Chapter 1

Introduction

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The fruitful interaction between research in physics and technological development in the field of particle accelerators and detectors is the main theme of this book. For accelerators, research is driven by the need for ever-higher energy and intensity, and to supply an increasingly diverse range of beams, from electrons and protons and their antiparticles to heavy or radioactive nuclei. For experimentation, measurement capabilities need to be continuously improved, taking advantage of an ever stronger symbiosis between detectors, electronics and computing technology.

Research, technology and innovation at CERN have been part of global developments in nuclear and particle physics for the past six decades (1954–2014) [1–5]. The basic motivation has always been to advance the understanding of the elementary particles and forces that shape our Universe. This, however, is not the main theme of this book. Instead, it presents some of the major, even spectacular, technological advances, and the framework and conditions that enabled them to propel this European organization into the league of world-leading physics laboratories (Fig. 1.1).

The field of particle physics has its roots in the pioneering studies of the atom that began towards the end of the 19th century, and the discovery of the most familiar particle, the electron. The first decades of the 20th century saw the development of quantum mechanics and special and general relativity on the theoretical side, while experimental studies showed — astonishingly — that the atom is mainly empty space, with electrons surrounding a tiny nucleus, generally consisting of protons and neutrons. At the same time, studies of the cosmic rays that rain down through the atmosphere began to reveal new, short-lived particles — for example, muons, pions and kaons — as well as a whole new realm of antimatter.

It was to take these investigations further that the first particle accelerators were developed. The European Organization for Nuclear Research — known as CERN after the Conseil Européen pour la Recherche Nucléaire that preceded it — was founded in 1954 for just this purpose. Since the early days of its first accelerator, the Synchrocyclotron, the Organization has made many significant contributions to the present understanding of the world of elementary particles, as embodied in the current Standard Model of particle physics [Box 6.4]. Over the decades, research at CERN and similar laboratories around the world has probed deep into the structure of matter to the level of the basic constituents — the quarks — that make up protons, neutrons, pions and other particles known collectively as hadrons. Figure 1.2 shows the families of quarks and leptons (which include the electron) that are basic elements of the Standard Model. These constituent particles are called elementary because they appear point-like and without sub-structure on the scale of 10^{-17} cm. They span more than 12 orders of magnitude in mass — from the tiny neutrino at < 0.23 eV/c^2 to the top quark at 173 GeV/c^2.

Fig. 1.1. Aerial view of the CERN laboratory today, indicating the location of most of the underground accelerator complex (PS (red), SPS (blue) and LHC (yellow)), and the four major experiments at the LHC (ALICE, ATLAS, CMS and LHCb). (Source: CERN).[a]

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[a] Unless noted otherwise, CERN is the source of all photos and figures in this publication.

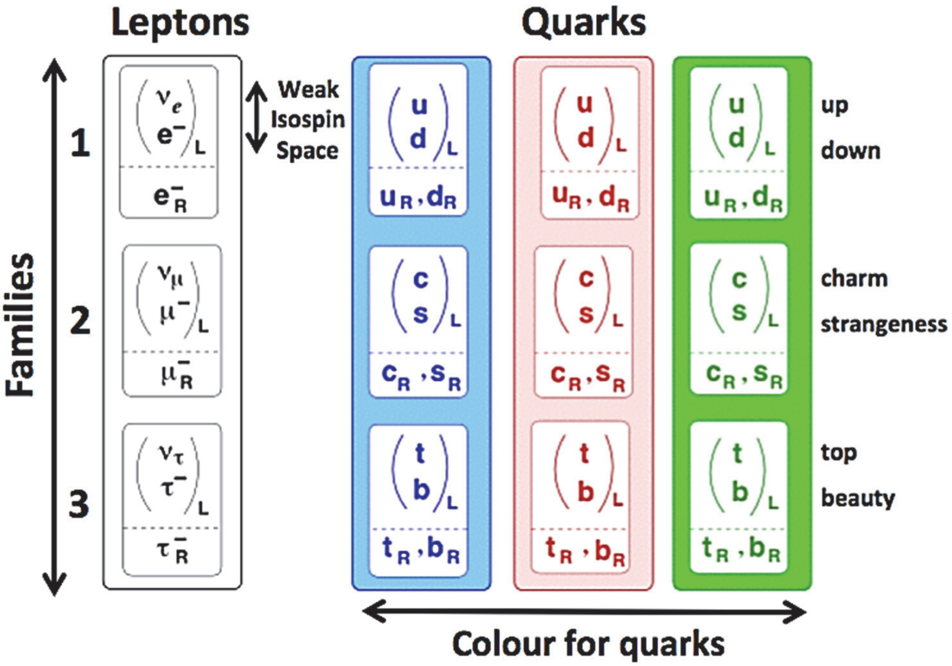

Fig. 1.2. The constituent leptons and quarks, all with spin ½ (fermions). They appear in three families, the reason for which remains mysterious. Quarks also come in three varieties or “colours” [Box 4.2]. L and R refer to the constituent “handedness” [Box 2.2], treated very differently in the Standard Model.

These investigations have also determined that the structure of matter as a whole depends critically on the way that these constituent particles interact through fundamental forces. Three forces — electromagnetic, weak and strong — are important at subatomic scales. A major success of the Standard Model has been to bring together the electromagnetic interaction (electrodynamics) and the weak interaction in a unified description in terms of an electroweak interaction, while the strong force is described in terms of interactions between quarks with a “strong charge” known as colour [Box 4.2] (chromodynamics). Within the Standard Model, the constituent particles with spin ½ interact through these forces via the exchange of a spin-1 particle, as illustrated in Fig. 1.3. A recent highlight at CERN was the discovery at the Large Hadron Collider (LHC) in 2012 of the last missing piece of the Standard Model, the spin-0 particle related to the Brout–Englert–Higgs mechanism through which particles acquire mass [Box 8.2]. This particle will be referred to as the Higgs particle throughout this book.

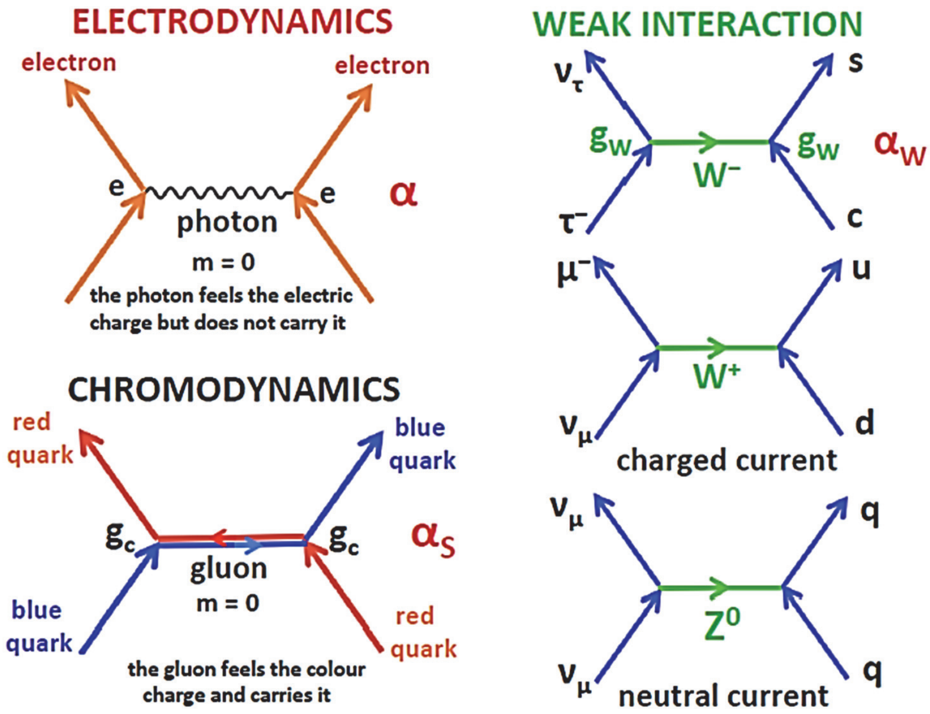

Fig. 1.3. These diagrams give an intuitive idea of the way the spin-½ fermions interact, by exchanging a spin-1 boson. This is a common feature of all three interactions (electrodynamic, chromodynamic and weak), the relevant force-carrying boson being indicated in the figure. These interactions are described in more detail in Boxes 2.3, 4.2 and 6.4.

A fourth force, gravity, influences matter on a truly cosmic scale. While for the time being, this force remains outside the Standard Model, there is nevertheless an intimate relationship between particle physics and cosmology, in the context of an expanding Universe. With the higher energies of particles at the LHC and, previously, at the Large Electron Positron (LEP) collider, experiments at CERN have reached back in time to cast light on the moments soon after the Big Bang, when our currently observable Universe was much smaller, hotter and denser than today. Figure 1.4 places the LHC and LEP accelerators on its timeline, in terms of the energy density of the collisions they produce. At about 10^{-11} s after the Big Bang, the Higgs field permeating the Universe underwent a "phase transition" giving mass to the elementary particles — a perfect illustration of the intimate relationship between particle physics and cosmology.

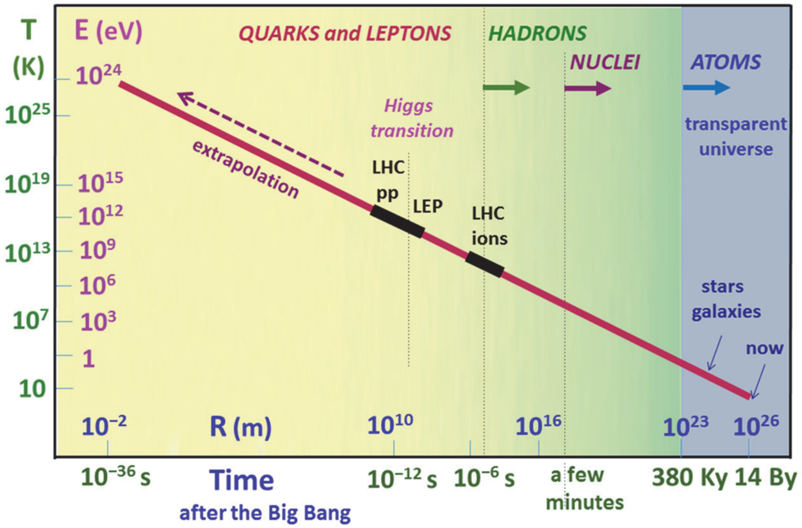

Fig. 1.4. Timeline of the Universe (logarithmic scale) with temperature T versus age. Observational astronomy is limited to the period after the Universe became transparent to photons (at an age of 380 000 years). Nuclear and particle physics experiments reproduce, on a microscopic scale, the energy per particle E (from Boltzmann's relation E = kT) that prevailed at much earlier times, as shown for LEP and LHC. The corresponding radius R of the observable Universe is also shown (courtesy F. Pauss).

1.1 CERN's First 30 Years: From Fixed Targets to the First Colliders

Until the late 1960s, the high energy frontier of nuclear and particle physics at CERN, as elsewhere, was explored with the great proton synchrotrons in which protons were directed at internal or external targets to produce secondary particles. However, it was recognized early on that head-on collisions between particle beams would be more effective than collisions between a beam and a fixed target as they exploit the full energy of the beams — e.g. for the production of new particles. The 1960s saw the construction of several successful electron–positron colliders in France, Italy, the Soviet Union and the US, but for proton machines the challenge was to produce colliding-beam intensities high enough to yield a useful interaction rate. CERN's technological contributions and inventions for solving this problem led in the early 1970s to the Intersecting Storage Rings (ISR) [6] and, a decade later, to the proton–antiproton collider [7].

On the experimental side, bubble chambers were prominent detectors in high-energy physics for several decades [8]. They were used to visualize individual interactions in the liquids they contained, but were slow as they recorded the interactions — "events" — on photographic film that had to be scanned and measured, often by hand. In parallel, experiments based on counter techniques were making major progress [9]. This transition to faster tracking detectors was accelerated with the development of wire "spark chambers" with electronic readout and data recording, and gathered important momentum at the end of the 1960s with the multi-wire proportional chambers (MWPCs) developed at CERN [10], in particular by Georges Charpak, who was honoured by the award of the Nobel Prize in Physics in 1992.

The Synchrocyclotron (SC) — Chapter 2

CERN's first accelerator, the Synchrocyclotron (SC), designed by CERN in its learning phase and constructed with the participation of industry in the 1950s, provided a record beam energy at the time. From the start it allowed important and innovative experiments with detectors based on developments in nuclear and cosmic-ray physics. Technological highlights included the SC Rotary Capacitor (ROTCO), which enabled beams of ions other than protons to be accelerated in the SC and opened up a long-lasting programme for the Isotope Separator On Line Device (ISOLDE). Pioneering experiments on pion-decay and the measurement of the anomalous magnetic dipole moment of the muon, are some of the early CERN success stories.

The CERN Proton Synchrotron (PS) — Chapter 3

The CERN Proton Synchrotron (PS), constructed after a daring design-switch to the alternating-gradient principle, underwent a remarkable evolution with increased proton intensity, allowing the production of beams of deuterons, alpha-particles, antiprotons, lead ions and CERN's first neutrino beam with the concept of the magnetic horn. The PS is still at the heart of CERN's accelerator network.

From the start, extracted beams from the PS were used with counter detectors and bubble chambers. These early experimental programmes allowed European physicists to enter increasingly into a fair competition with colleagues at well-established laboratories in the Soviet Union and the USA. Experiments with bubble chambers progressed from the 30 cm liquid-hydrogen chamber to the Big European Bubble Chamber (BEBC), and in the early 1970s, a first-generation neutrino experiment using Gargamelle, the large heavy-liquid bubble chamber built at Saclay, discovered weak neutral currents — a major breakthrough that helped to establish the Standard Model of particle physics.

Simultaneously, the introduction of Cherenkov counters, time-of-flight counters, and spark chambers, allowed for early electronic "non-bubble-chamber" experiments. Following the invention of MWPCs, large-area installations of these detectors were first used inside the OMEGA spectrometer, which was equipped with a large superconducting dipole magnet with forced cooling — itself a remarkable design by CERN engineers. Experiments at the PS continue today, e.g. at ISOLDE, n_TOF and CLOUD.

The Intersecting Storage Rings (ISR) — Chapter 4

The pioneering work on the Intersecting Storage Rings (ISR), the world's first proton–proton collider, is another success story of CERN's accelerator builders. This collider was the birthplace of many enabling technologies relevant for the future, such as ultrahigh vacuum, superconducting beam-focusing quadrupole magnets and, most notably, stochastic cooling, the ingenious technology for achieving high luminosity collisions in CERN's proton–antiproton collider.

A new era for experiments also began at this pioneering collider, ranging from the difficult detection of secondary particles emerging at small angles with respect to the beams (e.g. Roman pots) to detectors with nearly full 4π angular coverage (e.g. the Axial Field Spectrometer). With the large-scale deployment of MWPCs, the introduction of calorimeters, and the use of transition-radiation detectors, the ISR was the cradle of developments for the next step, the proton–antiproton collider experiments.

The Super Proton Synchrotron (SPS) — Chapter 5

In 1974, a new series of fixed-target experiments started at CERN with the first operation of particle beams at the Super Proton Synchrotron (SPS). Construction of the SPS was based on larger-scale application of the alternating-gradient principle, with refinement (separated function), together with installation in a deep underground tunnel as opposed to the shallow cut-and-fill galleries used previously. The first remote controls using computers were introduced to operate the large accelerator, the infrastructure and novel accelerator/operator interfaces were developed, and ingenious beam lines (e.g. muons and kaons) were set up.

At the same time, CERN adapted the West experimental area and constructed the large North area with a variety of primary, secondary and tertiary beams including a high energy neutrino beam. SPS beams served many experiments with a range of detectors, including the Big European Bubble Chamber (BEBC), streamer chambers, new variations of Cherenkov counters, and new kinds of calorimeter, e.g., with liquid krypton for experiments on CP violation or on a new scale for the giant electronic neutrino detectors. The first applications of micro-strip detectors and polarized targets also formed part of the early SPS physics programmes. The versatile PS–SPS complex also delivered high energy heavy-ion beams, opening the era of relativistic heavy-ion physics.

The proton–antiproton collider — Chapter 6

Only a few years after the start-up of the SPS, CERN launched the audacious proton–antiproton collider, leading to the experimental proof of the existence of the weak interaction mediator bosons — W and Z — in 1983 and the Nobel Prize in Physics in 1984 for Carlo Rubbia and Simon van der Meer.

The idea to use the SPS as a proton–antiproton collider triggered a chain of new technological challenges and inventions. In particular, it called for the development of an antiproton source, which in turn required a rapid test of proton-beam cooling in the Initial Cooling Experiment (ICE), made possible by CERN's development of the practical application of stochastic cooling. It also required the construction of the Antiproton Accumulator (AA) and the Antiproton Collector (AC), and led later to the Low Energy Antiproton Ring (LEAR) and the Antiproton Decelerator (AD). Experiments at the proton–antiproton collider called for the design and construction of large 4π detectors, together with online computing and data handling on an unprecedented scale.

1.2 CERN's Second 30 Years: The LEP and LHC Story

In 1981, following years of intensive discussions among physicists, and consensus formulated by the recommendation of the European Committee for Future Accelerators (ECFA), approval was given for the construction of the Large Electron Positron (LEP) collider. Unlike previous CERN projects such as BEBC, the ISR and the SPS, in the case of LEP the large-scale infrastructure, the 27 km tunnel and the collider itself, had all to be planned and constructed within the regular budget with no additional project funding. To free adequate resources, the CERN scientific community and management had to close major facilities, such as the ISR, as well as physics programmes. The increased collaboration and participation of universities in the design and construction of the large detectors needed for LEP went together with a major regrouping of technical and engineering teams at CERN. This restructuring allowed the organization of professional support on a new scale for the construction both of the collider and of four major detectors: ALEPH, DELPHI, L3 and OPAL.

By 1986, ideas, germinating since the LEP discussions, for a proton–proton collider to be built in the same tunnel had become much more concrete, making a long-term R&D programme mandatory. CERN's participation in this programme, at a time when most of its resources were committed to the construction phase of LEP, was facilitated through the LAA project [11]. This special programme, initiated and financed by Italy, approved by CERN Council, and implemented and executed at CERN, contributed to a broad detector R&D activity. In addition, LAA funds helped to recruit experts, particularly in the area of microelectronics, contributing to the success of the experiments at the Large Hadron Collider (LHC).

The technological challenges for the LHC machine and detectors to meet the expectations of research were different from those that faced the accelerator and detector builders when preparing LEP. One of the main challenges set by the energy envisaged for the LHC in the existing LEP tunnel concerned the dipole magnets needed to steer the proton beams around the ring. In order to stimulate interest for supplying the large number of high-field superconducting dipoles that would be required to provide the maximum possible bending power, CERN launched several collaborations with industry. In parallel, new detector concepts and experimental methods were required for the beam intensities and energies expected at the LHC. CERN responded with a focused detector R&D programme under the auspices of a CERN committee, the DRDC [12], which was set up in collaboration with physicists from participating institutions and sought funding support from the EU framework programmes.

With the emerging global collaboration on accelerator and detector development, communication became a key issue. CERN's answer was an Internet-based networking strategy. This brought a revolution in communication technologies, best exemplified by the invention of the World Wide Web at CERN in 1989. It came "just in time", enabling the computing boom, working tools and methods without which the LEP and LHC programmes could not have been accomplished.

Formally approved in 1994, the LHC would dominate CERN activity after the closure of LEP in November 2000. Following the first physics runs in 2009, its high energy proton collisions have taken research at CERN a step nearer to the origin of matter in the early Universe. In 2012, experimental observations by the LHC collaborations established the existence of the Brout–Englert–Higgs mechanism — a key ingredient of the Standard Model — leading to the award of the 2013 Nobel Prize in Physics to its originators.

The Large Electron Positron Collider (LEP) — Chapter 7

The choice of the size of the LEP tunnel was based on a careful balance between economic feasibility and physics discovery potential. A ring with a circumference of 27 km was adopted [13], largely driven by the need to minimize losses through synchrotron radiation — a consequence of the electron's small mass — and therefore power consumption. Compensating these losses required a powerful system of radiofrequency (RF) cavities and klystrons, while the large circumference for the design energy implied novel low-field bending magnets (dipoles), with superconducting quadrupole magnets needed for the final focus.

Although a smaller machine would have sufficed for the initial physics goal, i.e. to produce and study the neutral mediator of the weak interaction, the Z boson, the second goal, i.e. the production of W pairs and Z pairs and the search for the Higgs boson, called for higher energy. The large size of the ring enabled a gradual push of the LEP beam energy to 105 GeV, the maximum possible with the installed set of powerful niobium-clad superconducting cavities (which exceeded their design performance). However, the potential of LEP as determined by the limit of the bending magnets (125 GeV) was not fully exploited.

For the experiments at LEP, the particle-tracking chambers were either time projection chambers (TPCs) or of the advanced "jet chamber" type; particle identification was based on measurements of particle velocity with novel Cherenkov counters and the decay topology of short-lived particles; energy measurements were based on crystal or sampling calorimeters; and finally large solenoids were employed to determine particle momentum through measurements of the curvature of particle tracks in the magnetic field. The interactions of electrons — which, so far, seem to be structure-less — produce "clean" events. This motivated the LEP experiments to develop vertex detectors with high spatial resolution to reveal details close to the interaction point. Read-out electronics in this era progressed from electronic transistors to microchips on printed boards, and later to integrated microelectronic circuits incorporating event selection and data-recording techniques.

The Large Hadron Collider (LHC) — Chapter 8

The LHC complex, which includes the 27 km superconducting collider (thanks to the existence of the LEP tunnel) and several huge particle detectors, is the largest and most sophisticated research instrument ever built [14]. Chapter 8 outlines the main features and the highlights of the developments that paved the way from its conception in the early 1980s to the first years of exploitation from 2009 to 2013.

To reach its physics goals, the LHC had to achieve the highest collision energies and luminosity technically possible. Constrained by the size of the existing tunnel, this implied the use of the highest possible magnetic bending fields, given that for the massive protons of the LHC, synchrotron radiation is less of a problem than with lightweight electrons. Thus, CERN prepared for the LHC with ambitious R&D on superconducting cables and magnets. In addition, the envisaged high beam intensity, with the concomitant large beam power, required effective beam collimation, a new level of equipment protection, and reliable solutions for dumping the beams. The research agenda called for about one billion collisions per second. The interactions of protons, which are composite particles, produce hundreds of particles per collision. The experiments required the highest possible time and spatial resolution for vertex detection; radiation-tolerant materials and electronics; very large superconducting solenoidal/toroidal magnets; and novel technologies for event triggers, data processing and storage. Carrying out the experiments and recording the events seemed impossible to many experts during the early discussions in the 1980s. The international collaborations already mentioned, coordinated by the CERN DRDC, made it reality.

Data handling and communication — Chapter 9

To support its research activities, CERN's information technology and computing tools progressed over the decades from the Ferranti Mercury of the 1950s based on vacuum tubes, via the IBM 7090 in the 1960s with punched cards, magnetic tapes, and FORTRAN programming, to mainframes such as the CDC and CRAY computers (as well as online DEC PDP and NORD computers), before reaching the Internet-based computing of today. Chapter 9 traces this journey, and highlights include computing clusters and data storage, local data networks, high-speed worldwide networking, and simulation, as well as the World Wide Web and the CERN Computing Grid.

Knowledge and technology transfer — Chapter 10

The wealth of experience and knowledge acquired in fulfilling its research programme is a major asset of CERN, and transferring this expertise beyond the boundaries of the Laboratory is an important mission for the Organization. Since its founding, CERN has profited from the accumulation of its expertise in accelerator physics, RF engineering, superconductivity and cryogenics, instrumentation and controls, sensors, electronics and detector design, data acquisition and advanced informatics. In all of these areas, the research requirements have led to the innovations outlined in this book — many of which have gone to find applications not only at other, similar laboratories, but also in quite different fields. Chapter 10 describes the processes for knowledge and technology transfer that CERN has developed over the decades. The highlights focus on innovations that contribute to a wider benefit for society, in particular for medicine and the environment.

Managing the laboratory and large projects — Chapter 11

Chapter 11 gives an appraisal of CERN's past and present management approach to foster creativity on the scale discussed in this book, demonstrating an evolution that has led to what is sometimes referred to as the "CERN Model". The highlights illustrate the association with industry as applied to the accelerators and worldwide collaboration as applied to the LHC experiments. Compared to laboratories in the USA, where funding is approved on a yearly basis, CERN has benefitted greatly from regular funding and 5-year plans that have enabled it to follow through on long-term projects. However, the restrictions on the staff complement and the scale of the current collider experiments have made large worldwide collaborations the norm, albeit with strong backing from CERN. The responsibility for providing the beams remains squarely with the Laboratory, but sharing of tasks among associated institutes has also grown in the accelerator sector. The cost-effective use of accumulated infrastructure has been an important element and asset for CERN, but the true driving force resides in the endeavour to accomplish a common goal, which fosters team spirit and loyalty to the missions of the Organization.

R&D for the future — Chapter 12

CERN's scientific projects are generally characterized by timescales of the order of 30 years, from first discussions and planning through design and technological preparation, the proposal and approval, to construction and full exploitation, and finally completion. It is therefore not too early to start thinking about the next steps after the LHC, summarized in Chapter 12. Results from the LHC, the High Luminosity LHC and other experiments will ultimately determine the future of experimental particle physics. Preparing this future while keeping options open requires a multi-pronged approach in accelerator R&D. While the present focus at CERN is on a linear electron–positron collider in the Compact Linear Collider (CLIC) study, and on a proton–proton collider, the Future Circular Collider (FCC), other alternatives are also being actively pursued [15].

Acknowledgements

For more than 60 years, the interplay between physics and technology at CERN has led to the technological innovations that are the main subject of this book. The following chapters describe the context that gave rise to these achievements during the different periods of the Organization. They are illustrated by highlights that have been selected for their novel character and impact on physics and/or technology. Either "CERN firsts" or CERN-based breakthroughs, they were due to individuals or small teams as well as, particularly in later years, to work within larger, often international collaborations with other institutes, where CERN had a leading role. The selection does not purport to be exhaustive. Only Nobel laureates, CERN directors-general and leaders of the major accelerator projects are named where appropriate; in other cases the names of those involved can be found through the abundant references that allow interested readers to dig deeper into these many fascinating topics. The generous support of society at large is

gratefully acknowledged, without which research is not possible. In addition to activity financed via the CERN budget, the national funding agencies are supporting scientists and engineers at the home institutes and universities in their ambitious research programmes at the CERN facilities. Today, more than 12 000 such scientists and engineers are using these facilities: they are the motivators, shakers and shapers of the Laboratory.

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