Searches for invisible scalar decays at CLIC

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Abstract

The Compact Linear Collider (CLIC) is a proposed TeV-scale high-luminosity electron-positron collider at CERN. The first CLIC running stage, at 380 GeV, will focus on precision Higgs boson and top quark studies while the main aim of the subsequent high-energy stages, at 1.5 TeV and 3 TeV, is to extend the sensitivity of CLIC to different Beyond the Standard Model (BSM) scenarios.

We studied the prospects for measuring invisible Higgs boson and additional heavy scalar decays using CLIC data at 380 GeV and 1.5 TeV. The analysis is based on the WHIZARD event generator, with fast simulation of the CLIC detector response parametrised by the DELPHES package. We present the expected limits for the invisible decays of the 125 GeV Higgs boson, the cross section limits for production of an additional neutral Higgs scalar, assuming its invisible decays, and limits on the mixing angle between the SM-like Higgs boson and the new scalar of the "dark sector" in the framework of the vector-fermion dark matter model.

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1 Introduction

The Higgs boson of the Standard Model (SM) with a mass of about 125 GeV is expected to decay into a wide variety of final states, including unobservable ones such as two Z bosons decaying to neutrinos. A larger branching fraction of unobservable final states is predicted in many extensions of the Standard Model.

There are two general ways to set constraints on the invisible Higgs boson decays: indirect, by fitting production and decay channel measurements to different theoretical models, or direct, by model-independent tagging of the Higgs boson production, e.g. via associated production in the Higgsstrahlung process at e^+e^- colliders or via vector-boson fusion at hadron colliders. The best current limits obtained in the direct approach have been achieved at the LHC – at 95% C.L. the upper limit on the branching fraction is less than 13% for ATLAS [1] and

19% for CMS [2]. In this analysis, we studied the prospects of measuring invisible Higgs decays at CLIC with 380 GeV and 1.5 TeV data in the Higgs-strahlung process ($e^+e^- \to ZH$) [3]. The sensitivity is dominated by the hadronic Z boson decay channel providing an order of magnitude higher observed yield [4, 5].

Furthermore, the study of the invisible SM-like Higgs boson decays was extended to the search for invisible decays of exotic scalar particles, denoted as H', with an arbitrary mass. The results were translated into limits on the scalar sector mixing angle in a given Higgs-portal model. We chose the vector-fermion dark matter model (VFDM) [6, 7], extending the Standard Model with one exotic scalar, one gauge boson and two Majorana fermions.

2 Event generation and detector simulation

The presented results were achieved using DELPHES [9], a fast simulation framework parametrising the CLICdet detector [8] response with dedicated cards [10]. We modified them to ignore Higgs bosons at the level of modelling the detector response. Then, we were able to generate Higgs particles as stable and, effectively, to treat their decay as invisible. To generate event samples, we used WHIZARD 2.7.0 [11, 12], including the beam energy spectrum simulated for CLIC running at both energy stages. The Higgstrahlung-like process, $e^+e^- \to ZH'$, with a subsequent decay of the Z boson into a quark-antiquark pair and an invisible decay of the H' scalar, was defined as the signal. In the analysis, we considered masses of the new scalar in the range of 120-1200 GeV (120-280 GeV for the energy stage of 380 GeV and 150-1200 GeV for the stage of 1.5 TeV).

Several processes have been studied as background channels, including those with and without Higgs production. Furthermore, we studied not only processes induced by e^+e^- collisions, but also those resulting from hard $\gamma\gamma$ and $e^\pm\gamma$ interactions. They were simulated for both beamstrahlung photons and radiated EPA photons.

For 380 GeV collisions, two running scenarios are considered: a baseline scenario with an integrated luminosity of 1000 fb^{-1} [13] and an extended one with 4000 fb^{-1} of data collected at the first stage [14]. As the same integrated luminosity is expected for both electron beam polarisations, the data can be considered as unpolarised in the combined analysis. At 1.5 TeV, however, the two electron beam polarisations have to be treated independently, since 2000 fb^{-1} of data is assumed to be collected for the –80% polarisation and only 500 fb^{-1} with +80% polarisation [13].

3 Data analysis

Only events with the expected signal signature, two reconstructed jets with an invariant mass corresponding to the mass of the Z boson and no other activity in the detector, were accepted at the preselection stage. Precisely, all events with reconstructed isolated leptons (electrons or muons) and isolated energetic photons were excluded from the analysis. Variables describing event topology were then considered. First, the distributions of resolution parameters associated with the VLC jet clustering algorithm were analysed. The parameters y_{23} and y_{34} were used to suppress events with higher jet multiplicities. Only events for which $\mathrm{y}_{23} < 0.01$ and $\mathrm{y}_{34} < 0.001$ were considered. After forcing the event into a two-jet topology using the same algorithm, the invariant mass of the two-jet final state, m_{jj}, was also required to be consistent with the mass of the Z boson so only events with 80 GeV $< \mathrm{m}_{jj} <$ 100 GeV were selected for further analysis. A fiducial requirement, $|\cos(\theta)| > 0.8$, where θ is the polar angle of the reconstructed dijet, was made to exclude events produced close to the beam axis, where

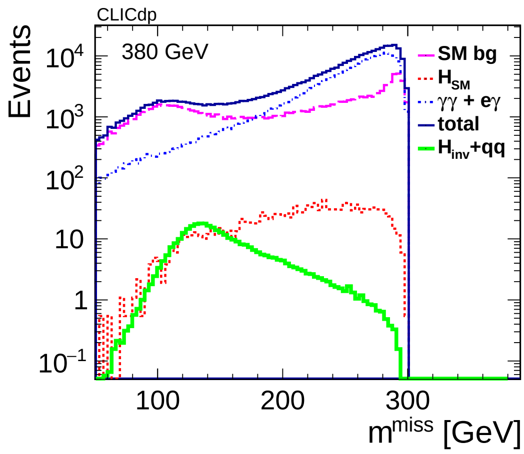


Figure 1: Distribution of the reconstructed mass of the invisible Higgs boson decay products, after preselection cuts, for different event samples: e^+e^- background without Higgs boson production (long-dashed pink line), background of SM Higgs boson production and decays (short-dashed red line), photon-induced interactions (dash-dotted blue line), sum of background contributions (thin solid indigo line) and signal (thick solid green line). Total integrated e^+e^- luminosity of 1000 fb^{-1} is assumed for 380 GeV CLIC stage. The signal sample is normalised to BR($H \to inv$) = 1%. Figure reproduced from [3].

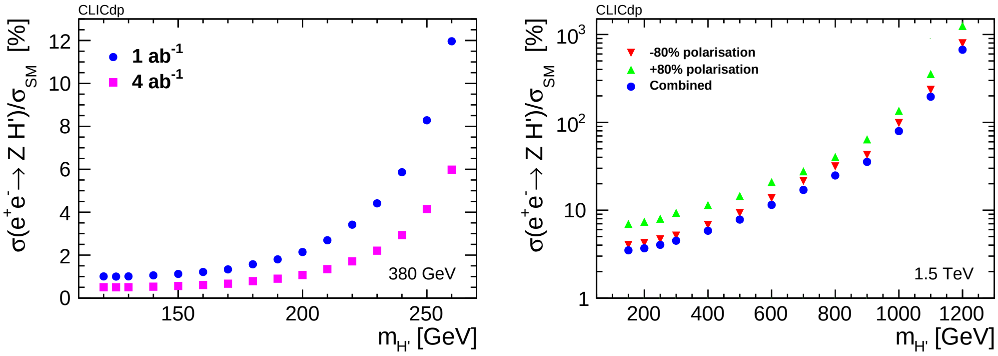
background dominates.

Figure 1 shows the expected distribution of the invariant mass of the invisible final state inferred from energy-momentum conservation for CLIC at 380 GeV after the preselection cuts. Two maxima are visible in the background channels: one at around 300 GeV, which is the kinematic limit (as we require two jets to have an invariant mass of at least 80 GeV) and the second one at around 90 GeV, which is mainly due to on-shell invisible Z boson decays. For signal events, with the cross section normalised in the Fig. 1 to BR($H \to inv$) = 1%, the expected recoil mass distribution is consistent with the SM Higgs boson mass of 125 GeV.

In the final analysis stage, the Boosted Decision Trees (BDT) algorithm, implemented within the TMVA framework [15], was employed for event classification, with five input variables: dijet energy, dijet invariant mass, reconstructed recoil mass, missing transverse momentum and angle between the two reconstructed jets in the laboratory frame. The cut on the BDT response was then selected to give the highest expected significance for the signal observation. For invisible decays of the 125 GeV Higgs boson at 380 GeV, a BDT response cut was set to about 0.14, corresponding to a signal selection efficiency of about 50% and rejection efficiency of the background channels of about 95%. The same analysis procedure was then used with signal and background samples generated at 1.5 TeV, separately for two considered polarisation settings of the electron beam. The purpose was to estimate the expected sensitivity of the second stage of the CLIC experiment to the production and invisible decays of an exotic scalar.

4 Results

For the 380 GeV operation, assuming the predictions of the Standard Model are consistent with the measured distributions and that systematic uncertainties are negligible comparing to the statistical uncertainties, the expected 95% C.L. limit on the invisible branching ratio of the



(a) 380 GeV (b) 1.5 TeV

Figure 2: Expected 95% C.L. cross section limits for new scalar H' production, as a function of its mass, relative to the expected SM Higgs production cross section, for the first stage of CLIC (380 GeV, left) and the second stage (1.5 TeV, right). The new scalar is assumed to decay to invisible finals states only, $\mathrm{BR}(H' \to inv) = 100\%$. Figure reproduced from [3].

125 GeV Higgs coming from the BDT analysis is:

$$\mathrm{BR}(H \to inv) < 1.0\% \quad (0.5\%)$$

for an integrated luminosity of $1000\,\mathrm{fb}^{-1}$ ($4000\,\mathrm{fb}^{-1}$). The discovery of an invisible decay channel at the standard level of 5σ (and therefore the discovery of new, invisible particles) is possible for a branching ratio higher than 3.0% (1.5%).

Figure 2 presents the 95% C.L. limits on the cross section for the production of the exotic scalar H' together with a Z boson, relative to the expected cross section for the production of the SM-like Higgs boson (for a given mass), as a function of the assumed scalar mass, for 380 GeV and 1.5 TeV. In Fig. 3, we compare the expected CLIC sensitivity to the existing limit coming from LEP [16] and the projected sensitivity of ILC for $2000\,\mathrm{fb}^{-1}$ ($4000\,\mathrm{fb}^{-1}$) collected at 250 GeV (500 GeV) [17]. The LEP and ILC limits have been evaluated in a decay-mode independent approach, using the leptonic Z boson decays ($Z \to e^+e^-$ and $Z \to \mu^+\mu^-$).

5 Interpretation

Since our results have been obtained in a model-indepent approach, we decided to illustrate them, translating the achieved limits into constraints on BSM scenarios. To show the possibility of constraining the parameters of a Higgs-portal model, we considered the VFDM model [6,7] as an example. In this model, the SM is extended by the the spontaneously broken extra $U(1)_X$ gauge symmetry, as well as one Dirac fermion. Mass of the dark vector X_μ is generated via the Higgs mechanism, involving a complex singlet S in the dark sector. A new scalar state ϕ, describing a real-part fluctuation of S, can mix with the SM Higgs field h, resulting in the existence of two mass eigenstates:

$$\begin{pmatrix} H \\ H' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix},$$

where we assume that H is the already discovered Higgs boson. Assuming $\alpha \ll 1$, H is SM-like, but it can also decay invisibly (to dark sector particles) via the ϕ component ($\mathrm{BR}(H \to inv) \sim \sin^2\alpha$). On the other hand, as long as H' is also light, it can be produced at e^+e^- colliders in the similar way as the SM-like Higgs boson.

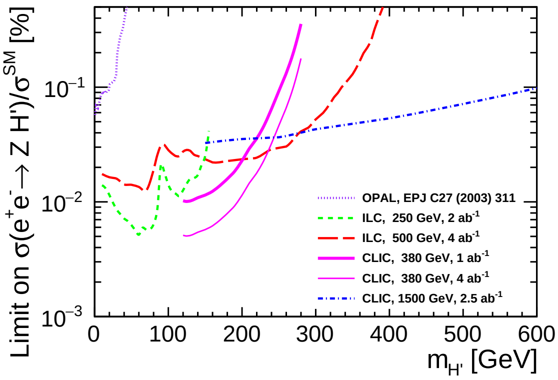


Figure 3: Expected sensitivity of CLIC running at 380 GeV (thick pink line for 1 ab^{-1} and thin pink line for 4 ab^{-1}) and 1.5 TeV (dotted-dashed blue line). For comparison, we show the existing limit from LEP (dotted violet line) [16] and the expected sensitivity of ILC running at 250 GeV (dashed green line) and 500 GeV (long-dashed red line) [17]. Expected cross section limits for new scalar H' production are shown as a function of its mass, relative to the expected SM Higgs production cross section. For CLIC limits, the exotic scalar is assumed to have only invisible decay channel, $\text{BR}(H' \to inv) = 100\%$, while LEP and ILC results were obtained in a decay-mode independent way. Figure reproduced from [3].

In Figure 4, we present limits on the mixing angle, $\sin\alpha$, obtained numerically from the cross section limits presented in Figure 2.

6 Conclusion

We studied the sensitivity of the first two stages of CLIC (380 GeV and 1.5 TeV) to invisible decays of the SM-like Higgs boson and the possible production of exotic scalar states. Associated production of a neutral scalar with a Z boson was considered. The analysis based on the WHIZARD event generation and fast simulation of the CLIC detector response with DELPHES. For 1000 fb^{-1} of data collected at 380 GeV operation of CLIC, invisible Higgs boson decays could be constrained at 95% C.L. up to the level of 1.0%. The analysis was extended to cover the production of the exotic scalar H' and the limits on the cross section were presented as a function of the scalar mass, for the first two stages of CLIC running.

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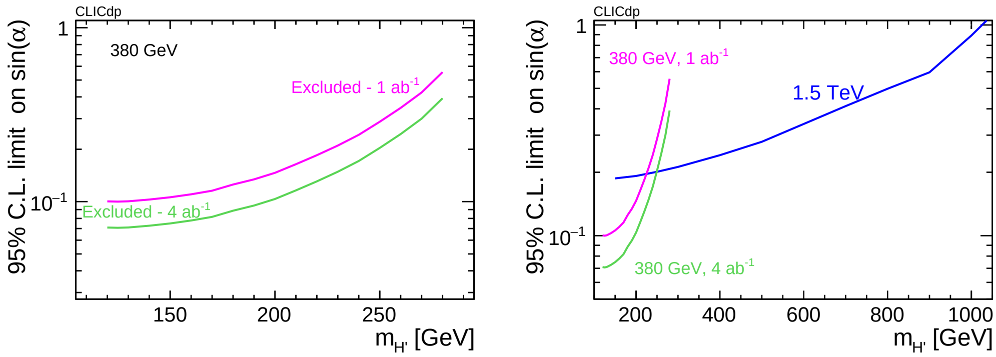

Figure 4: Expected limits on the scalar mixing angle expressed as a function of the H' mass, for CLIC at 380 GeV (both left and right plots) and 1.5 TeV (right plot). Figure reproduced from [3].

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