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Future Circular Collider

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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

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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.

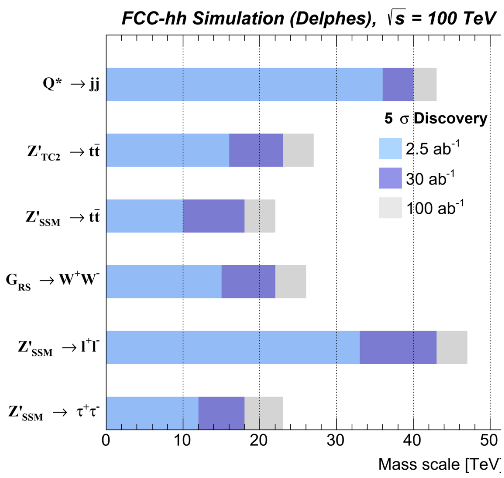

Figure 1: Discovery reach for heavy resonances.

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.

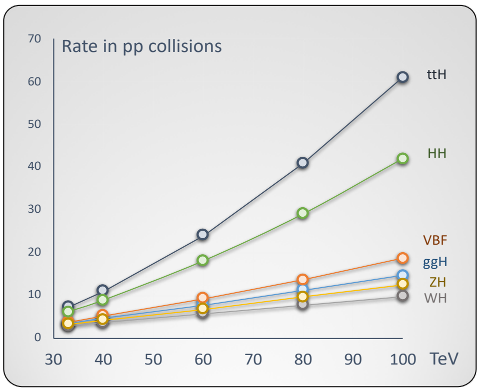

Figure 2: Higgs production cross sections versus collision energies normalized to the 14 TeV rates.

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 $t \to Hq$ (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 $eq \to \nu_S q'$. 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 $t \to Wb$ and $W \to qq$. 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.

6 Addendum

6.1 Community

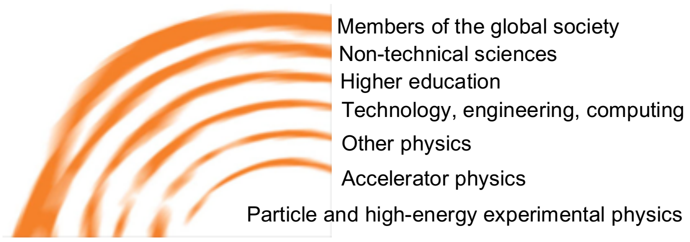

Figure 3: The "onion" model of involvement of and impact for different communities.

The impact on the community can be presented in terms of an "onion" type model, starting with the innermost layer comprising the **core scientific communities**, which need, conceive and use such a facility. Further communities in the European Research Area and beyond, which will benefit throughout the entire lifecycle, starting with the early design phase, include: **other sciences, engineering communities**, **higher education**, **industrial partners**, **researchers from non-technical domains**, and ultimately **all of members of society**.

Community	Impact potentials
Particle physics	The FCC-hh has broad physics discovery potential with **an opportunity to attract a worldwide community of more than 20,000 physicists** (see arXiv:1707.03711). It addresses the energy frontier, electroweak, Higgs, Dark Matter and heavy flavour physics communities as well as the heavy ion and lepton-hadron communities, presently working on the LHC, flavour factories, Dark Matter experiments and other particle collider experiments worldwide. The theory community is needed to develop scenarios that can be tested at this collider. Together with the experimental physics community they will define a comprehensive physics programme.
Experimental physics	The detectors for this machine will have to be highly versatile. Requirements include the measurement of multi-TeV jets, leptons and photons with masses up to 50 TeV. At the same time, detectors must be highly sensitive to known SM processes. Precision tracking and calorimetry are further fields of activity. The high occupancy and pile-up call for unprecedented time resolution and advances in data reduction. The need for high spatial resolution due to boosted objects needs ingenious approaches for particle identification techniques, precision tracking. Through the concurrent fixed target experiment programme and the heavy ion operation programme, additional experimental physics communities will be attracted by this research facility.
Accelerator physics	The FCC-hh with its unprecedented collision energy and luminosity will attract the world-wide community of accelerator physicists. Fully automated operation procedures ensuring the concurrent operation of CERN's injector complex and the future high-energy collider, integrating luminosity optimization, are topics that call for the integration of diverse domains of competence.
Other physics communities	The research at the FCC-hh will have implications for astrophysics and cosmology, offering an unprecedented opportunity to federate these scientific fields.
Technology, Engineering, Computing	The project will drive the development of superconductors for high-field magnet applications including large series production and precision machinery. The collider requires a novel approach to cryogenic refrigeration on a large-scale. The project also involves the development of systems for higher efficiency electrical to radio-frequency power conversion. The development of cost-effective, high-performance thin-film coated, superconducting cavities needs the material scientists and requires expertise from manufacturing experts. Specific engineering areas include precision mechanics, surface treatment, superconductivity, novel materials, electronic engineering and reliability engineering to improve the particle accelerator efficiency. Electrical engineering communities will be involved in bringing medium voltage DC technology to the market, to conceive lower-loss electricity distribution systems which are more reliable and develop environmentally friendly and sustainable energy recovery and buffering systems. Designers will be needed to develop waste-heat recovery and reuse systems.

	To design and construct the underground infrastructure in a cost-effective way, the civil engineering community needs to make advances in tunnelling technologies and to develop ways for the recovery and re-use of excavation materials. This work will be carried out as a joint endeavour with material scientists, geologists and chemists. Information and communication technology communities will be involved everywhere. Their activities include simulation algorithms and software infrastructure; parallel and high-performance computing; distributed computing; real-time and embedded systems; mechatronics to conceive new standards and technologies for low-maintenance and easy-to-repair systems in the areas of protection, access, remote handling and autonomous interventions; data acquisition, data visualisation, modelling and operation optimisation,; the introduction of artificial intelligence in machine and detector operation; radiation and fault tolerant systems; environmental information systems; data mining technologies; wireless communications including safety-related functions; data and document management facilities; worldwide computing infrastructures; long-term data stewardship; open access data models and infrastructures and much more.
Higher education	The design and construction of the accelerator and the detectors will offer many opportunities for science teachers and students at master, doctorate and post-doc levels. Eventually the findings from all the scientific activities will enrich the academic curricula: state-of-science today will become state-of-the art tomorrow. This project will enlarge the impact potentials of higher education to highly qualified personnel (HQP) and apprentices.
Industry	A project of such scale must be designed, constructed, operated and maintained with strong involvement of industrial partners from all of the participating nations. Where reasonably possible, a shift towards co-development will lead to a research infrastructure which is sustainable in the long-term on one hand and which has greater impact for industry on the other hand. A specific initiative during the detailed design phase will focus on identifying the fields of cooperation, also elucidating where companies can best profit from enhanced learning to increase their competitiveness and improve the quality of their product and internal processes. One particular area of interest is to develop ways to increase the technology level in the field of civil engineering: novel methods for on-line excavation material analysis and separation, pathways for reuse of the materials by other industries such as chemical and construction are important levers to increase the economic utility in this domain.
Non-technical sciences	This project will engage a variety of scientific communities, beyond physics, technology and engineering domains. Examples include, but are not limited to research in logistics and systems engineering around the world-wide production chain for the particle accelerator and detectors (logistics, operations, sales, HR, procurement, accounting, management and organisation, business administration). Architecture and arts will be involved in surface site development. Media and visual arts as well as museums and marketing experts are needed to efficiently engage the public and to communicate with institutional stakeholders. Radiation protection, technical risk management and waste management experts will facilitate the control of hazards and risks in all areas throughout the entire lifecycle. Environmental and urbanistic sciences will help avoiding, reducing and mitigating impacts. Economics, innovation management and political sciences form another group of non-technical sciences, which have already shown during the FCC study phase that they are essential for the successful preparation of a future project.
Members of the global society	The continued deep exploration of our universe tackles fundamental questions that intrigue everyone: What is the origin of the universe? What is the nature of the matter, that we are all made of? Where do we come from? Why is there something and not nothing? This project addresses these questions directly and creates opportunities to engage everyone interested. During the preparatory phase, an effort will be made to intensify such involvement through community science and a modern communications plan.

	The conceptual study phase has revealed that the greatest challenge is, however, to create interest among the majority of people who are unaware. FCC-hh is an opportunity to raise awareness on a global scale and to strengthen the support for continued investment in this research by policy makers, funding agencies and ultimately, by every member of society.

6.2 Timeline

6.2.1 Timeline for FCC-hh **without** prior implementation of FCC-ee

The overall duration for implementation of FCC-hh as a "stand-alone" project is 23 years, composed of two major parts: the preparation phase spanning 8 years and the construction phase spanning 15 years. The preparation phase includes apart from technology R&D:

- all administrative procedures with the host states, ultimately leading to the building permit and provision of the required surface and underground rights-of-way;
- consultation process with authorities and public stake holders;
- development of project financing, organisation and governing structures;
- site investigations, civil engineering design, and tendering for consultant and construction contracts.

The construction phase includes:

- all underground and surface structures;
- technical infrastructure;
- accelerators and detectors, including hardware and beam commissioning.

The implementation time line for FCC-hh without prior implementation of FCC-ee is shown in Fig. 4.

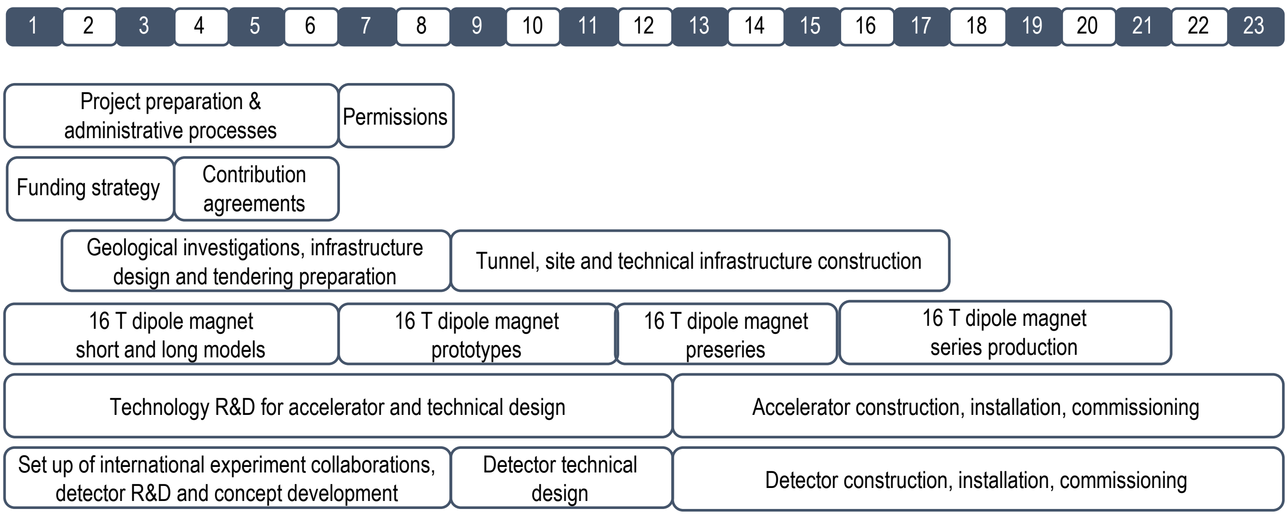

Figure 4: Overview of implementation timeline of FCC-hh starting in 2020 (without prior implementation of FCC-ee). Numbers in the top row indicate the year. Physics operation would start in the mid 2040ies.

The total construction time from ground breaking to start of physics operation is 15 years. The underground and surface civil engineering construction can be completed in less than 7 years. The first sectors would be ready for machine installation about 4.5 years after the start of construction.

6.2.2 Timeline for FCC-hh **with** prior implementation of FCC-ee

If the FCC-hh is constructed as a "combined project", i.e. following prior implementation of the FCC-ee lepton collider, the entire existing civil structures and technical infrastructures can be reused. In addition, the construction of two experiment caverns for the lower luminosity experiments, the two beam dump tunnels and the two hadron transfer lines from LHC will be needed. Technical infrastructure installation will be dominated by the construction of the cryogenics plants and distribution lines for the main magnet cooling. Accelerator construction, installation and commissioning will be similar to the FCC-hh "stand-alone" project.

The overall project duration for construction of FCC-hh in "combined" mode is around 10 years from the end of FCC-ee operation and is composed of three major parts: dismantling of FCC-ee, civil engineering construction and technical infrastructure adaptation, FCC-hh machine installation. This 10-year period is preceded by a preparatory phase covering construction and operation related agreements with host states, funding and in-kind agreements, technical designs and prototypes, similar to the one for the FCC-ee project. The implementation time line for FCC-hh after prior implementation of FCC-ee is shown in Fig. 5.

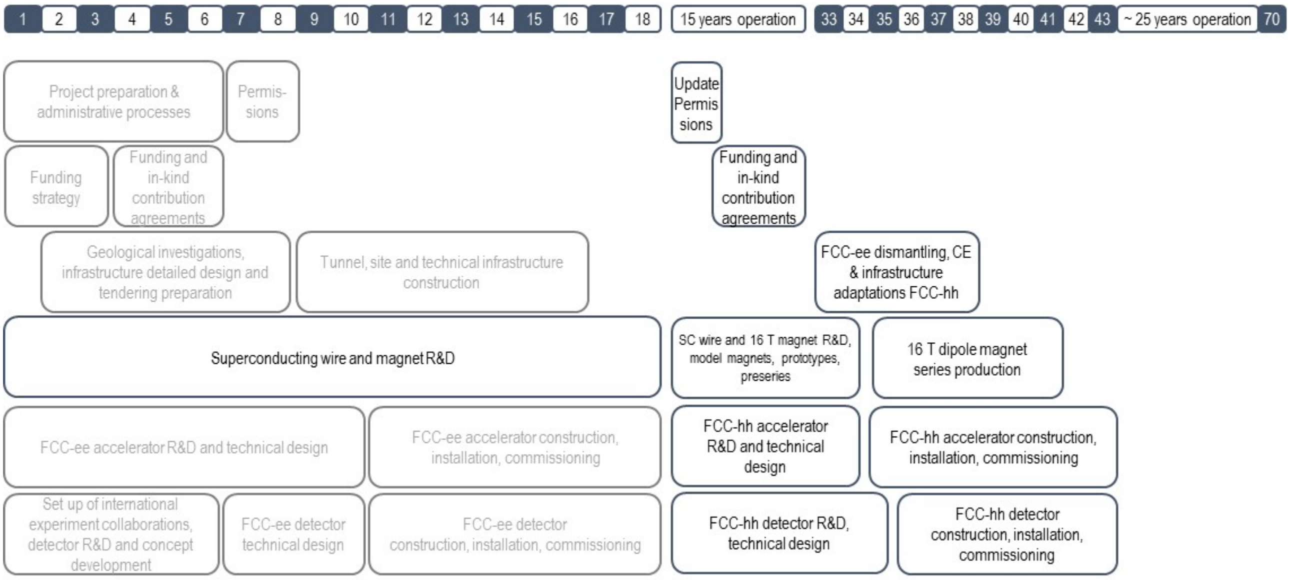

Figure 5: Overview of implementation timeline of FCC-hh after prior implementation of FCC-ee, starting from 2020. Numbers in the top row indicate the year. Physics operation of FCC-hh would start in the 2060ies.

6.3 Construction and operation costs

6.3.1 Capital cost for FCC-hh **without** prior implementation of FCC-ee

A cost study was performed based on the conceptual design of FCC-hh. The capital expenditure estimate for the construction as a "stand-alone" project, i.e. without prior implementation of the FCC-ee lepton collider, is summarised in Table 1. The precision of the overall cost estimate is at ±30% level.

Table 1: Summary of capital expenditure for implementation of FCC-hh project in stand-alone mode.

Domain	**Cost in MCHF**
Collider and injector complex	13,600
Technical infrastructure	4,400
Civil Engineering	6,000
TOTAL construction cost	**24,000**

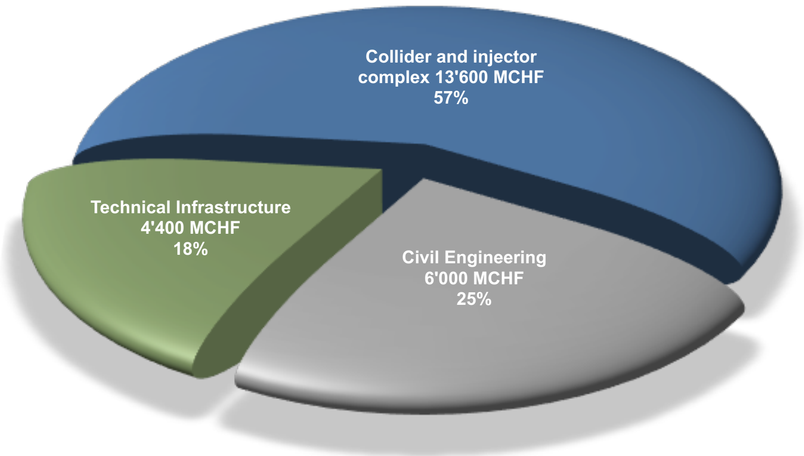

Figure 6: FCC-hh capital cost per project domain if FCC-hh is built as stand-alone project.

The **total construction cost amounts to 24,000 MCHF** as shown in Fig. 6, and is dominated by the by the accelerator and injector, amounting to 57% or 13,600 MCHF. The major part of the accelerator cost corresponds to the 4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,400 MCHF, at a cost target of 2 MCHF/magnet. The construction cost for surface and underground civil engineering is 6,000 MCHF or 25% of the total. The capital cost for the technical infrastructures is 4,400 MCHF corresponding to 18% of the total construction cost.

6.3.2 Capital cost for FCC-hh **with** prior implementation of FCC-ee

The capital cost for construction of the FCC-hh as a "combined project", i.e. following the prior implementation of the FCC-ee lepton collider with its civil engineering and technical infrastructures, is summarised in Table 2.

The **total construction cost amounts to 17,000 MCHF**.

In this case the capital cost is reduced by 7,000 MCHF compared to the stand-alone variant, since the civil engineering and technical infrastructures from FCC-ee can be fully re-used (see also Fig. 7).

The main additional civil engineering structures required for FCC-hh are two experiment caverns with four shafts for the lower luminosity experiments, the beam dump tunnels and the two transfer lines from LHC including one access shaft and injection cavern each, with a total construction cost of 600 MCHF. For technical infrastructures, all electrical, cooling and ventilation installations are reused. The cryogenics infrastructure for the main magnet cooling therefore drives the capital cost that amounts to a total of 2,800 MCHF, including any adaption of the other technical infrastructure systems. The accelerator construction cost is quasi unchanged, apart from a small saving from reuse of the RF system.

It should be noted that this scenario of constructing FCC-hh after FCC-ee operation opens the opportunity for a much longer R&D time period (+ 15 to 20 years) for the design of FCC-hh key technologies. Consequently, alternative technologies can be considered, e.g. high temperature super-conducting magnets, that in case of a successful R&D phase could lead to improved parameters (e.g. increase of collision energy) and reduced infrastructure requirements (cryogenics) and/or higher energy efficiency.

Table 2: Summary of capital cost for implementation of FCC-hh as a combined project after implementation of FCC-ee.

Domain	**Cost in MCHF**
Collider and injector complex	13,600
Technical infrastructure	2,800
Civil Engineering	600
TOTAL construction cost	**17,000**

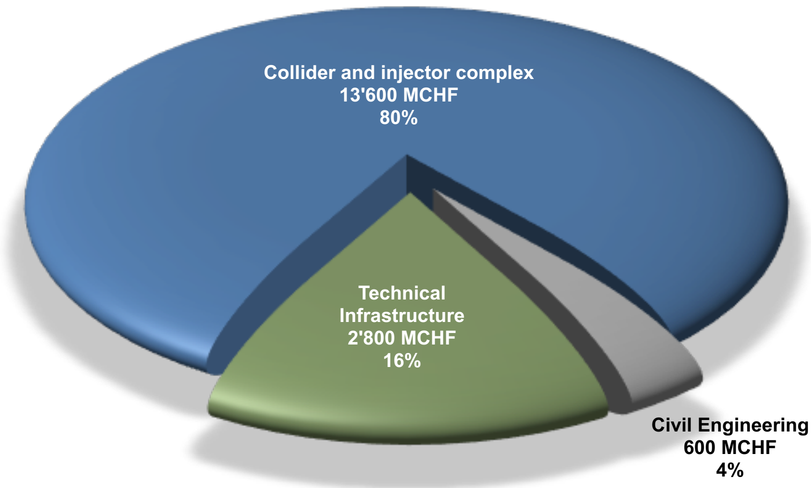

Figure 7: FCC-hh capital cost per project domain as a combined project, if FCC-hh is built after FCC-ee.

6.3.3 Operation Cost

Operating costs are a major factor for any research facility and design efforts need to be made from the early concept stage to enable sustainable operation. History of large-scale technical infrastructures reveals a trend of steadily decreasing normalised operating costs: While at the peak of LEP operation CERN had 3,300 staff members, in the LHC era the laboratory's staff complement has shrunk to 2,300 employees, even though the LHC together with its injectors is a much more complex machine. This decreasing number of personnel is a manifestation of progress in technology, operation and maintenance concepts.

This optimisation trend is expected to continue for the FCC-hh. Looking for example at the basic design unit of the collider, namely the arc FODO cell, reveals that the number of cells is only 1.8 times the one of the LHC, although the FCC-hh is nearly four times larger. Consequently, the multiplicity of many components does not scale with the size of the machine and the associated operation and maintenance costs will not do so either. An increase in the absolute number of components goes along with a growth in the maintenance, repair and restore effort required. However, this fact does not necessarily imply higher complexity, i.e. the emergence of dynamic system behaviour that leads to significantly higher operation and mitigation costs. The training and experience requirements for maintenance personnel are further optimised by the use of industry-based, standardised, modular designs for accelerator components. Still, a detailed technical design phase will focus on ensuring that the operation of such a machine is sustainable in the long term.

Sustainable maintenance: The machine design will place **an emphasis on conceiving the individual systems and subsystems such that they can be monitored, maintained and repaired by service suppliers as much as reasonably possible**. Experience with this approach for particle accelerators and imaging devices for healthcare applications has been gained over more than 15 years. Examples include the remote maintenance of power converters and the servicing of superconducting devices including cryogenic refrigeration infrastructures. The effects of this approach are 1) the possibility to re-negotiate operation and maintenance along the operation phase and, thus, to profit from an ever improving understanding of the infrastructure's operational behaviour, 2) the possibility to engage financial resources only when needed and with the possibility to reduce them when no longer needed at the end of the machine operation, 3) the creation of "local economic benefits" in the contributing nations and regions due to the financial revenues over sustained time periods for different companies and a long-term education effect for highly qualified personnel.

Modular design: Investing early-on in modular designs of basic components and equipment to be installed will enable streamlined operation, service and repair. The successfully demonstrated concept of a vertically integrated "column" that will be replicated many times is the underlying principle of this approach, leading to a scalable system. Thorough analysis with potential industrial partners and the consequent application of best practices will be one of the requirements in the preparatory work plan. One key topic in this approach is the reduction of, and facility-wide agreement on, standard interfaces at all levels (e.g. mechanical, electrical, fluids and their parameters, communication and software). A dedicated activity for interface management is the key to cost-effective production and testing, installation and long-term sustainable operation.

In-kind, collaborative operation: The LHC experiments have already indicated the way by which long-term operability of an experiment can be achieved through a committed involvement of the international collaborating institutes. Intensifying and extending this concept to the entire particle accelerator and experiment infrastructure is an essential lever to fully engage the entire community in this project. Particle accelerator experts and equipment specialists exist in numerous academic institutes around the globe. Operating a world-class particle-collider creates a unique learning experience for scientists and engineers at all levels and age categories. It is also one essential way to reduce the operating budget through the assignment of in-kind contributions to the operation, maintenance and repair. Information and communication technologies in twenty years from now will permit the distributed monitoring and root-cause analysis of numerous systems. Through unified supervisory control infrastructures, it should be straightforward to operate the technical infrastructures of all experiments with a single set of trained personnel and to share the task across the globe. The CMS "remote operations center" pioneered by FNAL in the US is a first step in this direction.

The **electrical energy consumption** is an important operating costs, but the analysis of the conceptual design indicates that it **is not a major driver of the operation cost**. In order to arrive at a long-term, sustainable highest-luminosity particle collider, the FCC-hh conceptual design already integrates a number of energy reduction measures:

- Use of **power-saving superconducting magnets and circuit layout optimisation**.
- A novel beamscreen design with an optimised temperature working point that permits efficient removal of the synchrotron radiation heat and minimises the load on the cryogenic refrigeration system.
- Use of an innovative cryogenic refrigeration system based on a neon-helium (nelium) light gas mixture, which reduces the electricity consumption and waste heat generation with respect to traditional plants by 20%.
- **Recovery and buffering of the energy stored in the superconducting magnets** at the end of the cycle for reuse during the subsequent ramp in order to save energy and to control the peak electricity demand.
- Use of superconducting radiofrequency cavities based on **thin-film coating technology at 4.5 K with a higher energy efficiency** than bulk superconducting materials at 2 K.
- Development of **high-efficiency klystrons** to increase the effectiveness of electrical to RF power conversion.
- Using **medium-voltage DC electricity distribution** to optimise the size of the powering infrastructure, enabling the introduction of renewable energy and storage systems and supressing the need for a power quality system.
- **Waste-heat recovery and reuse** inside the facility, and for storage and provision to district services (heating and air conditioning).

The total electrical energy consumption of the FCC-hh over the 25 years operation period is estimated to be 100 TWh, based on an average **electricity consumption of 4 TWh/year over the entire physics programme.** (Today's electricity consumption at CERN is 1.2 TWh/year. 1.4 TWh/year is expected in the HL-LHC era). For LEP2 the energy consumption ranged between 0.9 and 1.1 TWh/year. At the CERN electricity prices from 2014/15, the **electricity cost for FCC-hh collider operation would be about 180 Meuro per year**.

Considering the total luminosity production of 30 ab^{-1}, about 150 kEuro for electricity would need to be invested to produce 1 fb^{-1} of integrated luminosity. With more than 10^{10} Higgs bosons and 10^{12} top-pairs produced in total, this translates into an **electricity cost of about 45 cents per Higgs boson and per 100 top quark pairs**.

6.4 Computing requirements

The LHC operation era has shown that computing has evolved into a **service for a world-wide user community.** The existence of a large world-wide computing and data service infrastructure for the LHC programme today with a need for committed enlargement tomorrow will lead to a long-term sustainable, world-wide scientific computing and data management infrastructure for the physics community. Involving further **partners beyond the high-energy physics community** will facilitate this endeavour. Concrete examples include astronomy and astrophysics projects like SKA and ESO operated facilities, life-sciences via advanced medical imaging, microscopy and biomolecular data processing as supplied by EMBL and ELIXIR, photon and neutron sciences such as crystallography, and a broad spectrum of scientific domains with more limited requirements, but with a need for affordable access to computing and data processing. Carrier neutrality, vendor and operator independence as well as the continued availability of **open standards, hardware and software technologies** are essential ingredients to guarantee independent and effective progress of science and education on a long time scale.

Specifically, for the FCC-hh, the **computing capacity requirements significantly outpace those of the HL-LHC for event generation, detector performance simulation, data acquisition, on-line event filtering and off-line reconstruction**. Pile-up increase from 130 to 1000 raises the need to migrate sophisticated off-line algorithms all the way up to the trigger level. Event sizes in the hundred Mbyte range (factor 10 with respect to ATLAS/CMS phase II scenarios) create unprecedented data handling challenges. The possibility **to fully exploit the particle collider's capabilities depends much on the capability to** record as much data as possible, to buffer them and process them in a sustainable fashion. The experimental physics and information technology communities will need to be fully engaged in a cooperative effort from an early phase to develop approaches and solutions that can cope with these new performance requirements.

For the detector design, the high beam energies and the development of new detector materials creates a need for a new, common high-performance detector simulation and event generation ecosystem. The FCC study spawned such a development at a very early point in time. The **FCC detector software, integrating detector description, detector models, event generation and simulation as well as radiation-impact forecast is an active programme today** that federates contributors from numerous high-energy physics experiments. The software has also started to be used for the HL-LHC upgrade project. For the coming detector design phases, processing capacities need to make significant jumps. Data from detector developments and irradiation facilities need to be integrated on a continuous basis. This involves the **development of new event generation techniques**, in particular involving novel algorithms, ongoing adaptation to underlying processing platforms to be able to exploit the hardware well, standardised ways to describe detector models and to integrate real data from test beams, irradiation facilities and laboratory measurement campaigns.

Furthermore, **tools need to be developed to compare the experimental results and the theoretical predictions**. Such an activity is expected to **strengthen the cooperation between theoretical and experimental physicists**, leading to a more coherent world-wide community by developing common goals and a sense of shared responsibility. This work will be the **result of a world-wide collaborative effort of theoretical and experimental physicists and contributors from related relevant information technology** disciplines.

The FCC-hh project needs also computing infrastructure that supports the operation of the detectors over long periods of time. As demonstrated in domains such as detector controls and readout electronics of the LHC project, the **development of common services will further improve the cost-efficiency** of such a project, **during the cost-intense operation phase**. As the separation between off-line and on-line computing gradually vanishes, common services which were traditionally purpose-built by each collaboration, become attractive.

Embedded and real-time computing are of interest **for an infrastructure that is characterised by its longevity** and thus dominated by maintenance costs. Given the significant increase in the number of devices for a future collider, **standardisation**, **coordinated testing, certification**, **procurement** and **maintenance/repair** services, available to all users, will improve sustainability. These activities can create impact far beyond the particle accelerator community, if properly set up and coordinated with ICT communities.

Cyber-security plays an increasingly important role and scientific computing is no exception to this. Intensified support to ensure adequate coverage of this domain is an important requirement for a future project. The use of standard operating systems and embedded Web servers in all kind of equipment ranging from simple I/O devices, over measurement instruments to autonomous robots require an effective but lean infrastructure.

Cooperation on ICT standards, technology developments and relations with other research facilities with similar requirements (e.g. DESY, ESRF, ESS, Fermilab) needs to be strengthened. Synergies with other scientific domains (e.g. astronomy and radio astronomy facilities, light sources and FELs, neutrino and gravitational wave observatories, particle accelerators for medical applications and nuclear fusion experiments) can be developed to lead to more effective operation of **various IT services for research**. Activities spawned by DESY on front-end computing hardware and CERN's openlab are examples for such initiatives.

Considering the fast pace of information technology evolution, the long-term cost impact of in-house developments and their potentially limited industrial reach, it is prudent to base designs for a future project on widely accessible hardware, software and service infrastructures. The particular needs of an FCC-scale facility may also represent attractive test-beds for emerging technologies. Co-innovation projects with industrial partners during the early construction phase will facilitate launching co-funded pre-commercial procurement initiatives that can lead to high-performance infrastructure services at competitive costs.

Finally, **long-term data availability** has become an important feature to ensure the lasting impact of a facility. The accessibility of several decades of LHC data, metadata and analysis results has turned out to be a major topic for the community. With a future particle collider, the time span will extend to the end of the 21st century, calling for **evolving data storage and management systems that serve the core community** for long periods of time. Considering the continuous evolution of data formats, the ever-evolving particle detectors and a user community with significant turnover, **data quality management is a chief topic to be addressed**. **The value of a particle collider research facility depends directly on its data quality and long-term, worldwide open accessibility for as large a community of scientists as possible.**

7 Change Track

Revision	**Date**	**Description**
3.0	2018-12-18	Upload to site of European Particle Physics Strategy
3.01	2019-01-01	Section 2, page 6: clarification of educational value impact figures. 5% to 13% on top of regular academic training instead of 9% to 17% including academic training. 10 billion CHF of benefits are the sum of industrial spillovers and ICT. The industrial spillovers were missing and are now included as "earnings effects for industrial suppliers".
	2019-01-08	Removed spurious words from 6.2.1
	2019-01-11	4.1: 400.8 MHz instead of 400 MHz. 48 MV per beam instead of 48 MV
4.00	2019-01-14	Upload to public website.