PROCEEDINGS OF SCIENCE

Higgs and BSM physics at CLIC

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The Compact Linear Collider (CLIC) is a possible future multi-TeV linear electron-positron collider, offering the potential for a rich Standard Model physics programme and sensitivity to a wide range of phenomena beyond the Standard Model. The physics reach of CLIC has been studied for several centre-of-mass energies, motivating a staged construction and providing the opportunity for precise studies of the properties of the 125 GeV Higgs boson. Operation at a few hundred GeV allows the couplings and width of the Higgs to be determined in a model independent manner through the study of the Higgsstrahlung and WW-fusion processes. Operation at higher centre-of-mass energies, up to 3 TeV, provides higher statistics and the potential to study rare Higgs decays, the top Yukawa coupling and the Higgs self-coupling. The results at all energy stages are combined in a model independent global Higgs fit. The higher energy stages of CLIC are targeted to searches for physics beyond the Standard Model. Within the kinematic limit, new particles can be directly detected. Indirect searches using precision observables give access to much higher mass scales. Examples of both approaches are discussed, based on full simulation studies of a wide range of final states.

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1. Introduction

The Compact Linear Collider (CLIC) is a proposed future facility which would use a novel two-beam acceleration technique to provide high-energy e^+e^- collisions [1]. Energy staging is foreseen, giving access to several centre-of-mass energies up to a maximum of $\sqrt{s} = 3$ TeV [2]. Dense beams with small transverse size provide a luminosity of $6 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ at 3 TeV. The electron beam can be polarised up to ±80%, however unpolarised beams are assumed by default in the following physics analyses. The physics prospects for such a collider are explored by the CLICdp collaboration [3]. Section 2 presents our studies of the 125 GeV Higgs boson. Section 3 details the BSM reach of CLIC in both direct and indirect searches.

The construction and operation of CLIC is planned in stages, allowing access to several centre-of-mass energies. In this scenario, the accelerator length is extended to reach each energy stage. This allows a series of physics measurements to be performed at optimal centre-of-mass energies, without compromising the delivered luminosity of the accelerator. The three energy stages currently foreseen are $\sqrt{s} = 350$ GeV, 1.4 TeV and 3 TeV. Each energy stage will collect data for $4-5$ years, producing datasets with integrated luminosities of 500 fb^{-1}, 1.5 ab^{-1} and 2 ab^{-1} respectively (assuming 200 running days per year and 50% efficiency). The first energy stage of 350 GeV gives access to SM Higgs production via both Higgsstrahlung and WW-fusion. Top physics, including a $t\bar{t}$ threshold scan, is also possible [4]. The intermediate energy stage of 1.4 TeV provides better statistics for Higgs studies, enables the study of the top Yukawa coupling and allows the first BSM searches. The maximum energy stage of 3 TeV gives access to the rarest Higgs decays and double Higgs production, and provides the best sensitivity to BSM physics.

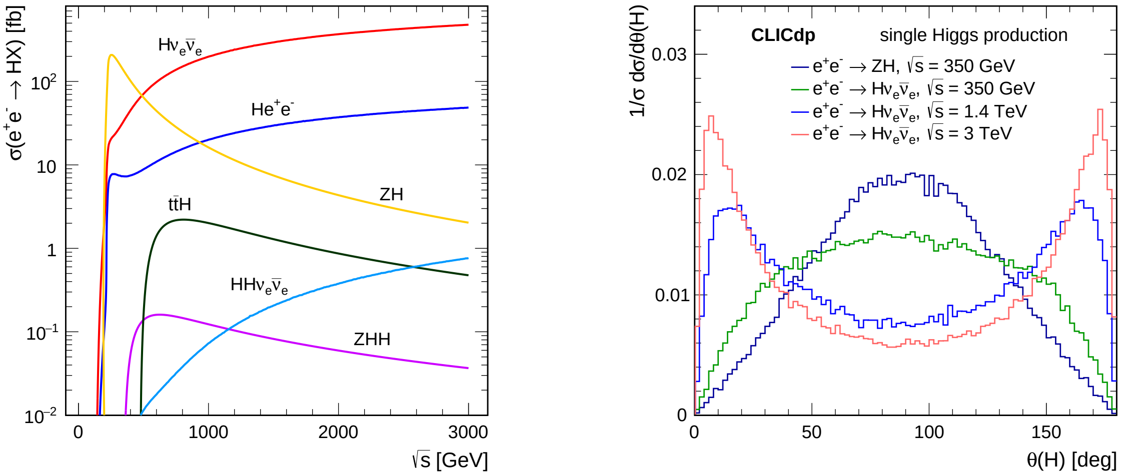
The dense bunches and high beam energies at CLIC cause strong electro-magnetic fields in the collision region, resulting in significant beam-induced backgrounds. Photons radiated from the incoming bunches can interact with each other or the particles in the approaching bunch, producing hadrons or e^+e^- pairs. The detected particles from these interactions have low momenta and mainly affect the forward region of the detector. However, their effect is significant: at $\sqrt{s} = 3$ TeV, 3.2 $\gamma\gamma \rightarrow$ hadrons interactions will occur during every bunch crossing, depositing ~ 20 TeV of energy into the calorimeters per bunch train. These particles can be removed during reconstruction with cuts on time and momentum information, which drives stringent timing requirements in the tracking detectors and calorimeters. Using hadron-collider-like jet clustering algorithms with beam-jets further mitigates their effect on physics measurements.

In order to perform the studies presented here two detector concepts were adapted from ILC designs to take into account the higher centre-of-mass energies at CLIC. Both detectors are designed to enable particle flow analysis techniques, with highly granular calorimeters and strong magnetic fields. The principle difference between the two concepts is the tracking system; CLIC_SiD comprises a full silicon tracker [5] whereas CLIC_ILD uses a TPC with a silicon envelope [6].

The studies presented here were performed using full simulation and reconstruction of all physics processes and relevant backgrounds, including beam-induced backgrounds. Details of the specific simulation and reconstruction software packages used can be found in [7].

2. Higgs physics at CLIC

Large samples of Higgs bosons will be produced at CLIC. Figure 1a shows the cross section of various Higgs production processes as a function of centre-of-mass energy. At the first energy stage Higgsstrahlung is the dominant Higgs production process, with 68,000 ZH events produced. At the higher energy stages, WW-fusion becomes the leading production process. Over a million Higgs bosons will be produced in the two higher energy stages of CLIC combined. The polar angle at which the Higgs boson is produced depends strongly on the production process and the centre-of-mass energy (see Figure 1b). At higher energies the Higgs is predominantly produced in the forward direction, demanding good detector coverage down to low polar angles.

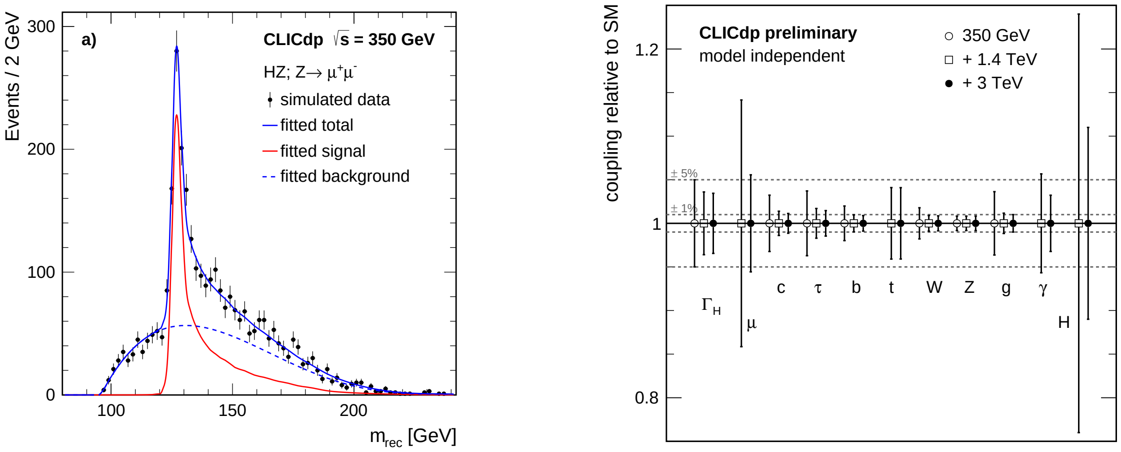


(a) (b)

Figure 1: (a) The cross section of various Higgs production processes as a function of centre-of-mass energy. (b) The polar angle of the Higgs for the leading production processes at each energy stage.

Higgsstrahlung events at $\sqrt{s} = 350$ GeV allow CLIC to perform a model independent measurement of the ZH coupling using the recoil mass technique. This measurement is unique to lepton colliders, and is possible due to the well-defined initial state and clean experimental conditions. By reconstructing only the Z decay products and calculating the mass of the system recoiling against it, the Higgs boson can be identified independent of its own decay (see Figure 2a). Leptonic Z decays give the cleanest signature, in these channels the ZH coupling can be measured with a statistical accuracy of 2%. Hadronic Z decays can also be used, where careful selection criteria ensure model independence [8]. The superior statistics of this channel give an uncertainty of 0.9%, resulting in a combined uncertainty on the ZH coupling of 0.8%.

Cross section times branching fraction measurements for the principal Higgs decay modes can be performed at the first energy stage of CLIC, with statistical precisions of a few %. This includes the separation and measurement of the $H \rightarrow b\bar{b}$, $H \rightarrow c\bar{c}$ and $H \rightarrow gg$ decays. The invisible Higgs decay branching fraction can be constrained to $< 1\%$ at the 90% confidence level. At the higher energy stages, increasing cross sections and luminosity lead to higher statistics. The full CLIC programme will allow $\sigma(\mathrm{H}\nu\nu) \times BR(\mathrm{H} \to \mathrm{b}\overline{\mathrm{b}})$ to be measured with 0.2% precision. Rare decays such as $\mathrm{H} \to \mu^+\mu^-$, $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{Z}\gamma$ are all within reach. Their cross section times branching fraction measurements can be performed with precisions in the tens of %.



(a)

(b)

Figure 2: (a) The reconstructed recoil mass of ZH events at $\sqrt{s} = 350$ GeV. The di-muon decay of the Z is used. The histogram is normalised to an integrated luminosity of 500 fb^{-1}. (b) The result of a model independent fit to all Higgs couplings and the Higgs width, using the results from each energy stage of CLIC. Electron beam polarisation of -80% is used at $\sqrt{s} = 1.4$ TeV and 3 TeV.

At $\sqrt{s} = 1.4$ TeV, $\mathrm{t}\overline{\mathrm{t}}\mathrm{H}$ production provides direct sensitivity to the top Yukawa coupling. Considering the dominant $\mathrm{t} \to \mathrm{bW}$ and $\mathrm{H} \to \mathrm{b}\overline{\mathrm{b}}$ channels, this decay comprises eight fermions in the final state, including four b-jets. Kinematic variables, such as the decay angle of the Higgs, and flavour tagging information are used to distinguish signal from the principle backgrounds of $\mathrm{t}\overline{\mathrm{t}}$ and $\mathrm{t}\overline{\mathrm{t}}\mathrm{Z}$. The signal-like contribution of $\mathrm{t}\overline{\mathrm{t}}$ pair-production with a Higgs radiated off the intermediate boson is corrected for. A combined analysis of the fully-hadronic and semi-leptonic channels yields an uncertainty on the top Yukawa coupling of 4.5%.

At the highest energy stage of CLIC double Higgs production is accessible in the $\mathrm{HH}\nu\nu$ state, enabling measurements of the Higgs self-coupling λ and the quartic HHWW coupling. High energy and high luminosity are crucial for these analyses; 1200 $\mathrm{HH}\nu\nu$ events are produced in 2 ab^{-1} at $\sqrt{s} = 3$ TeV. By reconstructing a four-jet topology the quartic coupling can be measured to 3%. The Higgs self-coupling can be measured to 16%, or 12% with -80% electron beam polarisation. Combining the $\sqrt{s} = 1.4$ TeV and 3 TeV results, this uncertainty drops to 11%.

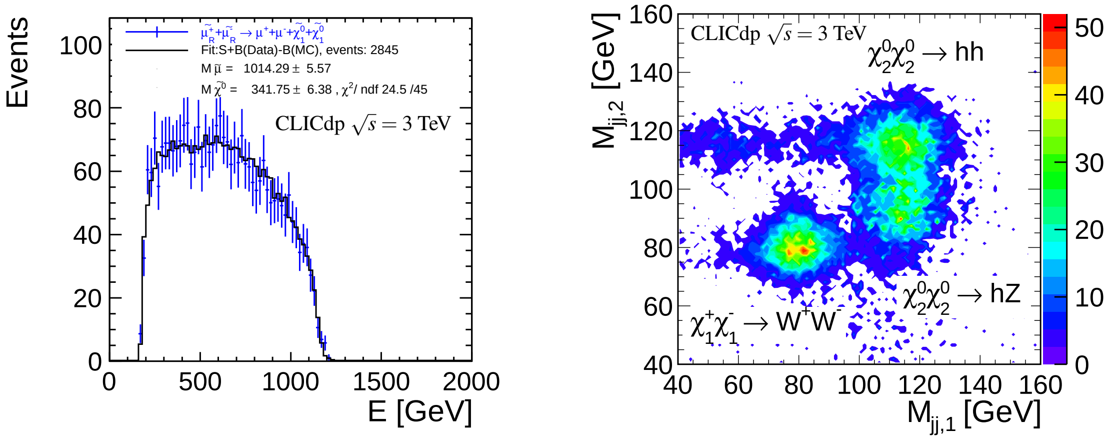
Bringing together the measurements made at all three energy stages, a model independent fit can be performed to extract the Higgs couplings and width. This fully model independent method is only possible at lepton colliders, and stems from the model independent measurement of the ZH cross section at $\sqrt{s} = 350$ GeV. Figure 2b illustrates the precision which can be achieved on the Higgs couplings and decay width by the full CLIC programme, showing that couplings can be determined at the %-level. The Higgs width is extracted with 3.5% precision.

Performing this combination in the same manner as the LHC experiments (requiring no unknown decays) improves the precision dramatically, for example the uncertainty on the Higgs decay width is sub-% level after the full CLIC programme. However, the results of this fit are strongly dependent on the assumptions made of the underlying model.

3. Beyond the Standard Model physics at CLIC

In addition to the SM Higgs physics programme, at the higher energy stages CLIC has excellent sensitivity to many possible BSM physics scenarios. CLIC is particularly well suited to studying weakly interacting states due to the clean experimental conditions and low backgrounds compared to hadron colliders. Direct searches for new particles can take place up to the kinematic limit of $\sqrt{s}/2$. Indirect searches, relying on the precise measurement of theoretically well-known observables, increase the reach of CLIC up to tens of TeV.

Three possible SUSY scenarios were used to quantify the precision with which the masses of new particles could be measured at CLIC [3]. The determination of slepton masses at $\sqrt{s} = 3\,\mathrm{TeV}$, for example in the decay $\mathrm{e^+e^-} \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$, can be achieved by measuring the end-points of the energy spectrum of the reconstructed leptons (see Figure 3a). The signature of this decay is extremely clean, consisting of two high-momentum leptons and missing energy. Precisions of $< 1\%$ are achievable for slepton masses of ~ 1 TeV. Hadronic events, such as chargino and neutralino pair-production and decay, can be reconstructed as four jets and missing energy. Figure 3b shows that the separation of different decays by their reconstructed di-jet invariant masses is possible at CLIC. For gaugino masses of a few hundred GeV, mass measurements with a precision of $1-1.5\%$ are possible using the same kinematic end-point technique as for the slepton analyses.



(a) (b)

Figure 3: (a) The reconstructed energy of the di-muon pair in the decay $\mathrm{e^+e^-} \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$. The end-points of this spectrum give the slepton masses. (b) The reconstructed di-jet masses from chargino and neutralino decays.

A direct search could also be performed for heavy Higgs bosons. A model consisting of four additional bosons, almost degenerate in mass, was studied in the decays $\mathrm{e^+e^-} \rightarrow \mathrm{HA} \rightarrow \mathrm{b\bar{b}b\bar{b}}$ and

$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$. Separating the heavy Higgs bosons requires flavour tagging of the final state b- and t-jets. The accuracy achieved on the heavy Higgs boson mass measurements is 0.3%.

The nature of BSM physics may require alternative indirect search techniques. Precise measurements of the cross section and asymmetries in $e^+e^- \rightarrow \mu^+\mu^-$ decays at CLIC could give sensitivity to heavy Z' bosons up to 40 TeV [9]. Using the single Higgs measurements performed at CLIC, composite Higgs models could be probed up to a scale of 70 TeV [10].

4. Summary

CLIC offers the possibility of a strong physics programme throughout its three energy stages. At the first stage of 350 GeV a model independent measurement of the ZH coupling can be performed. Higher energy stages, up to 3 TeV, improve statistics and give access to rare Higgs decays, the top Yukawa coupling and the Higgs self-coupling, which can be measured at the 10% level. Results from the Higgs studies are combined in a model independent fit. CLIC also provides significant potential for studying BSM phenomena. SUSY particle masses could be directly measured up to the kinematic limit. Indirect searches increase the reach of CLIC up to tens of TeV.

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