THE NEW PARTICLE

Physicists are planning the powerful accelerators they will need to study the Higgs boson and its interactions in detail.

BY MATTHEW CHALMERS

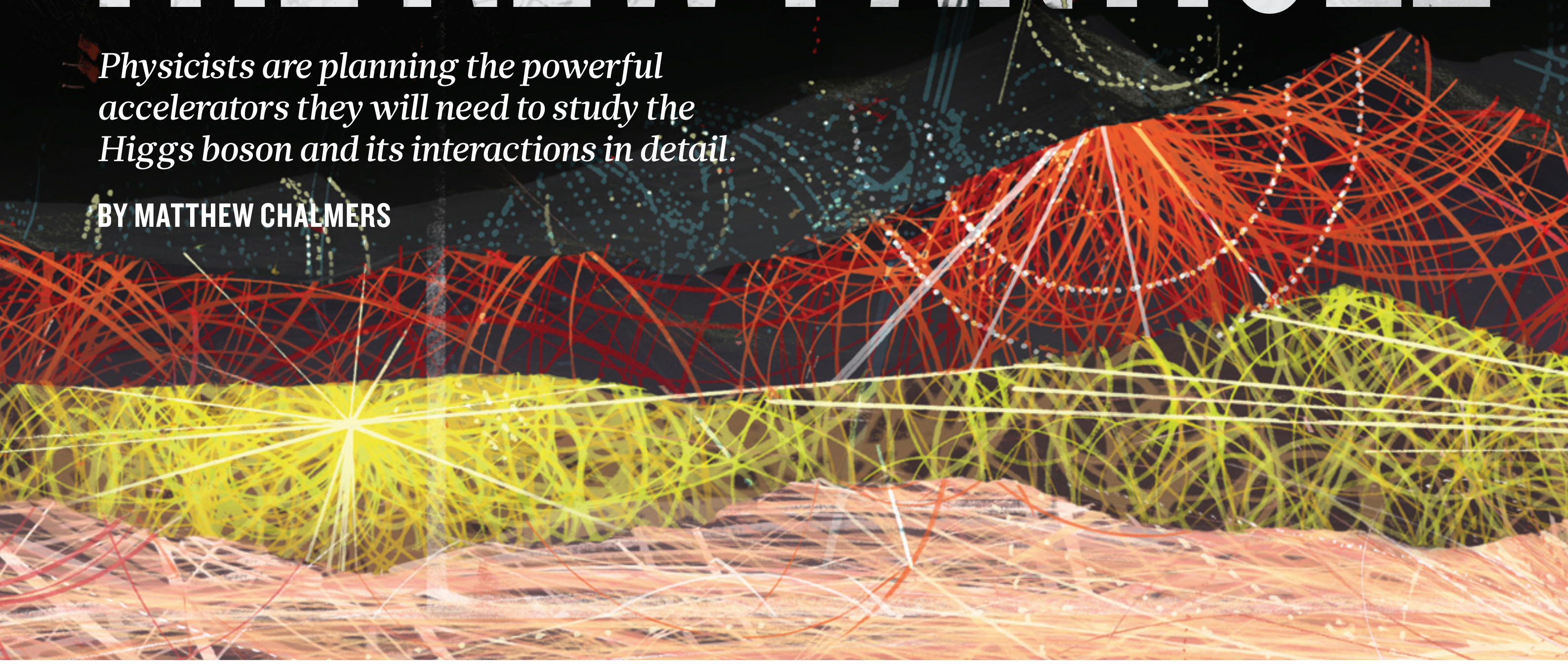

ILLUSTRATION BY BRENDAN MONROE

When particle physicists around the world woke up on 5 July, the scenes of joy, relief and tears were still fresh in their minds — along with a huge unanswered question. The memories were of celebrations the previous day, when researchers announced that a new particle very much like the long-sought Higgs boson had at last been found in data from the Large Hadron Collider (LHC) at CERN, Europe's particle-physics laboratory outside Geneva in Switzerland. The question promised to define their discipline's whole future. Is the particle a Higgs boson of maximum simplicity, as predicted by the 40-year-old standard model of particle physics? Or is it something more complex and interesting that will point towards a deeper, more complete theory?

Physicists hope and expect that the LHC will give them some answers over the next few years. But they are already honing their sales pitches for a machine to follow the LHC — a 'Higgs factory' that would illuminate such a theory with measurements far more precise than the LHC can provide.

"We know that there must be new physics beyond the standard model," says Barry Barish, a physicist at the California Institute of Technology in Pasadena. That's guaranteed, he and other physicists argue, by the existence of phenomena that don't easily fit into the model, such as the invisible scaffold of 'dark matter' suspected to comprise a quarter of the mass density of the Universe, or the ability of particles called neutrinos to 'oscillate' from one form to another. Barish heads the global consortium that is designing the International Linear Collider (ILC), one of the candidates for the next big machine. Even if no one yet knows what the new physics will involve, he says, "our strategy is to be ready in the event things fall in place".

The cost, timescales and capabilities of the ILC and other candidate machines will be scrutinized at the European Strategy for Particle Physics workshop in Krakow, Poland, on 10–12 September, which will set out the priorities for this field in Europe for the next five years. American particle physicists are planning a similar exercise at a meeting at Snowmass, Colorado, in June 2013.

But plans are one thing; reality is another. Funding any new machine, particularly in an economic downturn, will be a "daunting task", says Christopher Llewellyn-Smith, director of energy research at the University of Oxford, UK, and director of CERN at the time when the LHC was approved. "It will depend on what other new particles the LHC finds, on whether the new facility is unanimously supported by the community, and on its cost," he explains. "Even if the physics case is as strong as that for the LHC, and the cost is such that it can be done with a constant global high-energy physics budget, it will still be tough."

THE LHC LIVES ON

A key issue under discussion at the Krakow workshop will be how far the LHC teams can go in measuring the properties of the new particle. The physicists working there can expect much more data, plus major upgrades over the next ten years.

They already have one piece of good news: the mass of the Higgs-like particle — roughly 125 billion electron volts (GeV) in the energy units favoured by physicists — turns out to lie towards the light end of the range that theorists had estimated. This has two important consequences: it means that a relatively modest new collider would be

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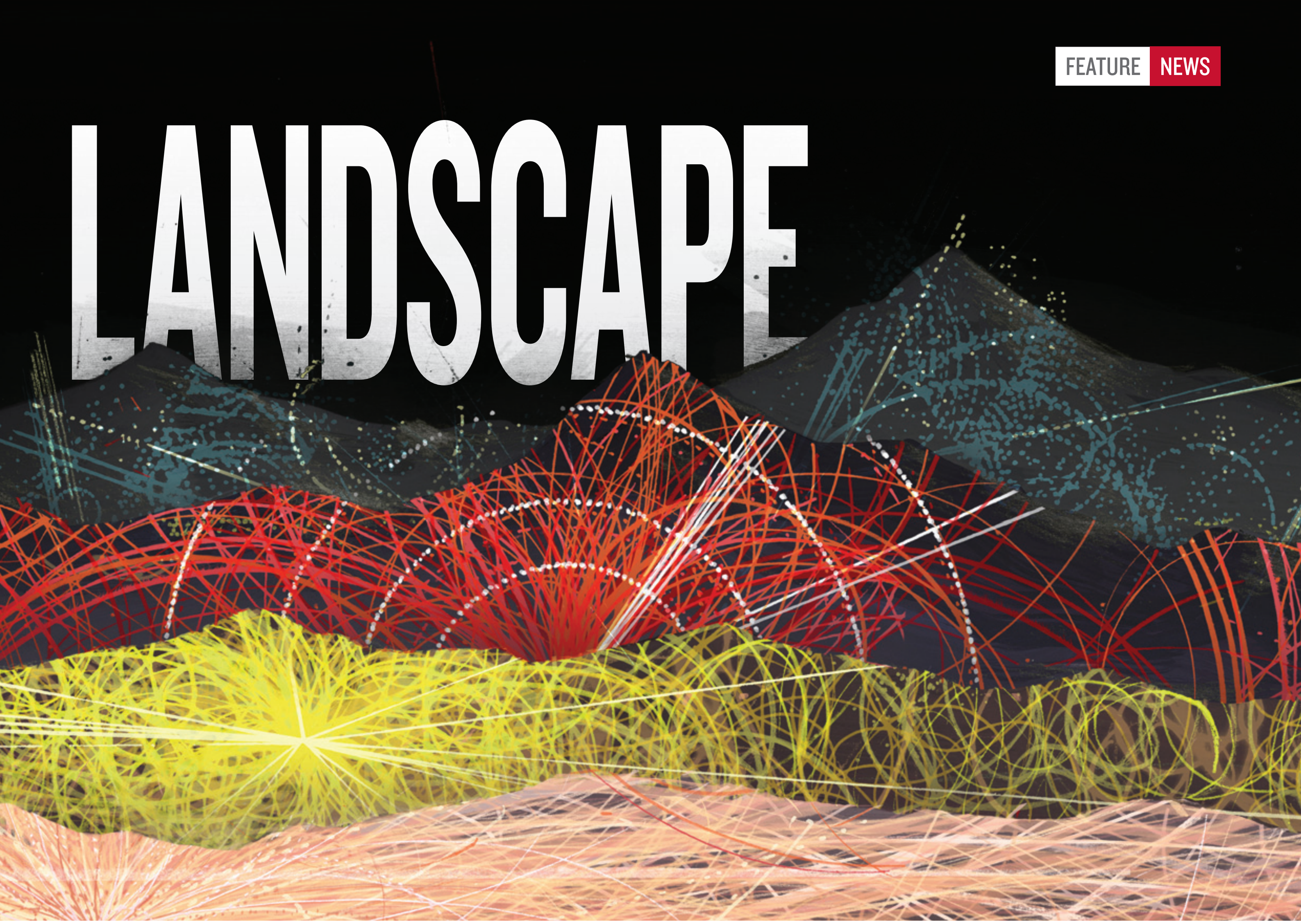

sufficient to produce the Higgs in bulk, and it gives the new particle a rich variety of decay modes that will make it easier for physicists to study its interactions with other standard-model particles.

One priority, for example, is to check the standard model's prediction for how the Higgs interacts with standard-model fermions: entities such as electrons, muons and quarks that have an intrinsic angular momentum, or 'spin', of ½ in quantum units. The probability of an interaction with each particle is supposed to be proportional to its mass — not least because, in the standard model, interaction with the Higgs is what creates the mass.

Another priority is to verify that the new particle's own intrinsic spin has the standard-model value of 0. The LHC physicists can already say that the new particle is a boson — meaning that its spin in quantum units is 0, 1, 2 or some other integer — and that the integer cannot be 1; both conclusions follow from the particle's observed decay into pairs of photons, which are spin-1 bosons. Physicists do not have crazy theories involving bosons with a spin greater than 2, says CERN physicist Albert de Roeck, a scientific coordinator for the team working on the Compact Muon Solenoid detector at the LHC, so their task now is to determine whether it is a spin-2 or a spin-0 'scalar' boson as predicted.

> "WE KNOW THAT THERE MUST BE NEW PHYSICS BEYOND THE STANDARD MODEL."

The LHC will settle the spin question, says CERN's director-general Rolf Heuer, but it is less clear how far the LHC can go in testing the new boson's couplings to other particles — in particular the 'self-interaction' by which the Higgs gives itself mass. At present, all the LHC physicists can say is that the new boson's interactions with other particles are consistent with the standard-model predictions within the present measurement uncertainties of 30–40%. According to de Roeck, the collider should get those uncertainties down to 20% by the end of this year, and conceivably down to "a few per cent" over the next 10–15 years.

But that, for many physicists, is precisely why they need a next-generation machine. A truly stringent test of the standard model, which would reveal tiny deviations that could point the way towards better models, demands that researchers measure the Higgs's interaction with other particles to within 1% uncertainty, possibly as little as 0.1% should the precision of theoretical predictions also improve in the next few years. And that is a level the LHC is unlikely to reach. The machine is like a sledgehammer: it crashes together beams containing hundreds of billions of protons at energies that will eventually reach 7 trillion electron volts (TeV) per beam. This is good for discovering new massive particles, but less so for making precision measurements, because protons are chaotic seas of quarks and gluons that make the collisions messy.

Instead, every proposal for a next-generation machine calls for some form of lepton collider (see 'After the Higgs'). Leptons, a group of light particles that includes electrons, muons and neutrinos, sidestep the

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messiness by not participating in the strong quark–gluon interactions that produce it. Leptons are elementary and interact only through the relatively feeble electromagnetic and weak forces. As a result, lepton machines are more like scalpels than sledgehammers: their collisions can be tuned to the mass of a particular particle and the spray of particles created would be comparatively clean and simple to interpret.

MUONS OR ELECTRONS

A relatively cheap option, argue some physicists, would be to place the tubes of a new accelerator alongside the LHC in the existing tunnel, and use them to collide opposing beams of electrons and antimatter electrons (better known as positrons). This proposal, known as LEP3 in honour of the Large Electron–Positron (LEP) collider that occupied the tunnel before the LHC's construction began in 2000, emerged only in the past year as preliminary evidence for the new particle piled up. LEP3 could produce Higgs bosons with just 120 GeV per beam — a total energy of 240 GeV — only a notch up from the original LEP's maximum of 209 GeV. Its production would be boosted further by recent technological advances that would allow for a collision rate, or 'luminosity', some 500 times greater than LEP could have achieved.

Building LEP3 in the LHC tunnel could allow some of the LHC's particle detectors to be reused, as well as making use of CERN's existing infrastructure for power, maintenance and data-taking. Such savings bring LEP3's estimated cost down to between US$1billion and $2 billion, far lower than the LHC's $6-billion price tag. "The idea is there to kill," says LEP3 advocate Alain Blondel at the University of Geneva, who points out that there should be room to build the new lepton collider without removing the LHC: the tunnel was originally intended to have both types of collider running simultaneously.

For all its advantages as a high-output Higgs factory, LEP3 would not be able to study anything much heavier than the Higgs. And that could be a problem if, as many particle physicists hope, the LHC ends up discovering heavier new particles that theorists are predicting from ideas such as supersymmetry, or even finding extra dimensions. Stepping up the energy of LEP3 to study the heavier particles would be virtually impossible because of losses from synchrotron radiation — the stream of photons emitted when any charged particle moves along a curved path. This isn't so much of a problem for the LHC's protons, because energy losses from synchrotron radiation fall off dramatically for particles of higher mass, and protons outweigh electrons by a factor of nearly 2,000. But losses in LEP3 would be severe. The only way to increase the accelerator's energy would be to increase its radius, which would require a new tunnel. Some physicists have talked about drilling a new tunnel stretching out beneath Lake Geneva, and installing an 80-kilometre circular electron–positron machine, although that's not something for the foreseeable future, says Heuer.

Meanwhile, physicists around the world have been exploring concepts for an alternative Higgs factory that would be much smaller than LEP3, perhaps as little as 1.5 km in circumference. By colliding beams of muons, electron-like particles with 207 times the mass of an electron, such a machine has negligible synchrotron-radiation losses and could produce tens of thousands of Higgs bosons from a total collision energy of just 125 GeV, as opposed to LEP3's 240 GeV. It would also be capable of going to much higher energies, to study heavier particles (see *Nature* **462,** 260–261; 2009).

But a muon collider faces major hurdles of its own, not least the fact that muons decay into electrons and neutrinos with a mean lifetime of 2.2 microseconds. That's a very long time in the subatomic realm, where particle lifetimes are often measured in fractions of a trillionth of a nanosecond. But in engineering terms, it is practically instantaneous. Muons for an accelerator would have to be produced by slamming a proton beam into a metal target; then 'cooled', or lined up into an orderly beam; and finally accelerated to the requisite energy, all in a time frame considerably shorter than the blink of an eye. That challenge is being addressed by the muon ionization cooling experiment (MICE) at the Rutherford Appleton Laboratory near Oxford, UK. MICE is expected to conclude its studies by 2016, at which point the cooling technology may be advanced enough for CERN to use it to build a neutrino factory — a stepping stone to a muon collider — that would fire beams of muon neutrinos through Earth to a detector thousands of kilometres away, such as one proposed in Finland.

Nonetheless, many physicists are sceptical. "I doubt I will see a muon collider working in my lifetime," says Brian Foster, a physicist at the University of Oxford. "We've been trying to cool muons for more than ten years, and it is just extremely difficult."

Foster is the European regional director for the rival concept of a linear electron–positron collider. This type of machine would essentially be a long, straight electron accelerator firing right down the barrel of an equally long, straight positron accelerator, with their beams slamming together in the middle. The lack of curvature would eliminate synchrotron radiation losses. And the accelerators could always be bumped up in energy by making them longer on the back end.

Ideas for a high-energy linear collider began to emerge in the 1980s, and eventually converged on two concepts. The ILC, developed by a worldwide consortium of laboratories and universities, would be some 30 kilometres long, and would use proven superconducting accelerator technology to reach energies of 0.5 TeV, with the possibility of upgrading to 1 TeV. The ILC team is soon to publish a technical design report and the cost of the project is currently estimated at $6.7 billion. The Compact Linear Collider (CLIC), championed by CERN, would be almost 50 kilometres long, but would use novel acceleration techniques to reach energies of 3 TeV. CLIC's costs are less clear than the ILC's because only a conceptual design report is available, but its higher energies would open up new realms for discovery as well as for precision measurements.

The performance of either design has been extensively studied theoretically, but in practice is a "wide open question" according to Blondel, current spokesperson for MICE. He points to the performance of the Stanford Linear Collider (SLC) at Menlo Park, California, which achieved energies of nearly 100 GeV. "The SLC finally worked very well, but it never quite produced the luminosity that they wanted. It was a very tough machine, and now with the ILC or CLIC we're discussing something that is much more difficult."

Nevertheless, for many, if not most, particle physicists, some form of linear collider seems like the best bet. In June, the International Committee for Future Accelerators, headquartered at Fermilab in Batavia, Illinois, brought the ILC and CLIC together under a single Linear Collider project, headed by former LHC director Lyn Evans. His aim is to deliver a proposal for a single linear collider by the end of 2015.

> "WE SHOULDN'T TAKE IT FOR GRANTED THAT MONEY IS AVAILABLE JUST BECAUSE THE HIGGS HAS BEEN FOUND."

A sensible plan, thinks Evans, is to build a linear collider starting at 250 GeV to probe the Higgs, and then boost its energy in stages until it reaches 500 GeV. At that point it could produce pairs of Higgs bosons and allow researchers to explore how the Higgs couples to itself and also interacts with the heaviest particle of matter, the top quark. Going to higher energies is technically feasible, he says, but requires more electricity — as much as a medium power station's worth. In practice, he says, "I think an upper limit in power [on the hypothetical new site] is the maximum that can be supplied to the CERN site, which is 300 MW."

Technology aside, the multi-billion-dollar question is who would

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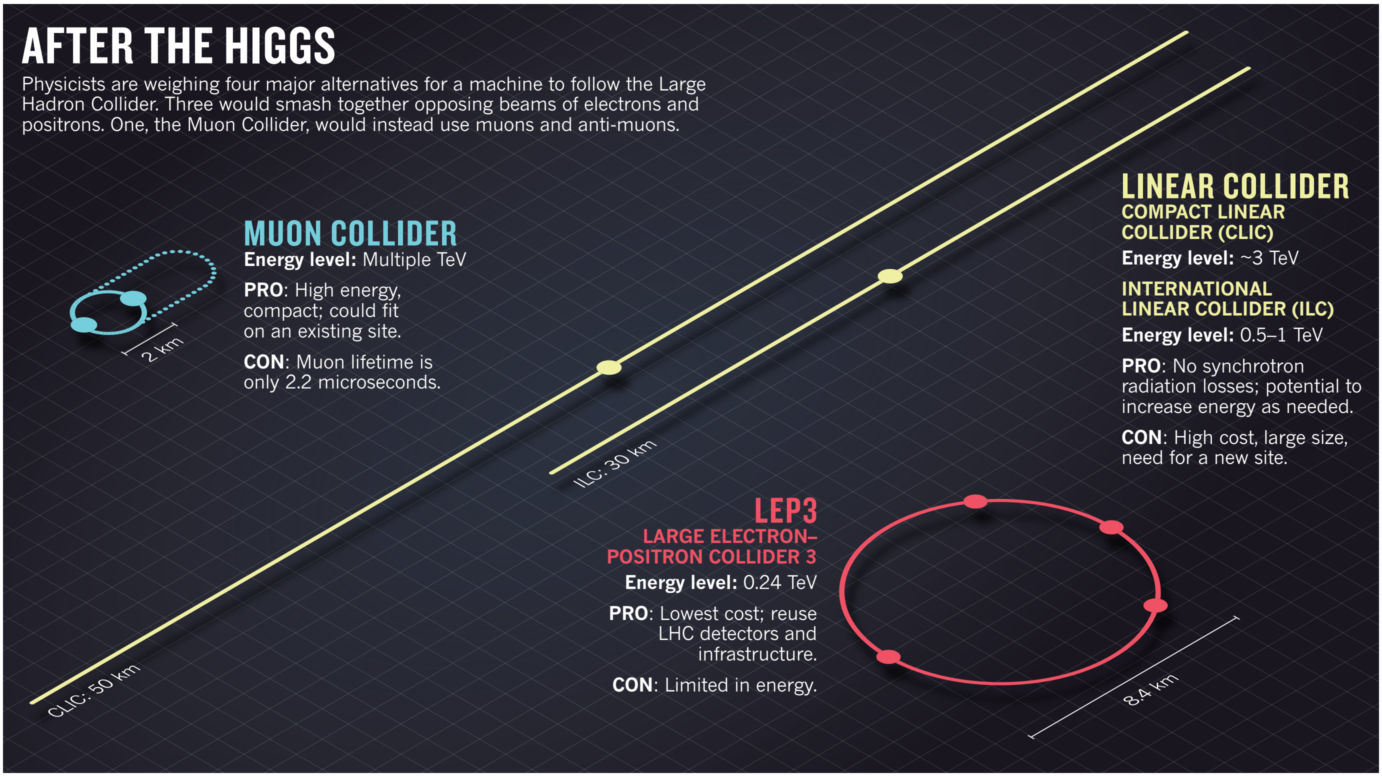

host the next lepton collider. A rule of thumb is that the host country puts up half the cost in expectation of long-term economic returns, says Foster. But this is not a good economic period to be making that case, especially not for a project that, from a politician's point of view, has no short-term benefit to voters.

GOING GLOBAL

If a linear collider is to be approved in the next few years, says Evans, it will probably not be built at CERN. Despite the European lab's wealth of technical and political infrastructure, it has its hands full with the LHC, which isn't even scheduled to reach its design energy of 7 TeV per beam until 2014 and is also scheduled to undergo a luminosity upgrade around 2022. "I'd bet that the highest priority of the European strategy workshop will be continuing to exploit and upgrade the LHC," says John Womersley, chief executive of Britain's Science and Technology Facilities Council, which controls the country's spending on particle physics.

The United States is also an unlikely site for a new collider, says Fermilab director Pier Oddone, who is chair of the International Committee for Future Accelerators. "Something drastic would have to change," he says. After the closure of Fermilab's 2-TeV Tevatron collider, the energy frontier crossed from the United States to Europe. So the current US strategy is to concentrate on the 'intensity frontier', studying rare particle interactions produced by, for example, intense beams of neutrinos. And yet, says Oddone, "we had a fairly severe budget cut at the beginning of this year and had problems fitting in a facility [a long-baseline neutrino experiment] that costs one-tenth of the ILC". Oddone says that it would also be "very difficult" at this time for the United States to contribute much to a lepton collider built elsewhere.

Many observers think that by far the strongest candidate to host the next project is Japan. After all, notes Evans, Japan made a significant contribution to the LHC in the mid-1990s when the project was under financial strain. "Perhaps it's time for Europe to return the favour," he says. The Japanese premier made positive references to the ILC in December 2011, just after the first preliminary sightings of the new boson were announced. There is a scent of extra funds, because the new accelerator is being discussed as part of a broader economic plan to boost regions devastated by the March 2011 earthquake; the idea is to make it the hub of an 'international city' comprising other research laboratories, industrial zones and education centres. And as Japanese particle physicists update their five-year roadmap this year, the ILC remains at the top of their new-project wish-list. Specifically, explains Atsuto Suzuki, director-general of the KEK laboratory in Tsukuba, the community's recommendation was that "Japan should take leadership of the early realization of an electron–positron linear collider should a particle such as a Higgs boson be confirmed at the LHC".

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So is an ILC finally looking like a safe bet? "Good god, no!" says Foster, "but this is the best chance that we've had in a long time." Womersley gives odds of the ILC being built as 50:50 at best. "We shouldn't take it for granted that money is available just because the Higgs has been found," he says, pointing out that there are also strong cases for next-generation neutrino experiments, for example. It would take around ten years from breaking ground to operating an ILC, estimates Oddone, plus the preparatory time. "You're talking 2025 at the earliest, but do you launch such a major project before you know what else the LHC might find? There could be things much wilder than the Higgs."

For many particle physicists, the dream scenario is the LHC exploring the high-energy frontier in Europe; multiple neutrino experiments exploring the intensity frontier in the United States; and a new lepton collider in Japan pinning down the details of all the exotic new particles that so far have not turned up in the LHC's collisions. "I would love to see us going in that direction, if countries put their weight behind the programmes in each region," says Terry Wyatt, a physicist at the University of Manchester, UK, who works on the ATLAS detector at the LHC.

As always in the world of big science, however, making such dreams come true is a question of making the sale to outsiders. "These things would probably be solved outside the particle-physics sphere," says Oddone. "It might be a phone call between a president and a prime minister that decides it." ■ SEE COMMENT P. 581

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