INSIDE THE MULTIBILLION-DOLLAR BATTLE FOR CERN'S FUTURE

A future mega-collider is supposed to cement the European physics laboratory's position as a global leader for the rest of the century. Critics say the plan could lead to its ruin. **By Davide Castelvecchi**

On the Swiss–French border, at the headquarters of the European laboratory CERN, a battle is under way for the future of particle physics. CERN's leaders want to build the biggest machine on the planet here: an enormous particle accelerator that would open in 2070 and would dwarf the Large Hadron Collider (LHC), the lab's current flagship facility.

Everything about the plan is unprecedented. The Future Circular Collider (FCC), as it's called, would sit in a tunnel 91 kilometres in circumference, more than three times the size of the LHC's. Its cost is likely to be at least US$30 billion and it would smash protons together at energies eight times greater than those in the LHC. It is hoped that expanding this energy frontier will reveal never-before-seen particles that could solve some pressing issues regarding the standard model — the current best theory of the Universe's fundamental particles and fields — and shed light on some of physics' greatest mysteries, such as the nature of dark matter.

The technologies to reach such energies aren't ready yet. So the plan is to dig the tunnel and insert a simpler machine that, starting around 2045, would collide electrons and their antiparticles, called positrons (see 'CERN's plan for a mega-collider'). This interim collider would produce and study copious numbers of elementary particles known as Higgs bosons to understand their pivotal role in nature. Later, this 'Higgs factory' would be dismantled.

The two-stage FCC plan is backed by many physicists. It is spearheaded by CERN's director-general (DG), Fabiola Gianotti, and supported by Mark Thomson, who is due to replace her in January 2026. "If approved, the FCC would become the most powerful instrument ever built to study the laws of nature at the most fundamental level," Gianotti said in a statement to *Nature*.

But many others are unhappy with it, *Nature* has found. Interviews with more than two dozen researchers show that many are critical of the FCC strategy, because it will take so long to come to fruition and because sinking resources into it could close off alternative ideas.

"The issue is whether the community is willing to sacrifice the next 50 years to get a toy which may or may not be the way for [fixing] the standard model," says Halina Abramowicz, a particle physicist at Tel Aviv University in Israel. Critics also say that CERN's leadership has decided to back the FCC without adequately consulting the community.

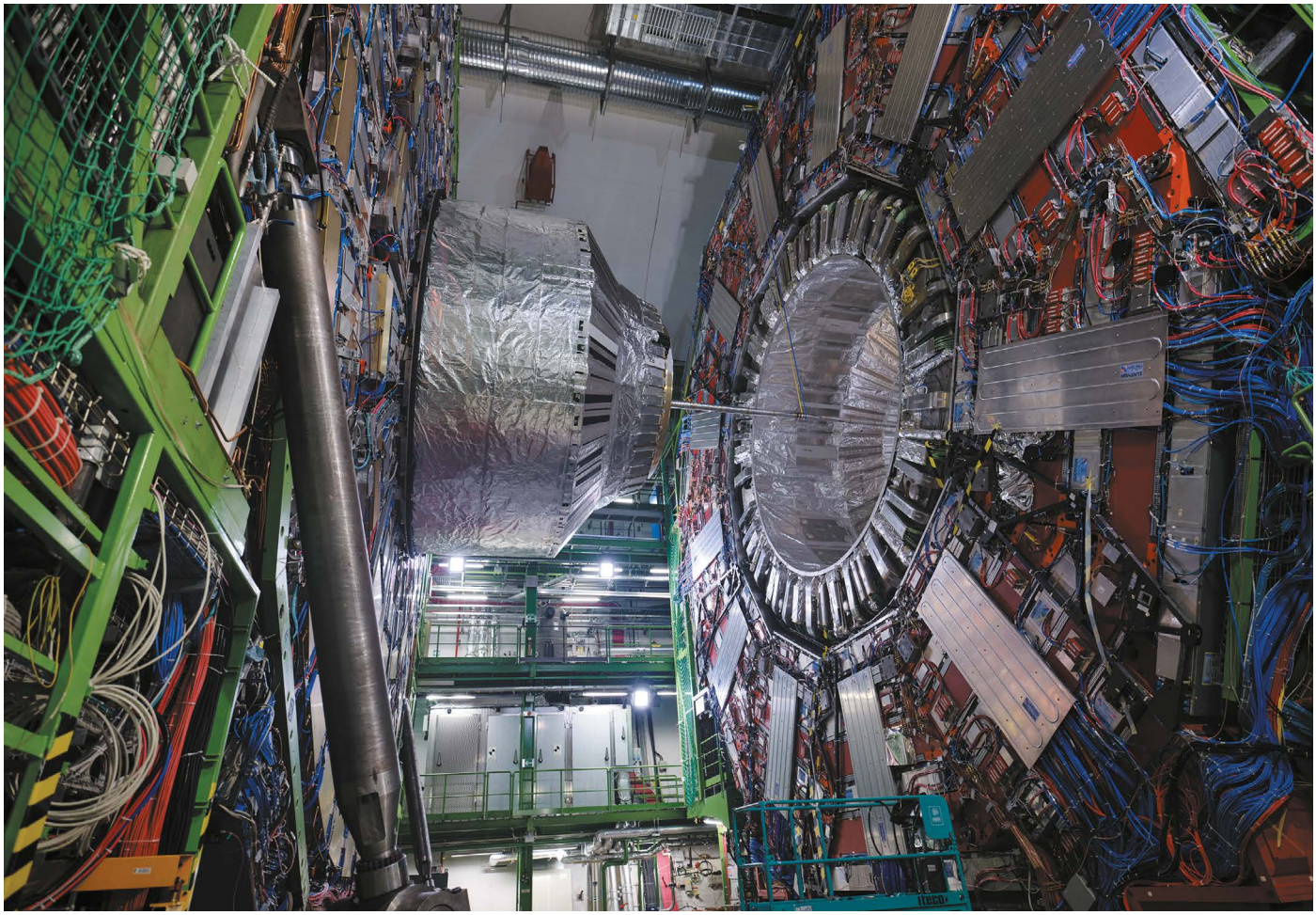
In such a giant and political project, which involves financial contributions from many of CERN's member countries and the opinions of tens of thousands of researchers, disagreements are inevitable. (When the LHC was built, Germany threatened to leave CERN if its budget-cut demands weren't met). But the discontent has reached an unprecedented pitch, many researchers told *Nature*.

It's also unclear whether CERN's member states will pay for the project. Germany has already said that it won't raise its budget contributions. And projects elsewhere might undercut the case for the FCC: in particular, China is deciding whether to approve a similar machine.

The next year could be decisive for the European mega-collider plan. By December, a strategy working group will submit its conclusions on the idea to the CERN Council, the organization's governing body. At stake is not only the ambitious experiment itself, but also the working lives of generations of physicists — and Europe's role in particle physics for the rest of the century.

Decades of circular colliders

CERN emerged after the Second World War as part of a deliberate effort to pursue science for peace, and it has been a key centre for particle-physics research ever since. With an annual budget of almost 1.5 billion Swiss francs (US$1.7 billion) set by an international convention, and funding from 24 member



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The CMS experiment at the Large Hadron Collider.

states as well as non-member countries such as the United States and Japan, it is a beacon for international scientific cooperation.

For nearly two decades, it has hosted the LHC, the world's largest and most powerful collider. The LHC itself replaced a previous electron–positron collider in the same tunnel, called LEP, that was built in the 1980s. But CERN hosts many other experiments and technology programmes, including work on antimatter, cosmic rays, alternative accelerator technologies, advanced magnets and isotopes for medical applications.

It was at the LHC that, in 2012, Gianotti announced the discovery of the Higgs boson. This is perhaps CERN's crowning discovery: not just another particle, but the linchpin of the standard model. The discovery of the Higgs was the first direct evidence of a field that permeates the Universe, the Higgs field. The varying interactions of other fundamental particles with this field explains why they have different masses.

The LHC has not managed to top that moment. The Higgs boson was shaken out by smashing protons at high energies, but the collider has so far failed to deliver further, much-anticipated discoveries, such as the nature of dark matter. With the LHC's life scheduled to end in 2040, thoughts of its successor have been brewing since the 2010s.

The standard model can't explain dark matter or the unknown particles that determine the nature of the Higgs field, among other major questions in particle physics. But it is not clear from theorists' models whether smashing higher-energy protons would turn up new, extremely massive particles that might provide answers.

Still, many researchers think that it is worthwhile. "Exploration of the energy frontier will enable us to deepen our understanding of physics at the shortest distances, which we know is intimately connected to the physics of the Universe on the largest scales," Gianotti says. "It's like an open ocean," says particle physicist Pierluigi Campana, who is based near Rome and chairs the International Committee for Future Accelerators. He compares the quest for the energy frontier to that of the first explorers who took their canoes across the Pacific Ocean and settled its many islands.

> "SCIENCE MANAGEMENT IS A LITTLE BIT LIKE HERDING CATS."

The two-stage FCC concept was first presented in 2019. The idea is that the initial-stage 'Higgs factory' might reveal some deviations from standard-model predictions, which could hint at whether new particles exist and how massive they might be. This question is linked to a central mystery about the standard model: how the Higgs boson 'breaks the symmetry' between two of the three fundamental forces in the standard model: the electromagnetic force and the weak nuclear force. At the high energies that existed straight after the Big Bang, these two forces were unified.

Then, once research has produced breakthroughs in the necessary technology, such as how to produce sufficiently high-strength superconducting magnets that steer and focus beams of particles, the second-stage FCC could be built to discover those particles — if they are within its reach. (Some physicists say that new particles could include the constituents of dark matter, but many theorists now think that such particles are likely to be much

lighter, not heavier, than the range already searched by the LHC.)

Costly collider

Although most particle physicists agree that both FCC machines would be good to have, the costs are daunting. No full costing is yet available; CERN documents have suggested the first phase alone might cost $17 billion. However, estimates by Vladimir Shiltsev, an accelerator physicist at Northern Illinois University in DeKalb, and his collaborators suggest that is a minimum value and that the two phases together would cost at least $30 billion, and probably much more (T. Roser *et al. J. Instrum.* **18**, P05018; 2023).

Researchers have proposed several other possible designs for future colliders. For decades, a leading proposal for a Higgs factory was not a circular collider but a straight one, called the International Linear Collider. It was studied in detail with the intent of placing it in Japan, but that country did not finalize its approval. Advocates of a linear Higgs factory modelled on the International Linear Collider say it would do all the Higgs studies of the circular version, but be cheaper and faster. Jenny List, a physicist at the German Electron Synchrotron (DESY) in Hamburg, says that a machine with a 21–33-kilometre tunnel could cost less than half as much as the first stage of the FCC. It could also study how two Higgs particles interact with each other. That research would not be directly accessible at the FCC, and could be crucial to understanding the nature of the Higgs field, says Michael Peskin, a theoretical physicist at the SLAC National Laboratory in Menlo Park, California. "We know how to build it; it has a reasonable cost, and it really can be running at the time the LHC ends, if we can get our act together," he says.

The linear and circular options each have their strengths and weaknesses, physicists say. Proponents of the FCC plan say a linear tunnel would be a dead end once it has served its purpose as a Higgs factory. But List counters that a linear collider can be upgraded by lengthening the tunnel later on. And it could host a future linear accelerator based on one of several advanced technologies that are being developed, such as the US-led Cool Copper Collider. This is a new concept for linear accelerators that could drastically reduce electricity consumption compared with machines of similar power.

"There is no reason in the world to build a circular Higgs factory" as opposed to a linear one, says Abramowicz, pointing in particular to its expected high electricity bill. And some researchers suggest that it would be better to explore a number of options than to lock future generations of scientists into an expensive path to 2070 and beyond, when it's unclear whether the FCC would be the right tool for answering physicists' questions. "I would find it very unfair to impose a physics programme on my grandchildren," says Jochen Schieck, a physicist at the Austrian Academy of Sciences in Vienna, who is a member of the CERN Council.

For many physicists, one persuasive argument for the FCC is that it can continue to support the large community of 15,000 researchers and support staff that has grown around the LHC experiments. That, says Abramowicz, is the real reason why many are behind the circular collider idea: it could produce collisions at four independent 'interaction points', each with a massive detector producing data that could involve a collaboration of thousands of physicists. A linear collider can conduct only one experiment at a time, so it would support fewer physicists.

Reach higher energies sooner

The thought that the giant proton collider wouldn't be ready until 2070 also worries some researchers, because it means they won't see the new energy frontier in their working lifetimes. Some say that CERN should make an all-out effort in research and development for advanced accelerator technologies that could enable facilities to reach higher energies sooner. This would include the magnet research necessary for the FCC, but would also take in new — but unproven — ideas, such as colliding beams of muons, particles that are heavier cousins of electrons.

Some researchers, including John Womersley, a former chief executive of the UK Science and Technology Facilities Council, and Tulika Bose, an LHC physicist at the University of Wisconsin–Madison, want to see higher-energy machines developed as quickly as possible.

Womersley has suggested cutting short the LHC's running time, to 2035, and using the allocated funding to develop technologies for the FCC's second stage. Bose suggests skipping the Higgs factory altogether.

A spokesperson for CERN says that the upcoming data from the upgraded LHC will already give early-career researchers "a fantastic, exciting and instructive position to be in", and that if all goes according to plan, there will be only a few years between the conclusion of that programme and the start of an electron–positron collider in the mid-2040s.

How CERN pushed forward its plan

A criticism of the current FCC plan is that CERN didn't listen sufficiently to the community before formulating it, and that the financial and human resources it has put into the feasibility study have dwarfed investment in other programmes, such as advanced accelerator research.

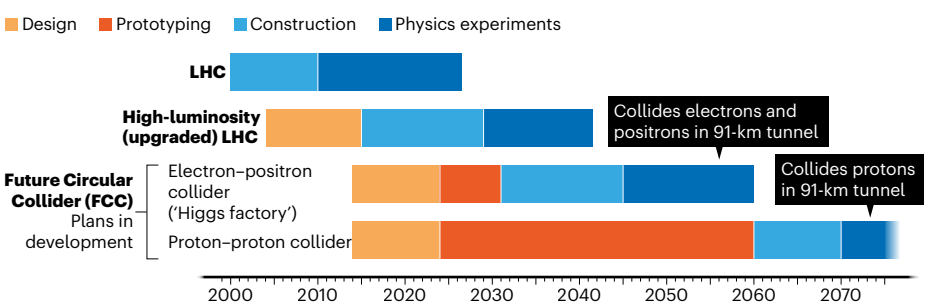
Some of the disagreement is about how to read a pivotal document released in 2020 after a symposium in Bad Honnef, Germany (see go.nature.com/4hrjmqp). Held by a working group appointed by the CERN Council and chaired by Abramowicz, its aim was to update the strategy for European particle physics and CERN's future. At that meeting, researchers who were present say, a representative from Germany's government privately told physicists (including Gianotti) that Germany couldn't afford to contribute to a massive new accelerator — views that would become public in 2024.

What emerged in the document, some say, was an unclear compromise between those who wanted endorsement of a two-stage FCC plan and alternative scenarios. The document listed a Higgs factory as 'highest priority' (without ruling out a linear collider), and then stated but didn't rank other priorities. These included investigating the feasibility of a future hadron collider at CERN with the possibility of a Higgs factory as a first stage, and ramping up efforts to develop technologies for future accelerators.

Some researchers who took part in the strategy process, including Schieck and Siegfried Bethke, a physicist at the Max Planck Institute for Physics in Garching, Germany, who is a former member of the CERN Council, say that this document was carefully written to leave the door open for alternative Higgs factory designs and to avoid making a two-stage FCC the top priority — calling only for its feasibility to be investigated. It did not back the precise option that CERN's leadership has pursued, the two-stage plan that reaches fruition as far away as 2070. CERN could have put more effort into exploring the linear collider option and more resources into advanced accelerator

CERN'S PLAN FOR A MEGA-COLLIDER

A two-stage effort at the European particle-physics laboratory on the Swiss–French border could involve digging a 91-kilometre tunnel that would first contain a 'Higgs factory' to study the Higgs boson. This might start taking data in 2045 after the Large Hadron Collider (LHC) ends its operations. A higher-energy collider might follow in 2070.



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technologies, they say.

Gianotti, however, says that CERN is investing in key areas of research that include linear colliders, high-field magnets and alternative accelerator technologies. "It should be noted that the resources that CERN has invested in linear collider studies over the years are almost three times larger than those invested in FCC," the CERN spokesperson added; the FCC feasibility study has cost 113 million Swiss francs, CERN told *Nature*. And Gianotti and others supporting the FCC say that they are following the strategy document in pursuing the 2070 FCC feasibility study. "It's certainly doing what the European strategy update told it to do," says Jonathan Butterworth, an LHC physicist at University College London who co-wrote the strategy document.

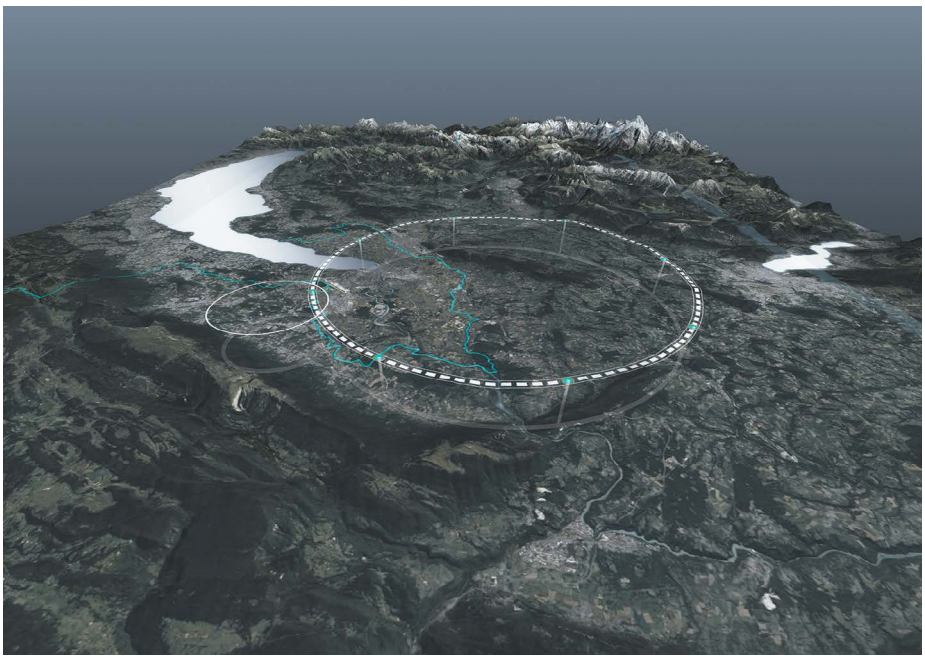
A mid-term report for this study was produced in February 2024 but was not made public; CERN said it had studied the geology of the 200-metre-deep tunnel and had set an optimal path for it south of Geneva in Switzerland. The final feasibility report is due at the end of this month and is intended to include detailed cost estimates and possible funding scenarios.

"Naturally, CERN has a limited budget, and the strategy made FCC a clear priority," says Ursula Bassler, a CNRS physicist at École Polytechnique in Paris who was president of the CERN Council from 2019 to 2021.

Some researchers told *Nature* they felt pressured to back the FCC to help present a unified front to the outside world, because, as some say, "bickering scientists don't get funding". Tatsuya Nakada, a particle physicist at the Swiss Federal Institute of Technology in Lausanne who chaired the 2013 iteration of the European strategy exercise, says that will be the right attitude once the community has reached a consensus. But while physicists are debating options, "it's a bit of a dangerous attitude that could also be used to suppress different opinions", he says.

Many critics, including List and Donatella Lucchesi, a particle physicist at the University of Padua in Italy, say that Gianotti has ignored warnings not to put so much of CERN's focus on the 2070 FCC plan. "People inside the community do say it's really the current DG's vision which has been pushed forward," adds Ruben Saakyan, a particle physicist at University College London, who chairs the UK Particle Physics Advisory Panel. When asked by *Nature*, Gianotti did not directly address those criticisms but highlighted CERN's ongoing research and development efforts, saying that the organization was working on studies for "various collider options", including the FCC, linear colliders and muon colliders, as well as accelerator research.

Bassler and others counter that the lab did take input from the community, but that it also had to show leadership. "Science management is a little bit like herding cats," Bassler says. "There are a lot of ideas floating around, but at some point, if you want to build a big project, you have to align people behind it, and you have to push. This is certainly what the FCC community did."



CERN

A CERN map shows where a 91-km circular tunnel might be dug; the smaller LHC is to its left.

"The national communities [of particle physicists] have been asked to provide their input about the preferred option for a future collider," says the CERN spokesperson, referring to the exercise that resulted in the 2020 strategy document. They add that CERN's management acted in response to that strategy document.

Looming decision

Hovering in the background of the CERN deliberations is the knowledge that China might soon approve a giant collider that would be similar to the two-stage FCC. A proposal for a 100-kilometre Circular Electron Positron Collider will go before the Chinese government this year for possible inclusion in its next five-year plan. Construction might begin in 2027 and would take around a decade. A June 2024 report estimated its cost at 36.4 billion yuan (US$5 billion), although Shiltsev says that is likely to be an underestimate (J. Gao *Radiat. Detect. Technol. Methods* **8**, 1–1105; 2024).

The collider would be a Higgs factory, like the first stage of the FCC. Again, depending on the availability of superconducting magnets, a proton–proton collider might follow that would reach energies similar to those envisaged in CERN's machine. The 2024 report put the earliest start date for construction at around 2050.

Most researchers who talked to *Nature* see it as inevitable that CERN will decide in favour of the FCC. Sometime in 2026, the council could make it official, even before funding is secured. "I think there'll be tremendous pressure on the council to say 'let's make the FCC our priority, and let's find the money later'," says Peskin.

But that doesn't mean the FCC will be built. FCC advocates want to finance it, in part, by raising member-state contributions by around 12%, but Bethke says this "will be out of the question". "I don't see that the funding agencies would coherently vote for a major increase of their contributions at this time – with all the other societal difficulties we are facing," he says.

Even if member states did increase their contributions, the project would still face a shortage of several billion Swiss francs. Many hope that France and Switzerland might step in with large sums of money, which could be justified as a stimulus for the local economies in the region where construction will take place. The most ruinous prospect, everyone agrees, would be for the money to run out after a few years of construction and for the project to be cancelled before completion. That was the fate that befell the US Superconducting Super Collider in the 1990s, which Congress cancelled in 1993 after $2 billion had been spent.

As deliberations continue, and in part because the LHC hasn't found any new elementary particles since 2012, some physicists have switched to studying other particles, such as neutrinos, or even to other fields, such as gravitational waves. Many worry that this migration will speed up if the uncertainty is protracted – especially if the gap widens between the LHC ending and a new accelerator starting.

"I would like to think that we, as a scientific community, are ourselves considered valuable. Fragmenting it should be done with care," says Vava Gligorov, a particle physicist at Sorbonne University in Paris who works on LHC experiments.

Davide Castelvecchi reports for *Nature* from London.

Correction
This news feature erroneously attributed the observation about the level of discontent to a specific researcher.

Corrected 19 March 2025