Future Circular Collider
The Hadron Collider (FCC-hh)

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Abstract:

This report describes a novel research infrastructure, based on a hadron collider with centre-of-mass collision energy of 100 TeV, collecting an integrated luminosity a factor of 5 or more larger than the HL-LHC. It will extend the current energy frontier by almost an order of magnitude. The mass reach for direct discovery will reach several tens of TeV, and allow, for example, to produce new particles whose existence could be indirectly exposed by precision measurements during a preceding e^+e^- collider phase. This collider will also precisely measure the Higgs self-coupling and thoroughly explore the dynamics of electroweak symmetry breaking at the TeV scale, to elucidate the nature of the electroweak phase transition. Thermal dark matter WIMP candidates will be discovered, or ruled out. Heavy ion and ep collisions will contribute to the breadth of the programme. As a single project, this particle collider infrastructure will serve the world-wide physics community for about 25 years and, in combination with a highest-luminosity energy frontier lepton collider (FCC-ee, see FCC conceptual design report volume 2), will provide a research tool until the end of the 21st century.

The FCC Conceptual Design Report volumes are available for download at
http://fcc-design-report.web.cern.ch

Table of Contents

1 Scientific Context

Particle physics has arrived at an important moment of its history. The discovery of the Higgs boson, with a mass of 125 GeV, completes the matrix of particles and interactions that has constituted the "Standard Model" for several decades. This model is a consistent and predictive theory, which has so far proven successful at describing all phenomena accessible to collider experiments. However, **several experimental facts do require the extension of the Standard Model** and **explanations are needed for observations** such as the abundance of matter over antimatter, the striking evidence for dark matter and the non-zero neutrino masses. Theoretical issues such as the hierarchy problem, and, more in general, the dynamical origin of the Higgs mechanism, do point to the existence of physics beyond the Standard Model.

While at least some of the new particles and phenomena needed to solve the open problems are anticipated to exist at the TeV scale, their masses could well be too large, or their couplings too small, to be observed at the LHC. Future indications or discoveries of new physics at the TeV scale, by the LHC and other facilities, will most certainly require increased sensitivity to pin down their origins. In addition to looking for well-hidden new physics, progress in our exploration also demands looking for phenomena appearing at energy scales beyond the current reach of direct detection and indirect evidence. A significant increase in the mass reach for direct discovery, with respect to the LHC, is an essential component of this research programme.

The recent history of particle physics has shown that most of the major discoveries (Z, W, Higgs, and top) have required high-energy hadron colliders. In this context, **increasing** the **mass reach by almost an order of magnitude** and **increasing** the **luminosity by a factor of 30 with respect to the LHC** (a factor of 5 with respect to the HL-LHC) play a crucial role in being able to access a large range of new physics opportunities.

Today high energy physics lacks unambiguous and guaranteed discovery targets. Therefore, the programme of a future collider facility must aim at conclusive responses to key quantitative and conceptual questions that may not be answered otherwise. For example: how does the Higgs particle couple to itself? Do the light generations of fermions get their mass from the Higgs boson? What was the nature of the electroweak phase transition? Are weakly interacting massive particles (WIMPs) a component of Dark Matter (DM)? Does the hierarchy problem admit a natural solution at the TeV scale? **The high-energy hadron collider (FCC-hh), with a total integrated luminosity of up to 30 ab^{-1} at a pp centre-of-mass energy of 100 TeV**, and the possibility to synchronously integrate 2 ab^{-1} of ep collisions (FCC-eh), provides a unique opportunity to address these questions. The synergy and complementarity with the circular lepton collider (FCC-ee) bring answers to those questions within reach.

The thermodynamic behaviour of Quantum Chromodynamics (QCD) presents features that are unique among all other interactions. Their manifestations play a key role in fundamental aspects of the study of the universe, not the least in cosmology and astrophysics. The studies of collisions with heavy nuclei (N) at RHIC and LHC have exposed new features, beyond the standard quark-gluon plasma (QGP) paradigm, adding new questions to the set of open issues: how is thermal equilibrium reached? What is the origin of the collective phenomena that have been seen also in pp and pN collisions? Collisions of heavy ions at high energies and luminosities allowed by the FCC-hh, will take the study of collective properties of quark and gluons to new heights.

High-energy physics requires a powerful, sustainable and versatile hadron collider at the energy frontier. A 100 km circular collider that extends the current accelerator complex at CERN, with four interaction points, the possibility to operate with protons and with heavy ions and with the potential to include an electron-hadron interaction point, meets that need. This scenario permits multifaceted exploration and maximises the possibilities for major discoveries in a rich physics programme. Such a machine would expand the physics reach with multiple synergies and complementarities for the worldwide fundamental physics research community, until the end of the 21st century.

2 Objectives

The objective is to **develop, build and operate a 100 TeV hadron collider**, with an integrated luminosity at least a factor of 5 larger than the HL-LHC, **to extend the current energy frontier by almost an order of magnitude**. The mass reach for direct discovery will approach several tens of TeV, allowing the production of new particles whose existence could be indirectly predicted by precision measurements during the earlier preceding e^+e^- collider phase. This collider will also measure the Higgs self-coupling precisely and thoroughly explore the dynamics of electroweak symmetry breaking at the TeV scale, to **elucidate the nature of the electroweak phase transition**. **WIMPs as thermal dark matter candidates will be discovered, or ruled out.** As a single project, this particle collider facility will **serve the global physics community for about 25 years** and, **in combination with a lepton collider, will provide a research tool until the end of the 21st century.**

2.1 Scientific Objectives

The European Strategy for Particle Physics **(ESPP) 2013 unambiguously recognized the importance of *"a proton-proton high-energy frontier machine…coupled to a vigorous accelerator R&D programme…in collaboration with national institutes, laboratories and universities worldwide*"**. Since its inception, the international **FCC** collaboration has therefore **delivered a hadron collider conceptual design (FCC-hh) that best complies with this guideline** and that offers the broadest discovery potential. Together with a heavy ion operation programme and with a lepton-hadron interaction point, it provides the amplest perspectives for research at the energy frontier. The visionary physics programme of about 25 years described in this section requires collision energies and luminosities that can only be delivered, within a reasonable amount of time, by a circular collider with four experimental interaction regions.

To be able to **definitely elucidate electroweak symmetry breaking**, to **confirm or reject the WIMP dark matter hypothesis** and to **directly observe new particles signalled indirectly by, e.g., the precision study of Higgs properties**, the energy reach of the particle collider must be significantly higher than that of the LHC, i.e. making a leap from ten TeV to the 100 TeV scale.

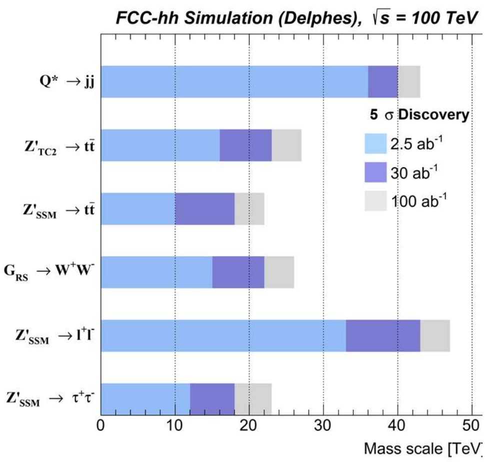

Figure 1: Discovery reach for heavy resonances.

Since cross sections for the production of a state of mass M scale like $1/M^2$, the integrated luminosity should be 50 times that of the LHC, at least 15 ab^{-1}, to be sensitive to seven times larger masses. The FCC-hh baseline design aiming at 20-30 ab^{-1} exceeds this target. It is sufficient to almost saturate the discovery reach at the highest masses. A further luminosity increase by a factor of 10 would only extend it by < 20%. Fig. 1 shows discovery reach examples for the production of several types of new particles including Z' gauge bosons carrying new weak forces and decaying to various SM particles, excited quarks Q*, and massive gravitons G_{RS} present in theories with extra dimensions. Other scenarios for new physics, such as supersymmetry and composite Higgs models, will likewise see a great increase of high-mass discovery reach. The top scalar partners will be discovered up to masses of close to 10 TeV, gluinos up to 20 TeV, and vector resonances in composite Higgs models up to masses close to 40 TeV.

Until new physics is found, two key issues, that will likely remain open after the HL-LHC, are at the top of the priority list of the FCC-hh physics objectives: **how does the Higgs couple to itself?** What was the nature of the **phase transition that accompanied electroweak symmetry breaking and the creation of the Higgs vacuum expectation value?** Today, neither the fundamental origin of the SM scalar field nor the origin of the mass and self-interaction parameters in the Higgs scalar potential are known. The next stage of exploration for any high-energy physics programme is to determine these microscopic origins. The puzzle of the Higgs potential can be resolved, if there is an additional new microscopic scale involving new particles and interactions near the electroweak scale. With more than 10^{10} Higgs bosons produced at the design luminosity, see Fig. 2, FCC-hh can complement an intensity frontier lepton collider by bringing the precision for several of the smallest Higgs couplings ($\gamma\gamma$, $Z\gamma$, $\mu\mu$), and for the coupling to the top below the percent level. The Higgs self-coupling can be measured with a precision of around 5%. Combined with the direct search potential for scalar partners of the Higgs boson, this will permit establishing the possible existence of conditions that allowed **the electroweak phase transition in the**

early universe to be of strong first order. This discovery would enable scenarios where the phase transition triggered the generation of the matter-antimatter asymmetry, or scenarios where detectable gravitational waves were generated by the collision of bubbles of the new vacuum during the Big Bang.

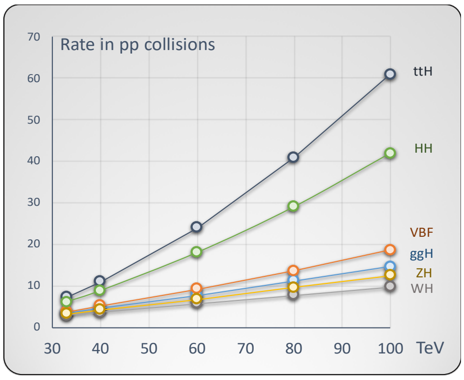

Figure 2: Higgs production cross sections versus collision energies normalized to the 14 TeV rates.

The Higgs particle could provide a portal to new sectors, otherwise completely decoupled from other SM particles. These interactions could lead to Higgs transitions to invisible or otherwise exotic final states. The FCC-hh will probe invisible Higgs decays down to branching ratios in the range of 10^{-4}, giving access to DM candidates with mass below 60 GeV. Flavour-changing-neutral-couplings of the Higgs boson, strongly suppressed in the SM, can be probed in the decays of the 10^{12} top quarks produced, with sensitivity down to branching ratios of order 10^{-5} in t→Hq (q=u,c).

The study of the Higgs and electroweak sector will also benefit from the FCC-hh's lever arm in energy. The production of Higgs bosons at large transverse momentum or of gauge boson and Drell-Yan dilepton pairs at high invariant mass, will test the existence of effective field theory couplings induced by new physics existing at scales well above the direct reach, in a way complementary to the sensitivity achieved by precision measurements. For example, the scattering of longitudinal gauge bosons at high mass, to be discovered at FCC-hh, will be measured with a precision of 3%, leading to a sensitivity to deviations in the coupling of the Higgs to W bosons at the percent level. Drell-Yan dileptons will be measured up to 15 TeV mass with a 10% statistical precision. This will constrain effective couplings induced by new interactions at mass scales up to the 100 TeV range.

WIMP dark matter scenarios will be thoroughly tested. The mass of higgsino and wino-like WIMP candidates is theoretically constrained to be 1 and 3 TeV, respectively. Dedicated searches, using also disappearing track signatures, **will conclusively detect, or exclude, these WIMP candidates** in the whole of the allowed region.

In the near future, flavour phenomena can reveal new physics beyond the LHC reach, as suggested by the current flavour anomalies in B decays. Interpretations of these anomalies point to mediators of these interactions (leptoquarks or Z' bosons) whose mass might be sufficiently large that only a hadron collider in the 100 TeV energy range can guarantee direct observation.

The FCC-hh collider can be extended to an **electron-hadron collider** with a centre of mass energy of 3.5 TeV, collecting up to 2 ab^{-1} of integrated luminosity in parallel to FCC-hh operation. Deep inelastic scattering is the cleanest probe to resolve the substructure and dynamics of hadronic matter. The FCC-eh will determine the partonic luminosities of gg, gq and qq initial states with a few per mille precision, throughout the large range of masses relevant to FCC-hh's precise measurements and searches of new physics. This precision will also improve the determination of the fine structure coupling constant α_s and, in the small-x region, will shed new light on dynamic issues such as gluon saturation. FCC-eh also covers a rich programme of Higgs and electroweak precision measurements, as well as searches for new physics. The Higgs boson will be studied through the well-known neutral and charged vector boson fusion channels, providing measurements of Higgs couplings complementary in precision, sensitivity and systematics to FCC-ee and FCC-hh. This will include precise measurements of the Higgs self-coupling, using Higgs pair production in vector boson fusion. FCC-eh has the best reach for a heavy sterile neutrino ν_S, which can be produced and detected up to TeV masses and over a broad range of mixings, through the clean process eq→ ν_Sq'. The FCC-eh option is based on the electron energy recovery linac under study for LHeC and the FCC-eh physics programme is a higher-energy version of the LHeC's.

The **operation with heavy-ion beams** at 39 TeV per nucleon-nucleon collision for PbPb and 63 TeV for pPb, with luminosities 10 to 30 times higher than in future LHC runs, allows unique new ways of addressing the fundamental questions about the nature of QCD matter. At the reachable temperatures, around 1 GeV, charm quarks start to contribute as active thermal degrees of freedom in the quark-gluon plasma (QGP) equation of state and this novel role in the QCD equilibrium process can be investigated. The time evolution of the QGP formation and equilibration, in a window around 10^{-24} s, can be monitored by measuring the medium interactions of the hadronic debris of boosted top quarks, as they emerge from the subsequent decays t→Wb and W→qq. The high density of gluons in the QGP is also expected to influence the propagation and decay of the Higgs boson. A first observation of ϒ formation from $b\bar{b}$ recombination is expected. More in general, all studies currently performed at the LHC will greatly benefit from the FCC-hh statistics, from the extended kinematic reach for hard probes, and from the prospects of colliding additional nuclear species, such as Ar, Kr and Xe.

2.2 Strategic Objectives

The ESPP 2013 stated *"To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update"*. The **FCC study has implemented the ESPP recommendation** by **developing a long-term vision for an *"accelerator project in a global context"***. This document **proposes the detailed design and preparation of a construction project** for a post-LHC circular energy frontier hadron collider *"**in collaboration with national institutes, laboratories and universities worldwide**"*, and enhanced by a **strong participation of industrial partners**. The **coordinated preparation effort** can be based on a core of already more than 130 collaborating institutes worldwide.

The window of opportunity for a post-LHC collider-based research infrastructure is narrow: on one hand, the HL-LHC project provides a limited period to attract new scientists until the mid twenty-thirties. These HL-LHC researchers may also dedicate part of their time to the development of the next machine and its experiments. On the other hand, the ever-faster pace of development of a large-scale particle-collider in Asia, which could already materialise during the next five years, introduces a serious risk of diverting resources and expertise built up in Europe. Hence, no time should be lost to profit from the current momentum, driven by a well-founded interest in building an infrastructure capable of addressing the burning open questions of particle physics in a sustainable and evolutionary way.

By spearheading the worldwide research in particle and high-energy physics, CERN offers a special opportunity. Through the active participation of both member and non-member states, CERN can establish a sustainable organisation and funding for a project, the scope of which extends far beyond national research centres, single nations, or even consortia of a few organisations. An endeavour like the Future Circular Collider can only be undertaken as a cooperative effort, stretching across nations and beyond the European Research Area (ERA), including all regions of the world, especially North America and Asia. It should also engage regions without a historically strong record of particle-accelerator based research (e.g. Africa, Middle and South America, Middle East and Oceania). Leveraging its existing tangible assets, notably CERN's HL-LHC, its pre-accelerators and technical infrastructures that can effectively serve as an injector for a new, highest-energy hadron collider, CERN's particle accelerator and technical infrastructure, in combination with its established efficient organisational and administrative structures, is the key to the successful realisation of a large-scale research infrastructure project that can federate the resources of individual contributors for the benefit of all. The Future Circular Collider study, launched in 2014, has so far attracted more than 130 universities and institutes from around the globe. In addition, the FCC has spawned several important R&D activities with dedicated funding from national agencies (e.g. US DOE high-field magnet programme and the Swiss CHART R&D programme) and from the European Commission (e.g. EC H2020 projects EuroCirCol and EASITrain; further FCC developments are included in other EC projects such as ARIES and RI-Paths). These substantial achievements demonstrate that developing a common vision for the worldwide research community is of utmost importance for the field.

2.3 Socio-economic Impact

A large-scale, international fundamental research infrastructure, tightly involving industrial partners and providing training at all education levels, **will be a strong motor of economic and societal development in the CERN member states and beyond**. Indeed, **its positive impact**, beyond the increase of scientific knowledge, is **quantitatively measurable**. The **cost benefit analysis of the LHC/HL-LHC programmes shows that construction and operation of a particle collider will pay back handsomely, through the numerous socio-economic benefits** they generate; the collider infrastructure **can even generate additional returns**, **in the billions of euro range**. Therefore, the main question is not how much the construction of a new particle collider and its experiments will cost, but rather **how the socio-economic impact can be optimised ab initio** and how long-term sustainability can be ensured.

A quantitative cost/benefit assessment of the LHC/HL-LHC programme was carried out to provide a foundation for planning the socio-economic impact of a new particle-collider facility. This assessment revealed that, even for combined capital and operation cost in excess of 20 billion CHF, a surplus of more than 5 billion CHF in socio-economic benefits could be created at the level of today's activities. In other words, the research infrastructure is not only paid for by its socio-economic value, but it even generates additional value for the society. Improving the quality of training, increasing the coordination of ICT technology developments for maximum impact, strengthening the cooperation with industry, and streamlining the creation of cultural products can increase the benefits further. **A credible forecast of socio-economic surplus amounts to 20% of combined capital and operational cost from the start of construction to the end of operation.** The single largest contributor is the creation of a lifetime salary premium on top of a regular academic degree ranging from 5% to 13% for early stage researchers who participated in the programme. **For LHC/HL-LHC, the earnings effects for industrial suppliers and the value of openly accessible standards, software and tools exceeds 10 billion CHF today.** However, this path remains largely underexplored due to there being too many ad-hoc developments with limited societal penetration. Industrial partners will profit the most from a research infrastructure project if co-developments and services are being carried out in the high-tech domain. This includes the engagement of small and medium-size companies for all types of developments and operational tasks. Today's utility/sales ratio[1] of about 3 can be increased further. The benefits for industry are directly proportional to the investment volume, the level of involvement (co-development vs. commercial-off-the-shelf) and to the period of time during which an industry is involved. For a new infrastructure with substantial investments in the civil-engineering domain, care must be taken to ensure that a sufficient level of high-tech will be included. Novel excavation techniques and the reuse of excavation materials are two pertinent examples. With the pervasiveness of media-rich web and social-media contents, the value of cultural goods has increased. Cultural impact correlates directly with the quality and reach of the products. Streamlining of contents distributed by media partners and a focus on actively engaging the public will enable the generation of annual benefits in the range of hundreds of millions of euros.

3 Methodology

An efficient **method to extend our current understanding of nature** consists of **significantly extending the direct discovery reach**. This approach to explore the unknown requires an energy reach beyond the ten TeV, up to the 100 TeV scale. It can potentially be combined with an ultra-sensitive precision instrument such as a luminosity-frontier lepton collider, which could be constructed in the tunnel first. **The only mature method to reach the 100 TeV scale within the century is a circular hadron collider based on significantly improved or novel superconducting technology**. The entire particle and high-energy physics community is called upon to combine their efforts in order to define a **rigorous and well-defined research programme at a highest-energy, circular hadron collider**. Such a collider is **technically feasible** and **it can be built within an acceptable time frame**, so that **project risks can be controlled.** The experimental research at the FCC-hh will be **based on international collaborations** with **open access** to detector data and on a **community-based scientific analysis** supported by a worldwide data processing infrastructure, as has been best practice in high-energy physics for almost two decades. This **programme is complementary to other on-going research activities** (e.g. long-baseline neutrino experiments in the US and Japan) and leverages cross-disciplinary synergies to expand our understanding of the universe (e.g. dark matter searches complementing astro-particle physics research projects). The FCC-hh also provides the basis for a lepton-hadron collider, the FCC-eh, which would be the cleanest, high-resolution microscope one can build to resolve the substructure of matter.

The FCC-hh addresses the open questions of the Standard Model with the most effective and versatile direct observation tool conceivable today: a large high-energy circular collider with multiple interaction points. The FCC-hh can host several experiment detectors designed, built and operated by international research collaborations. A global data processing infrastructure will facilitate the necessary powerful data analysis, naturally extending today's mode of operation in high-energy and particle physics. Collaboration members will benefit from unrestricted open access. The LHC experience demonstrates the need for long-term data maintenance. For the FCC-hh, the data conservation will be ensured by a consortium of national partners, which recognize a common long-term research interest. Such a consortium emerges naturally from the HL-LHC project.

Transparency is key when it comes to designing and building a large-scale research project based on a collaborative approach. The FCC-hh project profits from the lessons learnt at the LHC. International collaborations will generate technical detector designs linked to common services provided by CERN. For the collider, joint developments with universities, research institutes and industry will be reinforced to render the construction process sustainable and to maximise the economic impacts on industry and society. More than 50 years of successful accelerator and experiment projects coordinated by CERN are proof of CERN's capacity to design and build the proposed FCC-hh machine. The implementation section below sheds more light on the contemplated governing model and organisation structures, which should help ensure transparency and credibility from the early design onwards.

[1] The secondary economic "utility" is the sum of increased turnover and cost savings generated by a company as a result of orders placed. The utility/sales ratio expresses the benefit (the "utility") that the company perceives resulting from the "sales" to CERN.

The FCC-hh collider and its physics programme are complementary to other on-going or planned programmes in particle physics, high-energy physics and astrophysics. In addition to proton-proton collisions, it will include a comprehensive ion-beam based physics programme and offer the possibility for complementary research at a lepton-hadron interaction point. The FCC-hh infrastructure will permit concurrent operation of proton and ion fixed-target beams at CERN, thereby ensuring the continuation of a diverse and vibrant elementary particle physics research programme beyond colliders.

The in-depth exploration of the Higgs boson, the start of the exploration of the quantum structure of the Higgs potential, the elucidation of the electroweak phase transition and the significant progress in the understanding of Dark Matter, the elucidation of the origin of the matter/antimatter asymmetry that are all likely to emerge from these investigations will lead to a new understanding of nature.

The FCC-hh project is not only complementary to the neutrino research programme mentioned in the last ESPP, but it will also create new synergies between the various communities, e.g. through the predication of gravitational waves that can be observed with future, dedicated gravitational wave telescopes.

Already today the FCC design study involves the EC, the US DOE and several national research agencies in Europe, which are co-funding research and innovation aimed at developing the key technologies for the proposed future research infrastructures. This successful multi-pronged approach, by now well established and with functioning administrative support, will be continued during the technical design and preparatory phases. Concrete examples are the submission of design studies in the frame of H2020 and Horizon Europe, a successfully targeted Swiss technology programme (CHART), the U.S. and Russian high-field superconducting magnet development programmes and converging world-wide technology R&D initiatives on superconductors in Germany, Finland, Japan, South Korea and the U.S.

4 Readiness

The **technology** for constructing a high-energy circular hadron collider **can be brought to the technology readiness level required for constructing within the coming ten years through a focused R&D programme**. The FCC-hh **baseline** concept comprises a power-saving, low-temperature superconducting magnet system based on an evolution of the **Nb_3Sn** technology pioneered at the HL-LHC, an energy-efficient cryogenic refrigeration infrastructure based on a neon-helium (**nelium**) light gas mixture, a high-reliability and low loss cryogen distribution infrastructure based on **Invar**, highly segmented kicker, **superconducting septa** and transfer lines and **local magnet energy recovery and reuse** technologies that are already being gradually introduced at other CERN accelerators. **On a longer time scale, high-temperature superconductor R&D** together with industrial partners has the potential to achieve an **even more energy efficient particle collider or to reach even higher collision energies**.

The **re-use of the LHC and its injector chain**, which also serve for a concurrently running physics programme, is an essential component of a sustainable research infrastructure at the energy frontier.

Strategic R&D for FCC-hh aims at minimising construction cost and energy consumption, while maximising the socio-economic impact. For example, the FCC-hh R&D will mitigate technology-related risks and ensure that industry can benefit from an acceptable sales/utility ratio. Concerning the implementation, **a preparatory phase of about eight years is both necessary and adequate** to establish the project governing and organisational structures, to build the international machine and experiment consortia, to develop a territorial implantation plan in agreement with the host states' requirements, to optimise the disposal of land and underground volumes, and to prepare the civil engineering project.

4.1 Technical Feasibility

FCC-hh **requires high-quality accelerator dipole magnets with a 16 T field**. A focused **R&D programme** to bring the Nb_3Sn conductor to the required 1500 A/mm² current density at 4.2 K temperature **has been running since 2014** (currently 1200 A/mm² has been achieved). A US DOE Magnet Development Programme is working to demonstrate a 15 T superconducting accelerator magnet. Collaboration agreements are in place with the French CEA, the Italian INFN, the Spanish CIEMAT, the Swiss PSI and the Russian BINP organisations, to build short model magnets based on the designs that have been developed in the EuroCirCol H2020 EC funded project.

If the FCC-hh is implemented as a second step, following construction and operation of an intensity-frontier lepton collider (FCC-ee) in the same underground infrastructure, the time scale for design and R&D for FCC-hh is lengthened by 15 to 20 years. This additional time will be used to develop alternative technologies, e.g. magnets based on high temperature superconductors, with potentially important impact on the collider parameters (e.g. increase of beam energy), relaxed infrastructure requirements (cryogenics system) and increased energy efficiency (temperature of magnets and beamscreen).

The **high luminosity is achieved** with high brightness beams, a high beam current comparable to LHC parameters, and a small β* at the collision points. A crossing angle of about 200 μrad limits the impact of parasitic beam-beam crossings and the associated luminosity reduction is compensated by using crab cavities. Electron lenses and current carrying wire compensators may further improve the performance of the machine.

Today **helium cryogenic refrigeration** suffers from technological limitations, which translate into specific cycle efficiencies of about 30% with respect to an ideal Carnot cycle and consequently large electrical consumption. Improved cryogenic refrigeration is, therefore, considered key to operate a 100 km long superconducting particle accelerator. The system must continuously compensate heat loads of 1.4 W/m at a temperature below 2 K and 30 W/m/aperture due to synchrotron radiation at a temperature of 50 K, as well as absorb the transient loads from ramping of the magnets. The FCC study includes an R&D activity to raise the technological readiness level of novel, neon-helium (nelium) gas-mixture-based refrigeration down to 40 K, leading to a cycle with a specific efficiency higher than 40%. Overall, this technology is expected to lead to a reduction by 20% of the electrical energy consumption of the cryogenic system. When using high-temperature superconductors, the effect might be even more pronounced, since additional low-temperature steps become dispensable.

Many technical systems and operating concepts of FCC-hh can be scaled up from HL-LHC or can be based on technology demonstrations carried out in the frame of ongoing R&D projects. A **robust collimation and beam extraction system** to protect the machine from the energy stored in the beam (factor 20 above the LHC) can be constructed with technologies available today. The momentum collimation system is located in a 1.4 km insertion, taking advantage of the dispersion from the arcs to remove energy tails. In the 2.8 km long insertion for the betatron collimation system, the dispersion is suppressed to remove transverse tails more easily. Both systems are scaled up from the LHC, using a multi stage collimation approach to mitigate all beam induced risks. The **extraction system** is based on a segmented, dual-plane dilution kicker system that distributes all bunches of the beam onto a multi-branch spiral on a 20 m long absorber block with a radius of 55 cm. Novel superconducting septa capable of deflecting the rigid beams are currently being developed. The system features fault tolerance at design level, with limited effects from erratic firing of a single kicker element and other failure modes. Investigations of suitable absorber materials including 3D carbon composites and carbon foams are ongoing in the HL-LHC project.

The cryogenic beam vacuum system is a key element of the hadron collider. It protects the magnets from the synchrotron radiation of the high energy beam, which is 200 times more powerful than in LHC, and efficiently removes the heat; its size is an important feature which determines the magnet aperture and consequently cost. In addition, it suppresses beam instabilities due to parasitic beam-surface interactions as well as electron cloud effects. The LHC vacuum system design is not viable for FCC-hh, hence a novel design has been developed in the scope of the EuroCirCol H2020 funded project. It features an ante-chamber and is copper coated to limit the parasitic interaction with the beam. The shape also reduces seeding of the electron cloud by backscattered photons and additional carbon coating or laser treatment prevents the build-up. This novel system is operated at 50 K and a prototype is being validated experimentally in the KARA synchrotron radiation facility at KIT (Germany).

The RF system is the heart of any particle accelerator. For FCC-hh it will operate at a frequency of 400.8 MHz, similar to the LHC, but with 48 MV per beam it will deliver three times more voltage than the LHC. To balance the synchrotron radiation, relevant for 50 TeV beam energy, controlled longitudinal emittance blow-up by band-limited RF phase noise will be implemented. In its present form, the CW RF system is made up of 24 single-cell cavities per beam, operating at 2 MV. In order to improve the energy efficiency, superconducting Nb or A15 thin-film coated Cu cavities together with high-efficiency klystrons are being developed, in synergy with linear and circular lepton-collider studies. There are no concerns about the technical feasibility of the FCC-hh RF system.

For the injector, the choice of re-using CERN's Linac 4, PS, PSB, SPS and the LHC at 3.3 TeV as pre-accelerators and connecting the latter to FCC with transfer lines using 7 T superconducting magnets is the most straightforward approach and also permits the continuation of CERN's rich and diverse fixed-target physics programme in parallel with FCC-hh operation. The necessary modifications for the LHC have been studied and are considered feasible. In particular, the ramp speed can be increased as needed. Reliability and availability studies have confirmed that the operation and cycles can be optimised such that the FCC-hh collider will have an adequate availability for luminosity production. However, the power consumption of the aging cryogenic system is a concern. The required 80% to 90% availability of the entire injector chain - that would lead to an overall availability of 70% for luminosity production - could best be achieved with a new high energy booster. On a longer time scale, direct injection from a new superconducting synchrotron at 1.3 TeV that would replace the current 6.7 km long SPS could be considered. In this case, simpler normal conducting transfer lines with magnets operating at 1.8 T are sufficient.

To best serve the research community, the **FCC-hh experiment collaborations** will develop designs for complementary detectors. The baseline scenario has four interaction points. An early design concept for the detector has been developed as a collaborative effort, based on the experience from LHC experiment operation. This concept will form the foundation for detailed complementary experiment detectors that can be based on a set of common infrastructure systems and services, thus avoiding overlaps and duplication of development and leveraging common technology research wherever possible. This approach will help to tailor the technical experiment designs to the particle collider in an optimum way, such that the machine can be fully exploited and all the goals of a detailed physics programme can be achieved. Common topics of interest span all domains of particle detection technologies, detector magnets, mechanical supports, computing and communication technologies, as well as all the entire trigger / data acquisition and on-line/off-line processing path. In particular, the synergetic activities on a common simulation and analysis software ecosystem, for future colliders, which has been in place for five years, will be continued as a highly synergetic activity between collider studies and lepton/hadron physics communities.

4.2 Sustainable and Energy-Efficient Operation

From the beginning, the FCC-hh collider has been conceived with an emphasis on sustainability and energy efficiency. A storage ring maximises the energy efficiency for stepwise acceleration with the same RF system and for use of the accelerated beam through recirculation and by colliding the same beam many times. Combined with a high beam current, small emittance and low collision-point beta function, this beam recirculation results in an unbeatable figure-of-merit for luminosity per electrical input power. The most power-hungry element is the cryogenic refrigeration system needed to cool the 16 T superconducting magnets down to 1.9 K. With respect to an LHC-class system, which would for an FCC-hh collider consume 290 MW of electrical power, the nelium technology and temperature choices lead to a reduction by 50 MW or 17% in the baseline configuration. Ramping up the field of the magnets more slowly and with constant power substantially reduces the power demand, for all main dipoles from 270 MW for a constant-voltage ramp of 20 minutes to 100 MW for a constant-power ramp of 30 minutes. The external peak power demand during the ramp phase can be reduced further by recovering the energy stored in the superconducting magnets at the end of a cycle (50 MWh for the main dipoles), to buffer it locally, and to reuse it during the subsequent ramp-up. Losses in electricity transmission will be reduced by cooperating with industry to bring medium voltage DC distribution systems to market grade so that they can power the accelerator subsystems. The RF system efficiency will be optimised by increasing the electric to radiofrequency power conversion efficiency from 65% to above 80% in the scope of a klystron R&D programme that is being carried out in close cooperation with the linear collider and circular lepton collider communities. Superconducting thin-film coating technology will allow RF cavities to be operated at higher temperature, thereby lowering the electricity need for cryogenics, or by reducing the required number of cavities by having an increased acceleration gradient. Higher-temperature high-gradient Nb/Cu accelerating cavities and highly-efficient RF power sources developed in the frame of the FCC-ee R&D programme will find numerous other applications; they could greatly improve the sustainability and performance for accelerators of nearly all types and sizes around the world. These combined efforts lead to a yearly energy consumption forecast of 4 TWh, compared to 1.4 TWh expected for the HL-LHC.

The resource-saving strategy includes studies to avoid water cooling wherever possible and developing schemes to supply waste heat to nearby consumers. A pilot programme has recently been launched on French territory in the frame of the LHC programme. This programme is successfully integrated into a new, ecological residential and commercial district, built in the vicinity of one of the LHC access points. The detailed technical design of the FCC-hh will also investigate energy recovery opportunities within the accelerator infrastructure, for example, by working with industrial partners on either storing heat for later use or its conversion into mechanical or electrical energy.

4.3 Implementation Model

Assuming 2043 for the debut of the FCC-hh physics programme after two years of beam commissioning, and a start of civil engineering construction in 2028, the eight-year period for project preparation and administrative processes is required and adequate. Work with the host state authorities has already begun to develop a workable schedule. Activities will now aim at achieving a community consensus to support the project and the commitment of regions and funding agencies to contribute. The project scenario needs to be validated and a project legal framework needs to be agreed by the host states. Different stakeholders must be engaged in the design phase, for the assessment of environmental and socio-urbanistic impacts.

The first step of the implementation model is to establish governing and management structures for a lean and effective organisation, which is needed to advance at a good pace. The design period includes a detailed cost analysis and the development of a sustainable funding strategy. It will establish the necessary legal framework to manage the commitment of contributions from member and non-member states and to create a suitable procurement and in-kind supply framework based on competitive performance of suppliers leading to control of the overall total-cost-of-ownership. It will create the framework to employ human resources under conditions corresponding to the needs of sustainable project preparation and construction. This phase concludes with the set-up of an appropriate auditing scheme, ensuring transparency to all stakeholders.

The construction of a new tunnel with about twelve surface sites is the first, and administratively most challenging, part, due to the rapid urban evolution in the "Grand Genève" region, on both the Swiss and French sides. Therefore, **a swift start of the detailed design** of the **infrastructure is of utmost importance for the reservation of the locations, negotiating the land-plot and underground-volume rights-of-way,** and **reducing cost-uncertainties for the tendering procedures**. This activity comprises geological investigations, environmental impact screenings, geological surveys, work with authorities and representatives of the public to optimise the placement to minimise necessary compensation measures, and the development of concrete synergies.

At the same time, focused R&D will be carried out to demonstrate the key enabling technologies. This programme will be coordinated by CERN and will be led by institutes from around the world with a focus on topical complementarity and geographical balancing. This includes the development of novel detector technologies and a significant improvement of existing concepts such that the high-precision data provided by the machine can be recorded and exploited in an optimised way. The developments will be continually monitored during the advancement of the detailed technical design, so that, by the beginning of construction, cost-optimised technologies with the required performance level will be industrially available.

The **accelerator construction will proceed concurrently with the civil engineering.** Installation of the machine can start when a first section of the underground infrastructure is ready.

Detailed detector designs by established experiment collaborations will start as soon as the required expert researchers and engineers become available at the end of the HL-LHC design activities. **The evolution of the off-line and on-line computing services along with the world-wide data processing infrastructure** will be orchestrated to create unified computing services serving the entire community. **Common software developments and code sharing** will **increase the overall efficiency**, avoiding parallel or even redundant developments. Construction of the experiments can begin when the accelerator design is finalized. **Detector installation** can begin **as soon as experiment sites become available.** Experience with LEP, LHC and the B-factories suggests that **a two-year commissioning period for the machine, including injectors, and experiments** will be adequate.

5 Challenges

This project entails **a limited set of uncertainties** that could adversely impact its implementation. They **can all be addressed through a well-focused R&D** programme **and with an early start of the project preparatory phase**. Collaboration with and commitments by the host states are of prime importance for the development of the administrative and procedural frameworks and to prepare the project. The greatest technical challenge relates to the availability of large amounts of superconducting wire at the required performance and cost. A remaining challenge is the creation of a worldwide consortium of scientific contributors who reliably commit resources for the development and preparation of the FCC-hh science project from 2020 onwards.

Uncertainty	**Impacts**	**Mitigation**
Technical challenges		
Superconducting Nb_3Sn wire performance not attainable in time.	Target field level and quality of dipole magnets not achievable. Reduced collider performance and target field amplitude.	Increase the intensity of the low temperature superconducting wire R&D programme. On a longer time scale, reinforce an R&D programme including high temperature superconductors aiming at a performance/cost optimised energy frontier collider.
Nb_3Sn wire cost target not attainable in time.	Project not affordable or collider performance goals need to be adjusted.	Invest in building up a co-development with industries worldwide to avoid a vendor-locked-in situation and to prevent price limita-

		tion. Re On a longer time scale, reinforce an R&D programme including high temperature superconductors aiming at a performance/cost optimised energy frontier collider.
Inefficient magnet series manufacturing, limited availability of companies with the necessary capacities and quality management.	Project not affordable. Reduced performance and reliability. Unsustainable operation due to downtimes and excessive repair/maintenance.	Invest in R&D of easy to manufacture, test and install magnet designs. Optimise system interfaces. Launch studies to improve assembly efficiency and speed. Reduce production steps. Invest in automation of production, assembly, testing and integration allowing for a geographically distributed production process.
Cryogenic refrigeration system unsustainable.	Lower collider performance due to lower energy and intensity and longer cycles.	Bring nelium-based technology to a higher technological readiness level. Develop higher-temperature thin-film coated superconducting RF cavities. On a longer time scale, consider a high temperature superconductor based machine.
Electrical peak power requirement too high.	Electrical equipment and operation too expensive.	Make cryogenic refrigeration more efficient, implement energy recovery/buffering/reuse, use DC based electricity distribution and reduce losses. On a longer time scale, consider a high temperature superconductor based machine.
Particle detection technologies do not meet the performance, reliability and cost needs.	Under use of the collider's potential can lead to the physics programme goals not being met. Loss of interest of the worldwide community may be the consequence.	Launch of a worldwide coordinated strategic R&D initiative focusing on detector technologies and software ecosystems that meet the need of the preferred particle collider scenario and which engages the entire community in the definition of the physics programme and in the detailed design of the associated particle physics detector projects.
Implementation challenges		
Funding of construction project and sustained operation throughout the entire physics programme.	Insecure funding will delay or prohibit construction. Insufficient operation funding will lead to below optimum exploitation of the facility.	Early negotiations with member states to set up a funding strategy for the preparatory phase. Adjustment of collider performance parameters. The timely production of a cost/benefit assessment will catalyse negotiations with additional stakeholders (host states and the EU bodies for regional developments).
Governing and project organisation including effective administration services.	Insufficient support and control of a project management and insufficient resources for an organisation to execute a decade-spanning, international high-tech project can lead to runaway costs, significant delays, loss of scope and loss of community support.	Create a high-level international support group. Establish a dedicated organisational unit, adequately staffed with experienced personnel. Establish the legal framework for preparing the contributions from member and non-member states. Create a suitable procurement and in-kind supply framework, based on competitive performance of suppliers, and with overall TCO control. Create human resource conditions which provide for the required sustainable project preparation and construction. Establish an effective, but lean auditing scheme, transparent to all stakeholders.
Acceptance of infrastructure development project plan through public processes in both host states.	Delays or unforeseen needs to substantially adjust the project scope can stretch the preparation and construction phases or result in a project re-scoping; such actions would lead to reduced community benefits from the new infrastructure.	Winning the host states support through timely involvement as partners is key. Work has already started and a schedule for the preparatory phase has been developed. Adequate project government, organisation and resources must be invested early-on in the work with the host states, even if a decision about the construction will only be taken at a later stage. Optimisation of resource usage (water, real estate) and limitation of urban impacts (traffic, noise, visual impacts) are tasks during this phase.
Timely availability of rights of way on land plots and underground volumes.	Delay of construction start, cost increase due to real estate speculations.	Early optimisation of layout and implantation as a cooperative effort of project owner and designated governing bodies, involving all stakeholders. Early inclusion of the project in territorial development plans. A first iteration has already been completed and a plan been established to continue this joint work with the host states.