Chapter 10
The Large Machines: LEP, the LHC and Beyond

Although no longer at CERN after his retirement, Herwig maintained a keen interest in the Large Electron-Positron collider (LEP) throughout the machine's operational lifetime. "I considered it as a kind of child," he explained, "and with one member of my real family staying in Geneva, Andreas by this time was working on the pioneering CPLEAR experiment studying CP violation at CERN, we kept our home in Switzerland."

Following the excitement of LEP's first big result, announced on 13 October 1989, which had shown that there are three and only three families of fundamental particles in nature, each of the four LEP experiments went on further to pin down that number to 2.984 plus or minus 0.008. Why there are only three families remains, however, a mystery and a question for future research to address. Other key results were soon to follow, building LEP's legacy as the machine that put the standard model of particle physics on firm experimental foundations.

LEP ran in two phases: LEP I until 1996, and the higher energy LEP II until the machine was finally switched off in 2000. Each phase was designed to play a specific role. LEP I was a Z factory, producing Z particles in great numbers so the experiments could pin down its properties and thereby put the underlying electroweak theory to the test. LEP II took the collision energy above that needed to produce charged W particles in pairs, so the experiments could put them to a similar test. "By 2000, thanks largely to LEP," said Herwig, "the electroweak theory was confirmed as being among the greatest intellectual achievements of twentieth century science. The carrier W and Z particles had been measured with precision, and all the theoretical predictions about how they should behave and interact with other particles put to the test. LEP had transformed particle physics from a 10% accuracy science to a precision science with errors smaller than 1%."

On the political front, there were important developments through the LEP era too. Early in his mandate as CERN's Director-General, Carlo Rubbia presented plans to the CERN council that foresaw a large hadron collider (LHC) installed in the LEP

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tunnel and running along with LEP by 1998, but it was not to be. At least not in that form, or on that timescale.

Across the Atlantic, work began on the ambitious Superconducting Super Collider (SSC) project, a hadron collider over 80 km around with a projected collision energy of some 40 TeV. It too was not to be: Congress pulled the plug in 1993, leaving the high energy future for global particle physics looking bleak.

Throughout Rubbia's mandate, however, R&D continued for CERN's LHC, refining the design and reducing the costs. As a result, when Chris Llewellyn-Smith succeeded Rubbia as CERN's Director-General in 1994, the project was still very much alive. In December 1994, Llewellyn-Smith went to the CERN council with a plan for a reduced-cost LHC that would be built in two stages to spread the cost over a longer period of time, while simultaneously paring back the rest of the laboratory's research programme to a minimum. The plan worked, and the Council gave its blessing. The LHC was planned to start up in 2004 with only two-thirds of its magnets in place [1], and therefore able to operate at two-thirds of its design energy for a number of years before installing the remaining magnets and moving up to design energy. A decision on the precise schedule was deferred until 1997, but was eventually taken in 1996. By then, CERN had secured substantial support from non-member state countries, notably the USA, which, with the cancellation of the SSC was looking to Europe for its future, and Japan. Coupled with contributions from Russia, India and Canada, this global support for the project emboldened the CERN Council to approve construction in a single phase, albeit within a reduced overall budget for CERN. "This was a smart move by Chris," said Herwig, "very politically astute."

While all this was going on, LEP I concluded with around 18 million Z particles recorded and analysed [2]. By 1996, new superconducting cavities had been installed around the ring to boost the machine's energy to above the W-pair production threshold, with the collision energy gradually being increased over time towards its maximum of 209 GeV, a record for an electron machine to this day. By the year 2000, the LEP experiments had recorded some 80,000 W-pairs, and the experiment's job of precision testing the electroweak theory was reaching a conclusion. Civil engineering works for the LHC had been on-going in parallel. The time had come for LEP to make way for the LHC. But there was to be a twist in the tail.

A Nail-Biting Finish

By May 1999, a total of 288 superconducting accelerating cavities gave LEP the capacity to achieve a collision energy of 192 GeV. This was nominally the maximum energy that the machine would reach, with LEP due to be switched off at the end of the year, but circumstances conspired to change the course of events. First of all, although the mass of the Higgs boson was not predicted by theory, the range of masses available to it could be constrained by ever-more precise measurements of other parameters in the Standard Model. By 1999, such measurements had constrained the mass of the Higgs boson to be in the range of around 90 GeV to about 200 GeV, with the probability dropping with increasing mass. In other words, LEP had entered the most likely energy range to find this most elusive of particles.

In 1998, the pressure to keep LEP running was already high. Civil engineering work for the LHC was rescheduled in such a way as to give LEP one more year of running without delaying the LHC's start-up, and the CERN Council agreed to keep LEP for one more year. As 1999 drew to a close, ways were found to push LEP's superconducting cavities beyond their design limits. By November, they were delivering collisions at 202 GeV. 2000, LEP's extra year, was poised to be an exciting one.

The beams of LEP I had been accelerated by 128 normally conducting copper cavities, which gradually gave way to the superconducting ones as LEP I transformed into LEP II. At the end of 1999, 48 copper cavities remained in the ring, but there was plenty of room to reinstall eight more and push the collision energy up to 209 GeV from May 2000. With the Higgs appearing tantalisingly within reach, every extra GeV of energy mattered.

Already with 202 GeV collisions in the bag, two of the four LEP experiments were reporting potential candidates for Higgs bosons in their data. Regular meetings, each one packed to the rafters, were scheduled throughout the year for the experiments to report their latest analyses. "The Higgs candidate events remained, but the other two experiments continued to see nothing," remembered Herwig, "nevertheless, combining the results of all four experiments led the LEP experiments committee to conclude in November that the data were compatible with a Higgs particle with a mass of about 115 GeV, with a likelihood of around 50% that the measurement would stand the test of time." Those may sound like good odds, but in physics, signals such as that come and go with alarming frequency.

In July 2000, Fermilab had announced the discovery of the tau neutrino, leaving the Higgs boson as the last missing ingredient of the Standard Model to be discovered. With Fermilab's Tevatron scheduled to start its long-awaited Run II in 2001, with increased energy and luminosity, the stakes could not have been higher.

CERN's management, headed by Luciano Maiani since 1999, had a difficult decision to make. If they decided to run LEP for another year, they would delay the LHC, but they might just turn that 50% probability into a discovery. If they switched off LEP, they'd be leaving the field open to the Tevatron until the LHC started running. They chose the latter course, and at 8.00 a.m. on 2 November 2000, LEP was switched off for good. "A symposium was organised on this occasion," said Herwig, "and I was asked to give the eulogy."

Time has shown that the CERN management made the right call. Despite several years of glancing cautiously across the Atlantic, where the Tevatron experiments were inexorably narrowing the range of available masses available to the Higgs, it proved to be out of reach of both LEP and the Tevatron. The Higgs was discovered by the ATLAS and CMS experiments at the LHC, who announced the discovery on 4 July 2012. Its mass is 125 GeV. "LEP could have discovered it if more superconducting cavities had been installed," said Herwig, "but no spares were available and a new order to industry would have taken a long time."

Fig. 10.1 Left to right: Robert Aymar, Luciano Maiani, Chris Llewellyn-Smith, Carlo Rubbia and Herwig Schopper—the five CERN Directors-General who had presided over the lab through the LHC's long gestation—celebrate the machine's first beam on 10 September 2008 (©CERN, All rights reserved).

LEP's Contribution to Physics

CERN has a long history of contributions to the study of the fundamental interactions of nature, in particular, what we now know as the electroweak theory, which brings electromagnetic and weak interactions together in a single theoretical framework. Tito Fazzini, Giuseppe Fidecaro, Alec Merrison, Helmut Paul and Alvin Tollestrup set the scene in July 1958 when they published a paper showing evidence for the predicted decay of pions directly to electrons. This experiment provided an important measurement of an electromagnetic interaction, pre-dating the emergence of modern electroweak theory. It also it set a clear direction for CERN, and it made headlines around the world.

Electroweak theory was developed in the 1960s. By the 1970s it had reached theoretical maturity. With the discovery of weak neutral currents at CERN in 1973, and the W and Z bosons, carriers of the weak force, in the 1980s, CERN experiments had taken the first steps in laying the experimental foundations that underpin the theory. LEP's legacy would be to complete those foundations. It was built for that purpose, but when the machine started up in 1989, hopes were high that it might do more.

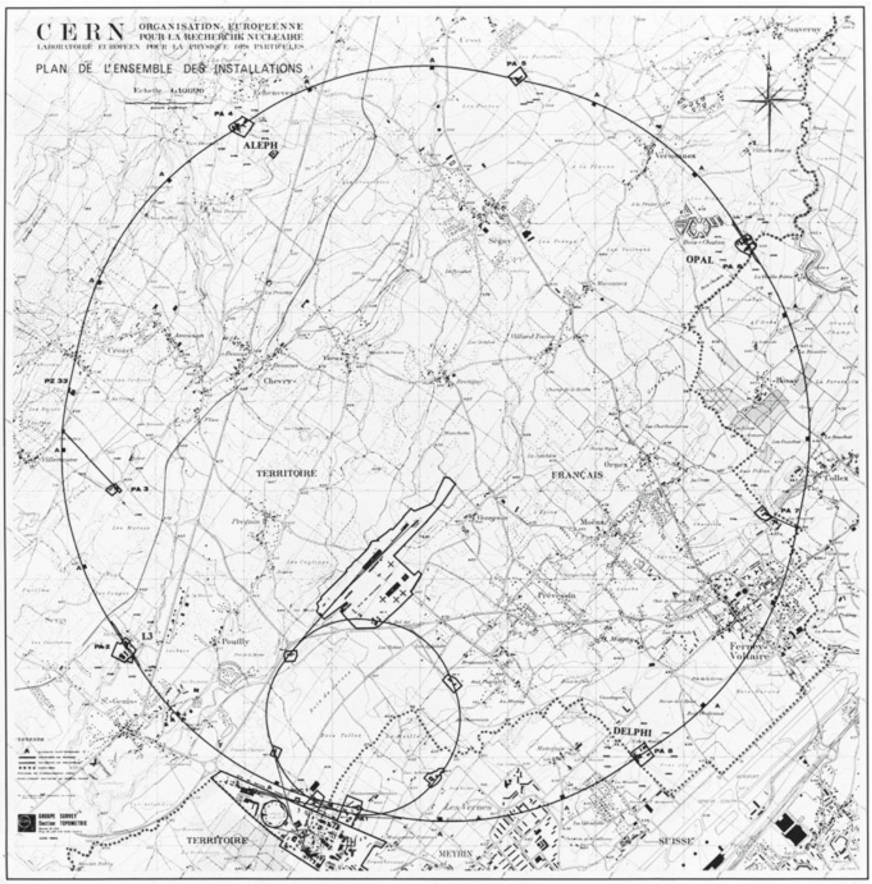

Fig. 10.2 The final position of LEP, with the sites of the four experiments marked on the map (©CERN, All rights reserved).

Theory and Experiment

"Whenever a new facility for particle physics starts up, it's a step into the unknown," said Herwig. "These machines are designed to venture into unexplored territory, which is why working with them is so exciting." LEP was no different. Designed specifically to put the electroweak theory to the test, it also ventured to higher energies than had been achieved before, and so opened up the enticing prospect of discovering something new and unexpected. "A good theory not only describes known experimental truths, it also makes predictions that can be tested," explained Herwig. "This was the case for the electroweak theory at the end of the 1980s. The job of experiments is to test those predictions to establish which theories best describe reality."

Fig. 10.3 An aerial view of CERN and its surroundings, showing the position of the LEP ring. The runway of Geneva airport gives an idea of the scale (©CERN, All rights reserved).

Even before LEP started up, however, it was already clear that the Standard Model of particle physics, of which electroweak theory is a key component, had limitations. New physics, and new theories, would be needed to explain some phenomena that had already been observed. “Sometimes something completely unexpected is found by experiments,” explained Herwig, “and we were all hoping for that with LEP. Such a discovery would not have destroyed the established knowledge—there are no real revolutions in physics, just steps beyond the domain of applicability of the existing theory.”

Einstein’s special theory of relativity is a key example. It superseded Newtonian gravity, but it did not invalidate it. Rather, it showed that Newton’s theory could only be applied at velocities that are low compared to the speed of light. Newtonian gravity is a special case of Einstein’s theories. In a similar way, physicists were hoping that LEP would be the machine to show that the Standard Model is a special case of some broader theory.

“When LEP started up, we had expectations in both directions,” said Herwig. “With beam energies of 50 GeV we expected to verify the Standard Model to high precision, but there was the hope, particularly with LEP II, that we’d find something new. After 12 years of hard work, we can safely say that LEP surpassed all expectations as far as verifying the Standard Model is concerned, turning it into a high-precision field. On the other hand, no spectacular new discovery was made at LEP, leaving physics beyond the Standard Model to the next generation."

In His Own Words: Incredible Precision and a Lasting Legacy

"We always refer to the big accelerators at CERN as machines, but really they are incredibly precise scientific instruments. In order to achieve the precision that it did, LEP I's beam energies had to be determined and kept constant with a precision of about 1 in 5000. This required great skill from both the accelerator teams and the experiments, and very close collaboration between the two. At the time, most experimental physicists carrying out experiments at CERN were used to turning up at the lab and simply having beams on tap. With LEP, they had to learn a whole new language. They acquired the accelerator physicists' and engineers' jargon, just as the accelerator teams learned theirs. As time went on, the experiments developed ways of working together as well, which bode well for the future. In research, it's important to keep human bias as far from the analysis as possible, since humans are very good at seeing what they want to see. That's partly why independent verification of results is a key part of any analysis. In the early days of LEP, the experiments kept very much to themselves to avoid any cross-contamination, but as time went on, they put procedures in place to combine their results when the time was right in order to get the best possible precision on the final measurement. This is standard practice these days, but at the end of the 1980s, that kind of collaboration between experiments was new.

Calibrating a scientific instrument is always a challenge, but when it's 27 km around, it becomes even more difficult. The beam energy of LEP was determined by the magnetic field along the beam path, and by the diameter of the ring. That's a fairly simple calculation, but with an instrument so big, even tiny changes in the diameter of the ring could have a significant influence on the calculated value for the beam energy. The magnetic field could be precisely measured, but the diameter of the ring was subject to factors beyond the control of even the best accelerator engineers. It was influenced by the sun, the moon, the amount of rainfall in the Geneva basin, and even the TGV trains accelerating out of Geneva's railway station on their way to Paris.

Earth tides caused by the influence of the sun and the moon, and rainfall changing the water levels within the Jura mountains and Lake Geneva could lead to variations in the diameter of as much as a metre. Once these effects were understood and implemented into the beam energy calculation, there remained one more fluctuation that took longer to understand. Its timing was regular, but not linked to any natural phenomenon that we could understand. We only solved it when someone noticed that it looked very much like the timetable for departures of the TGV to Paris, and that proved to be the cause. The TGV uses direct current electricity, which literally

Fig. 10.4 LEP's innovative so-called concrete magnets stored in the ISR tunnel awaiting installation. This was the first time the Laboratory had gone into mass production at this scale (©CERN,).

used the Earth as a return path. Since the tracks passed close to the LEP ring [3], the current preferred the low-resistance path offered by the LEP vacuum chamber and influenced the magnetic field along the beam path. When all these factors were understood, the residual systematic error in the beam energy for the mass of the Z particle was just 0.0017 GeV of the 90 GeV.

LEP, and above all the high precision achieved by the experiments, had established the basis for the further exploration of the standard model. For example, the mass of the top quark for which no theoretical prediction existed, could be deduced from the LEP results with high precision. The top quark was later detected at Fermilab, outside the range of masses available to LEP, but exactly where the LEP measurements had predicted it would be. Even more important for the future of CERN was the mere existence of the LEP tunnel. Although the original idea to install a hadron collider

Fig. 10.5 The spherical storage structure on top of LEP's copper accelerating cavities saved energy by ensuring that the accelerating field was applied only when beams were passing through the accelerating structures and stored at other times (©CERN, All rights reserved).

along with LEP had to be abandoned because of space limitations, the tunnel had nevertheless been designed with a hadron collider in mind. For the LHC, which replaced LEP in the tunnel, the 27 km circumference was essential. Had we only wanted to do electroweak physics with LEP, a circumference of about 20 km would have been sufficient. Despite going against the advice of many colleagues when we were designing the tunnel, insisting on the larger circumference proved the right thing to do. Without the existing tunnel, I doubt that the LHC would have been approved at all.

The great triumph of the LHC experiments so far has been the discovery of the Higgs boson with a mass within the range predicted by the LEP experiments. The LHC and its experiments, supported by amazing advances in scientific computing, have also proved their ability to do precision experiments. These have, so far,

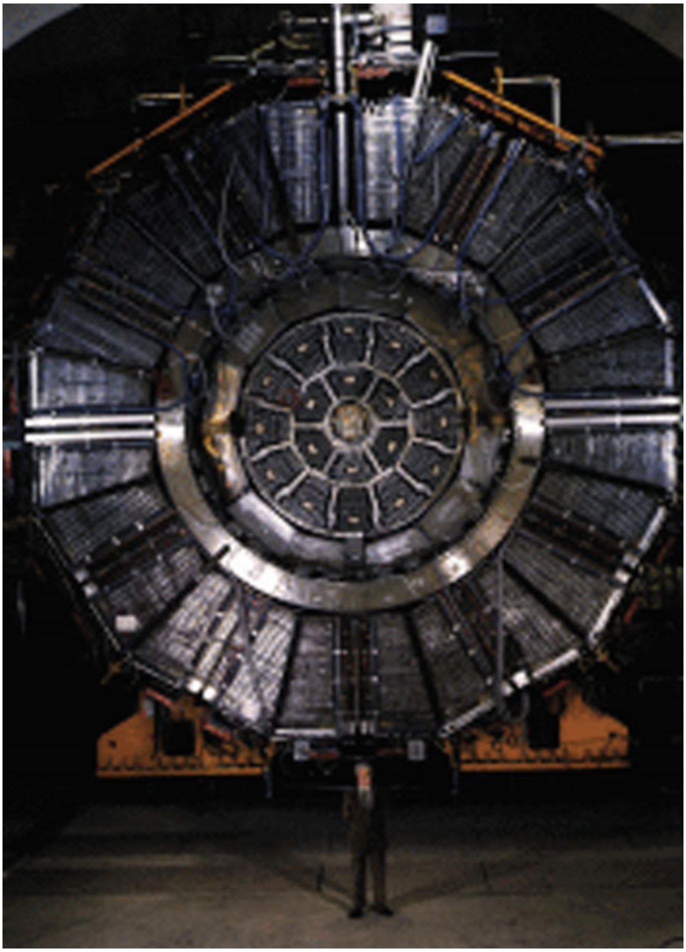

Fig. 10.6 Jack Steinberger stands in front of the ALEPH detector. Steinberger was the experiment's spokesperson ().

confirmed all expectations of the standard model, further cementing the monumental intellectual achievement that it represents. No definite signs of new physics beyond the standard model have been found, although there are some promising indications. Particle physics research is a painstaking process, a very important part of which is narrowing down the range of theories proposed to take the field beyond the standard model. The LHC is playing a valuable role in this respect. In a few years' time, it will begin a new phase, called high luminosity LHC, or HL-LHC for short. This will deliver much more data than the current LHC, improving the experiments' sensitivity to new physics. The whole community is looking forward to that.

LEP's legacy projects into the long-term future of CERN. The particle physics community has identified a future circular collider (FCC), with a circumference of

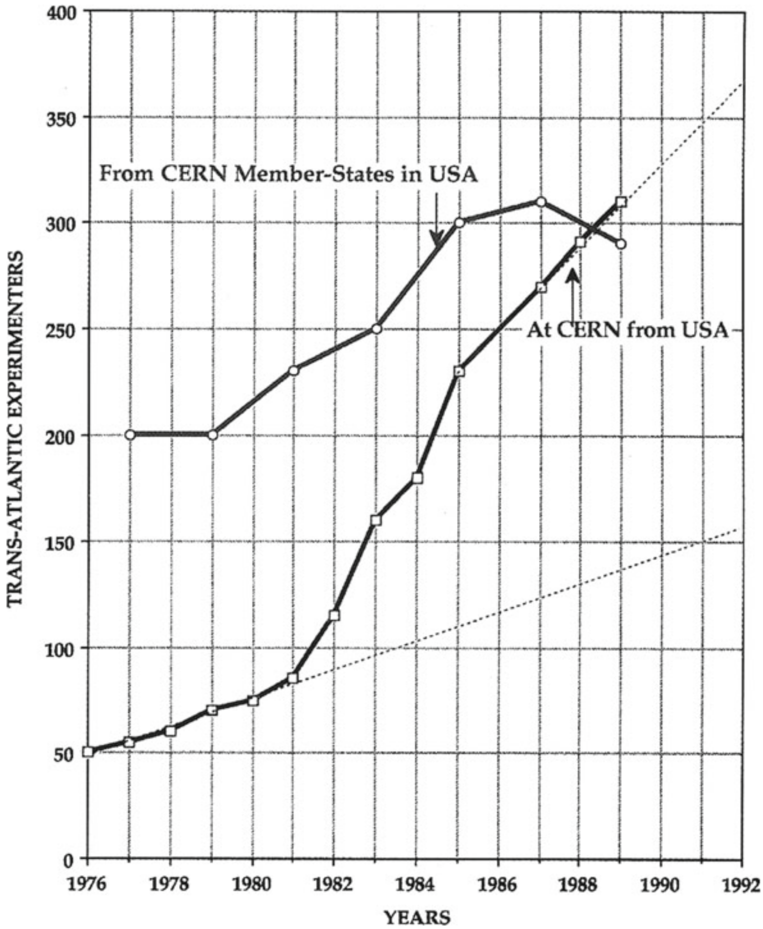

Fig. 10.7 A comparison of the number of particle physicists from CERN Member States working in the USA compared to the number of Americans working at CERN shows that there were more Americans at CERN for the first time in 1989—the year LEP started up (H. Schopper, LEP, 2009, 978-3-540-89300-4, ©Springer, All rights reserved).

about 90 km as the best facility from a pure physics perspective to take the field to the end of the twenty-first century. Such a machine would take over from the LHC in the 2040s. A study is underway with the goal of establishing whether it would be feasible from technological, geological, financial and environmental points of view. One thing that's already clear, however, is that if the FCC ever sees the light of day, it will follow the LEP–LHC strategy of first installing an electron collider, to be replaced later by a hadron machine. I think it's fair to conclude that LEP changed the course of high energy particle physics profoundly, and its legacy is still being played out.

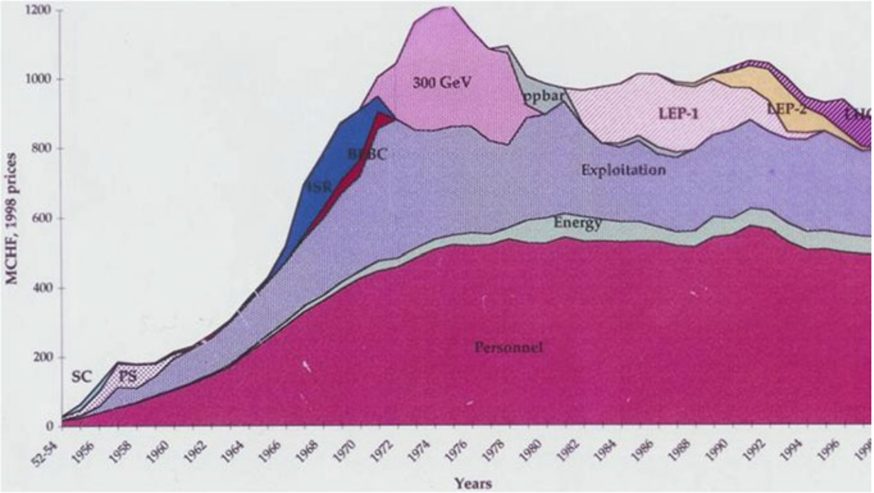

Fig. 10.8 CERN's budget rose rapidly in the early years of the Laboratory, reaching a peak in the 1970s. A constant budget was a condition for LEP's approval. The CERN budget has remained constant in real terms since then (H. Schopper, LEP, 2009, 978-3-540-89300-4, ©Springer, All rights reserved).

Over the 70 years that CERN has existed, it has achieved tremendous recognition. This is first and foremost due to its scientific achievements. But at the laboratory's foundation lies the concept of science for peace. This has allowed the positive values of science to be translated into international collaborations between countries—both for accelerators like LEP, the LHC and possibly the FCC in the future, as well as the experiments that study their collisions.

CERN and its experimental collaborations have demonstrated the benefit of diversity and inclusion: of non-discrimination between nationalities, races, religions, gender, political conviction or tradition. Over the years, CERN has grown, and maybe one day will evolve from being a European laboratory to a World laboratory by statute. Such a development would, of course, require certain changes in the Organization's convention and discussion in this direction have started already.

These days, it seems to me that CERN has become a byword for successful international collaboration. We hear people calling for 'a CERN for climate science', or 'a CERN for AI', or indeed for any number of major challenges facing humanity. Could the CERN model become a kind of template for collaboration between countries or even any new social structures that might emerge in the coming decades in our rapidly changing world? In 2023, as part of the UN-endorsed International Year of Basic Sciences for Sustainable Development, a panel discussion was organized at UN headquarters in New York. Moderated by my former colleague at CERN, Maurizio Bona, and with closing remarks from Michel Spiro, President of the International Union of Pure and Applied Physics, and a former President of the CERN Council, the session concluded with a call for international coordination of sustainability science.

With one of my successors as Director-General of CERN, Rolf Heuer, on the panel, the influence of CERN in this development is clear."

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