Calorimeters in HEP, I

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Aims

- To give a broad appreciation of the physical processes in calorimetry.
- To discuss the energy and position resolution of calorimeters in fundamental terms.
- To describe a variety of techniques for constructing practical calorimeters.
- To examine a few real calorimeter systems.

Information sources

Six good sources of information on ECAL and HCAL (there are many others)

1. T Ferbel "Experimental techniques in high-energy nuclear and particle physics" Addison-Wesley, 1987
2. T Ferbel ed. "Techniques and Concepts of High Energy Physics X" NATO Science Series Vol 534, 1988
3. G Gratta, H Newman, RH Zhu, *Ann.Rev.Nucl.Part.Sci.* **14** (1994) 453-500
4. R Wigmans "Calorimetry: Energy Measurement in Particle Physics", Clarendon Press, 2000
5. ATLAS, CMS, BaBar, LHCb, D0 etc. TDR reports (various dates)
6. F Sefkow et al, "Experimental Tests of Particle Flow Calorimetry" arXiv:1507.05893v2 [physics.ins-det] 17 Sep 2015

Why calorimeters

- Calorimeter
  - A device to measure *Energy*
- Current and future collider based experiments are based on an “onion” like arrangement of tracking (mass-less) and energy measuring (massive) detector systems.
  - Momenta of charged particles are determined by hits in silicon (or gaseous) detectors in a high magnetic field region.
  - Particle energies are measured by calorimeters (they also measure position)
  - Muons and neutrinos penetrate through with minimal interaction.

Calorimetry

- Neutral and charged particles when incident on a block of material deposit energy through creation and absorption processes.
- The deposited energy can be determined in a variety of ways:
  - ionisation, scintillation, Cerenkov light, bolometry
- The dense medium may be active or passive
  - Homogeneous calorimeters, e.g. CsI(Tl), BGO, Pb-glass, PWO, Xe(liq) etc,
  - Sampling calorimeters, e.g. Pb-scintillator or Pb-Ar(liq) etc.

Why are calorimeters important?

- Energies of neutral and charged particles
- Relative energy resolution *improves* with energy as

$$\sigma / E \propto 1/\sqrt{n} \propto 1/\sqrt{E}$$

Where *n* is the number of secondary cascade particles and is proportional to the incident energy *E*

Contrast this with the *decreasing* momentum resolution from tracking systems with *increasing* particle momentum.

Features

- Longitudinal depth to contain the cascades increases logarithmically with energy.
- Jet energies can be measured.
- Missing transverse energy, E_T, can be measured (if hermetic coverage). This can be a signature of neutrinos or other weakly interacting particles.
- Longitudinal and lateral development of electromagnetic cascades is different for electrons, photons, hadrons and muons.
- Calorimeters are intrinsically fast.
- If the calorimeter has good lateral and longitudinal segmentation then efficient triggering on e/γ, jets and missing E_T is possible.

Electromagnetic cascade

- A high energy electron or photon incident on a thick absorber produces a cascade of secondary electrons and photons via bremsstrahlung and pair production.
- As the depth increases the number of secondary particles increases, but their mean energy decreases.
- When the energies fall below the *critical energy* ε the multiplication process ceases and energy is now dissipated via the processes of ionisation and excitation.

Simple model

- ε is defined as the energy when the ionisation loss and radiation are equal. It can be calculated approximately as 560/*Z* (in MeV)
- Radiation length, X_0, is the distance in which, on average, an electron loses 1-1/*e* of its energy. It is also the length in which a photon has a pair conversion probability of 7/9. X_0 can be approximated as 180*A*/*Z*^{2} g.cm^2.
- Define two scaled variables

$$\boxed{t = \frac{x}{X_0} \quad y = \frac{E}{\varepsilon}}$$

Taking 1 X_0 as the generation length then the particle energy *e(t)* and the number of particles *n(t)* are given by

$$\boxed{e(t) = \frac{E}{2^t} \quad n(t) = 2^t}$$

At shower maximum

$$\boxed{n(t_{\max}) = y \quad t_{\max} = \ln y}$$

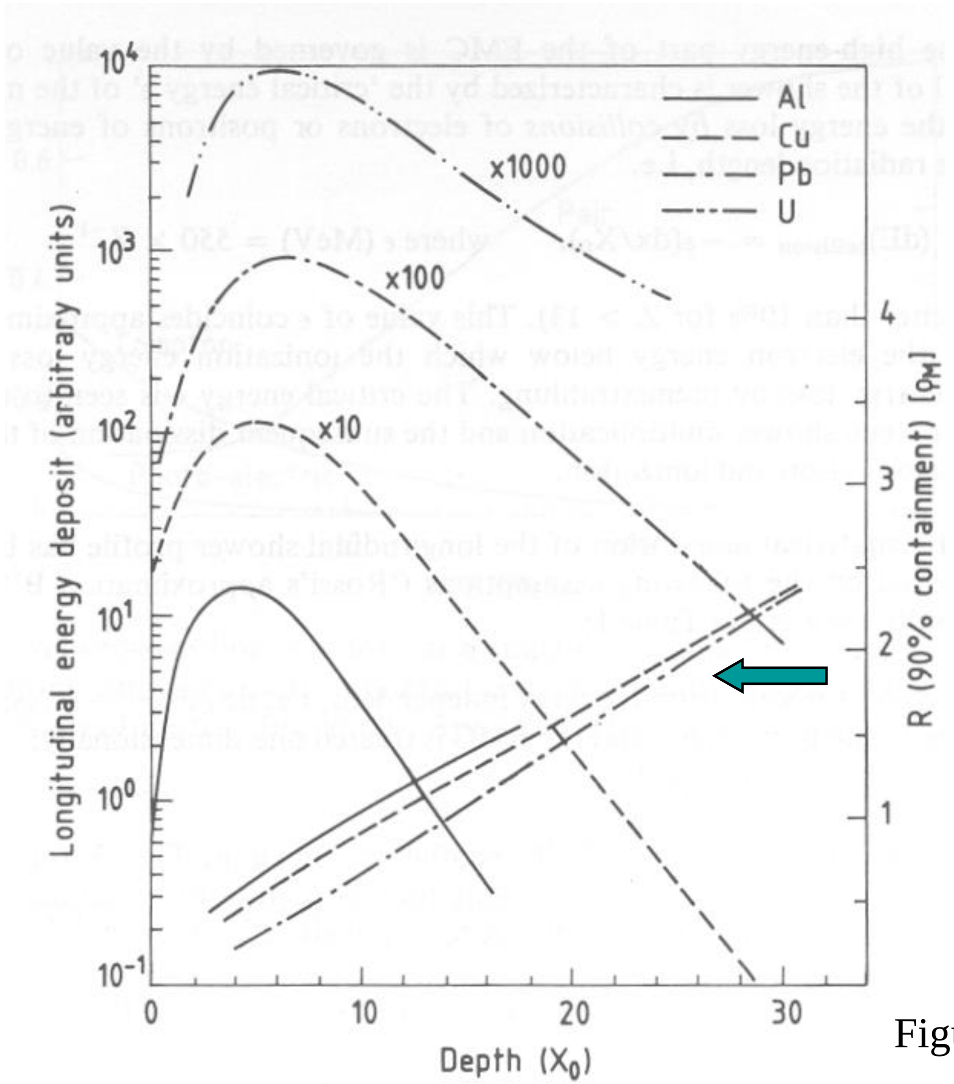
Properties of some dense elements

	Z	***Density***	$\boldsymbol{\varepsilon}$	$\boldsymbol{X_0}$	$\boldsymbol{\lambda}$
		g.cm^{-3}	MeV	cm	cm
Fe	26	7.9	24	1.76	16.8
Cu	29	9.0	20	1.43	15.1
W	74	19.3	8	0.35	9.6
Pb	82	11.4	7	0.56	17.1
U	92	19.0	6	0.32	10.5

Note:
λ is the *hadronic* interaction length

Shower containment

Longitudinal containment



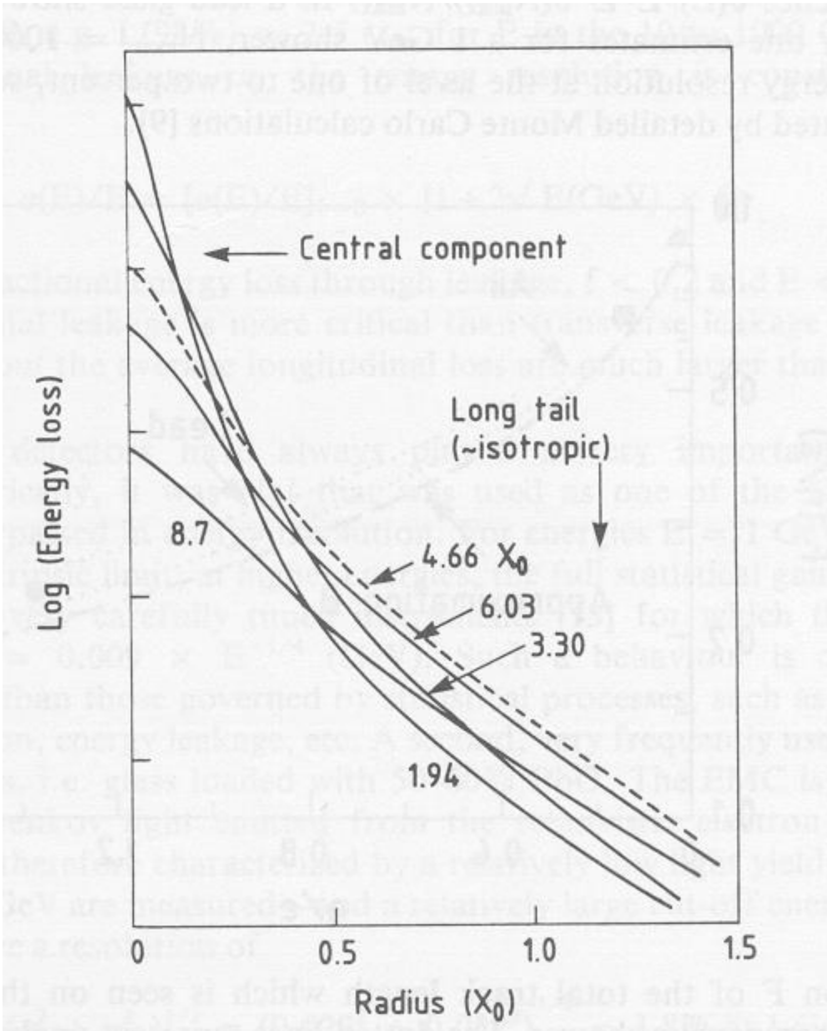
Lateral containment

Figure 3 from Fabjan C in Ferbel 1987

Lateral shower development

- As the shower develops it broadens laterally due to multiple scattering of electrons and low energy photons.
- This can be characterised by the *Moliere radius*, R_m.
- R_m is approximately $7A/Z$ g.cm^{-2}
- The shower starts (and persists) with a narrow core surrounded by a soft halo of scattering particles. An infinite cylinder of radius 1 R_m contains 90% of the shower energy.

Lateral shower development

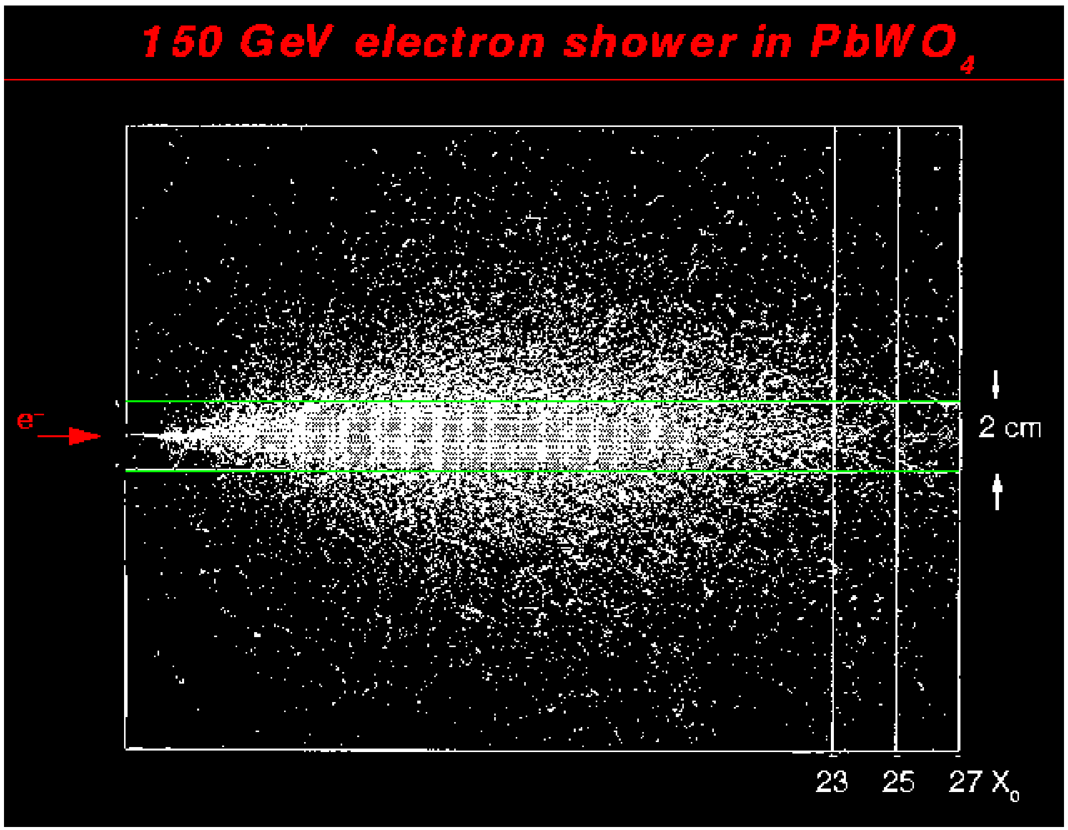


Calorimeter cells are typically one Moliere radius in size. Some lateral shower sharing between cells improves the position resolution.

Figure 4 from Fabjan C in Ferbel 1987

EM Simulation

- https://www.mppmu.mpg.de/~menke/elss/home.shtml



CMS Homogeneous ECAL. The green lines show the approximate location of a single crystal.

Hadronic calorimetry

- High energy hadrons interact with nuclei resulting in the production of secondary hadrons (pions, kaons).
- The hadronic analogue of X_0 is the interaction length λ which varies as $A^{1/3}$.
- The strong interaction results in a developing shower of particles. There are two distinct components
  - Electromagnetic arising mainly from π^0 production
  - Hadronic
- Multiplication continues until the pion production threshold is reached. The average number of secondary hadrons grows like $\ln(E)$. Their transverse momentum is fairly low (of order 300 MeV)

- Using scaled variables $\boxed{\nu = \frac{x}{\lambda} \quad E_{th} \approx 2m_\pi = 0.28\,\mathrm{GeV}}$
- The energy and number of the secondary particles can be modelled as

$$\boxed{\begin{aligned} e(\nu) &= \frac{E}{\langle n \rangle^{\nu}} \\ e(\nu_{\max}) &= E_{th} \\ n^{\nu_{\max}} &= \frac{E}{E_{th}} \Rightarrow \nu_{\max} = \frac{\ln(E/E_{th})}{\ln\langle n \rangle} \end{aligned}}$$

Note that the number of independent particles is smaller than in an EM shower by the ratio E_{th}/ε. Thus the intrinsic energy resolution will be poorer by about a factor of 6 in most materials

Shower containment

- About 9λ are required for longitudinal containment
- Lateral development
  - Secondary hadron p_T is about 300 MeV
  - This is comparable to energy lost in 1λ in most materials
  - At shower maximum (where the characteristic particle energy = 280 MeV) the radial extent will have a characteristic scale of 1 λ
  - High energy showers have a pronounced core surrounded by an exponentially decreasing halo

Nuclear Interaction Length

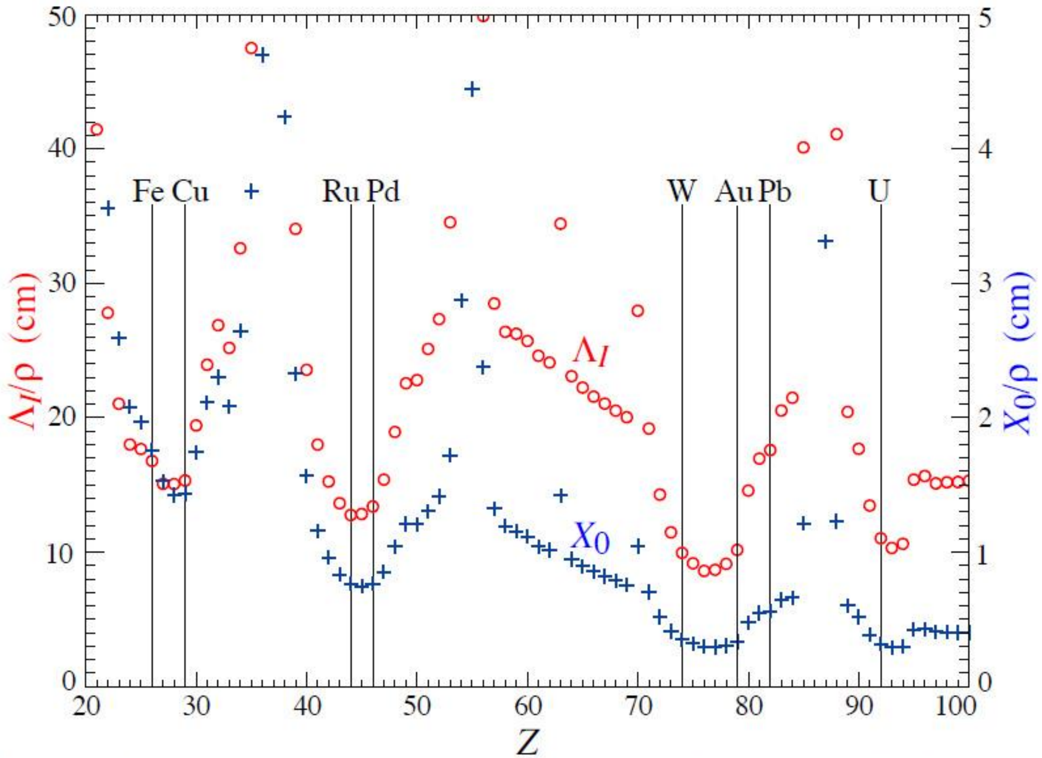
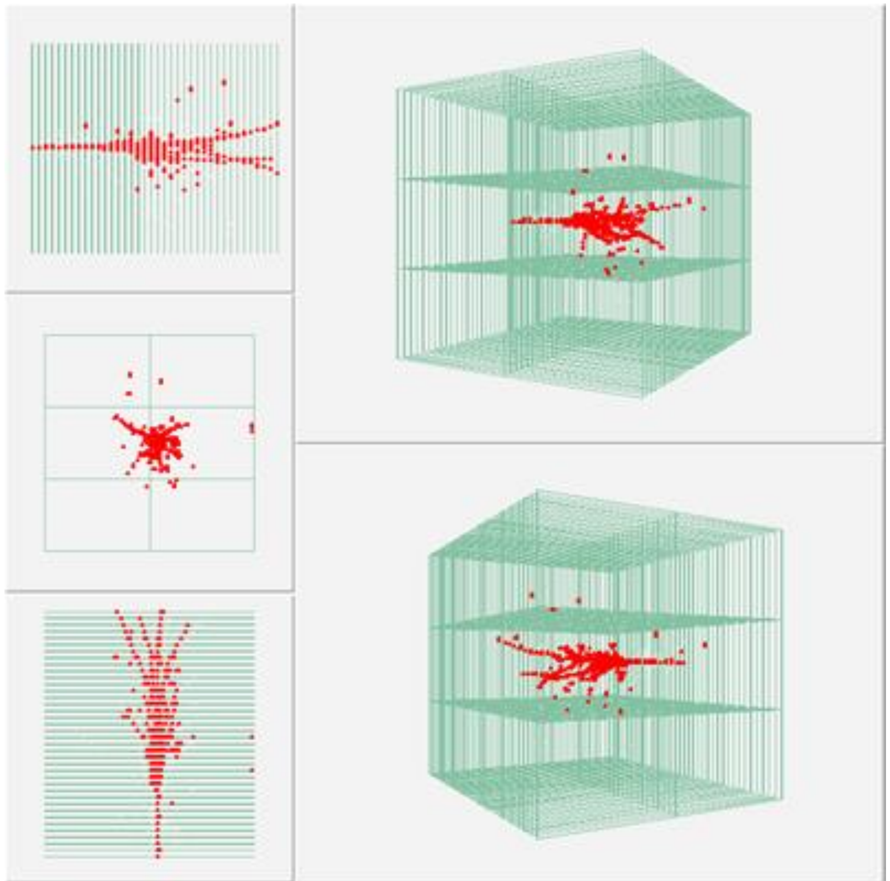


Figure 28.21: Nuclear interaction length λ_I/ρ (circles) and radiation length X_0/ρ (+'s) in cm for the chemical elements with $Z > 20$ and $\lambda_I < 50$ cm.

Hadron shower simulations



32 GeV pions in the CALICE “digital”HCAL (1 m^3, 8000 channels)

- http://www.ast.leeds.ac.uk/~fs/showerimages.html