

# FUTURE CIRCULAR COLLIDER STUDY

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## QUICK Q&A GUIDE

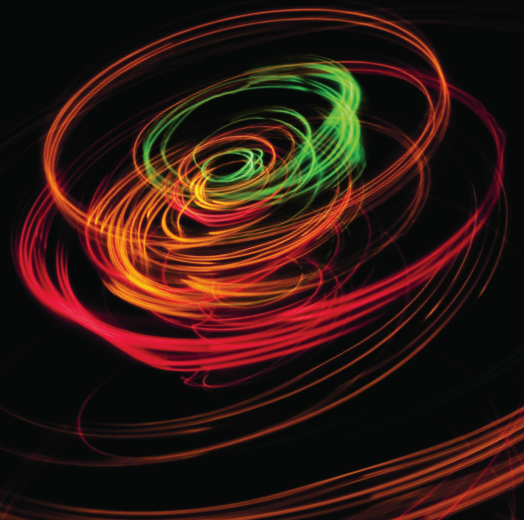
Attacking some of the most profound theoretical questions of the 21st century, particularly the ones associated with the Higgs particle and the search of physics beyond the Standard Model, will necessitate another leap to higher energies. **The future of fundamental physics on the timescale of the 21st century hinges on designing and building future colliders that will extend the energy and precision beyond the LHC.**

Many of the most profound mysteries are intimately connected with the Higgs particle, which is totally new, unlike anything we have seen before. In many ways, the Higgs is the simplest particle imaginable, with no charge and no spin. This simplicity is actually extremely surprising.

Secondly, the Higgs must have a dynamical property we have never seen for any of the other fundamental particles: it should be able to interact not only with other particles, but also with itself! Measuring the self-interaction of the Higgs particle is key in understanding the details of the mechanism that explains its mass.

Particle physicists for many years have been discussing the search for new physics beyond the Standard Model. However, it is essential to understand that the **Higgs particle itself represents “new physics” in a profound way.** It is thus important to study and understand in some depth this particle and its properties, as it may shed light on key theoretical concepts and the deepest structure of our theories.

The Higgs discovery closes the 20th century chapter of fundamental physics, while **at the same time opens the door to new questions of the 21st century. These questions are deeper and are related to do with one of the biggest theoretical frameworks developed in the course of the last century: Quantum Mechanics and Quantum Field Theory.**



# **WHICH** concepts are considered under the future under the FCC-study?

Concepts for three different scenarios are developed: An energy frontier hadron collider reaching out to 100 TeV collision energies in a 100 km tunnel provides the baseline. A concept for a circular intensity frontier lepton collider that is complementary to past linear collider studies, fitting in the same tunnel infrastructure is the second scenario. The concept for an interaction point of a smaller lepton accelerator with a high-energetic hadron beam is developed as a third scenario. Finally the option to construct a collider in the existing LHC tunnel collider using the technology developed for an energy frontier collider is assessed.

# **WHY** the LHC can't answer all the open questions?

The LHC has greatly advanced our understanding of matter and the Standard Model. However it cannot confirm every aspect of the SM nor explore other key questions about the Universe. To find out more about dark matter, the matter/ antimatter asymmetry, or the origin of neutrino masses, a collider with extended energy and mass reach is necessary.

The LHC is not expected to reach such high-energies, even after the High-Luminosity upgrade in the 2030s. Thus, the FCC Study aims to formulate a proposal for a next-generation accelerator that will open up new horizons in the field of fundamental physics.

# **WHY** do we study a future hadron circular collider?

The LHC will only scratch the surface of this physics, but with data from a 100 TeV proton-proton collider we will be able to unambiguously see and precisely measure the Higgs self-interaction process, that are deeply related to the origin and the mass of the Higgs itself.

At a more fundamental level, the proposal of a 100 TeV proton-proton collider stems from the bold leap into the completely uncharted new territory that it offers, probing energy scales, where fundamental new physical principles might be at play. The 100 TeV proton-proton collider will allow us to hunt for new fundamental particles roughly an order of magnitude heavier than we can possibly produce with the LHC. In addition, new particles that LHC may produce in small numbers will be produced with up to a thousand times higher rate, giving us a new window into the mechanisms at play in the evolution of our Universe with a 100-fold greater resolution than ever before.

Billions of Higgs bosons and trillions of top quarks will be produced, creating new opportunities for the study of rare decays and flavor physics, which tremendously benefit from higher collision energies. A hadron collider will also extend the study of the Higgs boson interactions to energies well above the TeV scale, providing a way to analyse in detail the mechanism underlying the breaking of the electroweak symmetry.

Most importantly the leap in energy at the 100 TeV gives a huge increase in the reach for new physics. A seven-fold increase of the centre-of-mass energies relative to the LHC with a luminosity comparable to that of the LHC increases the mass reach for new particles significantly.

Finally, the FCC-hh collider would offer an opportunity to push the exploration of the collective structure of matter at the most extreme density and temperature conditions to new frontiers through the study of heavy-ion collisions.

# **WHY** do we need to discuss again a new generation of lepton-lepton colliders after LEP?

The answer is included in the question: If the LEP performance can be multiplied by a huge factor – profiting from concepts developed for the latest designs from other studies – the new machine would be able to accumulate  $10^{12}$  to  $10^{13}$  Z decays, i.e., five to six orders of magnitude more than at LEP!

The FCC-ee has a unique programme of searches for new physics via high-precision studies of the W, Z and Higgs bosons and the top quark with very low uncertainties thanks to the huge luminosities foreseen and the exquisite control of the beam energy in the range of 90 to 350 GeV at centre of mass.

The centre-of-mass energy increase offered by the fourfold circumference compared to LEP will also allow millions of Higgs particles or top quarks to be produced, to mention the heaviest and perhaps most puzzling particles in the Standard Model.

The statistical precision of measurements that are sensitive to new physics would be improved by a factor of up to 500. Such a jump in precision provides very high precision measurements of electroweak observables (including a very detailed study of the Higgs boson) and could offer the discriminating power for new physics. Searches for tiny deviations with respect to the predictions of the Standard Model in a rich set of measurements may give us a hint for the physics lying Beyond the Standard Model. A

In addition, a future lepton collider could provide direct searches for physics beyond the S.M through rare and invisible decays of the Higgs and Z bosons that could shed light on questions about dark matter or the mass of sterile neutrinos.

Precision measurements are important as they could allow particles to be searched for and detected, even if they are far too heavy to be directly produced. The FCC-ee scenario is complementary to the FCC-hh and the two options could offer an extremely broad, rich and diverse programme of scientific exploration over at least half a century.

# **WHY** a hadron-lepton option is also considered under the FCC-study?

The study for a hadron-lepton collider aims to bring the physics of deep inelastic electron-proton scattering to a new horizon.

Lepton-nucleus scattering has made seminal contributions such as the discovery of quarks, the disambiguation of the weak neutral current couplings and the determination at HERA of high quark and gluon densities in protons.

The hadron-lepton collider under consideration will be a high-precision Higgs factory, with which new particles or interactions may be discovered and interpreted. With a resolution down to  $10^{-20}$  m, it represents the finest microscope for studying quark-gluon interactions and possible further substructure of matter in the world.

This programme, accompanied by unprecedented measurements of strong and electroweak interaction phenomena, the hadron-electron collider is a unique complement to the exploration of nature at high energies within the FCC complex.

# **WHY** can the LHC not be upgraded to answer the open questions?

There exists a fundamental relationship between the circumference of a circular particle collider, the field strength of the magnets that keep the beams on track and the energy of the beams. Given these constraints a post-LHC collider based in the same tunnel - of 27 km- with the technologies developed for the FCC-hh is studied. This would allow reaching collisions energies at ~30 TeV c.m; almost double compared to the present energy reach of the LHC.

Moreover, when the LHC was designed back in the 1980's a specific set of technical parameters were set which we can't overcome. The machine so far has shown an excellent performance and in certain instances it allowed to exceed its capabilities like was the case with the asymmetric proton & heavy-ion collisions that took place in 2013 and probed new physics for the nucleus.

Finally, it should be noted that modern accelerators are very complex machines that push the boundaries of technology and their design is based on a number of parameters that need to be carefully consider to ensure a reliable and sustainable operation that would allow reaching the scientific goals.

# **WHEN** will such a machine could be built?

To be ready to start a transition period from HL-LHC to a new machine by 2035 it is necessary to begin construction and handle all the enabling technologies around 2025.

A conceptual design report needs to be ready before the end of the decade - in order to inform the next European Strategy meeting on Particle Physics, followed by detailed technical designs, industrialisation and project management plans along with an established international collaboration of partners by 2025.

# **WHY** do we start now?

The lead times of large-scale research infrastructures that require state-of-science technologies to be deployed at industrial scales are long. It is prudent to develop different concepts (lepton, hadron, high-energy LHC) to have suitable technical designs, risks assessed and a set of healthy industrial partners at hand.

It is important to avoid a large time-gap as valuable know-how could be lost while it is important to strengthen and deepen the international collaboration following the lessons from the LHC. Finally it is also important to drive innovation and create more opportunities for high-tech industry of different sizes by continuously investing fundamental R&D in a numerous technological domains.



# HOW MUCH will it cost?

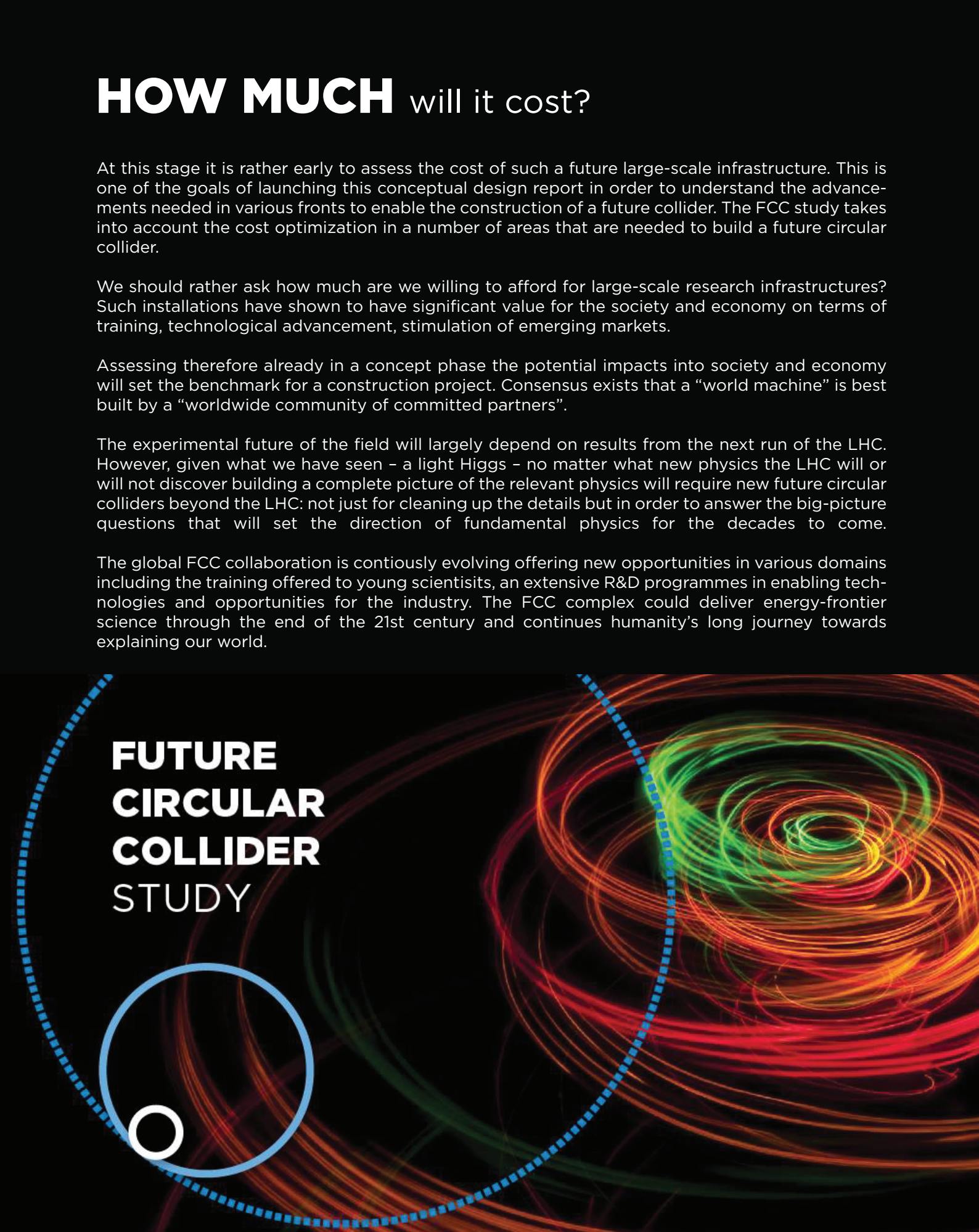
At this stage it is rather early to assess the cost of such a future large-scale infrastructure. This is one of the goals of launching this conceptual design report in order to understand the advancements needed in various fronts to enable the construction of a future collider. The FCC study takes into account the cost optimization in a number of areas that are needed to build a future circular collider.

We should rather ask how much are we willing to afford for large-scale research infrastructures? Such installations have shown to have significant value for the society and economy on terms of training, technological advancement, stimulation of emerging markets.

Assessing therefore already in a concept phase the potential impacts into society and economy will set the benchmark for a construction project. Consensus exists that a “world machine” is best built by a “worldwide community of committed partners”.

The experimental future of the field will largely depend on results from the next run of the LHC. However, given what we have seen – a light Higgs – no matter what new physics the LHC will or will not discover building a complete picture of the relevant physics will require new future circular colliders beyond the LHC: not just for cleaning up the details but in order to answer the big-picture questions that will set the direction of fundamental physics for the decades to come.

The global FCC collaboration is continuously evolving offering new opportunities in various domains including the training offered to young scientists, an extensive R&D programmes in enabling technologies and opportunities for the industry. The FCC complex could deliver energy-frontier science through the end of the 21st century and continues humanity’s long journey towards explaining our world.

The background of the lower half of the page features an abstract graphic. It consists of numerous thin, overlapping, swirling lines in vibrant colors like red, orange, yellow, green, and blue, creating a sense of dynamic movement and energy. Overlaid on this are several concentric circles. A prominent dashed blue circle is visible, along with a solid light blue circle and a smaller solid white circle in the bottom left corner.

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