Future Circular Collider

The Lepton Collider (FCC-ee)

Contact person: Michael Benedikt (Michael.Benedikt@cern.ch)

Abstract:

This report contains the description of a novel research infrastructure based on a highest-luminosity energy frontier electron-positron collider (FCC-ee) to address the open questions of modern physics. It will be a general precision instrument for the continued in-depth exploration of nature at the smallest scales, optimised to study with high precision the Z, W, Higgs and top particles, with samples of $5 \cdot 10^{12}$ Z bosons, 10^8 W pairs, 10^6 Higgs bosons and 10^6 top quark pairs. FCC-ee offers unprecedented sensitivity to signs of new physics, appearing in the form of small deviations from the Standard Model, of forbidden decay processes or of production of new particles with very small couplings.

This collider will be implemented in stages, successively spanning the entire energy range from the Z pole over the WW threshold and H production peak to the $t\bar{t}$ threshold. Most of the infrastructure (e.g. underground structures, surface sites, electrical distribution, cooling & ventilation, RF systems) can be directly reused for a subsequent energy-frontier hadron collider (FCC-hh, see FCC conceptual design report volume 3), serving the world-wide particle-physics community in a highly synergetic and cost-effective manner throughout the 21st century.

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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. On the other hand, **several experimental facts 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 that need to be addressed include the hierarchy problem, the neutrality of the Universe, the stability of the Higgs boson mass upon quantum corrections and the strong CP problem.

Possible answers to the open questions seem to require the existence of new particles and phenomena over an immense range of mass scales and coupling strengths, which could have masses too large or couplings too small to be observed at the LHC. To make things more challenging, it is worth recalling that the predictions of the top quark and Higgs boson masses from a wealth of precision measurements, collected in particular at e^+e^- colliders and from other precise low-energy experimental input, were made strictly within the Standard Model framework, without any kind of new physics. We are, therefore, looking for well-hidden new physics that does not significantly upset the quantum corrections upon which the predictions were made.

The observation of new particles or phenomena may happen by increasing the collision energy. History has shown, however, that the **existence, properties, and approximate mass values of heavier particles** (Z, W, Higgs, and top) **were predicted before their actual observation** from a long history of experiments and theoretical maturation. In this context, a decisive improvement in precision measurements of electroweak observables and of particle masses would play a crucial role, by integrating sensitivity to a large range of new physics possibilities. **The observation of significant deviation(s) from the Standard Model predictions would definitely be a discovery**. Such a discovery requires a considerable improvement in experimental and theoretical precision. It also requires the largest possible set of measured observables to eliminate spurious deviations, and most importantly to possibly reveal a pattern that would guide the theoretical interpretation and point to the source and the scale of new physics. Similarly, the search for new particles with extremely small couplings or for forbidden phenomena, in Z or Higgs boson decays in particular, could give the first clues towards the understanding of some of the remaining fundamental questions.

Improved precision on all these fronts increases the discovery potential. An e^+e^- collider with the highest luminosities at centre-of-mass energies between ~90 and ~400 GeV has the strongest of the physics case in this respect, as it covers the Z pole, the W- and top-pair production thresholds, and allows for copious Higgs boson production. **With such a device, precision electroweak physics, precision Higgs physics, and measurements of the top quark and W boson properties will give orders of magnitude improvements**. On the other hand, it is much harder to make a physics case for e^+e^- colliders with a centre-of-mass energy of 500 GeV or above, at least without clear evidence for new particles accessible and produced copiously in e^+e^- collisions, as acknowledged by the recent downscaling of linear collider projects to the electroweak scale (to 250 GeV for the ILC, and to 380 GeV for the first stage of CLIC).

High-energy physics requires an e^+e^- electroweak factory at the precision frontier. A 100 km circular lepton collider at CERN fills the bill perfectly. As the most powerful of all e^+e^- collider projects at the electroweak scale, it proposes, with centre-of-mass energies from 88 to 365 GeV and in a coherent research programme of about 15 years, **a multifaceted exploration to maximise opportunities for major discoveries.** Guided by the findings, high-energy physics will require direct access to the energy frontier. The 100 km infrastructure is designed to subsequently host a hadron collider with a centre-of-mass energy of at least 100 TeV, expanding the physics reach with multiple synergies and complementarities, allowing for the broadest and most versatile field of research, and providing the most ambitious future for CERN and for fundamental physics, for many years to come.

2 Objectives

The objective is to **develop, build and operate a highest-luminosity energy-frontier electron-positron collider (FCC-ee) to study with high precision the Z, W, Higgs and top particles, with samples of $5\cdot10^{12}$ Z bosons, 10^8 W pairs, 10^6 Higgs bosons and 10^6 top quark pairs. FCC-ee offers unprecedented sensitivity to signs of new physics**, appearing in the form of small deviations from the Standard Model, of forbidden decay processes or of production of new particles with very small couplings.

This collider will be **implemented in stages**, successively spanning the entire energy range from the Z pole over the WW threshold and H production peak to the $t\bar{t}$ threshold. Most of the infrastructure (e.g. underground structures, surface sites, electrical distribution, cooling & ventilation, RF systems) can be directly reused for a subsequent highest-energy hadron collider, FCC-hh, **serving the world-wide particle-physics community in a highly synergetic and cost-effective manner throughout the 21st century**.

2.1 Scientific Objectives

The European Strategy for Particle Physics **(ESPP) 2013 unambiguously recognised the importance of *"an electron-positron collider that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded"*.** Since its inception, the international **FCC** collaboration has therefore **aimed to deliver the conceptual design for an e^+e^- collider (FCC-ee) that best complies with this guideline** and which offers the broadest discovery potential. In addition, **it provides the most ambitious perspectives for future developments at the energy frontier.**

To provide relevant sensitivity to new physics, the FCC-ee must deliver integrated luminosities at centre-of-mass energies from around the Z pole to above the top-pair threshold, such that the statistical precision of a complete set of electroweak and Higgs observables improves by one to two orders of magnitude. The data samples needed to achieve this goal correspond to:

1. An integrated luminosity of **30 ab^{-1} at $\sqrt{s} \sim 88$ and at 94 GeV** for the direct measurement of the electromagnetic coupling constant at the Z mass scale. These data are also useful for the determination of the Z total width.
2. An integrated luminosity of **100 ab^{-1} at the Z pole** for the measurement of the effective weak mixing angle and for the search for and the study of rare Z decays. These data are also important for the determination of the Z mass and of the strong coupling constant at the Z mass scale.
3. An integrated luminosity of **10 ab^{-1} around the WW threshold**, for the measurement of the W mass and width, evenly shared between $\sqrt{s} \sim 157.5$ and 162.5 GeV. These data also provide the number of neutrino species and an independent measurement of the strong coupling constant.
4. An integrated luminosity of **5 ab^{-1} at $\sqrt{s} = 240$ GeV** for an absolute measurement of the Higgs boson couplings and decay width, that breaks the model-dependence inherent to hadron colliders.
5. An integrated luminosity of **~0.2 ab^{-1} in a 5-GeV-wide window around the top-pair threshold**, typically shared among eight points from ~340 to ~345 GeV for the measurement of the top-quark mass and width.
6. An integrated luminosity of **1.5 ab^{-1} above the top-pair threshold, $\sqrt{s} \sim 365$ GeV**, optimal for the measurement of the top electroweak couplings. These data provide a threefold improvement of the Higgs boson width accuracy with respect to the 240 GeV data, and allow for the first 3 σ evidence of the Higgs self-coupling.

As appears strikingly in Fig. 1, **only circular colliders can produce the necessary luminosity in a reasonable amount of time.** With two interaction points, and a conservative operation model based on past experience with e^+e^- colliders, **it takes 15 years for the FCC-ee to reach this objective**: four years at the Z pole, two years at the WW threshold, three years as a Higgs factory (phase 1), and five years at and above the top-pair threshold (phase 2), with one year shutdown between phase 1 and phase 2 to install RF accelerating cavities (Fig. 2). Another **feature unique to circular e^+e^- colliders is the possibility to use the transverse polarisation** of the stored beams for beam energy calibration, allowing **the centre-of-mass energy to be determined with a precision of the order of 100 keV**. The measurements of the beam energy and its spread with this precision are essential for the determination of the Z and W masses with the promised accuracy, and for that of several other electroweak observables.

To fully capitalise upon these high precision measurements by testing the predictions of the Standard Model, **theoretical uncertainties must be subdominant to experimental errors**. Improving the precision of electroweak and QCD calculations to levels that permit effectively leveraging the FCC-ee capabilities is a great challenge.

The associated discovery potential is sufficiently strong for the necessary theoretical developments to be recognised as a strategic R&D activity for this project.

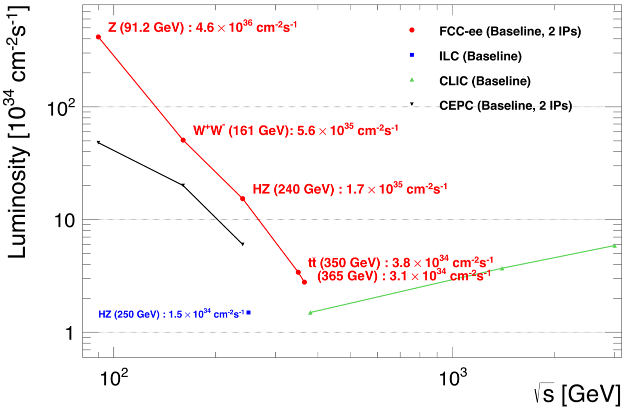

Figure 1: FCC-ee baseline luminosities summed over all interaction points as a function of the centre-of-mass energy (√s), compared to other e$^+$e$^-$ collider proposals (ILC, CLIC, and CEPC).

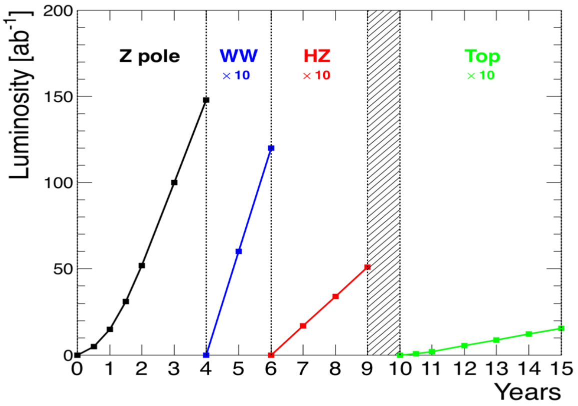

Figure 2: FCC-ee operation model showing the integrated luminosity in ab^{-1}, accumulated as a function of time in years at the Z pole (black), the WW threshold (blue), the Higgs factory (red) and the top-pair threshold (green). The hatched area indicates the shutdown time to prepare for the highest energy runs.

With 20 to 50-fold improved precision on all EW observables and with up to 10-fold more precise and model-independent Higgs couplings and width determination in a complementary way, the FCC-ee probes new physics effects at scales as high as 10 to 100 TeV, potentially guiding the physics programme of a subsequent energy-frontier hadron collider FCC-hh, and providing a quantum leap in the understanding of the Higgs boson. Furthermore, the high-statistics samples generated by the FCC-ee programme (5×10^{12} Z – about 10^5 times the LEP sample, 10^8 WW, 10^6 HZ, and 10^6 top pairs) offer **unique opportunities far beyond precision electroweak and Higgs measurements.** Other signals of new physics could arise from the observation of minute flavour-changing neutral currents or lepton-flavour-violating decays, from the observation of dark matter in Z and Higgs invisible decays, or by the direct discovery of particles with extremely weak couplings in the 5 to 100 GeV mass range, such as right-handed neutrinos and other exotic particles. These are well-motivated and, in spite of their low mass, consistent with the constraints imposed by precision measurements.

In 2013, the ESPP also inferred that a lepton collider with "*energies of 500 GeV or higher could explore the Higgs properties further, for example the coupling to the top quark, the self-coupling, and the total width*". As a consequence, the strategic question was raised whether the FCC-ee ought to consider a 500 GeV upgrade in its scientific objectives. The ESPP 2013 statement was revisited quantitatively with the following conclusions:

- The **FCC-ee can measure the total width of the Higgs boson with a precision of 1.3%** (the best achievable precision on a foreseeable time scale) at 240 and 365 GeV, **without the need of an upgrade to 500 GeV**.
- The **top Yukawa coupling** will already have been determined with a 2.4% precision at the HL-LHC, albeit with some model dependence. The **FCC-ee breaks the model dependence** and **improves the precision to about 2.3%, without the need of an upgrade to 500 GeV**.
- The **FCC-ee offers a model-independent precision of 34% on the Higgs self-coupling κ_λ** (reduced to 12% if only κ_λ is allowed to vary) from the precise measurement of the Higgs boson cross sections at 240 and 365 GeV, **to be compared to the 27% precision obtained from di-Higgs production with 4 ab^{-1} at 500 GeV**, in the context of the Standard Model.

Indeed, in a way similar to di-Higgs production, the next-to-leading order graphs of Fig. 3 (left) depend on the Higgs self-couplings, and interfere with the tree-level diagrams, impacting the Higgs production cross section by up to 2% at 240 GeV and 0.5% at 365 GeV. The **centre-of-mass energy dependence allows for a 3σ sensitivity to the Higgs self-coupling at the FCC-ee**, as illustrated in Fig. 3 (right). Probes of the Higgs self-coupling are also accessible by other e$^+$e$^-$ colliders that can reach centre-of-mass energies of 500 GeV or higher, but only with a much longer time of operation. The 3σ evidence could become the first 5σ discovery of the Higgs self-coupling if the luminosity of the FCC-ee were increased at high energy, e.g. with four detectors instead of two. Such an upgrade of the FCC-ee baseline would be significantly **more efficient than an upgrade of the centre-of-mass**

energy to 500 GeV or higher, which would be costly in time and resources, and which would be trivially superseded by the FCC-hh. Today, the only realistic possibility of percent-level measurement of the top Yukawa coupling (~1%) and Higgs self-coupling (~5%) is offered by the combination of the FCC-ee and FCC-hh data.

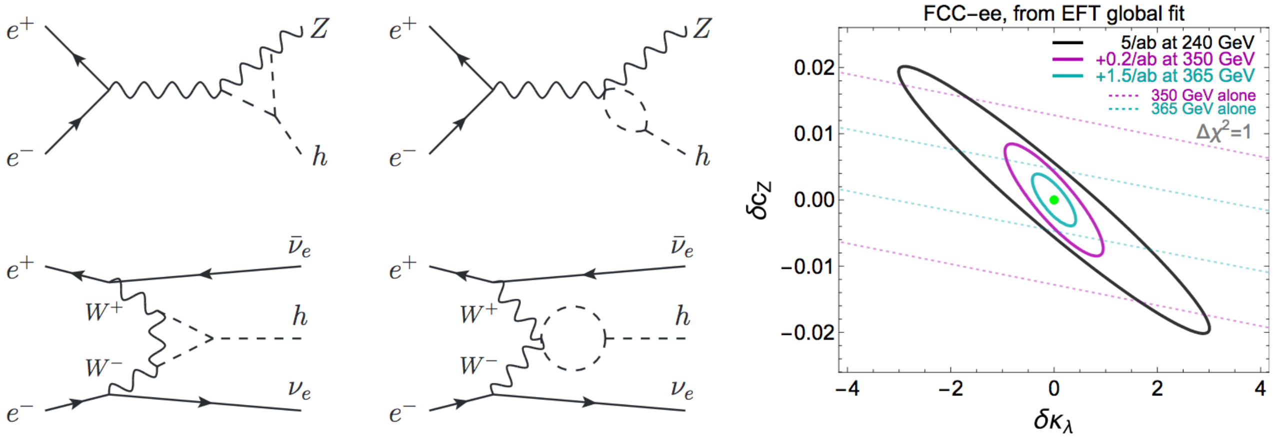

Figure 3: (Left) Sample diagrams illustrating the dependence on the Higgs self-coupling of single Higgs production at the FCC-ee. (Right) Standalone FCC-ee precision in the model-independent determination of the Higgs self-coupling ($\delta\kappa_\lambda$) and the HZZ coupling (δc_Z) deviations at 240 GeV (black), 350 GeV (purpled dashed), 365 GeV (green dashed) and by combining data at 240 and 350 GeV (purple), and at 240, 350 and 365 GeV (green).

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, as a first step, the detailed design and preparation of a construction project** for a post-LHC circular lepton 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 particle-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 development pace for 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 plays a unique role and 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, 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 for the women and men who participated in the programme, ranging from 9% to 15%. **For LHC/HL-LHC, the value of openly accessible standards, software and tools exceeds 10 billion CHF today,** but 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, in particular, of accurately computing the particle properties predicted by the Standard Model, measuring these properties with an ultra-high-precision instrument, and finally comparing the predictions with the measurements. Tiny discrepancies uncovered by a wealth of collision data can indicate the existence of yet unknown particles up to energies of 100 TeV. The extremely clean interactions and high-statistics data samples needed to pursue this discovery path call for a **rigorous and well-defined research programme at a highest-luminosity circular e^+e^-collider**. Undoubtedly, such a collider is **technically feasible**, and **it can be built within an appropriate time frame**, so that **project risks are quite limited.** A **naturally staged implementation** leads to **a continued in-depth exploration of the energy frontier**. The experimental research at the FCC-ee 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 it leverages cross-disciplinary synergies to expand our understanding of the universe (e.g. dark matter searches complementing astro-particle physics research projects).

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[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-ee project addresses the open questions of the Standard Model with the most cost-effective, most energy efficient, lowest-risk and most forward-looking tool conceivable today: a large high-energy circular collider with multiple interaction points. The FCC-ee 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-ee, the data conservation will be ensured by a consortium of national partners, which recognises 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 infrastructure based on a collaborative approach. **The FCC-ee project profits from the lessons learnt at the LHC and HL-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 re-enforced to render the construction process sustainable and to maximise the economic impact on industry and society. More than 50 years of successful accelerator and experiment projects coordinated by CERN are proof of its capacity to design and build the proposed FCC-ee machine. The implementation section below sheds more light on the proposed **governing model and organisation structures**, which should help **ensure transparency and credibility** from the early design onwards.

The FCC-ee collider and its physics programme are complementary to other on-going or planned programmes in particle physics, high-energy physics and astrophysics. The FCC-ee 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 Standard Model and the elucidation of stealth phenomena that are likely to emerge from these investigations will point the way forward, towards further explorations at future high-energy particle colliders, helping to suitably size and scope such future projects, including a next hadron collider**. The FCC-ee 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 search for right-handed neutrinos at FCC-ee. With the rigorous exploration of the hidden sector, research complementary to the on-going astro-particle-physics projects will be carried out, leading to a best-of-breed approach: the lepton collider-based research can point the way to further astrophysics experiments and help exclude existing hypotheses.

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 international HEIKA initiative for the development of high-efficiency klystrons and converging world-wide technology R&D initiatives on radiofrequency systems.

4 Readiness

The **technology** for constructing a high-energy highest-luminosity circular lepton collider **exists**. The FCC-ee concept comprises a power-saving twin-aperture magnet system, a continuous top-up injection scheme for stable operation and maximum integrated luminosity. Combined with an energy staging scheme, the FCC-ee represents the most efficient and most sustainable route for executing the research required to discover signs of new physics beyond the Standard Model. The **step-wise energy increase of the FCC-ee does not require any additional civil engineering activities**.

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

4.1 Technical Feasibility

A circular e^+e^- collider with centre-of-mass energies ranging from 88 GeV to 365 GeV is technically feasible. Many technical systems and operating concepts for FCC-ee can be **scaled up from LEP, LHC, the B-factories, DAΦNE, HERA and modern light sources**, or be based on technology demonstrations carried out in the frame of linear collider studies. The FCC-ee adopts a **double-ring design**. At low beam energies, with limited synchrotron radiation per electron, a high beam current can be stored to achieve ultra-high luminosities. At highest beam energy, with strong synchrotron radiation, the beam current is much lower. The **beam current is primarily varied by changing the number of bunches**. At higher energies, the **FCC-ee double-ring collider will use magnet "tapering"** to compensate for the local beam energy differences and to restore the ideal beam optics, which would not be possible for a common ring design like LEP. In addition to a high beam current, small emittances and low beta functions at the **multiple collision points** are required. The equilibrium emittances of a large-size ring are naturally small. The **FCC-ee horizontal emittance is extremely conservative if compared with scaled emittances from modern light sources**. In simulations, the target value for the FCC-ee vertical emittance is obtained with **traditional alignment tolerances of 100 μm**, as routinely achieved for past and present accelerators at CERN. The **vertical IP beta function is about three times larger than for the SuperKEKB design**. The resulting vertical rms IP beam size is in the order of 50 nm for all modes of operation. **Such beam sizes have already been demonstrated at linear-collider test facilities (SLAC FFTB and KEK/ATF2); they are also close to the SuperKEKB design values**. **Luminosity is further boosted by the "crab waist collision scheme", successfully implemented at DAΦNE** several years ago.

For the main dipole and quadrupole magnets, **novel dual-aperture designs** have been developed, which result in a compact and highly energy-efficient configuration. These designs **halve the electrical power demand compared with classical single-aperture magnets.** The dipole features aluminium busbars at low current density and the quadrupoles are based on 30-turn copper coils. The arc sextupole magnets are normal conducting single aperture magnets. For the final-focus sextupoles and final quadrupole magnets, superconducting technology is the appropriate choice, either based on established Nb-Ti or possibly on high temperature superconductors (HTS) as a demonstration of the use of novel materials for future particle accelerators.

The FCC-ee vacuum system must include specific measures to control the 50 MW/beam synchrotron radiation load. The design study has shown that a copper vacuum chamber with **strategically placed, water-cooled photon absorbers can mitigate the radiation effects, with power levels of around 5 kW per absorber**, typical for many of today's light sources. Different types of appropriate vacuum chambers exist. Operating examples are available, for instance from SuperKEKB. The definitive choice of NEG coating and the development of a pumping strategy need to be worked out during the detailed technical design stage. The same holds for the design of the chamber-supports, the alignment systems and the optimum placement of gate valves.

The RF system is the heart of the FCC-ee machine. It has to sustain beam currents of 1.39 A to 5.4 mA at beam energies ranging from 44 GeV to 182.5 GeV, at a fixed radiation power of 50 MW per beam. A **staged installation with optimised configurations for the Z, WW, ZH and $t\bar{t}$ operation points**, leads to a smooth learning curve and an advantageous capital investment profile. At the highest energy operating point about 2,600 RF gaps are needed at 400 or 800 MHz to produce the total RF voltage of 11 GV. Both prototype 400 MHz Nb on Cu coated cavities operating at 4.5 K and 800 MHz bulk Nb cavities at 2 K already show excellent performance. Hence, there are no fundamental concerns about the technical feasibility. Focused R&D aims at low-cost, series-manufactured high-quality cavities based on thin-film coating with a third of the present surface resistance. This would allow higher acceleration gradients and potentially remove the need for bulk material cavities. RF efficiency can be further improved by advanced longitudinal beam feedback and next-generation low-level RF systems.

For the injector, the choice of an SLC/SuperKEKB-type 6 GeV linac, coupled with a damping ring, and using CERN's SPS as pre-booster permits the continuation of CERN's rich and diverse fixed-target physics programme in parallel with FCC-ee operation. The top-up injection scheme, implemented with a full-energy booster ring installed next to the collider, provides a nearly constant beam current and luminosity to be maintained throughout the entire physics run. This mode of operation was pioneered by the SLAC and KEK B factories and is in use at several modern light sources. **In the Z operation phase, a maximum production rate of 10^{13} positrons per second is required to fill both rings from zero within 20 minutes. This maximum rate** does not exceed the routine performance of the SLC and SuperKEKB positron sources, by more than a factor 2 or 4, respectively. It **can be achieved with a SuperKEKB-like source operated at a linac repetition rate of 100 to 200 Hz, with up to two bunches per pulse.** A well-defined "bootstrapping" procedure during initial injection will ensure that the charge imbalance between the colliding beams is kept within the limits set by the beam-beam dynamics.

A key feature of the FCC-ee is the **precise measurement of the beam energy based on resonant depolarisation**, a technique already **successfully performed at LEP**. The FCC-ee design aims at less than 100 keV uncertainty for the Z mass and at around 500 keV for the W mass.

To best serve the research community, the FCC-ee experiment collaborations will develop designs for complementary detectors. The **baseline scenario has two interaction points and mature design concepts of detectors exist, e.g. based on the linear collider studies (ILC, CLIC)**. The preparatory phase of the project will be devoted to advance detector technologies and 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 the physics programme be achieved, if not exceeded. Today both **FCC-ee data acquisition and physics reconstruction are technically feasible**, efficiently leveraging the investments and continued developments of the LHC/HL-LHC programme.

The target values for the integrated luminosity in each operational phase assume **185 physics days per year and an accelerator availability above 80%, as routinely achieved by today's LHC complex**, plus initial learning periods for the Z and $t\bar{t}$ running of the first two or one year, respectively, at half the average luminosity, which is based on the **LEP experience. The FCC-ee integrated luminosity of 150 ab^{-1} in 4 years at the Z pole and 5 ab^{-1} in 3 years at 240 GeV is the best in terms of cost of construction and operation time amongst all proposed lepton colliders.**

4.2 Sustainable and Energy-Efficient Operation

From the beginning, the FCC-ee collider has been developed with an emphasis on sustainability and energy efficiency. A storage ring maximises the use of the accelerated beam through recirculation and by colliding the same beam many times. Combined with a **high beam current, small emittances and low collision-point beta function,** this **beam recirculation results in the unbeatable figure-of-merit for luminosity per electrical input power** which is already in the current baseline configuration with only two interaction points (**6×10^{35} cm^{-2}s^{-1} per 100 MW of the total facility electrical power at 240 GeV** and much higher luminosity values at lower energy). With such a luminosity efficiency, the **ambitious physics goals of the FCC-ee can be accomplished within 15 years of operation**, with a peak power consumption of the collider complex below 300 MW in the first ten years, and slightly above for the operation at the $t\bar{t}$ energy. Power consumption can be further reduced: novel superconducting thin-film coating technology will allow RF cavities to be operated at higher temperature, thereby lowering the electrical requirement for cryogenics, and reduce the required number of cavities thanks to an increase in the accelerating gradient. Additional power savings are within technical reach by developing more efficient RF power sources. An ongoing R&D activity, carried out in close cooperation with the linear collider community, aims at raising the peak efficiency of klystrons from 65% to above 80%. Higher-temperature high-gradient Nb/Cu accelerating cavities and highly-efficient RF power sources developed for FCC-ee will find numerous applications; they can improve the sustainability and performance of particle accelerators around the world.

Through the novel **twin-aperture magnet systems** and a continuous beam-current supply via **top-up injection**, that avoids ramping phases without physics, **energy efficiency and availability are integral parts of the design**.

Medium-voltage DC electricity distribution decouples from the electricity supplier, integrates renewable energy and storage systems seamlessly and suppresses static volt-ampere reactive (VAR) compensator power quality systems. Oversizing of the electrical infrastructure is avoided by limiting the peak power demand by energy buffering.

A comprehensive resource-saving strategy includes studies to **reduce water cooling** where possible and schemes to supply the **waste heat** to nearby consumers. A pilot project, recently launched on French territory in the frame of the LHC 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-ee 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.

From an operational point-of-view, the **FCC-ee intrinsically incorporates sustainability through its smart staging scenario**: The physics programme starts at the Z pole with a limited RF system. This period permits experience to be gained with the machine and operation. This time also provides a window for optimising and producing the additional RF systems that are needed for the next energy step, four years later. A two-year running period at the WW threshold will again provide time for the production of the next RF system upgrade. The following operation phase at the H energy will last for three years. A more significant re-configuration, requiring a one-year machine stop, will only occur to prepare the machine for the $t\bar{t}$ run for another five years. This upgrade also permits the maintenance necessary after almost ten years of operation to be carried out.

4.3 Implementation Model

Assuming 2039 for the debut of the FCC-ee physics programme after two years of beam commissioning, and a start of accelerator 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 nations 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 impact.

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 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 after a section of the underground infrastructure is ready.

Detailed detector designs by established experiment collaborations can commence**.** This activity needs to start as soon as the required expert researchers and engineers become available at the end of the current 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 in such a way that unified computing services are created to serve 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 finalised. **Detector installation** can start **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. Following these two full years of beam commissioning, the FCC-ee is assumed to operate, on average, at half the design luminosity for the next two years.

5 Challenges

The ultra-high-luminosity energy-frontier circular lepton collider entails **only a limited set of uncertainties** that could adversely impact the project 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 remaining challenge is the creation of a world-wide consortium of scientific contributors who reliably commit resources to the development and preparation of the FCC-ee science project from 2020 onwards.

Uncertainty	**Impacts**	**Mitigation**
Technical challenges		
Limited availability of high-power RF power amplifier (klystron) manufacturers.	Cost increase and delay of construction and operation; reduced performance, reliability and availability.	Dedicated R&D programme with industrial partners on highly efficient klystrons to ensure continued availability of such devices. To avoid a vendor locking situation, ensure in-house expertise on the technology and open standards and designs.
Power needs resulting from sustained supply of 100 MW RF power.	Higher-than-foreseen operation expenditures.	R&D on overall system optimisation including low-loss DC electricity distribution, high-efficiency electrical to RF power conversion, and more highly performant thin-film RF cavities.
Cost and performance of bulk superconducting RF cavities.	Unforeseen increases of construction and operation costs.	Dedicated R&D programme on advanced thin-film coating for RF cavities, focusing on curing the Q slope, and developing a high quality, low-cost manufacturing process.
Insufficient level of theoretical precision and accuracy.	Full exploitation of machine's capabilities depends on accurate theoretical predictions of SM phenomena at levels where higher-order contributions become significant.	Set up an international collaboration, leveraging existing world-wide HEP computing infrastructures, to develop the tools and to carry out the necessary computations. This effort is assumed to require substantial committed engagement of personnel by the collaborating institutes during the design, construction and operation phases.
Implementation challenges		
Funding of construction project and sustained operation throughout the entire physics programme.	Insecure funding will delay or prohibit construction. Insufficient funding of operation will lead to sub-optimal exploitation of the infrastructure.	Early negotiations with member states to set up a funding strategy for the preparatory phase. Construction cost profile with a staged energy upgrade scheme permits the project to be co-funded from the CERN operation budget. 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 hi-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 total cost of ownership 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.	Winning the host states support through timely involvement as partners is the 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 impact (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 has been established to continue this joint work with the host states.