which is roughly an order of magnitude worse than the energy resolution for electromagnetic showers.

1.3 Collider experiments

At a particle accelerator, the colliding beams produce individual interactions referred to as *events*. The large particle physics detector systems use a wide range of technologies to detect and measure the properties of the particles produced in these high-energy collisions with the aim of reconstructing the primary particles produced in the interaction. In essence, one tries to go from the signals in the different detector systems back to the Feynman diagram responsible for the interaction.

The basic structure of a modern particle physics detector is indicated in Figure 1.18. In general, a detector consists of a cylindrical (or polygonal) barrel part, with its axis parallel to the incoming colliding beams. The cylindrical structure is closed by two flat end caps, providing almost complete solid angle coverage down to the beam pipe. The inner region of the detector is devoted to the tracking of charged particles. The tracking volume is surrounded by an electromagnetic calorimeter (ECAL) for detecting electrons and photons. The relatively large-volume hadronic calorimeter (HCAL) for detecting and measuring the energies of hadrons is located outside the ECAL. Dedicated detectors are positioned at the outside of the experiment to record the signals from any high-energy muons produced in the collisions, which are the only particles (apart from neutrinos) that can penetrate through the HCAL. In order to be able to measure the momenta of

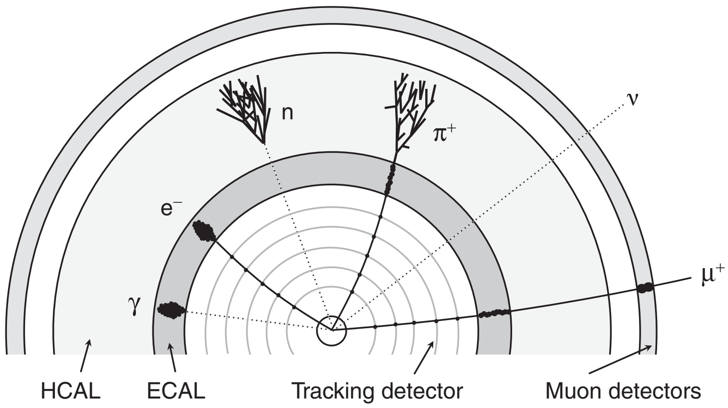

Fig. 1.18 The typical layout of a large particle physics detector consisting of a tracking system (here shown with cylindrical layers of a silicon detector), an electromagnetic calorimeter (ECAL), a hadron calorimeter (HCAL) and muon detectors. The solenoid used to produce the magnetic field is not shown. The typical signatures produced by different particles are shown.

charged particles, a detector usually has a solenoid which produces a strong axial magnetic field in the range $B = 1-4\,T$. The solenoid may be located between the tracking volume and the calorimeters.

The design of a collider experiment is optimised for the identification and energy measurement of the particles produced in high-energy collisions. The momenta of charged particles are obtained from the curvature of the reconstructed tracks. The energies of neutral particles are obtained from the calorimeters. Particle identification is achieved by comparing the energy deposits in the different detector systems as indicated in Figure 1.18. Photons appear as isolated energy deposits in the ECAL. Electrons are identified as charged-particle tracks that are associated with an electromagnetic shower in the ECAL. Neutral hadrons will usually interact in the HCAL and charged hadrons are identified as charged-particle tracks associated with a small energy deposit in the ECAL (from ionisation energy loss) and a large energy deposition in the HCAL. Finally, muons can be identified as charged-particle tracks associated with small energy depositions in both the ECAL and HCAL and signals in the muon detectors on the outside of the detector system.

Whilst neutrinos leave no signals in the detector, their presence often can be inferred from the presence of *missing momentum*, which is defined as

$$\mathbf{p}_{mis} = -\sum_i \mathbf{p}_i,$$

where the sum extends over the measured momenta of all the observed particles in an event. If all the particles produced in the collision have been detected, this sum should be zero (assuming the collision occurs in the centre-of-mass frame). Significant missing momentum is therefore indicative of the presence of an undetected neutrino.

The ultimate aim in collider experiments is to reconstruct the fundamental particles produced in the interaction. Electrons, photons and muons give clear signatures and are easily identified. Tau-leptons, which decay in 2.9×10^{-13} s, have to be identified from their observed decay products. The main tau-lepton decay modes are $\tau^- \to e^-\overline{\nu}_e\nu_\tau$ (17.8%), $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ (17.4%), $\tau^- \to \pi^-(n\pi^0)\nu_\tau$ (48%) and $\tau^- \to \pi^-\pi^+\pi^-(n\pi^0)\nu_\tau$ (15%). The hadronic decay modes typically lead to final states with one or three charged pions and zero, one or two π^0s which decay to photons $\pi^0 \to \gamma\gamma$. Tau-leptons can therefore be identified as narrowly collimated jets of just a few particles and the presence of missing momentum in the event, associated with the neutrino.

1.3.1 Detection of quarks

Owing to the nature of QCD, quarks are never observed as free particles, but are always found confined within hadrons. However, in high-energy collisions it is

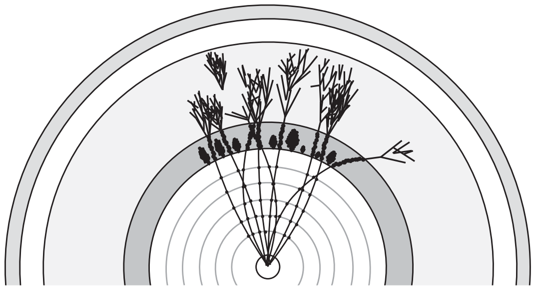

Fig. 1.19 An illustration of the appearance of a jet in a detector. In practice, the individual particles are not resolved.

quarks that are produced, not hadrons. For example, in the process $e^+e^- \to q\overline{q}$ the two quarks will be produced flying apart at relativistic velocities. As a result of the QCD interaction, the energy in the strong interaction field between the two quarks is converted into further pairs of quarks and antiquarks through a process call hadronisation (described in Chapter 10) that occurs over a distance scale of 10^{-15} m. As a result of hadronisation, each quark produced in a collision produces a jet of hadrons, as indicated in Figure 1.19. Hence a quark is observed as an energetic jet of particles. On average, approximately 60% of the energy in a jet is in the form of charged particles (mostly $\pi^\pm$), 30% of the energy is in the form of photons from $\pi^0 \to \gamma\gamma$ decays, and 10% is in the form of neutral hadrons (mostly neutrons and K_Ls). In high-energy jets, the separation between the individual particles is typically smaller than the segmentation of the calorimeters and not all of the particles in the jet can be resolved. Nevertheless, the energy and momentum of the jet can be determined from the total energy deposited in the calorimeters.

Tagging of b-quarks

In general, it is not possible to tell which flavour of quark was produced, or even whether the jet originated from a quark or a gluon. However, if a b-quark is produced, the hadronisation process will create a jet of hadrons, one of which will contain the b-quark, for example a $\overline{B}^0(b\overline{d})$ meson. It turns out that b-quark hadrons are relatively long-lived with lifetimes of order 1.5×10^{-12} s. When produced in high-energy collisions, this relatively long lifetime, combined with the Lorentz time-dilation factor, means that B hadrons travel on average a few millimetres before decaying. The decays of B hadrons often produce more than one charged particle. Because of the relatively large mass of the b-quark, the decay products can be produced at a relatively large angle to the original b-quark direction. Therefore the experimental signature for a b-quark is a jet of particles emerging from the point of the collision (the primary vertex) and a secondary vertex from the b-quark decay,