News on the CLIC physics potential

R. Ström\textsuperscript{a,\,*}

On behalf of the CLICdp Collaboration

\textsuperscript{a} CERN, Switzerland

Abstract

The Compact Linear Collider (CLIC) is a proposed TeV-scale high-luminosity electron-positron collider. For an optimal exploitation of its physics potential, CLIC is foreseen to be built and operated in three stages, with centre-of-mass energies ranging from 380 GeV up to 3 TeV. Electron beam polarisation is provided at all energies. The initial energy stage will focus on precision measurements of Higgs-boson and top-quark properties. The subsequent energy stages enhance the reach of many direct and indirect searches for new physics Beyond the Standard Model and give access to the Higgs self-coupling. Higgs and top-quark projections have been evaluated using full detector simulation studies. Many new phenomenology studies have been undertaken to explore the BSM reach of CLIC, from EFT interpretations of precision measurements through to signature-based searches; these include flavour dynamics, and dark matter and heavy neutrino searches. This talk will review some of the latest results that demonstrate the outstanding potential of CLIC in many physics domains.

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\*lars.rickard.stroem@cern.ch
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The Compact Linear Collider (CLIC) is a proposed TeV-scale high-luminosity electron-positron collider. For an optimal exploitation of its physics potential, CLIC is foreseen to be built and operated in three stages, with centre-of-mass energies ranging from 380 GeV up to 3 TeV. Electron beam polarisation is provided at all energies. The initial energy stage will focus on precision measurements of Higgs-boson and top-quark properties. The subsequent energy stages enhance the reach of many direct and indirect searches for new physics Beyond the Standard Model and give access to the Higgs self-coupling. Higgs and top-quark projections have been evaluated using full detector simulation studies. Many new phenomenology studies have been undertaken to explore the BSM reach of CLIC, from EFT interpretations of precision measurements through to signature-based searches; these include flavour dynamics, and dark matter and heavy neutrino searches. This talk will review some of the latest results that demonstrate the outstanding potential of CLIC in many physics domains.

1 The Compact Linear Collider (CLIC)

CLIC is a proposed TeV-scale high-luminosity $e^+e^-$ collider for the era beyond HL-LHC.\(^1\) It occupies a privileged spot between the precision and energy frontiers, reaching unprecedented precision for Standard Model (SM) physics and sensitivities up to tens of TeV for many beyond SM (BSM) physics scenarios. In addition, new physics can be discovered through direct production at the high-energy stages of CLIC. Indeed, many BSM scenarios, such as supersymmetry, have substantial parameter space in regions where CLIC has an advantage over other colliders: for example for models with highly compressed mass spectra or with BSM states that only have electroweak interactions.

CLIC is powered by an innovative two-beam accelerating scheme using a low-energy high-current drive beam to generate high power radiofrequency (RF) waves for efficient acceleration of the main beams of colliding particles. This enables a compact and cost-effective accelerator complex, with a site length ranging between 11 km and 50 km, for collisions at a centre-of-mass energy of 380 GeV and 3 TeV, respectively. The project features an advanced detector concept that matches the challenging physics performance requirements and the CLIC experimental conditions. It includes an ultra low mass tracking system and highly granular sampling calorimetry systems, all enclosed in a 4 T solenoidal magnet.

The main accelerator technologies such as drive beam production, two-beam acceleration, high-gradient X-band accelerating structures, and ultra-low transverse emittance have all been successfully demonstrated in beam experiments, hardware tests, and extensive simulations. Based on purely technological considerations, first beams could be realised by 2035, resulting in
a diverse physics programme spanning three decades. The CLIC project is hosted by CERN and consists of around 75 collaborating institutes worldwide. For optimal use of its physics potential, CLIC is foreseen to be built and operated in three stages, providing high-luminosity collisions at centre-of-mass energies 380 GeV ($1.0 \text{ ab}^{-1}$), 1.5 TeV ($2.5 \text{ ab}^{-1}$), and 3 TeV ($5.0 \text{ ab}^{-1}$) with $\pm 80\%$ longitudinal electron polarisation at all stages.

The project status has been summarised in a series of reports for the European Strategy for Particle Physics Update (ESPPU): [https://clic.cern/european-strategy](https://clic.cern/european-strategy).

## 2 Learning from Standard Model processes

A key element of the CLIC physics programme is the detailed study of the properties of the known SM particles. This section focuses on CLIC’s potential for precision measurements of Higgs and top-quark physics (Drell-Yan and multi-boson production have also been studied\(^3\)) and presents its global sensitivity to BSM effects in the Effective Field Theory (EFT) framework. The predictions for the Higgs and top-quark programme are based on detailed studies including realistic detector simulation, overlay of beam-induced background, and particle-flow reconstruction. In addition, jet substructure methods are used for the reconstruction of boosted top-quarks\(^4\).

The first CLIC stage at $\sqrt{s} = 380 \text{ GeV}$ gives access to the Higgsstrahlung process, $e^+e^- \rightarrow \text{HZ}$, which enables an absolute determination of the Higgs couplings to SM particles. Such model-independent extractions are only possible at lepton colliders. At the higher energy stages large Higgs boson samples are produced through WW fusion. The expected precision on $g_{\text{HZZ}}$ from a model-independent global fit of the Higgs programme is $0.6\%$\(^3\). Other couplings reach similar precision and the $g_{\text{Hcc}}$ coupling, which is very challenging at hadron colliders, can be probed with percent-level precision. It is also possible to set a model-independent upper limit on the level of invisible Higgs boson decays of $0.69\%$\(^3\) at 90% C.L. For a model-dependent global fit where non-SM Higgs boson decays are assumed to be zero (equivalent to the approach often adapted by hadron colliders) several Higgs couplings are constrained to per mille-level precision. Further, operation at 1.5 and 3 TeV gives access to the Higgs self-coupling at tree level through double-Higgs boson production, reaching an accuracy of about $10\%$\(^3\) for the full CLIC programme.

Top-quark pair production is accessible throughout the CLIC programme. An energy scan around the top-pair production threshold allows for the extraction of the top-quark mass with a total uncertainty of around 50 MeV\(^4\). High-energy operation also gives access to associated Higgs and top-quark production, enabling extraction of the top Yukawa coupling with a precision of $2.7\%$\(^4\), as well as study of top-quark pair production initiated by low-virtuality and highly energetic vector bosons in a vector-boson fusion topology.

In general, the high-energy operation of CLIC enables discovery of new particles almost up to the kinematic limit and provides indirect sensitivity far beyond the collision energy. The global sensitivity of the CLIC physics programme to BSM effects is probed through EFT dim-6 operators, extending the SM Lagrangian by introducing a new physics scale $\Lambda$ beyond the direct reach of CLIC. Fig. 1 shows the sensitivity of the different CLIC stages through a global fit of universal probes, i.e. direct couplings of heavy BSM particles to the SM gauge and Higgs bosons\(^3\). These results use predictions from the full physics programme and illustrate the reach of CLIC compared to and combined with projections for HL-LHC under two assumptions of systematic uncertainty. The results clearly demonstrate that even the initial stage of CLIC is highly competitive with HL-LHC for many operators. In addition, the high-energy $e^+e^-$ operation that is unique to CLIC, leads to significant improvements for operators that grow quadratically with the centre-of-mass energy, for example $c_{\text{HW}}, c_{\text{HB}}, c_{3\text{W}}, c_{2\text{W}},$ and $c_{2\text{B}}$.

Since universal probes are unavoidable in any BSM scenario that is connected with electroweak (EW) or EW symmetry-breaking physics, they are very robust as BSM probes. They
Figure 2 – Exclusion contour at 95% C.L. for heavy scalar singlets (left). Discovery (5σ) reach on composite Higgs in the \((m_\star, g_\star)\) plane (right).

contribute to top-quark physics but are generally probed better by other processes. Relevant operators for the top-quark physics programme are instead so-called “top-philic” non-universal operators that emerge from the direct BSM coupling to the fields of the 3rd generation of quarks. In fact, strong new physics couplings with the top-quark sector, leading to enhanced top-philic operators, are well motivated. In this case top-philic effects can be more effective indirect probes of new physics than the universal ones. Here, the sensitivity to four-fermion operators, which represent a massive new mediator beyond direct reach, rise steeply with energy and improve by more than one order of magnitude at the high-energy stages of CLIC, compared to the initial stage. Overall, CLIC probes the universal and “top-philic” EFT operator coefficients much more precisely than what is possible at the HL-LHC\(^3\).

3 Examples of new physics searches

In this section we discuss several concrete new physics phenomena, covering both direct and indirect detection. In general, CLIC can search indirectly for particles with electroweak-sized couplings well above the HL-LHC reach; where they are produced directly, precise measurements of properties such as mass and spin can be made.

3.1 Extended Higgs sector – heavy scalar singlets

An extended scalar sector with new states that are not charged under the Standard Model gauge group, appears in many BSM scenarios, for example in the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and in many realisations of Twin Higgs models. Such new “singlet” scalars may interact with the SM through mixing with the Higgs boson portal and can then be probed indirectly through their effects on the Higgs boson couplings and through the direct production of new particle states. For the latter we focus on a case where the extra singlet \(\Phi\) is at least two times heavier than the Higgs boson, and study Higgs pair production with four b-quarks in the final state. The resulting indirect and direct exclusion contours of CLIC are shown to the left in Fig. 2 and improve dramatically on the predictions for HL-LHC. This illustrates the complementarity of indirect and direct constraints and in addition, the capability of CLIC as a discovery machine. It is found that in the case of the NMSSM, CLIC can exclude a new scalar lighter than 1.5 TeV in the most well-motivated phase space region of the NMSSM\(^3\). In conclusion, CLIC is able to test thoroughly the extended Higgs sectors and exclude new scalar states up to multi-TeV masses.

3.2 Higgs and top-quark compositeness

A possible composite nature of the Higgs boson is investigated for a canonical scenario where a Higgs bound state arises as the pseudo-Nambu-Goldstone boson of an underlying strongly-
interacting composite sector, characterised by the mass scale $m_\ast$ (above direct reach) and coupling strength $g_\ast$. If realised, such scenarios could provide an improved understanding of the microscopic origin of the electroweak symmetry breaking and possibly also the fine-tuning (or Naturalness) problem associated with the SM Higgs mass parameter.

In CLIC, a composite Higgs could be searched for through precision measurements of EFT operators, which are either enhanced or suppressed depending on the characteristics of the composite sector. Constraints from the global fit of observables presented in Fig. 1 are here re-interpreted in terms of compositeness, with the 5$\sigma$ discovery contours presented to the right in Fig. 2, for optimistic and pessimistic values of the corresponding operator coefficients. While the measurement of single Higgs boson couplings provide the most stringent constraints at large values of $g_\ast$, the precision measurements of $c_{HW}$, $c_{HB}$, $c_{2W}$, and $c_{2B}$, which are possible at high-energy CLIC, dramatically improve the reach at small and intermediate values. In addition, top-quark compositeness emerges naturally in the composite Higgs framework. The associated flavour-dependent top-philic operator coefficients are best probed in the top-quark sector and are constrained by measuring the top Yukawa coupling and, very effectively, by top-quark pair production at high-energy CLIC. In conclusion, CLIC can discover Higgs and top-quark compositeness if the mass scale is below 8 TeV, and for certain favourable conditions, up to 40 TeV.

3.3 Exotic signatures of new physics – Higgsino reach from stub tracks

Exotic signatures of new physics are an important benchmark for future colliders. Such signatures may be realised in models with a small mass splitting between dark sector particles. For example in SUSY models where the charged component of the Minimal Dark Matter multiplet is long-lived, with a macroscopic decay length, giving rise to disappearing/stub tracks. Studies based on detailed tracking performance show that the discovery potential of CLIC reaches Higgsino masses of 1.1 TeV, required for DM relic mass density, even with some level of background.

4 Summary

CLIC is an attractive post-LHC facility for CERN with unprecedented, diverse and guaranteed physics reach. The key accelerator technologies have been demonstrated and the project is ready to proceed towards a Technical Design Report. The CLIC project foresees first beams by 2035, marking the start of a unique physics programme spanning three decades.

References