Chapter 20
High Energy Physics and the European Strategy

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Abstract Some remarks about the outcome of the European Strategy for Particle Physics and the future of high-energy physics in Europe.

On 7 March 1960 Bruno Touschek, then a researcher at the INFN laboratory in Frascati, gave a talk proposing the idea of a collider. More than 60 years later, Touschek's idea still underlies the most effective instrument at our disposal to investigate the world of elementary particles and to explore the structure of spacetime at the smallest possible distance scale.

Although I have never met Touschek, he has always been an inspiring figure for me. With his pure scientific genius and ironic sense of humour, he was a worthy successor of Fermi, belonging to a generation of physicists capable of working across the boundaries between theoretical and experimental physics. Indeed, while he is most famous for his accomplishments in experimental physics, he worked on many aspects of quantum field theory and I was told about an anecdote that refers to his studies on CP and time reversal. After a car accident, Touschek was brought to the emergency room of a hospital in Rome. The doctor started his visit with some simple questions to check if the patient suffered from brain damage as a result of the accident. The first question the doctor asked was what he was doing for a living, and Touschek replied: "I am thinking about temporal inversion." The medical examination ended immediately and Touschek was hospitalised with a diagnosis of serious concussion.

Sixty years of colliders have revolutionised our understanding of the microscopic behaviour of the physical world. The field of particle physics went through great discoveries, periods of confusion, unexpected results and brilliant breakthroughs that revealed an order in nature, which is embodied by the elegant conceptual structure now called the Standard Model. The theory is truly a monument of human scientific achievement, since it is able to explain the building blocks of matter and forces in terms of a geometrical principle, which is called gauge symmetry. It appears that gauge symmetry dictates the properties of all fundamental forces, gravity included.

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But the story of human discovery is not over. As long as civilisation exists, humans will always ask more and more fundamental questions about the origin of matter, of the universe and of spacetime. These questions still motivate particle physicists to continue their quest. The experimental tools at our disposal have certainly grown enormously since the time Touschek gave his visionary talk about colliders in Frascati, but colliders are still a central instrument for our field. Touschek's legacy is still alive today in the program of future colliders.

Before discussing the future of collider physics, I would like to consider another question: why do we need colliders? Our society, our planet are going through unprecedented challenges: epidemics, poverty, sustainable energy production, clean water supply, global warming and environmental protection. Given these pressing issues, are colliders really a priority for society? The answer to this question lies in the key role that science plays in addressing society urgent challenges. Of course, future scientific effort should focus on the most urgent issues that impact society, but investing only on immediate targets is a short-sighted strategy and, as shown repeatedly in history, it is not an effective way to find radical solutions. Focusing only on applied research simply doesn't work. Fundamental research is a necessary driver of innovation, and investments on fundamental science, which are comparatively small on the macro-economic level, can have a vast impact on the future of humanity. The global emergency caused by the covid-19 pandemic offers a good example. Particle physics cannot produce vaccines, but has produced the world wide web, which was instrumental for society to survive during the covid-19 crisis by allowing for the continuation of economical activities, global coordination, communication and social relations. CERN developed the web having the particle physicists' needs in mind, not the problems of society. But it is scary to think what would have been the impact of the covid-19 pandemic if CERN hadn't developed the web for particle physics.

Many technological advances of great benefit to society have come and will come from fundamental research which is targeted to problems that have nothing to do with society. Just to mention a few examples, research in detector developments led to new technologies for medical imaging and research for accelerators led to innovative therapies for cancer treatment. Future colliders require the development of a new generation of high-field superconducting magnets and research towards high-temperature superconductors. These materials could lead to new ways of storing and transporting energy with virtually no loss from resistance effects, solving one of the greatest limitations of renewable energy, such as wind and solar energy, which is available only for periods of time.

Moreover, collider experiments require the handling of unprecedented sets of big data. Dealing with these problems at the frontier of computing technology will certainly have an impact on our everyday life, when the technology developed for fundamental science is translated into applications for society. Future collider projects require cutting-edge advancements in cryogenics, vacuum, electronics. There is much that technologies developed for particle physics can offer society in the future. Fundamental science channels human talent and creativity towards complex problems, whose solutions lead invariably to unexpected applications. We can rarely predict what they will be, but these applications unfailingly happen.

Another byproduct of large projects at the frontier of science, such as experiments at collider, is scientific training. On average, each year CERN trains thousands of young researchers and PhD students. Not all these people go into academia. The vast majority brings to society and private industry their expertise in dealing with complex problems and in working in close contact with advanced technologies. Scientific training in a place like CERN is an invaluable resource for society. Another, more subtle, aspect that I would like to underline is related to the ethical values that are part of the scientific method. Practicing science helps developing certain principles of tolerance, respect, fairness and justice that contribute to make individuals better fit for society.

Of course, the aspect of fundamental research that is closest to my heart is the advancement of human knowledge. Understanding nature, understanding the universe, understanding physical reality have an immense value for humanity. The scientific exploration of the unknown has an extraordinary inspirational effect on the public and is a powerful driving force for civilisation. Humans simply cannot give up their intellectual curiosity to understand the world they live in.

Indeed, advancing scientific knowledge is CERN's primary mission. CERN is focusing on fundamental research in particle physics, but CERN is not blind to societal issues. Environmental sustainability is the biggest challenge that our society has to face today. As scientists, we cannot remain indifferent to these problems and our way of operating has to reflect the changing attitude. Particle physics should not simply adapt to societal changes, but should lead them. The tradition of particle physics is to be always at the forefront of changes, whether in scientific issues, information technologies, community practices. CERN is well aware of the challenge posed by environmental sustainability and is taking a leading role in the changes that we need to tackle. According to the current budgetary plan, during the period 2016-2026 CERN will invest about 53 MCHF in projects related to environmental protection. Moreover, CERN is carefully scrutinising large collider projects in terms of their environmental impact and studies include R&D on new environmentally friendly gases for the cryogenics of particle detectors. A critical aspect is optimising energy saving and reuse, and each new project is reviewed on the basis of energy consumption. Plans include heat recovery from computing facility, by converting it to heating for buildings during winter, and R&D on efficient power production with potential applications in industry. Another research direction is the development of technologies useful to protect the environment. This involves research with vacuum, high-temperature superconductors for electricity transport, and high-efficiency accelerator techniques.

The ultimate goal of collider research is the exploration of the particle world and the fundamental physical laws. As I mentioned before, today we have consolidated a superb description of nature at the fundamental level, which is given by the Standard Model of particle interactions together with General Relativity. Is this the final chapter of the story? Certainly not. While a perfectly consistent theory, the Standard Model cannot answer more structural questions about the origin of the underlying theory.

Some of the most puzzling aspects of the Standard Model come from the Higgs boson. The Higgs boson was discovered almost 10 years ago, although it was first proposed by theorists at the time that Touschek was pioneering the idea of particle colliders. The experimental data gathered at the LHC match very well the theoretical prediction for the Higgs boson, but the underlying nature of this particle remains a mystery. Its structure does not seem to follow from the same fundamental principles that determine the other particles in the Standard Model. This is why theorists are very much puzzled by the existence of the Higgs boson.

Most particle theorists believe that the Higgs boson must be only the tip of a more complex structure still unknown to us, submerged beyond the present frontier of knowledge. During the last decades, theorists came up with many new creative ideas of what could this submerged world be, and what could lie behind the Higgs boson. Many of these ideas are fascinating, introducing new kinds of forces, new particles, new symmetries, and even a new concept of spacetime. These ideas were put to empirical test with the experiments at the LHC, the CERN particle collider. However, none of these theoretical ideas was shown to be realised in nature.

Some people see in this result a failure of particle physics. I see only a success of the scientific method, which is based on theoretical hypotheses followed by experimental scrutiny. The current results from the LHC give only more reasons to pursue the search because the mysteries in particle physics remain unsolved. Actually, as a theorist, I think that the situation in particle physics is only more interesting today. What the LHC results are telling us is that, once again, nature hides surprises: the next layer of physical reality is very different from what we had imagined so far. The game for theorists is only becoming more intriguing and what we need today is a radical change of paradigm guiding us towards a revolutionary new vision of nature at small distances. This is the great challenge for the young generation of particle theorists. Some new theoretical ideas in this direction are starting to emerge, but it is still too early to tell if any of these ideas is really promising and could help us to resolve some of the mysteries left unexplained by the Standard Model. Of course, theory alone will never be able to tell us whether an hypothesis is correct or not, and we need more experiments to explore unknown territories. Needless to say, CERN has a thriving experimental program aimed at tackling the fundamental open questions in particle physics. In the short-term, the CERN scientific program has five main objectives.

The first objective is a successful Run 3 of the LHC. The LHC operates in alternating phases, with some years of data taking and some years of maintenance and upgrading. Today the Long Shut Down 2 phase has been completed and recently pilot beams have been circulating successfully in the LHC ring, in preparation for the Run 3 phase, in which ATLAS and CMS are expected to collect at least as much luminosity as in the previous run while LHCb and ALICE are expected to increase significantly their data set. After a risk assessment study, it has been decided that the optimal energy for the upcoming LHC run will be 13.6 TeV, slightly higher than in the previous run, but not yet at the ultimate target value of 14 TeV.

The second objective is the completion of preparatory work for the High-Luminosity LHC and the required upgrades of the detectors. The High-Luminosity phase follows Run 3 and will increase the total set of recorded data by a factor of

10. This will allow LHC physics to enter an era of precision measurements that will deliver a lot of important information about the properties of elementary particles. The High-Luminosity LHC is expected to start operating in the late twenties.

The third goal is to reinforce the scientific diversity program. A high-energy collider program is not sufficient to tackle the many open questions in particle physics. More and more, we need a variety of experimental strategies and approaches. A very constructive synergy is building up between particle physics and neighbouring fields, such as observational cosmology, multi-messenger astronomy, underground dark-matter detection, gravitational waves, nuclear physics, and even atomic and condensed-matter physics. New experimental techniques are starting to emerge especially in the search for light dark-matter particles and feebly-interacting particles.

The fourth objective is the support of neutrino experiments in the US and Japan through the Neutrino Platform. In particular, CERN is constructing cryostats for the Dune experiment.

Last, but not least, is theoretical physics, which CERN recognises as an essential objective to open new avenues of exploration and motivate experimental investigation. CERN will continue to support a vast range of theoretical studies, not only related to the laboratory's experimental programme but in a much broader perspective, which will serve as a vehicle of scientific progress and intellectual advancement.

CERN, and the particle-physics community in general, are looking beyond a short-term vision and dream about the future. This dreaming is done in a coherent and comprehensive way through the European Strategy for Particle Physics. This is a community-driven exercise, which first took place in 2005 and has been updated twice, at intervals of about 7 years. The last update took place in 2020 and I had the privilege of participating in the physics preparatory phase as CERN representative. The 2020 European Strategy was a particularly important event because the particle physics community is at a critical moment when decisions about the long-term strategy have to be pondered and debated. The process involved an open call for proposals, a general conference in which the community got together, a preparatory work in which the physics case was outlined in a Briefing Book, and finally a one-week closed session, where representatives from each European country and major labs were present, and where the final document was written.

From the physics point of view, the recommendations made by the European Strategy covered three points. (1) "An electron-positron Higgs factory is the highest-priority next collider." (2) "For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy." (3) "A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy".

The first point refers to the Higgs boson as a priority target. The discovery of the Higgs boson was a milestone in the history of science, but it has left us with many unanswered questions. The true nature of the Higgs boson is a big question mark for particle theorists. Luckily, we have the means to gain further information about its nature and this can be done only by measuring its properties with high precision. At present, we know the couplings of the Higgs to gauge bosons at the level of 10% and the couplings to third generation fermions at the level of 20%. But the goals of future Higgs factories are more ambitious and aim at going below the percent level in precision. This corresponds to testing a possible substructure of the Higgs particle up to distances hundreds of thousand times smaller than the proton radius. This superb probe of the intimate structure of the Higgs boson investigates in depth the question of whether the particle is composite or a truly elementary object.

Besides this fundamental task, future Higgs research aims at probing: *(i)* the Higgs couplings to second-generation fermions, which contain information about the mechanism that feeds mass to matter; *(ii)* invisible decay modes of the Higgs, which contain information about the nature of dark matter; *(iii)* the Higgs self-coupling, which contains information about the nature of the electroweak phase transition; *(iv)* possible rare Higgs decays, which contain information about the symmetry structure of the Standard Model. The experimental program of Higgs precision measurements goes straight into the heart of the many mysteries still enshrouding the origin of electroweak symmetry breaking.

There are several proposals around the world for exploring the properties of the Higgs boson. Other speakers have presented projects in Japan and China. As far as CERN is concerned, we have two projects on the table. The first one is called CLIC and is a linear e^+e^- collider which can be extended in stages, with a first stage in which the tunnel length is 11 km and the machine operates as a Higgs factory. The tunnel can then be extended up to 50 km, with the energy increasing accordingly, to explore the high-energy domain. The justification of this phase could be linked to possible discoveries at the LHC.

The second proposal is called FCC, Future Circular Collider. Essentially, it is a way of repeating the successful story of LEP and the LHC at a larger scale. The plan is to have a new tunnel, about 100 km long, which will host first a circular e^+e^- collider and then a proton-proton collider. In terms of precision, this machine would be a wonder, producing a million Higgs bosons and 10^5 more Z bosons than the full LEP program. The next stage of the FCC would accomplish what the European Strategy defined as "the ambition of the European particle physics community to operate a proton-proton collider at the highest achievable energy." If 16T magnets of Nb3Sn superconducting material are put in the FCC tunnel, one could build a hadron collider operating at about 100 TeV. With high-temperature superconducting material, one could dream of even higher energy, say 150 TeV. But even with regular 6T NbTi magnets, one could already do as well as the SSC.

Another priority identified by the European Strategy is accelerator research with special emphasis on new technologies. Along this line, CERN has doubled the budget on new accelerator projects. The most prominent project is AWAKE, which develops a new plasma wakefield acceleration, and new investments are made also for a far-future muon collider, which could be hosted in the FCC tunnel.

Lacking any precise hint for the scale of new physics from the LHC, we need, on one hand, to explore as deep as possible with the highest possible energy allowed by new technologies and, on the other hand, to broaden the research programme using a variety of different techniques, as recommended by the European Strategy. In this broad landscape of research, it is clear that colliders play an essential role and are irreplaceable tools for exploration. For example, the Higgs boson could have been discovered only through colliders and no other experimental tool or technique could have led to this discovery.

A crucial lesson learned from the LHC is that hadron colliders are not only discovery machines but also excellent precision machines. This result could not have been anticipated at the time the LHC started and was possible only because of the successful interplay between different elements: unprecedented technological advancements, exceptional accelerator performances, excellent detector resolutions, high-performance computing and data handling, higher-order theoretical calculations of background processes with accuracies unthinkable only a few years ago. The merging of different expertise from different scientific communities was the secret behind the success of the LHC precision programme, which brought new knowledge and opened new prospects in research beyond traditional frontiers. Precision has become key for present and future explorations in high-energy physics. There is a lot to learn from precision measurements even without direct access to high-energy process.

A good example of the value of precision measurements are the LHCb results on rare *B* meson decays, which are showing unexpected discrepancies with the Standard Model predictions. It is too early to tell if these results are real and not only statistical fluctuations or poorly understood systematics, but lots of new data from the LHC and Belle II will come and clarify the situation. If true, these results would be a revolution in particle physics because they cannot be explained by a small deformation of the Standard Model. They would really shatter the basic structure of the Standard Model and imply the existence of a new sector of the theory.

Bruno Touschek was a visionary. His vision is still alive today in present and future CERN scientific projects. Research at future colliders has an impact on society well beyond the boundaries of scientific knowledge, since it can boost technological developments in many areas in ways that are unimaginable without the driving force from fundamental science. But, most of all, it is going to allow us to explore nature at even smaller distance scales and provide humanity with new knowledge about the fundamental principles that govern the physical world. With a rich program in collider physics, CERN is keeping Touschek's dream alive, inspiring today some young girls or boys to say what Touschek wrote in a letter to his father in 1946: "Ich will ein Physiker werden." I want to become a physicist.