This document provides input from the CLIC \( e^+e^- \) linear collider studies to the update process of the European Strategy for Particle Physics. It is submitted on behalf of the CLIC/CTF3 collaboration and the CLIC physics and detector study.

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1 Introduction

The Compact Linear Collider (CLIC) is a TeV-scale high-luminosity linear \( e^+e^- \) collider under development. It is based on a novel two-beam acceleration technique providing acceleration gradients at the level of 100 MV/m. A high-luminosity high-energy \( e^+e^- \) collider allows for the exploration of Standard Model (SM) physics, such as precise measurements of the Higgs, top and gauge sectors, as well as for a multitude of searches for New Physics, either through direct discovery or indirectly, via high-precision observables. Given the current state of knowledge, following the observation of a \( \sim 125 \) GeV Higgs-like particle at the LHC, and pending further LHC results at 8 TeV and 14 TeV, a linear \( e^+e^- \) collider built and operated in centre-of-mass energy stages from a few-hundred GeV up to a few TeV will be an ideal physics exploration tool, complementing the LHC.

This document provides short summaries of the CLIC accelerator design, performances and implementation studies, the layout and performances of the CLIC experiments under study and the projected CLIC physics potential, followed by an outlook on the CLIC programme in the coming years. For more detailed descriptions we refer to the following documents:

- The Physics Case for an \( e^+e^- \) Linear Collider, eds. J. Brau et al., submitted to the update process of the European Strategy for Particle Physics, July 2012 [1];
- A Multi-TeV Linear Collider based on CLIC Technology, CLIC Conceptual Design Report, 2012, eds. M. Aicheler et al. [2];
- Physics and Detectors at CLIC, CLIC Conceptual Design Report, eds. L. Linssen et al. [3];
- The CLIC Programme: towards a staged \( e^+e^- \) Linear Collider exploring the Terascale, CLIC Conceptual Design Report, 2012, eds. P. Lebrun et al. [4].

The above CLIC CDR reports are supported by more than 1300 signatories\(^1\) from the world-wide particle physics community.

2 Accelerator Complex

The CLIC layouts at 500 GeV and 3 TeV are shown in Figures 1 and 2, respectively, and the key parameters are given in Tables 1 and 2. The conceptual design is detailed in [2] and [4]. The CLIC design is based on three key technologies, which have been addressed experimentally:

- The use of normal-conducting accelerating structures in the main linac with a gradient of 100 MV/m, in order to limit the length of the machine. The RF frequency of 12 GHz and detailed parameters of the structure have been derived from an overall cost optimisation at 3 TeV. Experiments at KEK, SLAC and CERN verified the structure design and established its gradient and breakdown-rate performance.

\(^1\)https://edms.cern.ch/document/1183227/
The use of drive beams that run parallel to the colliding beams through a sequence of power extraction and transfer structures, where they produce the short, high-power RF pulses that are transferred into the accelerating structures. These drive beams are generated in a central complex. The drive-beam generation and use has been demonstrated in a dedicated test facility (CTF3) that has been constructed and operated for many years at CERN by the CLIC/CTF3 collaboration.

The high luminosity that is achieved by the very small beam emittances, which are generated in the damping rings and maintained during the transport to the collision point. These emittances are ensured by appropriate design of the beam lines and tuning techniques, as well as by a precision pre-alignment system and an active stabilisation system that decouples the magnets from the ground motion. Prototypes of both systems have demonstrated performance close to or better than the specifications.
Related system parameters have been benchmarked in CTF3, in advanced light sources, ATF(2) and CesrTA, and in other setups. In addition, a broad technical development programme has successfully addressed many critical components. Among them are those of the main linac, which are most important for the cost, and their integration into modules. The drive-beam components have largely been addressed in CTF3. Other performance-critical components have been developed and tested, e.g., the final focus magnets, which will be located in the detector and need to provide a very high field, and high-field damping ring wigglers, which rapidly reduce the beam emittances. Design studies foresee 80% polarisation of the electrons at collision, and the layout is compatible with addition of a polarised positron source. The successful validation of the key technologies and of the critical components establish confidence that the CLIC performance goals can be met.

Several of these technologies have applications for and are being developed with other communities, e.g., synchrotron light sources, free electron lasers and medical accelerators.

Detailed site studies show that CLIC can be implemented underground near CERN, with the central main and drive beam complex on the CERN domain, as shown in Figure 3. The site specifications do not constrain the implementation to this location.

As indicated above, the current CLIC parameters are the result of a cost optimisation at 3 TeV, see Chapter 2.1 in [2]. However, the technology can be used effectively over a wide range of centre-of-mass energies. The project can be built in energy stages, which can re-use the existing equipment for each new stage. At each energy stage the centre-of-mass energy can be tuned to lower values within a range of a factor three and with limited loss on luminosity performance. Two example scenarios of energy staging are given in [4] with stages of 500 GeV, 1.4 (1.5) TeV and 3 TeV, see Table 1 for scenario A and Table 2 for scenario B. For both scenarios the first and second stage use only a single drive-beam generation complex to feed both linacs, while in stage 3 each linac is fed by a separate complex. Based on future physics findings, the choice of energy stages will be reviewed and the design optimised. In case of growing interest in a lower energy Higgs factory, studies of a klystron-based initial stage with a faster implementation could become part of this evaluation.
### Table 1: Parameters for the CLIC energy stages of scenario A.

| Parameter                        | Symbol | Unit      | Stage 1 | Stage 2 | Stage 3 |
|----------------------------------|--------|-----------|---------|---------|---------|
| Centre-of-mass energy           | $\sqrt{s}$ | GeV      | 500     | 1400    | 3000    |
| Repetition frequency            | $f_{\text{rep}}$ | Hz      | 50      | 50      | 50      |
| Number of bunches per train     | $n_b$  |           | 354     | 312     | 312     |
| Bunch separation                | $\Delta t$ | ns       | 0.5     | 0.5     | 0.5     |
| Accelerating gradient           | $G$    | MV/m     | 80      | 80/100  | 100     |
| Total luminosity                | $\mathcal{L}$ | $10^{34}$ cm$^{-2}$s$^{-1}$ | 2.3     | 3.2     | 5.9     |
| Luminosity above 99% of $\sqrt{s}$ | $\mathcal{L}_{0.01}$ | $10^{34}$ cm$^{-2}$s$^{-1}$ | 1.4     | 1.3     | 2       |
| Main tunnel length              | km     |           | 13.2    | 27.2    | 48.3    |
| Charge per bunch                | $N$    | $10^9$   | 6.8     | 3.7     | 3.7     |
| Bunch length                    | $\sigma_z$ | µm      | 72      | 44      | 44      |
| IP beam size                    | $\sigma_z/\sigma_y$ | nm     | 200/2.6 | ~ 60/1.5 | ~ 40/1 |
| Normalised emittance (end of linac) | $\varepsilon_z/\varepsilon_y$ | nm | 2350/20 | 660/20 | 660/20 |
| Normalised emittance (IP)       | $\varepsilon_z/\varepsilon_y$ | nm | 2400/25 | —      | —      |
| Estimated power consumption     | $P_{\text{wall}}$ | MW     | 272     | 364     | 589     |

Staging scenario A aims at achieving high luminosity at 500 GeV collision energy with increased beam current. This requires larger apertures in the accelerating structures which therefore operate at a lower gradient. The re-use of these structures in the second stage limits the achievable collision energy to 1.4 TeV. Staging scenario B aims at reducing the cost of the 500 GeV stage using full-gradient accelerating structures at nominal beam current, resulting in lower instantaneous luminosity. The re-use of these structures allows reaching 1.5 TeV collision energy in the second stage.

### Table 2: Parameters for the CLIC energy stages of scenario B.

| Parameter                        | Symbol | Unit      | Stage 1 | Stage 2 | Stage 3 |
|----------------------------------|--------|-----------|---------|---------|---------|
| Centre-of-mass energy           | $\sqrt{s}$ | GeV      | 500     | 1500    | 3000    |
| Repetition frequency            | $f_{\text{rep}}$ | Hz      | 50      | 50      | 50      |
| Number of bunches per train     | $n_b$  |           | 312     | 312     | 312     |
| Bunch separation                | $\Delta t$ | ns       | 0.5     | 0.5     | 0.5     |
| Accelerating gradient           | $G$    | MV/m     | 100     | 100     | 100     |
| Total luminosity                | $\mathcal{L}$ | $10^{34}$ cm$^{-2}$s$^{-1}$ | 1.3     | 3.7     | 5.9     |
| Luminosity above 99% of $\sqrt{s}$ | $\mathcal{L}_{0.01}$ | $10^{34}$ cm$^{-2}$s$^{-1}$ | 0.7     | 1.4     | 2       |
| Main tunnel length              | km     |           | 11.4    | 27.2    | 48.3    |
| Charge per bunch                | $N$    | $10^9$   | 3.7     | 3.7     | 3.7     |
| Bunch length                    | $\sigma_z$ | µm      | 44      | 44      | 44      |
| IP beam size                    | $\sigma_z/\sigma_y$ | nm     | 100/2.6 | ~ 60/1.5 | ~ 40/1 |
| Normalised emittance (end of linac) | $\varepsilon_z/\varepsilon_y$ | nm | —      | 660/20 | 660/20 |
| Normalised emittance (IP)       | $\varepsilon_z/\varepsilon_y$ | nm | —      | —      | —      |
| Estimated power consumption     | $P_{\text{wall}}$ | MW     | 235     | 364     | 589     |

Possible operating scenarios for the complete CLIC programme are sketched in Figure 4: the duration of each stage is defined by the integrated luminosity targets of 500 fb$^{-1}$ at 500 GeV, 1.5 ab$^{-1}$ at 1.4 (1.5) TeV and 2 ab$^{-1}$ at 3 TeV collision energy. The integrated luminosity in the first stage can be
obtained for scenario B by operating for two more years; this is partly regained in the next stage, so that the overall duration of the three-stage programme is comparable for both cases, about 24 years from start of operation.

Construction schedules (Figure 5) are essentially driven by civil engineering, infrastructure and machine installation. Production of the large-series components proceeds at rates such that they become available for installation as soon as preceding construction activities allow it. In the first stage, construction of the injector complex, experimental area and detectors just matches the construction time for the main linacs, thus allowing commissioning with beam to start in year 7. In order to minimize interruption of operation for physics, civil engineering and series component production for the second stage must re-start in year 10, thus allowing commissioning in year 15 (scenario A): this can be achieved without interference with operation for physics in the first stage.

The nominal electrical power consumption of all accelerator systems and services, including the experimental area and the detectors and taking into account network losses for transformation and distribution on site, is given in Table 3 for staging scenarios A and B. The table also shows residual power consumption without beams for two modes corresponding to short (“waiting for beam”) and long (“shutdown”) beam interruptions. The large variations and volatility of power consumption will allow CLIC to be operated as a peak-shaving facility, matching the daily and seasonal fluctuations in power demand on the network. Several paths aiming at reducing power consumption or improving the energy footprint of the machine have been identified and are under investigation, e.g., reduction of design current density in magnet windings and cables, replacement of normal-conducting by permanent or superferric magnets, development of high-efficiency klystrons and modulators, recovery and valorisation of waste heat.

The cost estimates follow the “value” and “explicit labour” methodology used for the ILC Reference Design report [5]. They are based on the work breakdown structures established for the different stages of the two scenarios, and on unit costs obtained for other similar supplies or scaled from them, and from specific industrial studies. Uncertainties include technical and procurement risks, the latter being estimated from a statistical analysis of procurement for the LHC. The value estimates are expressed in Swiss francs (CHF) of December 2010 and can thus be escalated using relevant Swiss official indices. Explicit labour is estimated globally by scaling from LHC experience. The results are given in Table 4. The cost structure of the accelerators at 500 GeV collision energy for staging scenarios A and B is illustrated in Figure 6. The incremental value from the first to the second stage is about 4 MCHF/GeV
Fig. 5: Overall “railway” schedule for the first two stages of scenario A. The horizontal scale is proportional to tunnel length, with the experimental area in the centre. The vertical scale shows years from the start of construction. The construction schedule for the main-beam, the drive-beam injectors and the experimental area are shown in the centre.

Table 3: CLIC power consumption for staging scenarios A and B.

| Staging scenario | √s [TeV] | P_{nominal} [MW] | P_{waiting for beam} [MW] | P_{shutdown} [MW] |
|------------------|---------|------------------|--------------------------|------------------|
| A                | 0.5     | 272              | 168                      | 37               |
|                  | 1.4     | 364              | 190                      | 42               |
|                  | 3.0     | 589              | 268                      | 58               |
| B                | 0.5     | 235              | 167                      | 35               |
|                  | 1.5     | 364              | 190                      | 42               |
|                  | 3.0     | 589              | 268                      | 58               |

Table 4: Value and labour estimates of CLIC 500 GeV.

| Staging scenario | Value [MCHF] | Labour [FTE years] |
|------------------|--------------|--------------------|
| A                | 8300^{+1900}_{−1400} | 15700              |
| B                | 7400^{+1700}_{−1400} | 14100              |

(scenario B). Potential savings have been identified for a number of components and technical systems, amounting to about 10% of the total value. Examples of such savings are the substitution of the hexapods for the stabilisation of the main-beam quadrupoles with beam steering, the doubling in length of the support girders for the two-beam accelerator modules, or the alternative of using assembled quadrants instead of stacked disks for construction of the accelerating structures. Moreover, significant additional savings are expected from re-optimising the design of the chosen energy stages.
3 Detectors

The detector requirements and resulting layout proposals discussed in the following are based on the final 3 TeV accelerator stage, which constitutes the most challenging environment for the detectors.

**Detector Requirements**

The performance requirements for the detector systems at CLIC are driven by the physics goals described in Section 4. The jet-energy resolution should be adequate to distinguish between di-jet pairs originating from \(Z\), \(W\) or \(H\) bosons. This can be achieved with a resolution of \(\sigma_E / E \sim 3.5\% - 5\%\) for jet energies from 1 TeV down to 50 GeV. The momentum-resolution requirement for the tracking systems is driven by the precise measurement of leptonic final states, e.g., the Higgs mass measurement through \(Z\) recoil, where \(Z^0 \rightarrow \mu^+ \mu^-\), or the determination of slepton masses in SUSY models. This leads to a required resolution of \(\sigma_p / p_T \sim 2 \times 10^{-5}\) GeV\(^{-1}\). High-resolution pixel vertex detectors are required for efficient tagging of heavy quarks through displaced vertices, with an accuracy of approximately 5 \(\mu m\) for determining the transverse impact parameters of high-momentum tracks and a multiple scattering term of approximately 15 \(\mu m\). The latter requires a very low material budget at the level of \(< 0.2\%\) of a radiation length per detection layer, corresponding to a thickness equivalent to less than 200 \(\mu m\) of silicon, shared by the active material, the readout, the support and the cooling infrastructure.

The time structure of the collisions, with bunch crossings spaced by only 0.5 ns, in combination with the expected high rates of beam-induced backgrounds, poses challenges for the design of the detectors and their readout systems. At most one interesting physics event per 156 ns bunch train is expected, overlaid by an abundance of particles originating from two-photon interactions. These background particles will lead to large occupancies in the inner and forward detector regions and will require time stamping at the 1–10 ns level in most detectors, as well as sophisticated pattern-recognition algorithms to disentangle physics from background events. The gap of 20 ms between consecutive bunch trains will be used for trigger-less readout of the entire train. Furthermore, most readout subsystems will be operated in a power-pulsing mode with the most power-consuming components switched off during the 20 ms gaps, thus taking advantage of the low duty cycle of the machine to reduce the required cooling power.

**Detector Concepts**

The detector concepts ILD [6] and SiD [7] developed for the International Linear Collider (ILC) at a centre-of-mass energy of 500 GeV form the starting point for the two general-purpose detector concepts CLIC_ILD and CLIC_SiD. Both detectors will be operated in one single interaction region in an alternating mode, moving in and out every few months through a so-called push-pull system. The main
CLIC-specific adaptations to the ILC detector concepts are an increased hadron-calorimeter depth to improve the containment of jets at the CLIC centre-of-mass energy of up to 3 TeV and a redesign of the vertex and forward regions to mitigate the effect of high rates of beam-induced backgrounds.

Figure 7 shows cross-section views of CLIC_ILD and CLIC_SiD. Both detectors have a barrel and endcap geometry with the barrel calorimeters and tracking systems located inside a superconducting solenoid providing an axial magnetic field of 4 T in case of CLIC_ILD and of 5 T in case of CLIC_SiD.

The highly granular electromagnetic and hadronic calorimeters (ECAL/HCAL) of both detectors are designed for the concept of particle-flow calorimetry, allowing one to reconstruct individual particles combining calorimeter and tracking information and thereby improving the jet-energy resolution to the required unprecedented levels. The total combined depth of the ECAL and HCAL is about 8.5 hadronic interaction lengths, realised by changing the HCAL absorber material from steel to tungsten in the barrel layers.

In the CLIC_ILD concept, the tracking system is based on a large Time Projection Chamber (TPC) with an outer radius of 1.8 m complemented by an envelope of silicon strip detectors and by a silicon pixel vertex detector. The all-silicon tracking and vertexing system in CLIC_SiD is more compact with an outer radius of 1.3 m.

The vertex detectors foresee semiconductor technology with pixels of approximately 20 µm × 20 µm size. In case of CLIC_ILD, both the barrel and forward vertex detectors consist of three double layers, while for CLIC_SiD, a geometry with five single barrel layers and seven single forward layers was chosen. The high rates of incoherently produced electron-positron pair-background events constrain the radius of the central beam pipes to 29 mm for CLIC_ILD and to 25 mm for CLIC_SiD. For the initial 500 GeV machine, the lower background rates allow for modified vertex-detector geometries with reduced inner radii.

The superconducting solenoids are surrounded by instrumented iron yokes allowing one to measure punch-through from high-energy hadron showers and to identify muons. Two small electromagnetic calorimeters cover the very forward regions down to 10 mrad. They are foreseen for electron tagging and for an absolute measurement of the luminosity through Bhabha scattering.

Full detector simulation studies with event reconstruction demonstrate that both detector proposals meet the performance requirements and that physics observables can be measured to high precision.
Preliminary value estimates aiming for an uncertainty of ±30% and following the general methodology used for the accelerators place the CLIC_ILD detector at 560 MCHF and the CLIC_SiD detector at 360 MCHF, excluding explicit labour\textsuperscript{2}. Main cost drivers for both concepts are the cost of silicon sensors for the ECAL, and of tungsten for the HCAL.

**Suppression of Beam-induced Background**

Even at 3 TeV, the high levels of beam-induced background can be suppressed by making use of the high spatial and temporal granularity provided by the detectors. For this, a scheme was developed, which considers time stamping capabilities of 10 ns for all silicon tracking elements, and of 1 ns time resolution for all calorimeter hits. Broad timing cuts around the time of the physics event, identified offline, are followed by a tighter set of cuts applied to reconstructed low-\(p_T\) particle-flow objects. As a result, the average background level can be reduced from approximately 20 TeV per bunch train to about 100 GeV per reconstructed physics event. This background rejection, which is exemplified in Figure 8, is achieved without significantly impacting the detector performance.

![Fig. 8: Left: Reconstructed particles in a simulated \(e^+e^-\rightarrow t\bar{t}\) event at 3 TeV in the CLIC_ILD detector concept with background from \(\gamma\gamma\rightarrow\) hadrons overlaid. Right: The effect of applying tight timing cuts on the reconstructed cluster times.](image)

4 **Physics Potential**

Recently the ATLAS and CMS collaborations have announced evidence for a state consistent with a SM Higgs boson with a mass of 125 GeV. The production cross-sections as a function of \(e^+e^-\) centre-of-mass energy of a SM Higgs boson of that mass is given in Figure 9 (left). The cross-sections are in the hundreds of fb. Therefore, tens of thousands of events can be obtained with hundreds of fb\textsuperscript{-1} of integrated luminosity, which is anticipated for CLIC running.

CLIC is able to measure this boson’s couplings to SM states with extraordinary precision. A summary of Higgs observables and the precision with which they can be determined is provided in Table 5. These numbers are obtained from studies that employ full detector simulations with backgrounds overlaid. For several standard channels the statistical error is at the percent level. For other channels, such as the low-rate \(H \rightarrow \mu^+\mu^-\) and the Higgs pair production, both of which will be severe challenges for the LHC, the statistical error is near the 20% level. These levels of precision, which generally go well beyond LHC capabilities, are needed to resolve the subtle shifts in Higgs boson couplings that are present in many beyond the SM theories.

\textsuperscript{2}The preliminary CLIC detector value estimates were extrapolated, for their major part, from the ILC LoI cost estimates, taking the significant changes (technology, dimensions) for CLIC into account and using modified unit costs. Therefore they cannot be directly compared with the ILC estimates.
Fig. 9: Left: Production cross-sections of the SM Higgs boson in $e^+e^-$ collisions as a function of $\sqrt{s}$ for $m_H = 125$ GeV. Right: SUSY production cross-sections of model III as a function of $\sqrt{s}$. Every line of a given colour corresponds to the production cross-section of one particle in the legend.

Table 5: Summary of results obtained in the Higgs studies for $m_H = 120$ GeV. All analyses at centre-of-mass energies of 350 GeV and 500 GeV assume an integrated luminosity of 500 fb$^{-1}$, while the analyses at 1.4 TeV (3 TeV) assume 1.5 ab$^{-1}$ (2 ab$^{-1}$).

| $\sqrt{s}$ (GeV) | Process | Decay mode | Measured quantity | Unit | Generator value | Stat. error | Comment |
|-----------------|---------|------------|-------------------|------|-----------------|-------------|---------|
| 350             | $ZH \rightarrow \mu^+\mu^-X$ | $\sigma$ | fb | 4.9 | 4.9% | Model independent, using Z-recoil |
| 500             | SM Higgs production | $ZH \rightarrow q\bar{q}q\bar{q}$ | $\sigma \times \text{BR}$ | fb | 34.4 | 1.6% | ZH $\rightarrow q\bar{q}q\bar{q}$ mass reconstruction |
| 500             | $ZH, H\nu\bar{\nu}$ | $\sigma \times \text{BR}$ | fb | 80.7 | 1.0% | Inclusive sample |
| 1400            | $H \rightarrow \tau^+\tau^-$ | $\sigma$ | BR | 19.8 | <3.7% |
| 3000            | $WW$ fusion | $H \rightarrow b\bar{b}$ | $\sigma \times \text{BR}$ | fb | 285 | 0.22% |
|                 |                  | $H \rightarrow c\bar{c}$ | $\sigma$ | 13 | 3.2% |
|                 |                  | $H \rightarrow \mu^+\mu^-$ | $\sigma$ | 0.12 | 15.7% |

| $\sqrt{s}$ (GeV) | Process | Decay mode | Measured quantity | Unit | Generator value | Stat. error | Comment |
|-----------------|---------|------------|-------------------|------|-----------------|-------------|---------|
| 1400 WW fusion  | Higgs  | tri-linear | $g_{HHH}$ | $\sim 20\%$ | |
| 3000 fusion     | Higgs  | coupling  | $\sim 20\%$ | | |
Table 6: Summary of full detector-simulation results obtained under realistic CLIC beam conditions in the top quark studies. The first (second) threshold scan contains 6 points (10 points) separated by 1 GeV and with 10 fb\(^{-1}\) of luminosity at each point.

| \(\sqrt{s}\) (GeV) | Technique        | Measured quantity | Integrated luminosity (fb\(^{-1}\)) | Unit | Value | Generator value | Stat. error |
|------------------|------------------|-------------------|-------------------------------------|------|-------|-----------------|-------------|
| 350              | Threshold scan   | Mass              | 6 \times 10                         | GeV  | 174   | 0.021           |             |
|                  |                  | Mass \(\alpha_s\) | 10 \times 10                        | GeV  | 174   | 0.118           | 0.0009      |
| 500              | Invariant mass   | Mass              | 100                                 | GeV  | 174   | 0.060           |             |

Being the heaviest particle in the SM, the top quark couples more strongly to the Higgs boson than any other fermion in the SM. The precise knowledge of the properties of the top quark also provides important sensitivity to physics beyond the SM. Normal kinematic determinations of the top quark mass are beset by significant QCD uncertainties when trying to map it to a theoretically well-defined mass definition. These subtleties can be overcome most easily by performing a measurement of the \(t\bar{t}\) cross-section at multiple points near threshold. Table 6 shows the results of two threshold scans, one of 6 points and one of 10 points, each separated by 1 GeV with 10 fb\(^{-1}\) of luminosity at each point. In the latter scan the value of \(\alpha_s\) is allowed to vary in the fit and is determined simultaneously with the top quark mass from the scan data. A third row shows the invariant mass measurement from 100 fb\(^{-1}\) of integrated luminosity at \(\sqrt{s} = 500\) GeV.

The Higgs boson and top quark measurements form a core component of the physics programme for a staged CLIC collider. Going into the energy frontier there are opportunities to discover new physics and to do precision studies of potential discoveries at the LHC. A useful example to study in this context is supersymmetry, since it is a well-motivated idea and the particle content is rich, calculable and illustrative of many new physics ideas that have new particles. In Figure 9 (right) we show the production cross-section spectrum of an example supersymmetry scenario (model III [4]) as a function of the centre-of-mass energy. One sees the light Higgs boson and top quark at lower energies. At higher energies the electroweak gaugino and slepton thresholds open up, which could be accessible at a second intermediate stage. At still higher energies some of the strongly interacting squark thresholds become accessible, as well as the heavy Higgs bosons. When kinematically accessible they can be measured with excellent precision.

As an example of how well new particles can be discovered and their masses and interactions precisely studied, we present in Table 7 the results of simulation studies of supersymmetry model II [3]. The table shows the masses of these various sparticle states, associated to this model, and the statistical accuracy by which they could be determined at 3 TeV CLIC with 2 ab\(^{-1}\) of integrated luminosity. In addition, Table 8 shows the results of full simulation benchmark studies including background overlay for various processes relevant to supersymmetry model III at 1.4 TeV CLIC. In both cases, many of the determinations are at the percent level of accuracy or better. The precision of these measurements are by no means excessive – they are crucial for making distinctions between various underlying supersymmetry breaking and transmission scenarios that have different unification characteristics at the high scale (e.g., the grand unified scale).
Table 7: Values of the SUSY particle masses of the chosen benchmark point (model II) and estimated experimental statistical accuracies at CLIC, as obtained in the analyses presented in Chapter 12 of [3], and also in [8] (indicated with *). All values are in GeV. The last column is either out of kinematic reach or not studied. All studies are performed at a centre-of-mass energy of 3 TeV and for an integrated luminosity of 2 ab$^{-1}$.

| Particle | Mass | Stat. acc. | Particle | Mass | Stat. acc. |
|----------|------|------------|----------|------|------------|
| $\tilde{\chi}_1^0$ | 340.3 | $\pm 3.3$ | $h$ | 118.5 | $\pm 0.1^*$ |
| $\tilde{\chi}_2^0$ | 643.1 | $\pm 9.9$ | $A^0$ | 742.0 | $\pm 1.7$ |
| $\tilde{\chi}_3^0$ | 905.5 | $\pm 19.0^*$ | $H^0$ | 742.0 | $\pm 1.7$ |
| $\tilde{\chi}_4^0$ | 916.7 | $\pm 20.0^*$ | $H^\pm$ | 747.6 | $\pm 2.1$ |
| $\tilde{\chi}_1^\pm$ | 643.2 | $\pm 3.7$ |          |      |            |
| $\tilde{\chi}_2^\pm$ | 916.7 | $\pm 7.0^*$ |          |      |            |
| $\tilde{\ell}_R^0$ | 1010.8 | $\pm 2.8$ |          |      |            |
| $\tilde{\mu}_R^0$ | 1010.8 | $\pm 5.6$ |          |      |            |
| $\tilde{\nu}_i$ | 1097.2 | $\pm 3.9$ |          |      |            |

Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full detector simulations with background overlaid. All studies are performed at a centre-of-mass energy of 1.4 TeV and for an integrated luminosity of 1.5 ab$^{-1}$.

| $\sqrt{s}$ (TeV) | Process | Decay mode | SUSY model | Measured quantity | Unit | Generator value | Stat. uncertainty |
|------------------|---------|------------|------------|-------------------|------|-----------------|------------------|
| 1.4              | Sleptons production | $\tilde{\mu}_R^0 \tilde{\mu}_R^0 \rightarrow \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ | III | $\sigma$ | fb | 1.11 | 2.7% |
|                  |         | $\tilde{\ell}^0 \tilde{\ell}^0 \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ | III | $\ell$ mass | GeV | 560.8 | 0.1% |
|                  |         | $\tilde{\chi}_1^0$ mass | GeV | 357.8 | 0.1% |
|                  | Stau production | $\tilde{\tau}_1^+ \tilde{\tau}_1^- \rightarrow \tau^+ \tau^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ | III | $\tau_1$ mass | GeV | 517 | 2.0% |
|                  | Chargino production | $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h/Z^0/Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$ | III | $\tilde{\chi}_1^0$ mass | GeV | 487 | 0.2% |
|                  | Neutralino production | $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h/Z^0/Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$ | III | $\tilde{\chi}_1^0$ mass | GeV | 487 | 0.1% |

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A complementary and less model-dependent approach of probing physics beyond the SM aims for detecting evidence for higher-dimensional operators, or contact interactions, of SM states, which may arise from integrating out exotic particles. Dimension-six operators $\mathcal{O}^{(6)}/\Lambda^2$ can be probed up to scales of $\Lambda = 60$ TeV, with some variability for each particular operator and beam polarisation [3]. The analogous reach at the LHC with $100 \text{ fb}^{-1}$ is currently projected to be less than 8 TeV.

Finally, we summarise the CLIC reach at 3 TeV compared to other collider options for several New Physics models. The sensitivity scale for squarks is better at the LHC than at a 3 TeV CLIC, except for some difficult cases with small mass splittings. On the other hand, weakly interacting particles, such as sleptons, have much higher direct reach at a 3 TeV CLIC than LHC. The $Z'$ searches are generally up to about 20 TeV at 3 TeV CLIC, although the details depend on the precise model. The analogous sensitivity at the LHC is about 5 TeV. Further concepts of new physics are catalogued in Table 9, including triple gauge coupling (TGC) deviations from the SM values, the contact interaction scale involving electrons and muons (“$\mu$ contact scale”), and the scale of Higgs compositeness that would result in detectable shifts in the Higgs boson observables away from their SM values.

Table 9: Discovery reach of various theory models for different colliders and various levels of integrated luminosity $\mathcal{L}$ [9]. LHC14 and the luminosity-upgraded SLHC are both at $\sqrt{s} = 14$ TeV and with performance assumptions which will likely be updated in the context of this strategy process. LC800 is an 800 GeV $e^+e^-$ collider and CLIC3 is at $\sqrt{s} = 3$ TeV. TGC is short for Triple Gauge Coupling, and “$\mu$ contact scale” is short for LL $\mu$ contact interaction scale $\Lambda$ with $g = 1$ (see Chapter 1 in [3] and references therein).

| Particle / parameter | Collider: $\mathcal{L}$ | LHC14 | SLHC | LC800 | CLIC3 |
|----------------------|--------------------------|-------|------|-------|-------|
|                      | 100 fb$^{-1}$            | 1 ab$^{-1}$ | 500 fb$^{-1}$ | 1 ab$^{-1}$ |
| Squarks [TeV]        | 2.5                      | 3      | 0.4  | 1.5   |
| Sleptons [TeV]       | 0.3                      | -      | 0.4  | 1.5   |
| $Z'$ (SM coupling) [TeV] | 5                      | 7      | 8    | 20    |
| 2 extra dims $M_D$ [TeV] | 9                      | 12     | 5-8.5 | 20-30 |
| TGC (95%) ($\lambda_\gamma$ coupling) | 0.001 | 0.0006 | 0.0004 | 0.0001 |
| $\mu$ contact scale [TeV] | 15                      | -      | 20   | 60    |
| Higgs compos. scale [TeV] | 5-7                | 9-12   | 45   | 60    |

5 Summary and Outlook

Linear $e^+e^-$ colliders have an impressive physics potential that is in many ways complementary to LHC. A comprehensive overview document of the Linear Collider physics capabilities has been composed by a small team of nominated experts from the ILC and CLIC communities and submitted to the update process of the European Strategy for Particle Physics [1]. This document outlines the strong physics case for a LC. It has been reviewed and is supported by the full international LC community.

The CLIC studies that are relevant for the European Strategy Process have been carried out in the framework of preparing the CLIC Conceptual Design Report, with two main volumes covering the accelerator studies [2] and the physics and detector studies [3], respectively. These two volumes demonstrate the feasibility of the CLIC accelerator concept in detail, and show the large physics potential of such an accelerator based on detailed detector and physics simulations in a realistic experimental environment. They are particularly focused on the technical challenges of construction and operation of a 3 TeV CLIC-technology-based accelerator and corresponding detectors. Intermediate energies, in particular an initial stage at 500 GeV, are also introduced in these volumes. Several of these studies have also been carried out in synergy and close collaboration with the ILC studies.
Recent work carried out by the CLIC collaboration and the CLIC physics and detector study has also addressed project-implementation issues such as: site studies, cost and power, the construction and operation of CLIC in three energy stages and its positive impact on the physics potential. These subjects are described in a third CDR volume [4] that also includes summaries of the two other CDR reports and forms the basis for this input to the European Strategy for Particle Physics.

The CLIC project as outlined is an ambitious long-term programme, with an initial 7 year construction period and three energy stages each lasting 6–8 years, interrupted by 2 year upgrade periods. A development programme for the CLIC project has been established and is being carried out concurrently with LHC operation at 8 TeV and later full energy, covering the period until 2016. By that time both the LHC physics results and technical developments should have reached a maturity that would allow a decision about the most appropriate next project(s) at the energy frontier. The major contenders, with particular relevance for the European Strategy, are a Linear Collider or an energy-upgraded LHC.

These options can provide a long-term strategy for European Particle Physics well beyond 2030. They represent investments, commitment and physics scope well beyond the LHC programme, including its luminosity upgrade, that is likely to remain the main experimental facility at the energy frontier until 2030. Construction start for CLIC could be around 2023 after an initial Project Preparation Phase 2017–2022, in time for completion by 2030 when the LHC programme reaches a natural completion. The currently foreseen timeline for the CLIC project is shown in Figure 10, with details presented in [4].
With the recent discovery of a new Higgs-like state at \( \sim 125 \text{ GeV} \) at LHC and considering the importance of studies near the top threshold, it is evident that an initial CLIC stage at 400–500 GeV will already provide exceptional physics. A second stage around 1.2–1.5 TeV would allow measurements of several more difficult Higgs branching ratios and in particular the Higgs self-coupling. With the present knowledge a third stage well beyond 1.5 TeV can only be justified by the general arguments of improved production cross-sections and precision on the measurements mentioned above, and a significantly increased search capability. It is however important to keep in mind that the very recent results from LHC open a completely new experimental territory. We can look forward to more LHC results during 2012–2013 and when LHC moves to full energy running in 2015, potentially providing even more exciting prospects for a future CLIC programme, including ultimate energy stages beyond 1.5 TeV.

**Messages for the Strategy Process**

The feasibility studies for the CLIC accelerator have over the last years systematically and successfully addressed the main technical challenges of the accelerator project. Similarly, detailed detector and physics studies confirm the ability to perform high-precision measurements at CLIC. Recent preliminary implementation studies show that a coherent staged implementation can be done, leading to an impressive long-term and timely physics programme at the energy frontier, beyond the LHC programme. New results at the LHC have started to open the experimental door to some of the key physics questions ahead of us where a future CLIC project can play a determining role, and further LHC data at 8 and 14 TeV will lay out the landscape in much more detail by 2016–2017.

With relevance to the European Strategy process three clear messages stand out for the next steps of the CLIC project:

- A focused technical development programme on accelerators and detectors is needed in the period 2012–2016 to lay the ground work for a complete Project Implementation Plan for the CLIC project, to be ready by 2016. This will also entail a possible revision of the energy stages currently considered, taking into account LHC results at 8 and 14 TeV, and include a re-optimisation of the initial stages. Such a programme is well underway but relies on continued and, in some cases, extended support by the CLIC collaborating institutes and funding agencies throughout the full period.

- A comprehensive common high-energy physics and detector study programme is needed on the same time scale to assess the various options for CERN’s future. These include LHC luminosity upgrades (providing the yardstick for comparisons), LC options, LHC energy upgrades, and other potential facilities. Evaluation of the physics performance and capabilities of each is necessary to decide on the future energy-frontier facility at CERN after the LHC.

- Sufficient funding and resources should be foreseen in the years 2017–2022 for advancing the project(s) chosen. Such support should be given a common high priority within CERN, by the collaborating institutes and funding agencies, and within the European Commission programmes that are relevant for developing projects of this type. This requires coordinated resource planning between the LHC luminosity upgrades and the preparation of a future facility to be ready around 2030.
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