Queen Mary University of London

Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 18

Peter Hobson

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What is this lecture about?

- Calorimeters
  - Basic principles (quick reminder, see Lecture 16)
  - Homogeneous vs Sampling
  - Energy resolution
  - Generation of signal
  - Examples

Key points from previous lecture

- Time-of-flight (TOF) systems can be used to determine particle mass if momentum is known.
- Only useful for $\beta\gamma < \sim 4$
- Measuring time of flight requires very fast scintillators and photodetectors.
- TOF also useful for ensuring particles associated with the correct interaction and for cosmic ray muon rejection in ATLAS, CMS for e.g.

EM Calorimeter Energy Resolution

- For EM calorimeters we can parameterise the energy resolution as

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{a_0}{E}\right)^2 + \left(\frac{a_1}{\sqrt{E}}\right)^2 + b^2$$

Systematic (or "constant") term

Electronic noise summed over a few channels (3x3 or 5x5 typically)

Photoelectron statistics (Poisson)

Systematic effects

- The systematic term has a number of distinct contributions:
  - Shower leakage, usually not less than about 0.3%
  - Interchannel calibration, again of order 0.3%
  - Channel non-uniformity
    - E.g. Optical attenuation length (intrinsic and known)
    - E.g. Radiation-induced optical attenuation (induced and changing)
  - Pile-up due to extremely high luminosity, a major effect at hadron colliders such as the LHC.
  - Fluctuations in the EM component in hadronic showers.

An example of contributions to resolution

Table shows simulation results on contributions to energy resolution in % for the BaF_2 ECAL of the proposed GEM detector for the Superconducting Super Collider (USA)

E(GeV)	*5*	*10*	*20*	*50*	*100*	*200*	*500*
Electronic noise	0.4	0.2	0.1	0.04	0.02	0.01	0.004
Photoelectron	0.2	0.14	0.1	0.063	0.045	0.03	0.02
Leakage	0.6	0.43	0.32	0.3	0.3	0.3	0.36
Intercalibration	0.4	0.4	0.4	0.4	0.4	0.4	0.4
TOTAL	0.85	0.63	0.53	0.51	0.50	0.50	0.54

Homogeneous calorimeters

- Based on dense materials that are also active in generating the signal
- Archetype is the crystal calorimeter of L3 at LEP
  - Scintillating crystals (or glasses) such as BaF_2, $PbWO_4$, CsI
  - Cherenkov radiators such as Pb-glass (e.g. OPAL ECAL)
- Almost without exception used for EM calorimetry due to cost and technical difficulty of growing 9λ (number of hadronic interaction lengths needed for LHC experiments) long crystals

Dense and high Z scintillators

Bismuth germanate ($Bi_4Ge_3O_{12}$)

	NaI(Tl)	*CsI(Tl)*	*CsI*	*BaF_2*	*BGO*	*$PbWO_4$*
Density ($g.cm^{-3}$)	3.67	4.51	4.51	4.89	7.13	8.3
X_0 (cm)	2.6	1.9	1.9	2.1	1.1	0.9
R_M (cm)	4.8	3.5	3.5	3.4	2.3	2.2
Decay (ns)	230	1000	35	600/1	300	10
Light	100%	45%	5%	20/4%	13%	1%

BaBar (SLD)

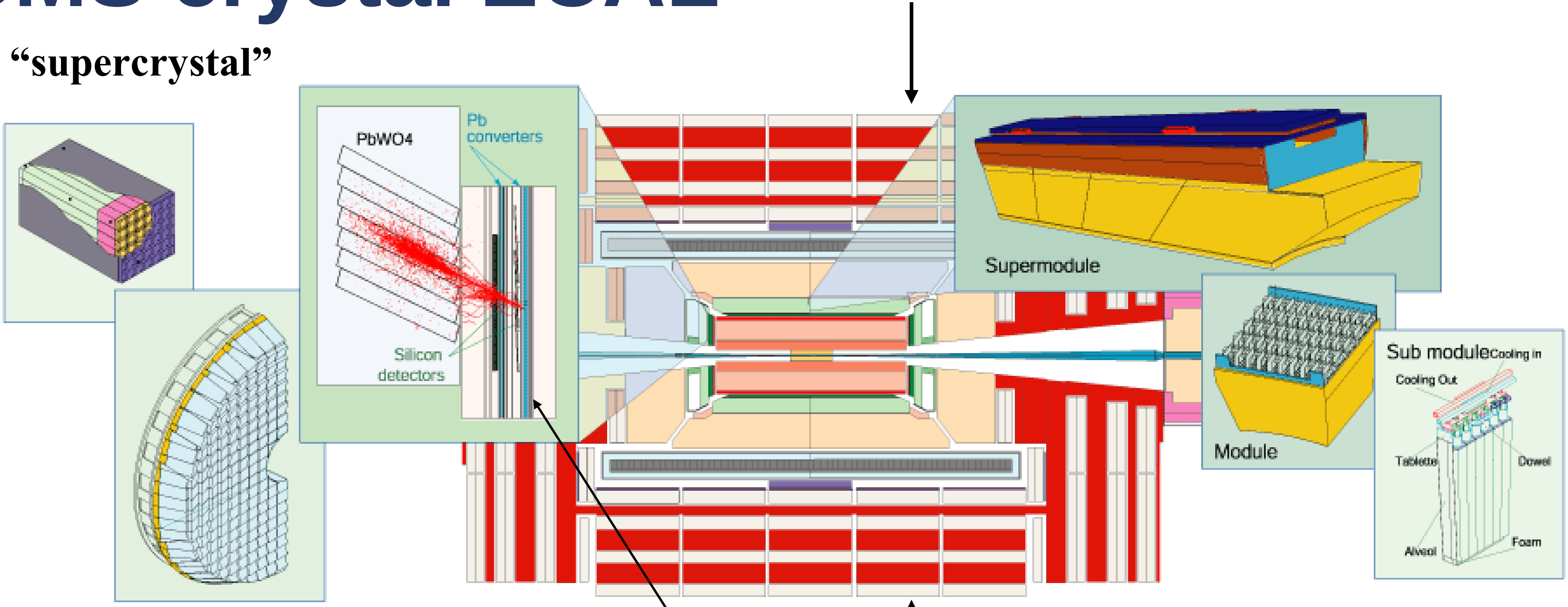
GEM (SSC)

L3 (LEP)

CMS (LHC)

CMS crystal ECAL

5x5 "supercrystal"



Endcap, readout with VPT

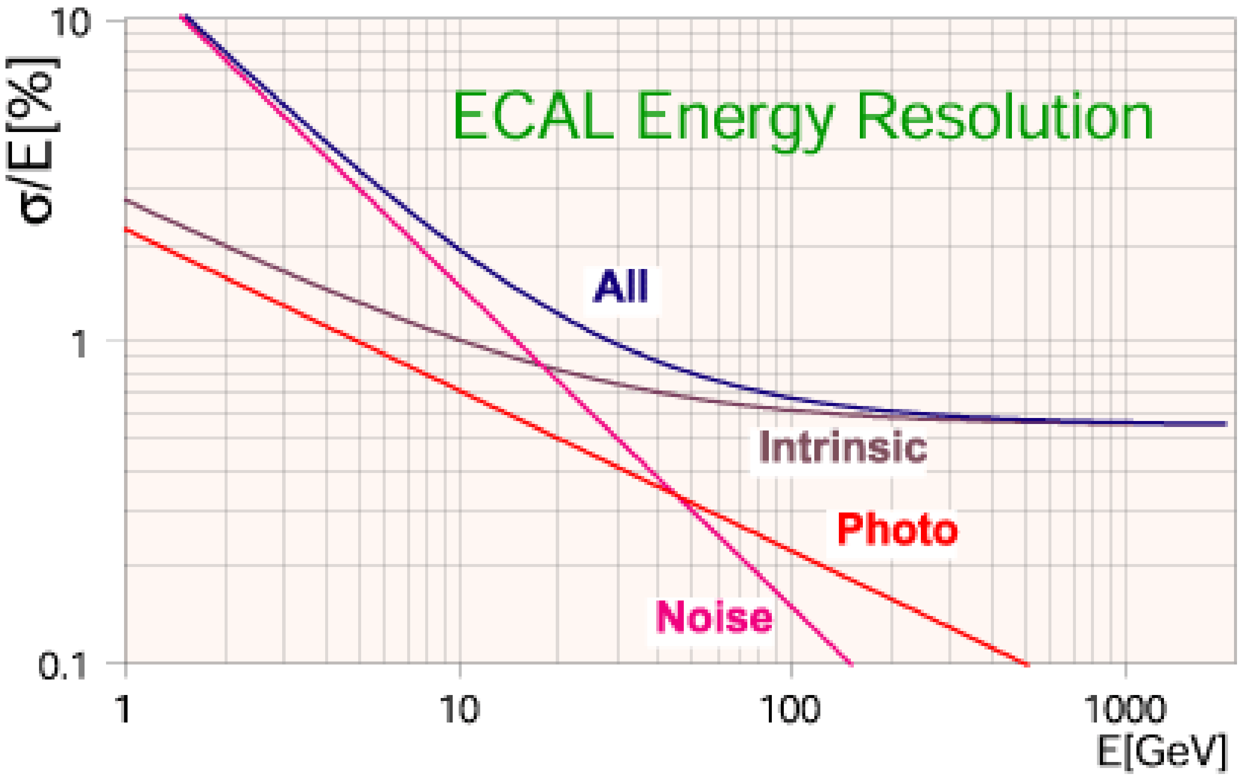
Preshower

15 m diameter

Barrel, readout with APD

Parameterised energy resolution (CMS)

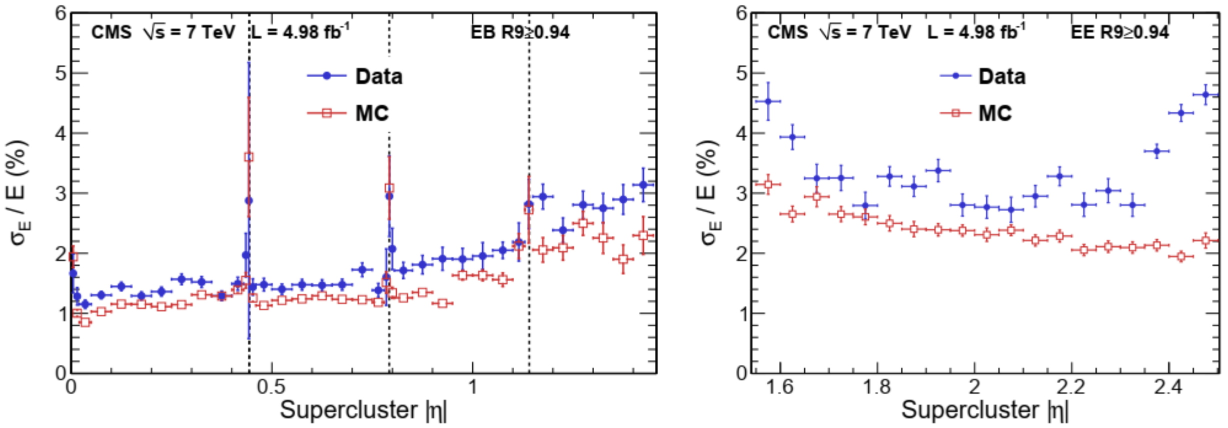
Critical Higgs discovery region



Barrel calorimeter, parameterisation from experimental data.

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{12\%}{E(\text{GeV})} \oplus 0.3\%,$$

Measured from test beam



Barrel (EB) and endcap (EB) calorimeter. Measured resolution from Z decaying to e^+e^-

Sampling calorimeters

- Layers of inactive, dense material (e.g. Cu, Fe, Pb, W, U) mixed with active layers
- Active layers can be
  - Scintillators (plates or fibres) or Cherenkov in SiO_2 fibres
  - Silicon strips
  - Cryogenic noble liquids (Ar, Kr)
  - Gaseous detectors (e.g. “Iarocci” tubes in OPAL HCAL)
- The technology for HCAL, but also used in ECAL (e.g. the ATLAS ECAL)

HCAL energy resolution

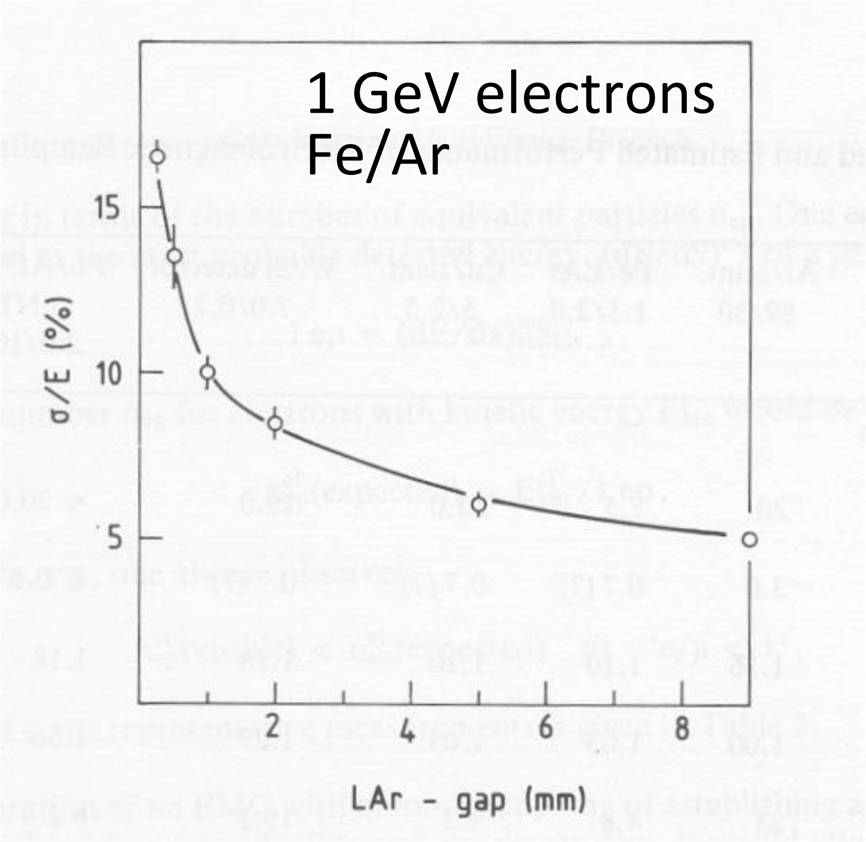
- Only a fraction of the deposited energy is sampled.
- Intrinsic sampling fluctuations reflect fluctuations in the number of electron/positron pairs traversing the active planes. A *lower bound* is given by

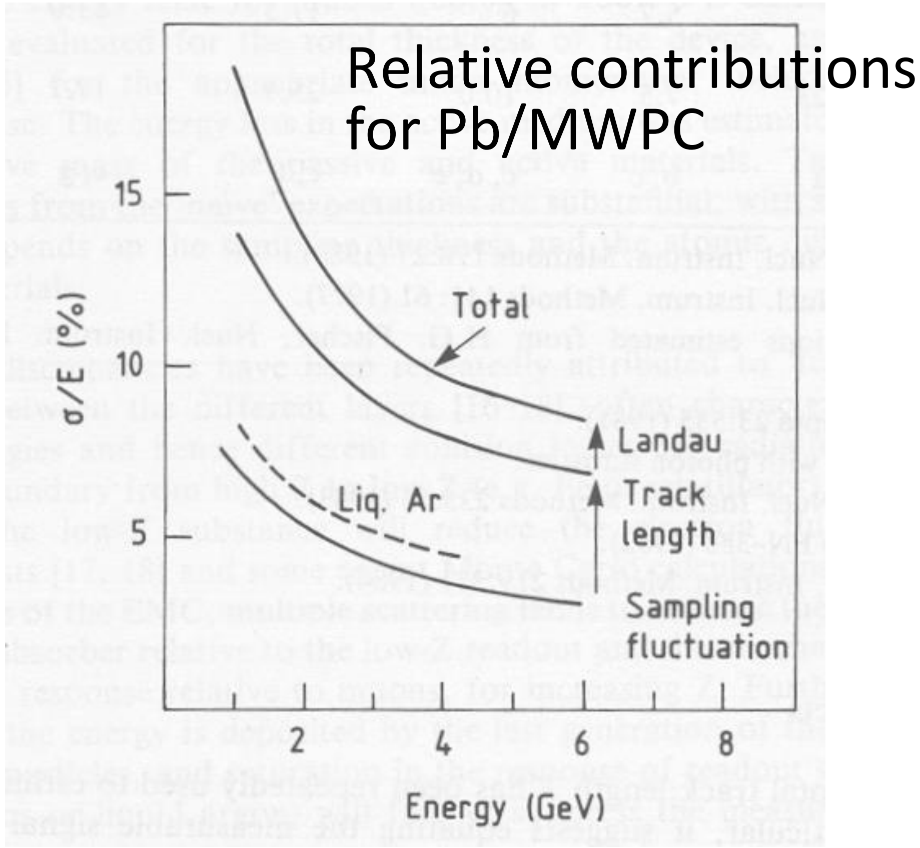
$$\sigma(E)/E = \sigma(N_x)/N_x = 3.2\% \left[\Delta E(\text{MeV})/E(\text{GeV})\right]^{1/2}$$

where N_x is the number of pairs crossing the active plates and ΔE is the energy loss per unit cell.

This expression ignores "Landau" losses in the active planes which may be significant in thin detectors (e.g. silicon or gaseous detectors). It also ignores the effects of multiple scattering.

Effects of sampling



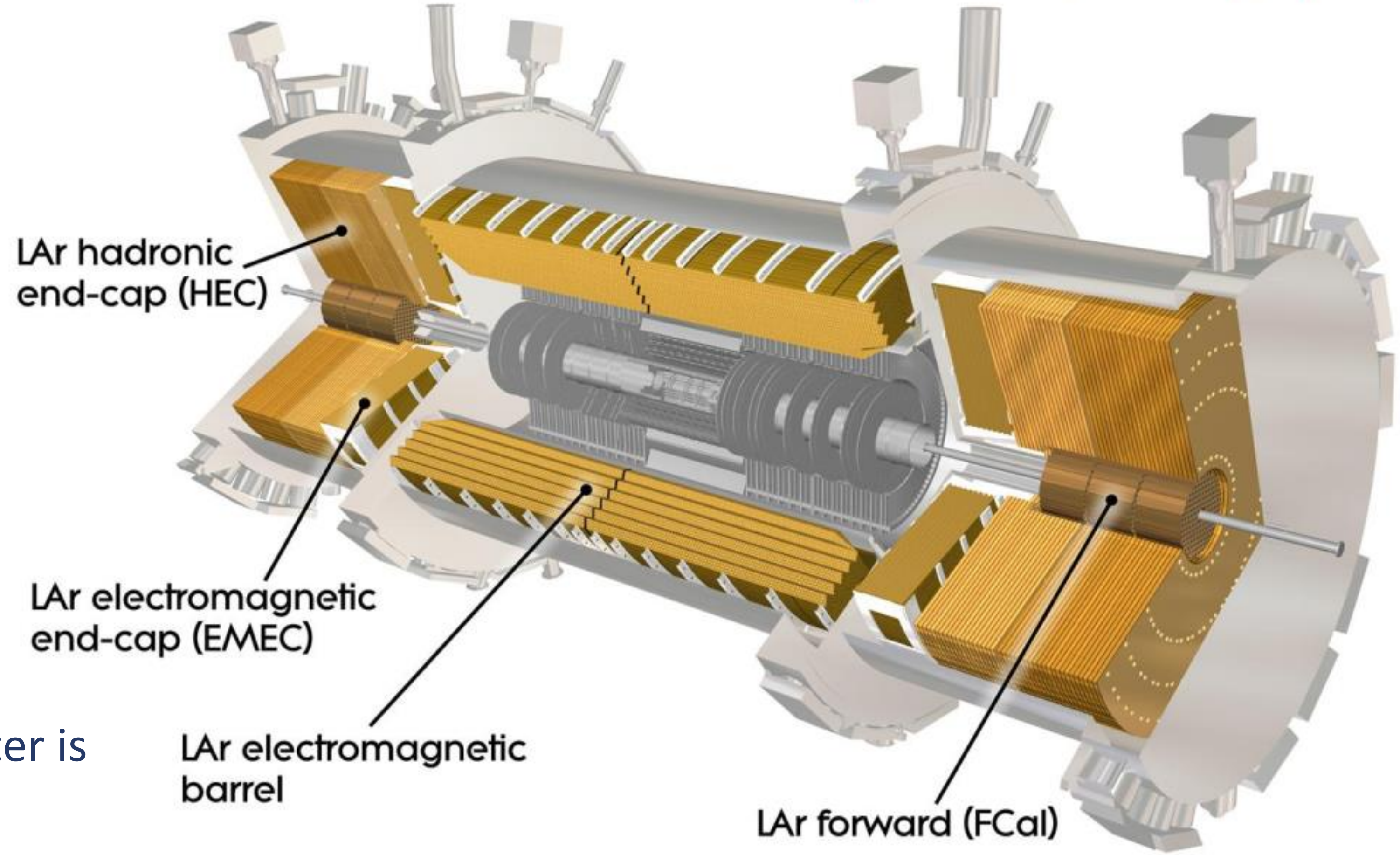


Figures 7a and 7b from Fabjan C in Ferbel 1987

ATLAS calorimeters (Liquid Argon)

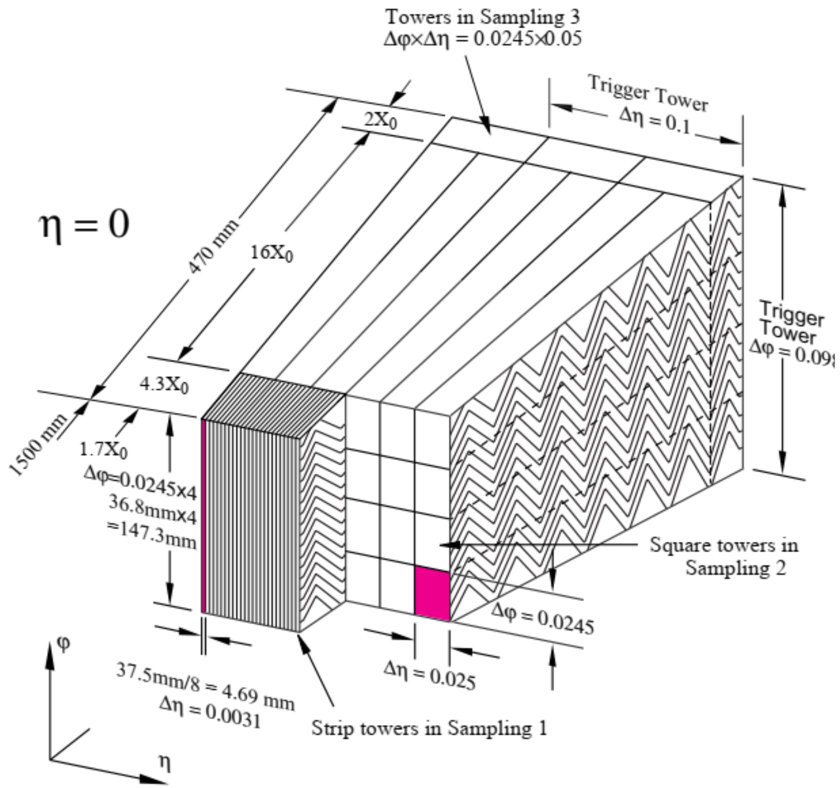
Active material: Liquid Argon
Absorber: Pb (EMB)

To keep argon in liquid phase the detector is kept at 88K by three big cryostats

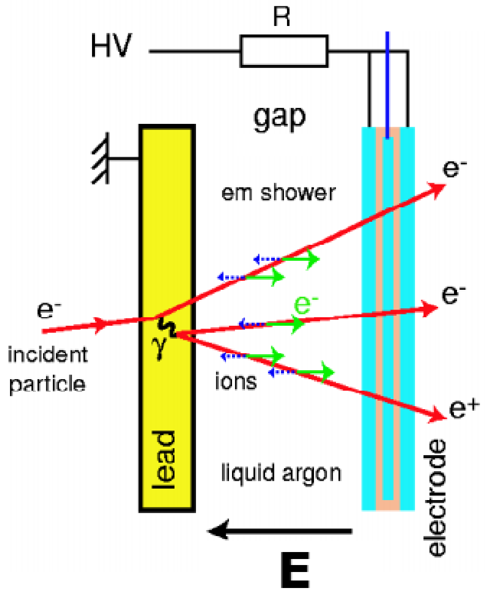


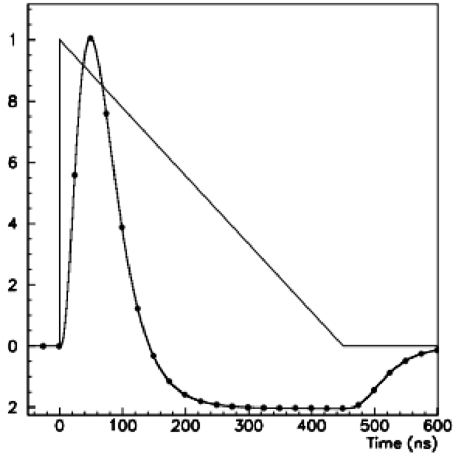
Barrel calorimeter is 6.4 m long

ATLAS EM calorimeter (Liquid Argon)

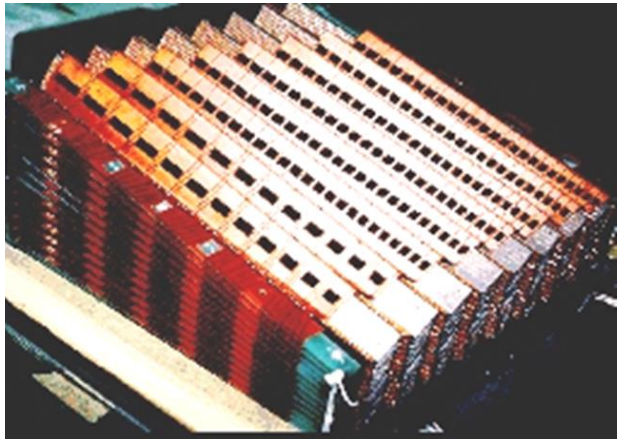


$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$$





Signal before/after shaping. Dots every 25 ns indicate bunch crossing interval at LHC.

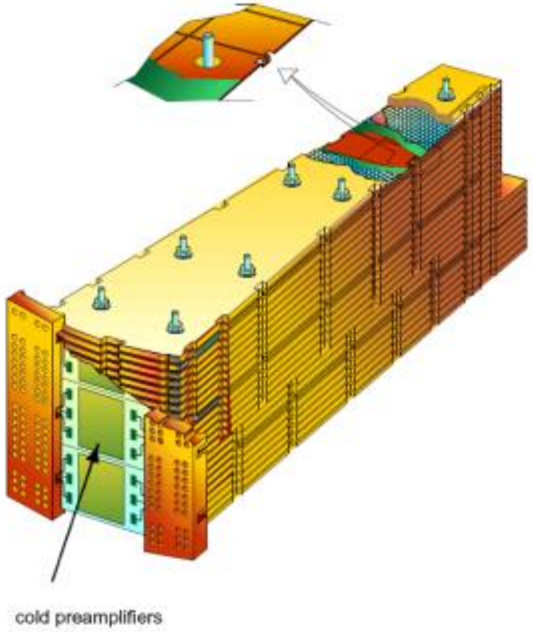


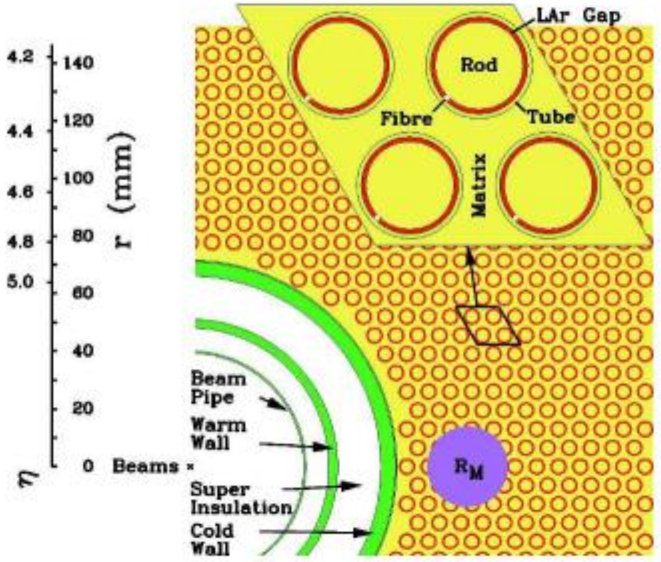
EM calorimeter (and part of hadron calorimeter). Lead with liquid argon as the active medium.

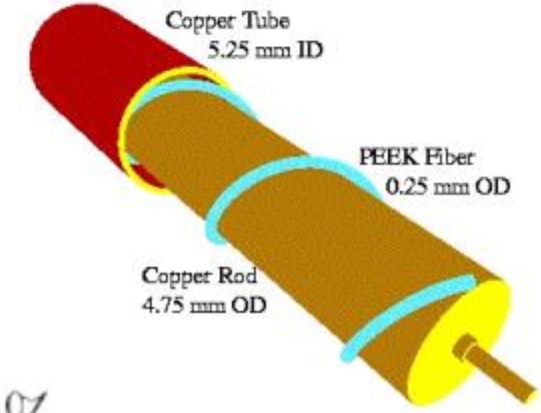
Technical Design Report: CERN/LHCC 96-41 (1996)

ATLAS hadron calorimeters (Liquid Argon)

Same principle as the Pb/Lar calorimeter but different materials (copper)







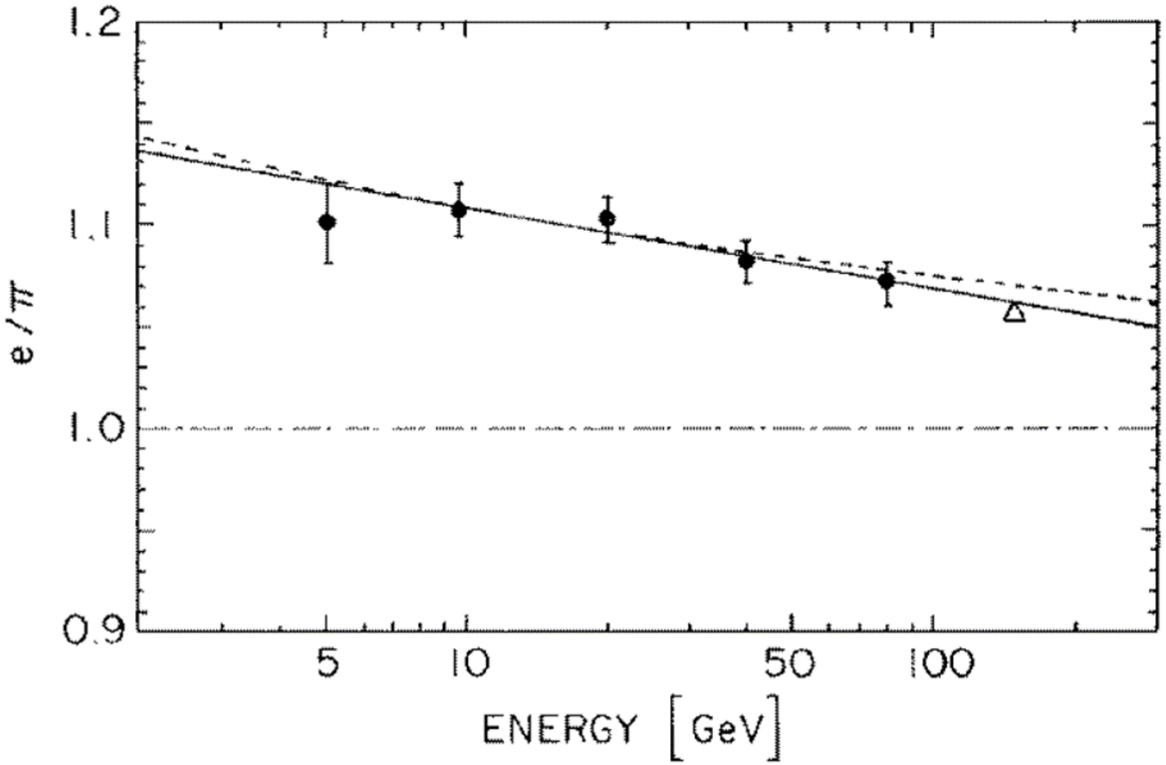
HEC $$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$$

FCAL $$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%$$

Compensation (hadron calorimeters)

- Hadronic showers have an EM component F_0 determined essentially by the *first* interaction.
- Roughly 1/3 of the mesons provide the neutral EM component, f_0
- Thus at generation 1) we have $F_0 = f_0$
- At generation 2) we have $F_0 = f_0 + f_0(1-f_0)$ etc.
- This leads to F_0 tending to one for very high energies. The response of most HCAL to electrons is different to hadrons; the ratio of these responses, known as e/h is critical to achieve compensation.

e/π ratio



Lead/scintillating-fibre calorimeter

Table 11. Energy deposition in 5 GeV proton showers neglecting the π^0 component.

Absorber	U	Pb	Fe
Ionization (fraction due to spallation protons) (%)	38 (0.70)	43 (0.72)	57 (0.74)
Excitation γ(%)	2	3	3
Neutrons $<$ 20 MeV(%)	15	15	8
Invisible energy, i.e. binding energy and target recoil (%)	45	42	32

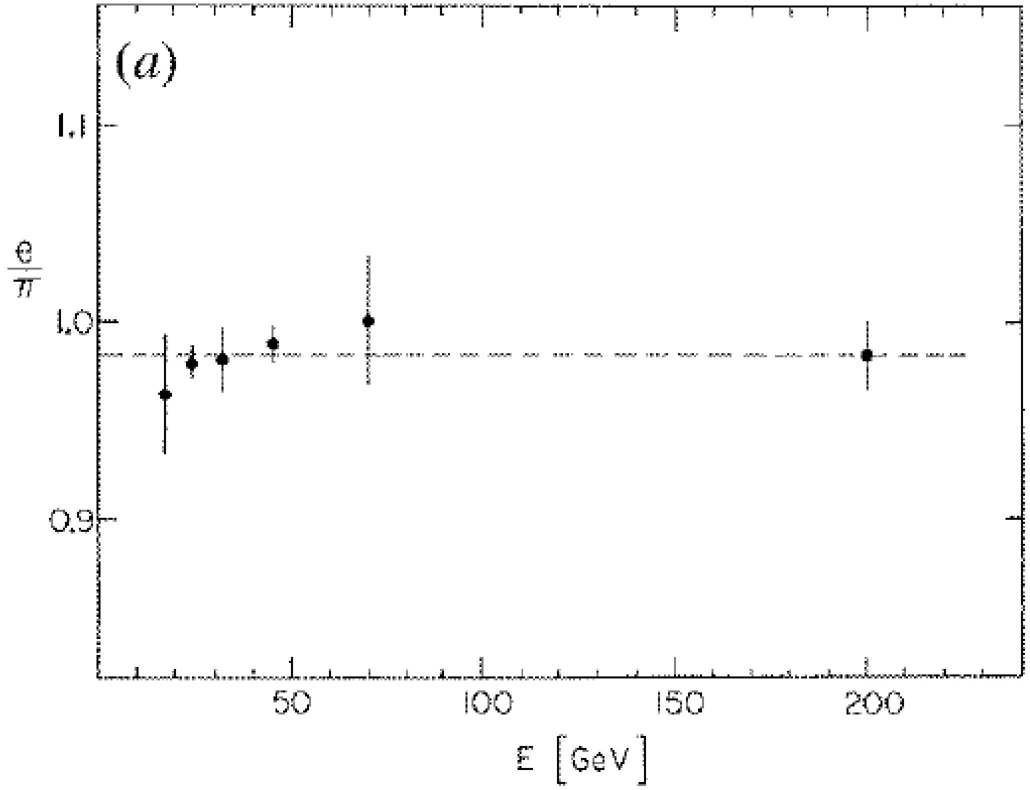
Compensation

- If e/h is not close to 1.0 then
  - Non-Gaussian response to mono-energetic hadrons
  - e/h ratio changes with energy
  - Additional component that degrades energy resolution
  - σ/E does **not** improve as $1/\sqrt{E}$
- Solution, compensate by
  - Boosting the non-EM response using Uranium
  - Suppressing the EM response
  - Boosting the response to low energy neutrons (increase hydrogen, e.g. plastic scintillator as active medium)
- Warning! Good EM energy response is *not* compatible with compensation.

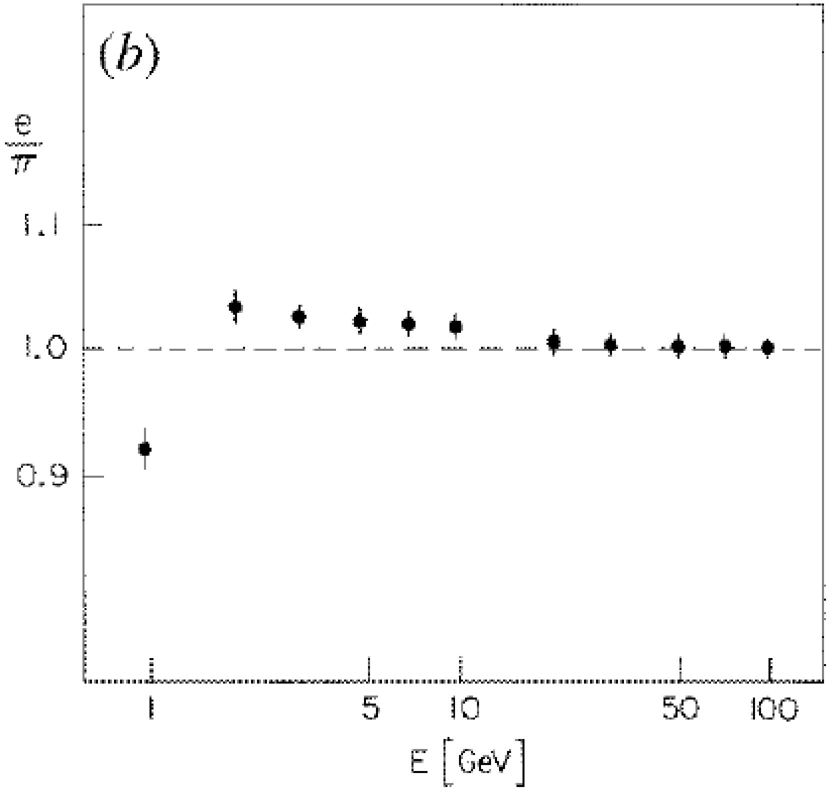
Example, ZEUS at DESY

- U/scintillator or Pb/scintillator?
- If U, then 1:1 absorber/scintillator ratio is compensating, if Pb then a 4:1 ratio is required
- The *intrinsic* fluctuations in a Pb sampling calorimeter are smaller than those for a U calorimeter
  - Pb: 13% vs U: 20% for hadrons
  - Pb: 0.3% vs U: 2.2% for EM
- However the much poorer sampling ratio for Pb resulted in the choice of Uranium.

Two uranium-based calorimeters (historic)



NA34 (HELIOS) at CERN



ZEUS at DESY

More information

Claude Leroy and Pier-Giorgio Rancoita

Physics of cascading shower generation and propagation in matter: principles of high-energy, ultrahigh-energy and compensating calorimetry

Rep. Prog. Phys. **63** (2000) 505–606