Overview of the CLIC detector and its physics potential

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Abstract. The CLIC detector and physics study (CLICdp) is an international collaboration that investigates the physics potential of the Compact Linear Collider (CLIC). CLIC is a high-energy electron-positron collider under development, aiming for centre-of-mass energies from a few hundred GeV to 3 TeV. In addition to physics studies based on full Monte Carlo simulations of signal and background processes, CLICdp performs cutting-edge hardware R&D. In this contribution CLICdp will present recent results from physics prospect studies, emphasising Higgs studies. Additionally the new CLIC detector model and the recently updated CLIC baseline staging scenario will be presented.

1 Introduction

The Compact Linear Collider (CLIC) [1] is a proposal for a future electron-positron collider at CERN in the post HL-LHC era. It is the only mature option for an electron-positron multi-TeV accelerator. Figure 1 shows the CLIC project timeline including important milestones such as the decision at the update of the European Strategy for Particle Physics in 2019-2020, and first beams scheduled for 2035 following a decade of development and construction. Compared to hadron colliders CLIC has a superior sensitivity to electroweak states. This is due both to the cleaner experimental environment (including well-defined initial states) as well as the lower background from QCD processes.

CLIC is using a novel two-beam acceleration scheme going up to the full design energy of 3 TeV in 50 km, providing an instantaneous luminosity of $6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The accelerator is foreseen to be built in several stages, each operated for 5-7 years [2]. The staging is designed to make full use of the physics potential of CLIC with initial operation at lower centre-of-mass energy focusing on precision top and Higgs physics. The initial stage is at a collision energy of 380 GeV (500 fb^{-1}) with an additional dedicated run to measure the top quark mass using a threshold scan around 350 GeV (100 fb^{-1}). Subsequent stages at higher energies of 1.5 TeV (1.5 ab^{-1}) and 3 TeV (3 ab^{-1}) focus on exploring physics beyond the Standard Model (BSM) as well as studies dedicated to the top Yukawa coupling, direct probing of the Higgs self-coupling through double-Higgs production, rare decays, etc. Overall, the CLIC project offers a rich physics program for ~ 20 years, with discovery potential to new physics, that can reach scales of up to several tens of TeV, through indirect searches with precision measurements.

CLICdp is a collaboration consisting of 28 institutes from 17 different countries. The work focuses on evaluating the physics prospects through simulation studies, detector optimisation, and R&D for a future CLIC detector.

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Figure 1. CLIC project timeline including important decisions and various planned phases for development, preparation, and construction. First beams are planned for 2035 and will be followed by 20 years of operation resulting in a rich physics program of both precision measurements as well as discovery. Credit: CLIC and CLICdp Collaboration.

In section 2 we will give a brief introduction to the accelerator complex and the challenging beam conditions at CLIC. In section 3 we will go through the detector requirements for a future CLIC experiment followed by an update of the latest CLIC detector model in section 4. The following sections go through the physics potential using illustrative example studies to map out the detector key capabilities. We conclude in section 8 with a short summary of these proceedings.

2 The CLIC accelerator

The CLIC accelerator [3] uses normal-conducting radio-frequency (RF) cavities to accelerate the main beams of electrons and positrons. In order to meet the energy and luminosity target within a few tens of kilometres many accelerating cavities ($\sim 150,000$) are needed, each with a high acceleration field of $\sim 100 \text{ MV m}^{-1}$. Since standard RF sources scale unfavourably to high frequency, the CLIC approach is to make use of a low-frequency high-current drive beam to generate high-frequency RF (12 GHz). The drive beam itself is accelerated using conventional klystrons, and its frequency is increased using a series of delay loops and combiner rings as indicated in figure 2. The drive beam is then decelerated through a series of Power Extraction and Transfer Structures (PETS) creating high RF power that can be used to accelerate the main beams to 1.5 TeV. This two-beam concept, where the drive beam is used to deliver RF power to all the cavities along the main beam, has been demonstrated at CERN in the dedicated CLIC Test Facility (CTF).

The large number of accelerating cavities and decelerating structures constitute a big challenge, not only in precision during production but also in terms of operation where the breakdown rate needs

Figure 2. The CLIC accelerator at 3 TeV, including the drive beam complex at the top and the main beam at the bottom. The drive beam frequency is increased through a series of delay loops and combiner rings before reaching the desired bunch structure used to generate the high frequency RF power needed for the main beam acceleration. Credit: CLIC Collaboration.

to be kept at a manageable level. Further challenges for the CLIC accelerator complex come from the luminosity requirement, where a very small and dense beam, 40 nm x 1 nm in the transverse plane and $\sim 10^9$ particles per bunch, is needed to reach high enough statistics for rare processes at high energy. This puts constraints on both beam stability and alignment.

The beam and bunch structure of CLIC is rather distinct, with a bunch train repetition rate of 50 Hz. Each train consists of 312 bunches with a bunch spacing of 0.5 ns. Individual bunch crossings cannot be identified online, but the slow train repetition rate allows a readout of the complete detector during the 20 ms between bunch trains, making an offline selection possible (it is estimated that only about one hard e^+e^- physics interaction will be produced per bunch train crossing) [1].

The very small beam size and high bunch charge leads to large electromagnetic fields and interactions between colliding bunches. The resulting background of e^+e^- pairs and $\gamma\gamma \rightarrow$ hadrons, so-called beamstrahlung, constitute a large experimental background for CLIC, predominately in the forward regions. It is estimated that around 3 $\gamma\gamma \rightarrow$ hadrons interaction occurs for every bunch crossing at 3 TeV, depositing ~ 20 TeV per bunch train in the calorimeters. The background can be reduced to a manageable level by applying combined p_T and timing cuts for the different subdetectors. Figure 3 shows an $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t}b\bar{b}$ event before (left) and after (right) such cuts have been applied. The cuts are designed to protect high p_T physics objects. Using hadron-collider-like jet clustering algorithms with beam-jets further reduces the impact of the background on physics measurements.

The chiral nature of the weak force offers enhancement or suppression of different physical processes by introducing polarisation of the main beams. For example WW-fusion Higgs production is greatly enhanced but the effect is less significant in other channels. In the baseline CLIC design a polarisation of 80% in the electron beam is foreseen. Positron polarisation is considered an option for future upgrades of the CLIC facility.

Figure 3. The beam and bunch structure at CLIC induces a challenging experimental background of beam-strahlung events. The background is reduced by combined cuts in the different subdetectors protecting the important high p_T physics objects. The left (right) hand side show an multi-jet $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$ event at 3 TeV overlaid with $\gamma\gamma \rightarrow \text{hadrons}$ background before (after) such cuts have been applied. Figures taken from [1].

3 Detector requirements

The performance requirements for the CLIC detector are driven by the physics goals, requiring:

- Precise impact parameter resolution: $\sigma_{d_0}^2 = (5 \mu\text{m})^2 + (15 \mu\text{m GeV})^2/p^2 \sin^3 \theta$, needed for accurate vertex reconstruction to enable flavour-tagging with clean b-, c- and light-quark jet separation,
- Excellent track-momentum resolution: $\sigma_{p_T}/p_T^2 \lesssim 2 \cdot 10^{-5} \text{ GeV}^{-1}$, needed for Higgs recoil analysis (see section 5), extraction of the position of kinematic edges (see section 7.1), etc. The impact of different resolutions is illustrated in the left of figure 4 [4], showing the reconstructed di-muon invariant mass for $H \rightarrow \mu^+\mu^-$ events.
- Jet-energy resolution for high-energy jets: at least 3.5% above 100 GeV, needed to distinguish e.g. W/Z/H di-jet decays. The effect of using various jet-mass resolutions is shown in the right of figure 4 [1] (a mass resolution of 2.5% corresponds to a jet-energy resolution of 3.5%),
- Overall need for precise timing to suppress background: translates to about 10 ns hit time-stamping resolution in the tracking region and about 1 ns accuracy for calorimeter hits (the resolution for a cluster of hits < 0.5 ns),
- Overall detector coverage (hermeticity), particularly in the forward region. This is needed for lepton identification and missing energy.

4 CLIC detector overview

The CLIC detector design is based on the requirements outlined in section 3 and is optimised for a wide range of physics benchmark analyses. The current detector model is illustrated in figure 5 with the main features described below.

The innermost part of the CLIC detector consists of a low-mass vertex detector, containing 3 cylindrical double layers in the barrel and 3 spiral double layers in the forward regions. Each layer corresponds to $0.2\% X_0$ (equivalent to about $200 \mu\text{m}$ of Si). Such a small radiation length is needed to reach the impact parameter resolution described in section 3. The detector design has roughly 2

billion pixels, each $25\ \mu\text{m}$ square with a single point resolution of $\sim 3\ \mu\text{m}$. The vertex detector covers the area $\theta > 7^\circ$ and is designed to consume very little power since there is no material budget for liquid cooling. Cooling is achieved via an active air cooling strategy that induces a spiral airflow, and the power consumption is kept low via power-pulsing of the front-end electronics.

Moving outwards, the tracking system is complemented by a large silicon tracker with a radius of 1.5 m (4.6 m long) operating in a 4 T solenoid field. The inner (outer) tracker has 3 (3) barrel layers and 7 (4) forward disks. The material budget allowed is only 1-2% X_0 per layer. The sensors will contain either large pixels or short strips with a granularity of approximately $50\ \mu\text{m} \times (1 - 10)\ \text{mm}$, and a single point resolution of $\sim 7\ \mu\text{m}$. A minimum number of hits is required for pattern recognition, which is why the tracking system is designed for at least 8 hits at $\theta > 8^\circ$ per event.

The Electromagnetic calorimeter consists of 40 layers of tungsten absorbers interleaved with silicon sensors of 300 micron thickness and with $5 \times 5\ \text{mm}^2$ pads. The full depth of the electromagnetic calorimeter corresponds to $23\ X_0$. The hadronic calorimeter consists of 60 layers of steel absorbers interleaved with scintillator tiles of $30 \times 30\ \text{mm}^2$. The total depth of the hadronic calorimeter is $7.5\ \lambda_{\text{int}}$. The whole calorimeter system is optimised for particle flow analysis (PFA) [5, 6].

The above mentioned detector components are all enclosed in a 4 T superconducting solenoid magnet with an inner radius of 3.4 m and a length of 8.3 m. The iron return yoke enclosing the magnet is instrumented with muon chambers than are used for muon identification. The detector also has a complex forward region with two important sub-detector systems: LumiCal (luminosity monitoring through Bhabha scattering) and BeamCal (beam monitoring and extended coverage for electromagnetic particles in the very forward region).

The physics studies presented in this proceeding were done using predecessors to the CLIC detector model presented above. These predecessors, CLIC_ILD and CLIC_SiD [1], are variants of the ILD and SiD [7] designs used at the International Linear Collider (ILC) but adapted for the CLIC environment. These two models differ from each other primarily in the tracking system where the former is using a time projection chamber (TPC), whereas the latter utilises a silicon tracker. All studies were performed using a detector simulation of the physics events of interest overlaid with $\gamma\gamma \rightarrow \text{hadrons}$ background.

Figure 4. Left: Di-muon invariant mass distribution in a search for $H \rightarrow \mu^+\mu^-$ decays at $\sqrt{s} = 3\ \text{TeV}$ for different σ_{p_T}/p_T^2 resolutions. Figure taken from [4]. Right: The required W/Z jet mass separation is obtained for mass resolutions below 2.5%, corresponding to a jet-energy resolution of 3.5%. Figure taken from [1].

Figure 5. The CLIC detector model. Starting from the innermost part it consists of a low mass vertex detector, a large radius tracker detector, and a calorimeter system optimised for particle flow analysis. These parts are enclosed in a 4 T solenoid field. The outermost layer consists of the return yolk of the magnetic field and is instrumented with muon detectors. Credit: CLICdp Collaboration.

5 Higgs physics at CLIC

The clean collision environment of an electron-positron collider is ideal for precision physics studies of the Higgs boson, a prime target of CLIC operation at 380 GeV. CLIC is a Higgs factory covering several Higgs production processes as can be seen on the left hand side of figure 6 where the cross-sections of various Higgs processes are shown as a function of centre-of-mass energy of the collisions. At the initial energy stage roughly 70,000 Higgsstrahlung events are produced, and about 3 million Higgs bosons will be produced at the two higher energy stages.

5.1 Higgsstrahlung

The Higgsstrahlung production mode ($e^+e^- \rightarrow HZ$), illustrated in the leftmost diagram of figure 7, allows for a model-independent measurement of the absolute coupling of the Higgs boson to the Z boson, which is unique for lepton colliders [8]. This is achieved by studying the mass recoiling against the Z boson for events with two oppositely charged leptons that have an invariant mass consistent with m_Z . The right side of figure 6 shows the Z-recoil mass for $Z \rightarrow \mu^+\mu^-$ events at a studied benchmark energy of 350 GeV where the cross-section is dominant and close to maximal. The remainder of the event, i.e. the particles from the Higgs decay, is not considered in the event selection, giving a result that is independent of specific Higgs decay modes. Note that this also applies to potential invisible final states. This technique for determining the absolute HZZ coupling is possible due to the well-defined initial state and clean experimental conditions at a linear collider.

The uncertainty on the HZZ coupling is calculated to 2% using the leptonic Z decays. These decays give the cleanest signature, but the result can be improved significantly by adding the large statistics from the hadronic Z decays. The combined uncertainty on the HZZ coupling is about 0.8%. The analysis described above can also be used to put constraints on the Higgs branching ratio to invisible states: the estimated uncertainty is below 1% at 90% confidence level [9].

5.2 Higgs production at higher energies

At higher energies the Higgs production is dominated by vector boson fusion where either W or Z bosons fuse to produce a Higgs boson, see the middle and right diagram of figure 7. The dominant WW-fusion process gives a constraint on the H coupling to W and also gives the best sensitivity for the Higgs mass and Higgs total decay width. The Higgs mass can be extracted with a precision of 24 MeV (including electron polarisation) using a combination of both high energy stages (1.5 and 3 TeV). This precision compares favourably with the HL-LHC projection of 50 MeV per experiment [10].

Rarer Higgs decays, with branching ratios at the sub-% level, such as $H \rightarrow \mu^+\mu^-$, $H \rightarrow \gamma\gamma$, and $H \rightarrow Z\gamma$, also benefit from the higher statistics at high energies. Here we reach an uncertainty on the cross-section $\times$ branching ratio for the three processes mention above of 25% (with CLIC at 3 TeV), 15% (with CLIC at 1.4 TeV), and 42% (with CLIC at 1.4 TeV) respectively [9].

Once the Higgs coupling to the Z, g_{HZZ} , has been determined using the recoil mass technique, the Higgs coupling to W, g_{HWW} , can be determined by studying the cross-section $\times$ branching ratio fraction between Higgsstrahlung and WW-fusion events, e.g. using b-tagged events,

$$\frac{\sigma(e^+e^- \rightarrow ZH) \times \text{BR}(H \rightarrow b\bar{b})}{\sigma(e^+e^- \rightarrow \nu_e \bar{\nu}_e H) \times \text{BR}(H \rightarrow b\bar{b})} \propto \left(\frac{g_{HZZ}}{g_{HWW}} \right)^2. \quad (1)$$

Figure 6. Left: Dominant Higgs production cross-sections at CLIC as a function of center-of-mass collision energy. The distributions shown correspond to unpolarised beams and do not include the effects of initial-state radiation (ISR) or beamstrahlung. The plot is produced using perturbative NLO calculation with the generator Whizard 1.95. Figure taken from [9]. Right: The Z-recoil mass for $Z \rightarrow \mu^+\mu^-$ events at a studied benchmark energy of 350 GeV. Figure taken from [9].

Figure 7. The three highest cross-section Higgs production processes at CLIC.

Figure 8. Higgs processes at CLIC involving the top Yukawa coupling g_{Htt} , the Higgs boson trilinear self-coupling λ and the quartic coupling g_{HHWW} .

In order to determine absolute measurements of other Higgs couplings, the Higgs total decay width needs to be derived from the data¹. For example it can be determined by measuring the Higgs decay to WW^* in the WW -fusion process,

$$\sigma(H\nu_e\bar{\nu}_e) \times \text{BR}(H \rightarrow WW^*) \propto \frac{g_{HHWW}^4}{\Gamma_H}, \quad (2)$$

given that the model-independent measurement of g_{HHWW} was derived following equation 1 above. In practice however, both the Higgs couplings and the total decay width are determined through a global fit of all available experimental measurements involving the Higgs boson processes, see section 5.2.1.

Another interesting process accessible at the second and third stages of CLIC is the top Yukawa process illustrated in the left diagram of figure 8. In this process a Higgs boson is produced in association with a pair of top quarks. The channel with the dominant decay mode, $H \rightarrow b\bar{b}$, has eight fermions in the final sample, including four b -jets. Naturally flavour tagging information is one of the crucial elements to distinguish the signal from the background. Therefore this process also provides an excellent detector benchmark test. The precision reached with CLIC using both the fully-hadronic and semi-leptonic final states is 4-5% [9] at 1.4 TeV. As a comparison, for HL-LHC the prediction is 7-10% [10] per experiment.

Double Higgs production $e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$, as illustrated in the middle and right diagrams of figure 8, is best reachable at the highest energy scale of 3 TeV. The high energy is crucial in order to

¹The total Higgs decay width, Γ_H , is less than 5 MeV and hence too small to be measured directly with current experiments.

Figure 9. Illustration of the precision of the Higgs couplings and decay width of the studied three-stage CLIC programme. Figures taken from [9]. Left: Results using a model-independent fit. Right: Results using a model-dependent fit as described in 5.2.1.

profit from the higher cross-section and higher luminosity at this energy. This channel gives access to the Higgs tri-linear self-coupling λ , a direct probe of the Higgs potential, at the precision of about 10% for 1.4 TeV and 3 TeV operation combined [9]. This is considerably more precise than the predicted precision of $\sim 30\%$ for the HL-LHC.

5.2.1 Global Higgs fit

The global fit results of the full CLIC program, i.e. ~ 5 -7 years of running at each stage, is presented in figure 9, where the model-independent (model-dependent) couplings are shown to the left (right). In general, model-independent couplings can be determined down to $\sim 2\%$ for most couplings while model-dependent couplings can be determined to ~ 0.1 - $1\%^2$. The accuracy on the Higgs total decay width is $\sim 3.6\%$ (model-independent) [9], $\sim 0.3\%$ (model-dependent, derived) [9]. It should be noted that CLIC sensitivity is significantly better than HL-LHC for the couplings to c , b , W , Z , and g , the self-coupling and the Higgs total decay width. Further the couplings to μ , τ , t , γ , and $Z\gamma$ are at a similar level of sensitivity.

6 Top physics at CLIC

The top quark is of particular interest due to its strong coupling to the Higgs field; a precise measurement of the top quark mass is needed to verify the relation between the top quark and the SM gauge bosons. Further, precision top quark studies may be a prominent place where indications of potential new physics show up. The determination of the top quark mass and the top quark couplings to Z and γ with high precision are among the main focuses of the initial stage of CLIC. Rare decays such as $t \rightarrow cH$ and $t \rightarrow c\gamma$ can also be studied and here CLIC provides competitive limits.

²The fit is done in the same manner as for the LHC experiments, i.e. assuming no invisible Higgs decays, leading to a model-dependence.

As mentioned in section 1 the CLIC staging program includes a dedicated threshold scan around 350 GeV to measure the top quark mass. This is shown in the left of figure 10, where the $t\bar{t}$ production cross-section is shown as a function of centre-of-mass energy for 10 measurements of 10 fb^{-1} each [11]. The position of the threshold is related to the top quark mass, and the slope of the rise in cross-section around the threshold reflects its natural width. From the normalisation we can extract a measurement of the strong coupling constant and the top Yukawa coupling. While the former is sensitive to QCD corrections close to the threshold where the $t\bar{t}$ -system experiences QCD bound state effects, the latter is related to H loop corrections.

Extraction of the theoretically well-defined 1S top quark mass can be done with a statistical accuracy of about 30 MeV [11, 12]. At this level of precision we expect the experimental and theoretical systematic uncertainties to become relevant. The theoretical uncertainty includes the uncertainty in the NNNLO description of the threshold shape and the uncertainty in the conversion of the threshold mass to the minimal subtraction $\overline{\text{MS}}$ scheme [13]. A total uncertainty on the top quark mass of about 50 MeV [12] seems feasible, which is about one order of magnitude beyond the capabilities of HL-LHC.

The top gauge couplings can be determined through measurements of cross-sections and forward-backward asymmetries for different polarisations [14]. The general $t\bar{t}V$ vertex can be parameterised using either form factors or effective operators. The related parameters are substantially modified in many BSM models, e.g. in models with extra dimensions and new heavy gauge bosons. The right side of figure 10 shows a comparison of the uncertainty on the measured top quark form factors. The precision reached by CLIC (at the level of 1% or below) is shown in green, and foresees an order of magnitude better precision than HL-LHC shown in red [2]. Further, the fact that the top quark decays before it hadronizes allows access to its polarisation by measuring the angular distributions of the decay products. This is a sensitive probe for CP violation in the top sector.

Figure 10. Left: Cross-section of $t\bar{t}$ production as function of centre-of-mass energy for 10 measurement points of 10 fb^{-1} each around the top quark threshold mass. For illustration a ± 200 MeV mass shift is indicated by dashed lines. Figure taken from [11]. Right: Comparisons of the uncertainty on the measured top quark form factors (considering parity conserving couplings). Figure taken from [2].

Figure 11. Left: The reconstructed di-jet masses from the decay product of directly produced charginos and neutralinos. Figure taken from [1]. Right: The reconstructed di-jet mass in a scenario with heavy Higgs bosons. Figure taken from [1].

At high-energy CLIC operation, an increased boost leads to better separation between the decay products of the two top quarks. A top tagging algorithm based on the method presented in [15] is under development and currently being re-optimised for electron-positron collisions. The focus is on further exploration of top gauge couplings. For example for effective D6 operators we see a significant improvement going to higher energies. Further, initial studies of the CKM matrix element v_{tb} , through the study of single top production $e^+ \gamma \rightarrow t + b + \bar{\nu}$ look promising. This process has no background from $t\bar{t}$.

7 BSM physics at CLIC

In addition to the Higgs and top physics programs outlined in section 5 and 6, CLIC also has an excellent sensitivity to BSM physics through both direct and indirect measurements. Due to the clean collision environment CLIC is particularly suited to study non-colored TeV-scale particles such as for example sleptons and charginos in supersymmetry (SUSY). These might be hidden in the large QCD backgrounds at the LHC. To quantify the performance and give input to the detector optimisation effort, three different SUSY scenarios were defined and used as benchmark signal samples for various BSM analyses [1]. In general each analysis was able to measure the mass and other basic properties of the particles set out to find. A small selection of the BSM benchmark analyses are highlighted in section 7.1 and 7.2.

7.1 Direct searches for BSM physics

Direct production of new particles is possible up to the kinematic limit ($\sqrt{s}/2$ for particles produced in pairs). This includes studying e.g. mono-photon events allowing model-independent searches for dark matter. Below we show a few examples of analyses concerning the reconstruction and direct measurements of possible SUSY particles.

Slepton signatures are particularly clean with two high-momentum leptons and missing energy in the final state ($e^+e^- \rightarrow \widetilde{\mu}_R^+\widetilde{\mu}_R^- \rightarrow \mu^+\mu^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$). The slepton and gauginos masses are extracted from the position of the kinematic edges of the lepton energy distribution, the so-called endpoints. The precision on slepton masses is below 1 % for sleptons with a mass ~ 1 TeV.

Also hadronic events were studied, e.g. through the pair-production of charginos ($e^+e^- \rightarrow \widetilde{\chi}_1^1\widetilde{\chi}_1^1 \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_1^0 W^+W^-$) and neutralinos (e.g. $e^+e^- \rightarrow \widetilde{\chi}_2^0\widetilde{\chi}_2^0 \rightarrow HH\widetilde{\chi}_1^0\widetilde{\chi}_1^0$), reconstructed into 4 jets and missing energy, see figure 11. The precision, $\Delta m/m$, on gaugino masses of a few hundred GeV is roughly 1-1.5%.

Scenarios with heavy Higgs bosons typically have complex final states, e.g. $e^+e^- \rightarrow H^0 A \rightarrow b\bar{b}b\bar{b}$ and $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$, requiring precise flavour tagging. The H_0 , A_0 , and $H^\pm$ states are almost degenerate in mass. The right side of figure 11 shows the di-jet invariant mass distribution for the $b\bar{b}b\bar{b}$ final states. Here CLIC reaches as mass precision $\Delta m/m = 0.3\%$ [1].

7.2 Indirect searches for BSM physics

Indirect searches are conducted by studying the variables and couplings in the SM with very high precision and allow discovery of BSM signals beyond the centre-of-mass energy of the collider. For example Z' and Higgs compositeness models can be probed up to scales of tens of TeV [10, 16].

Z' is a hypothetical gauge boson arising from extensions of the electroweak symmetry of the SM. This can be described e.g. in so-called Minimal anomaly-free Z' models (AFZ). These are accessible by precision studies of $e^+e^- \rightarrow \mu^+\mu^-$ including measurements of the cross-section and both the forward-backwards and left-right asymmetry. Model-dependence arise through mixing of the Z' and Z and allow for discovery up to 50 TeV [16]. In case a Z' is indeed found in LHC or HL-LHC data, CLIC can measure the effective couplings with high precision.

Another important analysis is the study of vector boson scattering (VBS). While the SM Higgs preserve the unitarity of scattering amplitudes in longitudinal VBS, anomalous couplings or additional resonances can be introduced in BSM models. At first glance, CLIC at 3 (1.5) TeV is roughly two (one) orders of magnitude more precise for anomalous couplings than LHC at 8 TeV.

8 Conclusions & Summary

CLIC has a well-established physics program that spans over several decades with a three-stage implementation. CLIC opens up the possibility of e^+e^- collisions with $\sqrt{s} \gg 1$ TeV, giving improved precision of many observables, access to rare Higgs decays, and discovery potential for BSM physics at the energy frontier with a reach in indirect search up to tens of TeV.

A model-independent measurement of the HZZ coupling can be extracted at the initial stage at 380 GeV. This stage also includes a dedicated threshold scan to precisely measure the top mass. At the two higher energy stages, 1.5 TeV and 3 TeV, statistics improve for the rare Higgs decays and we get direct access to e.g. the top Yukawa coupling and the Higgs self-coupling.

The feasibility of the CLIC program has been demonstrated through extensive simulation, prototyping, and accelerator and detector R&D. Results from the LHC provide an important input for the CLIC physics program, a strategy that can be adapted to potential LHC/ HL-LHC discoveries.

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