Chapter 1
Introduction

Christian W. Fabjan and Herwig Schopper

Enormous progress has been achieved during the last three decades in the understanding of the microcosm. This was possible by a close interplay between new theoretical ideas and precise experimental data. The present state of our knowledge has been summarised in Volume I/21A "Theory and Experiments". This Volume I/21B is devoted to detection methods and techniques and data acquisition and handling.

The rapid increase of our knowledge of the microcosm was possible only because of an astonishingly fast evolution of detectors for particles and photons. Since the early days of scintillation screens and Geiger counters a series of completely new detector concepts was developed. They are based on imaginative ideas, sometimes even earning a Nobel Prize, combined with sophisticated technological developments. It might seem surprising that the exploration of an utterly abstract domain like particle physics, requires the most advanced techniques, but this makes the whole field so attractive.

The development of detectors was above all pushed by the requirements of particle physics. In order to explore smaller structures one has to use finer probes, i.e. shorter wavelengths implying higher particle energies. This requires detectors for high-energy particles and photons. At the same time one has to cope with the quantum-mechanical principle that cross sections for particle interactions have a tendency to fall with increasing interaction energy. Therefore accelerators or colliders have to deliver not only higher energies but at the same time also higher collision rates. This implies that detectors must sustain higher rates. This problem is aggravated by the fact that the high-energy frontier is at present linked to hadron

---

C. W. Fabjan (✉)
Austrian Academy of Sciences and University of Technology, Vienna, Austria
e-mail: Chris.Fabjan@cern.ch

H. Schopper
CERN, Geneva, Switzerland

C. W. Fabjan, H. Schopper (eds.), *Particle Physics Reference Library*,
https://doi.org/10.1007/978-3-030-35318-6_1

collisions. Electron-positron colliders are characterised by events with relatively few outgoing particles since two pointlike particles collide and the strong interaction is negligible in such reactions. After the shutdown of LEP in 2000 the next electron-positron collider is far in the future and progress is now depending on proton-proton collisions at the LHC at CERN or heavy ion colliders, e.g. GSI, Germany, RHIC at BNL in the USA and also LHC. Protons are composite particles containing quarks and gluons and hence proton collisions produce very complicated events with many hundreds of particles. Consequently, detectors had to be developed which are able to cope with extremely high data rates and have to resist high levels of irradiation. Such developments were in particular motivated by the needs of the LHC experiments.

It seems plausible that accelerators and colliders have to grow in size with increasing energy. But why have detectors to be so large? Their task is to determine the direction of emitted particles, measure their momenta or energy and in some cases their velocity which together with the momentum allows to determine their mass and hence to identify the nature of the particle.

The most precise method to measure the momentum of charged particles is to determine their deflection in a magnetic field which is proportional to $B \cdot l$ where B is the magnetic field strength and l the length of the trajectory in the magnetic field. Of course, it is also determined by the spatial resolution of the detector to determine the track. To attain the highest possible precision superconducting coils are used in most experiments to produce a large B. Great efforts have been made to construct detectors with a spatial resolution down to the order of several microns. But even then track lengths l of the order of several meters are needed to measure momenta with a precision of about 1% of particles with momenta of several 100 GeV/c. This is the main reason why experiments must have extensions of several meters and weigh thousands of tons.

Another possibility to determine the energy of particles are so-called "calorimeters". This name is misleading since calorimeters have nothing to do with calorific measurements but this name became ubiquitous to indicate that the total energy of a particle is measured. The measurement is done in the following way. A particle hits the material of the detector, interacts with an atom, produces secondary particles which, if sufficiently energetic, generate further particles, leading to a whole cascade of particles of ever decreasing energies. The energy deposited in the detector material can be measured in various ways. If the material of the detector is a scintillator (crystal, liquid or gas), the scintillating light is approximately proportional to the deposited energy and it can be observed by, e.g., photomultipliers. Alternatively, the ionisation produced by the particle cascade can be measured by electrical means.

In principle two kinds of calorimeters can be distinguished. Electrons and photons produce a so-called electromagnetic cascade due to electromagnetic interactions. Such cascades are relatively small both in length and in lateral dimension. Hence electromagnetic calorimeters can consist of a homogenous detector material containing the whole cascade. Incident hadrons, however, produce in the cascade also a large number of neutrons which can travel relatively long ways before losing their energy and therefore hadronic cascades have large geometrical extensions even in the densest materials (of the order few meters in iron). Therefore the detectors for hadronic cascades are composed of a sandwich of absorber material interspersed with elements to detect the deposited energy. In such a device, only a certain fraction of the total energy is sampled. The challenge of the design consists in making this fraction as much as possible proportional to the total energy. The main advantage of calorimeters, apart from the sensitivity to both charged and neutral particles, is that their size increases only logarithmically with the energy of the incident particle, hence much less than for magnetic spectrometers, albeit with an energy resolution inferior to magnetic spectrometers below about 100 GeV. They require therefore comparatively little space which is of paramount importance for colliders where the solid angle around the interaction area has to be covered in most cases as fully as possible.

Other detectors have been developed for particular applications, e.g. for muon and neutrino detection or the observation of cosmic rays in the atmosphere or deep underground/water. Experiments in space pose completely new problems related to mechanical stability and restrictions on power consumption and consumables.

The main aim in the development of all these detectors is higher sensitivity, better precision and less influence by the environment. Obviously, reduction of cost has become a major issue in view of the millions of detector channels in most modern experiments.

New and more sophisticated detectors need better signal processing, data acquisition and networking. Experiments at large accelerators and colliders pose special problems dictated by the beam properties and restricted space. Imagination is the key to overcome such challenges.

Experiments at accelerators/colliders and for the observation of cosmic rays have become big projects involving hundreds or even thousands of scientists and the time from the initial proposal to data taking may cover one to two decades. Hence it is sometimes argued that they are not well adapted for the training of students. However, the development of a new detector is subdivided in a large number of smaller tasks (concept of the detector, building prototypes, testing, computer simulations and preparation of the data acquisition), each lasting only a few years and therefore rather well suited for a master or PhD thesis. The final "mass production" of many detection channels in the full detector assembly, however, is eventually transferred to industry. These kinds of activities may in some cases have little to do with particle physics itself, but they provide an excellent basis for later employment in industry. Apart from specific knowledge, e.g., in vacuum, magnets, gas discharges, electronics, computing and networking, students learn how to work in the environment of a large project respecting time schedules and budgetary restrictions—and perhaps even most important to be trained to work in an international environment.

Because the development of detectors does not require the resources of a large project but can be carried out in a small laboratory, most of these developments are done at universities. Indeed most of the progress in detector development is due to universities or national laboratories. However, when it comes to plan a large experiment these originally individual activities are combined and coordinated which naturally leads to international cooperation between scientists from different countries, political traditions, creeds and mentalities. To learn how to adapt to such an international environment represents a human value which goes much beyond the scientific achievements.

The stunning success of the “Standard Model of particle physics” also exhibits with remarkable clarity its limitations. The many open fundamental issues—origin of CP-violation, neutrino mass, dark matter and dark energy, to name just few—are motivating a vast, multi-faceted research programme for accelerator- and non-accelerator based, earth- and space-based experimentation. This has led to a vigorous R&D in detectors and data handling.

This revised edition provides an update on these developments over the past 7–9 years.

We gratefully acknowledge the very constructive collaboration with the authors of the first edition, in several cases assisted by additional authors. May this Open Access publication reach a global readership, for the benefit of science.