5
Leapfrogging into the Future

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5.1 Introduction

The primary objective of particle physics is to understand the underlying structure of matter and its role in the history and structure of the Universe. As discussed in the previous chapters of this book, much progress has been made in recent decades, particularly with the LHC hadron–hadron collider and the previous LEP electron–positron collider, housed in the existing 27 km tunnel straddling the Franco-Swiss border in the Geneva region. Nevertheless, despite this progress there remain many open questions in particle physics and open cosmological issues that future colliders may be able to resolve.

The most effective and the most comprehensive approach to explore thoroughly the open questions in modern particle physics is research infrastructures offering a staged research programme that combines precision measurements with direct exploration at previously uncharted energies. This vision lies at the heart of the Future Circular Collider (FCC) study that integrates a lepton collider (FCC-ee) (FCC Collaboration, 2019) as a first step followed by a hadron collider (FCC-hh) (FCC Collaboration, 2019b) in a manner reminiscent of the complementarity between the LEP and the LHC.

Today, there is overwhelming consensus on the research agenda of particle physics for a lepton collider that could operate as a Higgs factory, producing copious Higgs bosons, yielding precise knowledge of this unique particle. The novelty of the Higgs boson, and thus the great interest in studying its properties and interactions with the other known particles of the Standard Model (SM), derives largely from its scalar nature. It is the only fundamental particle without spin.

Four Higgs-factory designs are presently being considered. Two are based on linear accelerators, namely the International Linear Collider (ILC) under consideration in Japan and the Compact Linear Collider (CLIC) proposed at CERN, which have been studied since 1975 (Amaldi, 1976) as they are considered to be the most mature approach towards high energy lepton collisions. The advantages of linear accelerators are that they can be extended to higher energies, though this would require additional

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civil engineering work, and the beams can be polarised longitudinally. The other two concepts are circular: the lepton option of the Future Circular Collider (FCC-ee) at CERN; and as discussed in detail in Chapter 13, the Circular Electron Positron Collider (CEPC) in China. A circular collider can provide higher luminosities and better performance for energies up to 400 GeV, while the same infrastructure can be used to host energy-frontier proton colliders like the proposed FCC-hh.

While one of the main motivations for a future lepton collider is the precise study of the interactions of the Higgs boson, seeking answers to open questions in particle physics requires many high-precision measurements of the other three heaviest SM particles, namely the W and Z electroweak bosons and the top quark. The proposed operation models for the circular colliders comprise data taking at and around the Z pole (90 GeV), at the WW threshold (180 GeV), at the ZH cross-section maximum (240 GeV) and, for FCC-ee, an extension up to 365 GeV at and above the top pair threshold. With the highest luminosities at the Z pole, the WW threshold, and the top-pair threshold, and with transverse polarisation to precisely calibrate the beam energies, precision electroweak measurements are the realm of FCC-ee. The designs are sufficiently flexible to allow for operation at other centre-of-mass energies, if justified by compelling physics arguments.

The experience from the FCC-ee would be valuable for the next step: a future high energy collider (FCC-hh), which could be the hadronic successor to the LHC. The FCC-hh would be a circular proton collider housed in the same tunnel as the FCC-ee. It could reach energies of some 100 TeV (approximately seven times higher than the 14 TeV of the LHC) and luminosities 50 times higher than at the LHC, using new high-field magnets reaching 16 T (fields twice as high as the 8 T magnets of the LHC). Exploring the multi-TeV regime is the only way to study how the Higgs interacts with itself. Experimental searches at the FCCs will offer an exhaustive understanding of the SM and guide our theoretical understanding as we face the pressing questions (FCC Collaboration, 2019c) that we discuss in the next sections.

The Conceptual Design Reports (CDRs) of the FCC-ee and FCC-hh projects were published in January 2020, in time to inform the update of the European Particle Physics Strategy. At present, as recommended by this 2020 update, a feasibility study for the FCC (including both FCC-ee its subsequent hadron-collider stage, FCC-hh) is ongoing, with the goal of presenting an updated conceptual design report in 2026, in time for the next strategy update.

5.2 What We Know

The visible matter in the Universe is described very accurately by the so-called Standard Model (SM) of Particle Physics. Ordinary matter is built out of molecules, which are made out of atoms that contain nuclei surrounded by clouds of electrons. The nuclei are bundles of particles called protons and neutrons that are themselves composed of apparently fundamental constituents called quarks. The SM prescribes how molecules and atoms are held together by photons, particles that produce light

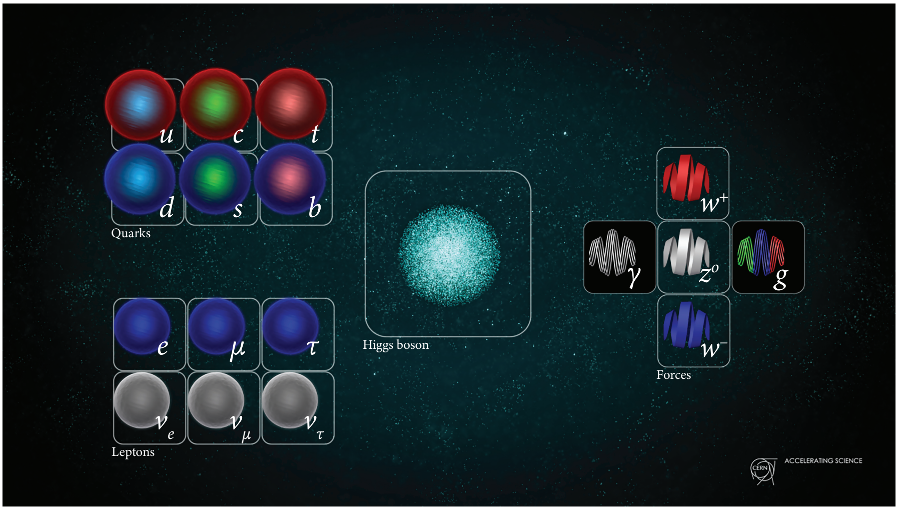

Figure 5.1 Constituents of the SM of particle physics

Source: © CERN

and radio waves when they escape these bound states. Similarly, the quarks are held together inside protons and neutrons by particles called gluons, though these are never detected directly, because they are confined inside nuclear matter.

In addition to the electromagnetic interactions mediated by photons and the strong interactions mediated by gluons, there are weak interactions that cause radioactive decays of heavier particles into lighter ones. These weak interactions are mediated by massive particles, the W and Z bosons.

The particles introduced above and shown in Figure 5.1 are the fundamental building blocks of Nature and through their interactions they make up the visible matter that we observe around us. The SM describes all these physical phenomena in a framework that is consistent with quantum mechanics and Einstein's Special Theory of Relativity and has been used to make many very accurate and successful predictions.

5.3 What We Do Not Know

Nevertheless, the SM is deeply unsatisfactory, for several reasons: Why these specific particles, rather than others? Why not more? Why not less? These questions are frequently labelled collectively as the problem of 'flavour'.

We also ask why these specific interactions? Perhaps there are others? Can we find a more unified description of all the fundamental interactions, perhaps including gravity, which is currently left outside the SM? These questions are often grouped as the problem of unification.

Then there is the problem of mass: the SM accommodates particle masses via a mechanism whose physical manifestation is the Higgs boson. However, nothing within the SM explains the magnitudes of these particle masses, nor the vast hierarchies between their measured values.

Beyond these intrinsic shortcomings of the SM, our observations of the Universe around us pose several other problems that are extrinsic to the SM.

How did the matter in the Universe originate? One would have expected the numbers of matter and antimatter particles produced by the Big Bang to be almost identical but, somehow, it produced significantly more matter than antimatter, and the latter all annihilated with matter, leaving behind the excess of matter that surrounds us today, and no significant quantities of antimatter. The SM is unable to explain the magnitude of the matter–antimatter imbalance.

And what is the nature of the unseen dark matter that has formed massive halos around galaxies, holding their stars together? The SM contains no candidates for dark matter, which might be composed of one or more unknown species of particle. Dark matter is essential for the formation and existence of galaxies and other structures in the Universe, but what sowed the seeds from which they grew? They may have originated from quantum processes in the very early Universe within some extension of the SM or Einstein's general theory of relativity.

Finally, cosmologists tell us that the majority of the density of matter and energy in the Universe is in the form of dark energy, which does not cluster, but is spread universally and is causing the expansion rate of the Universe to accelerate. Here the problem is not so much the existence of dark energy, but rather why it is so small. The SM suggests a density with a magnitude far greater than the measured value.

5.4 What the FCC Integrated Programme Offers

The FCC programme offers a comprehensive, multi-pronged approach to these outstanding problems beyond the SM. Experiments at FCC-ee, an intensity-frontier lepton collider, lay the basis for offering unparalleled precision in measurements of the SM, including the Higgs boson, the electroweak gauge bosons Z and W, and the top quark, opening indirect windows on new physics. Experiments at FCC-hh, on the other hand, will directly explore possible new physics at the highest accessible energy scales, and will also produce vast numbers of SM particles, providing opportunities for more precision measurements that will enable further indirect probes of new physics (Biscari and Rivkin, 2019).

The different phases of the FCC project depicted in the planned plot include: administrative steps, infrastructure development, the FCC-ee schedule, and the FCC-hh schedule (see Figure 5.2).

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The integrated programme for the FCCs, combining FCC-ee and FCC-hh, extends over 70 years in time, as illustrated in Figure 5.2. The capabilities offered by the combination of a lepton circular collider (FCC-ee) with a hadron circular collider (FCC-hh) are illustrated in the following sections for the examples of the Higgs

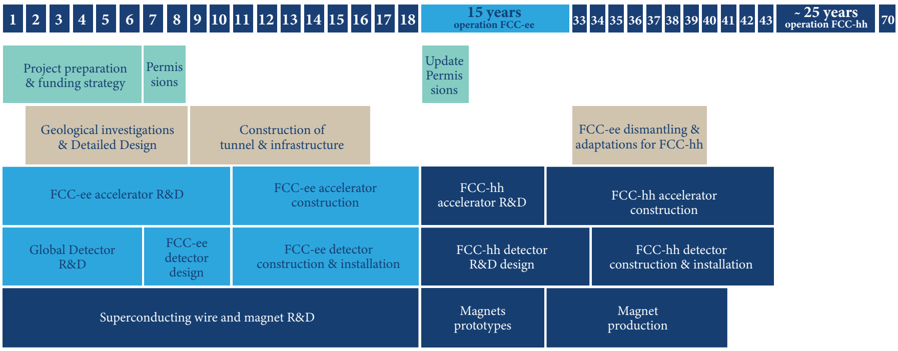

Figure 5.2 The FCC project extends over 70 years from its starting date (year 1)

Note: The different phases of the FCC project depicted in the plot include: administrative steps, infrastructure development, the FCC-ee schedule, and the FCC-hh schedule.

Source: Created by author

boson and dark matter, which are among the most mysterious puzzles in particle physics and cosmology, respectively.

The different phases of the FCC project depicted in the plot include: administrative steps, infrastructure development, the FCC-ee schedule, and the FCC-hh schedule.

5.5 A Puzzling Particle

The discovery of the Higgs boson, the last particle in the SM to be detected, leaves many questions unanswered while also raising new ones (ESPPU, 2019). It is the first and only example so far of a novel type of elementary particle, one without any spin. Is it truly elementary, or is it a composite object made out of more fundamental constituents? The latter possibility was considered actively before the discovery of the Higgs boson, but the LHC experiments have found no evidence in its favour. The best way to explore this possibility may be to measure its properties as accurately as possible, a task at which FCC-ee will excel (Blondel et al., 2019). If it is indeed composite, it is likely to be accompanied by other, heavier particles in which its constituents are arranged in different ways, a possibility that will be explored comprehensively at FCC-hh. Whether the Higgs boson is elementary or not, it may well be accompanied by other spin less particles, such as scalar particles, whose existence can be indirectly confirmed at the FCC-ee or directly at the FCC-hh through various experiments.

If the Higgs boson is indeed elementary, many more questions arise. What determines its mass and those of other elementary particles? The existence of the Higgs boson is a manifestation of the mechanism that gives masses to elementary particles but does not explain how large they are. The sizes of atoms depend on the mass of the electron, and the strengths of radioactive decays depend on the mass of the W particle that generates them, so understanding their magnitudes would give important insights into major features of the Universe. This issue is particularly problematic because the Higgs has no spin which makes the measured value of its mass seem unnaturally low and, by extension, the masses of other elementary particles as well, such as the electron, raise the question of why atoms are not much smaller than we observe.

Many theoretical approaches to this problem postulate the existence of additional particles, as yet unseen. Examples include the composite Higgs models mentioned above, theories with additional dimensions of space, and theories that partner particles of different spins in which the mass of the Higgs boson would be protected by its spinning partner and other new particles, an idea called supersymmetry. But where are these additional particles? The LHC has found no evidence of additional particles beyond the Higgs boson. Is this because they behave in ways that were not experimentally considered, or explored thoroughly? Or is it because of energy limitation or because the LHC has not simply collected enough data or analysed such data to find rare particles? Or is it beyond our current understanding and experimental capabilities? In that case the very clean experimental conditions and high collision rates provided by FCC-ee may enable us to find them. Or is the absence of additional particles so far simply because they are too heavy to have been produced by the LHC? In that case the very high collision energies provided by FCC-hh offer the best chances of finding them.

There are other issues, which concern the way in which the Higgs boson interacts. The SM controls the possible forms of its interactions but does not specify their strengths. For example, the mechanism for fixing the overall density of the Higgs field in the Universe today requires that it has self-interactions. What determines their strengths? A priori, they could have been strong, but present data suggest that they are rather weak, though the LHC is unable to measure them directly. FCC-ee could provide a first indirect measurement by studying the production of the Higgs boson very precisely, but an accurate, direct measurement will require studies of pairs of Higgs bosons at FCC-hh.

The Higgs particle is a quantum manifestation of a field extending throughout space, much as the photon is a quantum of the electromagnetic field. If the self-interactions of the Higgs boson are indeed weak, the energy of the Higgs field whose quantum is the Higgs boson does not depend strongly on its value, and other questions arise. How was the present value of the Higgs field determined during the evolution of the Universe, and could it change in the future?

Within the SM, the answers to these questions depend on the interactions of the Higgs boson with the top quark and their masses, and calculations of their effects are subject to considerable uncertainties. However, they indicate that the present configuration of the Higgs field may be unstable in principle, though on a time-scale longer than the present age of the Universe. Accurate measurements at FCC-ee and FCC-hh will resolve this issue, which has interesting implications at the frontier between physics and philosophy. What if FCC measurements and SM calculations confirm the Higgs instability problem? Would this mean that the Universe as we know it is doomed? Or does it rather suggest that there must be some physics beyond the SM that restores stability? If the latter, FCC-hh would be the most powerful instrument to search directly for any such new physics.

The interactions of the Higgs boson with matter particles also pose many puzzles that are linked to the problem of flavour (de Blas et al., 2019). In the SM the strong and weak interactions are similar for different flavours of matter particles with identical electric charges but varying masses. On the other hand, the interactions of the Higgs boson do not share these universality properties. Instead, the SM predicts that they are proportional to these different masses, which range over several orders of magnitude. Will this prediction hold up under the scrutiny of FCC-ee and FCC-hh? A corollary question is, what is the origin of the big differences between the masses of different matter particles? Will FCC studies of the interactions of different matter species find deviations from the universality predicted by the SM?

The Higgs boson is the most recent particle to have been discovered, and it is possible that it may have other interactions beyond those predicted in the SM, that are yet undiscovered. For example, there are many proposed extensions of the SM with an entire hidden sector of new particles that connect to the particles of the SM via the Higgs boson. In such 'Higgs portal' models more decays of the Higgs boson into invisible particles than just the neutrinos of the SM may appear.

Another possibility is that the Higgs boson interacts with unseen massive particles, too heavy to be seen directly, that in turn, generates supplementary interactions between the Higgs boson and other SM particles. Measurements of any such interactions can guide us towards understanding the properties of these massive particles, just as studies of the weak interactions in the 1930s, 1940s, and 1950s guided us towards the massive W and Z particles in the SM. The LHC high-luminosity upgrade (HL-LHC) will provide insights into the Higgs boson couplings to the SM gauge bosons and to the heaviest SM fermions (t, b, τ, μ). Together, FCC-ee and FCC-hh will provide the most sensitive probes of such supplementary interactions and whatever massive particles cause them (FCC Collaboration, 2019b, de Blas, 2019), as illustrated in Figure 5.3.

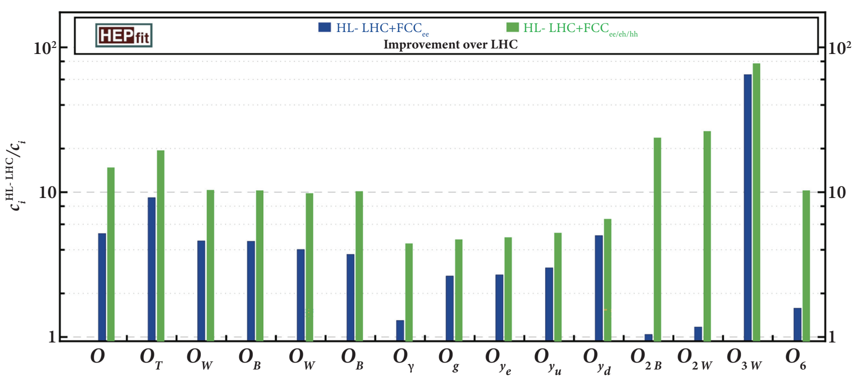

Figure 5.3 Achievable precisions for modified Higgs and electroweak couplings at proposed next-generation e+e− colliders including FCC-ee

Source: de Blas, J., Durieux, G., Grojean, C. et al. (2019). On the future of Higgs, Electroweak and Diboson Measurements at Lepton Colliders. *Journal of High Energy Physics*. 2019, 117. https://doi.org/10.1007/JHEP12(2019)117

5.6 Dark Secrets

The shortcomings discussed above do not detract from the success of the SM in describing all the visible matter in the Universe, from the stars to human beings. However, this visible matter provides only about 4% of the overall density of matter and energy in the Universe. Astrophysicists and cosmologists have discovered that there is a much larger percentage of invisible dark matter, and that an even larger percentage of the density of the Universe is not material at all but is spread uniformly throughout the Universe in the form of dark energy.

An astronomer, Fritz Zwicky, was the first to predict the existence of dark matter in the 1930s (Zwicky, 1933, 1937). Zwicky's observations of the Coma cluster of galaxies showed that the galaxies were moving much faster than expected. So fast, in fact, that it was impossible to understand how the cluster held together unless there was some additional source of gravity beyond the visible matter. It took several decades for this radical suggestion to become generally accepted. A key additional piece of evidence for dark matter was provided by Vera Rubin and collaborators in the 1970s (Rubin and Ford, 1970; Rubin et al., 1980, 1985, and 1992).

They observed the motions of stars in many galaxies and found that they were also moving too fast to be held together by the gravity generated by the visible galactic matter. Observations of distant supernovae and the cosmological background radiation in the 1990s also indirectly confirmed the existence of dark matter and established the existence of dark energy, which contributes about a quarter and 70% of the density of the Universe, respectively.

The FCC will be able to shed light on the nature of dark matter or dark energy depending on their natures and how they are related to ordinary matter. We know very little about dark matter, apart from the fact that it generates a gravitational field. The possibility that it might consist mainly or partially of black holes has been extensively considered since the detections of black hole mergers by the LIGO and Virgo collaborations (Abbott et al., 2016), but it now seems that black holes with masses similar to those detected so far can provide only a small fraction of the total dark-matter density. For this reason, it is widely expected that dark matter consists mainly of one or more unknown types of particles that are not contained within the SM.

Two general categories of particles have been proposed by the physics community. One is some novel type of fermionic weakly-interacting massive particle (WIMP), and the other is some type of very light bosonic particle that is present in waves throughout the Universe. Both of these could clump together, help visible structures such as galaxies and clusters form, and hold them together as proposed by Zwicky and Rubin in particular. However, there are constraints on the masses that the particles must have in order to perform these tasks. Dark matter particles should be non-relativistic during the period of structure formation in order to form and hold together dwarf galaxies. This implies, in particular, that WIMPs should be heavier than the neutrinos in the SM. Likewise, observations of dwarf galaxies also set (much smaller) lower limits on the possible mass of a boson dark matter particle.

The fact that telescopes do not see dark matter implies that it does not emit much light, though it might consist of particles with a very small electric charge capable of emitting small amounts of light. Many theories suggest that dark matter particles might have some interactions of strength intermediate between the known weak interactions and gravity. These would have played key roles, together with their mass, in fixing the overall cosmological density of dark matter during the expansion of the Universe. Many proposed extensions of the SM, such as supersymmetry and theories with extra dimensions, suggested the existence of stable, neutral WIMPs that could have been produced soon after the Big Bang and would still be present in the Universe today, providing dark matter. Calculations of the present density of such WIMPs could reproduce the density of dark matter indicated by astrophysics and cosmology if the dark matter WIMP weighs about a TeV, possibly within reach of experiments at the LHC and elsewhere and motivating WIMP searches in laboratory experiments.

A generic prediction of WIMP models is the occurrence of events in which energy and momentum are carried away by invisible dark matter particles that do not leave signals in detectors, often called 'missing-energy' events. Some of these events are expected in the SM when neutrinos are produced in the decays of heavier particles, and the missing-energy events detected so far by experiments at both LEP and LHC are quite compatible with these expected SM sources. FCC experiments continuing these searches for additional missing-energy events beyond those predicted in the SM will have unequalled potential for detecting WIMP candidates for dark matter (FCC Collaboration, 2019c). The sensitivity of the FCC-ee and FCC-hh to invisible decays of the Z and Higgs bosons adds a further dimension to the FCC programme of searches for dark sectors, probing regions of parameter space otherwise inaccessible. For example, the very clean experimental conditions at FCC-ee will allow very sensitive searches for invisible decays of the Z and Higgs bosons beyond those predicted in the SM, as in models with additional neutrinos heavier than those currently known. Moreover, FCC-hh will be able to produce much heavier particles than can be detected at previous accelerators including the LHC. In particular, they will be able to look for missing-energy events due to the direct production of heavy WIMPs, and also events in which WIMPs are produced indirectly via the decays of heavier particles, as may occur in models based on supersymmetry or extra dimensions. FCC-hh searches should be able to discover or exclude WIMPs as dark matter.

FCC searches for dark matter will be largely complementary to those by future non-accelerator experiments, but only the combination of these strategies will be able to pin down the nature of whatever dark matter particle may be discovered. For example, missing-energy events at a collider could be due to particles that are relatively long-lived but not long enough to have survived since the Big Bang. On the other hand, if some non-accelerator experiments were to detect a WIMP, it would be unable to provide many clues to the nature of the underlying theory.

5.6 Back to the Beginning, and the Future

D'où venons-nous? Que sommes-nous? Où allons-nous? is the title of a painting by Paul Gauguin, which may be translated as 'Where do we come from? What are we (made of)? Where are we going?' The questions raised by Gauguin in the painting shown in Figure 5.4 are universal questions that human beings have been asking, perhaps, in their different ways, for hundreds of thousands of years.

They constitute the primary motivation for the research programme of the FCC, though physicists approach these questions from a perspective that is perhaps rather different from that of the people in Gauguin's painting. The sections above have mainly addressed the second of Gauguin's questions, namely 'What are we (made of)?' The search for dark matter is a natural extension of this question to include all the matter in the Universe, invisible as well as visible. However, it is just one of many ways in which FCC experiments will probe the fundamental physics underlying the evolution of the Universe and seek answers to all of Gauguin's questions.

For a physicist or cosmologist, Gauguin's first question, 'Where do we come from?', becomes the question—what physics has governed the evolution of the Universe from its beginning almost 14 billion years ago in the Big Bang? Measurements of the cosmological microwave background (CMB) radiation inform us about the state of the Universe some 380,000 years after the Big Bang, when atoms condensed out of a primordial electromagnetic plasma of photons, electrons, protons, and light nuclei. These CMB observations provide the most accurate measurements of the amounts of conventional matter, dark matter, and neutrinos in the Universe and also constrain the possibilities for other forms of undetected matter. The light nuclei such as deuterium, helium, and lithium were formed out of protons and neutrons by nuclear reactions some three minutes after the Big Bang. Protons and neutrons were themselves formed a few microseconds after the Big Bang, out of quarks and gluons that had previously filled the Universe with a strongly interacting plasma. Experiments measuring heavy-ion collisions at the LHC are studying the properties of this quark-gluon plasma, which is among the most perfect fluids known.

Figure 5.4 *'D'où venons-nous? Que sommes-nous? Où allons-nous?'* Paul Gauguin's painting exhibited in the Museum of Fine Arts in Boston, Massachusetts, US

Source: Paul Gauguin, Public domain, via Wikimedia Commons

A key aspect of the FCC physics programme will be to extend these studies to the conditions that existed earlier in the history of the Universe, addressing Gauguin's first question, 'Where do we come from?' In addition to proton collisions, FCC-hh will be able to collide heavy-ions with each other or with protons. Therefore, FCC offers the opportunity for experiments observing ultra-relativistic heavy-ion collisions to study the behaviour of the quark-gluon plasma at an energy density orders of magnitude higher than those studied so far and will be able to cast light on its evolution towards the near-perfect fluidity measured at the LHC. FCC-ee collisions will measure the fundamental processes that governed the Universe when it was about a picosecond (a millionth of a millionth of a second) old with unequalled precision and may help reveal whether there is an unseen dark sector of matter and radiation existing in parallel to what we know. FCC-hh experiments observing proton–proton collisions will extend these measurements back to the processes that controlled the evolution of the Universe when it was a fraction of a femtosecond (some 10^{-16} seconds) old. Figure 5.5 shows different stages in the history of the universe, emphasising that its evolution in the early stages was controlled by fundamental particles and their interactions.

What else may have happened so early in the history of the Universe? According to the SM, at some moment during the time period to be explored by FCC experiments the Higgs mechanism for giving masses to fundamental particles must have switched on. However, we do not know whether this was a gradual process, or whether it occurred suddenly via a phase transition that might have led to observable signatures in the Universe today, such as a background of gravitational waves. Measurements of the interactions of the Higgs boson by the FCC experiments offer our best prospects for exploring the dynamics behind the generation of mass. Also, at some time during this early era probed by the LHC, WIMP particles of dark matter are likely to have disconnected from SM particles, with their subsequent density determined. It is only by recreating early-Universe conditions in the Universe that

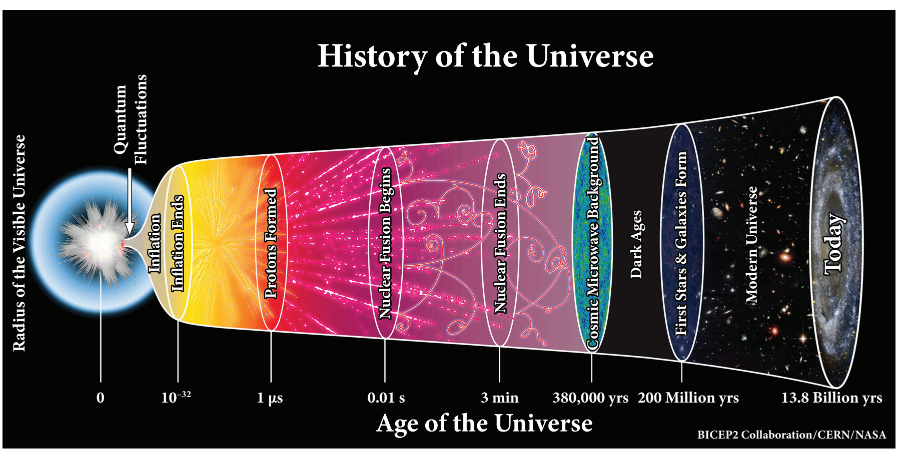

Figure 5.5 Different stages in the history of the Universe

Source: TheAstronomyBum, CC0, via Wikimedia Commons we may be able to understand the processes leading to the present density of dark matter.

Another puzzle whose solution may have been found during the FCC era is the origin of matter itself. The Universe today contains over a billion times more radiation than matter, there are no known concentrations of antimatter. Why is there asymmetry between matter and antimatter, and why is there any antimatter at all? As noted in Chapter 2, in 1967 the Russian physicist Andrei Sakharov proposed a possible mechanism based on the microscopic differences observed between the weak interactions of matter and antimatter particles. The differences that have been observed to date in laboratory experiments can be accommodated within the SM, though without a deep explanation. However, Sakharov's mechanism requires some additional source of matter-antimatter differences and posits that the expansion of the early Universe must have deviated from the smooth expansion observed today. FCC-ee and -hh experiments will produce enormous numbers of particle-antiparticle pairs. These will allow detailed explorations of the possible differences between particles and antiparticles, potentially uncovering one element of Sakharov's mechanism that is missing. Another missing element could be identified if FCC experiments can establish whether particle masses were generated suddenly causing a departure from smooth expansion.

What of Gauguin's third question, 'where are we going?' The expansion of the Universe is currently accelerating, driven by an apparently near-constant density of energy in empty space, the dark energy mentioned earlier. If, indeed, it does not change with time, it can be identified with Einstein's cosmological constant. However, according to the SM, although it may be constant nowadays, it would have changed while quarks and gluons morphed into protons and neutrons, and while fundamental particles acquired their masses. These changes would have been many orders of magnitude larger than the density of dark energy today, raising the question of why the cosmological constant is so small today. FCC experiments will cast more light on the processes occurring in the early Universe, and perhaps reveal missing aspects of our current understanding of the dark energy problem. As mentioned earlier, one possibility is that the dark energy density will change in the future, putting an end to the current expansion of the Universe and causing it to terminate in a Big Crunch. This possibility is currently favoured by calculations within the SM based on present-day measurements of the masses of the top quark and the Higgs boson, and the scale of the strong interactions. Measurements by FCC experiments will provide a more accurate basis for these calculations, and possibly also uncover evidence for some extension of the SM that could avert the Big Crunch.

5.8 Boldly Going Where Only the Universe Has Gone Before

Every advance in human knowledge raises new, intriguing, and more profound questions. This is true, in particular, in fundamental physics following the establishment of the SM by experiments at the LEP and the LHC. Many questions have been raised in the previous paragraphs, and many possible answers. have been proposed. We do not know which, if any, of these answers are correct. That can only be resolved by experiments. As described above, the FCC experimental programme offers many ways to address the open questions and provide some of the key answers. However, it is also likely that FCC experiments will unearth new puzzles not mentioned above. With apologies to Einstein, we do know what the FCC will be doing, namely reproducing the particles, collisions, and other processes that have formed our Universe. However, we do not know what they are, nor what FCC experiments will discover, and that is the nature of fundamental research.

5.9 Marching Together: Brief Lessons from the History of Physics

A brief history of physics suggests that theoretical and experimental physics go hand in hand. Victor Weisskopf, the former director-general of CERN (1961 to 1966), values the dynamics of the experimental processes within the context of particle physics experiments and claims:

> There are three kinds of physicists, namely the machine builders, the experimental physicists, and the theoretical physicists. …. the machine builders are the most important ones, because if they were not there, we would not get into this small-scale region of space. …. The experimentalists were those fellows on the ships who sailed to the other side of the world and then jumped upon the new islands and wrote down what they saw. The theoretical physicists are those fellows who stayed behind in Madrid and told Columbus that he was going to land in India.
>
> Weisskopf (1977)

The above allegory capturing the dynamic relationship between theory, experiment and instrumentation that defines the pace in particle physics research but also in other fields of fundamental science.

Looking back at the history of physics, one can find numerous relevant examples that led to breakthroughs in areas such as electromagnetism and general relativity. These examples should inform the balance between theory, experiment, and instrumentation, a discussion that is particularly pertinent as we discuss the physics motivation for a post-LHC generation of particle colliders.

Fundamental research that aims to push the boundaries of our knowledge further forward is—by definition—unpredictable. At certain junctures, theory may offer useful guidance, but at various other times in the history of science, experimental results have guided theoretical developments.

Tycho Brahe's main observations of stellar and planetary positions were noteworthy both for their accuracy and quantity. Though a geocentrist himself, his results led to Kepler's laws and the Newtonian revolution in physics. Before Tycho, probably no-one had ever thought to measure the position of Mars with such a degree of accuracy.

Likewise, when Willis Lamb and Robert Rutherford carried out an experiment using microwave techniques to stimulate radio-frequency transitions between the two hydrogen levels, there was no theoretical discrepancy to be solved. Yet the observation of the so-called Lamb shift led to the development of quantum electrodynamics that same year. To quote Freeman Dyson (Cohen et al., 2009): 'Those years, when the Lamb shift was the central theme of physics, were golden years for all the physicists of my generation. You were the first to see that this tiny shift, so elusive and hard to measure, would clarify our thinking about particles and fields.' The minor inconsistencies revealed by the precise measurement of the H-atom spectrum helped to point theorists in the right direction.

Similarly, another observation calling for a theoretical explanation was the φ (phi) meson decaying to the theoretically unfavoured kaon-antikaon channel instead of the favoured decay to a ρ (rho) and a π (pi) particle. The observed suppression of this decay process by two orders of magnitude, compared to the theoretical prediction, led George Zweig to theorise the existence of quarks[1] (called aces by Zweig): 'if mesons contained aces with the proper quantum numbers, and if the aces in a decaying meson were conserved, that is, became constituents of the decay products' (Zweig, 2013) the decay pattern of the phi meson could be understood. And although Feynman thought that the experiment was flawed, it turned out that quarks do indeed exist and were experimentally observed a few years later. Other instances of experimental leadership include the discoveries of radioactivity and the CMB, which did not come about because of a well-defined theoretical target, but nevertheless opened the way towards a much deeper understanding of Nature.

When Galileo perfected the telescope, he could not predict how many moons would be discovered around Jupiter. Similarly, when studying the feasibility of future colliders, we cannot predict how many new particles we may discover, but only define the questions we wish to address in the spirit of fundamental research. In spite of the exploratory nature of collider projects, future colliders are not merely shots in the dark. Fully exploiting their potential calls for unity between theory, experiment, and instrumentation (Galison and Hevly, 1992; Galison, 1997). FCCs offer a solid, multi-decade-long, research programme with well-defined goals that can greatly contribute to the expansion of our knowledge of particle physics and the Universe.

5.10 Shaping a Vision for a New Research Infrastructure for the Twenty-First Century

According to our arguments above, the most efficient and comprehensive approach to thoroughly explore some of the open questions about our Cosmos is a new research infrastructure offering a staged research programme that would combine

[1] These were proposed independently by Murray Gell-Mann (who played a preeminent role in the development of the theory of elementary particles) and André Petermann (who pioneered the renormalization group, paving the way for the modern theory of phase transitions), for different reasons.

precision measurements with direct exploration of previously uncharted energies. In December 2018, the Future Circular Collider (FCC) collaboration submitted its Conceptual Design Report (CDR) (FCC Collaboration, 2019; 2019b), exploring the physics opportunities that opened up the next-generation of particle colliders housed in a new 100 km circumference tunnel in the Geneva area. A lepton collider (FCC-ee), as the first step, would push the precision frontier, followed by a 100 TeV hadron collider (FCC-hh) that would allow the direct exploration of previously inaccessible experimental areas. Further opportunities offered by the FCC complex include heavy-ion collisions, lepton-hadron collisions, and fixed-target experiments.

Succeeding in this challenge relies on a number of factors beyond the pure scientific merit of the project, as reflected in the history of previous Big Science projects. Realising an ambitious project like the FCC calls for efficiently building and managing an international collaboration across organisational, sectoral, and national boundaries. Particle physics and CERN are no strangers to this approach. At the heart of this effort lies the development of a global and diverse collaboration; this includes building a large and diverse community of users that seeks to exploit the physics opportunities as well as the means for leveraging resources and mitigating risks during the design, construction, and eventually the operation phase of the proposed colliders. The answers to these questions, together with the scientific opportunities offered by the FCC and results from the technological R&D programme, will inform the final decision on investing in a truly international research infrastructure at the heart of Europe.

The numerical and geographical growth of the FCC collaboration, from the first kick-off meeting in 2014 to the publication of the FCC CDR in 2020, testifies to the attractiveness of the project and the openness of the collaboration-building approach. A number of global R&D efforts were launched during the preparation of the FCC Conceptual Design Report to understand the present technological limitations and identify pathways for reaching the ambitious technical goals of the FCC and to demonstrate the feasibility and sustainability of this project. Adopting a clear long-term vision and a set of target performance parameters for the construction and operation of the FCC has promoted co-operation among diverse groups of researchers from academia and industry within the FCC collaboration, helping to clarify objectives and priorities as well as focus efforts towards them. From a managerial perspective, our goal has been to clearly articulate strategies and sets of goals among all the partners involved, in a transparent and open way, to help align their R&D innovation efforts with their business strategies.

The long timelines involved in this project and the ambitious but tangible technological challenges uniquely position large-scale projects like the FCC to set up an innovation system that maximises the participants' capacity for innovation. This system includes a coherent set of interdependent processes and structures for sharing the desired results with the participants. These processes also assisted in sharing resources and communicating past lessons and technical knowhow, as well as organising regular topical meetings and workshops (including the annual FCC meetings) for companies to exchange their problems and explore solutions. Diverse perspectives are critical to successful innovation. But without a strategy to integrate and align those perspectives around common priorities, the power of diversity is blunted (Massimi, 2019). Clearly defined targets, openness in communication and CERN's previous reputation were catalysers in enabling a culture of trust that allowed this ecosystem to work efficiently and produce results—and the first prototype solutions for many technologies are already being tested and refined. By 2021, the FCC collaboration will count more than 150 institutes including universities, research centres, and industries from 34 countries collaborating to advance the key technologies that will enable the efficient and sustainable realisation of the FCCs.

In addition to the geographical distribution it is perhaps worth discussing the time profile of the FCC project. The implementation of the first stage, the intensity-frontier lepton collider FCC-ee, commences with a preparatory phase of eight years, followed by the construction phase (all civil and technical infrastructure, machines, and detectors, including commissioning) lasting ten years. A duration of 15 years is projected for the subsequent operation of the FCC-ee facility, to complete the currently envisaged physics programme. The total time for construction and operation of FCC-ee is nearly 35 years. The preparatory phase for the second stage, the energy-frontier hadron collider FCC-hh, will begin during the first half of the FCC-ee operation phase. After the end of FCC-ee operation, the FCC-ee machine will be removed followed by the installation and commissioning of the FCC-hh machine and detector, which will take about 10 years in total. The subsequent operation of the FCC-hh facility is expected to last 25 years, resulting in a total of 35 years for the construction and operation of FCC-hh. It is important to note that the proposed staged implementation with FCC-ee as the first step followed by FCC-hh provides a time window of 25–30 years for critical R&D on key technologies that could reduce the cost and further improve the performance for the second-stage energy-frontier collider that will use the same infrastructure. In conclusion, the vision opened by the FCC study offers a solid and credible way to push the energy frontier further within the twenty-first century while advancing novel technologies to do that in a cost-efficient and environmentally friendly way.

Following the recommendations of the last update in 2020 of the European Strategy for Particle Physics (ESPPU, 2020), CERN has launched a feasibility study to understand the environmental and socio-economic impacts of the proposed research infrastructure. The goal is to study in depth the scientific, environmental, social, and economic impact of the project along with the physics opportunities that this research infrastructure could offer. The feasibility study report is expected in 2025 or 2026 as input to the next Strategy update, offering an opportunity to assess the technological challenges of realising the next generation of particle colliders for the twenty-first century. One of the main outcomes expected is the determination of the best placement and layout, balancing the territorial, geological, and physical constraints. The approach that the FCC team has adopted is to mitigate any risks and whenever possible reduce the environmental impact of the project while compensating for any potential impact in line with the principle 'avoid, reduce, compensate' foreseen in the European legal framework and adopted by CERN's Host States. The feasibility study will also serve to optimise the parameters of the two machines and maximise the positive effects of the development of new research infrastructure (RI) in the region.

Currently the FCC project foresees the next steps:

- **2025–2026**: Execution of the FCC feasibility study and production of a report that will inform the next European Strategy Update;
- **2027–2028**: Decision of the CERN Member States to launch the project if the conditions are met, within the framework of the European strategy for particle physics;
- **2030–2031**: Finalisation of the detailed study phase and deliberation in CERN's council for a final decision;
- **after 2033**: Start of civil engineering works, which should last until 2040;
- **mid 2040s**: Commissioning of the first collider (FCC-ee) for operation for around twenty years, alternating periods of operation and maintenance along with the necessary upgrades; and
- **mid 2060s–2070s**: The FCC-ee would then be replaced, in the second phase, by a hadron collider allowing for collisions of both protons and ions (FCC-hh).

As shown during the preparatory phase of the FCC Conceptional Design Report (CDR), the integrated FCC programme minimises the uncertainties that could potentially adversely impact its implementation. An early start of the project's preparatory phase is needed to allow for the timely implementation of the intensity-frontier lepton collider (FCC-ee) that marks the first stage of the project. Residual technical challenges for the subsequent energy-frontier hadron (FCC-hh) collider can be addressed through a well-focused R&D programme during the construction and operation of the FCC-ee.

An eight-year preparatory phase, which includes a feasibility study, is adequate to carry out the relevant administrative processes and develop a funding model for the first stage of the FCC, focusing on a new infrastructure and a high-intensity lepton collider. An immediate and related challenge is the creation of a worldwide consortium of scientific contributors who commit to providing resources for the development and preparation of the scientific part of the project.

5.11 Advancing New Technologies for New Discoveries

The proposed FCC will profit from CERN's existing accelerator complex and infrastructure that have developed over time to push the frontiers of knowledge by drawing on the latest technological advances. Today CERN operates several generations of accelerators, in particular: LINAC4 since 2017, the Proton Synchrotron Booster (PSB) since 1972, the Proton Synchrotron (PS) since 1959, the Super Proton Synchrotron (SPS) since 1976, and the LHC, (which was installed in the tunnel that had hosted the LEP between 1989 and 2000) commissioned in 2008 with the first physics results in 2010. The LHC, following the HL-LHC upgrade, will continue its operation until the 2040s, offering more data to tackle some of the open questions in particle physics. It is worth noting that LEP and LHC, like any large infrastructure, went through several phases during their development: in the case of the LHC a design phase (ten years), a construction phase (ten years) and operations (20–30 years).

Looking back at the history of particle colliders, we are reminded that in particle physics, like other scientific fields, scientific advancements are closely coupled with technological breakthroughs. For example, over the past 30 years, the exploration of the infinitely small has gone hand-in-hand with advances in superconducting magnets (Rossi and Bottura, 2012). Specifically, the increasingly powerful hadron colliders, from the Tevatron, commissioned in 1983, to the LHC in 2008, have led to spectacular discoveries thanks to developments in superconducting technologies that were used for building these colliders on an unprecedented scale.

Advances in accelerator technologies must be accompanied by advances in detector technology as larger numbers of more complicated particle collisions are produced. The technological sophistication of the LHC detectors is remarkable, as they include several subdetector systems, contain millions of detecting elements and support a research programme for the international particle physics community. The volume of data that will be produced during the high-luminosity upgrade of the LHC and by future colliders calls for even more sophisticated technologies. Further advances are necessary to enable the processing of larger and more complex data samples that eventually boost performance beyond today's state-of-the-art. For example, at least two areas that need immediate attention for technology development are superconducting materials and gases. Big Science projects such as CERN LHC, and in particular the greenhouse gases (GHG) of the present ATLAS and CMS gas detectors pose a big environmental issue. Resistive Plate Chamber (RPC) detectors are widely used at the CERN LHC experiments as muon trigger due to their excellent time resolution. They are operated with a Freon-based gas mixture of C2H2F4 and SF6 and these greenhouse gases have a very high global warming potential (GWP). Research is necessary to find environmentally friendly gas mixtures that help reduce GHG emissions and optimise RPC performance at a reasonable cost (Guida et al., 2020).

From an early stage, the FCC collaboration launched a number of R&D programmes bringing together academia with industry while also mixing traditional with new players. In this way combining valuable experience with fresh approaches in a number of technologies is essential to reach the desired performance and exploiting the physics opportunities offered by pushing the energy and intensity frontiers. Tackling the challenges of building and operating a research infrastructure of this scale in a sustainable fashion calls for technological breakthroughs beyond the improvement of existing technologies. From an early stage, and to succeed in preparing a Conceptual Design Report (CDR), the FCC tried to establish an environment characterised by creativity, agility, and openness as the conditions for nurturing research and innovation.

To this end, the FCC collaboration sets thematic priorities and focuses efforts on fields that show particular relevance for the sustainable implementation and operation of next-generation colliders, present great potential for growth and deployment thus maximising the societal impact, and exhibit a high potential for developing innovative solutions that could find applications in tackling other pressing issues of our societies. At the same time, the FCC management has been consistently developing all the competencies in technological skills, training and education that are necessary for the FCC study to offer a progressive research and innovation space, thereby strengthening the viability of this new research infrastructure.

Technology research and development during the FCC CDR preparation phase allowed us to identify the most relevant technical uncertainties and mitigate potential risks while paving the way to evolve the key technologies to the appropriate readiness levels to permit construction and efficient operation. Pushing the boundaries of accelerator and detector technologies for FCC further forward is an important step in the decision-making process for such large-scale scientific projects and is key for ensuring the sustainable and efficient operation of a new research infrastructure that will respect the UN's 2030 agenda for sustainable development.

5.12 A Tale of Science and Collaboration

In the following we briefly highlight some of the lessons learned from the global R&D activities launched in the framework of a global Big Science project like the FCC:

a) The FCC collaboration offers a physical and digital space and consequently the spatial and technological proximity among innovators in technology 'hotspots', academia, research centres, industrial parks, and technology incubators that is needed for the accelerating development of technology;
b) The number of different technological domains covered by the FCC study (e.g. beam control, vacuum systems, superconductivity and high-field magnets, radio frequency (RF) cavities, detector technologies, cryogenic and refrigeration, safety, environmental protection, etc.) boost the cross-fertilisation of technologies across various disciplines and result in a broader portfolio of competencies that are fundamental to the competitiveness of technology-based firms;
c) Industry innovation is frequently path-dependent and firms find it costly to break away from existing routines towards radically new or different concepts. The FCC collaborative R&D has encouraged risk-taking and supported different industries to open up to more innovative R&D solutions that they would otherwise not pursue alone. This approach paves the way to more cost-efficient technologies that could be industrialised at large scales, meeting the demand of future large-scale projects and also opening up the potential of

using these technologies in market applications beyond HEP, while improving the performance and hence maximising the research potential of future facilities;

d) The ability to build a common vision with the project partners and stakeholders along with a path for turning this vision into reality has been critical for success in the R&D lines. During the first phase of the FCC study that led to the publication of the FCC CDR, it became increasingly apparent that vision can be both conceived in and directly impacted by the context of the times, while it is important from a managerial point of view to possess the ability to oversee that vision's implementation. Vision divorced from context can produce very erratic and unpredictable results;

(e) Alliances like those fostered by the FCC R&D programme are organisationally complex and require considerable resources to maintain collaborative activity compared with more arms-length agreements such as outsourcing. In other words, the collaborative effort that we develop comes at a certain cost and requires the allocation of well-defined resources for setting up a healthy collaboration environment among the different partners;

f) Two important factors that often characterise R&D efforts are risk and uncertainty. This has been the case for the FCC R&D programme. The concept of uncertainty within the innovation process is well-understood, and we will not delve into it in detail here. In general, the newer the sector, the closer it is to 'basic research' in the sense that the outcome of the research can lead to fundamental changes in knowledge, rather than technology. This is the case for many of the technological fields explored within the FCC study, with the domain of superconducting technologies (for RF cavities, high-field magnets, or detector components) being one of the most characteristic examples, given the interplay between instrumentation, theory and experiment that characterises this field. The FCC integrated programme can greatly benefit from such 'blue sky' research and, despite the higher level of uncertainty, the results can have a huge impact on high energy physics and beyond; and

g) Ongoing R&D efforts in the framework of FCC have demonstrated that the rate of technical change is determined not just by the level of uncertainty of technological change, but also by the number of possible directions in which it can develop. Thus, while technological change may not always be perceptible or discrete, it is continuous. It is not, however, determined by one company or concept but by numerous path-dependent solutions being developed independently by several aspiring innovators. A level of optimisation must be integrated into each step during a well-coordinated collaborative R&D effort.

Finally, the FCC study strives to assess the wider socio-economic benefits of collaborative R&D and understand how to maximise them for the FCC study stakeholders involved. To achieve that, from a very early stage the FCC study formed a group of economists, programme managers and policy-makers launching a number of research activities to understand and quantify the wider socio-economic impact

(Florio and Sirtori, 2016). While there is extensive evidence in the literature that innovative R&D leads to considerable economic benefits, there is still little agreement on the methodologies for assessing them. The FCC study invests in creating the space for debating and refining the different methodologies (Beck and Charitos, 2021), profiting from the intense ongoing R&D activities and offering an immediate interaction between the economists, the scientists and the firms working on these R&D programmes.

The discussion above confirms that working hand in hand throughout the entire innovation process is the key to success: from scientists who develop ideas; to innovators who bring ideas into the economy and society; and to people who use the innovations in their everyday lives. To ensure that the FCC research results feed even more effectively into practical application, we are strengthening transfer, supporting open forms of innovation and the development of breakthrough innovations, promoting entrepreneurial spirit and innovative strength in small and medium enterprises, and intensifying our integration into European and international networks and innovation partnerships.

The implementation of the 2020 update of the European Strategy for Particle Physics and the exploration of the feasibility of a post-LHC circular collider like the FCC are adaptive processes. We will therefore tackle its implementation and further technological developments jointly with representatives from science, industry, and society, developing synergies for a participative implementation strategy. At the same time, the success of the FCC feasibility study relies on the involvement and mobilisation of citizens more closely in research and innovation, to inspire the next generation of experts who can join the field and shape the scientific and societal potential offered by a new research infrastructure (RI).

5.13 Big Science and Public Investment in Fundamental Science

Ultimately, the value for money to be obtained from such large-scale scientific facilities will depend on the scientific discoveries they help make and the effective exploitation of that science. However, over the past years there has been growing evidence that though the scientific outcomes (and their economic benefits) remain uncertain, RIs bring a number of concrete economic outputs for society extending from industrial procurement and human capital formation to the cultural and educational impact of these facilities.

Given the intangible nature of certain benefits and the long duration of these projects it proves difficult to identify a common methodology for measuring this impact and designing good practices. From its inception, the FCC study together with the HL-LHC worked with a team of economists to develop the right tools.

Cost Benefit Analysis (CBA) represents the most widely used methodological tool to quantify such impacts and its theoretical background and application to large-scale Research Infrastructures (RIs) have been discussed (Florio et al., 2016). Each

RI involves a different set of benefits, costs, and stakeholders that need to be carefully identified and measured at the very beginning of the design of the CBA. Nevertheless, each RI has its own distinguishing features, goals, and time horizons.

Previous studies of the LHC/HL-LHC programme identified six economically relevant benefits: (1) the value of scientific publications; (2) technology spillover; (3) training and education; (4) cultural effects; (5) services for industries and consumers; and (6) the value of knowledge as a public good. The socio-economic impact assessment of the LHC/HL-LHC programme, carried out in the scope of an European Investment Bank (EIB) project by the University of Milano (Italy), has revealed the added value of public investment in research infrastructures. This was the first application of this method and yielded some encouraging results indicating how this impact can be better measured and also on the tools that would allow it to be further maximised. Today, the H2020 EuroCirCol project is a reference case to apply the EU recommended framework for infrastructure CBA to the research community.

The long-time frame of the FCC programme adds complexity to the design of a CBA for a post-LHC collider. However, the CBA of the LHC/HL-LHC serves as a foundation for an evaluation of the societal costs and benefits of different FCC scenarios. The CBA model developed in the frame of the LHC/HL-LHC programme assessment is thus both methodologically appropriate and also necessary for the FCC programme. It could be accompanied by technology forecasting analysis that might help improve the estimation of benefits for firms and other economic agents.

It is assumed that the existing diverse and vibrant set of FCC R&D activities in the field of particle accelerator and detector technologies will continue and will lead to a converging programme for a future research infrastructure, nourished by cross-fertilisation of different particle acceleration technologies, design studies, and the continuous optimisation of facilities in operation. To that end, FCC will continue its unprecedented work with academia and industry and develop an entire ecosystem of innovation and entrepreneurship addressing the sustainable construction and operation of a post-LHC collider as well as societal challenges.

Understanding the socio-economic impact of Big Science demands a large-scale institutional response and is an open challenge for FCC as well as for other large-scale global RIs. There is a rich landscape of potential stemming from public investment in such projects, reaching society long before—and in addition to—the scientific lessons we gain. The methodologies applied and the interpretation of results should be a major subject in public policy, and at grant agencies and universities—reminding us that a project like FCC calls for co-innovations and synergies between multiple disciplines.

5.14 An Adventure beyond Particle Physics

Why it's simply impassible!
ALICE: Why, don't you mean impossible?
DOOR: No, I do mean impassible. (chuckles) Nothing's impossible!
Lewis Carroll, *Alice's Adventures in Wonderland*

CERN has always had aspects that reach far beyond those of a particle physics laboratory, since its operation epitomises European unity and its dynamics on a material level. As far back as its establishment in 1954, it has played an important part in the attempt to coalesce the ruined and fragmented European space into a vigorous and unified scientific, technological, financial, political, diplomatic, and social sphere.[2] At present, when the vision of European integration is challenged once more through increasingly intensifying nationalist and populist tendencies, CERN's mission as a unifying mechanism becomes exceptionally relevant again. Thus, a new dynamic project, such as the FCC, would allow CERN to place the heart of global science on European soil once again: a heart that will be able to 'pump blood' around the entire globe, acting as a circulatory network for workforces, research methods and innovations, and presenting a tangible example of scientific, political, financial—and even social—relationships.

Large-scale research infrastructures like the proposed FCC have the potential to catalytically reshape the world around us also through the technological spin-offs that accompany them. We will not delve into the famous technological applications that emerged via CERN (the World Wide Web, PET scans, touch screens, etc.), but we will focus instead on one decisive historical event for post-war science. Shortly before the flames of the war were extinguished, in 1945, the President of the USA, Franklin Roosevelt, tasked the acclaimed Vannevar Bush with proposing guidelines on how science should be supported so that it would meet the practical demands that lay ahead in the peacetime era to come. The issue at hand lay in outlining a funding policy for science that could be expected to stimulate progress in practical matters. Bush suggested that basic research is pivotal in making practical progress. As he argued, technological innovation is not likely to be brought about by research narrowly targeted at the problem at hand.

A superior strategy would be to perform broad fundamental research. The chief argument given was that the theoretical resources suitable for resolving a practical difficulty cannot be identified in advance. Rather, practical success may be made possible by findings that are prima facie unrelated to the problem at hand (Massimi, 2021). Post-war science policy was structured upon this idea, developing not only our scientific but also our technological culture. The same spirit seems to still inspire the scientists of our time.

So, some decades after Vannevar Bush, CERN's former director Rolf-Dieter Heuer claimed: 'If you only do targeted research, you lose the side-routes. You lose the way to use different routes, to go into a completely different domain, and to go into a completely different way of making breakthroughs. If you do not invest in basic research at some stage, you start losing the basis of applied research. The two are intimately interconnected' (Jung, 2012). In the same interview Heuer gives a pertinent example: 'If you look back some eighty years, then basic research completely revolved around trying to introduce the concept of antimatter. Nobody would have dreamt at the time of the introduction of antimatter, as a theoretical concept, that it would be used 40 years

[2] For instance, one of the main factors which led to the establishment of CERN was to minimise the effect of 'brain drain' out of Europe and into the US.

later in the hospital. Hospitals that combine the PET with the MRI are using detectors that were developed from our experiments.'

Particle physics finds itself today at a critical juncture, mirroring that of the societies around us, which find themselves in a unique historical period: grand social visions are disfavoured, financial and ideological challenges test the limits of the social fabric, and faith in scientific knowledge is frequently called into question while unscientific narratives swirl within public discourse. In this context, scientific projects such as the FCC could potentially contribute more expansive visions for our societies, operating akin to road signs at crossroads like these.

This is not a guaranteed result, of course, but rather a challenge both for science policy makers to provide opportunities for engagement, as well as for the broader public to debate issues relating to inclusivity, diversity, and sustainability. Let us not forget, moreover, that CERN's own establishment, at another critical historical juncture over 65 years ago, inspired a world that was finding its way out of the darkness of two world wars and the atom bomb.

At present then, when contemporary particle physics is characterised more by an open-ended explorative kind of research rather than research that has been tailored to test any particular theoretical prediction, the situation should not be regarded as unprecedented (ESPPU, 2019). The fact that this particular situation is not terra incognita does not of course mean that there exist ready-made patterns for us to follow. The path towards discovering New Physics will be long and arduous, something that becomes apparent when looking at the numerous unsuccessful attempts through the years.

Our efforts to discover the underlying laws and the fundamental building blocks of the Universe are a universal and enduring endeavour that dates from Leucippus and Democritus to the discovery of the electron and the rise of modern high energy particle physics. The FCC study, designing the next generation of post-LHC particle colliders, continues this extraordinary story of exploration. Discovering the global character of the physical laws allows us to understand both the micro- and macro-structures of the Universe, while curiosity and the ability to learn and pose new questions are part of our shared human experience.

5.15 Conclusions

We have discussed some of the open questions scientists face in the current landscape of particle physics, along with the theoretical and experimental evidence for the existence of new physics beyond the Standard Model. Answering the big open questions about our Universe calls for synergies with other fields beyond particle physics, including astrophysics and cosmology. It was highlighted how collider physics, astrophysics and observational cosmology can help to shed light on the questions of dark matter and dark energy. Progress in particle physics could have a tremendous impact on other fields, contributing to our understanding of the origin as well as the future of our Universe.

Furthermore, it is important when debating Big Science projects to recognise the essential contributions made by different communities—not just theorists and experimentalists, but also engineers, technicians and postgraduate students who collaborate to develop new and more efficient, scientific tools that could advance us along the path of discovery. Progress in science calls for unity among the different communities. Rapid scientific development also requires the cooperation of various other stakeholders besides particle physicists, including information technologists and other specialists, as well as various industrial stakeholders and government research laboratories. A project like the FCC requires international cooperation across organisational, sectoral, and national boundaries, which is a basic feature of large research programmes.

We have focused on the FCC as the facility that offers the most diverse particle physics research programme for the twenty-first century. However, we believe that similar lessons apply when thinking about other proposed frontier colliders as well as instruments in astronomy that will help us to explore the twenty-first-century landscape of physics and astrophysics.

What key lessons can we draw from this chapter? The following are some important messages that we wish to share:

1. Answering the grand questions 'How did the universe evolve after the Big Bang? What are we [made of]? What is the fate of our universe?' are universal questions that people have asked throughout human history and they are the main motivations behind the scientific research programme of the Future Circular Collider (FCC);
2. The LHC has shown how Big Science experiments can not only probe fundamental theories such as the Standard Model but also look beyond it to explore how the majority of the mass and energy in our universe could originate from physics that is currently unknown;
3. FCC experiments will cast more light on the processes that occurred in the early Universe, offering unprecedented precision measurements and direct access to new energy regimes;
4. Theory is important, but the history of science reminds us that scientific progress is dependent on a continuous dialogue between theory and experiment—a healthy balance between theory, experiment, and instrumentation is essential;
5. Progress results from asking the right questions and addressing them experimentally—how else do we know what we know to be true?;
6. To answer key questions about the origins, structure, and behaviour of the Universe, international research infrastructures offering staged research programmes are necessary—Big Science research infrastructures such as CERN, ESO, and other scientific facilities unite the global community of researchers and combine their wisdom and intense scientific curiosity;
7. International collaboration across organisational, sectoral, and national boundaries is crucial for a new programme like the FCC and effective

international collaboration is a fundamental tenet for the success of Big Science programmes;

8. Proper management strategies by partners and stakeholders are the key success factors and are necessary to ensure smooth and cost-effective operations—‘*short cuts make long delays*’;
9. A new programme like the FCC would enable CERN to continue to make possible world-leading scientific research and help CERN to continue to provide leadership for research into new physics, phenomena, and industrial applications. Such knowledge has the potential to spin off many technological and social innovations in medicine, new materials, energy, complex climate change phenomena, and industry applications; and
10. The FCC has the potential to expand our understanding of the fundamental laws of physics, matter, and the universe and open up new frontiers in high energy physics.

The open and diverse FCC collaboration will require a balance between traditional and innovative players with strong industry involvement from the early stages of the life cycle of such a long-term project. Furthermore, in designing any of the next generation of Big Science projects, the study of their broader socio-economic impacts should be considered from an early phase, as this can also maximise the social returns from such a large public investment, by attracting broader engagement and support from the various stakeholders.