Queen Mary University of London

Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 16

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What is this lecture about?

- Scintillators
  - Basic principles
  - Important materials in current use
  - Light detection
  - Low energy applications (gamma spectroscopy, medicine)
  - High energy applications (calorimeters, Time-of-flight)

Key points from previous lecture

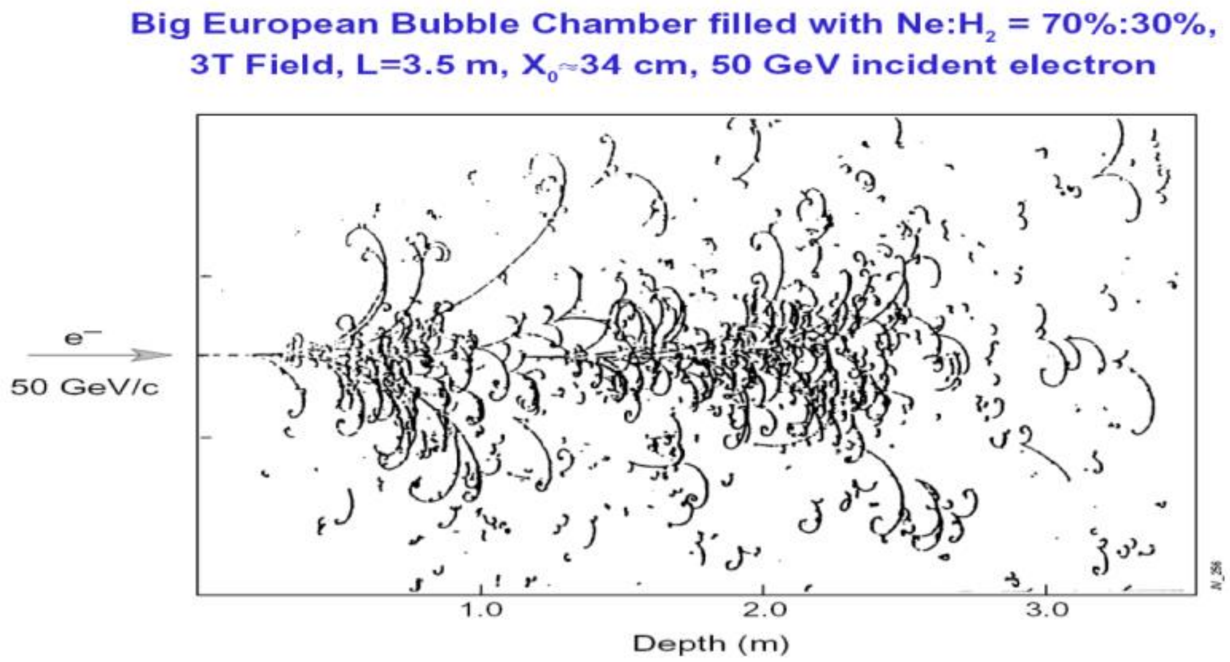
- Inorganic scintillators have non-linear responses to energy, particularly for gamma-rays below 100 keV
- The way finite size scintillators respond to even monochromatic sources can be quite complicated (Compton edge, single and double escape peaks, annihilation peak etc.)
- Most scintillators show a resolution that scales as $1/\sqrt{E}$ (Poisson statistics ultimate limit)
- Positron Emission Tomography (as an example of medical imaging using radiation sensors) has some very specific requirements on the luminosity and speed of scintillators.

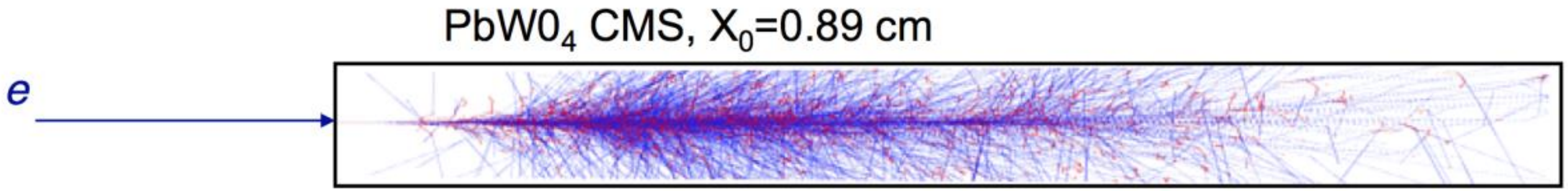
Calorimeters

A detector 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.

How do we understand these?





Calorimeters

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, Cherenkov light, bolometry
- The dense medium may be active or passive
- Homogeneous calorimeters, e.g. CsI(Tl), BGO, Pb-glass, $PbWO_4$, Ar (liq), Xe(liq) etc,
- Sampling calorimeters, e.g. Pb-scintillator or Pb-Ar(liq) etc.

Key features

- Energies of neutral and charged particles
- Relative energy resolution *improves* with increasing particle 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.

Key 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.

ε is defined as the energy when the ionisation loss and radiation loss are equal. It can be calculated approximately as 560/Z (in MeV)

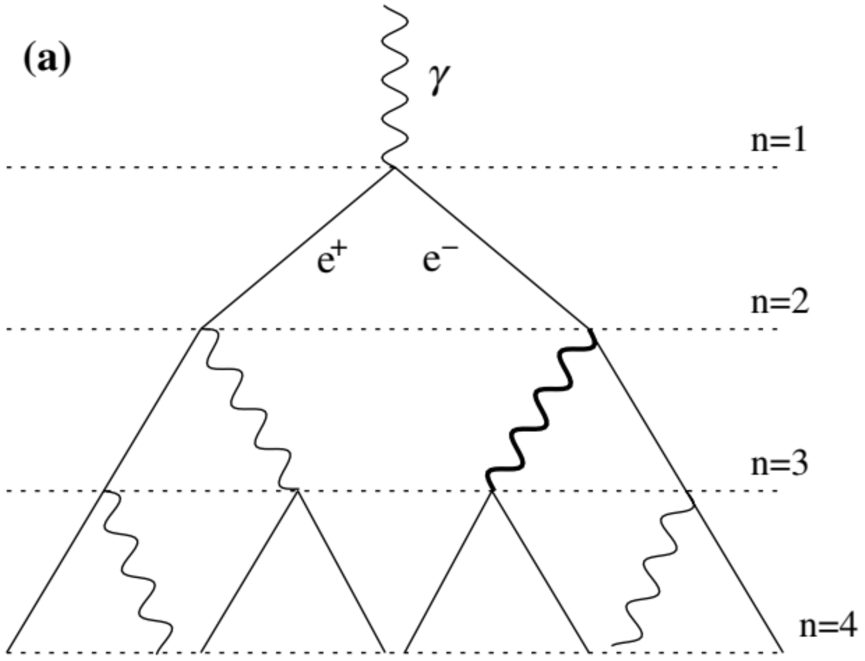
Simple model

Model due to Heitler. Neglects Compton scattering. At each stage we have bremsstrahlung (from electron/positron) and pair production from the radiated (or incident) photons.

After *n* stages there are 2^n particles. Process stops abruptly when the particle energy falls below the *critical energy.*

Two important features are well accounted for: the final total number of electrons, positrons, and photons is proportional to the primary particle energy and the depth of maximum shower development is logarithmically proportional to it.

See [6] in "Further sources of information" (slide 19)



Simple model

- ε is defined as the energy when the ionisation loss and radiation loss 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 $180A/Z^2$ g.cm^2.
- Define two scaled variables

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

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

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

At shower maximum

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

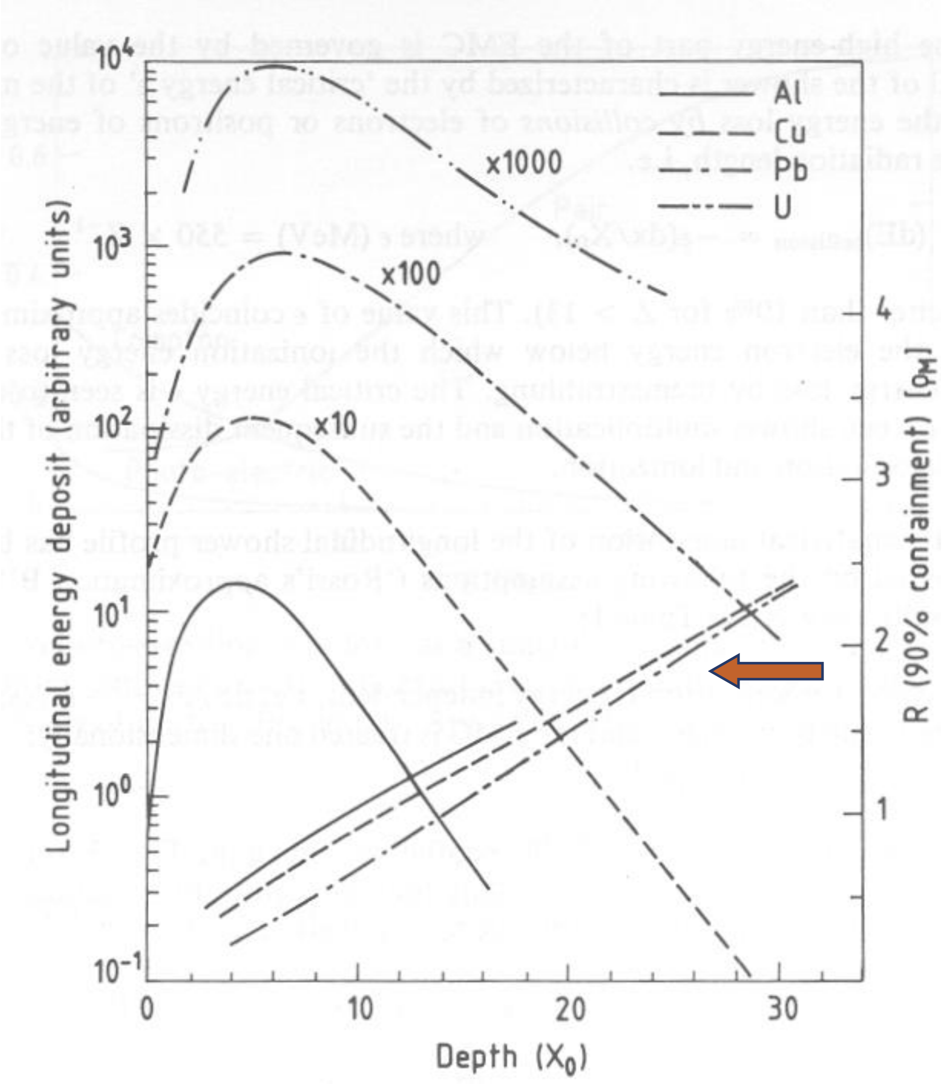
Key properties of some dense elements

	Z	*Density*	ε	X_0	λ
		$g.cm^{-3}$	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 development

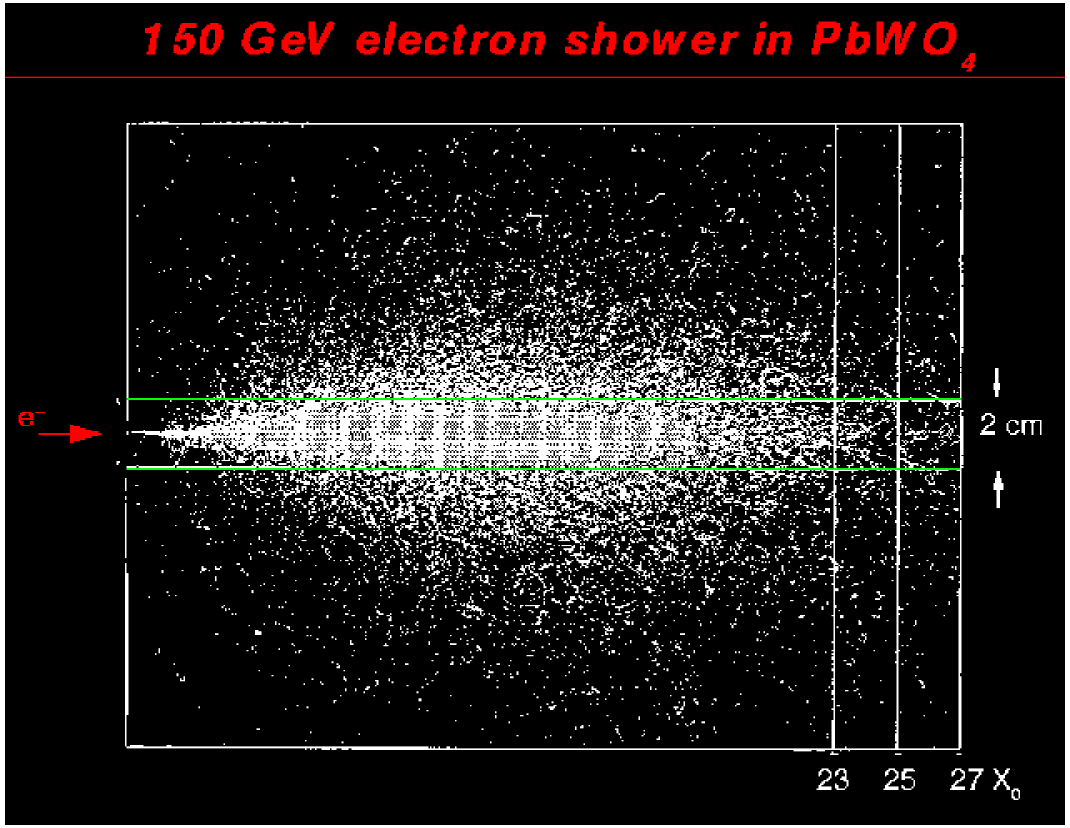
Longitudinal containment



Lateral containment

Figure 3 from Fabjan C in Ferbel 1987

Simulated electromagnetic showers

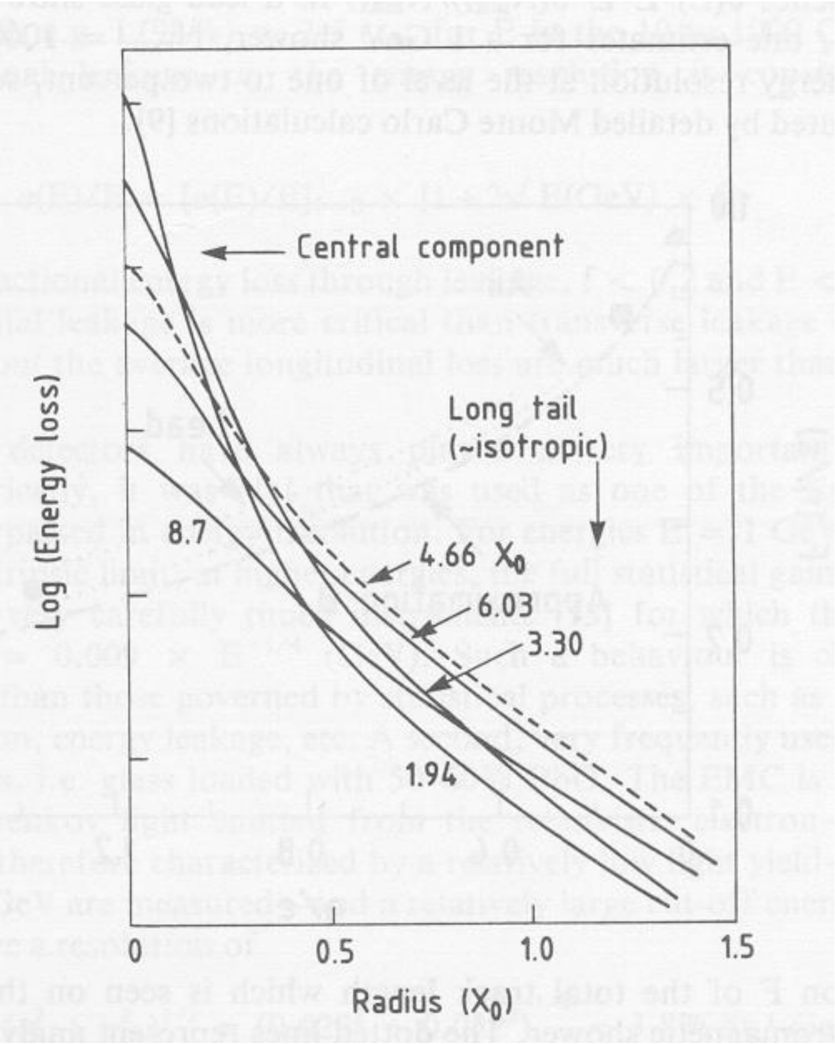


CMS Homogeneous ECAL scintillator simulation. The green lines show the approximate location of a single crystal.

Note the significant sharing of energy into adjacent crystals; this is useful for determining accurately the position the particle entered the calorimeter.

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

Shower containment - lateral



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

Hadron calorimeters

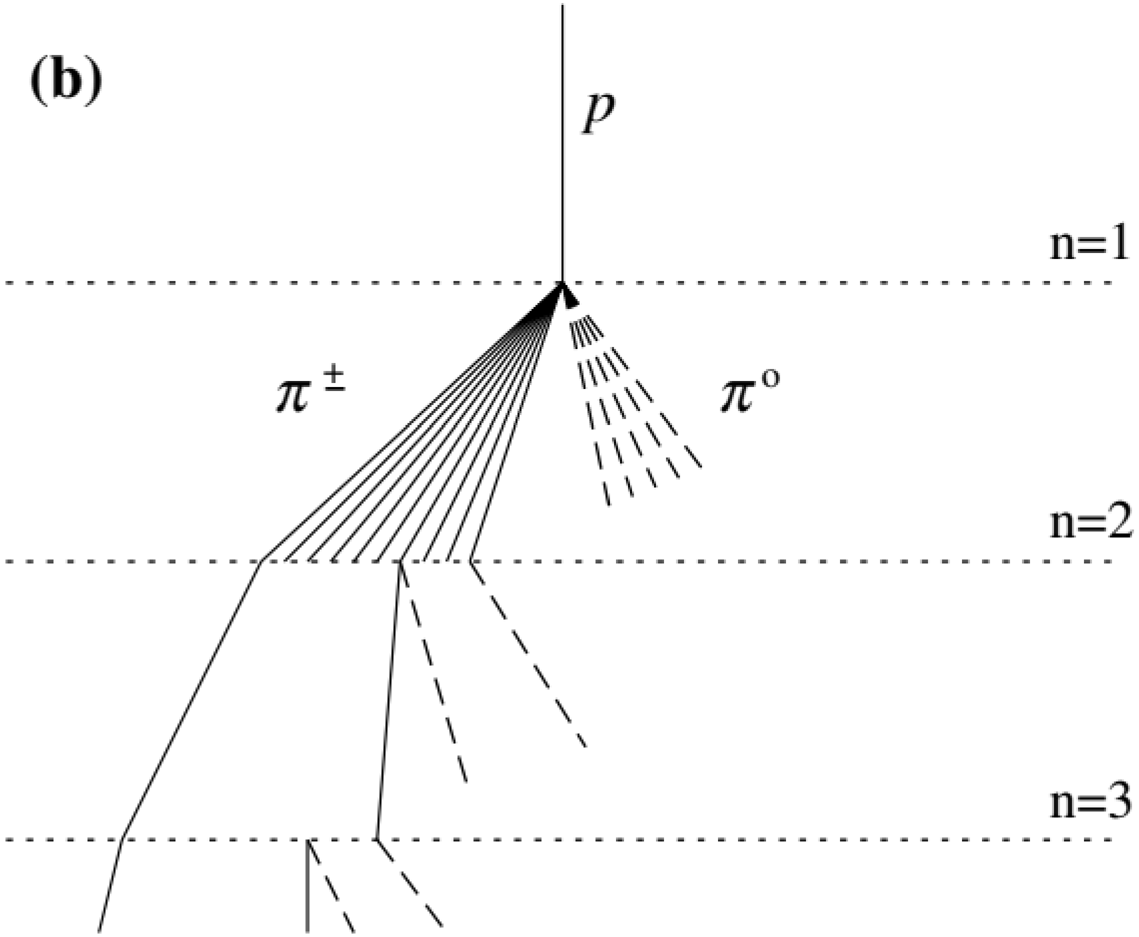
- High energy hadrons interact with nuclei resulting in the production of secondary hadrons (pions, kaons).
- The hadronic analogue of X_0 is the interaction length λ which varies as $A^{1/3}$.
- The strong interaction results in a developing shower of particles. There are two distinct components
  - Electromagnetic arising mainly from π^0 production (decays to $\gamma\gamma$ with $c\tau$ = 25 nm)
  - Hadronic (mainly pions)
- Multiplication continues until the pion production threshold (140 MeV/c^2) is reached. The average number of secondary hadrons grows like ln(E). Their transverse momentum is fairly low (of order 300 MeV)

Heitler model

Very similar to that used for EM cascades.

Note that on average two charged pions are produced for every single neutral pion (π^0)

Here the incoming particle is a proton, but this cascade model just assumes a *hadron* (strongly interacting particle containing quarks)



Simple model predictions

Use scaled variables:

$$\nu = \frac{x}{\lambda} \qquad E_{th} \approx 2m_\pi = 0.28\,\text{GeV}$$

The energy and number of the secondary particles can be modelled as

$$e(\nu) = \frac{E}{\langle n \rangle^{\nu}}$$

$$e(\nu_{\max}) = E_{th}$$

$$n^{\nu_{\max}} = \frac{E}{E_{th}} \Rightarrow \nu_{\max} = \frac{\ln\left(E/E_{th}\right)}{\ln\langle n \rangle}$$

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

Hadronic shower containment

- About 9λ are required for longitudinal containment
- Lateral development
  - Secondary hadron transverse momentum (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

Further sources of information

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. G Gratta, H Newman, RH Zhu, *Ann.Rev.Nucl.Part.Sci.* **14** (1994) 453-500
3. R Wigmans "Calorimetry: Energy Measurement in Particle Physics", Clarendon Press, 2000
4. ATLAS, CMS, BaBar, LHCb, D0 etc. TDR reports (various dates)
5. F Sefkow et al, "Experimental Tests of Particle Flow Calorimetry" arXiv:1507.05893v2 [physics.ins-det] 17 Sep 2015
6. J Matthews, "A Heitler model of extensive air showers", *Astroparticle Physics* **22** (2005) 387–397