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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 Higss boson and the new scalar of the "dark sector" in the framework of the vector-fermion dark matter model.

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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.

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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 to unobservable final states is predicted in many extensions of the Standard Model. Experimental constraints on the invisible Higgs boson decays can be set either directly, by searching for such decays in channels where Higgs boson production can be tagged independently of the decay mode e.g. via vector boson fusion in pp collisions or associated production with a Z boson in e^+e^- collisions, or indirectly, based on a global fit to all production and decay channel measurements, assuming that the total width of the Higgs boson can also be directly measured. As of today, the best direct limits on invisible Higgs boson decays come from experiments at the LHC – at 95% C.L. upper limits 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, we extend our search for invisible decays of the SM-like Higgs boson to the search for production and invisible decays of another scalar particle, H', with an arbitrary mass. We then interpret our results in terms of the limits on the scalar sector mixing angle in the Higgs-portal scenarios. For illustration, we employed the vector-fermion dark matter model (VFDM) [6, 7], an extension of the Standard Model with one extra scalar, two Majorana fermions and one gauge boson.

2 Event generation and detector simulation

The results are based on a fast simulation of the CLICdet [8] detector response provided by the parametric DELPHES framework [9]. Control cards prepared for the new detector model CLICdet [10] were modified to make Higgs particles 'invisible' in the simulation (ignored when generating detector response), so that the invisible scalar decays can be modeled by defining the Higgs boson as stable. Signal and background event samples were generated using WHIZARD 2.7.0 [11, 12], using the beam energy profile expected for CLIC running at 380 GeV and 1.5 TeV. The $e^+e^- \to ZH'$ process, where the Higgs-like scalar is produced (with decay into an invisible final state) together with a Z boson decaying into a quark-antiquark pair was considered as the signal. Masses of the new scalar in the range 120–280 GeV (for the first stage of CLIC) and 150–1200 GeV (for the second stage) were considered.

As the background, we studied processes both with and without Higgs boson production. We also took into account possible background contributions from hard $\gamma\gamma$ and $e^\pm\gamma$ interactions, where we included beamstrahlung photons, as well as photon radiation by the incoming electrons, as described by the Equivalent Photon Approximation.

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, the two electron beam polarisations are considered separately, with 2000 fb^{-1} collected with –80% polarisation and 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. In particular, all events with reconstructed isolated leptons (electrons or muons) or isolated energetic photons were excluded from the analysis. Quantities describing event topology were then considered. First, the distributions of resolution parameters associated with the VLC jet clustering algorithm were analyzed. The parameters y_{23} and y_{34} were used to suppress events with higher jet multiplicities. Only events for which $y_{23} < 0.01$ and $y_{34} < 0.001$ 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<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 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. For the background sample, the distribution has two maxima: 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

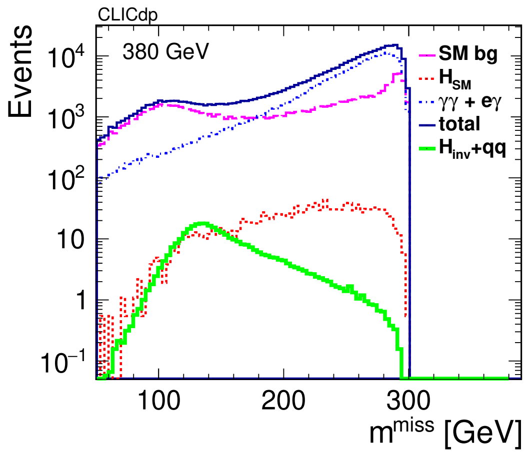


Figure 1: Reconstructed invariant mass of the products of the invisible Higgs boson decay expected for different event samples after preselection cuts: total background (thin solid black line), e^+e^- background without Higgs boson production (long-dashed pink line), background of SM Higgs boson production and decays (short-dashed red line), photon interactions (dash-dotted blue line) and signal (thick solid green line), assuming integrated e^+e^- luminosity of 1000 fb^{-1} collected at 380 GeV. The signal sample is normalised to BR$(H \to inv) = 1\%$.

expected recoil mass distribution is consistent with the SM Higgs boson mass of 125 GeV.

In the final analysis stage a Boosted Decision Trees (BDT) algorithm, as implemented in TMVA framework [15], was used 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 of about 0.14 was used, corresponding to a signal selection efficiency of about 50% and background rejection efficiency of about 95%. The same analysis procedure was applied to signal and background samples generated at 1.5 TeV, separately for two considered electron beam polarisation settings. The purpose was to estimate the expected sensitivity of CLIC experiment to production and invisible decays of a new scalar state.

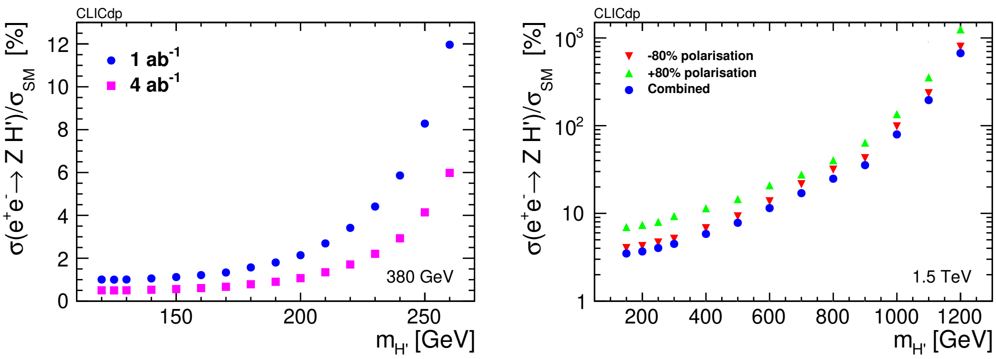
4 Results

For the 380 GeV operation, assuming that the measured event distributions are consistent with the predictions of the Standard Model and that systematic uncertainties are small relative to statistical uncertainties, the expected 95% C.L. limit on the invisible branching ratio of the 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 fb^{-1} (4000 fb^{-1}). The discovery of a new decay channel at 5σ level (and therefore also of new, invisible particles) is possible for an invisible Higgs boson branching ratio above 3.0% (1.5%).

Figure 2 presents the 95% C.L. limits on the cross section for the production of the new scalar H' in association with a Z boson, relative to the expected cross section for the production of the SM Higgs boson (for a given mass), as a function of the assumed scalar mass,



(a) 380 GeV (b) 1.5 TeV

Figure 2: Expected 95% C.L. limits on the production cross section of the new scalar H', relative to the expected SM Higgs production cross section, as a function of its mass, for CLIC running at 380 GeV (left) and 1.5 TeV (right). The new scalar is assumed to have only invisible decay channels, BR($H' \rightarrow inv$) = 100%.

for 380 GeV and 1.5 TeV. In Fig. 3, the expected CLIC sensitivity is compared to the existing limit from LEP [16] and the expected sensitivity of ILC for 2000 fb^{-1} (4000 fb^{-1}) collected at 250 GeV (500 GeV) [17]. The LEP and ILC limits were evaluated in a decay-mode independent approach, based on the reconstruction of leptonic Z boson decays ($Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$).

5 Interpretation

The expected limits on the invisible decays of the 125 GeV Higgs boson and limits on the production of new "invisible" scalars, which were obtained in a model-independent approach, can also be used to constrain various BSM scenarios. We demonstrate the possibility of constraining parameters of the Higgs-portal models taking the VFDM model [6,7] as an example. The SM is extended by the spontaneously broken extra $U(1)_X$ gauge symmetry and a Dirac fermion. To generate mass for the dark vector X_μ, the Higgs mechanism with a complex singlet S is used in the dark sector. A new scalar state ϕ, which describes a real-part fluctuation of S, can mix with the SM Higgs field h implying 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 observed 125 GeV state. If $\alpha \ll 1$, it is SM-like, but it can also decay invisibly (to dark sector particles) via the ϕ component (BR($H \rightarrow inv$) $\sim \sin^2\alpha$). If H' is also light, it can be produced in e^+e^- collisions in the same way as the SM-like Higgs boson. Limits on the mixing angle, $\sin\alpha$, resulting from the cross section limits presented in Figure 2, are shown in Figure 4.

6 Conclusion

We studied the sensitivity of CLIC running at 380 GeV and 1.5 TeV to invisible decays of the 125 GeV Higgs boson and the possible production of new scalar states. Associated production of a Higgs-like 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.

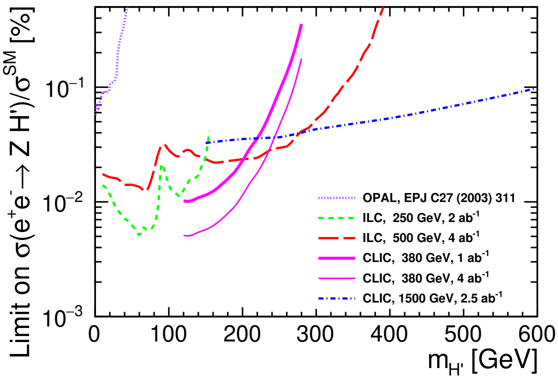


Figure 3: Expected sensitivity of CLIC running at 380 GeV (thick pink line for 1 ab^{-1} and thin pink line for 4 ab^{-1}) and 1.5 TeV (dotted-dashed blue line) compared to the existing limit from LEP (dotted violet line) [16] and the expected sensitivity of ILC running at 250 GeV (dashed green line)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

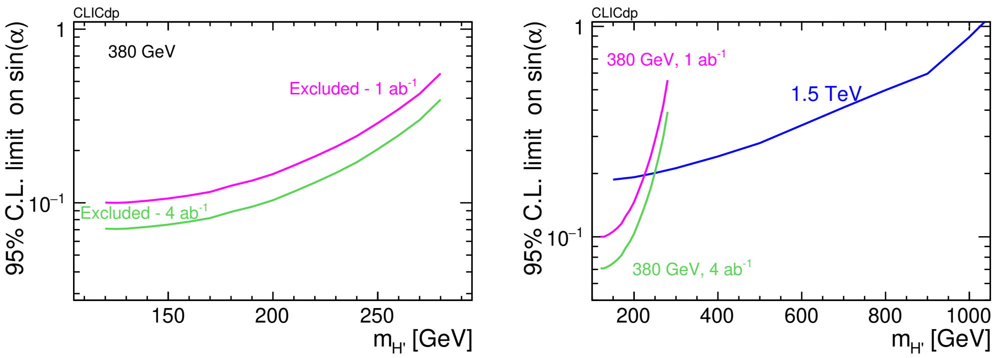


Figure 4: Expected limits on the scalar mixing angle expressed as a function of the H' mass, for CLIC running at 380 GeV (left and right plots) and 1.5 TeV (right plot).

For 1000 fb^{-1} of data collected at 380 GeV operation of CLIC, invisible Higgs boson decays at the level of 1.0% can be excluded at 95% C.L. Expected limits on the production cross section of the new scalar H' were presented as a function of its mass, for CLIC running at 380 GeV and 1.5 TeV.

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