0.1 Calorimetry

Lecture 5. *Tuesday 24th March, 2020. Compiled: Tuesday 31st March, 2020.*

Conceptually, a calorimeter is a block of matter, which intercepts the primary particle and is of sufficient thickness to cause it to interact and deposit all its energy inside the detector volume in a subsequent cascade or "shower" of increasingly lower-energy particles. Eventually most of the incident energy is dissipated and appears in the form of heat. Some (usually a very small) fraction of the deposited energy goes into the production of a more practical signal (e.g. scintillation light, Cerenkov light, or ionization charge), which is proportional to the initial energy.
In principle, the uncertainty in the energy measurement is governed by statistical fluctuations in the shower development, and the fractional resolution $\frac{\sigma}{E}$ improves with increasing energy E as $E^{-\frac{1}{2}}$.

Main features of calorimeters

At the outset it was noted that calorimetric detectors offer many other attractive capabilities, aside from the energy response, all of which have since been exploited in varying degrees:

- They are sensitive to charged and neutral particles
- The size of the detector scales logarithmically with the particle energy E, whereas for magnetic spectrometers the size scale with momentum p as $p^{\frac{1}{2}}$, for a given relative momentum resolution $\frac{\Delta p}{p}$.
- Through the use of segmented detectors the information of the shower development allows precise measurements of the position and angle of the incident particle.
- The shower development is a statistical process and the number of secondary particles $\langle N \rangle$ is proportional to the energy E of the incident particle.
- The different response of the materials to electrons, muons and hadrons can be exploited for particle identification.
- Their fast time response allows operation at high particle rates, and the patterns of energy deposition can be used for real-time event selection.

0.1.1 Electromagnetic shower development

The theory of electromagnetic shower development is relatively simple. Electrons and positrons lose energy by ionization and by radiation. The first process dominates at low energy, the second one at high energy. Photons interact either through the photoelectric effect, Compton scattering or pair production. The photoelectric effect dominates at low energies, pair production at high energies. So in our case, for electrons the loss of energy is dominated by bremmstrahlung, for photons by pair production.

E.M. shower model

A simplified electromagnetic shower model in a homogeneous detector has the following assumptions: we assume a material with radiation length of X_0 and we suppose that we have 2^t particles after $t \cdot X_0$ radiation lengths, each with energy $\frac{E}{2^t}$. So the shower stops when $E < E_C$ and the number of particles generated along the path is:

$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_C} \tag{1}$$

The maximum expansion of the shower is obtained at:

$$t_{\max} \propto \log\left(\frac{E_0}{E_C}\right) \tag{2}$$

Molière radius

The lateral development of the shower is described by the **Moliere Radius** ρ_M:

$$R_M \approx (21 \text{ MeV})\frac{X_0}{E_C} \tag{3}$$

It is important to note that both X_0 and ρ_M are defined for the asymptotic energy regime (> 1 GeV).
Transversally, the 95% of the energy of shower is contained in a cone of radius $R \sim 2\rho_M$. For lateral shower containment, material differences are much smaller than longitudinally. In addition, there is no energy dependence. A given (sufficiently long) cylinder will thus contain the same fraction of the energy from 1 GeV electromagnetic showers as from 1 TeV ones. Some examples are showed in Figures 1 and 2.

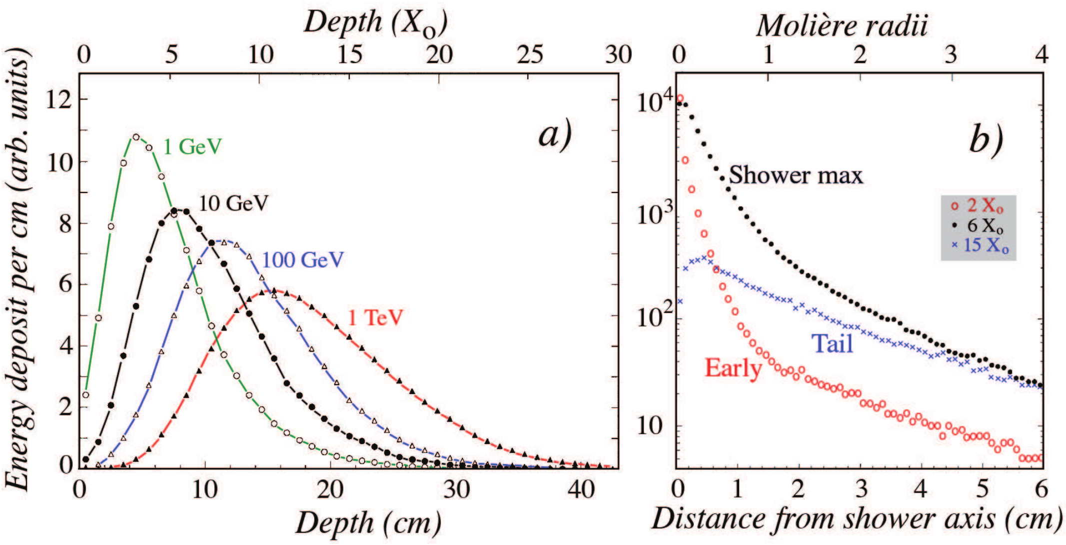

Figure 1: Left: the energy deposited as a function of depth for 1, 10, 100 and 1000 GeV electron showers developing in a block of copper; the integral of these curves have been normalized to the same value in order to compare the shower profiles. Right: radial distributions of the energy deposited by 10 GeV electron shower in copper at various depths.

0.1.2 Hadronic shower development

Nuclear interaction length

Showers generated and developed by hadrons are affected by strong interactions, characterized by the **nuclear interaction length** λ_{int}, namely the average distance hadrons travel before inducing a nuclear interaction. It is expressed in g/cm^2 and for energies up to 100 GeV it scales as:

$$\lambda_{\text{int}} \sim A^{\frac{1}{3}} \tag{4}$$

On average, hadronic shower profiles look very similar to the electromagnetic ones, except that the scale factor is usually much larger for the hadronic showers. For example, for copper X_0 amounts to 1.4 cm, while $\lambda_{\text{int}} = 15$ cm.

Effects of strong interactions

Strong interaction is responsible for:

- The production of hadronic shower particles, of which $\sim 90\%$ are pions. The neutral pions decay in 2 γs, which develop an electromagnetic component in the shower. The fraction of this component depends on the energy of the initial particle.
- The occurrence of nuclear reactions. In these processes, neutrons and protons are released from atomic nuclei, however the nuclear binding energy of these

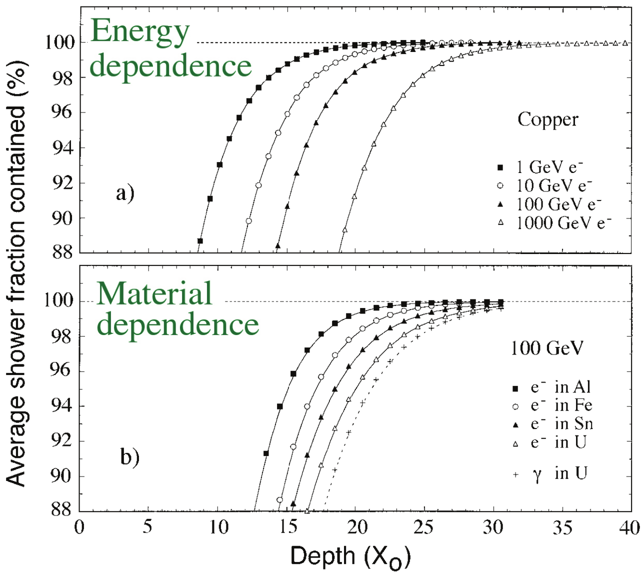

Figure 2: Average energy fraction contained in a block of matter with infinite transverse dimensions, as a function of the thickness of the absorber. Up: results for showers induced by by electrons of various energies in a copper absorber. Down: results for 100 GeV electron showers in different absorber materials.

nucleons has to to be provided. Therefore, the fraction of the shower energy needed for this purpose does not contribute to the calorimeter signals. This is the so called **invisible energy** phenomenon.

So we get in function of the distance travelled inside the calorimeter:

$$N(x) = N_0 e^{-\frac{x}{\lambda_{\text{int}}}} \tag{5}$$

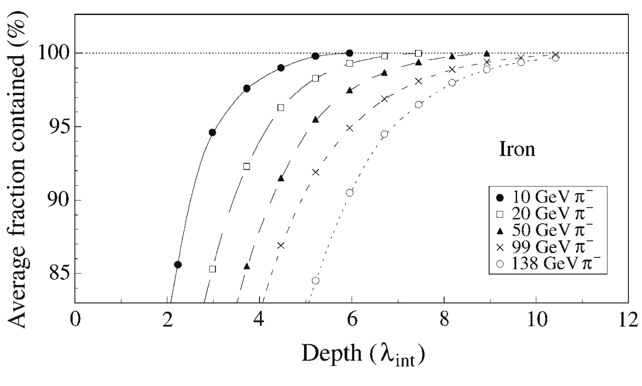

Figure 3: Average energy fraction contained in a block of matter with infinite transverse dimensions, as a function of the thickness of the absorber.

The large majority of the non-em energy is deposited through nucleons and not through relativistic particles such as pions. These nuclear interaction properties have important consequences for calorimetetry:

Consequences od nuclear interaction properties

- As a result of the invisible energy phenomenon, the calorimeter signals for hadrons are in general smaller than for electrons of the same energy.

- Since the electromagnetic energy fraction is energy dependent, the calorimeter is non-linear for hadron detection.

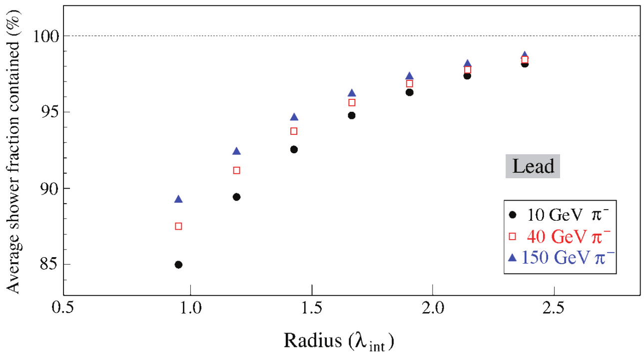

Figure 4: Average energy fraction contained in an infinitely long cylinder of absorber material, as a function of the radius of this cylinder, for pions of different energies showering in a lead-based calorimeter.

0.1.3 Classification and response of calorimeters

Calorimeters classification

Calorimeters are distinguished according to their composition into two classes:

- **Homogeneous calorimeters**, in which the absorber and the active (signal producing) medium are one and the same. They are used to get high precision results.
- **Sampling calorimeters**, in which these two roles are played by different media. These are layers of active material and high density absorber. This type of calorimeter is more common.

Calorimeters response

The calorimeter response is defined as the average calorimeter signal per unit of deposited energy. The response is thus expressed in terms of photoelectrons per GeV, pico-coulombs per MeV or something similar. Electromagnetic calorimeters are in general linear, since all the energy carried by the incoming particle is deposited through processes that may generate signals (excitation /ionization of the absorbing medium). Non-linearity is usually an indication of instrumental problems, such as signal saturation or shower leakage. An example of non-linear calorimeter data is given in Figure 5.

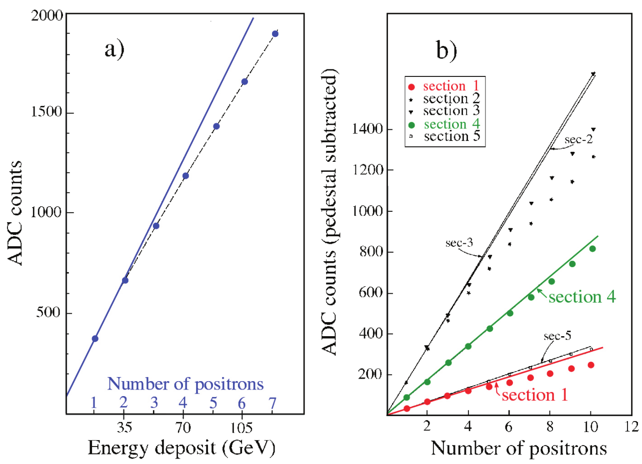

Figure 5: Average electromagnetic shower signal from a calorimeter read out with wire chambers operating in the "saturated avalanche" mode, as a function of energy. The calorimeter was longitudinally subdivided.

Fluctuations

Calorimeters are based on physical processes that are inherently statistical in nature, so the precision of calorimetric measurements is determined and limited by fluctuations. We examine here the fluctuations that may affect the energy resolution. Many of them will affect electromagnetic and hadronic calorimeters, but the last one has additional term of uncertainty to be discussed later. Fluctuations and contributions to the energy resolution are:

- Signal quantum fluctuations, such as photoelectron statistics:
$$\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}} \tag{6}$$
- Shower leakage fluctuations:
$$\frac{\sigma_E}{E} \sim \frac{1}{\sqrt[4]{E}} \tag{7}$$
- Fluctuations resulting from instrumental effects, such as electronic noise, light attenuation, structural non-uniformities.
$$\frac{\sigma_E}{E} \sim \frac{1}{E} \tag{8}$$
- Sampling fluctuations:
$$\frac{\sigma_E}{E} \sim \text{const} \tag{9}$$

So, the calorimeter energy resolution has different contribution from several fluctuation processes, which add in quadrature:
$$\sigma_T^2 = \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_n^2 = \sigma_1 \oplus \sigma_2 \oplus \cdots \oplus \sigma_n \tag{10}$$
For electromagnetic showers, the relevant contributions to the energy resolution can be summarized as:
$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \tag{11}$$
with a the stochastic term (due to intrinsic shower fluctuations, ...), b the constant term, c the noise term.
For hadronic showers, we have some types of fluctuations as in electromagnetic showers, however, there are some additional effects that tend to dominate the performance of hadron calorimeters.

- Fluctuations in visible energy play a role in all hadron calorimeters and form the ultimate limit to the achievable hadronic energy resolution. So this is an irreducible contribution.
- Fluctuations in the electromagnetic shower fraction causes differences between p and π induced showers since in p showers there are no π^0.

In the case of hadron calorimeter, the relation used before does not describe the energy resolution due to the two additional effects. For the majority of calorimeters the energy resolution can be approximated by:
$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} + b \tag{12}$$
where a can reach values of 90% and b can be around few %. Therefore, why do we build hadronic calorimeters? In HEP experiments we do not measure single hadrons, we do not reconstruct p, π, etc. We reconstruct jets! Jet reconstruction is complex and *TODO*

0.1.4 Particle identification

TODO

Short lived particles are identified through the resonance. Stable or long lived particles are identified exploiting time of flight, Cerenkov, energy loss, conmbination of tracking and calorimeter.

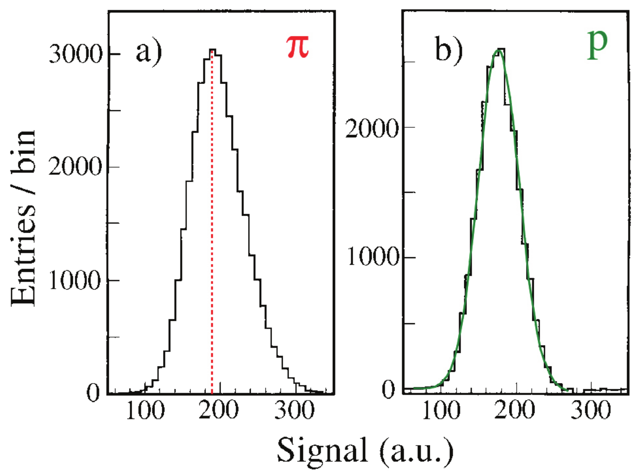

Figure 6: Signal distributions for 300 GeV pions and protons detected with a quartz-fiber calorimeter. The curve on the right represents the result of a gaussian fit to the proton distribution.