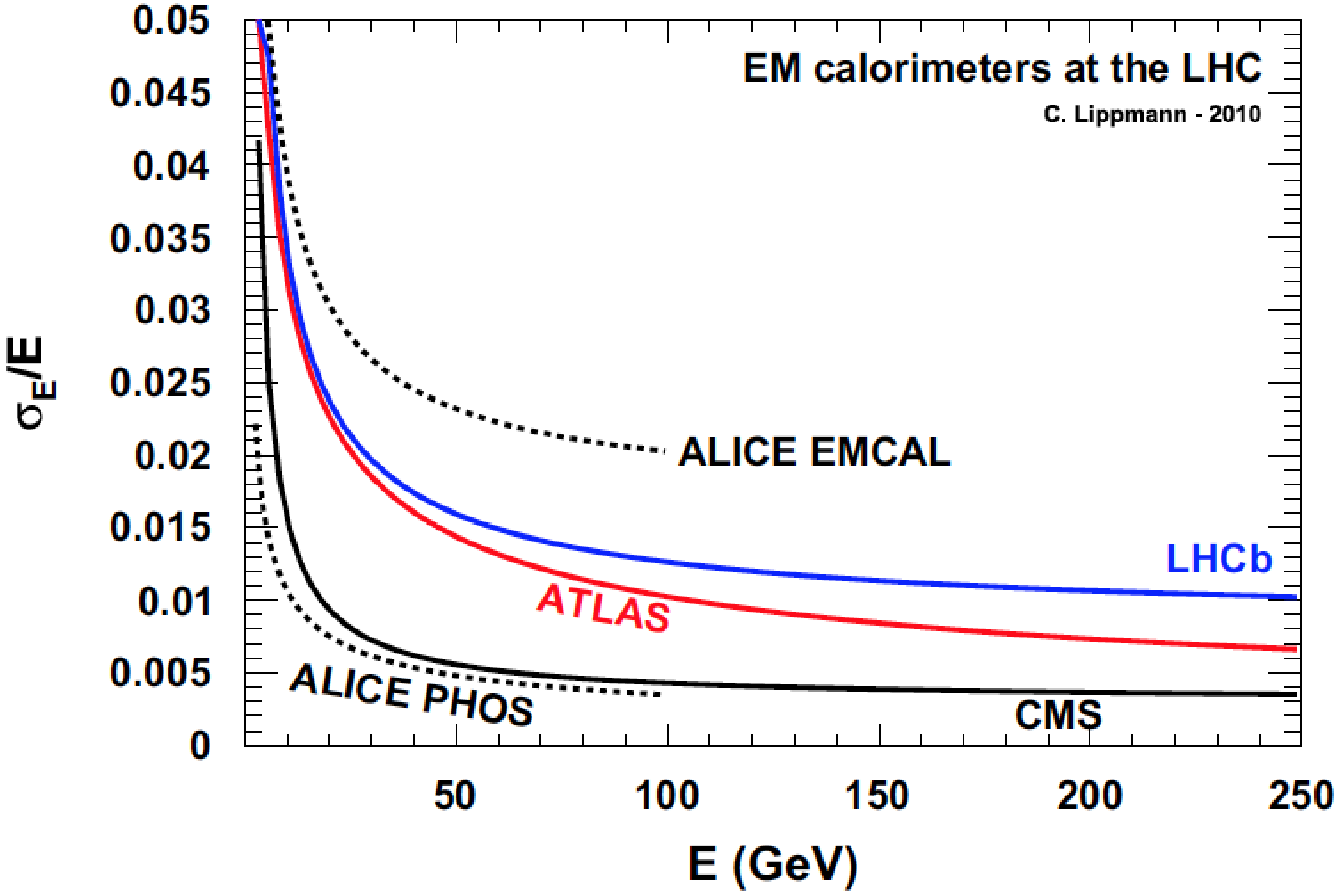
EMCAL: Lead-scintillator (Shashlik)

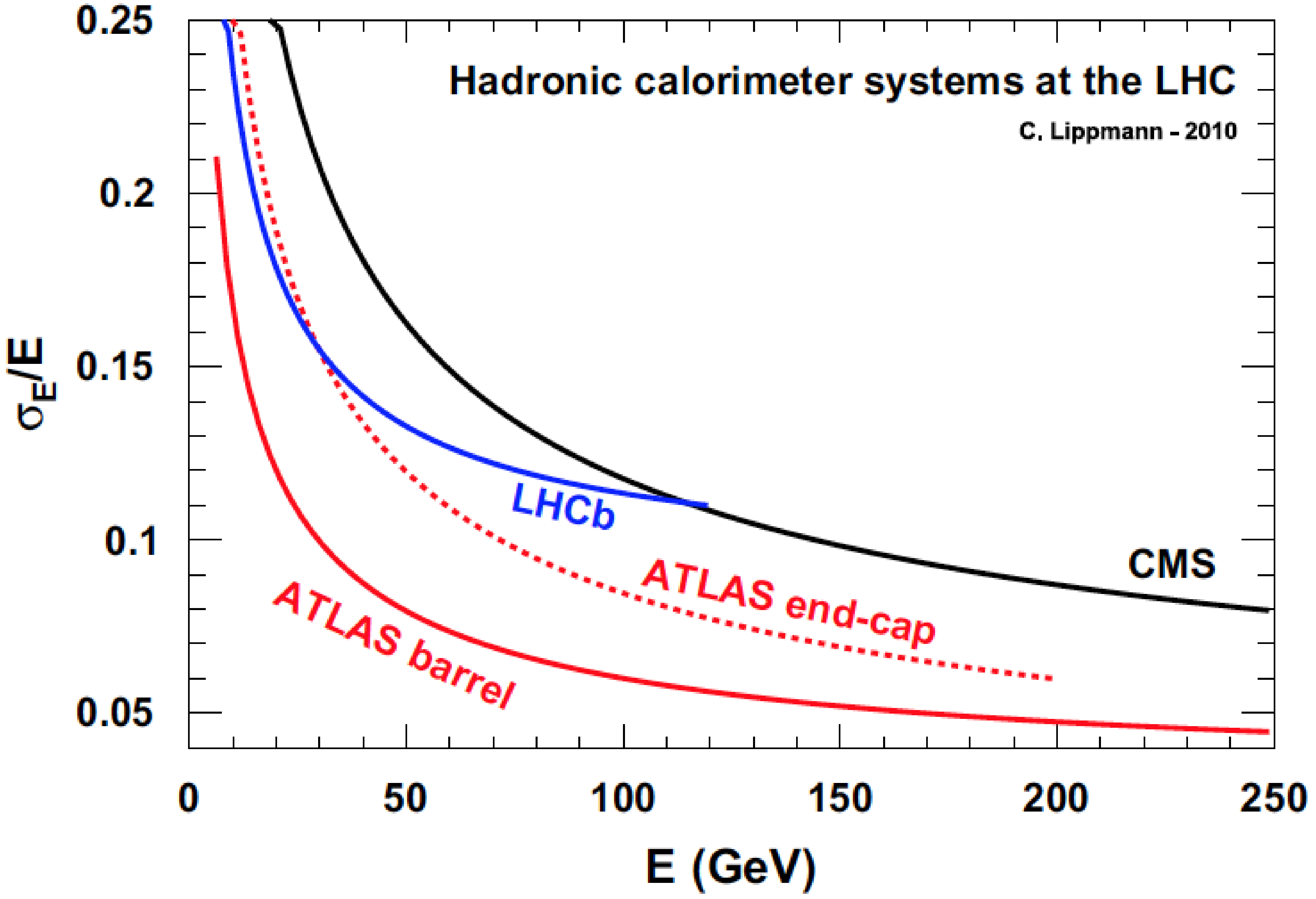
- WLS fibre readout
- Hamamatsu PMTs
- Light yield: ~ 3 pe/MeV
- Depth: 25 X_0
- Energy resolution: $\sigma_E/E = 9\% / \sqrt{E} + 0.9\%$

HCAL: Iron-scintillator (à la Atlas) + WLS + PMTs

- Light yield: 0.1 pe/MeV
- Volume ratio: Fe:Scint = 16:3
- Depth: 5.6 λ_I
- Energy resolution: $\sigma_E/E = 69\% / \sqrt{E} + 9\%$

Energy resolution of main LHC calorimeters





Upgrades for Hi-Lumi LHC

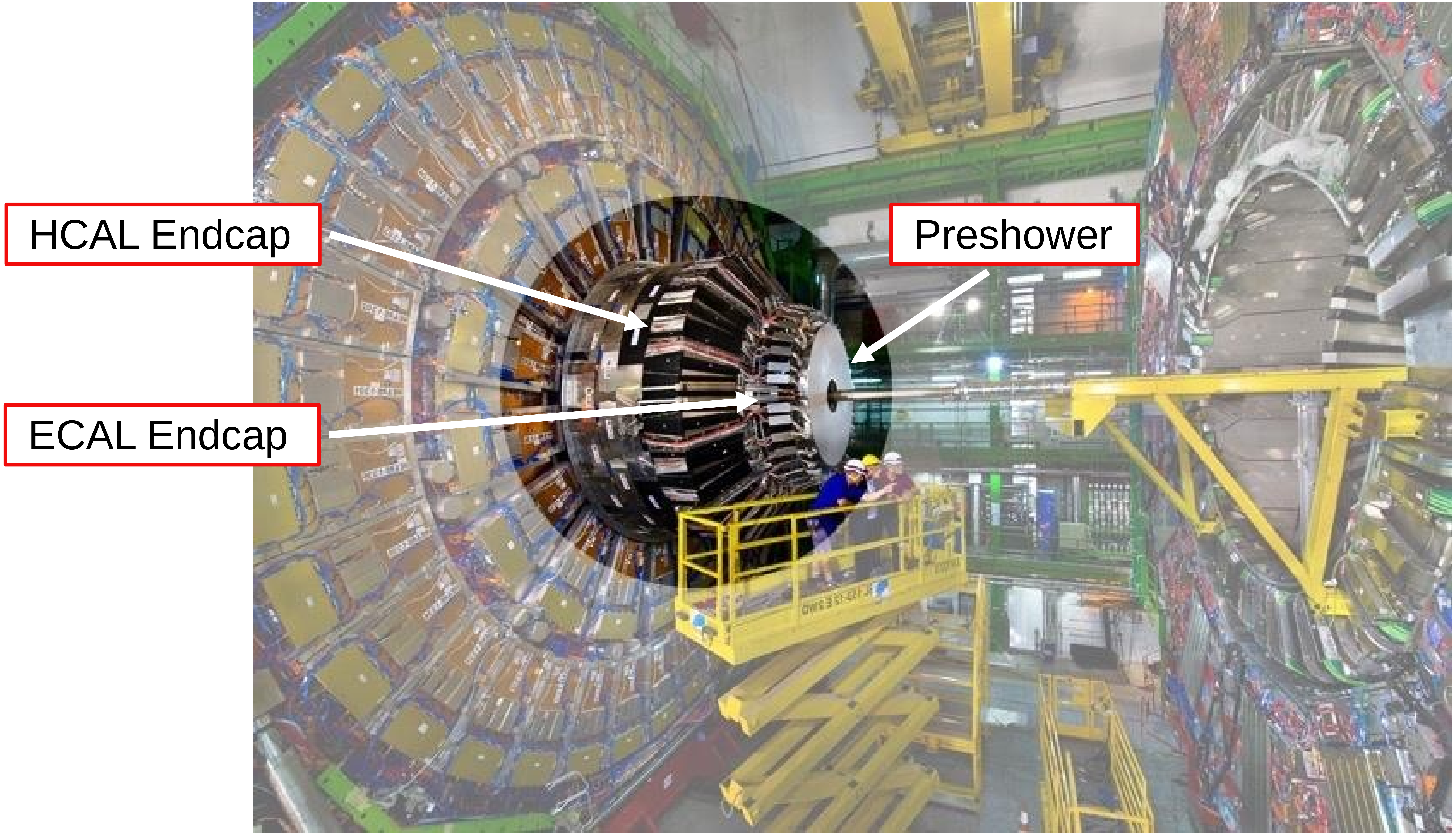
High-Lumi LHC

- huge radiation environment: ~10^{16} n/cm^2 , ~1 MGy
- 150-200 pileup events per bunch-crossing:
  → high-granularity 4D detector

CMS: High-Granularity Calorimeter (HGCAL) will replace all endcap calorimeter

HGCAL: Particle-Flow Calorimeter

CMS Endcap Calorimeters


HCAL Endcap

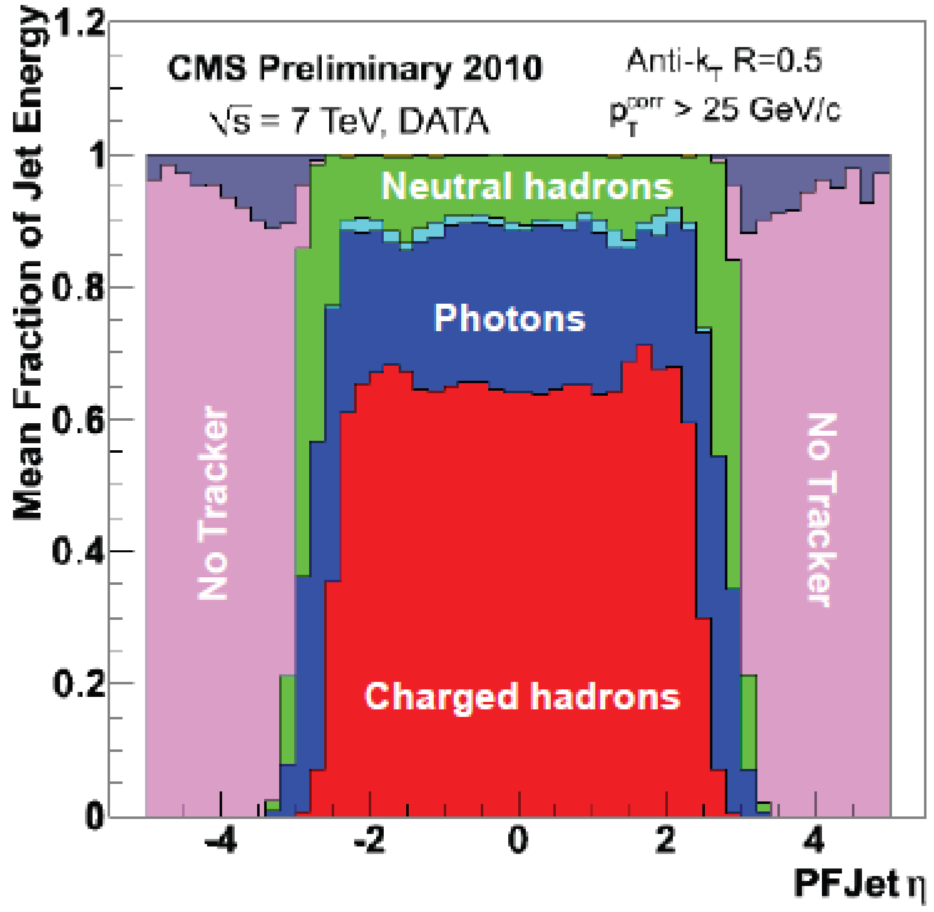
Preshower

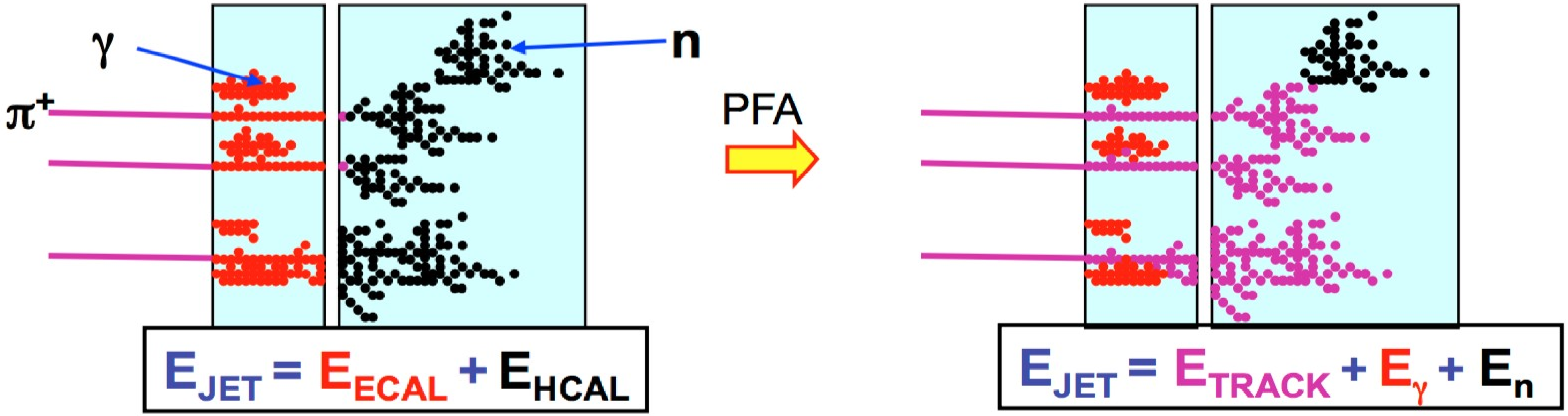
ECAL Endcap

Particle Flow Paradigm

Jet energy measurement:

1) Majority of jet particles measured with high precision by Trackers and ECALs:
   - charged tracks → Tracker
   - e/γ → ECAL
2) Only neutral hadrons (~ 10%) need HCAL measurement





$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

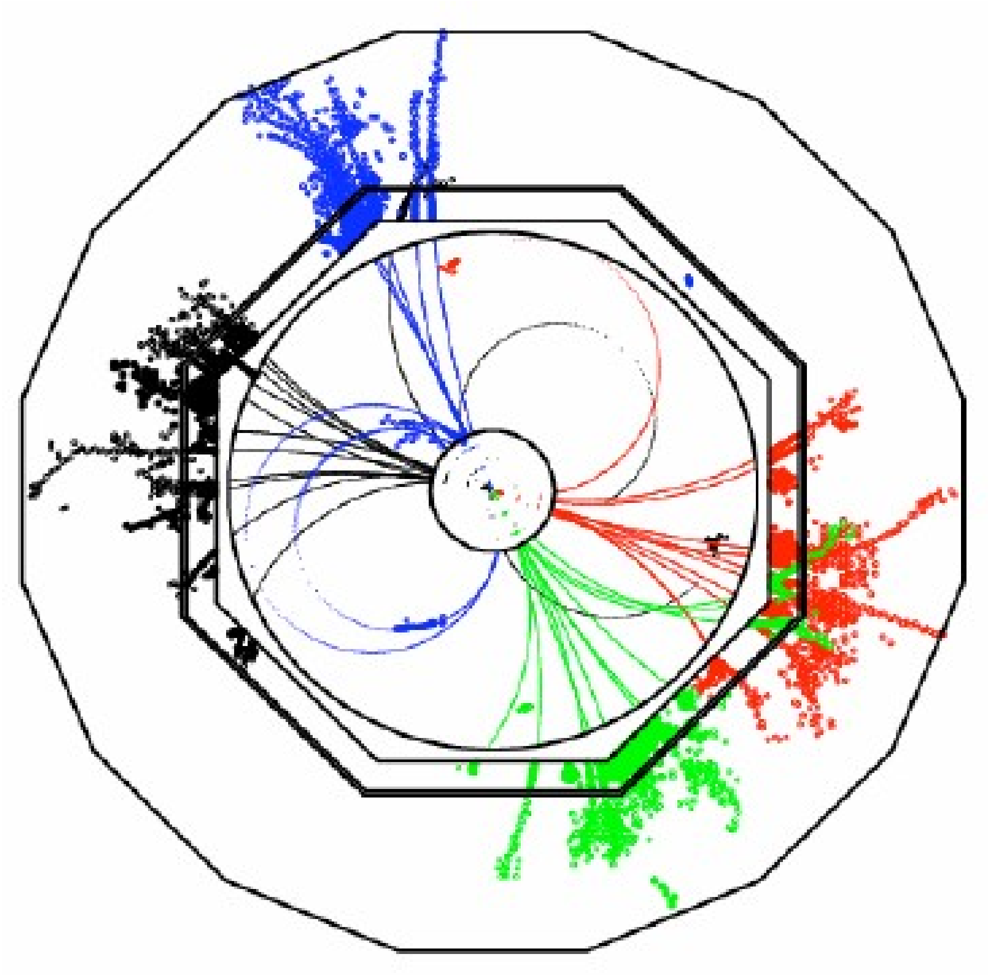
Particle Flow Paradigm

Granularity more important than energy resolution

Lateral granularity below Molière radius in ECAL and HCAL

Small Molière radius → good two-shower separation
→ tungsten absorber (lowest X_0)
→ silicon sampling elements (highest sampling density)

Pretty complex reconstruction software

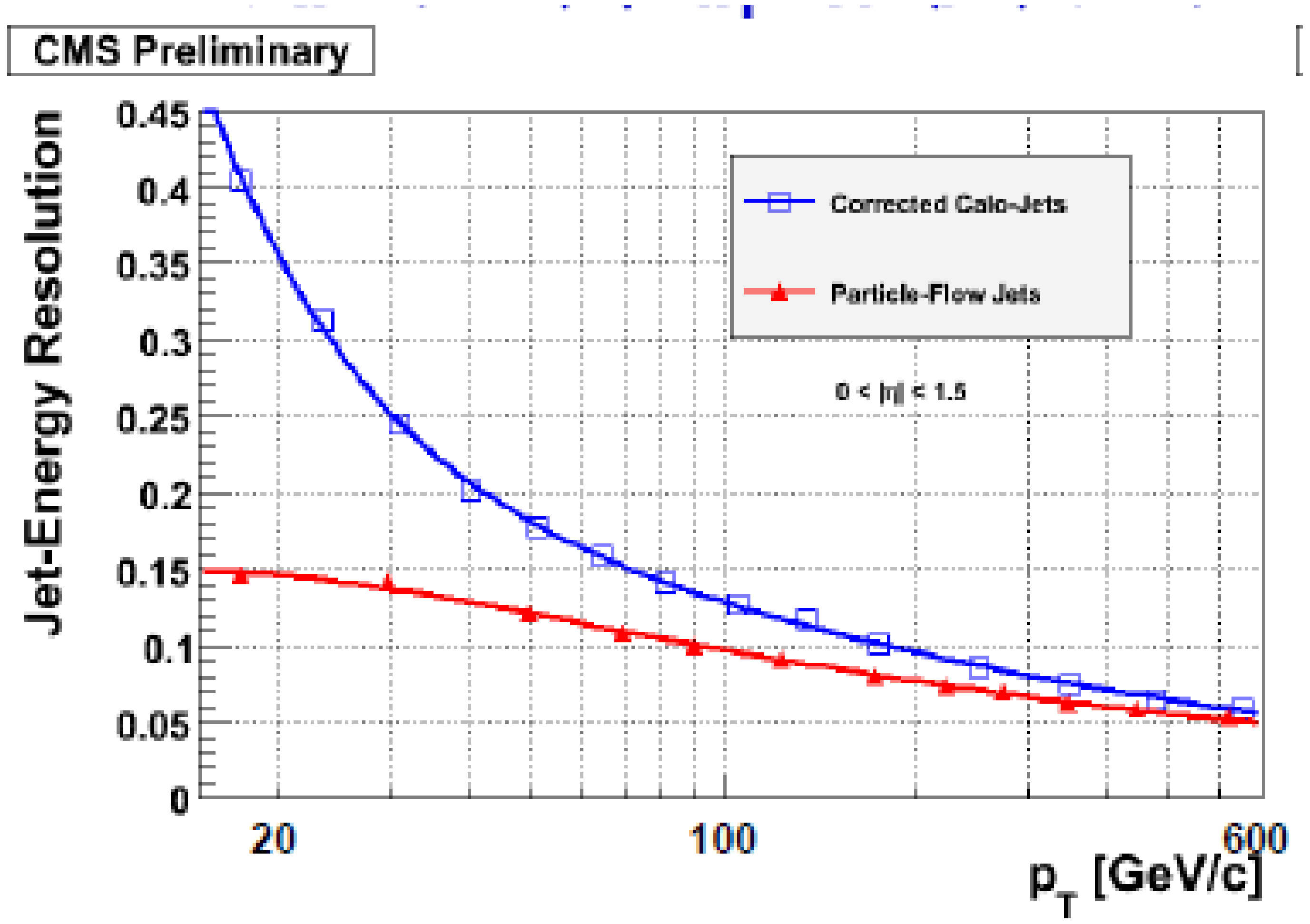


Extensively developed and studied in past decade for Linear Collider detectors

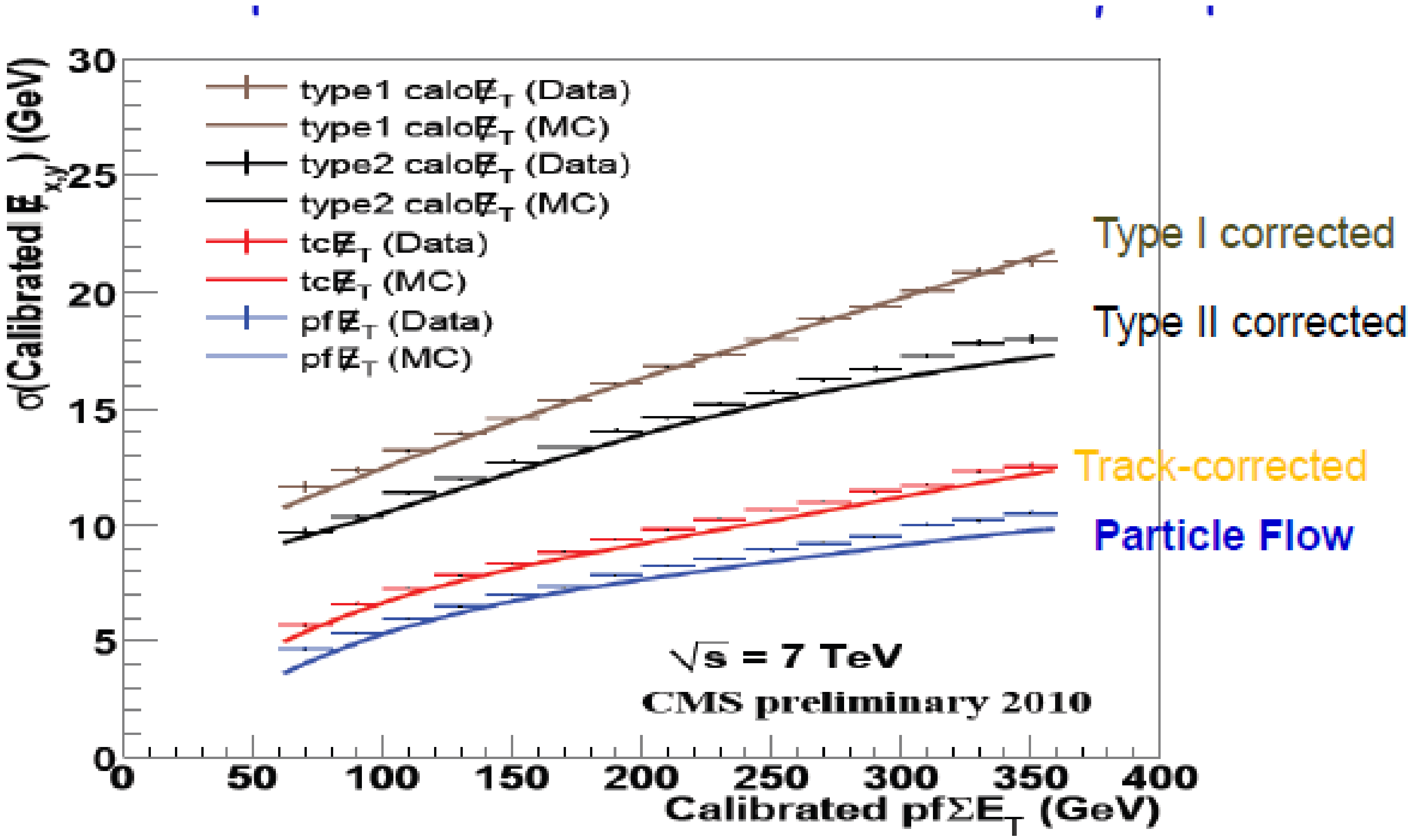
PFA already (significantly) used in Aleph & CMS

Both have low resolution HCALs

Simulation: jet energy resolution

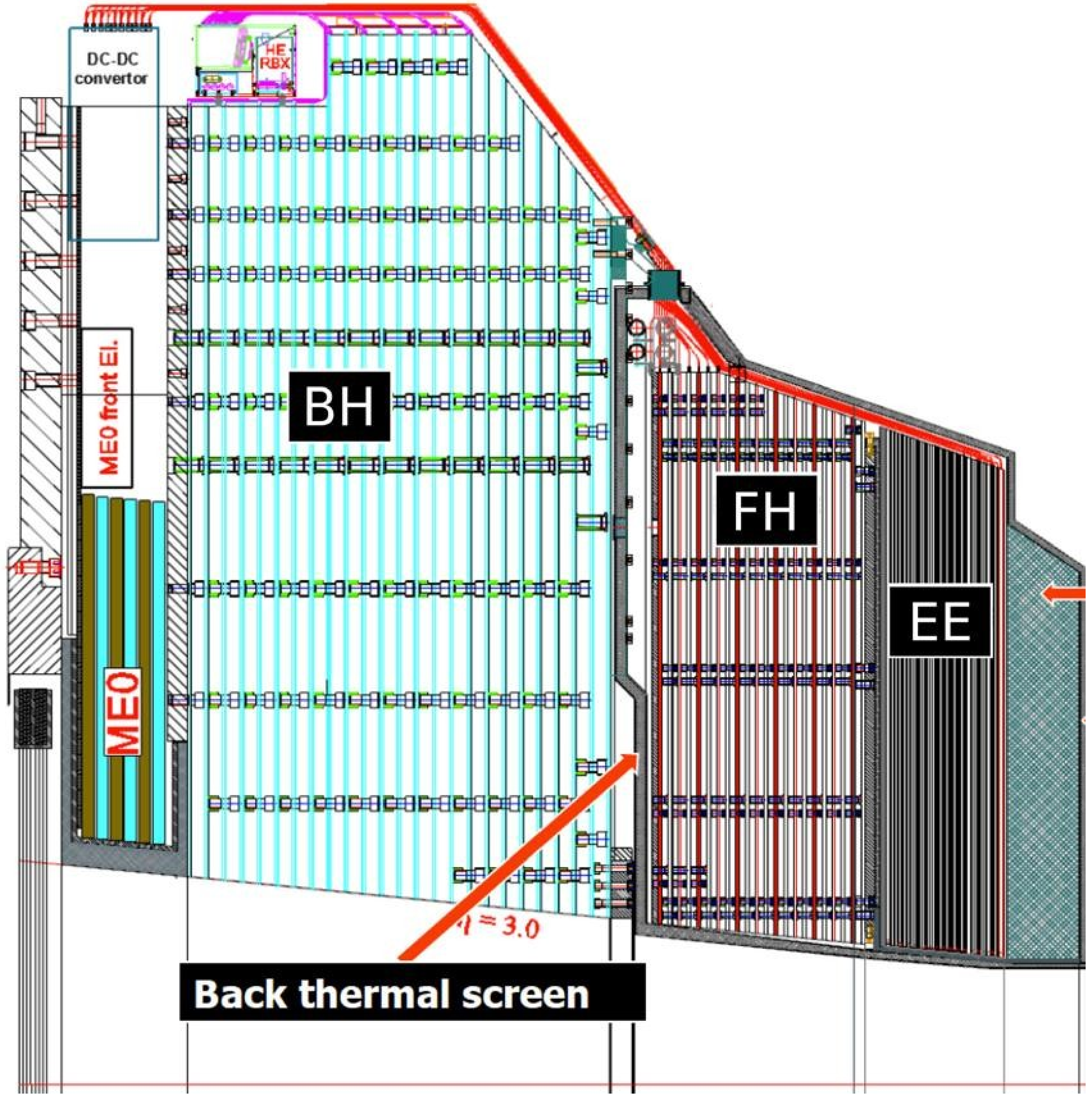


Data: missing energy resolution



Jet measurements in CMS greatly enhanced with particle flow techniques

CMS HGCAL



Combines tracking and calorimetry to get a PFA calorimeter

Key parameters:

- 620 m^2 of silicon (3 × CMS Trk)
- 6M ch, 0.5-1.1 cm^2 cell size
- ~20,000 modules (8” or 2x6” sensors)
- ~100,000 front-end ASICS
- ~200 tonnes per endcap

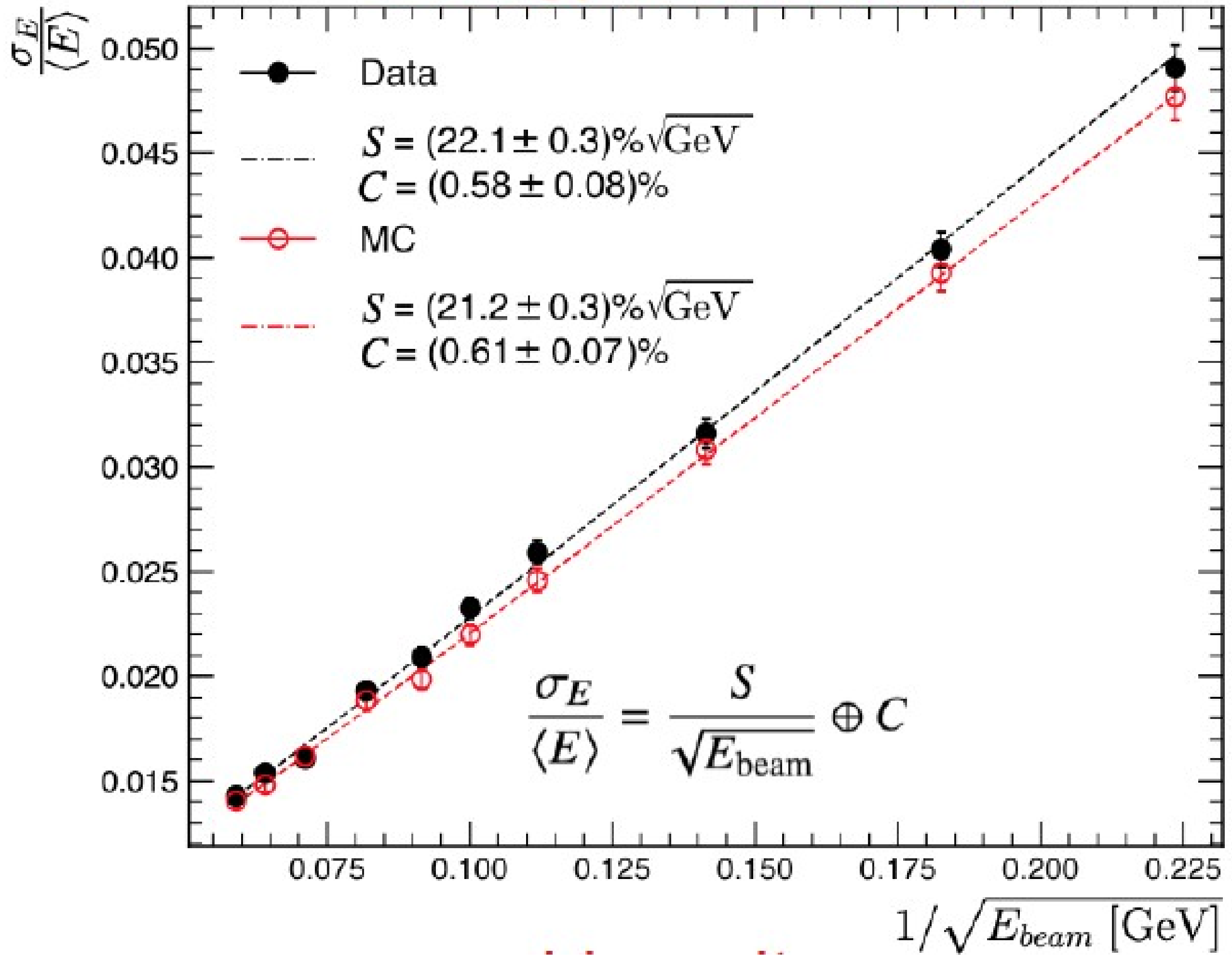
Three separate regions:

EE – Silicon with tungsten absorber – 28 sampling layers – 25 X_0 + ~1.3 λ_I
FH – Silicon with steel absorber – 12 sampling layers – 3.5 λ
BH – Scintillator with steel absorber – 11 layers – 5.5 λ

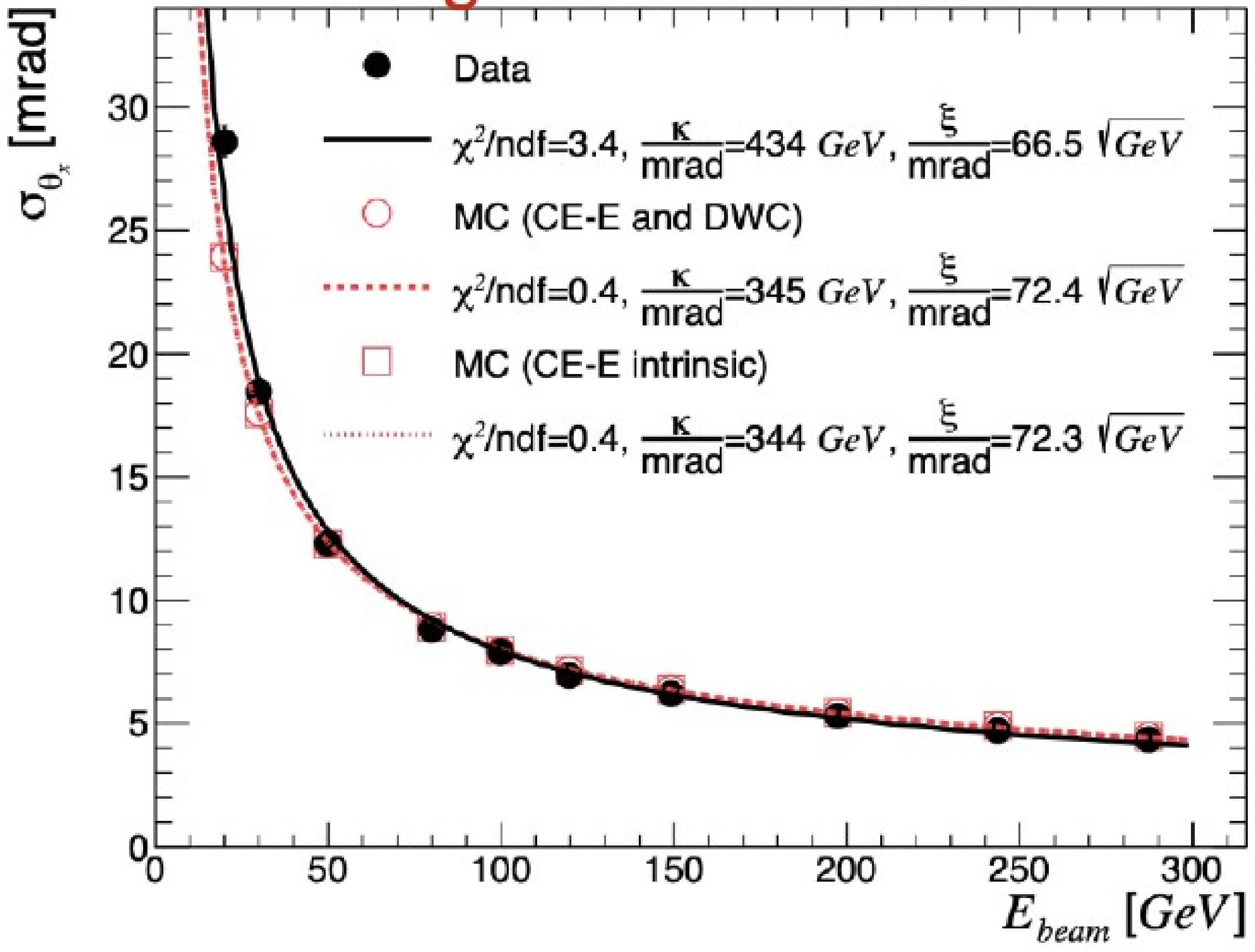
Testbeam results for positrons

- Stochastic term (EM resolution) ~ 22%
- Constant term ~ 0.6%
- Linearity within 3%
- Good agreement with simulation, also for angular resolution

Energy Resolution

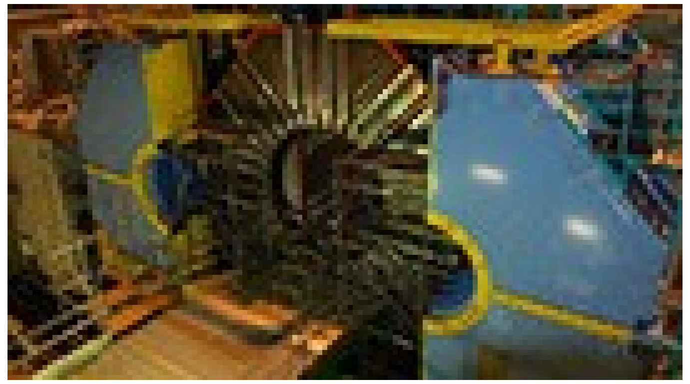


Angular Resolution

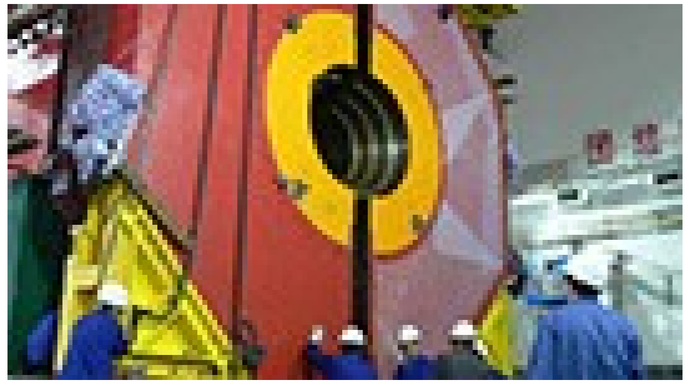


Intensity Frontier and Trend in HEP

Intensity Frontier

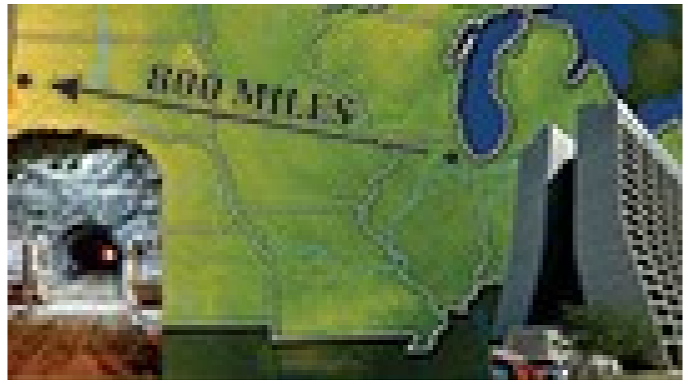


Belle II



BES III

Mu2e



DUNE

MINERvA

Muon g-2

...

Calorimeters for Intensity Frontier

Belle II: CsI(Tl) crystal → 50000 pe/MeV   resolution 0.8% / √E + 1%

BES III: CsI EMC → ~ 2.5% at 1 GeV

Mu2e: CsI, resolution <10% at 100 MeV

Muon g-2: PbF (Cherenkov → prompt signal) → ~3% / √E

MINERvA: Lead/scintillator sampling calo

DUNE: single- or dual-phase LAr TPC → LAr purity the issue

trend in high-energy physics

a) improve granularity → critical for pile-up rejection and PFA

b) improve timing performance → critical for pile-up rejection

c) improve hadronic resolution → critical for lepton colliders

d) improve e.m. resolution → relevant for most sampling calorimeters

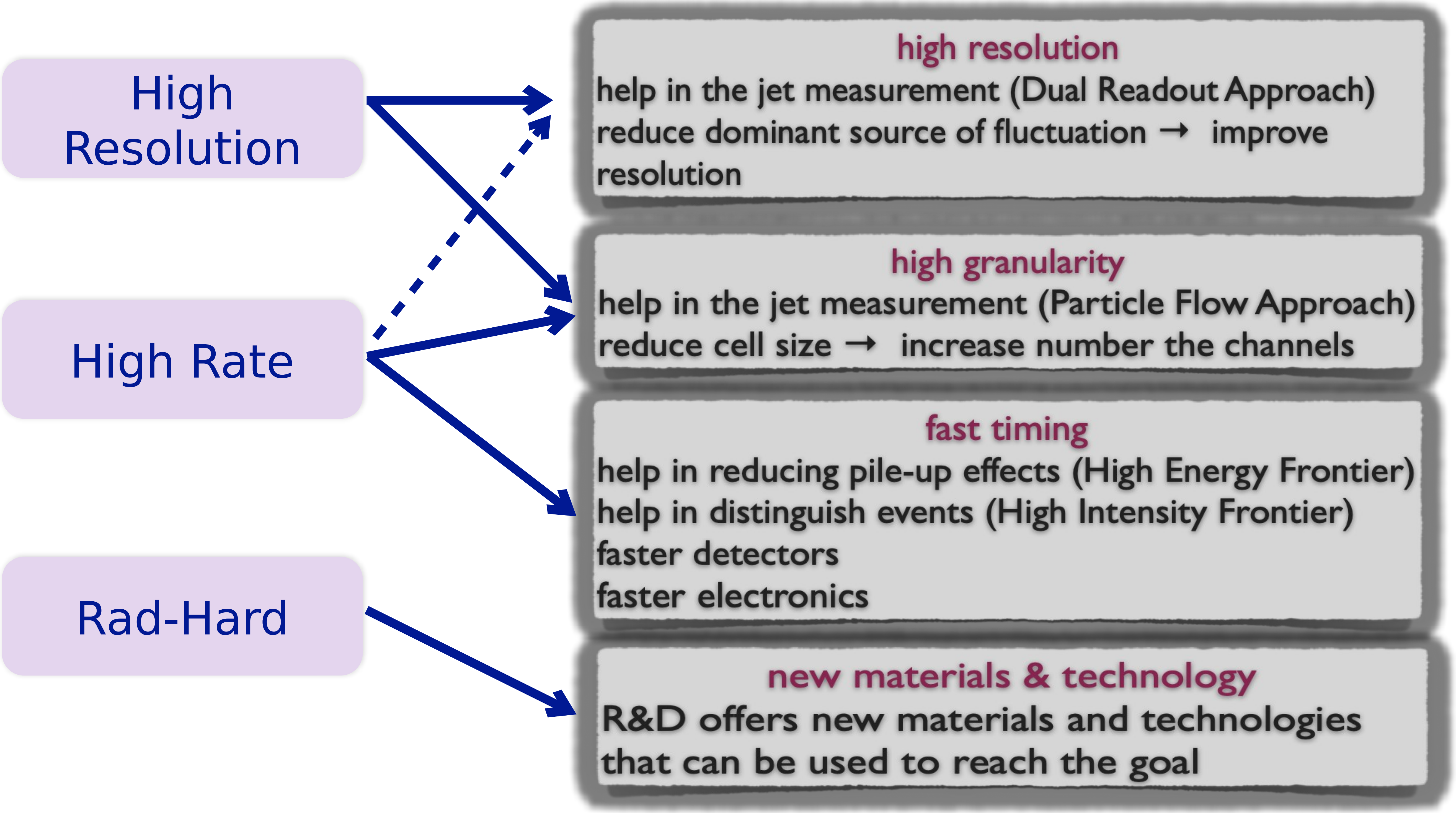
e) improve radiation hardness → critical for hadron colliders
…

f) low noise, low power, high speed, high throughput data processing

function of proposed implementation and scenario (facility)

work for you ...

How to cope with physics and performance requirements?



High Resolution

High Rate

Rad-Hard

high resolution
help in the jet measurement (Dual Readout Approach)
reduce dominant source of fluctuation → improve resolution

high granularity
help in the jet measurement (Particle Flow Approach)
reduce cell size → increase number the channels

fast timing
help in reducing pile-up effects (High Energy Frontier)
help in distinguish events (High Intensity Frontier)
faster detectors
faster electronics

new materials & technology
R&D offers new materials and technologies that can be used to reach the goal

example: physics requirements @ FCC-ee

a) Jet energy (invariant mass) resolution (separate H / W / Z → 2j final states):

H→ qq → 2j
H → WW, ZZ → 4j

b) EM energy resolution (identify and measure single photons and photon pairs from π^0):

H → γγ
hadronic tau final states (π^0‘s)
heavy flavour physics (π^0‘s)

invariant mass resolution → requires both energy and angular resolution

Outside Physics w/ Beams ?

beams you don’t pay for ...

e.g. Astroparticle and Neutrino Physics

non considering bolometers, microcalorimeters, ... ,
low-energy deposits (μeV → meV)

beams you don’t pay for ...

Calorimetry for cosmic-ray detection

VHE gamma rays, GRBs, EASs
neutrinos from many sources (atmospheric, solar, galactic, … ,
supernova neutrinos)

e.g.: Water Cherenkov detectors → Super(Hyper)-Kamiokande

Even absorber often (or sometimes) “for free” → can be ice, water, air

neutrino telescopes and observatory

Water Cherenkov detectors: Antares, KM3NeT, Hyper-Kamiokande, ...

Ice Cherenkov detectors: Amanda, IceCube

Liquid scintillator: Juno

… pretty long list …

In most (almost all) cases, arrays of PMTs used to detect Cherenkov or scintillating light

Air shower detectors

Air shower (Cherenkov) detectors: Pierre Auger Observatory (Surface Detector)

Pierre Auger Observatory made of two components:

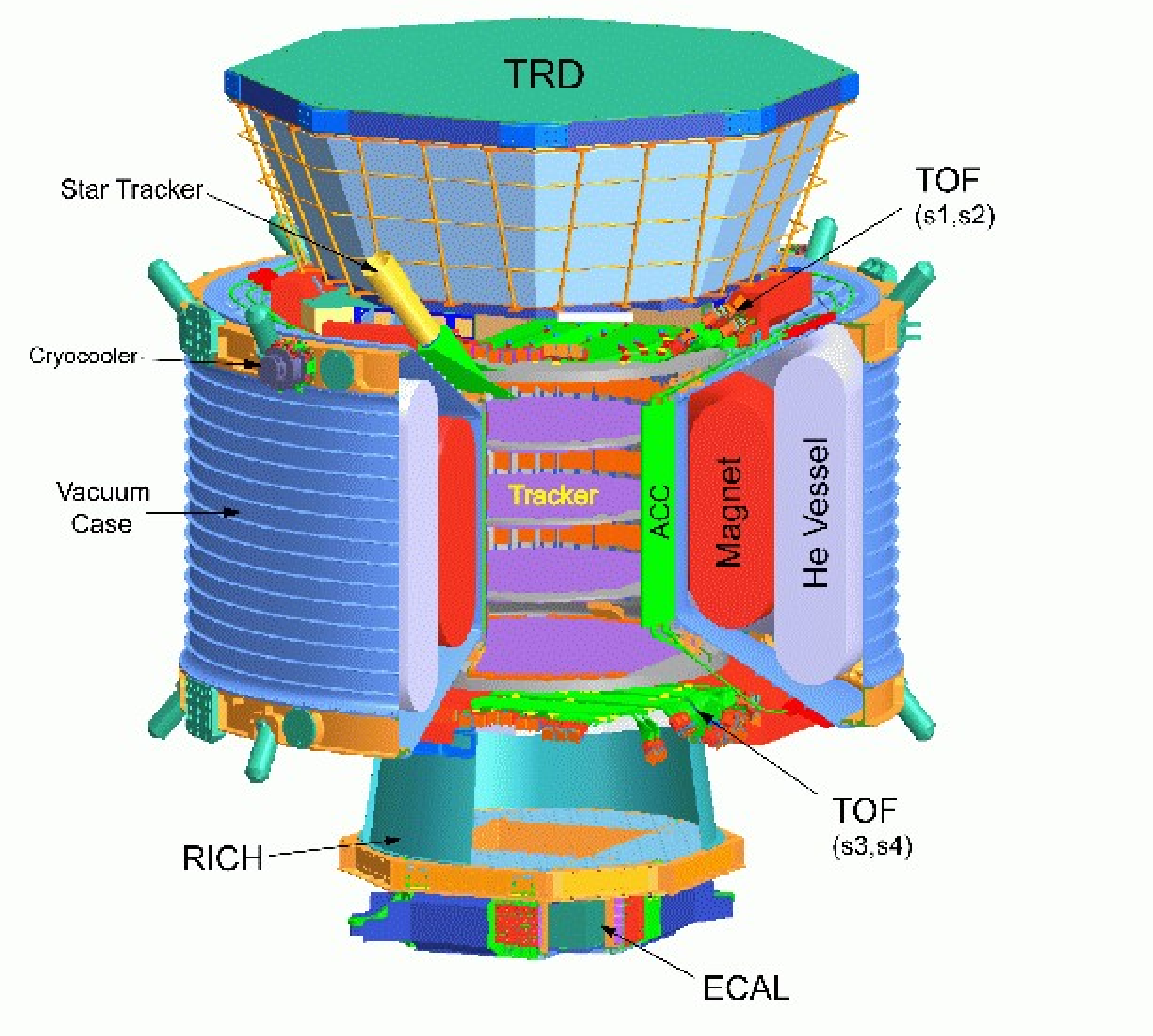
Surface Detectors: 1600 stations (water tanks) each hosting 3 large PMTs for detection of Cherenkov light emission in water by highly relativistic particles

Fluorescence Detectors: 27 atmospheric telescopes observing ultraviolet light emitted high in atmosphere, using mirrors and PMTs (440 PMTs)

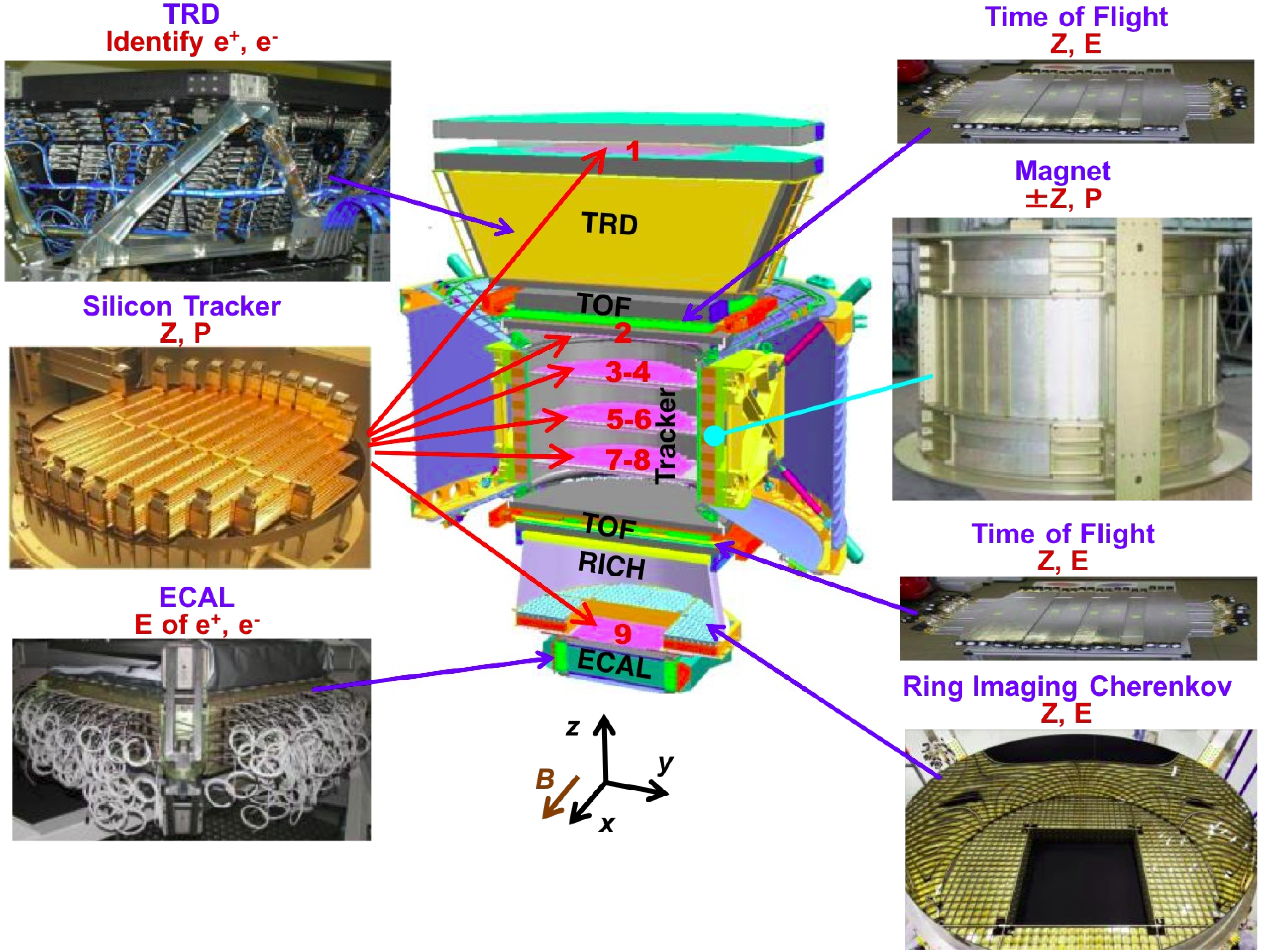
Calorimetry in space

AMS @ ISS

search for anti-matter and dark matter through precision measurements of flux and composition of primary cosmic rays



AMS detector



TRD
Identify e^+, e^-

Silicon Tracker
Z, P

ECAL
E of e^+, e^-

Time of Flight
Z, E

Magnet
±Z, P

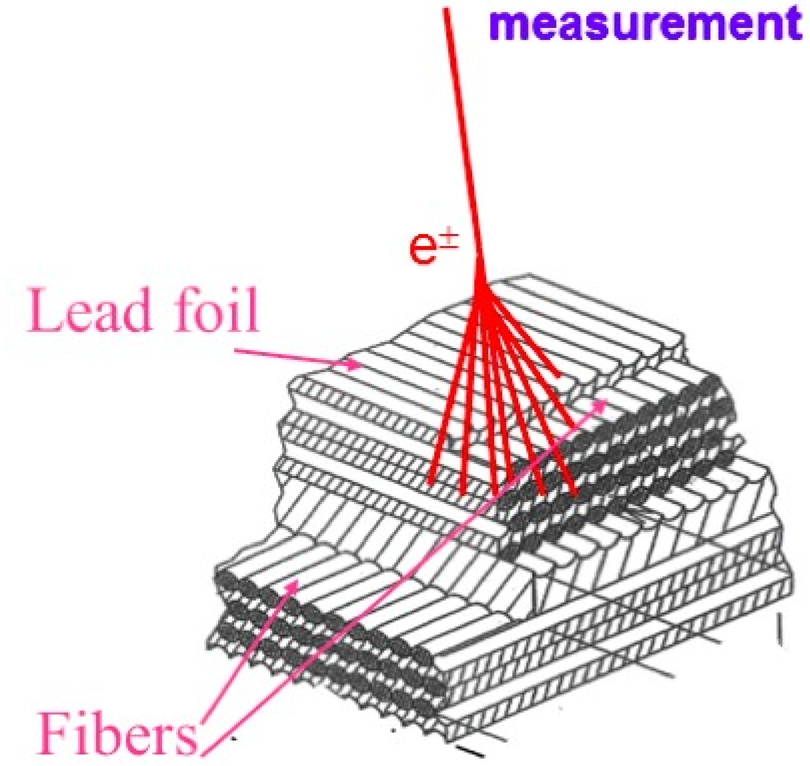
Time of Flight
Z, E

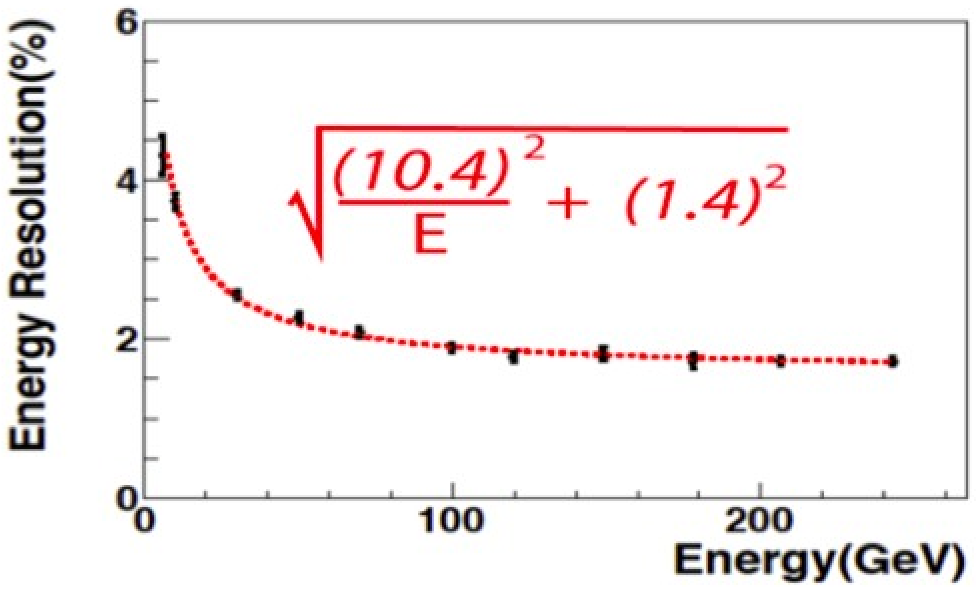
Ring Imaging Cherenkov
Z, E

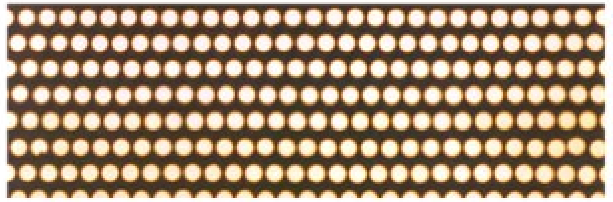
AMS ECAL

Electromagnetic Calorimeter

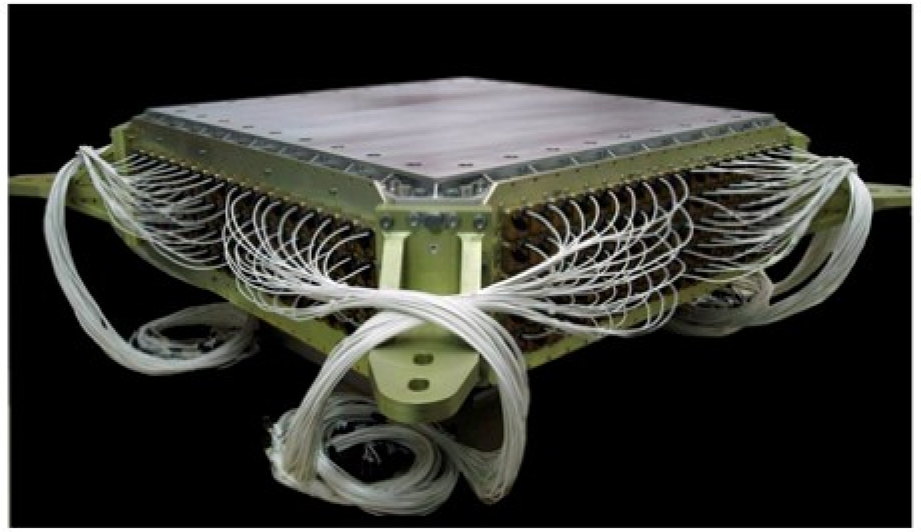
provides a precision, 17 X_0, TeV, 3-dimensional measurement of the directions and energies of electrons







50 000 fibers, $\phi = 1$ mm distributed uniformly inside 600 Kg of lead



3D imaging capability

multilayer sandwich of lead foils and (50,000) scintillating fibres, read out by 324 PMTs

depth ~17 X_0

9 alternate superlayers with fibers parallel to x and y axes

Key detector for measurements of electrons and positrons

Lecture recap

Lessons from past:

a) Importance of all boundary/environmental conditions

→ calorimeters are complex systems
→ calorimetric measurements depend on full “picture”
→ can NOT optimise all parameters at same time

Search compromises driven by physics goals
(unknown → actual choice may be wrong)

b) Game changer: from integral (global) to differential (local) measurements

→ high granularity, high timing precision keywords for future detectors backup

ECAL examples (from Eva's slides)

Homogeneous calorimeters:

Experiment	Material	Energy resolution (E in GeV)
NA48	Liquid Kr	4.8%/√E ⊕ 0.22%
BELLE	CsI(Tl)	0.8%/√E ⊕ 1.3%
CMS	$PbWO_4$	2.7%/√E ⊕ 0.55%*

Sampling calorimeters:

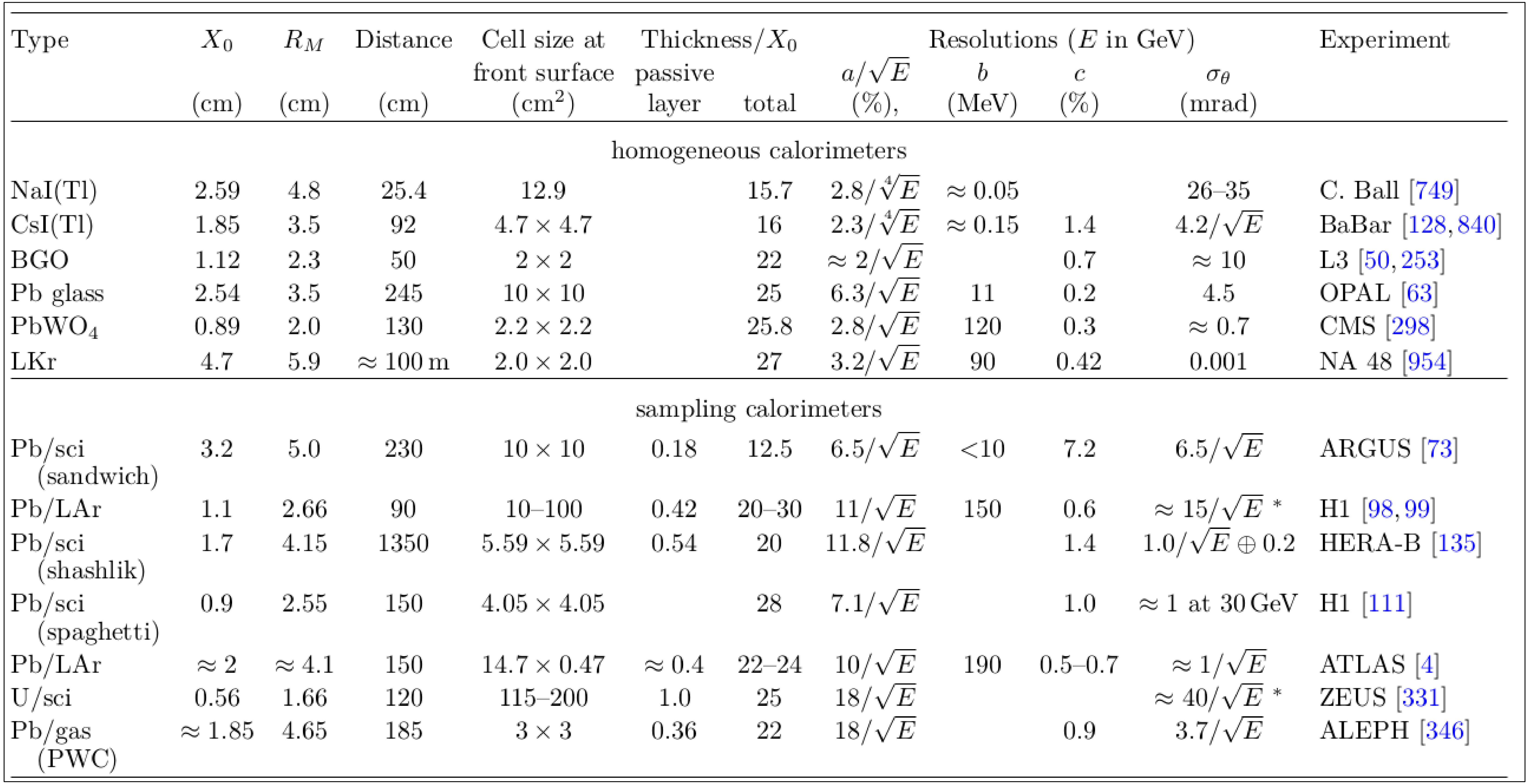
Experiment	Detector	Detector thickness [mm]	Absorber material	Absorber thickness [mm]	Energy resolution (E in GeV)
UA1	Scintillator	1.5	Pb	1.2	15%/√E
SLD	liquid Ar	2.75	Pb	2.0	8%/√E
DELPHI	Ar + 20% CH_4	8	Pb	3.2	16%/√E
ALEPH	Si	0.2	W	7.0	25%/√E
ATLAS	liquid Ar		Pb		10%/√E ⊕ 0.7%*
LHCb	Scintillator		Fe		10%/√E ⊕ 1.5%*

* Design values

with some more details (from Eva's slides)

Homogeneous

Sampling



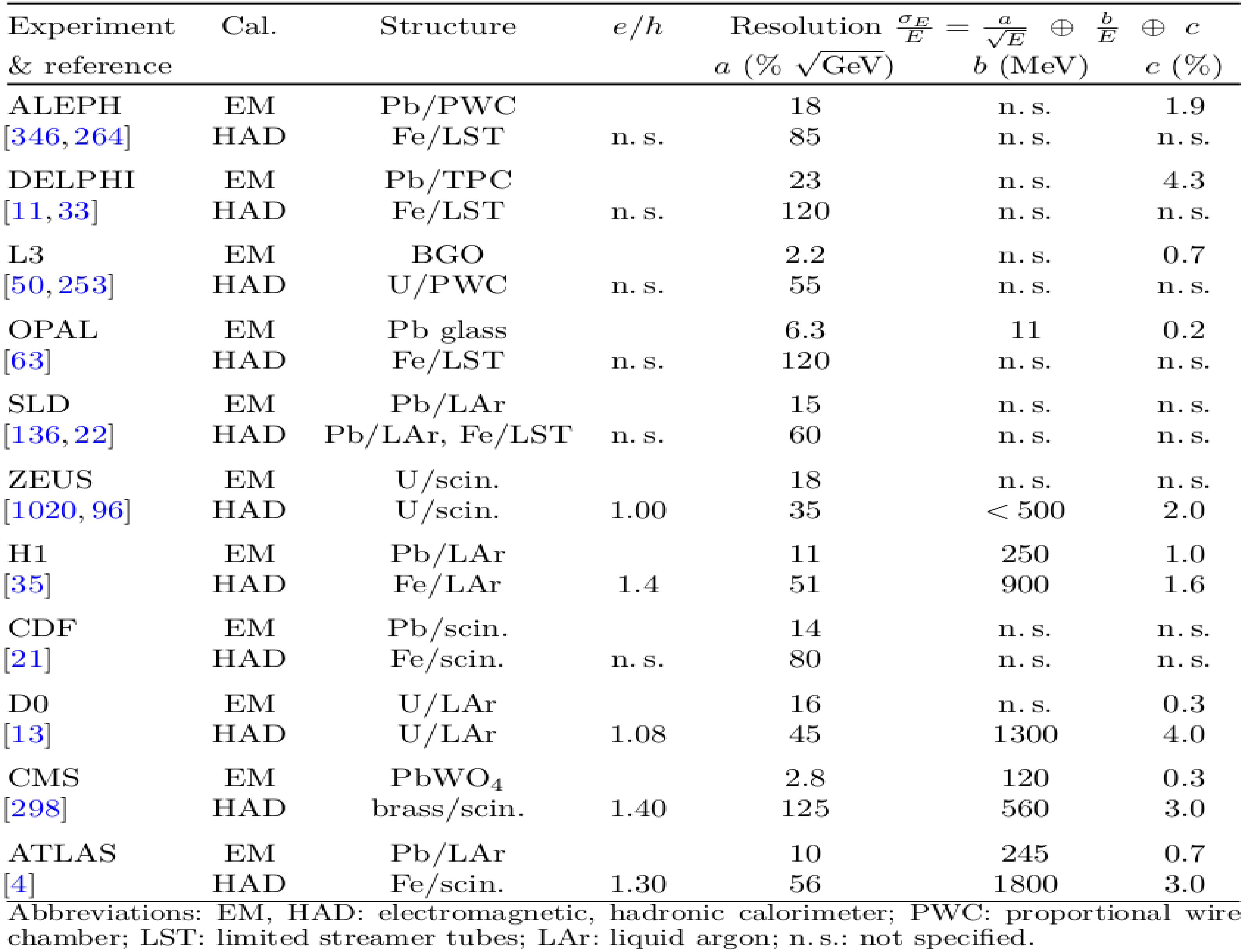
Type	X_0 (cm)	R_M (cm)	Distance (cm)	Cell size at front surface (cm^2)	Thickness/X_0 passive layer	Thickness/X_0 total	Resolutions (E in GeV) $a/\sqrt{E}$ (%),	b (MeV)	c (%)	σ_θ (mrad)	Experiment
					homogeneous calorimeters						
NaI(Tl)	2.59	4.8	25.4	12.9		15.7	$2.8/\sqrt[4]{E}$	≈ 0.05		26–35	C. Ball [749]
CsI(Tl)	1.85	3.5	92	4.7×4.7		16	$2.3/\sqrt[4]{E}$	≈ 0.15	1.4	$4.2/\sqrt{E}$	BaBar [128, 840]
BGO	1.12	2.3	50	2×2		22	$\approx 2/\sqrt{E}$		0.7	≈ 10	L3 [50, 253]
Pb glass	2.54	3.5	245	10×10		25	$6.3/\sqrt{E}$	11	0.2	4.5	OPAL [63]
$PbWO_4$	0.89	2.0	130	2.2×2.2		25.8	$2.8/\sqrt{E}$	120	0.3	≈ 0.7	CMS [298]
LKr	4.7	5.9	≈ 100 m	2.0×2.0		27	$3.2/\sqrt{E}$	90	0.42	0.001	NA 48 [954]
					sampling calorimeters						
Pb/sci (sandwich)	3.2	5.0	230	10×10	0.18	12.5	$6.5/\sqrt{E}$	<10	7.2	$6.5/\sqrt{E}$	ARGUS [73]
Pb/LAr	1.1	2.66	90	10–100	0.42	20–30	$11/\sqrt{E}$	150	0.6	$\approx 15/\sqrt{E}$ *	H1 [98, 99]
Pb/sci (shashlik)	1.7	4.15	1350	5.59×5.59	0.54	20	$11.8/\sqrt{E}$		1.4	$1.0/\sqrt{E} \oplus 0.2$	HERA-B [135]
Pb/sci (spaghetti)	0.9	2.55	150	4.05×4.05		28	$7.1/\sqrt{E}$		1.0	≈ 1 at 30 GeV	H1 [111]
Pb/LAr	≈ 2	≈ 4.1	150	14.7×0.47	≈ 0.4	22–24	$10/\sqrt{E}$	190	0.5–0.7	$\approx 1/\sqrt{E}$	ATLAS [4]
U/sci	0.56	1.66	120	115–200	1.0	25	$18/\sqrt{E}$			$\approx 40/\sqrt{E}$ *	ZEUS [331]
Pb/gas (PWC)	≈ 1.85	4.65	185	3×3	0.36	22	$18/\sqrt{E}$		0.9	$3.7/\sqrt{E}$	ALEPH [346]

HCAL examples (from Eva’s slides)

Experiment	Detectors	Absorber material	e/h	Energie resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	$80\%/\sqrt{E}$
ZEUS	Scintillator	Pb	≈ 1.0	$34\%/\sqrt{E}$
WA78	Scintillator	U	0.8	$52\%/\sqrt{E} \oplus 2.6\%$*
D0	liquid Ar	U	1.11	$48\%/\sqrt{E} \oplus 5\%$*
H1	liquid Ar	Pb/Cu	≤ 1.025*	$45\%/\sqrt{E} \oplus 1.6\%$
CMS	Scintillator	Brass (70% Cu / 30% Zn)	$\neq 1$	$100\%/\sqrt{E} \oplus 5\%$
ATLAS (Barrel)	Scintillator	Fe	$\neq 1$	$50\%/\sqrt{E} \oplus 3\%$**
ATLAS (Endcap)	liquid Ar	Brass	$\neq 1$	$60\%/\sqrt{E} \oplus 3\%$**

* After software compensation
** Design values

ECAL+HCAL systems (from Eva’s slides)



Experiment & reference	Cal.	Structure	e/h	Resolution $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$		
				a (% $\sqrt{\text{GeV}}$)	b (MeV)	c (%)
ALEPH	EM	Pb/PWC		18	n. s.	1.9
[346, 264]	HAD	Fe/LST	n. s.	85	n. s.	n. s.
DELPHI	EM	Pb/TPC		23	n. s.	4.3
[11, 33]	HAD	Fe/LST	n. s.	120	n. s.	n. s.
L3	EM	BGO		2.2	n. s.	0.7
[50, 253]	HAD	U/PWC	n. s.	55	n. s.	n. s.
OPAL	EM	Pb glass		6.3	11	0.2
[63]	HAD	Fe/LST	n. s.	120	n. s.	n. s.
SLD	EM	Pb/LAr		15	n. s.	n. s.
[136, 22]	HAD	Pb/LAr, Fe/LST	n. s.	60	n. s.	n. s.
ZEUS	EM	U/scin.		18	n. s.	n. s.
[1020, 96]	HAD	U/scin.	1.00	35	< 500	2.0
H1	EM	Pb/LAr		11	250	1.0
[35]	HAD	Fe/LAr	1.4	51	900	1.6
CDF	EM	Pb/scin.		14	n. s.	n. s.
[21]	HAD	Fe/scin.	n. s.	80	n. s.	n. s.
D0	EM	U/LAr		16	n. s.	0.3
[13]	HAD	U/LAr	1.08	45	1300	4.0
CMS	EM	$PbWO_4$		2.8	120	0.3
[298]	HAD	brass/scin.	1.40	125	560	3.0
ATLAS	EM	Pb/LAr		10	245	0.7
[4]	HAD	Fe/scin.	1.30	56	1800	3.0

Abbreviations: EM, HAD: electromagnetic, hadronic calorimeter; PWC: proportional wire chamber; LST: limited streamer tubes; LAr: liquid argon; n. s.: not specified.