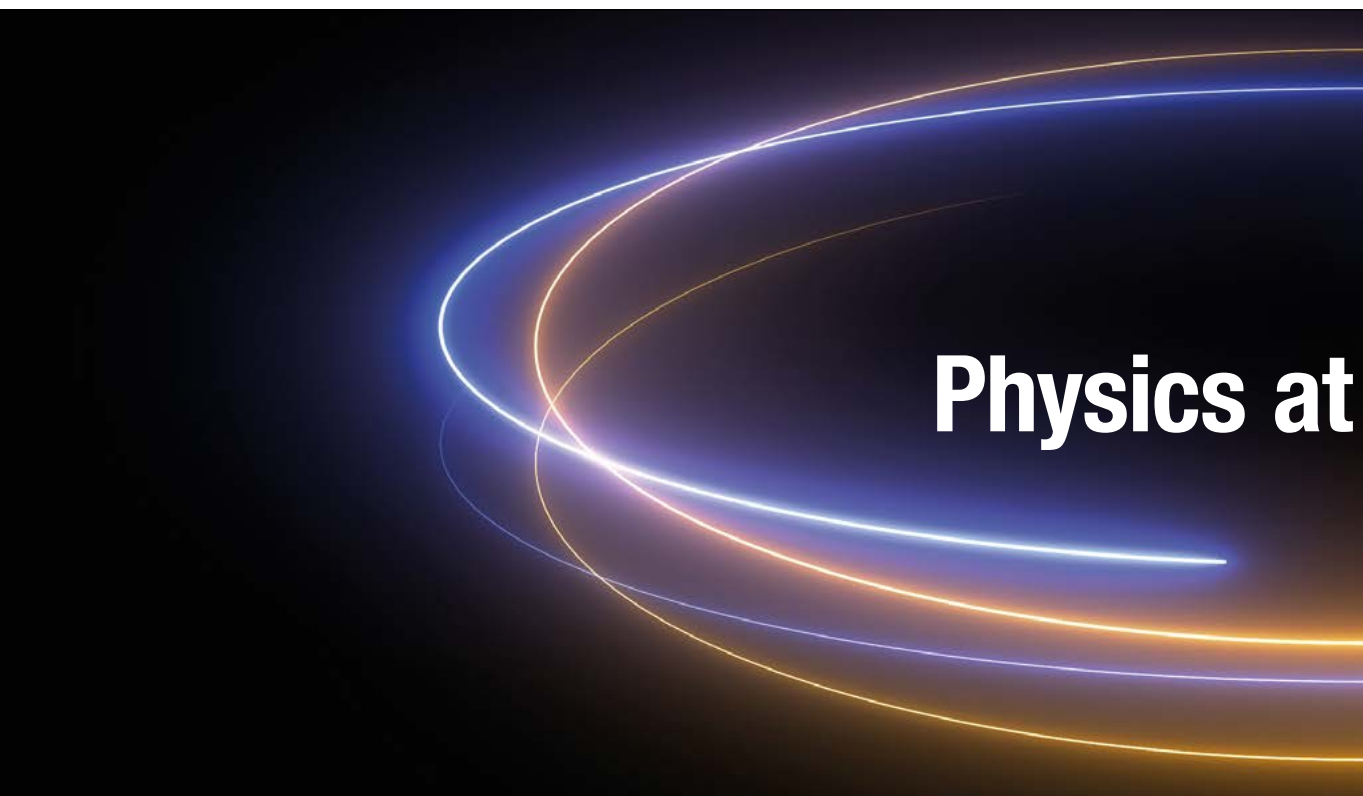




Physics at

A 100 km-circumference collider would address many of the outstanding questions in modern particle physics and secure our exploration of the microscopic world for generations.

Since Democritus, humans have wondered what happens as we slice matter into smaller and smaller parts. After the discovery almost 50 years ago that protons are made of quarks, further attempts to explore smaller distances have not revealed tinier substructures. Instead, we have discovered new, heavier elementary particles, which although not necessarily present in everyday matter are crucial components of nature's fundamental make-up. The arrangement of the elementary particles and the interactions between them is now well described by the Standard Model (SM), but furthering our understanding of the basic laws of nature requires digging even deeper.

Quantum physics gives us two alternatives to probe nature at smaller scales: high-energy particle collisions, which induce short-range interactions or produce heavy particles, and high-precision measurements, which can be sensitive to the ephemeral influence of heavy particles enabled by the uncertainty principle. The SM was built from these two approaches, with a variety of experi-

ments worldwide during the past 40 years pushing both the energy and the precision frontiers. The discovery of the Higgs boson at the LHC is a perfect example: precise measurements of Z-boson decays at previous lepton machines such as CERN's Large Electron-Positron (LEP) collider pointed indirectly but unequivocally to the existence of the Higgs. But it was the LHC's proton-proton collisions that provided the high energy necessary to produce it directly. With exploration of the Higgs fully under way at the LHC and the machine set to operate for the next 20 years, the time is ripe to consider what tool should come next to continue our journey.

Aiming at a high-energy collider with a clean collision environment, CERN has for several years been developing an e^+e^- linear collider called CLIC. With an energy up to 3 TeV, CLIC would combine the precision of an e^+e^- collider with the high-energy reach of a hadron collider such as the LHC. But with the lack so far of any new particles at the LHC beyond the Higgs, evidence is mounting that even higher energies may be required to fully explore the next layer of phenomena beyond the SM. Prompted by the outcome of the 2013 European Strategy for Particle Physics, CERN has therefore undertaken a five-year study for a Future Circular Collider (FCC) facility built in a new 100 km-circumference tunnel (see image overleaf).

Such a tunnel could host an e^+e^- collider (called FCC-ee) with an energy and intensity much higher than LEP, improving by orders of magnitude the precision of Higgs and other SM measurements. It could also house a 100 TeV proton-proton collider (FCC-hh) with



its limits

a discovery potential more than five times greater than the 27 km-circumference LHC. An electron–proton collider (FCC-eh), furthermore, would allow the proton’s substructure to be measured with unmatched precision. Further opportunities include the collision of heavy ions in FCC-hh and FCC-eh, and fixed-target experiments using the injector complex. The earliest that such a machine could enter operation is likely to be the mid 2030s, when the LHC comes to the end of its operational lifetime, but the long lead times for collider projects demand that we start preparing now (see timeline overleaf). A Conceptual Design Report (CDR) for a 100 km collider is expected to be completed by the end of 2018 and hundreds of institutions have joined the international FCC study since its launch in 2014. An independent study for a similar facility is also under way in China.

The CDR will document the accelerator, infrastructures and experiments, as well as a plethora of physics studies proving FCC’s ability to match the long-term needs of global high-energy-physics programmes. The first FCC physics workshop took place at CERN in January to review the status of these studies and discuss the complementarity between the three FCC modes.

The post-LHC landscape

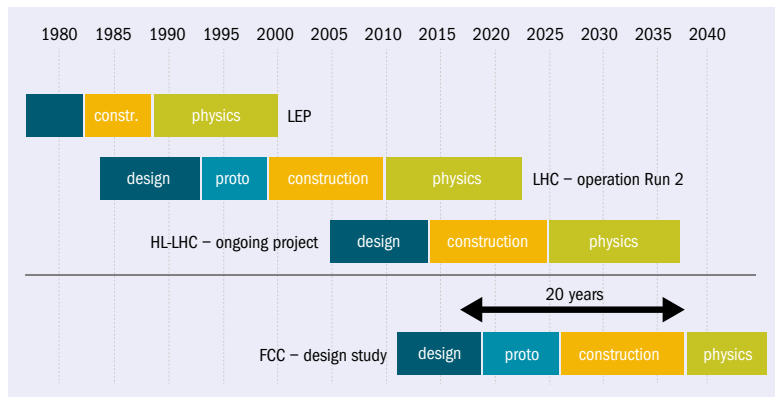
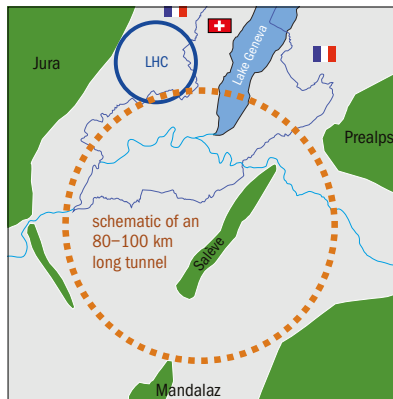
To chart the physics landscape of future colliders, we must first imagine what questions may or may not remain at the end of the LHC programme in the mid-2030s. At the centre of this, and

perhaps the biggest guaranteed physics goal of the FCC programme, is our understanding of the Higgs boson. While there is no doubt that the Higgs was the last undiscovered piece of the SM, it is not the closing chapter of the millennia-old reductionist paradigm. The Higgs is the first of its kind – an elementary scalar particle – and it therefore raises deep theoretical questions that beckon a new era of exploration (figure 1, p39).

Consider its mass. In the SM there is no symmetry that protects the Higgs mass from large quantum corrections that drag it up to the mass scale of the particles it interacts with. You might conclude that the relatively low mass of the Higgs implies that it simply does not interact with other heavy particles. But there is good, if largely theoretical, evidence to the contrary. We know that at energies 16 orders of magnitude above the Higgs mass where general relativity fails to provide a consistent quantum description of matter, there must exist a full quantum theory that includes gravity. The fact that the Higgs is so much lighter than this scale is known as the hierarchy problem, and many candidate theories (such as supersymmetry) exist that require new heavy particles interacting with the Higgs. By comparing precise measurements of the Higgs boson with precision SM predictions, we are indirectly searching for evidence of these theories. The SM provides an uncompromising script for the Higgs interactions and any deviation from it would demand its extension.

Even setting to one side grandiose theoretical ideas such as quantum gravity, there are other physical reasons why the Higgs may ►

Future colliders



provide a window to undiscovered sectors. As it carries no spin and is electrically neutral, the Higgs may have so-called “relevant” interactions with new neutral scalar particles. These interactions, even if they take place only at very high energies, remain relevant at low energies – contrary to interactions between new neutral scalars and the other SM particles. The possibility of new hidden sectors already has strong experimental support: although we understand the SM very well, it does not account for roughly 80% of all the matter in the universe. We call the missing mass dark matter, and candidate theories abound. Given the importance of the puzzle, searches for dark-matter particles will continue to play a central role at the LHC and certainly at future colliders.

Furthermore, the SM cannot explain the origin of the matter–antimatter asymmetry that created enough matter for us to exist, otherwise known as baryogenesis. Since the asymmetry was created in the early universe when temperatures and energies were high, we must explore higher energies to uncover the new particles responsible for it. With the LHC we are only at the beginning of this search. Another outstanding question lies in the origin of the neutrino masses, which the SM alone cannot account for. As with dark matter, there are numerous theories for neutrino masses, such as those involving “sterile” neutrinos that are in the reach of lepton and hadron colliders. These and other outstanding questions might also imply the existence of further spatial dimensions, or larger symmetries that unify leptons and quarks or the known forces. The LHC’s findings notwithstanding, future colliders like the FCC are needed to explore these fundamental mysteries more deeply, possibly revealing the need for a paradigm shift.

Electron–positron potential

The capabilities of circular e^+e^- colliders are well illustrated by LEP, which occupied the LHC tunnel from 1989 to 2000. Its point-like collisions between electrons and positrons and precisely known beam energy allowed the four LEP experiments to test the SM to new levels of precision. Putting such a machine in a 100 km tunnel and taking advantage of advances in accelerator technology such as superconducting radio-frequency cavities would offer even greater levels of precision on a larger number of processes. We would be able to change the collision energy in the range 91–350 GeV, for example, allowing data to be collected at the Z pole, at the WW production threshold, at the peak of ZH

production, and at the top–antitop quark threshold. Controlling the beam energy at the 100 keV level would allow exquisite measurements of the Z- and W-boson masses, while the high luminosity of FCC-ee will lead to samples of up to 10^{13} Z and 10^8 W bosons, not to mention several million Higgs bosons and top–quark pairs. The experimental precision would surpass any previous experiment and challenge cutting-edge theory calculations.

FCC-ee would quite literally provide a quantum leap in our understanding of the Higgs. Like the W and Z gauge bosons, the Higgs receives quantum electroweak corrections typically measuring a few per cent in magnitude due to fluctuations of massive particles such as the top quark. This aspect of the gauge bosons was successfully explored at LEP, but now it is the turn of the Higgs – the keystone in the electroweak sector of the SM. The millions of Higgs bosons produced by FCC-ee, with its clinically precise environment, would push the accuracy of the measurements to the per-mille level, accessing the quantum underpinnings of the Higgs and probing deep into this hitherto unexplored frontier. In the process, $e^+e^- \rightarrow HZ$, the mass recoiling against the Z has a sharp peak that allows a unique and absolute determination of the Higgs decay width and production cross-section. This will provide an absolute normalisation for all Higgs measurements performed at the FCC, enabling exotic Higgs decays to be measured in a model-independent manner.

The high statistics promised by the FCC-ee programme go far beyond precision Higgs measurements. Other signals of new physics could arise from the observation of flavour-changing neutral currents or lepton-flavour-violating decays by the precise measurements of the Z and H invisible decay widths, or by direct observation of particles with extremely weak couplings such as right-handed neutrinos and other exotic particles. Given the particular energy and luminosity of a 100 km e^+e^- machine, the precision of the FCC-ee programme on electroweak measurements would allow new physics effects to be probed at scales as high as 100 TeV. If installed before FCC-hh, it would therefore anticipate what the hadron machine must focus on.

The energy frontier

The future proton–proton collider FCC-hh would operate at seven times the LHC energy, and collect about 10 times more data. The discovery reach for high-mass particles – such as Z' or W' gauge bosons corresponding to new fundamental forces, or gluinos and squarks in supersymmetric theories – will increase by a factor five or $\triangleright$

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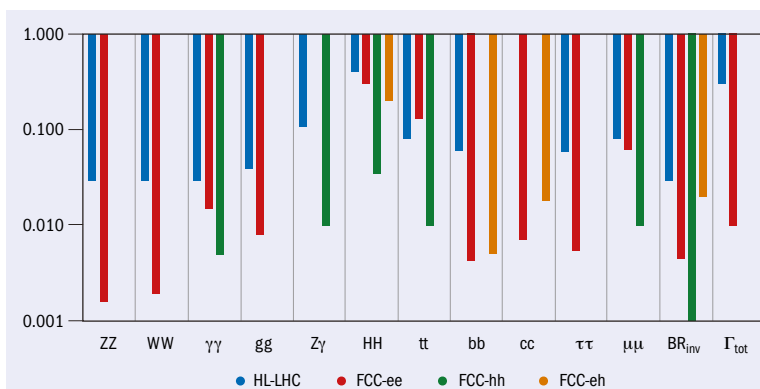


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Future colliders



(Far left). The FCC accelerator complex in the Geneva region, showing the LHC for comparison. (Middle) Technical timeline of the FCC project shown in comparison with previous and existing CERN colliders. (Left) Fig. 1. Together, FCC-ee, hh and eh can provide detailed measurements on the Higgs properties. The figure shows indicative precision in the determination of couplings to gauge bosons, quarks and leptons, as well as of the Higgs self-coupling, of its total width and of the invisible decay rate. Firmer estimates will appear in the CDR.

more, depending on the luminosity. The production rate of particles already within the LHC reach, such as top quarks or Higgs bosons, will increase by even larger factors. During its planned 25 years of data-taking, more than 10^{10} Higgs bosons will be created by FCC-hh, which is 10,000 times more than collected by the LHC so far and 100 times more than will be available by the end of LHC operations. These additional statistics will enable the FCC-hh experiments to improve the separation of Higgs signals from the huge backgrounds that afflict most LHC studies, overcoming some of the dominant systematics that limit the precision attainable from the LHC.

While the ultimate precision on most Higgs properties can only be achieved with FCC-ee, several demand complementary information from FCC-hh. For example, the direct measurement of the coupling between the Higgs and the top quark necessitates that they be produced together, requiring an energy beyond the reach of the FCC-ee. At 100 TeV, almost 10^9 of the 10^{12} produced top quarks will radiate a Higgs boson, allowing the top-Higgs interaction to be measured with a statistical precision at the 1% level – a factor 10 improvement over what is hoped for from the LHC. Similar precision can be reached for Higgs decays that are too rare to be studied in detail at FCC-ee, such as those to muon pairs or to a Z and a photon. All of these measurements will be complementary to those obtained with FCC-ee, and will use them as reference inputs to precisely correlate the strength of the signals obtained through various production and decay modes.

One respect in which a 100 TeV proton–proton collider would come to the fore is in revealing how the Higgs behaves in private. The Higgs is the only particle in the SM that interacts with itself. As the Higgs scalar potential defines the potential energy contained in a fluctuation of the Higgs field, these self-interactions are neatly

defined as the derivatives of the scalar electroweak potential. With the Higgs boson being an excitation about the minimum of this potential, we know that its first derivative is zero. The second derivative of the potential is simply the Higgs mass, which is already known to sub-percent accuracy. But the third and fourth derivatives are unknown, and unless we gain access to

Higgs self-interactions they could remain so. The rate of Higgs pair-production events, which in some part occur through Higgs self-interactions, would grow precipitously at FCC-hh and enable this unique property of the Higgs to be measured with an accuracy of 5% per cent. Among many other uses, such a measurement would comprehensively explore classes of baryogenesis models that rely on modifying the Higgs potential, and thus help us to understand the origin of matter.

FCC-hh would also allow an exhaustive exploration of new TeV-scale phenomena. Indirect evidence for new physics can emerge from the scattering of W bosons at high energy, from the production of Higgs bosons at very large transverse momentum, or by testing the far “off-shell” nature of the Z boson via the measurement of lepton pairs with invariant masses in the multi-TeV region. The plethora of new particles predicted by most models of symmetry-breaking alternative to the SM can be searched for directly, thanks to the immense mass reach of 100 TeV collisions. The search for dark matter, for example, will cover the possible space of parameters of many theories relying on weakly interacting massive particles, guaranteeing a discovery or ruling them out. Theories that address the hierarchy problem will also be conclusively tested. For supersymmetry, the mass reach of FCC-hh pushes beyond the regions motivated by this puzzle alone. For composite Higgs theories, the precision Higgs coupling measurements and searches for new heavy resonances will fully cover the motivated territory. A 100 TeV proton collider will even confront exotic scenarios such as the twin Higgs, which are nightmarishly difficult to test. These theories predict very rare or exotic Higgs decays, possibly visible at FCC-hh thanks to its enormous Higgs production rates.

Beyond these examples, a systematic effort is ongoing to categorise the models that can be conclusively tested, and to find the loopholes that might allow some models to escape detection. This work will influence the way detectors for the new collider are designed. Work is already starting in earnest to define the features of these detectors, and efforts in the FCC CDR study will focus on comprehensive simulations of the most interesting physics signals. The experimental environment of a proton–proton collider is difficult due to the large number of background sources and the additional noise caused by the occurrence of multiple interactions among the hundreds of billions of protons crossing each other at the same time. This pile-up of events will greatly exceed those observed ▷

Future colliders like the FCC will be needed to explore these fundamental mysteries more deeply.

Future colliders

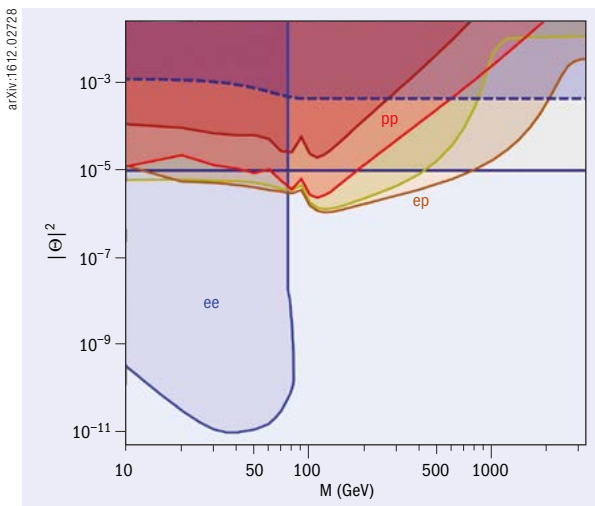


Fig. 2. The complementary role of the ee , pp and ep colliders in probing a sterile neutrino of mass M and mixing angle θ with ordinary neutrinos.

at the LHC, and will pose a significant challenge to the detectors' performance and to the data-acquisition systems. The LHC experience is of immense value for projecting the scale of the difficulties that will have to be met by FCC-hh, but also for highlighting the increasing role of proton colliders in precision physics beyond their conventional role of discovery machines.

Asymmetric collisions

Smashing protons into electrons opens up a whole different type of physics, which until now has only been explored in detail by a single machine: the HERA collider at DESY in Germany. FCC-eh would collide a 60 GeV electron beam from a linear accelerator, external and tangential to the main FCC tunnel, with a 50 TeV proton beam. It would collect factors of thousands more luminosity than HERA while exhibiting the novel concept of synchronous, symbiotic operation alongside the pp collider. The facility would serve as the most powerful, high-resolution microscope to examine the substructure of matter ever built, with high-energy electron-proton collisions providing precise information on the quark and gluon structure of the proton.

This unprecedented facility would enhance Higgs studies, including the study of the coupling to the charm quark, and broaden the new-physics searches also performed at FCC-hh and FCC-ee. Unexpected discoveries such as quark substructure might also arise. Uniquely, in electron-proton collisions new particles can be created in lepton-quark fusion processes or may be radiated in the exchange of a photon or other vector boson. FCC-eh could also provide access to Higgs self-interactions and extended Higgs sectors, including scenarios involving dark matter. If neutrino oscillations arise from the existence of heavy sterile neutrinos, direct searches at the FCC-eh would have great discovery prospects in kinematic regions complementary to FCC-hh and FCC-ee, giving the FCC complex a striking potential to shine light on the origin of neutrino masses.

Unknown unknowns

In principle, the LHC could have – and still could provide – answers to many of these outstanding questions in particle physics. That no new particles beyond the Higgs have yet been found, or any significant deviations from theory detected, does not mean that these questions have somehow evaporated. Rather, it shows that any expectations for early discoveries beyond the SM at the LHC – often based on theoretical, and in some cases aesthetic, arguments – were misguided. In times like this, when theoretical guidance is called into question, we must pursue experimental answers as vigorously as possible. The combination of accelerators that are being considered for the FCC project offer, by their synergies and complementarities, an extraordinary tool for investigating these questions (figure 2).

There are numerous instances in which the answer nature has offered was not a reply to the question first posed. For example, Michelson and Morley's experiment designed to study the properties of the ether ended up disproving the existence of the ether and led to Einstein's theory of special relativity. The Kamiokande experiment in Japan, originally built to observe proton decays, instead discovered neutrino masses. The LHC itself could have disproven the SM by discovering that the Higgs boson is not an elementary but a composite particle – and may still do so, with its future more precise measurements.

The possibility of unknown unknowns does not diminish the importance of an experiment's scientific goals. On the contrary, it demonstrates that the physics goals for future colliders can play the crucial role of getting a new facility off the ground, even if a completely unanticipated discovery results. This is true of all expeditions into the unknown. We should not forget that Columbus set sail to find a westerly passage to Asia. Without this goal, he would not have discovered the Americas.

• Further reading

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Résumé

La physique poussée dans ses limites

Un collisionneur de 100 km de circonférence, tel qu'imaginé par l'étude du CERN sur un futur collisionneur circulaire, pourrait répondre à plusieurs questions de la physique des particules moderne. Une machine électron-positon permettrait d'améliorer considérablement la précision des mesures du Higgs et d'autres particules du Modèle standard, un collisionneur proton-proton de 100 TeV aurait plus de cinq fois le potentiel de découverte du LHC, et un collisionneur électron-proton permettrait de mesurer la sous-structure du proton avec une précision inégalée.

Michelangelo Mangano, CERN, Patrizia Azzi, INFN Sezione di Padova, Monica D'Onofrio, University of Liverpool, and Matthew McCullough, CERN.

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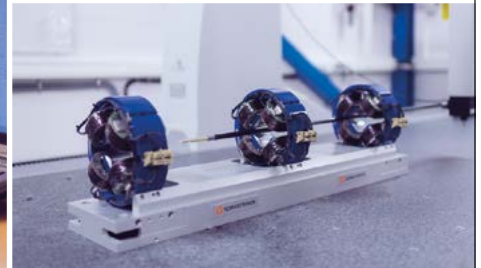
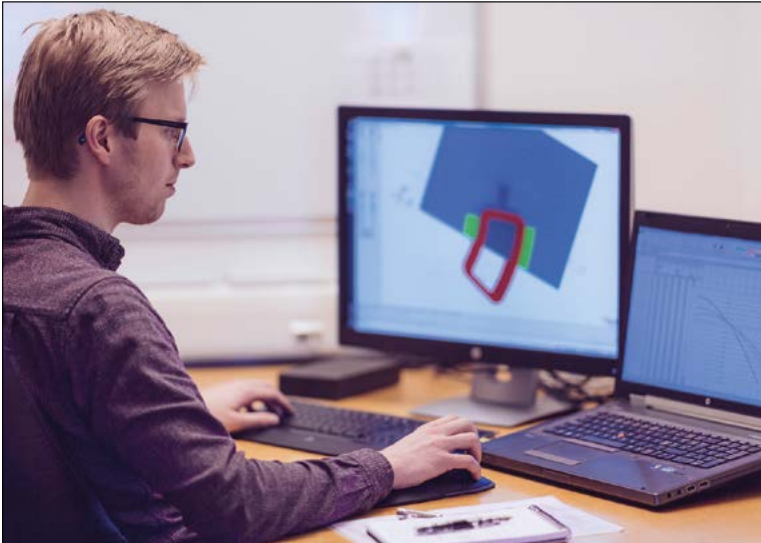
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