

Particle physicists hash out long-term strategy for Europe

CERN

Among the goals are to pick a Higgs factory, carry out R&D on accelerators and detectors, conduct feasibility studies, and improve environmental sustainability.

The European particle-physics community aims to build an electron-positron collider for precision studies with the Higgs boson. And it plans to determine the feasibility of an estimated €21 billion (\$24 billion), 100 TeV hadron-hadron collider, known as the Future Circular Collider (FCC), at CERN; as a first stage, the FCC tunnel and infrastructure could be used as a so-called Higgs factory. Those are two top priorities in the latest European Strategy for Particle Physics, which the CERN Council adopted unanimously in June.

In parallel with its pursuit of future colliders, the European particle-physics community should press ahead with established activities, the strategy says. Foremost among them are the high-luminosity upgrade to CERN's Large Hadron Collider (LHC) and support and participation in the neutrino programs in Japan and the US—in particular, the Long-Baseline Neutrino Facility and its associated Deep Underground Neutrino Experiment.

The strategy envisions Europe collaborating with partners around the globe while at the same time ensuring its “continued scientific and technological leadership” in accelerator-based particle physics and related technologies. To realize the strategy goals, and to avoid a large gap in the availability of operational colliders, a quick decision among four possibilities for a Higgs factory is necessary. Additionally, the feasibility studies for the FCC should be completed within seven years to make solid recommendations possible in time for the next strategy update. The current strategy is the second update to the original from 2006.

Thousands of scientists contributed over two years to the strategy. The approval process “was sensitive, and we discussed each comma,” says Siegfried Bethke of the Max Planck Institute for



THE 100-KM-CIRCUMFERENCE FUTURE CIRCULAR COLLIDER (orange circle) would pass beneath Lake Geneva. It could start out as an electron-positron collider and be upgraded to a 100 TeV hadron collider. A feasibility study on whether to go ahead with it is a top priority in the 2020 European Strategy for Particle Physics. The blue circle shows the position of the Large Hadron Collider.

Physics in Munich and a member of the CERN Council. That body consists of a scientist and a government delegate from each of the laboratory's 23 member states. Halina Abramowicz of Tel Aviv University chaired the strategy process. “We hope our recommendations will put wind in the sails to move these ideas forward,” she says.

A Higgs factory?

“The obvious place to look for deviations from the standard model is a dedicated study of the Higgs boson, because it couples to everything,” Abramowicz says. That’s why the strategy’s first recommendation is a Higgs factory that would involve clean collisions between elementary particles rather than the more complicated mess produced in hadron collisions.

The Higgs was observed in 2012 at the LHC (see PHYSICS TODAY, September 2012,

page 12). Although the particle’s existence had been predicted, its mass was not pinned down by theorists. The particle-physics community is more in the dark as to what to look for next, with no clear predictions despite many theories. “We have no reliable theoretical guidance,” says the University of Liverpool’s Max Klein, who coordinates electron-hadron collider developments at CERN (see PHYSICS TODAY, May 2017, page 29). “This calls for a balanced program, and we should perhaps make fewer promises about discoveries,” he says. “Increased energy, luminosity, and diversity in collision processes will all be required to explore nature and search for answers to persistent puzzles of particle physics.”

“We need a new physics theory that is more complete than the standard model,” says Young-Kee Kim of the University of Chicago. She is leading the cur-

rent Snowmass study, which has until late 2021 to provide input for the US counterpart to the European Strategy for Particle Physics.

Of the four candidates for a Higgs factory, the design that is furthest along is the International Linear Collider (ILC), which would be sited in Japan. The idea has been around for about two decades (see, for example, *PHYSICS TODAY*, April 2007, page 26). The ILC would create 250 GeV center-of-mass collisions in a 20 km tunnel. The estimated price tag is \$5 billion–\$6 billion, not including labor. The energy could be increased by extending the length or perhaps by upgrading to new accelerator technologies that have steeper gradients. The strategy document says that the European particle-physics community “would wish to collaborate” if the ILC is realized quickly. “It would be a great addition to the community if Japan carried this project forward,” says Abramowicz.

Yasuhiro Okada, an executive director of KEK, says that Japan “welcomes the European statement” and that it “can make a difference” for proceeding with the seemingly stalled ILC. The project requires financial and labor commitments not only by Japan but also by Europe, the US, and other partners. A 22 February 2020 statement on the ILC by the International Committee for Future Accelerators could also nudge Japan to get moving on it, Okada notes.

Work started this summer on a final ILC engineering design. In parallel, Okada expects Japan’s Ministry of Education, Culture, Sports, Science, and Technology “to intensify discussions with other countries.” The ILC could start operations in the mid 2030s, he says. That would have the advantage of overlapping with the high-luminosity LHC, which is expected to start up in 2027 and run through the end of the next decade.

Another Higgs factory option is the Compact Linear Collider (CLIC), a long-standing project at CERN (see *PHYSICS TODAY*, May 2012, page 27). With CLIC, electrons and positrons could be accelerated to collide at 380 GeV over a comparatively short distance of 11 km, and the design could be extended to 3 TeV. Although the strategy doesn’t favor it, CLIC could be revived if the 100 km FCC “ends up with a thumbs down,” Bethke says.

The other Higgs factory candidates are circular. CERN is contemplating an



DOZENS OF PARTICLE PHYSICISTS MET IN BAD HONNEF, GERMANY, in January to hammer out the details of the 2020 European Strategy for Particle Physics. Halina Abramowicz (center, front) chaired the strategy group. Just behind Abramowicz are CERN director general Fabiola Gianotti (plaid scarf) and CERN Council president Ursula Bassler (blue sweater). Several people quoted in this story are in the front row: Siegfried Bethke (second from left), Jorgen D’Hondt (fifth from left), and Leonid Rivkin (far right).

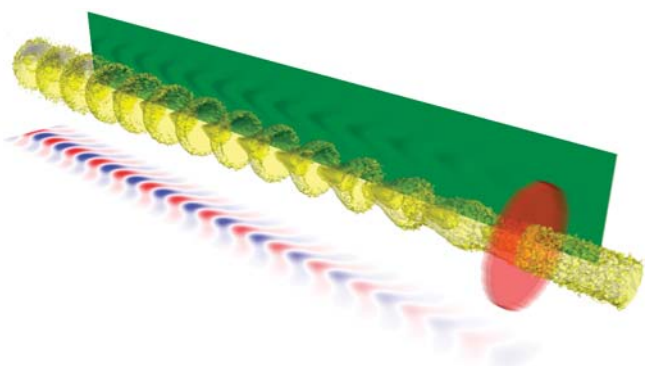
electron-positron collider, the FCC-ee, in the same 100 km tunnel that would later house the FCC hadron-hadron collider. China has a similar proposal, the 100 km Circular Electron Positron Collider (CEPC; see “China plans a Higgs factory,” *PHYSICS TODAY* online, 17 December 2018). It too could later be converted into a hadron collider. Synchrotron radiation limits a circular accelerator’s energy reach; the foreseen energy range for both machines’ electron-positron incarnation is roughly 90–350 GeV. At those energies, circular machines offer higher luminosity than do linear ones and could accommodate multiple detectors.

Even if the ILC goes ahead, it could still be worth building the FCC-ee. “They can be complementary,” says Abramowicz. The ILC would start earlier, and if it gets extended to 500 GeV, Higgs self-coupling could be studied. With the FCC-ee, “we

can go to lower energies and do extremely precise measurements of other standard model couplings,” she says. “And we could obtain huge statistics to study the conservation or violation of flavor symmetry.” But given the enormous costs involved, building two electron-positron colliders is questionable, says Klein, and many particle physicists say that if the ILC goes ahead, Europe should go directly to a pure hadron FCC.

The energy frontier

The ultimate goal is an FCC that produces hadron collisions, says Sijbrand de Jong of Radboud University in Nijmegen, the Netherlands. “By extending the energy frontier, we go into a region of energy that no human has explored. To convince others, we will have to come up with more tangible bread-and-butter goals for the funding agencies. There is a



JOHN FARMER

THIS SIMULATION shows a laser pulse (red) flying to the right through a neutral gas and creating a plasma. Behind it, injected protons (yellow) accelerated by the Super Proton Synchrotron at CERN travel through the plasma and form bunches that drive the plasma wake that accelerates injected electrons (not shown). The European Strategy for Particle Physics recommends that physicists continue to advance plasma wakefield acceleration. In addition to their potential use in future colliders, plasma wakefield accelerators based on lasers could be incorporated into tabletop accelerators in hospitals.

lot of potential, but not everything is sorted out."

Building the FCC at CERN will entail passing its 100 km tunnel under Lake Geneva (see "CERN considers a 100 TeV circular hadron collider," *PHYSICS TODAY* online, 5 February 2019). Determining whether the geology is suitable and permits could be obtained is part of the feasibility study. The project would also pass

under private lands and include above-ground shafts and a surface power grid, so local public acceptance is crucial. Environmental issues, such as where to put the extracted dirt, also come into play.

"The big elephant is power consumption," says Jorgen D'Hondt of Vrije University Brussels and a strategy coordinator. A Higgs factory will consume up to three times as much energy as the current LHC, he says. "If you are part of the problem, you should be part of the solution. We need to develop better and alternative technologies to use less power." In addition, he says, waste heat from the accelerators and cooling and computing systems can be more effectively reused.

The main technological hurdle is to produce superconducting 16 tesla magnets—nearly double the strength of the existing LHC magnets—to steer and focus the circulating protons. Work is underway using niobium-tin, but the material's brittleness makes it tricky to form into the superconducting wires needed to make an electromagnet. So far, 11 T magnets are set to be tested in the high-luminosity LHC, and scientists have achieved stronger demonstrator magnets. "We estimate it will take 20–25 years to make 16–20 T niobium-tin magnets," says Bethke. Scientists are also working on high-temperature superconducting magnets.

Finally, a robust financial plan with committed partners has to be in place before the European particle-physics community could recommend going ahead with the FCC. "The FCC will be far outside the CERN budget," Bethke says.

"We would need substantial additional contributions from the member states, and also from Japan, the US, Russia, and others."

It could be difficult to justify building the FCC if China goes ahead with a similar machine. The CEPC "would be a big, ambitious project, even for China," says the University of Chicago's Kim, who is on the CEPC International Advisory Committee. "It could be an object of pride." The collider is among several big international projects that may be considered in the country's next five-year funding plan. To succeed, says Kim, "the project would need significant technical contributions and scientific involvement from the international community. It would also need financial contributions from other regions."

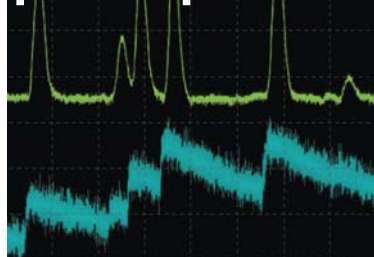
The rising tensions between the US and China could make it difficult to implement a new project in which the two would be involved. But if China goes ahead with a Higgs factory, it could change Europe's plans, says D'Hondt. "Whatever new collider emerges across the globe would trigger a reevaluation of our strategy."

The European strategy recommends that the particle-physics community continue research on alternate acceleration techniques. "We have made up our mind for the FCC program," says D'Hondt, "but to be prudent, we continue to investigate other options." Chiefly, muon colliders, plasma wakefield accelerators, and CLIC; all three are widely viewed as approaches that could be adopted in the more distant future or serve as backups should the FCC not work out.

The US particle-physics community considered muon colliders, and then in 2014 largely abandoned them. But the idea is gaining renewed attention worldwide. The advantage of colliding muons, says D'Hondt, "is that you could access comparable physics with 10–15 TeV muon collisions as with 100 TeV proton collisions." The difficulty with muons, he explains, is their short lifetime. "You have to put them in bunches immediately and collide them." In addition, high-intensity, high-energy muon beams generate neutrinos and other particles at fluxes that, through interactions with atoms that create hadron showers, can be hazardous to experimental equipment and humans.

In plasma wakefield acceleration, an

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photomultipliers
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incident laser beam or other source makes the electrons in an ionized gas oscillate along the beam's transverse field. (See PHYSICS TODAY, January 2015, page 11.) That creates a bubble of missing charge that moves near the speed of light; particles injected into the bubble experience a strong accelerating field. "It's useful for acceleration because of the strong electric field, but positrons still look difficult," says Allen Caldwell of the Max Planck Institute for Physics. And reaching high luminosities along with high energies is a challenge, he says. "It's not shovel ready."

Caldwell is pleased that the strategy mentions plasma wakefield and other alternative acceleration approaches and that it acknowledges the importance of neutrino physics, dark-matter searches, and other research directions. Still, he says, "the big colliders are front and center in the strategy. It's possible that non-collider particle physicists feel left out." Caldwell continues, "The strategy is conservative for my taste. This is a program that will go on for decades if it's realized. Is it enough to capture the imaginations of the next generations? Is it bold enough to keep the attention and focus of the particle-physics community for the next 50 or more years?"

Sustainability and society

A first in the 2020 strategy is a statement on environmental and societal impacts. "We are big energy consumers, and we want to think about how to recirculate energy," says Abramowicz. "We use gases that are not good for the planet, and we want to avoid liquids that if spilled pollute the environment." The strategy document encourages reducing travel. It also says that "a detailed plan for the minimization of environmental impact and for the saving and re-use of energy should be part of the approval process for any major project."

Leonid Rivkin, of the Paul Scherrer Institute in Switzerland and one of the strategy coordinators, notes that the goals stretch out until at least 2080. That's why the strategy puts a strong emphasis on accelerator R&D and the associated educational push, he says. The strategy calls for particle physicists to "work with educators and relevant authorities to explore the adoption of basic knowledge of elementary particles and their interactions in the regular school curriculum." Says de Jong, "People should know

about the structure of matter at a level deeper than the proton. It's part of mainstream culture, and it touches on societal issues—nuclear power, fusion power, medical diagnostic and treatment tools. These are relevant to people's daily lives."

More immediate is the question of whether and how COVID-19 may affect implementing the strategy. CERN's annual budget of about 1.3 billion Swiss francs (\$1.4 billion) comes from member nations and is fixed through a legal con-

vention. So far it appears stable. The pandemic and associated economic woes are a great concern, says Rivkin. "We hope that the member states realize the importance of particle physics and science to humanity to develop technologies and address societal problems. We motivate our bright young people and challenge them to come up with ideas for the future." It's important to fund the smaller national labs, too, he adds. "If you let the roots die, the tree will also die."

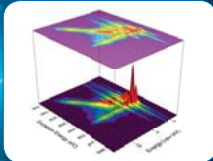
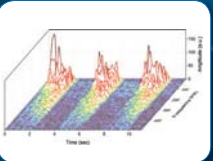
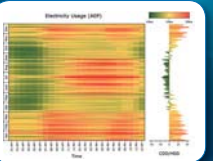
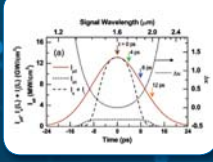
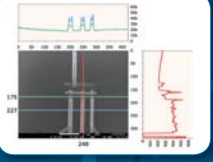
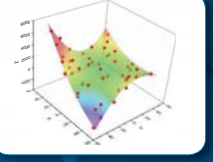
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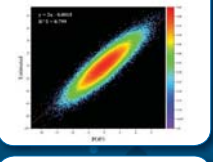
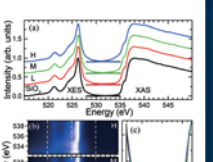
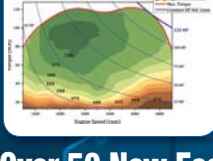


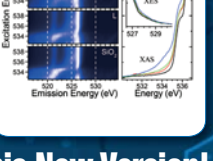
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