Chapter 4

Particle detection

After reading this chapter, you should be able to manage the basics of particle detection, and to understand the sections describing the detection technique in a modern article of high-energy particle or astroparticle physics.

Particle detectors measure physical quantities related to the outcome of a collision; they should ideally identify all the outcoming (and the incoming, if unknown) particles, and measure their kinematical characteristics (momentum, energy, velocity).

In order to detect a particle, one must make use of its interaction with a sensitive material. The interaction should possibly not destroy the particle one wants to detect; however, for some particles this is the only way to obtain information about them.

In order to study the properties of detectors, we shall first need to review the characteristics of the interaction of particles with matter.

4.1 Interaction of particles with matter

4.1.1 Charged particle interactions

Charged particles interact basically with atoms, and the interaction is mostly electromagnetic: they might expel electrons (ionization), promote electrons to upper energy levels (excitation), or radiate photons (bremsstrahlung, Cherenkov radiation, transition radiation). High energy particles may also interact directly with the atomic nuclei.

Ionization energy loss

This is one of the most important sources of energy loss by charged particles. The average value of the specific (i.e., calculated per unit length) energy loss due to ionization and excitation whenever a particle goes through a homogeneous
material of density $\rho$ are described by the so-called Bethe formula\footnote{The 24-year old Hans Bethe, Nobel prize in 1967 for his work on the theory of stellar nucleosynthesis, published this formula in 1930; the formula – not including the density term, added later by Fermi – was derived using quantum mechanical perturbation theory up to $z_p^2$. The description can be improved by considering corrections which correspond to higher powers of $z_p$; Felix Block obtained in 1933 a higher-order correction proportional to $z_p^4$, not reported in this text, and sometimes the formula is called “Bethe-Block energy loss” – although this naming convention has been discontinued by the Particle Data Group since 2008 [?].}. This has an accuracy of a few % in the region $0.1 < \beta \gamma < 1000$ for materials with intermediate atomic number.

$$\frac{dE}{dx} \simeq \rho D \left( \frac{Z}{A} \right) \left( \frac{z_p}{\beta^2} \right)^2 \left[ \frac{1}{2} \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 - \frac{\delta(\beta, \rho)}{2} \right]$$  \hspace{1cm} (4.1)$$

where

- $\rho$ is the material density, in g/cm$^3$;
- $Z$ and $A$ are the atomic and mass number of the material, respectively;
- $z_p$ is the charge of the incoming particle, in units of the electron charge;
- $D \simeq 0.307$ MeV cm$^2$/g;
- $m_e c^2$ is the energy corresponding to the electron mass;
- $I$ is the mean excitation energy in the material; it can be approximated as $I \simeq 16eV \times Z^{0.9}$ for $Z > 1$;
- $\delta$ is a correction term which takes into account the reduction in energy loss due to the so-called density effect. This becomes important at high energy because media have a tendency to become polarised as the incident particle velocity increases. As a consequence, the atoms in a medium can no longer be considered as isolated.

The energy loss by ionization (Figure 4.1) is thus in first approximation:

- independent of the mass of the particle;
- typically small for high energy particles (about 2 MeV/cm in water; one can roughly assume a proportionality to the density of the material);
- proportional to $1/\beta^2$ for $\beta \gamma \leq 3$ (the minimum of ionization: minimum ionizing particle, or mip);
- basically constant for $\beta > 0.96$ (logarithmic increase after the minimum);
- proportional to $Z/A$ ($Z/A$ being about equal to 0.5 for all elements but Hydrogen and the heaviest nuclei).
Figure 4.1: Specific ionization energy loss for muons, pions and protons in different materials [?].
In practical cases, most relativistic particles (e.g., cosmic-ray muons) have mean energy loss rates close to the minimum; they can be considered within less than a factor of two as minimum-ionizing particles. The radiation from a mip is well approximated as

$$\frac{1}{\rho} \frac{dE}{dx} \simeq 3.5 \left( \frac{Z}{A} \right) \text{MeV cm}^2/\text{g}.$$ 

The statistical nature of the ionizing process during the passage of a fast charged particle through matter results in large fluctuations of the energy loss in absorbers which are thin compared with the particle range. The energy loss is distributed around the most probable value according to an asymmetric distribution (named the Landau distribution). The average energy loss is about twice as large as the most probable energy loss.

The main characteristics of Eq. (4.1) can be derived classically. Add here Fernando’s exercise.

Photoluminescence. In some transparent media, part of the ionization energy loss goes into the emission of visible or near-visible light by the excitation of atoms and/or molecules. This phenomenon is called photoluminescence; often it results into a fast ($< 100\mu$s) excitation/deexcitation; in this case we talk of fluorescence, or scintillation².

High-energy radiation effects

According to the classical electromagnetic theory, a charged particle emits electromagnetic waves whenever it undergoes an acceleration, and the intensity of the emitted radiation, calculated in the so-called dipole approximation, is directly proportional to the square of the acceleration.

While the dipole approximation is appropriate also in quantum electrodynamics for the description of the radiation by a particle bended by a magnetic field (synchrotron radiation), it cannot be applied in the case of interactions with the electric fields of the atoms of the material traversed by a charged particle. We speak in this case of bremsstrahlung, or braking radiation; a calculation based on relativistic quantum mechanics has to be applied in this case – see for example [?].

The result at first order is that the emitted energy is still (as in the classical case) proportional to the inverse of the square of the mass. On top of the ionization energy loss described by Eq. 4.1, above $\beta\gamma \sim 1000$ (which means an extremely high energy for a proton, $E \sim 1$ TeV, but just $E \sim 100$ GeV for a muon), radiation effects become important (Figure 4.2).

Bremsstrahlung is particularly relevant for electrons and positrons, particles for which the approximation starts to be inadequate at even lower energies. The average fractional energy loss by radiation for an electron of high energy

²Specialists often use definitions which distinguish between fluorescence and scintillation; this separation is, however, not universally accepted.
Figure 4.2: Stopping power \((-dE/dx)\) for positive muons in copper as a function of \(\beta\gamma = p/Mc\) over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy) \([7]\).

\((E \gg m_e c^2)\) is approximately independent of the energy itself, and can be described by the equation

\[
\frac{1}{E} \frac{dE}{dx} \simeq -\frac{1}{X_0}
\]

(4.2)

where \(X_0\) is called radiation length, and is characteristic of the material – for example it is about 300 m for air at Normal Temperature and Pressure (NTP)\(^3\), about 36 cm for water, about 0.5 cm for lead; see Appendix B for a table with the characteristics of different materials.

With good approximation

\[
\frac{1}{X_0} = 4 \left(\frac{\hbar}{m_e c}\right)^2 Z(Z + 1)\alpha^3 n_a \ln \left(\frac{183}{Z^{1/3}}\right),
\]

(4.3)

where \(n_a\) is the density of atoms per cubic centimeter in the medium, or more simply

\[
\frac{1}{\rho} X_0 \simeq 180 \frac{A}{Z^2} \text{cm} \left(\frac{\Delta X_0}{X_0}\right) < \pm 20\% \text{ for } 12 < Z < 93.
\]

\(\Delta X_0/X_0\) is commonly used as a standard condition: it is defined as air at 20°C (293.15 K) and 1 atm (101.325 kPa). Density is 1.204 kg/m\(^3\). The definition of Standard Temperature and Pressure STP, another condition frequently used in physics, is defined by IUPAC (International Union of Pure and Applied Chemistry) as air at 0°C (273.15 K) and 100 kPa.

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\(^3\)NTP
The total average energy loss by radiation increases then rapidly (linearly in the approximation of the equation (4.2)) with increasing energy, while the average energy loss by collision is practically a constant. Thus, at large energies radiation losses are much more important than collision losses (Figure 4.3).

The energy at which the radiation loss overtakes the collision loss (critical energy, $E_c$) decreases with increasing atomic number:

$$E_c \simeq \frac{550 \text{ MeV}}{Z} \left( \frac{\Delta E_c}{E_c} < \pm 10\% \text{ for } 12 < Z < 93 \right). \tag{4.5}$$

Critical energy for air at NTP is about 84 MeV; for water is about 74 MeV.

The photons radiated by bremsstrahlung are distributed at leading order in such a way that the differential loss per unit energy is constant, i.e.,

$$N_\gamma \propto \frac{1}{E_\gamma}$$

between 0 and $E$. This results in a divergence for $E_\gamma \to 0$, which anyway does not contradict energy conservation.

The emitted photons are collimated: the typical he angle of emission is $\sim m_e/E$.

**Cherenkov radiation**

The Vavilov-Cherenkov (commonly called just Cherenkov) radiation occurs when a charged particle moves through a medium faster than the speed of light in that medium. The total energy loss due to this process is negligible; however, Cherenkov radiation is important related to the possibility of use in detectors.
The light is emitted in a coherent cone (Figure 4.4) at an angle

\[ \theta_c = \frac{1}{n\beta} \]

from the direction of the emitting particle. The threshold velocity is thus \( \beta = \frac{1}{n} \), where \( n \) is the refractive index of the medium. The presence of a coherent wavefront can be easily derived by using the Huygens-Fresnel principle.

The number of photons produced per unit path length and per unit energy interval of the photons by a particle with charge \( z_p e \) is

\[
\frac{d^2 N}{dE dx} \simeq \frac{\alpha z_p^2}{\hbar c} \sin^2 \theta_c \simeq 370 \sin^2 \theta_c \text{eV}^{-1}\text{cm}^{-1} \tag{4.6}
\]

or equivalently

\[
\frac{d^2 N}{d\lambda dx} \simeq \frac{2\pi \alpha z_p^2}{\lambda^2} \sin^2 \theta_c \tag{4.7}
\]

(the index of refraction \( n \) is in general a function of photon energy \( E \); Cherenkov radiation is relevant when \( n < 1 \) and the medium is transparent, and this happens close to the range of visible light).

The total energy radiated is small, some \( 10^{-4} \) times the energy lost by ionization. In the visible range (300 nm to 700 nm), the total number of emitted photons is about 40 per meter in air, about 500 per centimeter in water. Due to the dependence on \( \lambda \), it is important that Cherenkov detectors are sensitive close to the ultraviolet region.
Dense media can be transparent not only to visible light, but also to radio waves. The development of Cherenkov radiation in the radiowave region, due to the interactions with matter electrons, is often referred to as the Askar’yan effect. The effect has been experimentally confirmed in accelerator experiments at SLAC in media such as sand, rock salt and ice; presently attempts are in progress to use this effect for in particle detectors.

**Transition radiation**

X-ray transition radiation (XTR) occurs when a relativistic charged particle passes from one medium to another of a different dielectric permittivity.

The energy radiated when a particle with charge $z_p e$ and $\gamma \approx 1000$ crosses the boundary between vacuum and a different transparent medium is typically concentrated in the soft x-ray range 2 keV to 40 keV.

The process is closely related to Cherenkov radiation, and also in this case the total energy emitted is low. ?? Specify better; ask the Bari people to add a few lines with number of photons etc.

**Multiple scattering**

When a charged particle passes near a nucleus it undergoes a deflection which, in most cases, is accompanied by a negligible (approximately zero) loss of energy. This phenomenon, called elastic scattering, is caused by the same electric interaction between the passing particle and the Coulomb field of the nucleus. The global effect is that the path of the particle becomes a random walk (Figure 4.5), and information on the original direction is partly lost — this fact can create problems for the reconstruction of direction in tracking detectors. For very-high energy hadrons, also hadronic cross section can contribute to the effect.

Summing up many relatively small random changes of the direction of flight for a thin layer of traversed material, the distribution of the projected scattering angle of a particle of unit charge can be approximated by a Gaussian distribution.
of standard deviation (projected on a plane: one has to multiply by $\sqrt{2}$ to determine the variance in space):

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z_p \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln \frac{x}{X_0} \right].$$

The above expression comes from the so-called Molière theory, and is accurate to some 10% or better for $10^{-3} < x/X_0 < 100$. We will obtain now a simple derivation.

?? Add here Fernando’s simple calculation of multiple scattering.

The underlying assumption of a Gaussian distribution makes this approximation a crude one; in particular, large angles are underestimated by a Gaussian form, and some 2% of the particles can suffer more important kicks due to Rutherford scattering and contribute to a sizeable tail [?].

### 4.1.2 Photon interactions

Photons mostly interact with matter via photoelectric effect, Compton scattering, and electron-positron pair production. Other processes, like Rayleigh scattering and photonuclear interactions, have in general much smaller cross sections.

#### Photodetectors

**Photodetectors**

No simple relationship between the attenuation coefficient and the photon energy $E$ can be derived, since the process is characterized by the interaction with the (quantized) orbitals. The plot of the attenuation coefficient as a function of the photon energy displays sharp peaks at the binding energies of the various orbital shells and has a strong dependence on the atomic number of the atom. A reasonable approximation for the cross section $\sigma$ is

$$\sigma \propto Z^\nu \frac{E}{E^3},$$

with the exponent $\nu$ varying between 4 and 5 depending on the energy. The cross section rapidly decreases with energy above the typical electron binding energies (Figure 4.6).

The photoelectric effect can be used for detecting photons below the MeV; a photosensor (see later) sensitive to such energies can read the signal generated by a photodetector, possibly amplified by an avalanche process.

**Compton scattering**

The Compton scattering is the collision between a photon and an electron.
Let $E$ be the energy of the primary photon and suppose the electron to be initially free and at rest. As a result of the collision, the photon is scattered at an angle $\theta$ and comes out with a reduced energy $E'$; the electron acquires an energy $E - E'$. The conservation laws of energy and momentum yield the following relation (Compton formula):

$$\lambda' - \lambda = \lambda_C (1 - \cos \theta) \quad \rightarrow \quad E' = \frac{E}{1 + \frac{E}{m_e c^2} (1 - \cos \theta)}$$

where $\theta$ is the scattering angle of the emitted photon; $\lambda_C = h/m_e c \approx 2.4$ pm is the Compton wavelength of the electron.

It should be noted that, in case the target electron is not at rest, the energy of the scattered photon can be larger than the energy of the incoming one. This regime is called inverse Compton, and it has great importance in the emission of high-energy photons by astrophysical sources: in practice, thanks to inverse Compton, photons can be “accelerated”.

The differential cross section for this process has been calculated by Klein and Nishina around 1930. If the photon energy is much below $m_e c^2$, so the scattered electrons would be non-relativistic, then the total cross section is given by the Thomson cross section and we speak of the Thomson limit. The cross section for $E \ll m_e c^2$ (Thomson regime) is about

$$\sigma_T \simeq \frac{8\pi\alpha^2}{3m_e^2} = \frac{8\pi r_e^2}{3}, \quad (4.8)$$

where $r_e = (1/4\pi\epsilon_0)(m_e c^2) \approx 0.003$ pm is the classical radius of the electron. If the photon energy is $E \gg m_e c^2$, we are in the so-called Klein-Nishina regime and the total cross section falls off rapidly with increasing energy (Figure 4.6):

$$\sigma_{KN} \simeq \frac{3\sigma_T \ln 2E}{8} \frac{1}{E}. \quad (4.9)$$

As in the case of the photoelectric effect, the ejected electron can be detected (possibly after multiplication) by an appropriate sensor.

**Pair production**

Pair production is the most important interaction process for a photon above an energy of a few tenth of MeV.

A high energy photon, traversing the intense electric field in the neighborhood of a nucleus, has a non negligible probability of transforming itself into a positive and a negative electron - the process being kinematically forbidden unless an external field, irrespective of how little, is present.

Conservation of energy yields the following relation between the energy $E$ of the primary photon and the total energies $U$ and $U'$ of the electron pair:

$$E = U + U'$$
With reasonable approximation, for 1 TeV > E > 100 MeV the fraction of energy 
\( u = \frac{U}{E} \) taken by the secondary electron/positron is uniformly distributed 
between 0 and 1 (becoming peaked at the extremes as the energy increases to 
values above 1 PeV).

The cross section grows quickly from the kinematical threshold of about 1 
MeV to its asymptotic value reached at some 100 MeV:

\[
\sigma \simeq \frac{7}{9} \frac{1}{n_a X_0},
\]

where \( n_a \) is the density of atomic nuclei per unit volume, in such a way that the 
interaction length is

\[
\lambda \simeq \frac{9}{7} X_0.
\]

The angle of emission for the particles in the pair is is typically \( \sim m_e/E \).

**Rayleigh scattering and photonuclear interactions**

Rayleigh scattering (the dispersion of electromagnetic radiation by particles with 
radii less than or in the order of 1/10 the wavelength of the radiation) is usually 
minor importance for the conditions of high energy particle and astroparticle 
physics, but it can be important for light in the atmosphere, and thus for the 
design of instruments detecting visible light. The photonuclear effect, i.e., the 
extcitation{excitation of nuclei by photons, is mostly restricted to the region around 10 
MeV, and it may amount to as much as 10 percent of the total cross section 
due to electrodynamic effects.}

**Comparison between different processes for photons**

The total probability for Compton scattering decreases rapidly with increasing 
photon energy, while the total probability for pair production is a slowly in-
creasing function of the energy. Thus, at large energies, most of the photons are 
absorbed by pair production, while at small energies most of the photons are 
absorbed by Compton effect (being photoelectric effect characteristic of even 
smaller energies). The absorption of photons by pair production, Compton and 
photoelectric effect is compared in Figure 4.6.

As a matter of fact, above about 30 MeV the dominant process is pair 
production, and the interaction length of a photon is with extremely good approx-
imation equal to 9X_0/7.

At extremely high matter densities and/or at extremely high energies (typ-
cally above \( 10^{16} \) eV – \( 10^{18} \) eV, depending on the medium composition and 
density) the Landau-Pomeranchuk-Migdal effect, or simply LPM effect\(^4\), entails 
a reduction of the pair production cross section, as well as of bremsstrahlung.

\(^4\)Here a short qualitative description of where the LPM effect comes from ??
4.1.3 Nuclear (hadronic) interactions

The nuclear force is felt by hadrons, charged and neutral; at high energies (above a few GeV) the inelastic cross section for hadrons is dominated by nuclear interaction. High-energy nuclear interactions can be characterized by an inelastic interaction length $\lambda_H$. Values for $\rho \lambda_H$ are typically of the order of 100 g/cm$^2$; a listing for some common materials is provided in Appendix B.

The final state products of inelastic high-energy hadronic collisions are mostly pions, since these are the lightest hadrons. The rate of positive, negative, and neutral pions is more or less equal - as we shall see, this depend on a fundamental symmetry of hadronic interactions, the isospin symmetry.

4.1.4 Range

From the rate of energy loss as a function of energy, we can calculate the rate of energy loss as a function of the distance $x$ travelled in the medium. This is called the Bragg curve. For charged particles, most of the ionization loss occurs near the end of the path where the speed is smallest, and the curve has a pronounced peak close to the end point before falling rapidly to zero at the end of the particles path length. The range $R$ for a particle of energy $E$ is the average distance traveled before reaching the energy at which the particle is absorbed (Figure 4.7):

$$R = \int_E^{M^2 c^2} \frac{1}{\frac{dE}{dx}} dx.$$
Below the energy of minimum ionization ($\beta\gamma < 3$),

?? Add here the exercise on range by Fernando

4.2 Particle detectors

The aim of a particle detector is to measure the momenta and discover the identity of the particles that pass through it after being produced in a collision or a decay - an “event”. The position in space where the event occurs is known as the interaction point.

In order to identify every particle produced by the collision, and plot the paths they take - i.e., to “completely reconstruct the event” - it is necessary to know the mass and momentum of the particles. The mass can be found by measuring the momentum and either the velocity or the energy.

The characteristics of the different instrument that allow these measurements are presented in what follows.

4.2.1 Track detectors

A tracking detector reveals the path taken by a particle by measurements of sampled points (hits). Momentum measurements can be made by measuring the curvature of the track in a magnetic field, this causes the particle to curve into a spiral orbit with a radius proportional to the momentum of the particle. This requires the calculation of the best fit of a helix to the hits (particle fit).

For a particle of unit charge

\[ p \approx 0.3B_\perp R, \]

where $B_\perp$ is the component of the magnetic field perpendicular to the particle velocity, expressed in tesla (which is the order of magnitude of typical fields in detectors), the momentum $p$ is expressed in GeV, and the radius $R$ in meters.

A source of noise for this measurement is given by the errors in the measurement of the hits; another (intrinsic) noise is given by multiple scattering. In what follows we will review some detectors of the trajectory of charged tracks.

Cloud chamber and bubble chamber

The cloud chamber was invented by C.T.R. Wilson the beginning of XX century, and was an instrument for reconstructing the trajectories of charged cosmic rays. The instrument is a container with a glass window, filled with air and saturated water vapour (Figure 4.8); the volume can be suddenly expanded, and the adiabatic expansion causes the temperature to drop bringing the vapour to a supersaturated (metastable) state. A charged particle crossing the chamber produces ions, which act as seeds for the generation of droplets along the trajectory. One can record the trajectory by taking a photographic picture. If the chamber is immersed in a magnetic field $B$, momentum and charge can be measured by the curvature.
Figure 4.7: Range of heavy charged particles in liquid (bubble chamber) hydrogen, helium gas, carbon, iron, and lead. For example: For a $K^+$ whose momentum is 700 MeV/c, $\beta\gamma \simeq 1.42$. For lead we read $R/M \simeq 396$, and so the range is 195 g/cm$^2$ [?].
The working principle of bubble chambers (Figure 4.9) is similar to that of the cloud chamber, but here the fluid is a liquid. Along the tracks’ trajectories, a trail of gas bubbles evaporates around the ions.

Due to the higher density of liquids compared with gases, the interaction probability is larger, and bubble chambers act at the same time both as target and as detector. Different liquids can be used, depending on the type of experiment: hydrogen to have protons as a target nucleus, deuterium to study interactions on neutrons, etc. The weak point of such detector is dead time; however, from 1950 to 1980, before the advent of electronic detectors, bubble chambers were the reference tracking detectors. Very large chambers were built (the Big European Bubble Chamber BEBC now displayed at the entrance of the CERN exhibition is a cylinder with an active volume of 35 cubic meters), and wonderful pictures have been recorded.

Bubble and cloud chambers provide a complete information: the measurement of the bubble density (their number per unit length) provides an estimate for the specific ionisation energy loss \( dE/dx \), hence \( \beta\gamma = p/Mc \); the range, i.e., the total track length before the particle eventually stops (if the stopping point is recorded), provides an estimate for the initial energy; the multiple scattering (see below) provides an estimate for the momentum.

A weak point of cloud bubble chambers is the dead time: after an expansion, the fluid must be re-compressed. This might take a time ranging from some 50 ms for small chambers (LEBC, the Little European Bubble Chamber, used in the beginning of the 1980s for the study of the production and decay of particles containing the quark charm, had an active volume of less than a liter) to several seconds. Due to this limitation and to the labor-consuming visual scanning of the photographs, bubble chambers have been abandoned in the 1980s (cloud chambers had been abandoned much before).
Nuclear emulsions

A nuclear emulsion plate is a photographic plate with a particularly thick emulsion layer and with a very uniform grain size. Like bubble chambers and cloud chambers they record the tracks of charged particles passing through, by changing the chemical status of grains that have absorbed photons (which makes them visible after photographic processing). They are compact, have high density and produce a cumulative record, but have the disadvantage that the plates must be developed before the tracks can be observed.

Nuclear emulsions have very good space resolution of the order of few µm. They had great importance in the beginning of cosmic-ray physics; they are still unsurpassed from what is related to single-point space resolution, and are still used for example in the OPERA experiment at Gran Sasso.

Ionization counter, proportional counter and Geiger-Müller counter

These three kinds of detectors have the same principle of operation: they consist of a tube filled with a gas, with a charged metal wire inside (Figure 4.10). When a charged particle enters the detector, it ionizes the gas, and the ions and the electrons can be collected by the wire and by the walls (the mobility of electrons being larger than the mobility of ions, it is convenient that the wire’s potential is positive). The electrical signal of the wire can be amplified and read by means of an amperometer. The tension $V$ of the wire must be larger than a threshold below which ions and electrons spontaneously recombine.

Depending on the tension $V$ of the wire, one can have three different regimes:

- The ionization chamber regime when $V < I/e$ (where $I$ is the ionization energy of the gas, and $e$ the electron charge). The primary ions produced

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Figure 4.9: Left: the BEBC bubble chamber. Center: A picture taken in BEBC, and Right: its interpretation.
by the track are collected by the wire, and the signal is then proportional to the energy released by the particle.

- The proportional counter regime when $V > I/e$, but $V$ is smaller than a breakdown potential $V_{GM}$ (see below). The ions and the electrons are then accelerated at an energy such that they can in turn ionize the gas. The signal is thus amplified and it generates an avalanche of electrons around the anode. The signal is then proportional to the energy of the incident particle.

- Above a potential $V_{GM}$, the gas is completely ionized; the signal is then a short pulse of height independent of the energy of the particle (Geiger-Müller regime). Geiger-Müller tubes are also appropriate for detecting gamma radiation, since a photoelectron can generate an avalanche.

**Wire chamber**

The multiwire chamber is basically a sequence of proportional counters. Tubes are replaced by two parallel cathodic planes; the typical distance between the planes is 1 to 2 cm and the typical distance between the anodic wires is 1 mm (Figure 4.11). A charged particle deposits the ionization charge on the closest wire, inducing an electric current; by a sequence of two parallel detectors with the wires aligned perpendicularly one can determine the position of a particle. The typical response time is of the order of 30 ns.

**Streamer chamber and flash chamber**

These are multianode (can be multiwire) chambers operating in the Geiger-Müller regime. Short electric pulses of the order of 10 kV/cm are sent between subsequent planes; when a particle passes in the chamber, it can generate a series of discharges which can be visible – a sequence of flashes along the trajectory, Figure 4.12.
Drift chamber

The drift chamber is a multiwire chamber in which spatial resolution is achieved by measuring the time electrons need to reach the anode wire, starting from the moment that the ionizing particle traversed the detector. This results in wider wire spacing with respect to what can be obtained using multiwire proportional chambers. Fewer channels have to be equipped with electronics, but the overall space resolution can be comparable; in addition, they are often coupled to high-precision space measurement devices like silicon detectors (see below).

Drift chambers use longer drift distances, hence can be slower than multiwire chambers [?]. Since the drift distance can be long and drift velocity needs to be well known, the shape and constancy of the electric field needs to be carefully adjusted and controlled. To do this, besides the anode (signal) wires, thick field-shaping cathode wires called field wires are often used.

An extreme case is given by time projection chambers (TPC), for which drift lengths can be very large (up to 2 m), and the sense wires are arranged in one end face; the signals induced in pads or strips near the sense wire plane can be used to obtain three-dimensional information.

Semiconductor detectors

Silicon microstrip detectors are are solid-state particle detectors, whose principle of operation is similar to that of a ionization chamber: the passage of ionizing
particles produces in them a number of electron-hole pairs proportional to the energy released.

The electron-hole pairs are collected thanks to an electric field, and generate an electrical signal.

The main feature of silicon detectors is the small energy required to create an electron-hole pair – about 3.6 eV, compared with about 30 eV necessary to ionize an atom in an Ar gas ionization chamber.

Furthermore, compared to gaseous detectors, they are characterized by a high density and a high stopping power, much greater than that of the gas detectors: they can thus be very thin, typically about 300 µm.

The general pattern of a silicon microstrip detector is shown in Figure 4.13. The distance between two adjacent strips is the pitch and can be of the order of 100 µm, as the width of each strip.

From the signal collected on the strip one can tell if a particle has passed through the detector. The accuracy can be smaller than the size and the pitch: the charge sharing between adjacent strips improves the resolution to some 10 µm. As in the case of multiwire chambers, the usual geometry involves adjacent parallel planes of mutually perpendicular strips.

A recent implementation of semiconductor detectors is the Silicon pixel detector. Wafers of silicon are segmented into little squares (the pixels) that are as small as 100 µm on a side. Electronics is more expensive (however with modern technology it can be bonded to the sensors themselves): the advantage is that one can measure directly the hits getting rid of ambiguities.

**Scintillators**

Scintillators are among the oldest particle detectors. They are slabs of transparent material, organic or inorganic; the ionization induces fluorescence, and the light is conveyed towards a photosensors (photosensors will be described later). The light yield is large (can be as large as $10^4$ photons per MeV of energy de-
posed), and the time of formation of the signal is very fast (typically less than 1 ns): they are appropriate for the use in trigger systems.

To make the light to travel efficiently towards the photosensor (photomultiplier), light guides are frequently used (Figure 4.14). Sometimes the fluorescence is dominated by low wavelengths; in this case it is appropriate to match the photosensor with a wavelength shifter (a material which induces absorption of light and re-emission in an appropriate wavelength).

The scintillators can be used as tracking devices, in the so-called “hodoscope” configuration (from the Greek "hodos" for path, and "skope" for observation). The experimenter could use two segments shaped like strips, arranged in two layers. One layer of strips could be arranged horizontally, while a second layer could be arranged vertically. A particle passing through the wall would hit a strip in each layer; the vertical scintillator strip would reveal the particle's horizontal position when it crossed the wall, while the horizontal strip would indicate the particle's vertical position (as in the case of two wire chambers with perpendicular orientation of the wires, but with poorer resolution). Scintillator hodoscopes are some of the cheapest detectors for tracking charged particles.

Resistive-Plate Chambers

The resistive-plate chamber (RPC) is a low-cost alternative to large scintillator planes. Most commonly, an RPC is constructed from two parallel high-resistivity glass or melaminic plates with a gap of a few millimeters between them, which is filled with gas at atmospheric pressure. A high potential (of the order of 10 kV) is maintained between the plates.

The passage of a charged particle initiates an electric discharge, whose size and duration are limited since the current reduces the local potential to below that needed to maintain the discharge. The signal induced can be read by metallic strips on both sides of the detector and outside the gas chamber; such strips are separated from the high voltage coatings by thin insulating sheets.

Comparison of the performance of tracking detectors

The main characteristics of tracking detectors are summarized in Table 4.1.
Detector type | Space resolution | Time resolution | Dead time
---|---|---|---
RPC | ≤ 10 mm | ∼ 1 ns | –
Scintillation counter | 10 mm | 0.1 ns | 10 ns
Emulsion | 1 µm | – | –
Bubble chamber | 10 – 100 µm | 1 ns | 50 ms- 1 s
Proportional chamber | 50 – 100 µm | 2 ns | 20-200 ns
Drift chamber | 50 – 100 µm | few ns | 20-200 ns
Silicon strip | Pitch/5 (few µm) | few ns | 50 ns
Silicon pixel | 10 µm | few ns | 50 ns

Table 4.1: Typical characteristics of different kinds of tracking detectors (data come from [?]).

4.2.2 Photosensors

Most detectors in particle physics and astrophysics rely on the detection of photons near the visible range, i.e., in the eV energy range. This range covers scintillation and Cherenkov radiation as well as the light detected in many astronomical observations.

Essentially, one needs to extract a measurable signal from a (usually very small) number of incident photons. This goal can be achieved by generating a primary photoelectron or electron-hole pair by an incident photon (typically by photoelectric effect), amplifying the signal to a detectable level (usually by a sequence of avalanche processes), and collecting the secondary charges to form the electrical signal.

The important characteristics of a photodetector include the quantum efficiency QE (the probability that a primary photon generates a photoelectron), the collection efficiency C (the overall acceptance factor), the gain G (the number of electrons collected for each photoelectron generated), Dark Noise (the electrical signal when there is no photon), and the intrinsic response time of the detector.

Several kinds of photosensor are used in experiments.

Photomultiplier tubes

Photomultiplier tubes (photomultipliers or PMTs for short) are detectors of light in the ultraviolet, visible, and near-infrared ranges of the electromagnetic spectrum; they are the oldest photon detectors used in high energy particle and astroparticle physics.

They are constructed (Figure 4.15) from a glass envelope with a high vacuum inside, housing a photocathode, several intermediate electrodes called dynodes, and an anode. Incident photons strike the photocathode material, which is present as a thin deposit on the entry window of the device, with electrons
being produced as a consequence of the photoelectric effect. These electrons are directed by the focusing electrode toward the electron multiplier, where electrons are multiplied by the process of secondary emission.

The electron multiplier consists of a number of dynodes. Each dynode is held at a more positive voltage than the previous one (the typical total voltage in the avalanche process being of 1kV - 2kV). The electrons leave the photocathode, having the energy of the incoming photon (minus the work function of the photocathode). As the electrons move toward the first dynode, they are accelerated by the electric field and arrive with much greater energy. Upon striking the first dynode, more low energy electrons are emitted, and these electrons in turn are accelerated towards the second dynode. The geometry of the dynode chain is such that a cascade occurs with an ever-increasing number of electrons being produced at each stage. Finally, the electrons reach the anode, where the accumulation of charge results in a sharp current pulse indicating the arrival of a photon at the photocathode.

The photocathodes can be made of a variety of materials, with different properties. Typically these materials have low work function.

The typical quantum efficiency of a photomultiplier is about 30% in the range from 300 nm to 800 nm of wavelength for the light, and the gain $G$ is in the range $10^5$ to $10^6$.

A recent improvement to the photomultiplier was obtained thanks to hybrid photon detectors (HPD), in which a vacuum PMT is coupled to a Silicon sensor. A photoelectron ejected from the photocathode is accelerated through a potential difference of about $V \approx 20$ kV before it impinges on a silicon sensor/anode. The number of electron-hole pairs that can be created in a single acceleration step is $G \sim eV/(3.6 \text{ eV})$, the denominator being the mean energy required to create an electron-hole pair.

**Gaseous photon detectors**

In gaseous photomultipliers (GPM) a photoelectron in a suitable gas mixture (a gas with low photoionization work function, like the tetra dimethyl-amine
ethylene TMAE) starts an avalanche in a high-field region, producing a large number of secondary ionization electrons. The charge multiplication and collection processes are identical to those employed in gaseous tracking detectors.

Since GPMs can have a good space resolution and can be made into flat panels to cover large areas, they are often used as position-sensitive photon detectors. Many of the ring imaging Cherenkov (RICH) detectors (see later) use GPM as sensors.

**Solid-state photon detectors**

Semiconductor photodiodes were developed during World War II, approximately at the same time when the photomultiplier tube became a commercial product. Only in recent years, however, a technique was engineered which allows the Geiger-mode avalanche in Silicon, and the semiconductor photodetectors reached sensitivities comparable to photomultiplier tubes. Solid-state photodetectors (often called SiPM) are more compact, lightweight, and they might become cheaper than traditional PMTs in the near future. They also allow fine pixelization, of the order of 1 mm × 1 mm, are easy to integrate into large systems, and can operate at low electric potentials.

One of the most promising recent developments in the field is the construction of large arrays of tiny avalanche photodiodes (APD) packed over a small area and operated in Geiger mode.

?? Specify advantages and disadvantages of SiPM and solid-state photon detectors.

**4.2.3 Cherenkov detectors**

Cherenkov detectors use photodetectors to detect Cherenkov photons. The yield of Cherenkov radiation us usually generous so to make these detectors performant.

If one does not need particle identification, a cheap medium (radiator) with large \( n \) can be used so to have a threshold for the emission as low as possible. A typical radiator is water, with \( n \approx 1.33 \). The IceCube detector in Antarctica uses ice as a radiator (the photomultipliers are embedded in the ice).

Since the photon yield and the emission angle depend on the mass of the particle, some Cherenkov detectors are also used for particle identification.

Threshold Cherenkov detectors make a yes/no decision based on whether a particle is above or below the Cherenkov threshold velocity \( c/n \) – this fact depends on the velocity; if the momentum has been measured, it is in practice a threshold measurement on the value of the mass. A more advanced version of such detectors uses the number of observed photoelectrons to discriminate between species.

Imaging Cherenkov detectors measure the ring-correlated angles of emission of the individual Cherenkov photons. Since low-energy photon detectors can measure the position (and, sometimes, the arrival time) of the individual Cherenkov photons, the photons must be “imaged” onto a detector so that their
angles can be derived. Typically the optics map the Cherenkov cone onto (a portion of) a conical section at the photodetector.

Among imaging detectors, in RICH detectors, a cone of Cherenkov light is produced when a high speed charged particle traverses a suitable gaseous or liquid radiator. This light cone is detected on a position sensitive planar photon detector, which allows reconstructing a ring or disc, the radius of which is a measure for the Cherenkov emission angle. Both focusing and proximity-focusing detectors are in use. In a focusing detector, the photons are collected by a spherical mirror and focused onto the photon detector placed at the focal plane. The result is a conic section (a circle for normal incidence); it can be demonstrated that the radius of the circle is independent of the emission point along the particle track. This scheme is suitable for low refractive index radiators, as gases, due to the larger radiator length needed to create enough photons. In the more compact proximity-focusing design, a thin radiator volume emits a cone of Cherenkov light which traverses a small distance - the proximity gap - and is detected on the photon detector plane. The image is a ring of light, the radius of which is defined by the Cherenkov emission angle and the proximity gap.

Atmospheric Cherenkov telescopes for high-energy γ astrophysics are also in use. If one uses a parabolic telescope, again the projection of the emission by a particle along its trajectory is a conical section in the focal plane. If the particle has generated a shower, the projection is a spot, whose shape can allow distinguishing if the primary particle was a hadron or an electromagnetic particle (electron, positron or photon).

4.2.4 Transition radiation detectors

The main problem in the transition radiation detectors (TRD) is given by the low number of photons. In order to intensify the photon flux, periodic arrangements of a large number of foils are in use, interleaved by X-ray detectors, e.g. multiwire proportional chambers filled with xenon or a xenon/CO₂ mixture. Thin foils of lithium, polyethylene or carbon are common. Randomly spaced radiators are also in use, like foams.

4.2.5 Calorimeters

Once entering an absorbing medium, particles undergo successive interactions and decays, until their energy is degraded. Calorimeters are blocks of matter in which the energy a particle is measured through the absorption to the level of detectable atomic ionizations and excitations. Such detectors can be used to measure not only the energy, but also the spatial position, the direction and, in some cases, the nature of the primary particle.

Electromagnetic showers

Electrons of large energy lose most of their energy by radiation. Hence by the interaction of high energy electrons with matter only a small fraction of the
energy is dissipated, while a large portion is spent in the production of photons of high energy. The secondary photons, in turn, undergo pair production (or, at lower energies, Compton scattering); in the first case, electrons and positrons can in turn radiate. This phenomenon continues generating cascades (showers) of electromagnetic particles; at each step the number of particles increases while the average energy decreases, until the energy falls below the critical energy.

Given the characteristics of the interactions of electrons/positrons and of photons with matter, it is natural to describe the process of electromagnetic cascades in terms of the scaled distance

\[ t = \frac{x}{X_0} \]

and of the scaled energy

\[ \epsilon = \frac{E}{E_c}; \]

since the opening angles for Bremsstrahlung and pair production are small, the process can be in first approximation (above the critical energy) considered as one-dimensional (the lateral spread will be discussed at the end of this section).

A simple approximation, by Heitler, assumes that:

- the incoming charged particles have a starting energy \(E_0\) much larger than the critical energy \(E_c\);
- each electron travels one radiation length and then gives up half of its energy to a bremsstrahlung photon;
- each photon travels one radiation length creates an electron-positron pair with each particle carrying away half the energy of the original photon.

In the above model, asymptotic formulas for radiation and pair production are assumed to be valid; the Compton effect and the collision processes are neglected. The branching stops abruptly when \(E = E_c\), and then electrons and positrons lose their energy by ionization.

The model is schematically shown in Figure 4.16. This simple branching model suggests that after \(t\) radiation lengths the shower will contain \(2^t\) particles. There will be roughly equal numbers electrons, positrons and photons each with an average energy given by

\[ E(t) = \frac{E_0}{2^t}. \]

The cascading process will stop abruptly when \(E(t) = E_c\). The thickness of absorber at which the cascade ceases, \(t_{max}\), can be written in terms of the initial and critical energies:

\[ t_{max} = \frac{\ln(E_0/E_c)}{\ln 2}, \]

and the number of particles at this point will be

\[ N_{max} = \frac{E_0}{E_c} = y. \]
Figure 4.16: Scheme of the Heitler approximation for the development of an electromagnetic shower.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Incident electron</th>
<th>Incident photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak of shower $t_{max}$</td>
<td>$1.0 \times (\ln y - 1)$</td>
<td>$1.0 \times (\ln y - 0.5)$</td>
</tr>
<tr>
<td>Centre of gravity $t_{med}$</td>
<td>$t_{max} + 1.4$</td>
<td>$t_{max} + 1.7$</td>
</tr>
<tr>
<td>Number of $e^+$ and $e^-$ at peak</td>
<td>$0.3y/\sqrt{\ln y} - 0.37y$</td>
<td>$0.3y/\sqrt{\ln y} - 0.31y$</td>
</tr>
<tr>
<td>Total track length</td>
<td>$y$</td>
<td>$y$</td>
</tr>
</tbody>
</table>

Table 4.2: Shower parameters according to Rossi approximation B.

The model suggests that the shower depth at the maximum varies as the logarithm of the primary energy, a feature that emerges from more sophisticated models of the process and is observed experimentally.

Rossi [?] computed analytically the development of a shower in the so-called “approximation B” in which electrons lose energy by ionization and bremsstrahlung (described by asymptotical formulae); photons undergo pair production, also described by asymptotical formulae. All the process is 1-dimensional. The results of the “Rossi approximation B” are summarized in the Table 4.2. In Rossi’s approximation, the number of particles grows exponentially in the beginning and up to the maximum, and then decreases as shown in Figure 4.17 and Figure 4.18.

A common parametrization of the longitudinal profile for a shower of initial energy $E_0$ is

$$\frac{dE}{dt} = E_0 \frac{\beta}{\Gamma(\alpha)} (\beta t)^{\alpha-1} e^{-\beta t},$$

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where $\Gamma$ is the Euler's gamma function. In the above approximation, $t_{\text{max}} = (\alpha - 1)/\beta$, which should be thus equal to $\ln(E_0/E_c) - C$ with $C = 1$ for an electron and $C = 0.5$ for a photon.

Fluctuations on the total track length are dominated by the fluctuations on the total number of particles, and thus they grow as $\sqrt{E_0}$.

However, most of the calculations are performed nowadays by Monte Carlo. Monte Carlo calculations of electromagnetic cascades have the advantages of using the exact cross sections for bremsstrahlung and pair production, the correct energy dependence of ionization loss, and including all electromagnetic interactions. Monte Carlo calculations, in addition, give correct account for the fluctuations in the shower development, as well as for the angular and lateral distribution of the shower particles. Rossi approximation B, however, is faster and represents a rather accurate model.

The transverse dimension of the shower is dictated by the so-called Molière radius $R_M$:

$$t \simeq \frac{21 \text{MeV}}{E_c} X_0.$$  

About 90% of the shower energy is deposited in a cylinder of radius $R_M$; about 95% in a radius of $2R_M$, and about 99% in a radius of $3R_M$. In air at NTP, $R_M \approx 80$ m, in water $R_M \approx 9$ cm.

A rule of thumb for the longitudinal containment of 95% of the shower is

$$T(95\%) = t_{\text{max}} + 0.08Z + 9.6X_0;$$  

an incomplete longitudinal containment badly increases fluctuations on the deposited energy.
Electromagnetic calorimeters

An ideal calorimeter should have a short radiation length and the signal should travel unimpeded through the absorber (homogeneous calorimeters). However, sometimes materials which can be good converters and conductors of the signals are very expensive: one then uses sampling calorimeters, where the degraded energy is measured in a number of sensitive layers separated by passive absorbers.

The performance of calorimeters is limited both by the unavoidable fluctuations of the elementary phenomena through which the energy is degraded and by the technique chosen to measure the final products of the cascade processes.

Homogeneous calorimeters. Homogeneous calorimeters may be built with heavy (high density, high $Z$) scintillating crystals, i.e., crystals in which ionization energy loss results in the emission of visible light, or Cherenkov radiators such as lead glass and lead fluoride. Scintillation light and/or ionization in noble liquids can be detected.

Sampling calorimeters. Layers of absorbers are typically alternated to layers of active material (sandwich geometry). Different geometries can be used: for example sometimes rods of active material cross the absorber (spaghetti geometry).

Figure 4.18: A Monte Carlo simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).
Converters have high density, short radiation length. Typical materials are Iron (Fe), Lead, Uranium. Typical active materials are plastic scintillator, Silicon, liquid ionization chamber gas detectors.

Disadvantages of sampling calorimeters are that only part of the deposited particle energy is detected in the active layers, typically a few percent (one or two orders of magnitude less for gas detectors). These sampling fluctuations typically result in a worse energy resolution for sampling calorimeters.

**Electromagnetic calorimeters: comparison of the performance.** The fractional energy resolution $\Delta E/E$ of a calorimeter can be parametrized as

$$\Delta E/E = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E},$$

where $\oplus$ represents addition in quadrature. The stochastic term $a$ represents statistics-related intrinsic fluctuations in the shower, photoelectron statistics, dead material at the front of the calorimeter, and sampling fluctuations – we remind that the number of particles is roughly proportional to the energy, and thus the Poisson statistics gives fluctuations $\propto \sqrt{E}$. While $a$ is at a few percent level for a homogeneous calorimeter, it is typically 10% for sampling calorimeters. The main contributions to the systematic, or constant, term $b$, are detector non-uniformity and calibration uncertainty. In the case of the hadronic cascades discussed below, non-compensation (?? define) also contributes to the constant term. The constant term $b$ can be reduced to below one percent. The term $c$ is due to electronic noise. Some of the above terms can be negligible in calorimeters.

The best energy resolution for electromagnetic shower measurement is obtained in total absorption homogeneous calorimeters, e.g., calorimeters built with heavy crystal scintillators like the Bi$_4$Ge$_3$O$_{12}$, called BGO). These are used when ultimate performance is pursued. A relatively cheap scintillator with relatively short $X_0$ is the Cesium Iodide CsI, which becomes more luminescent when activated with Tallium, and is called CsI(Tl); this is frequently used for dosimetry in medical applications.

Energy resolutions for some homogeneous and sampling calorimeters are listed in Table 4.3.

**Hadronic showers and calorimeters**

The concept of hadronic showers is similar to the concept of electromagnetic showers: primary hadrons can undergo a sequence of interactions and decays creating a cascade. However, on top of electromagnetic interactions one has now nuclear reactions. In addition, in hadronic collisions with nuclei of the material, a significant part of the primary energy is consumed in the nuclear processes (excitation, emission nucleons low energy etc.). One thus needs ad-hoc Monte Carlo corrections to account for the energy lost, and fluctuations are larger. The development of appropriate Monte Carlo codes for hadronic interactions has been a problem in itself, and still the calculation require huge computational
<table>
<thead>
<tr>
<th>Technology (experiment)</th>
<th>Depth ($X_0$)</th>
<th>Energy resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGO (L3)</td>
<td>22</td>
<td>$2%\sqrt{E} + 0.7%$</td>
</tr>
<tr>
<td>CsI (kTeV)</td>
<td>27</td>
<td>$2%\sqrt{E} + 0.45%$</td>
</tr>
<tr>
<td>PbWO$_4$ (CMS)</td>
<td>25</td>
<td>$3%\sqrt{E} + 0.5% + 0.2%/E$</td>
</tr>
<tr>
<td>Lead glass (DELPHI, OPAL)</td>
<td>20</td>
<td>$5%\sqrt{E}$</td>
</tr>
<tr>
<td>Scintillator/Pb (CDF)</td>
<td>18</td>
<td>$18.5%\sqrt{E}$</td>
</tr>
<tr>
<td>Liquid Ar/Pb (SLD)</td>
<td>21</td>
<td>$12%\sqrt{E}$</td>
</tr>
</tbody>
</table>

Table 4.3: Main characteristics of some electromagnetic calorimeters (data from [?]).

loads. At the end of a hadronic cascade, most of the particles are pions, and one third of the pions are neutral and decay almost instantaneously ($\tau \sim 10^{-16}$ s) into a pair of photons; thus in average one third of the hadronic cascade (but it can be more or less, subject to fluctuations) is indeed electromagnetic.

In first approximation, the development of the shower can be described by the inelastic hadronic interaction length $\lambda_H$; however, the approximation is worse than the scaling of electromagnetic reactions with $X_0$.

Detectors capable to absorb hadrons and detect a signal related to it were developed around 1950 for the study of cosmic rays. It was assumed that the energy of the incident particle was proportional to the multiplicity of charged particles.

Most large hadron calorimeters are sampling calorimeters which are parts of complicated detectors at colliding beam facilities. Typically, the basic structure of plates is absorber (Fe, Pb, Cu, or Occasionally U or W) alternating with plastic scintillators (plates, tiles, bars), liquid argon (LAr), or gaseous detectors (Figure 4.19). The ionization is measured directly, as in LAr calorimeters, or via scintillation light observed by photodetectors (usually photomultipliers).

The fluctuations in the invisible energy and in the and hadronic component of a shower contribute to the resolution of hadron calorimeters. As for the same energy of the incident particle the energy measurable in a hadronic shower is less than that in the electromagnetic part, the response to hadrons is not compensated with respect to the response to electromagnetic particles (or to the electromagnetic part of the hadronic shower).

Due to all these problems, typical fractional energy resolutions are in the order of $30%/\sqrt{E}$ to $50%/\sqrt{E}$.

### 4.3 High-energy particles

If we want to use a beam of particles as a microscope, like Rutherford did in his experiment, the minimum distance we can sample (for example, to probe a
possible substructure in matter) decreases with increasing energy. According to de Broglie’s equation, the relation between the momentum $p$ and the wavelength $\lambda$ of a wave packet is given by
\[
\lambda = \frac{h}{p}.
\]
Therefore, larger momenta correspond to shorter wavelengths and access to smaller structures. Particle acceleration is thus a fundamental tool for research in physics.

In addition, it is possible to use high-energy particles to produce new particles in collisions. This requires the more energy the more massive the particles we want to produce are.

### 4.3.1 Artificial accelerators

A particle accelerator is an instrument using electromagnetic fields accelerate charged particles at high energies.

There are two schemes of collision:

- collision of a beam with another beam running in opposite direction (collider experiments);
- collision with a fixed target (fixed-target experiments).

We also distinguish two main categories of accelerators depending on the geometry: linear accelerators and circular accelerators. In linear accelerators the bremsstrahlung energy loss is much reduced since there is no centripetal acceleration, but particles are wasted after a collision, while in circular accelerators the particles which did not interact can be re-used.
The center of mass energy $E_{CM}$ sets the scale for the maximum mass of the particles we can produce (the actual value being in general smaller due to constraints related to conservation laws). We want now to compare fixed target and colliding beam experiments concerning the available energy.

In the case of beam-target collisions between two particles of mass $m$ and energy $E$,

$$E_{CM} \simeq \sqrt{2mE}.$$  

This means that, in the case of a fixed target experiment, the center of mass energy grows only with square root of $E$. In beam-beam collisions, instead,

$$E_{CM} = 2E.$$ 

Therefore, it is much more efficient to use two beams in opposite directions. As a result, most of the recent experiments at accelerators are done at colliders.

Making two beams to collide, however, is not trivial: one must control the fact that the beams tend to defocus due to mutual repulsion. In addition, the Liouville theorem states that the phase space volume (the product of the spread in terms of the space coordinates times the spread in the momentum coordinate) of an isolated beam is constant: reducing the momentum dispersion is done at the expense of the space dispersion – and one needs small space dispersion in order that the particles in the beam actually collide. Beating the Liouville theorem requires feedback on the beam itself.

Since beams are circulated for several hours, circular accelerators are based on beams of stable particles and antiparticles, such as electrons, protons, and their antiparticles. In the future, muon colliders ??

The accelerators and detectors are often situated underground in order to provide the maximal shielding possible from natural radiation such as cosmic rays that would otherwise mask the events taking place inside the detector.

**Acceleration methods**

A particle of charge $q$ and speed $\vec{v}$ in an electric field $\vec{E}$ and a magnetic field $\vec{B}$ feels a force

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}).$$

The electric field can thus accelerate the particle; the work by the magnetic field is zero, nevertheless the magnetic field can be used to control the particle’s trajectory. For example, a magnetic field perpendicular to $\vec{v}$ can constrain the particle along a circular trajectory perpendicular to $\vec{B}$.

An acceleration line (which corresponds roughly to a linear accelerator) works as follows. In a beam pipe (a cylindrical tube in which vacuum has been made) cylindrical electrodes are aligned. A pulsed (radiofrequency RF) source of electromotive force $V$ is applied. Thus particles are accelerated when passing to the RF cavity (Figure 4.20): the period is adjusted in such a way that half of the period corresponds of the time needed to the particle to cross the cavity.
To have a large number of collisions, it is useful that particles are accelerated in bunches. This introduces an additional problem, since the particles tend to diverge due to mutual electrostatic repulsion. Divergence can be compensated thanks to focusing magnets (for example quadrupoles, which squeeze beams in a plane).

A collider consists of two circular or almost circular accelerator structures with vacuum pipes, magnets and accelerating cavities, in which two beams of particles travel in opposite directions. They may be both protons, or protons and antiprotons, or electrons and positrons, or electrons and protons, or also nuclei and nuclei. The two rings intercept each other at a few positions along the circumference, where bunches can cross and particles can interact. In a particle-antiparticle collider (electron-positron or proton-antiproton), as particles and antiparticles have opposite charges and the same mass, a single magnetic structure is sufficient to keep the two beams circulating in opposite directions.

**Parameters of an accelerator**

An important parameter for an accelerator is the maximum centre-of-mass (c.m.) energy available, since this sets the maximum mass of new particles that can be produced.

Another important parameter is luminosity, already discussed in Chapter 2. Imagine a physical process has a cross section $\sigma_{\text{proc}}$; the number of outcomes of
this process per unit time can be expressed as

\[ \frac{dN_{\text{proc}}}{dt} = \frac{dL}{dt} \sigma_{\text{proc}}. \]

\( dL/dt \) is called differential luminosity of the accelerator, and is measured in cm\(^{-2}\) s\(^{-1}\); however, for practical reasons it is customary to use “inverse barns” and its multiples instead of cm\(^{-2}\) (careful: due to the definition, 1 mbarn\(^{-1}\) = 1000 barn\(^{-1}\)).

The integrated luminosity can be obtained by integrating the differential luminosity over the time of operation of an accelerator:

\[ L = \int_{\text{time of operation}} dL(t) \frac{dt}{dt}. \]

In a collider, the luminosity is proportional to the product of the numbers of particles, \( n_1 \) and \( n_2 \), in the two beams. Notice that in a proton-antiproton collider the number of antiprotons is smaller than that of protons, due to the cost of the antiprotons. The luminosity is also proportional to the number of crossings in a second \( f \) and inversely proportional to the transverse section \( A \) at the intersection point

\[ \frac{dL}{dt} = fn_1n_2/A. \]

### 4.3.2 Cosmic rays as very-high-energy beams

As we have already shown, cosmic rays can attain energies much larger than human-made accelerators.

The distribution in energy (the so-called spectrum) of cosmic rays is quite well described by a power law \( E^{-p} \) with \( p \) a positive number (Figure ??). The so-called spectral index \( p \) is the slope is around 3 in average. After the low energy region dominated by cosmic rays from the Sun (the so-called solar wind), the spectrum becomes steeper for energy values of less than \( \sim 1000 \) TeV (150 times the maximum energy foreseen for the beams of the LHC collider at CERN): this is the energy region that we know to be dominated by cosmic rays produced by astrophysical sources in our galaxy, the Milky Way. For higher energies a further steepening occurs, the point at which this change of slope takes place being called the “knee”; we believe that this region is dominated by cosmic rays produced by extragalactic sources. For even higher energies (more than one million TeV) the cosmic-ray spectrum becomes less steep, resulting in another change of slope called the “ankle”.

The majority of the high-energy particles in cosmic rays are protons (hydrogen nuclei); about 10% are helium nuclei (nuclear physicists call them usually “alpha particles”), and 1% are neutrons or nuclei of heavier elements. These together account for 99% of the cosmic rays, and electrons and photons make up the remaining 1%. The number of neutrinos is estimated to be comparable to that of high-energy photons, but it is very high at low energy because
of the nuclear processes that occur in the Sun: such processes involve a large production of neutrinos.

Cosmic rays hitting the atmosphere (called primary cosmic rays) generally produce secondary particles that can reach the Earth’s surface, through multiplicative showers.

About once per second, a single subatomic particle enters the Earth’s atmosphere with an energy larger than 10 J. Somewhere in the Universe there are accelerators that can impart to a single proton energies 100 million times larger than the energy of the most powerful accelerators on Earth. We believe that the ultimate engine of the acceleration of cosmic rays is gravity, and these are the remnants of gigantic gravitational collapses, in which part of the potential gravitational energy is transformed, through mechanisms not yet fully understood, into kinetic energy of the particles. The reason why human-made accelerators cannot compete with cosmic acceleration is simple. Acceleration requires confinement within a radius $R$ by a magnetic field $B$, and the final energy is proportional to the product of $R$ times $B$. On Earth, it is difficult to imagine reasonable radii of confinement greater than one hundred kilometers and magnetic fields stronger than ten tesla (one hundred thousand times the Earth’s magnetic field). This combination can provide energies of a few tens of TeV, such as those of the LHC accelerator at CERN. In nature there are accelerators with much larger radii, as the remnants of supernovae (hundreds of light years) and active galactic nuclei of galaxies (tens of thousands of light years): one can thus reach energies as large as $10^{21}$ eV.

The conditions are clearly illustrated by the so-called Hillas plot (Figure 4.21).

We shall see, however, that around $10^{21}$ eV there is an intrinsic limitation affecting also the energy of cosmic rays.

4.4 Detector systems and experiments at accelerators

Detectors at experimental facilities are in general hybrid, i.e., they combine many of the detectors discussed so far, such as the drift chambers, Cherenkov detectors, electromagnetic and hadronic calorimeters. They are built up in a sequence of layers, each one designed to measure a specific aspect of the particles produced after the collision.

Starting with the innermost layer the successive layers are typically:

- A tracking system: this is designed to track all the charged particles and allow for complete event reconstruction. It is in general the first layer
crossed by the particles, in such a way that their properties have not yet been deteriorated by the interaction with the material of the detector. It should have as little material as possible, so to preserve the particles for the subsequent layer.

- A layer devoted to electromagnetic calorimetry.
- A layer devoted to hadronic calorimetry.
- A layer of muon tracking chambers: any particle releasing signal on these tracking detectors (often drift chambers) has necessarily travelled through all the other layers and is very likely a muon$^6$.

The particle species can be identified by energy loss, curvature in magnetic field and Cherenkov radiation. However, the search for the identity of a particle can be significantly narrowed down by simply examining which parts of the detector it deposits energy in:

- Photons leave no tracks in the tracking detectors (unless they undergo pair production) but produce a shower in the electromagnetic calorimeter.
- Electrons and positrons leave a track in the tracking detectors and produce a shower in the electromagnetic calorimeter.
- Muons leave tracks in all the detectors (likely as a mip in the calorimeters).
- Long-lived charged hadrons (protons for example) leave tracks in all the detectors up to the hadronic calorimeter where they shower and deposit all their energy.
- Neutrinos are identified by missing energy-momentum when the relevant conservation law is applied to the event.

The signatures are summarized in Figure 4.22.

### 4.4.1 Examples of detectors for fixed-target experiments

In a fixed target experiment, relativistic effects make the interaction products to be highly collimated. In such experiments then, in order to enhance the possibility of detection in the small-$x_T$ ($x_T = p_T/\sqrt{s}$, where $p_T$ is the momentum component perpendicular to the beam direction), different stages are separated by magnets opening up the charged particles in the final state (lever arms).

The first detectors along the beam line should be non-destructive; at the end of the beam line, one can have calorimeters. An example is given in the following.
Figure 4.22: Overview of the signatures by a particle in a multilayer hybrid detector.

Figure 4.23: A configuration of the European Hybrid Spectrometer (a fixed target detector at the CERN Super-Proton Synchrotron).
The European Hybrid Spectrometer at the SPS

The European Hybrid Spectrometer EHS has been operational during the years 1970s and the beginning of the 1980s at the North Area of CERN, where beams of protons were extracted from the SPS accelerator at energies of 300 GeV-400 GeV. They might possibly generate secondary beams of charged pions of slightly smaller energies by a beam-dump and a velocity selector based on magnetic field. EHS was a multi-stage detector serving different experiments (NA16, NA22, NA23, NA27). Here we describe a typical configuration; Figure 4.23 shows a schematic drawing of the EHS set-up.

In the Figure, the beam particles come in from the left. Their direction is determined by the two small wire chambers U1 and U3. From the collision point inside a rapid cycling bubble chamber(RCBC; LEBC for example) most of the produced particles will enter the downstream part of the spectrometer. The fast ones (typically with momentum \( p > 30 \text{ GeV}/c \)) will go through the aperture of the magnet M2 to the so-called second lever arm.

The RCBC acts both as a target and as a vertex detector. If an event is triggered, stereopictures are taken with 3 cameras and recorded on film.

The momentum resolution of the secondary tracks depends on the number of detector element hits available for the fits. For low momentum tracks, typically \( p < 3 \text{ GeV}/c \), length and direction of the momentum vector at the collision-point can be well determined from RCBC. On the other hand, tracks with \( p < 3 \text{ GeV}/c \) have a very good chance to enter the so-called 1st lever arm. This is defined by the group of 4 wire chambers W2, D1, D2 and D3 placed between the two magnets M1 and M2.

Fast tracks, typically \( p > 50 \text{ GeV}/c \), have a good chance to go in addition through the gap of the magnet M2 and enter the 2nd lever arm, consisting of the 3 drift chambers D4, D5 and D6.

To detect gammas, two electromagnetic calorimeters are used in EHS, the intermediate gamma detector (IGD) and the forward gamma detector (FGD). IGD is placed before the magnet M2. It has a central hole to allow fast particles to pass into the second lever arm. FGD covers this hole at the end of the spectrometer. The IGD has been designed to measure both position and energy of a shower in a two-dimensional matrix of lead-glass counters 5cm × 5cm in size, each of them connected to a PMT. The FGD consists of three separate sections. The first section is the converter, a lead glass wall, to initiate the electromagnetic shower. The second section, the position detector, is a three-plane scintillator hodoscope with a finger width of 1.5 cm. The third section is the absorber, a lead-glass matrix deep enough (60 rad. length) to totally absorb showers up to the highest available energies. For both calorimeters, the relative accuracy on energy reconstruction was \( \Delta E/E \simeq 0.1/\sqrt{E} \pm 0.02 \).

Neutrinos have extremely low interaction cross sections. Most probably they cross also the muon chambers without leaving any signal.

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4.4.2 Examples of detectors for colliders

The modern particle detectors in use today at colliders are as much as possible hermetic detectors. They are designed to cover as much as possible of the solid angle around the interaction point (a limitation being given by the presence of the beam pipe). The typical detector consists of a cylindrical section covering the “barrel” region and two endcaps covering the “forward” regions.

In the standard coordinate system, the $z$ axis is along the beam direction, the $x$ axis points towards the centre of the ring, and the $y$ axis points upwards. The polar angle to the $z$ axis is called $\theta$ and the azimuthal angle around the $z$ axis is called $\phi$; the radial coordinate is $R = \sqrt{x^2 + y^2}$.

Frequently the polar angle is replaced by a coordinate called pseudorapidity $\eta$ and defined as

$$\eta = \ln \left( \tan \left( \frac{\theta}{2} \right) \right);$$

the region $\eta \approx 0$ corresponds to $\theta \approx \pi/2$, and is called the central region.

The detector has the typical onion-like structure described in the previous section: a sequence of layers, the innermost being the most precise for tracking.

The configuration of the endcaps is similar to that in a fixed-target experiment except for the necessary presence of a beampipe, which makes it impossible to detect particles at very small polar angles, and entails the possible production of secondary particles in the pipe wall.

We analyze three generations of collider detectors operating at the European Organization for Particle Physics, CERN: UA1 at the SPS $p \bar{p}$ accelerator, DELPHI at the LEP $e^+e^-$ accelerator, CMS at the LHC $pp$ accelerator. We shall see how much the technology developed and the required labour increased; the basic idea is anyway still in one of the prototype detectors, UA1.

UA1 at the $Sp\bar{p}S$

The UA1 experiment, named as the first experiment in the CERN Underground Area (UA), was a high-energy physics experiment running at CERN’s $Sp\bar{p}S$ (Super-proton-antiproton-Synchrotron) accelerator-collider from 1981 till 1993. The discovery of the $W$ and $Z$ bosons, mediators of the weak interaction, by this experiment in 1983, led to the Nobel Prize for physics to Carlo Rubbia and Simon van der Meer in 1984 (the motivation of the prize being more related to the development of the collider technology). The $Sp\bar{p}S$ was colliding protons and antiprotons at a typical c.m. energy of 540 GeV; 3 bunches of protons and 3 bunches of antiprotons, $10^{11}$ particles per bunch, were colliding, and the luminosity was about $5 \times 10^{27}$ cm$^{-2}$/s (5 inverse millibarn per second).

UA1 was a huge and complex detector for its day, and it was and still is the prototype of collider detectors. The collaboration constructing and managing the detector included approximately 130 scientists from all around the world.

UA1 was a general-purpose detector. The central tracking chamber was an assembly of 6 drift chambers 5.8 m long and 2.3 m in diameter. It recorded the tracks of charged particles curving in a 0.7 T magnetic field, measuring their
momenta with typical accuracy $\delta p/p \simeq 0.01 p$ (GeV/c) and possibly identifying them by the specific energy loss $dE/dx$. The geometrical arrangement of the about 17000 field wires and 6125 sense wires allowed a three-dimensional reconstruction of events. UA1 introduced also the concept of event display (Figure 4.24).

After the tracking chamber and an air gap of 0.5 m, the particles next encounter the calorimeter plus 60 cm of additional iron shielding, including the magnet yoke. The calorimeter starts with an electromagnetic calorimeter made of a sandwich of lead and scintillator, with a total relative energy resolution about $0.2/\sqrt{E}$. The iron shielding is partially instrumented with streamer tubes measuring the position and the number of minimum ionizing particles, and thus, acting as a hadronic calorimeter with relative energy resolution about $0.8\sqrt{E}$. Together, the calorimeter and the shielding correspond to more than 8 interaction lengths of material, which almost completely absorb strongly interacting particles. Finally, muons are detected in the outer muon chambers, which cover about 75% of the solid angle in the pseudorapidity range $|\eta| < 2.3$. Muon trigger processors require tracks in the muon chambers which point back to the interaction region to retain an event as significant.

**DELPHI at LEP**

DELPHI (DEtector with Lepton Photon and Hadron Identification, Figure 4.25) is one of the four experiments built for the LEP (Large Electron-Positron) collider at CERN. The main aim of the experiment was the verification of the theory known as the Standard Model of particle physics. DELPHI started col-
lecting data in 1998 and it been running about 8 months per year, 24h a day, until the end of 2000; it recorded the products of collisions of electrons and positrons at c.m. energies from 80 GeV to 200 GeV (most of the data being taken at the Z peak, around 91.2 GeV). Typical luminosity was $2 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1}$ (20 inverse microbarn per second).

DELPHI has been built and operated by approximately 600 scientists from laboratories all over the world.

DELPHI consists of a central cylindrical section and two endcaps, in a solenoidal magnetic field of 1.2 T provided by a superconducting coil. The overall length and the diameter are over 10 meters and the total weight is 2500 tons.

The electron-positron collisions take place inside the vacuum pipe in the centre of DELPHI and the products of the annihilations fly radially outwards. The products of the annihilations are tracked by several layers of detectors and read out via some 200 000 electronic channels. A typical event requires about
The DELPHI detector is composed of subdetectors as described in Figure 4.25.

In the barrel part of the detector there was an onion-like structure of tracking detectors, the ones closest to the collision point being characterized by best resolution: the Silicon Vertex Detector (VD), a cylinder of proportional counters called the Inner Detector (ID), the Time Projection Chamber (TPC), another cylinder of proportional counters called the Outer Detector (OD) and the Barrel Muon Chambers (MUB). Also in the forward part, a sequence of tracking chambers: the Forward Silicon Detector, the Forward Chambers A and B (FCA and FCB), the Forward Muon Chambers (MUF) are devoted to precise measurement of the trajectories of charged particles, and hence to the precise determination of the directions and momenta of the charged particles.

The Time Projection Chamber (TPC), shown as the big cylinder in the figure, is the principal tracking device of DELPHI. As well it helps in charged particle identification by measuring the specific ionization energy loss $dE/dx$. It is a cylinder of 2x130 cm situated between the radii 29 cm and 122 cm. The detector provides points per particle trajectory at radii from 40 to 110 cm between polar angles from 39 to 141 degrees.

In the barrel part of the detector precise measurement of the trajectories varies from 5-10 micrometers for a single hit in the Vertex Detector, to a fraction of a millimeter in the Time Projection Chamber and to 1-3 mm in the Barrel Muon Chambers after traversing 5 m of the detector.

Electron and photon identification is provided primarily by the electromagnetic calorimetry system. This is composed mainly of a barrel calorimeter (HPC) and a forward calorimeter (FEMC); a smaller calorimeter in the forward region was used mainly for luminosity measurement. The High-density Projection Chamber (HPC) is the barrel electromagnetic calorimeter and is installed as a cylindrical layer outside the Outer Detector. It is mounted inside the solenoid. The HPC is a cylinder of 2x254 cm situated between the radii 208 cm and 260 cm and consists mainly of lead. The polar angle coverage is from 43 to 137 degrees. The Forward ElectroMagnetic Calorimeter (FEMC) is the forward electromagnetic calorimeter and consists of two 5 m diameter disks (made of lead-glass). The front faces are placed at $|z| = 284$ cm, covering the polar angles from 8 to 35 degrees and from 145 to 172 degrees.

The hadron calorimeter (HCAL) is a sampling gas detector incorporated in the magnet yoke (it consists mainly of iron), the barrel part covering polar angles from 42.6 to 137.4 degrees, and two end-caps from 11.2 to 48.5 degrees and from 131.5 to 168.8 degrees. It provides calorimetric energy measurements of charged and neutral hadrons (strongly interacting particles).

The identification of charged hadrons in DELPHI relied on the specific ionization energy loss per unit length in the TPC, and on two Ring Imaging Cherenkov (RICH) detectors. The Barrel RICH detector is located between the Time Projection Chamber and the Outer Detector. It is a 350 cm long cylinder with inner radius 123 cm and outer 197 cm, divided into two halves by a central support wall, 6.4 cm thick. It covers polar angles between 40 and 140
degrees. The Forward RICH Detector is located between $1.7 \, \text{m} < |z| < 2.7 \, \text{m}$ and covers polar angles between 15 and 35 degrees.

The overall performance of the DELPHI detector is summarized in Table 4.4; two reconstructed events are shown in Figure 4.26.

**CMS at LHC**

The Compact Muon Solenoid (CMS) experiment is one of two large general-purpose particle physics detectors built on the proton-proton Large Hadron Collider (LHC) at CERN. Approximately 3000 scientists, representing 183 research institutes and 38 countries, form the CMS collaboration who built and now since 2008 operate the detector. The detector is shown in Figure 4.27. Proton-proton collisions at c.m. energies of 8 TeV are recorded; typical luminosity is $7 \times 10^{34} \, \text{cm}^{-2}/\text{s}$ (70 inverse nanobarn per second).

As customary for collider detectors, CMS is structured in layers. Layer 1 is devoted to tracking. Immediately around the interaction point the inner silicon tracker serves to identify the tracks of individual particles.
and match them to the vertices from which they originated. The curvature of charged particle tracks in the magnetic field allows their charge and momentum to be measured. The CMS silicon tracker consists of 13 layers in the central region and 14 layers in the endcaps. The innermost three layers (up to 11 cm radius) consist of 100 \times 150 \mu m pixels, 66 million in total. The next four layers (up to 55 cm radius) consist of silicon strips. There are 9.6 million strip channels in total. This part of the detector is the world’s largest silicon detector; it has 205 m² of silicon sensors (approximately the area of a tennis court) comprising 76 million channels.

Layer 2 is devoted to Electromagnetic Calorimetry. The Electromagnetic Calorimeter (ECAL) is constructed from crystals of lead tungstate, PbWO₄; this is an extremely dense but optically clear material. It has a radiation length of 0.89 cm, and has a rapid light yield, with 80% of light yield within one crossing time (25 ns). The light yield is of about 30 photons per MeV of incident energy. The crystals used have a front size of 22 mm \times 22 mm and a depth of 23 cm. They are set in a matrix of carbon fibre to keep them optically isolated, and backed by silicon avalanche photodiodes for readout. The barrel region consists of about 60 thousand crystals, with a further about 7 thousand in each of the endcaps.

Layer 3 is devoted to Hadronic Calorimetry. The Hadronic Calorimeter (HCAL) consists of layers of dense material (brass or steel) interleaved with tiles of plastic scintillators, read out via wavelength-shifting fibres by hybrid photodiodes. This combination was determined to allow the maximum amount of absorbing material inside of the magnet coil.

Layer 4 is the magnet. It is 13 m long and 6 m in diameter, and it is a refrigerated superconducting niobium-titanium coil providing a solenoidal field of 3.8 T (the current being about 18000 A, giving a total stored energy of about 2.5 GJ, equivalent to about 500 kg of TNT; there are dump circuits to safely dissipate this energy should the magnet quench).

Layer 5 is occupied by the muon detectors and the return yoke. To identify muons and measure their momenta, CMS uses mostly drift tubes and RPCs. The drift tubes are used for precise trajectory measurements in the central barrel region. The RPCs provide a fast signal when a muon passes through the muon detector.

To have a good chance of producing a rare particle, such as a Higgs boson, a very large number of collisions is required. Most collision events in the detector do not produce interesting effects. The amount of raw data from each crossing is approximately 1 megabyte, which at the 40 MHz crossing rate would result in 40 terabytes of data a second, an amount that the experiment cannot hope to store or process properly. The trigger system reduces the rate of interesting events down to a manageable 100 per second. To accomplish this, a series of “trigger” stages are employed. All the data from each crossing are held in buffers within the detector while a small amount of key information is used to perform a fast, approximate calculation to identify features of interest such as high energy jets, muons or missing energy. This “Level 1” calculation is completed in around 1 \mu s, and the event rate is reduced by a factor of about thousand down to 50 kHz.
Table 4.5: Summary of the performance of CMS.

All these calculations are done on fast, custom hardware using reprogrammable field-programmable gate arrays (FPGA). If an event is passed by the Level 1 trigger, all the data still buffered in the detector are sent over fibre-optic links to the “High Level” trigger, which is software (mainly written in C++) running on ordinary computer servers. The lower event rate in the High Level trigger allows time for a much more detailed analysis of the event to be done than in the Level 1 trigger. The High Level trigger reduces the event rate by a further factor of about a thousand down to around 100 events per second.

The overall performance of the CMS detector is summarized in Table 4.5.
ADD events, and ATLAS ???
Something on pile-up ???