news feature

The show goes on

CERN, the centre for particle physics in Europe, has been smashing its way through the subatomic world for the past 50 years. Alison Abbott finds out what's in store for the future.

CERN

Where art and science meet: the DELPHI experiment takes a starring role in a dance about antimatter.

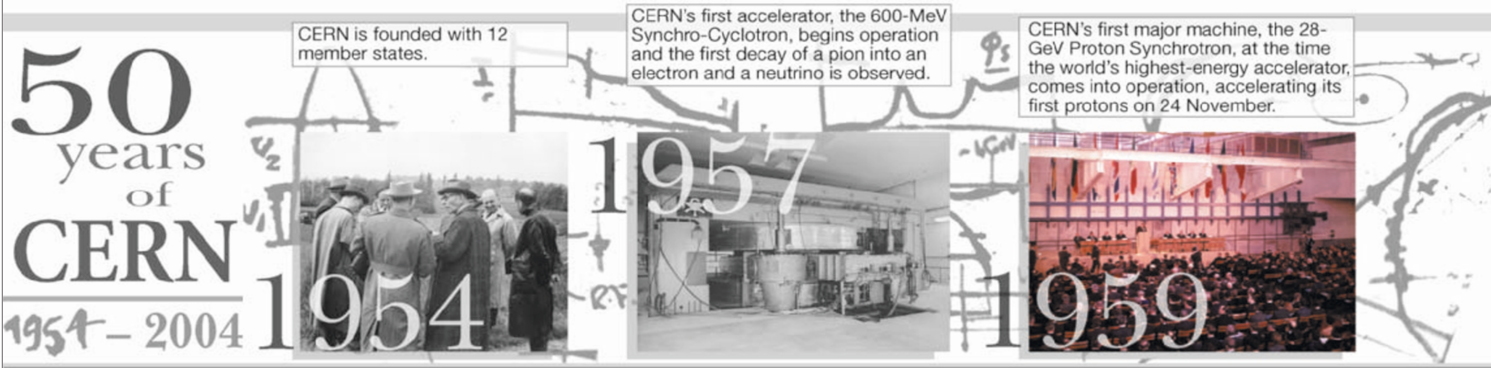
During CERN's routine maintenance shut-down in 1999, acrobats and mime artists turned one of the vast halls within the laboratory's 27-kilometre tunnel into a stage. Light and shadows played around the nine-storey cavern, illuminating a poetic ballet of aerial gymnastics. On ropes, trapezes and ledges, the performers enacted Paul Dirac's creative struggle with his 1920s theory of antimatter and his pessimistic belief that such theories could never be confirmed experimentally. In the show's final scene, the huge backdrop parted to reveal the DELPHI experiment, where for the past decade CERN physicists have been observing collisions between electrons and positrons, their antimatter counterparts.

The show symbolized everything that CERN has achieved in its first 50 years (see '50 years of CERN', below). The lab's *raison d'être* has been to develop increasingly sophisticated machines to provide answers to the questions that plague theorists seeking fundamental truths about the Universe.

If science ever comes close to poetry, it does here, in the ugly sprawl of CERN's flat-roofed buildings overlooked by the beautiful Jura mountains near Geneva. Not just in the deep and fundamental questions with which the laboratory concerns itself — What is our Universe made of? How did it arise? — but also in the idealism of its scientific approach, and the charm of its working atmosphere.

Founded in the ruins of post-war Europe as a cross-border partnership to recreate the base in particle physics destroyed by the Second World War, CERN continues to live by its philosophy that science has no borders.

Ask any of the tens of thousands of physicists from 80 countries who have worked at the lab over the past half-century, and exchanged views in its famous cafeteria, and they'll wistfully recall a touch of magic. "The intense but non-aggressive scientific style, the extraordinary variety of international scientists — I loved it, and it completely changed my perspective," says Harry Nelson, a particle astrophysicist at the University of California, Santa Barbara, who spent three years at CERN in the late 1980s as a postdoc. "And it's a place where some really great discoveries have been made. I sometimes dream of going back."



(FROM LEFT) CERN/SPL; CERN

But will the accolades still be coming in when CERN celebrates its 75th anniversary? The technical demands of particle physics have increased at an alarming rate — much to the dismay of governments that have to pay for machines that now cost billions. As purse-strings tighten, stresses have emerged in the traditionally cohesive international particle-physics community.

The community is expected to announce its technology choice for the next big machine by the end of this week. Despite the display of unity, behind the scenes CERN is gambling that an alternative technology it is developing will, at some future date, become a scientifically superior option.

Early days

For its opening act, in the early 1950s, the mood was upbeat. The concept of CERN was first proposed by the French physicist and Nobel prizewinner Louis de Broglie at the 1949 European Cultural Conference in Lausanne. Five years later, 12 states signed the founding treaty, making CERN the first post-war organization to include West Germany as a member. CERN now has 20 member states, and although the Soviet Union never joined, many of its scientists worked there alongside Westerners during the cold war.

Back in 1954, the frontier of knowledge was nuclear, not particle, physics, as CERN's full name, the Conseil Européen pour la Recherche Nucléaire, reflects. Theorists recognized three fundamental forces governing atomic matter — the strong nuclear interaction, the weak nuclear interaction and the electromagnetic force — but had little idea of how to integrate them in a way that would explain the physical Universe.

"The non-aggressive scientific style, the variety of international scientists. I loved CERN, and it completely changed my perspective."
— Harry Nelson

But they had some idea about what was missing. Although only protons, neutrons and electrons had been described as the basic constituents of an atom, cosmic-ray research had shown that there were a lot more exotic particles, with names such as 'pions' and 'muons', to be discovered.

The best way to make discoveries was to smash a beam of charged particles, such as protons or electrons, into a target at high speed and then capture the resulting fireworks with cleverly designed detectors. The properties of newly discovered particles fed back into theories that became collectively known as the standard model of the structure of matter.

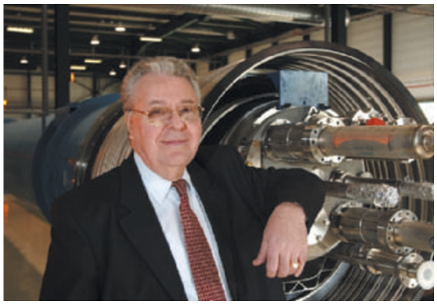
CERN's first machine, the Synchro-Cyclotron, accelerated a beam of protons up to energies of 600 million electron volts (eV) and smashed it into a fixed target. This relatively low collision energy was sufficient to generate pions, unstable particles formed from a mixture of matter and antimatter. The CERN pioneers were thrilled to watch pions decay into electrons and neutrinos in line with predictions from the standard model. Each new machine took collision energies higher, revealing new particles with properties predicted by the standard model.

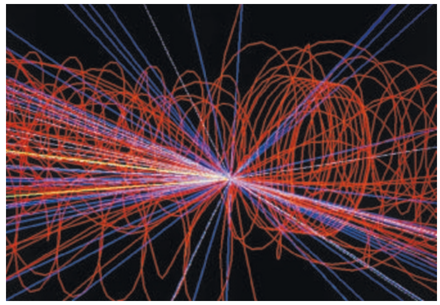
CERN's second act opened in the early 1980s with technological innovation. In the late 1960s, CERN accelerator physicist Simon van der Meer had developed a key technology, called stochastic cooling, for storing antimatter particles. This made it possible to collide a beam of protons precisely with a beam of anti-protons travelling in the opposite direction. If both beams are accelerated to similar speeds, the collision energy is doubled.

In the 1970s, the experimental physicist Carlo Rubbia, who held joint positions at CERN and Harvard University, championed this high-stakes technology. And in 1981, CERN upgraded its Super Proton Synchrotron (SPS) into a collider able to reach energies of up to 500 billion eV.

With its souped-up SPS, CERN scored two great discoveries, the heavy *W* and *Z* particles, carriers of the weak nuclear force, just five months apart in 1983. This established CERN as a world leader, and won Rubbia and van der Meer the 1984 Nobel prize in physics (see 'Winning personalities', overleaf).

CERN





D. PARKER/SPL

CERN's director-general, Robert Aymar, is responsible for ensuring the success of the lab's next big machine, the Large Hadron Collider, which will hunt the Higgs boson (simulated, right).

Upping the ante

CERN's most recent machine, the Large Electron Positron (LEP) collider, whose 27-kilometre tunnel straddles the Franco-Swiss border, hurled a beam of electrons into a beam of positrons. Unlike protons, electrons have no internal structure, so their collisions are less messy, although their lighter mass means that they cannot reach such high collision energies. Still, LEP was able to better characterize particles that had been discovered with the SPS, and was only switched off in 2000 to make room in the tunnel for its successor, the Large Hadron Collider (LHC). Until the LHC starts operating in July 2007, only a handful of small experiments are running at the lab.

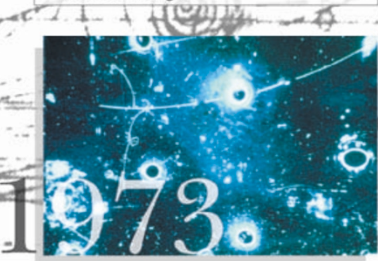
As the machines get bigger, so do the collaborations. Rubbia's *W* and *Z* team involved 150 scientists. Today, teams at accelerator labs often number 500. The biggest experiment planned for the LHC, called ATLAS, involves 2,000 physicists.

Although the numbers may sound frightening, those working in big collaborations say that individuals are not condemned to anonymity. Michel Spiro, now director of the National Institute of Nuclear and Particle Physics in Paris, remembers working on the *W* and *Z* experiment: "Rubbia was number one, of course, but I made my own contribution which was recognized by my

(FROM LEFT) D. PARKER/SPL; CERN

Georges Charpak invents the multiwire proportional chamber that will win him the Nobel prize in 1992.

First observation of a neutral current, in which the charges of interacting particles — electrons or neutrinos — do not change.



The world's first proton–anti-proton collider, the Super Proton Synchrotron (SPS), comes into operation.

The *W* and *Z* bosons are discovered, which wins Carlo Rubbia and Simon van der Meer the 1984 Nobel prize.

CERN

Brain food: cafe society is at the heart of CERN's relaxed atmosphere.

Q. SCHIERMEIER

Surf's up: the World Wide Web was devised at CERN.

colleagues." And it all happened "in an atmosphere of thrilling enthusiasm", he adds, "because we knew that the experiment could be a breakthrough for particle physics".

In the ATLAS collaboration, experiments are split into subprojects. Karlheinz Meier of the University of Heidelberg, a principal investigator in ATLAS, says his own 'Trigger' project, which will design an electronics system to filter out the most interesting physics from LHC collisions, involves only 30 physicists from five institutes. "It's sort of like the old days," he says. "The group is small and we are getting to know each other very well."

Project teams are scattered geographically, but share information over the World Wide Web, invented at CERN for this purpose. In future they will use the Grid, a global supercomputing network that CERN is developing to handle and distribute the vast data sets that the LHC will spew out.

Universal truths

The next half-century will be dedicated to research into the big unknowns. To complete the standard model, physicists predict the existence of one more particle, called the Higgs boson, which is needed to explain why particles have mass. Other theories that hope to extend the standard model predict 'supersymmetrical' partners of the known particles at higher masses. These particles have not yet been seen, but they should be created by the high-energy collisions, accelerating protons up to 7 trillion eV, within the LHC.

Discovering particles is one way to answer deeper questions about the Universe. We now know that the standard model describes barely 5% of the Universe. The rest is invisible to us. Some of this is thought to be composed of 'dark matter', which is apparent only through its gravitational pull and which might include supersymmetrical particles. This was joined in 1998 by the even more mysterious 'dark energy', whose existence was needed to explain observations that the rate at which the Universe is expanding is accelerating.

> "Knowing more about the Higgs and supersymmetry will let us pose the next questions more sensibly."
> — Frank Wilczek

Theoretical physicists are already working on ideas that go beyond the standard model. "We have worked on overarching theories such as 'superstrings' and 'extra dimensions' to try to explain how the Universe may fit together, but they are very speculative," says John March-Russell, a theoretical physicist at the University of Oxford, UK, who spent four years at CERN. Like his colleagues, he hopes that the LHC will help reduce speculation.

"Knowing more about the Higgs and supersymmetry will let us pose the next questions more sensibly," says Frank Wilczek, a theoretical physicist at the Massachusetts Institute of Technology.

As CERN reaches this dramatic crunch point — if the LHC does not find the Higgs, particle physics will be thrown into crisis — it takes centre stage in particle physics. No other organization has won political support for such a massive, yet esoteric, project.

The first sign that particle physicists had priced themselves out of the market came in 1993, when the US Congress pulled the plug on the planned Superconducting Supercollider, also designed to chase the Higgs. US physicists were glad that CERN member states held faith, because it gave them the opportunity to keep working. And when the LHC's finances looked wobbly in 2001, the United States, Japan and Russia pitched in with in-kind contributions amounting to 12% of the overall building costs of SFr3.2 billion (US$2.5 billion).

CERN still pays the lion's share towards the LHC's infrastructure, but the detectors that will record the collisions are being built by 500 research institutes around the world from their own budgets. These institutes also provide most of the 5,000 or so physicists who will conduct the experiments, only two-thirds of whom come from CERN member states.

This international mix will continue CERN's ideal of science without borders for at least another two decades. "We have Indians working on the same LHC experiments with Pakistanis, Chinese with Taiwanese, Israelis with Arabs," says CERN's current director-general, Robert Aymar. "This 'romance' of CERN, the way it contributes to good relations, is not fading — quite the opposite."

Aymar's reputation is built on his management skills for large projects; most recently he headed the international ITER project to build a prototype fusion reactor. He is a pragmatist, who was brought in by the CERN council to restore political confidence in the LHC. Since his arrival in January he has restructured top management at the lab to ensure an iron grip on LHC development and costs. The collider's finances are now assured, thanks to a system of bank loans that

LEP comes into operation, colliding electrons and positrons together.

Tim Berners-Lee, working at CERN, proposes the World Wide Web.

After a long search along the closed, 27-km beamline of LEP, the cause of a mysterious beam blockage is found to be two empty Heineken beer bottles.

Civil engineering on the LHC begins. The huge underground caverns leading to the tunnel are used to perform a dance based on the life of Paul Dirac and his theory of antimatter.

(FROM LEFT) CERN; HEINEKEN

must be paid back by the end of the decade. The world's most expensive ground-based science kit "will stay on target and within budget", Aymar promises.

"CERN will only be free to get involved in other projects after 2011, when the LHC debts are paid off," he adds. This is a crucial point, because CERN must think about life beyond the LHC, which is expected to operate until 2020, and possibly to 2025. The global physics community has already decided what machine it wants next, an electron–positron collider that will be able to characterize more precisely the particles that the LHC discovers. The machine of choice is a linear collider that can reach higher energies with electrons than did the circular LEP.

Two designs for such a sub-TeV linear collider, which will achieve energies just below 1 trillion eV, are on the table. The 'cold' design, which depends on superconducting technology, is led by DESY in Hamburg, and the 'warm' option by US and Japanese labs. The International Technology Recommendation Panel of the International Linear Collider Steering Committee met in Korea on 11–13 August to select one of these options for development by a global collaboration, with hoped-for operation in 2015. As *Nature* went to press, it was expected to announce its decision this week at the International Conference on High Energy Physics in Beijing.

This timetable would seem to rule out CERN as a host for the proposed machine, but with Aymar's arrival the stakes have been raised. Since 1986, CERN has been developing an alternative linear collider design called the Compact Linear Collider (CLIC). In a standard collider, the electromagnetic waves that accelerate the beams are created within special cavities called klystrons. Instead, CLIC uses a second set of intense low-energy beams to provide the waves that the accelerating electrons surf. This allows it, in theory at least, to achieve much greater accelerations. It may even be possible to achieve energies of between 3 trillion and 4 trillion eV.

Most physicists agree that, all things being equal, CLIC makes more sense scientifically. If the Higgs boson turns out to be heavier than expected, a sub-TeV machine may not be powerful enough to analyse it. A higher energy range also means greater chances of spotting more supersymmetrical particles. And if the LHC sees no hint of the Higgs or supersymmetry, then the case for a sub-TeV machine looks distinctly weak.

But all things are not equal. The CLIC technology is far less advanced than the other designs. Until Aymar arrived, the project was progressing in a leisurely fashion towards a feasibility decision in 2013. He has brought this forward to 2009.

Future plans

This date is crucial. By then the LHC could have glimpsed the Higgs boson, and CERN will be almost free of its debts. The design phase of the sub-TeV machine will also be advanced, but it is unlikely that any country will have committed itself to the project's biggest expense — its construction. If feasibility studies show CLIC to be viable, it could present itself as an alternative. Spiro, who now heads the French delegation to CERN, is a strong believer in this strategy. "It would be better than committing to a less ambitious machine," he says.

But it's a long shot. Even if CLIC were shown to be feasible, it could not start operating until 2021 at the earliest, a long time for even particle physicists to wait. And the idea of building a sub-TeV machine first and CLIC later is not politically viable.

Although Aymar stresses that CERN's decision to accelerate CLIC should not influence plans for the sub-TeV collider, and he has never suggested that a CLIC machine, if built, should be sited in Geneva, CLIC's new lease of life has ruffled the feathers of many of those involved in developing collider technology.

Part of the discontent is down to a perception outside Europe that CERN wants to consolidate its present leading position, even if this is at the cost of the well-being of the US particle-physics community, which, most agree, will suffer if all the big machines continue to be located elsewhere.

On balance, CERN's chances of hosting the next big accelerator are slim, so when it celebrates its 75th anniversary in 2029, it is likely to be a very different place. The stream of visiting scientists will have reduced to a trickle and the exciting discoveries will be taking place elsewhere. Nevertheless, Aymar is positioning CERN for a leading role in any future machine, wherever it might be located. He says he wants any European participation to be funnelled through CERN, rather than through national agencies or governments.

Even if CERN were no longer in the forefront, could its unique spirit relocate to the lab hosting the next big accelerator? Probably, although some worry that if current problems with visas continue, this would hamper any international project located in the United States. In the meantime, the place where the World Wide Web was born, and where fresh insights into the Universe will be argued over in that most celebrated of cafeterias, is set for a glorious finale. ■

Alison Abbott is *Nature*'s senior European correspondent.

Winning personalities

CERN garnered two Nobel prizes in physics in its first 50 years, won by three very dissimilar characters. Simon van der Meer, from the Netherlands, and Carlo Rubbia, an Italian, shared the 1984 prize for the discovery of the *W* and *Z* bosons. Van der Meer was as shy as he was brilliant and inventive, whereas Rubbia's acknowledged genius was allied to a powerful personality.

Van der Meer shunned all publicity, whereas Rubbia became director-general of CERN from 1989 to 1994. His excitable nature generated some tension, but was offset by his impulsive genius, say some former colleagues.

The *W* and *Z* discoveries, and many others, would not have been possible without an earlier CERN invention for which Georges Charpak won the 1992 prize. Charpak's 'multiwire proportional chamber' replaced photographic methods for particle detection with electronic ones, improving both sensitivity and spatial resolution.

Charpak, born in Poland and now a French citizen, spent some of his earlier life in the French resistance and in the Dachau concentration camp. Elegant and charming, Charpak was reputedly ham-fisted in the lab and gave a handsome portion of his winnings to the technician who had helped him out. **A.A.**

CERN

CP violation, the effect that helps to explain nature's preference for matter over antimatter, is confirmed by the fixed-target experiment NA48.

Thousands of anti-hydrogen atoms are produced and measured for the first time.

CERN celebrates its 50th anniversary, while construction of the LHC continues apace.