The Future Circular Collider

Its potential and lessons learnt from the LEP and LHC experiments

As researchers seek to learn more about the fundamental nature of our universe, new generations of particle accelerators are now in development in which beams of particles collide ever more precisely and at ever higher energies. Professor Stephen Myers, former Director of Accelerators & Technology at CERN and currently Executive Chair of ADAM SA, identifies both the positive and negative lessons which future projects can learn from previous generations of accelerators. Building on the extraordinary feats of researchers in the past, his findings offer particularly important guidance for one upcoming project: the Future Circular Collider.

The Standard Model of particle physics aims to provide a complete picture of all elementary particles and forces which comprise our universe. So far, the model has held up to even the most rigorous experiments which physicists have thrown at it, but there are still many aspects of the universe that it can't explain. Among these is dark matter: the enigmatic substance which makes up much of the universe's overall mass, but whose composition remains completely unknown to researchers.

In addition, there are still no concrete answers to the question of why the universe contains so much more matter than antimatter, or why tiny, chargeless neutrinos have any mass. For many physicists, it is now clear that the Standard Model in its current form isn't enough to answer these questions. This ultimately calls for a new theory which can encompass all of these as-yet mysterious phenomena and offer a deeper understanding of how our Universe evolved after the Big Bang.

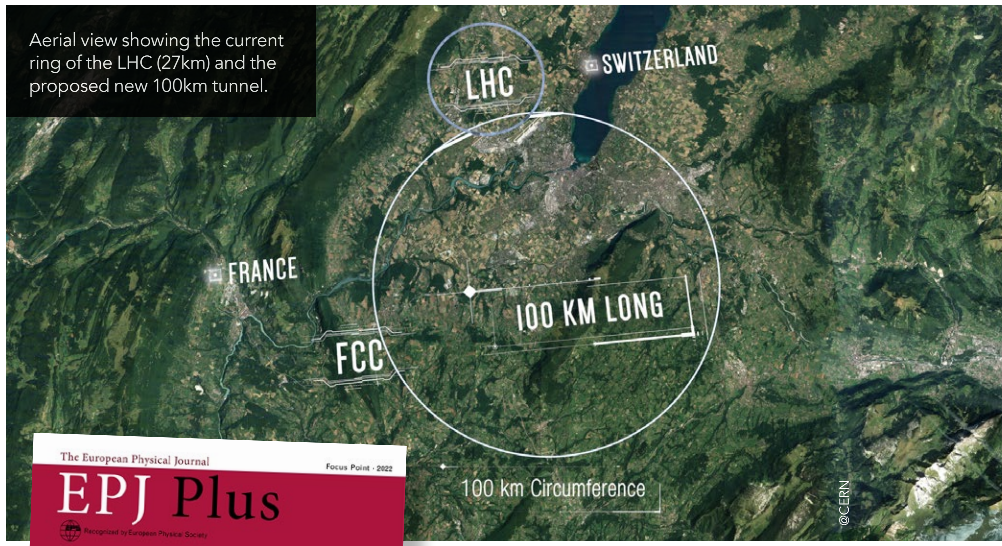
This may sound like an immensely ambitious goal, but the discoveries made by particle physicists so far have been no less transformative for our understanding of how the universe works. So far, the Standard Model has been tested by the Large Electron Positron collider (LEP). Already, the measurements of particle interactions offered by this experiment have had huge implications for our understanding of the infinitesimally small and the universe itself. Even further advances have since been made by the Large Hadron Collider (LHC) leading to the discovery of the Higgs boson and the study of how it interacts with other fundamental particles. Studying the properties of the newly found Higgs boson opens a new chapter in particle physics.

In a recently published essay, entitled 'FCC: Building on the shoulders of giants', in a special issue of the *EPJ Plus* journal, Professor Stephen Myers looks back at the building of the LEP and LHC colliders that contributed to the development of the Standard Model. His essay also discusses what the building and commissioning of the LEP can teach researchers in the design of the newly proposed circular electron-collider (FCC-ee).

POSSIBILITIES WITH PARTICLE ACCELERATORS

Particle colliders are at the core of all experimental research in fundamental physics. After inducing head-on collisions between beams of particles, travelling in opposite directions at close to the speed of light, researchers can closely analyse the particles formed in the aftermath. Ideally, this will allow them to identify any elementary particles contained within the colliding particles and the fundamental forces which govern the interactions between them.

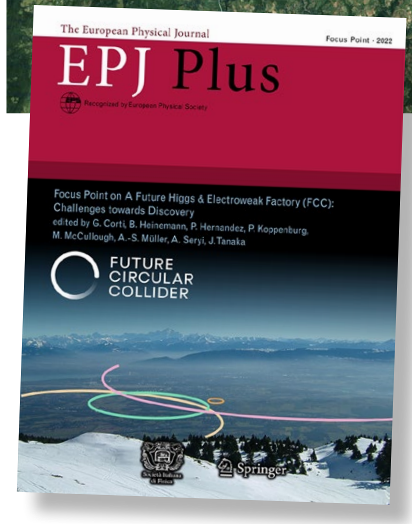
Artistic impression of the FCC accelerator and tunnel. Credit: Polar Media



Aerial view showing the current ring of the LHC (27km) and the proposed new 100km tunnel.

Among the first experiments to do this successfully on a large scale was the LEP, which induced collisions between beams of electrons and positrons – their antimatter counterparts. 'In the autumn of 1989, the LEP delivered the first of several results that still dominate the landscape of particle physics today', Myers recalls. 'It is often said that LEP discovered 'electroweak' radiative corrections to a high degree of certainty'.

This discovery relates to two fundamental forces described by the Standard Model: electromagnetism (which governs interactions between charged particles) and the weak nuclear force in atoms (which is responsible for radioactive decay). Although the two forces appear very different from each other at low energies, they essentially merge into the same force at extremely high energies – implying that they split apart in the earliest moments of the universe.



Myers, S, *Eur. Phys. J. Plus* (2021).

The integrated FCC programme is the fastest and most effective way of exploring the electroweak sector and searching for new physics.

The unification of these two forces in a single theory was undoubtedly one of the most important advances in particle physics to date, and ultimately opened up a new era of precision in the field. Although the LEP finished operating in 2000, it continues to set the standard for both modern and future experiments.

NEW DISCOVERIES

Building on the foundations provided by the LEP, the LHC began its operation at CERN in 2009. The collider and its four experiments were housed in the same 27-kilometre circular tunnel, originally built for the LEP, which straddles the border between France and Switzerland.

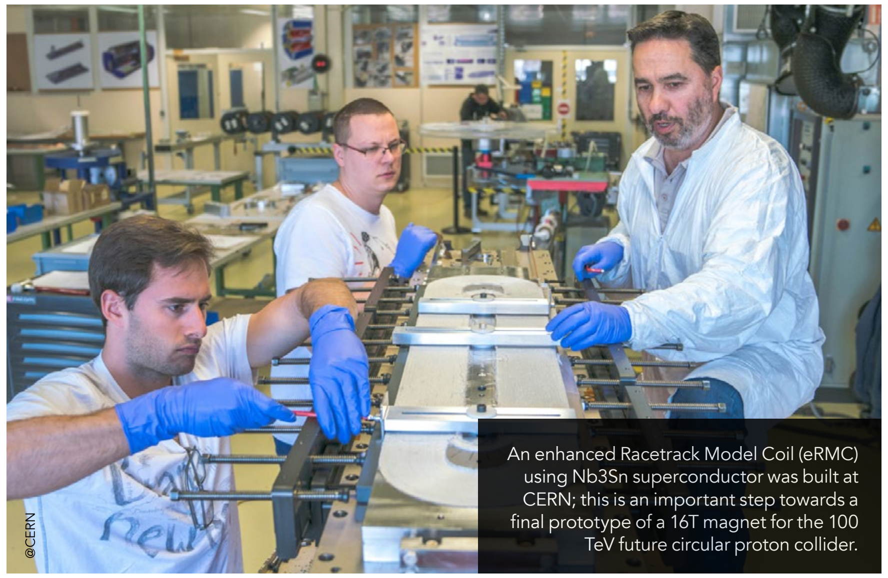
A young fellow measuring the properties of novel superconductors developed for future, more powerful magnets like those of the HL-LHC project and the FCC-hh.

The LEP was designed to induce collisions between elementary Standard Model particles named 'leptons', and specifically electrons and positrons. For the LHC, however, the hadrons contained in the colliding particle beams are made up of other Standard Model particles named 'quarks'. Initial experiments at the LHC culminated in the 2012 discovery of the Higgs boson: a highly unstable elementary particle which is now known to interact with all mass in the universe.

Together, the LEP and LHC experiments have enabled physicists to prove their earlier theories of the Standard Model. However, our understanding of fundamental physics still has a long way to go. This ultimately calls for new experiments, which are more advanced still. The LEP experiments demonstrated conclusively that only three families of matter particles exist – each containing two types of quarks and leptons', Myers describes. 'Why this should be the case remains another intriguing question for a new generation of researchers as we move into the LHC era and beyond'. Moreover, the discovery of the Higgs boson at the LHC was a historic event, but we are still only at the beginning in our understanding of the properties of this new particle and how it interacts with other particles.

INTRODUCING: THE FCC

To address this challenge, a new generation of researchers at CERN are now developing concepts for post-LHC



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An enhanced Racetrack Model Coil (eRMC) using Nb3Sn superconductor was built at CERN; this is an important step towards a final prototype of a 16T magnet for the 100 TeV future circular proton collider.

colliders housed in a new circular tunnel around 92 km in length. The Future Circular Collider (FCC) study explores a staged approach that combines a lepton with a proton collider, like previously LEP and LHC, thus offering a diverse physics programme until the end of the 21st century. The first stage of the project will be an 'intensity-frontier circular lepton collider' (FCC-ee). It will be contained in a circular tunnel some 100 kilometres long, making it far larger than its two predecessors and allowing it to generate brighter, more energetic beams. Eventually, the FCC-ee could be followed by an even more advanced energy-frontier hadron collider (FCC-hh) increasing by 8 times the present energy reach of the LHC.

The FCC isn't without competition, however. As the race to understand fundamental physics accelerates, three additional projects for a lepton collider are currently in development, including the International Linear Collider in Japan, the Compact Linear Collider, also at CERN, and the Circular Electron Positron Collider in China. Yet compared with these competitors, Myers believes that FCC-ee has several key advantages. Not only does it deliver the highest intensity beams out of all four projects, but it does so in a clean, well-understood, and highly predictable environment.

In turn, the FCC-ee could enable physicists to probe fundamental physics in unprecedented levels of detail. 'The integrated FCC programme is the fastest and most effective way of exploring the electroweak sector and searching for new physics', Myers explains. 'Experiments at the new accelerator would allow scrutiny of the newly discovered Higgs boson, and its interaction with the Standard Model particles.'

The FCC-ee's capabilities may be groundbreaking, but Myers stresses that the principles which physicists and engineers must draw upon to ensure its success have been in continual development for several decades – with the concept of electron-positron colliders dating back over 70 years.

Throughout this long history, many positive breakthroughs have been made in accelerator designs, which have provided important foundations for future projects such as the FCC. Inevitably, however, these projects also ran into problems which ultimately limited the quality of their results. In his essay, Myers analyses these positive and negative outcomes in detail – placing particular focus on the lessons we can learn from the LEP.

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LESSONS FROM THE LEP

Through his examination, Myers has identified a diverse variety of factors which led to both successes and shortcomings in the LEP project. These include several technical aspects of the accelerator itself: for example, while the LEP could determine the energy of its particle beams with ultra-high precision, the boring machines used to dig its circular tunnel were not well suited to the hard rock beneath the Jura mountains – leading to significant unforeseen delays.

Elsewhere, Myers emphasises that the human side of the FCC project cannot be ignored. The lessons he identifies offer important guidance for project management, in aspects including budget control, scheduling and planning, quality assurance, and resource saving and optimisation. He also suggests how the project could ensure a happy, healthy working environment for scientists, engineers, and their families.

Even further, Myers stresses the importance of building strong networks of researchers and industry stakeholders around the world, while offering high-quality training for new generations of experts. 'Altogether, the essay derives lessons related to the importance of international collaboration, the development of a user community to use the proposed research infrastructure, and the importance of developing the right managerial and funding tools', he summarises.

By drawing from these lessons, Myers hopes that researchers involved in the FCC will avoid the pitfalls of previous projects, while also 'building on the shoulders' of previous scientists and engineers, whose contributions transformed our ability to explore physics at a fundamental level. In turn, his work could help to ensure a highly successful research programme, which may one day produce long-awaited answers to questions about the true nature of our universe.

Behind the Research

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www.facebook.com/FCCstudy www.youtube.com/c/FutureCircularColliderStudy
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Research Objectives

In sight of the proposed FCC integrated programme, Professor Myers reviews lessons learnt from the LEP experiments.

Detail

Bio

Professor Stephen Myers worked at CERN from 1972 until 2015. He was responsible for the commissioning and energy upgrade of the Large Electron Positron Collider (LEP). During his time as Director of Accelerators and Technology (2008–2014), he directed the repair of the Large Hadron Collider (LHC) after the 2008 accident and then steered its operation. On 4th July 2012, the data from the collider allowed the discovery of a 'Higgs' boson for which Peter Higgs and Francois Englert received the Nobel Prize for Physics in 2013.

Professor Myers has received many international awards, honorary doctorates, and prizes as well as an OBE for services to science. Currently, he is Executive Chair of ADAM SA – a Geneva-based company which is developing a linear accelerator for proton therapy of cancer. He is also Executive Director of the parent company Advanced Oncotherapy (AVO).

Funding

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- EuroCirCol

Collaborators

- Michael Benedikt
- Frank Zimmermann

FUTURE CIRCULAR COLLIDER

CERN

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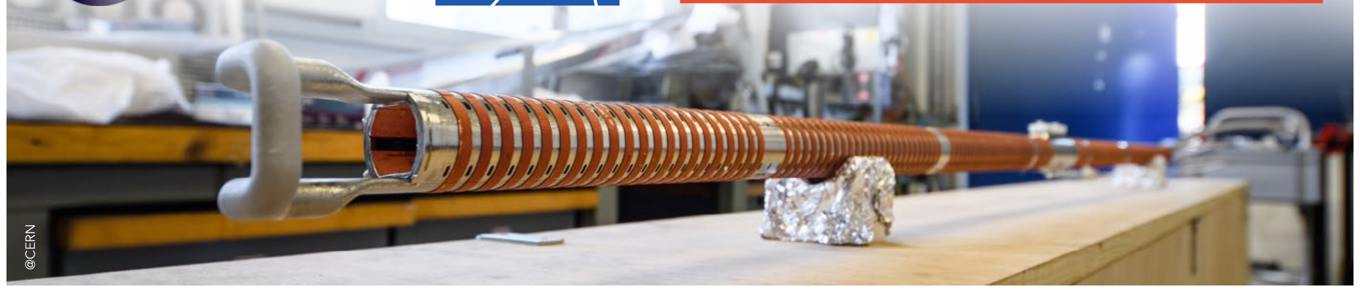
Personal Response

What is the value of diversity for the FCC collaboration?

"The diversity of the FCC study, as testified in the number of participants in the different areas of the study, is a key strength of the collaboration as everyone's different backgrounds and culture bring unique perspectives to the project and accelerate its progress. This is in line with CERN's previous history, bringing together a diverse mix of people to pursue a common vision. Diversity has driven the organisation's success over the decades and is key for designing a future post-LHC infrastructure. CERN's diversity programme is strengthening the high-energy physics tradition of inclusiveness. The history of LEP and LHC testifies to the value of an open environment, allowing individuals to contribute to their full potential. The FCC collaboration should continue actively pursuing targeted incentives to encourage underrepresented groups and support gender equality in an international scientific environment."



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