Linear Collider Vision

The Linear Collider Facility (LCF) at CERN

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In this paper we outline a proposal for a Linear Collider Facility as the next flagship project for CERN. This proposal offers the opportunity for a timely, cost-effective and staged construction of a new collider that will be able to comprehensively map the Higgs boson's properties, including the Higgs field potential, thanks to a large span in centre-of-mass energies and polarised beams. A comprehensive programme to study the Higgs boson and its closest relatives with high precision requires data at centre-of-mass energies from the Z pole to at least 1 TeV. It should include measurements of the Higgs boson in both major production mechanisms, $e^+e^- \to ZH$ (Higgs-strahlung) and $e^+e^- \to \nu\bar{\nu}H$ (WW fusion), precision measurements of gauge boson interactions as well as of the W boson, Higgs boson and top-quark masses, measurement of the top-quark Yukawa coupling through $e^+e^- \to t\bar{t}H$, measurement of the Higgs boson self-coupling through HH production, and precision measurements of the electroweak couplings of the top quark. In addition, e^+e^- collisions offer discovery potential for new particles complementary to HL-LHC. The facility we propose robustly satisfies these scientific goals. With a total length of 33.5 km, two interaction regions as well as additional R&D and fixed-target experiments, it offers significant flexibility to take into account scientific and strategic developments. From today's perspective, we propose to equip the Linear Collider Facility in a first stage with superconducting RF cavities for polarised e^+e^- collisions at a centre-of-mass energy of 250 GeV with a luminosity of $2.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which requires an investment of about 8.3 BCHF. With a preparatory phase of eight years, followed by ten years of construction starting earliest in 2034, this first stage could start beam commissioning and data-taking a decade later. First upgrades comprise doubling of the luminosity for 0.8 BCHF and an increase of energy up to at least 550 GeV, which can be achieved with the same accelerator technology for about 5.5 BCHF. Later stages will involve further increase of luminosity and energy as well as other new capabilities that will further enhance the Higgs programme and extend the discovery potential for new physics. These upgrades will primarily be accomplished by accelerator technology innovations rather than by additional civil construction.

1 Introduction

The aim of the current update of the European Strategy for Particle Physics (ESPP) is to develop a "visionary and concrete plan" for the realisation of the next flagship project at CERN [1]. In this report, we propose that the next CERN flagship project after the High Luminosity LHC should be a linear e^+e^- collider spanning centre-of-mass energies from the Z pole to at least 1 TeV. We will give a cost and timeline for the initial stage of this project and describe options for later stages that encompass high-energy running and flexible responses to possible contingencies.

A linear collider, in its run at 250 GeV in the centre of mass, will already bring the precision on Higgs boson couplings, both to Standard Model and potential exotic particles appearing in its decay, to the percent level. At higher energies, it can provide precision measurements of the top quark mass, the top quark Yukawa coupling and the Higgs self-coupling. Also, it will make precision measurements of the electroweak couplings of the top quark relevant to the physics of its mass generation. A linear collider offers a high degree of flexibility due to its intrinsic upgradability. The scope of its initial stage and the nature and timeline of upgrades can be chosen and adjusted throughout the project taking into account scientific developments and competition, availability of resources and global cooperation. The previous European Strategy report stated, "An electron-positron Higgs factory is the highest-priority next collider" [2]. A linear collider is a true Higgs factory, capable of carrying out a comprehensive suite of measurements relevant to the Higgs boson that we have just described and that we will quantify below.

CERN has the resources and experience to host this linear collider programme. With CERN's experience in building and operating the LHC, the laboratory is well prepared to lead an ambitious programme of linear collider physics, one that encompasses a complete exploration of the Higgs boson's properties. We present a broad project, with high energy reach, with two interaction regions allowing complementary detectors and optionally a rich beyond-collider programme. This machine allows that close attention can be paid to the needs of physics, including the flexibility to respond to possible unexpected outcomes of the HL-LHC – and of the first stage of the linear collider itself. Whatever the circumstances over the next decade and a half, this program will produce physics by mid 2040s, with results continuously expanding into the future.

This paper is organised as follows: In Section 2, we will discuss the needs of a comprehensive programme to measure the properties of the Higgs boson with high precision. This programme includes running at energies well above the top quark threshold to measure the crucial observables of top quark and Higgs boson pair production. In Section 3, we will present our proposal for a Linear Collider Facility at CERN. This is a staged plan to maximise the flexibility of the proposal, allowing to respond to future physics discoveries and technology advancements. The initial stage is a linear e^+e^- collider and beam delivery region of length 20.5 km in a tunnel of total length 33.5 km, with two interaction regions sharing luminosity. The cost of the initial stage is 8 BCHF. The initial centre of mass energy would be 250 GeV, but upgrades to the accelerator would reach 550 GeV, 1 TeV, or as high as 3 TeV, depending on the technology and the physics objectives. In Section 4, we will describe paths for these energy upgrades, any of which will fulfil the comprehensive Higgs program outlined in Section 2. We will also present additional upgrade paths to provide dramatically increased luminosity, energy reach, or new physics capabilities – addressing the long-term goal of a 10 TeV parton centre-of-mass collider. In Section 5 we will outline the next steps towards the realisation of the Linear Collider Facility. We will give our conclusions in Section 6.

2 Precision study of the Higgs boson

The study of the Higgs boson has been given priority in all recent planning studies from Europe, the US, and Japan. There is a good reason for this. The gauge couplings of the Standard Model

(SM) are now well understood and well-tested. But many questions in particle physics remain unanswered. These include the origin of electroweak symmetry breaking, the hierarchy of quark and lepton masses, the origin of CP violation, and the origin of neutrino masses. In the SM, all of these are accounted for by terms involving the Higgs boson whose coefficients are adjusted by hand. The true explanations must involve new interactions and particles that couple to the Higgs boson.

For more than 40 years, particle physicists have been searching for new physics beyond the SM, but no convincing evidence has yet been found. The most promising approaches are now at the energy frontier, where the LHC experiments have carried out extensive new particle searches and have made great progress in understanding the Higgs boson. Still, much opportunity for discovery is still available here. This motivates a study of the Higgs boson that is as precise and as complete as possible.

It is well appreciated now that studying the interactions of the Higgs boson at an e^+e^- collider provides the best route to high-precision measurements of the Higgs properties. The required programme has been enunciated in many places, in particular in [3, 4] and, more recently, in [5] and [6]. The programme requires several stages, at different e^+e^- centre-of-mass energies.

1. An initial stage at 250 GeV, recording a large data set of reactions $e^+e^- \to ZH$. This will measure the Higgs branching fractions to 1 % precision, measure the ZH total cross section to 1 % precision to determine the absolute normalisation of Higgs couplings, measure the Higgs boson mass to 10^{-4} precision, and search for non-standard Higgs boson decays, including invisible ones, to the 10^{-4} level of branching fractions. The expected precisions on the individual Higgs couplings from collecting 3 ab^{-1} of polarised data are shown as green bars in Fig. 1(a).

   This data set will also give the most precise measurements of the W boson non-linear interactions and of electroweak fermion pair production, providing further opportunities for discovery. The W boson's mass can be measured to about 2 MeV using the 250 GeV data. An optional one-year threshold scan could improve this to 1.4 MeV. Also, at this stage, one can collect a few 10^9 events on the Z pole with polarised beams, to test the SM electroweak sector with high precision. In this regard, the use of beam polarisation compensates almost three orders of magnitude in integrated luminosity with respect to unpolarised colliders.

2. A second stage at 550 GeV, where the WW fusion reaction $e^+e^- \to \nu\bar{\nu}H$ has become the dominant production mechanism for Higgs bosons. This will provide an independent setting for the measurement of Higgs branching fractions and searches for exotic decays. It also allows the measurement of the top quark Yukawa coupling and the trilinear Higgs self-coupling through the processes $e^+e^- \to t\bar{t}H$ and $e^+e^- \to ZHH$, respectively. The blue bars in Fig. 1(a) show the expected gain in precision on the individual Higgs couplings from 8 ab^{-1} of polarised data at 550 GeV, including a precision of 2 % or better on the top Yukawa and of 11 % or better on the Higgs self-coupling (SM case). Figure 1(b) illustrates that thanks to the two complementary di-Higgs production processes, the expected combined precision on the self-coupling is nearly independent of the actual value nature might have chosen.

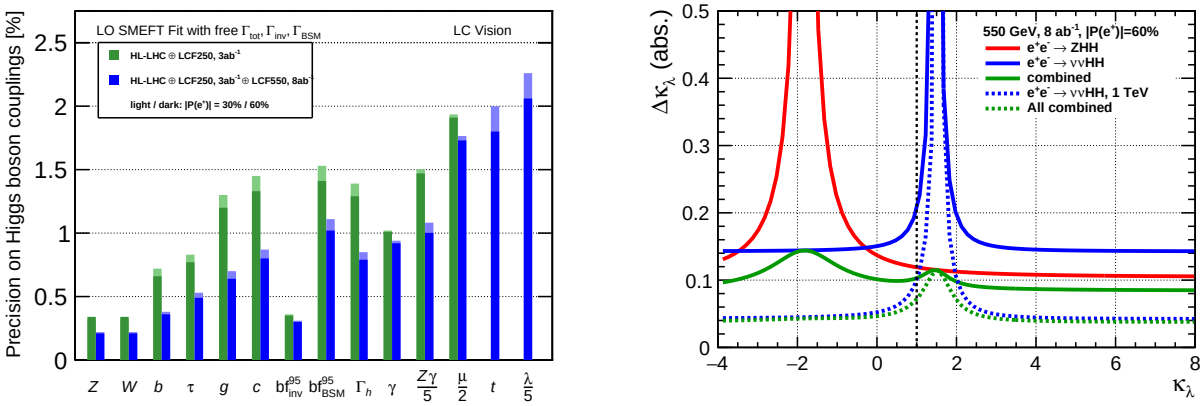
   The top quark is the SM particle most strongly coupled to the Higgs boson and thus most likely to be affected by new Higgs interactions. This stage, well above the top quark threshold, will also provide precision measurements of the top quark electroweak couplings at the level of 1 % or better, and include a short run around the top pair production threshold for a precise mass determination.

3. A third stage at at least 1 TeV, where the reaction of WW fusion to HH is the dominant Higgs pair production mechanism. This energy stage thus provides a second method to determine the trilinear Higgs self-coupling, and can put constraints on the quartic Higgs self-coupling [7]. The two Higgs pair production processes, ZHH and WW fusion, are strikingly complementary

(see also Fig. 1(b)); as the self-coupling is increased from its SM value, the ZHH cross section increases while the WW fusion cross section decreases. Observing these deviations in the same experiment would give the most persuasive evidence for a non-standard value of the Higgs self-coupling.

Anomalies in top quark or multi gauge boson couplings suggested in earlier stages will be dramatically larger, proportionally to E_{CM}^2 in typical cases. The ample production of (single) Higgs bosons in WW fusion and $t\bar{t}H$ will allow us to further scrutinise the couplings of the Higgs boson to SM particles including the top quark and the W boson.

Any of these stages, but increasingly so the higher-energy ones, provide opportunities for discoveries via largely loophole-free tests of new particle existence to mass scales approaching the kinematic limit. A linear e^+e^- collider can provide all these stages and, as we will discuss below, could be upgraded to energies of up to 3 TeV. This would allow precision studies of heavy Higgs bosons and other electroweak states discovered at the HL-LHC, or at the linear collider itself.



(a) (b)

Figure 1: Projected uncertainties on Higgs boson couplings corresponding to the run plan in Fig. 2. The methodology used to make these projections and projections for other choices of the run plan are presented in [6]. (a) Overview on various Higgs couplings; the bars for the muon Yukawa and the trilinear Higgs self-coupling λ have been scaled by 1/2 and 1/5, respectively. (b) Absolute precision on trilinear Higgs self-coupling scaled to its SM value (κ_λ) as function of κ_λ from the ZHH and WW fusion processes at 550 GeV and 1 TeV.

Our understanding of the Higgs boson and top quark couplings will be best informed through global fitting of the entire data set to specific UV-complete extensions of the SM or – as long as there is no hint which extension of the SM could be realised in nature – to Effective Field Theories like e.g. Standard Model Effective Field Theory (SMEFT). Such fits, and in particular the SMEFT fit, require even better knowledge of precision electroweak parameters, the W and top quark masses, and the cross sections for $e^+e^- \to W^+W^-$ and other electroweak reactions. That will naturally be achieved in the course of this programme, with the additional brief runs at the Z pole and the $t\bar{t}$ threshold. Because the SMEFT Lagrangian contains chiral operators, global SMEFT fits typically have degeneracies involving left- vs. right-handed couplings. At a linear collider, the availability of e^- and e^+ beam polarisation will resolve these degeneracies, to bring out the maximum information available from the data.

A full discussion of the linear collider physics programme, with descriptions of all of the above measurements, their combination through SMEFT fitting, and estimates of expected precision as a

function of integrated luminosity, can be found in [6]. Other, more extensive, discussions of the Higgs factory physics programme, can be found in earlier papers [3, 5, 8–10].

There is one more important point about this program that we would like to especially emphasise. Though there are windows for the discovery of new particles at the HL-LHC, it may be that our only opportunity to discover new physics with accelerators using current technologies will be through the discovery of deviations from the SM in precision measurements. Such a discovery will need to overcome a very substantial burden of proof. Deviations at the 3σ level are common in LHC analyses, yet are not sufficient to question the SM. The 7σ deviation in the W boson mass reported by the CDF collaboration [11] has been greeted by our community with great scepticism. A discovery via precision measurements will require not only a high level of precision, including control and detailed understanding of systematic uncertainties, but also the independent observation of the anomaly in different settings with different experimental challenges. Beam polarisation allows non-trivial cross-checks on any observed deviation. More importantly, the qualitative evolution of e^+e^- physics with centre-of-mass energy will provide many opportunities for confirmation of discoveries. In the programme that we have outlined above, the observation of an anomaly in Higgs boson couplings observed at 250 GeV could be confirmed by observation of the same anomaly in WW fusion. A deviation from the SM in the Higgs self-coupling or the top quark Yukawa coupling observed at 550 GeV could be confirmed at the TeV stage through data from new processes. A precision Higgs programme that does not have this option invites confusion and stalemate. A multi-stage linear collider programme has the robustness needed to cement a true discovery.

3 The Linear Collider Facility at CERN (up to about 550 GeV)

The multi-stage e^+e^- programme described in the previous section would be carried out step by step, ideally with each step affordable within the current CERN budget. What is needed today is a detailed plan for the first stage, for which construction could begin around 2034 and be completed a decade later as the HL-LHC programme is completed (c.f. Sec. 5 and [12] for more information on the timeline).

The timing here is important, especially for young scientists who will be key to both the HL-LHC program and the future Higgs factory. Prolonged uncertainty or delays in decision-making risk discouraging Early Career Researchers, leading to a loss of talent and expertise that could undermine the vitality of collider physics. Ensuring a clear and timely transition from HL-LHC to the next collider project will provide young scientists with long-term research opportunities, allowing them to contribute to both late-stage HL-LHC analyses and the design and construction of future detectors. The plan we propose aligns with the priorities identified in the European Early Career Researcher strategy submission [13], which emphasises technological innovation, alongside an ambitious baseline physics programme, as the driving factor in deciding CERN's next flagship project. Additionally, the lower priority [13] places on a predefined upgrade path aligns with flexibility to shape the LCF's upgrade strategy based on future developments.

To provide for this, the first-stage linear collider should be based on well-understood technology and planning. Our proposal builds upon decades of work on the most mature linear collider concepts ILC [14] and CLIC [15], for which technical design reports, project implementation plans etc. have been presented [16, 17]. The ILC technical design has been under review for more than 10 years by ICFA and by several Japanese government committees. The costs given in this document have been obtained in the following way, as detailed in [12]:

- **Accelerator costs:** The costs for everything but the civil construction have been derived from the 2024 cost update for the ILC in Japan, which was based to a significant extent on new quotes from industry and reviewed by an international expert committee [14].

- **Civil engineering and conventional systems:** The civil engineering required at CERN is very similar to that needed for the first and second stages of the CLIC project, and has been costed in 2025 with unit prices in agreement with other CERN-hosted projects. The conventional systems have been taken from the TDR estimate and escalated to 2024.
- **Operation costs:** The annual operating costs have been evaluated in 2025 according to common standards for CERN projects, e.g. CLIC.

Superconducting RF as initial technology Aiming for a minimal time to physics, we see a strategic advantage in choosing an accelerator based on superconducting radio-frequency cavities (SCRF) for the first stage. By now, many SCRF-based accelerators are being built or successfully operated (e.g. Eu.XFEL, LCLS-II, SHINE) and the corresponding technological expertise and industrialisation is available in laboratories and companies around the world. In addition, SCRF technology has seen important developments towards higher gradients and higher quality factors (for a recent summary of the state-of-the-art c.f. [6]). In particular, a factor of two improvement in quality factors over the specification chosen about 15 years ago for ILC is now reliably achievable with a small modification of the cavity production recipe. The alternative possibility of starting with warm technology is discussed in the CLIC submission to the ESPPU [15, 18].

We envision that succeeding stages of the programme will bring in new accelerator technologies that are now under development. We plan to build on the original footprint of the Linear Collider Facility using technical innovation without requiring new civil construction. Decisions for these stages can be deferred until the 2030s and beyond. We will describe some of the upgrade possibilities in Sec. 4.

The first-stage LCF configuration We propose a facility with a site length of 33.5 km, including a 5 km beam delivery region sized for up to 3 TeV collisions. We plan that the project will include two interaction points, which would share the collider luminosity. We note that both ILC and CLIC have produced beam delivery system (BDS) designs with two interaction points.[1] For the initial technology, we propose superconducting cavities with a gradient of 31.5 MV/m, as developed for the ILC, but with a quality factor Q_0 of 2×10^{10}. At its first stage, this facility would be equipped to reach a centre-of-mass energy of 250 GeV, with both beams polarised ($|P(e^-, e^+)| = (80\%, 30\%)$), leaving part of the tunnel equipped only with a transfer line. As we will discuss below, this approach allows to flexibly increase the centre-of-mass energy up to 550 GeV by installing more accelerating modules at any time, at a speed adjustable to availability of resources (e.g. from non-member-states, which in this scenario could contribute additional cryomodules from their local industries in-kind) and scientific competition.

The RF and cooling systems will provide for trains of 1312 bunches ($n_e = 2 \times 10^{10}$ per bunch) with a repetition rate of 10 Hz, resulting in an instantaneous luminosity of $2.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a factor of two higher than for the ILC as proposed in Japan. The construction cost of this baseline configuration, without the detectors, is 8.3 BCHF; the total required AC site power is 143 MW.

An attractive upgrade, either immediately if resources allow, or after a few years of running, is a further doubling of the luminosity to $5.4 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by doubling the number of bunches per train. This would add 0.77 BCHF to the accelerator construction cost, and increase the required site power to 182 MW.

On the other hand, reducing the facility length to 20.5 km, imposing the use of a novel technology (c.f. Sec. 4) to go beyond a centre-of-mass energy of 250 GeV, would reduce the initial cost by about

[1] The ILC BDS has been designed for up to 1 TeV, the CLIC BDS for up to 3 TeV. The precise BDS design for our proposal would still need to be optimised based on the existing ILC/CLIC designs.

Quantity	Symbol	Unit	Initial-250	Upgrades		Initial-550	Upgrade
Centre-of-mass energy	$\sqrt{s}$	GeV	250	250	550	550	550
Inst. Luminosity	$\mathscr{L}$	$(10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	2.7	5.4	7.7	3.9	7.7
Polarisation	$\lvert P(e^-)\rvert / \lvert P(e^+)\rvert$	(%)	80 / 30	80 / 30	80 / 60	80 / 30	80 / 60
Bunches per pulse	n_{bunch}	1	1312	2625	2625	1312	2625
Average beam power	P_{ave}	MW	10.5	21	46	23	46
Site AC power	P_{site}	MW	143	182	322	250	322
Construction cost		BCHF	8.29	+0.77	+5.46	13.13	+1.40
Operation & maintenance		MCHF/y	170	196	342	291	342
Electricity		MCHF/y	66	77	142	115	142
Operating Personnel		FTE	640	640	850	850	850

Table 1: Summary table of the LCF accelerator parameters in the initial 250 GeV configuration (4th column) and possible upgrades (first to 2625 bunches per train, then to 550 GeV), as well as a configuration for starting directly at 550 GeV with 1312 bunches (7th column) and its upgrade to 2625 bunches per train. All options based on a 33.5 km long facility.

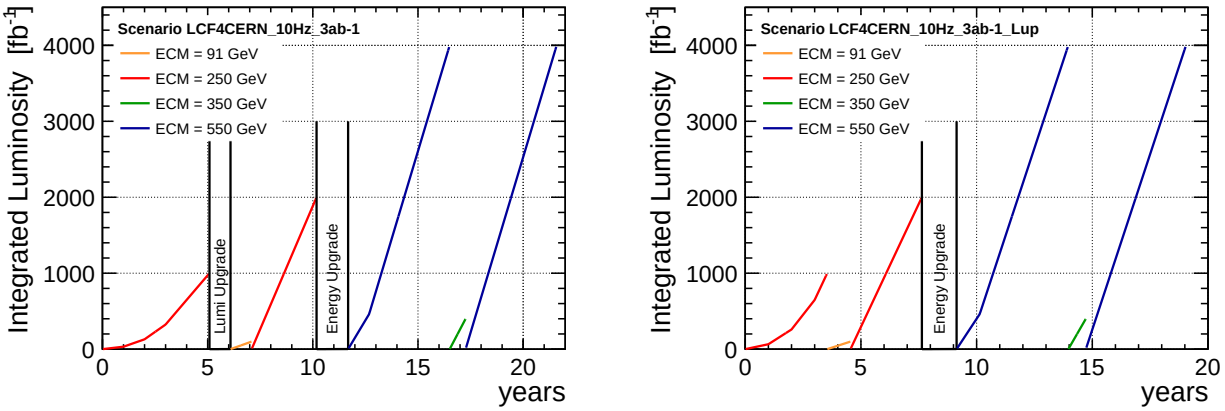
0.7 BCHF; removing the second beam delivery system saves about 0.3 BCHF; reducing the repition rate to 5 Hz saves about 0.5 BCHF. Thus a minimal 250 GeV machine would cost 6.8 BCHF.

The second-stage LCF configuration In the 33.5 km facility, a centre-of-mass energy of at least 550 GeV can be reached by equipping the additional tunnel length with further SCRF accelerator modules. This would require an additional 5.5 BCHF, assuming that the same production facilities as for the initial stage cryomodules can be reused. With a total AC power of 322 MW an instantaneous luminosity of $7.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ would be achieved. After several years of experience with operating the positron source in the more challenging 250 GeV configuration, the positron polarisation can be increased to $|P(\mathrm{e}^+)| = 60\%$ [16] for the 550 GeV stage. Table 1 summarises some key parameters for these scenarios. A more comprehensive version of the table can be found in the back-up document [12].

Run Plan Figure 2(a) shows a possible run plan starting with the 250 GeV machine with 1312 bunches per train, and including a luminosity upgrade to 2625 bunches per train as well as an energy upgrade to 550 GeV. Figure 2(b) shows the impact on the real time needed for the same total luminosities, but starting immediately with 2625 bunches per train. More possible data-taking scenarios are discussed in [6].

In Fig. 1, we showed the expected uncertainties on Higgs boson couplings that the run plan in Fig. 2 would provide. We highlight here that with the envisioned $8\,\mathrm{ab}^{-1}$ at 550 GeV and $|P(e^-, e^+)| = (80\%, 30\%)$, the Higgs self-coupling can be measured with a precision of 11 %, and the top Yukawa coupling to 2 %, both improving further with $|P(e^+)| = 60\%$.

Start at 550 GeV Should the scientific and/or strategic need arise, the purchase and installation of a sufficient number of acceleration modules for reaching 550 GeV (or as an intermediate step the $\mathrm{t\bar{t}}$ production threshold) could be advanced – provided sufficient resources are made available. In such a scenario, the operation of the collider facility could start directly at 550 GeV, providing a set of measurements complementary to those at lower centre-of-mass energies, listed in the second bullet of Section 2. This starting point offers the flexibility to optionally collect polarised data at lower energies if the scientific need arises, or to directly increase the centre-of-mass energy further with one of the technology upgrade options discussed in the following section, addressing the programme



(a) (b)

Figure 2: Two of the suggested run plans for a CERN linear collider, based on 1.2×10^7 s operation time per year, and including assumptions on performance ramp-up analogously to [19]. (a) starting in the "low-power" configuration (b) starting directly with the "full-power" option. The technical time zero would be close to 2044.

outlined in the third bullet of Section 2. Constructing the 550 GeV machine immediately would require 13.8 BCHF for operation with 1312 bunches per train, which includes costs for creating twice the production capacity. Upgrading the power to double the luminosity (2625 bunches per train) costs an additional 1.4 BCHF.

Beyond a collider A linear collider facility offers the opportunity to cater to a diverse "beyond collider" programme, including beam dump experiments with several 10^{21} electrons / positrons on-target per year, experiments with beam extracted before the collisions for fixed target experiments, test beams and irradiation facilities as well as large scale accelerator R&D. The R&D and physics opportunities, spanning from light new particle searches to strong-field QED, are described in more detail in [6]. The necessary underground construction is best done together with the initial facility, based on a design to be developed together with the "beyond colliders" community. Since no detailed designs exist yet, the "beyond colliders" facilities are not included in the costing.

4 Upgrade Scenarios for the Linear Collider Facility

As we emphasised in the previous section, energy upgrades of the Linear Collider Facility would be achieved with technological progress rather than with new civil construction. The proposed facility offers numerous options to increase the energy, the luminosity and/or the type of colliding particles. Choices can be made at later stages taking into account scientific and technological developments – or even revolutions. We give here a brief summary of the opportunities described in [6].

4.1 Energy upgrades beyond 550 GeV

There are four technical solutions now under consideration to reach much higher accelerating gradients, targeting gradients of at least 70 MV/m, reaching up to 155 MV/m. An accelerator with these gradients would reach a centre-of-mass energy between 1 and 3 TeV in the 33.5 km tunnel. For the first two technologies, this gradient has already been achieved and substantially exceeded in test modules. All four technologies have fully engaged R&D programmes that should reach maturity

by the early 2030s. Once the construction of the first-stage LCF has begun, CERN can evaluate these options to find the best solution. One should remember that, in the ILC design, the actual linear accelerator accounts for less than half the project cost. Depending on the chosen technology, not only the tunnel but also damping rings, transfer lines, BDS elements etc., can be re-used. Such an upgrade is expected to be substantially more cost-effective and sustainable than building a facility from scratch. The LCVision document [6] gives a more detailed description of the accelerator technologies, status of the accelerator R&D, and plans for re-use of the first-stage linear collider elements in each of these cases.

- **CLIC technology**: By replacing the SCRF linacs with an X-band accelerator with CLIC-like cavities [20], running at a gradient of 72 MV/m a centre-of-mass energy of about 1.5 TeV could be reached in the LCF.
- **C^3 technology**: Alternatively, the SCRF linacs could be replaced with a C-band copper accelerator using the innovations of distributed coupling and cryogenic liquid N_2 operation envisioned for the C^3 proposal [21, 22]. Depending on the future achievable gradient and advances in high-efficiency RF sources, centre-of-mass energies between 1.5 TeV and 3 TeV could be reached in the LCF [23].
- **HELEN technology**: By replacing the initial SCRF with travelling-wave Nb cavities with gradients of 60 MV/m, like in the HELEN proposal [24, 25], a centre-of-mass energy of at least 1 TeV could be reached in the LCF.
- **Nb_3Sn technology**: Advanced superconducting technology based on the use of Nb_3Sn [26] can reach gradients as high as 90 – 100 MV/m. Once these become application-ready, a centre-of-mass energy of at least 1.5 TeV could be reached in the LCF.

4.2 Additional upgrade paths

Either further raising centre-of-mass energy or addressing other technical goals may benefit the study of Higgs bosons and other particle physics reactions. Solutions directed at these goals are less developed than the options just discussed, but they could become relevant in later stages of the Higgs factory programme.

A linear collider with two interaction regions can share luminosity between these regions in an arbitrary ratio, and can also allow the two regions to see collisions of different kinds of particles, e.g. photons. Alternatively to sharing the e^+e^- luminosity equally between two detectors, the CERN Linear Collider Facility could operate with one interaction region dedicated to accumulating luminosity while the other interaction region serves also as a development platform for new concepts, which eventually would be applied in upgrades of the facility.

There are three approaches that are now under consideration (for more details, and in particular a discussion of their application in the context of the CERN Linear Collider Facility, see [6]):

- **Photon collider**: Observing the Higgs boson in $\gamma\gamma$ collisions adds a new set of processes with powerful observables complementary to those available in e^+e^- collisions. In particular, the Higgs self-coupling can be (re-)measured at lower centre-of-mass energy in $\gamma\gamma \to HH$. At the LCF, one of the interaction points could host a $\gamma\gamma$ collider either based on the classic scheme with optical lasers or on X-ray lasers as in the XCC design [27].
- **Energy and particle recovery**: At a linear collider, the luminosity is proportional to the beam power. A superconducting accelerator can in principle recover and reuse the beam power and even the beam particles, to produce luminosities up to $10^{36}\,cm^{-2}s^{-1}$, for instance in a scheme like ReLiC [28] or ERLC [29].

- **Plasma wakefield acceleration**: By offering accelerating gradients of several GV/m, this technology opens a route to much higher energies. At the LCF, it could provide higher energies by adding plasma cells to the electron arm of a conventional accelerator producing asymmetric collisions à la HALHF [30–32]. For the longer future, it may make possible e^+e^- or $\gamma\gamma$ colliders with energies of 10 TeV and above [33–35]. At CERN, also p-driven PWA [36] is an option.

4.3 Beyond the Linear Collider Facility

As "high-energy" physicists, we are dedicated to the exploration of increasingly higher energies. It is important, then, to have a path to a collider operating at the 10 TeV parton energy scale. Today, we do not have any accelerator technology that can achieve this for a reasonable cost. Substantial, and expensive, accelerator R&D is required. Three paths are being pursued, with high-field magnets for a proton collider, with muon cooling for a muon collider, and with plasma wakefield acceleration for an e^+e^- or $\gamma\gamma$ collider. Funding for all three R&D paths needs to be increased. It is important that CERN retain enough financial headroom beyond immediate projects to undertake this R&D. This will be especially critical when these approaches require major technology demonstrators. In the 2030s, we will see a competition for resources between Higgs factory construction and R&D toward a 10 TeV technology. We are pleased that R&D for all three approaches is pursued in the framework of the accelerator roadmap of the European Lab Directors Group [37]. The cost must be shared globally, but Europe can best play its part by opting for a staged and flexible Higgs factory plan.

5 Next Steps Towards a Linear Collider Facility for CERN

The project implementation for the LCF foresees two preparation phases of three and five years, respectively:

Phase 1, ideally starting directly in 2026 after the finalisation of the EPPSU, builds on and integrates the on-going work of the ILC Technology Network (ITN) on the key technologies [14, 38], complementing it with siting and implementation studies, in parallel with design and technical studies to determine and confirm the final LCF parameters. This phase is required to prepare a project decision by CERN Council, which is not expected before 2028, and should deliver the following:

- **Final placement of the collider complex** and its infrastructure after assessment of their territorial compatibility, both for its initial phase and potential upgrades. Preparation and documentation for wider implementation studies with the host regions / states in Phase 2.
- **Optimisation of LCF design:** Review of the accelerator design along with updated cost, power and risk assessments, including in particular
  - a detailed study of the interaction region for two experiments – including re-optimised beam delivery systems – that is suitable for an initial SCRF-based accelerator as well as for future technology upgrades like CLIC, C^3, ERLs or PWA;
  - studies of the implications for civil engineering and the equipment used in the initial SCRF-based facility, in order to allow collider upgrades in the future, and to accommodate the "beyond colliders" physics described in Sec. 4;
  - design and parameter optimisation of the entire machine including further nanobeam studies, and further R&D on key components.

The estimated resources needed for Phase 1 are 35 MCHF material and 180 FTEy of personnel effort, in addition to the ITN efforts that are of the same size.

Phase 2 requires a formal decision to proceed with the project. It targets the final engineering design, larger industrial pre-series and an extensive site preparation, in particular

- SCRF industrialisation of a design based on more ambitious goals for cavity quality factors (Q_0) and power (klystron) efficiency, with higher repetition rate and hence cryogenic needs than foreseen in the ILC TDR design. This task builds on the work of the ITN [38];
- detailed studies of the cryogenics system and infrastructure systems (e.g. cooling and ventilation, electrical, access and safety systems, transport and installation) adapting them to standard solutions used by CERN and industry;
- final site preparation including documentation and specifications for the time-critical civil engineering contracts.
- environmental studies and integration of the collider in the local area with the host states.

The estimated resources needed for Phase 2 are 120 MCHF for pre-series production and 420 FTEy of personnel effort for the technical studies, pre-series, engineering design and laboratory infrastructure. With the widespread expertise built up worldwide for SCRF-based free-electron lasers (e.g. the Eu.XFEL or LCLS-II) as well as for the ILC, a significant part of this work can be done outside CERN for an LCF starting with SCRF technology. In parallel, civil engineering preparation including continued environmental studies will require significant resources, typically 5% of the civil engineering budget.

During the preparation period, detector collaborations need to be prepared and set up, building on the well developed detector concepts for Higgs factories, yet embracing new ideas.

Construction could start earliest in 2034, preceded by a formal decision by CERN Council. Note further that in the current planning laid out in the addendum, the construction time is increased beyond the purely technical limitation of eight years to ten years in order to accommodate the fact that the transition between phases might require some time, and also to avoid the clear conflict between HL-LHC operation and beam commissioning of a new collider.

6 Conclusions

In this report, we have outlined a proposal for a cost-effective, staged construction of a Linear Collider Facility at CERN that will be able to comprehensively map the Higgs boson's properties, including the Higgs field potential, and to account for potential discoveries at the HL-LHC. The need for a Higgs factory for the global particle physics community is urgent. This is the key to solving the most important mysteries left unresolved by the Standard Model. The Higgs boson is the most likely particle to couple to new fundamental interactions, yet, still, it is the least studied.

The programme that we have put forward, spanning centre-of-mass energies from the Z pole to at least 1 TeV, is attentive to the requirements for making a true discovery from precision measurements. Its variety of precision observables allows deviations from the Standard Model to be measured in different ways that can be cross-checked against one another. The discovery of deviations from the Standard Model – or, better, a pattern of deviations in different Higgs couplings – will guide us to the discovery of new fundamental laws operating at higher energies.

A new generation of particle physicists, brought up with the LHC, will need a well-defined and timely plan towards new opportunities once the HL-LHC ends. Our staged and flexible programme provides a conservative yet upgradable starting point that can be constructed on the timescale of the HL-LHC, and can be the site to realise ambitious new accelerator and detector technologies. It can host continued strong R&D on advanced accelerator concepts and a suite of smaller-scale

experiments. The advanced stages of our programme will give targets for technical developments that will be useful to the particle physics community, to other scientific fields, and potentially to society in general.

The Linear Collider Facility proposed in this document will be an excellent flagship project for CERN. It addresses all of the issues associated with the next CERN project and provides a route to the higher-energy colliders of the future. This is the project that CERN and the global particle physics community needs now.

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