Sensitivity to invisible scalar decays at CLIC

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Received: 2 May 2020 / Accepted: 13 January 2021
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Abstract We studied the possibility of constraining production of new scalar particles at CLIC running at 380 GeV and 1.5 TeV, assuming the associated production of Higgs-like neutral scalar with Z boson and its invisible decays. The analysis is based on the WHIZARD event generation and fast simulation of the CLIC detector response with DELPHES. We considered e^+e^- background processes but also relevant $\gamma\gamma$ and $\gamma e^\pm$ interactions. The approach consisting of a two-step analysis was used to optimise separation between signal and background processes. First, a set of preselection cuts was applied; then, multivariate analysis methods were employed to optimise the significance of observations. We first estimated the expected limits on the invisible decays of the 125 GeV Higgs boson, which were then extended to the cross section limits for production of an additional neutral scalar, assuming its invisible decays, as a function of its mass. Extracted model-independent branching ratio and cross section limits were then interpreted in the framework of the Higgs-portal models to set limits on the mixing angle between the SM-like Higgs boson and the new scalar of the “dark sector”.

1 Introduction

All available experimental results seem to confirm that the new particle discovered in 2012 by the ATLAS and CMS experiments at LHC [1, 2] is the last missing constituent of the Standard Model (SM), the Higgs boson. The Standard Model predicts that the Higgs boson with a mass of about 125 GeV should decay predominantly to $b\bar{b}$ (about 58% of all decays), but also to WW^* (21%), $\tau^+\tau^-$ (6,3%) or ZZ^* (2,6%) [3], the latter channel resulting also in about 0.1% of ‘invisible’ decays (with both Z bosons decaying to neutrinos). Some extensions of the Standard Model predict additional channels for invisible Higgs boson decays—into new, unobservable particles. These particles could contribute to the dark matter (DM) density of the Universe. As of today, the best direct limits on invisible Higgs boson decays come from ATLAS and CMS experiments at the LHC—at 95% C.L. the branching fraction is less than 13% [4] and 19% [5], respectively.

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 from the decay mode (e.g. via vector boson fusion in pp collisions or production

This work was carried out in the framework of the CLICdp Collaboration.

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together with a Z boson in e^+e^- collisions), or indirectly, based on the global fit to all production and decay channel measurements, assuming that the total width of the Higgs boson can also be directly measured. Prospects for constraining properties of the 125 GeV Higgs boson at high luminosity LHC (HL-LHC) and different future collider projects were recently summarised in [6]. For all considered electron–positron Higgs factories, the Future Circular Collider (FCC-ee) [7], the Circular Electron Positron Collider (CEPC) [8], the International Linear Collider (ILC) [9] and the Compact Linear Collider (CLIC) [10], expected indirect constraints on the “untagged” Higgs boson decays are on the level of 1–2%. Stronger constraints are expected from direct searches at e^+e^- Higgs factories, where the Higgs-strahlung process, $e^+e^- \rightarrow ZH$, allows for decay-mode independent tagging of Higgs boson production events. Both leptonic and hadronic decay modes of the Z boson can be considered. While the leptonic final state allows for more precise reconstruction of the event and better background suppression, sensitivity to invisible Higgs boson decays is dominated by hadronic Z boson decay channel providing an order of magnitude higher statistics [11].

Invisible decays of the SM-like Higgs boson are considered as one of the possible signatures for existence of DM particles and physics Beyond the Standard Model (BSM) [12–14]. In the so-called Higgs-portal models, existence of additional fundamental scalars of the “hidden sector” is assumed [15–17]. These new particles could mix with the SM Higgs, and thus, open new decay channels of the SM-like 125 GeV state into DM particles. The new scalars, if they are relatively light, could also be produced in e^+e^- collisions in the process corresponding to the Higgs-strahlung process in the SM: $e^+e^- \rightarrow ZH'$. We extend our search for invisible decays of the SM-like Higgs boson to the search for production and invisible decays of a scalar particle, H' , with 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) [18, 19], a simple extension of the Standard Model with one extra scalar, two Majorana fermions and one gauge boson. The choice was primarily based on our previous experience with this model [20, 21].

Considered in this paper is sensitivity of CLIC running at 380 GeV and 1.5 TeV to invisible decays of the scalar particle produced in association with the Z boson. Only hadronic Z boson decays are considered, following the approach described in [22, 23]. The expected sensitivity of CLIC running at 380 GeV to invisible decays of the 125 GeV Higgs boson is weaker than that expected for other Higgs factories running at energies of 240–250 GeV, close to the maximum of the Higgs-strahlung cross section [6]. However, larger collision energy allows to search for production of new scalars in a wider mass range. For CLIC running at 1.5 TeV, scalar masses of up to about 1 TeV can be probed. Production of new scalars in the Higgs-strahlung process has not been considered before for CLIC. Similar study, based on the leptonic Z boson decays, has been recently presented for ILC [24].

2 Event generation and fast simulation of the detector response

Results presented in this paper are based on a realistic simulation of events, including fast simulation of the CLICdet [25] detector response. Signal and background event samples were generated using WHIZARD 2.7.0 [26, 27], taking into account the beam energy profile expected for CLIC running at 380 GeV and 1.5 TeV parametrised with the CIRCE2 package [28]. As the signal, we considered the Higgs-strahlung process: Higgs boson production (with decay into an invisible final state) together with a Z boson decaying into a quark–antiquark pair. Samples of events with production of the new, hypothetical scalar particle H' with the emission of two quarks ($e^+e^- \rightarrow H'Z \rightarrow inv + qq$) were also generated using the Standard

Model implementation in WHIZARD (SM_CKM model), but with the modified Higgs boson mass and width (according to SM predictions for given mass).¹ 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.

For the background, we studied processes both with and without Higgs boson production. We also took into account the possible background contribution from $\gamma\gamma$ and $e^\pm\gamma$ interactions, where both beamstrahlung photons (γ^{BS}) and photon radiation by the incoming electrons, as described by the effective photon approximation² (γ^{EPA}), were taken into account. The baseline design of CLIC [10] includes polarisation of the electron beam only. For the first running stage, at 380 GeV, the same integrated luminosity of data is expected to be collected with negative and positive electron beam polarisation. We could therefore analyse this data as a single, unpolarised, dataset with an integrated luminosity³ of 1000 fb^{-1} [29]. We also consider the alternative running scenario presented recently [30], where up to 4000 fb^{-1} of data can be collected at the initial CLIC stage. At 1.5 TeV we consider the two electron beam polarisations separately, assuming 2000 fb^{-1} to be collected with -80% polarisation and 500 fb^{-1} with +80% polarisation [29]. Cross sections for processes taken into account in the presented study⁴ calculated by WHIZARD and numbers of generated events are shown in Tables 1 (for 380 GeV running) and 2 (for 1.5 TeV). The cross sections include standard cuts at generator level, as applied in [23]. Only for the $\gamma^{\text{BS}}\gamma^{\text{BS}} \rightarrow q\bar{q}$ sample, the cut on the invariant mass of the produced quark pair was increased to 50 GeV, to avoid large contribution from soft events. Similarly, four-momentum transfer value between the incoming and outgoing electron (or positron) was required to be greater than 100 GeV for $e^+e^- \rightarrow e^+e^-$ events. Numbers of Monte Carlo events generated for some of the background channels are below the event statistics expected in the actual experiment. However, it was verified that the resulting statistical uncertainties of the presented results are on percent level. The statistical cross section uncertainties resulting from the WHIZARD integration are of the order of one permille or below and have been neglected in the analysis.

To simulate detector response, the fast simulation framework DELPHES was used [31]. Control cards prepared for the new detector model CLICdet [32] were modified to make Higgs particles ‘invisible’ in the simulation (ignored when generating detector response), so that the invisible Higgs boson decays can be modelled by defining the Higgs boson as stable in WHIZARD and PYTHIA. An event reconstruction begins with searching for isolated electrons, muons and photons (assuming reconstruction efficiency resulting from the full detector simulation). For CLICdet, DELPHES identifies isolated electrons and photons with energy of at least 2 GeV and muons of 3 GeV. Jet clustering was carried out with the VLC algorithm [33] run in exclusive mode for reconstruction of two hadronic jets with minimal transverse jet momentum of 20 GeV. The algorithm was run with parameters $\beta = 1$ and $\gamma = 1$, and the optimal value for the parameter describing the jet cone size was found to be $R = 1.5$

¹ As the Higgs boson is defined as stable in WHIZARD, to model its invisible decays, it is always produced with the assumed mass, corresponding to the narrow-width approximation.

² For generation of EPA events WHIZARD 2.8.3 was used, with a fix introduced to give correct matching of e^+e^- and $\gamma^{\text{EPA}}e^\pm$ samples.

³ The integrated luminosity for $\gamma^{\text{BS}}\gamma^{\text{BS}}$ interactions is assumed to be 23% (64%), and for $e^+\gamma^{\text{BS}}$ and $\gamma^{\text{BS}}e^-$ interactions 45% (75%) of the e^+e^- luminosity, for CLIC running at 380 GeV (1.5 TeV). These estimates, based on the detailed simulation of the accelerator performance, were obtained for the previous study [23].

⁴ Not included are e^-e^+ processes, in particular those with six fermions in the final state, e.g. $qqqq\ell\bar{\nu}$ and $qqqq\nu\bar{\nu}$, for which no events passed preselection cuts. For interactions involving EPA photons, only the process with the largest background contribution, $\gamma e^\pm \rightarrow q\bar{q}\nu$, was considered, as $\gamma\gamma$ and $e^\pm\gamma$ interactions are dominated by BS photon interactions.

Table 1 Cross sections, σ , and numbers of generated events, N_{GEN} , for each final state considered at 380 GeV; the reference cross section for $H_{\text{inv}} + \text{qq}$ channel is the SM Higgs boson production cross section for $H_{\text{SM}} + \text{qq}$ final state

Final state	σ [fb]	N_{GEN}
qq	22,190	2,000,000
ll	19,920	1,000,000
qqqq	5080	500,000
qqll	1730	200,000
qqvv	317.4	300,000
qqlv	5559	2,000,000
qqlvvv	1.36	100,000
$H_{\text{SM}} + \text{qq}$	82.33	100,000
$H_{\text{SM}} + \text{ll}$	15.48	100,000
$H_{\text{SM}} + \text{vv}$	54.45	100,000
$\gamma^{\text{BS}} \gamma^{\text{BS}} \rightarrow \text{qq}$	1914	200,000
$\gamma^{\text{BS}} \gamma^{\text{BS}} \rightarrow \text{qqqq}$	1.84	10,000
$\gamma^{\text{BS}} \gamma^{\text{BS}} \rightarrow \text{qqll}$	33.0	10,000
$\gamma^{\text{BS}} \gamma^{\text{BS}} \rightarrow \text{qqlv}$	0.72	10,000
$\gamma^{\text{BS}} \gamma^{\text{BS}} \rightarrow \text{qqvv}$	0.03	10,000
$\gamma^{\text{BS}} e^- \rightarrow \text{qqv}$	1420	1,000,000
$\gamma^{\text{BS}} e^+ \rightarrow \text{qqv}$	1426	1,000,000
$\gamma^{\text{EPA}} e^- \rightarrow \text{qqv}$	881.5	1,000,000
$\gamma^{\text{EPA}} e^+ \rightarrow \text{qqv}$	883.8	1,000,000
$H_{\text{inv}} + \text{qq}$		100,000

for 380 GeV and $R = 0.7$ for 1.5 TeV CLIC running. While the algorithm is configured to reconstruct two hadronic jets, VLC distance values at which an event transitions from four to three jets and from three to two jets are stored as parameters y_{34} and y_{23} , respectively. We further require that each jet includes at least two charged particles.

Because of the 0.5 ns bunch spacing in the CLIC beams, the pile-up of beam-induced backgrounds can affect the event reconstruction. Realistic levels of pile-up from the most important beam-induced background, the $\gamma\gamma \rightarrow \text{hadrons}$ process, were included in full simulation studies to verify the impact on event reconstruction results [23]. A selection based on the time stamp and transverse momentum of the reconstructed particles can be used to reduce this background significantly. Further suppression results from use of the VLC algorithm which was designed to be more resilient to the impact of backgrounds [33]. Effects of the beam-induced backgrounds turned out to be negligible for CLIC running at 380 GeV. To take into account their contribution at 1.5 TeV, additional energy smearing is applied for jets reconstructed at 1.5 TeV: for central jets ($|\cos \theta| < 0.64$), the pile-up contribution is expected to result in an additional 1% jet energy smearing, while for more forward jets ($|\cos \theta| \geq 0.64$) 5% smearing is assumed [32]. Jet momentum is scaled by the same factor

Table 2 Cross sections, σ^{neg} and σ^{pos} , for -80% and $+80\%$ electron beam polarisation, respectively, at 1.5 TeV CLIC, and numbers of generated events, N_{GEN} , for each considered final state; the reference cross sections for $H_{inv} + qq$ channel are the SM Higgs boson production cross sections for $H_{SM} + qq$ final state

Final state	σ^{neg} [fb]	σ^{pos} [fb]	N_{GEN}
qq	2873	1807	1,000,000
ll	1396	1218	1,000,000
qqqq	1971	265.5	1,000,000
qqll	2740	2570	1,000,000
qqvv	1459	187.3	3,000,000(neg.)/1,000,000(pos.)
qqlv	6990	1713	3,000,000(neg.)/1,000,000(pos.)
qqlvvv	40.1	5.4	100,000
$H_{SM} + qq$	9.42	6.59	100,000
$H_{SM} + ll$	31.65	22.09	100,000
$H_{SM} + vv$	466.6	53.49	500,000(neg.)/100,000(pos.)
$\gamma_{BS}\gamma_{BS} \rightarrow qq$	6030	6030	1,000,000
$\gamma_{BS}\gamma_{BS} \rightarrow qqqq$	6330	6330	100,000
$\gamma_{BS}\gamma_{BS} \rightarrow qqll$	2790	2790	100,000
$\gamma_{BS}\gamma_{BS} \rightarrow qqlv$	6700	6700	100,000
$\gamma_{BS}\gamma_{BS} \rightarrow qqvv$	6.57	6.57	100,000
$\gamma_{BS}e^- \rightarrow qqv$	28,240	3138	2,000,000(neg.)/500,000(pos.)
$\gamma_{BS}e^+ \rightarrow qqv$	15,650	15,650	2,000,000
$\gamma_{EPA}e^- \rightarrow qqv$	6617	735	2,000,000
$\gamma_{EPA}e^+ \rightarrow qqv$	3668	3668	2,000,000
$H_{inv} + qq$			100,000

as the jet energy ⁵ and possible impact of pile-up on the reconstruction of the jet direction is neglected. Validity of the proposed approach for the reconstruction of hadronic vector boson decays has been recently demonstrated in a similar study [34]. Impact of the jet energy smearing on the expected cross section limits presented in this work for CLIC running at 1.5 TeV was found to be small, at the level of 3–5%.

3 Signal event selection

3.1 Preselection of events

A main purpose of the preselection is to remove all background events which are not consistent with the expected signature of the signal process. For the process $e^+e^- \rightarrow HZ \rightarrow inv + qq$, the two reconstructed jets are expected to have an invariant mass consistent with the mass of the Z boson. In the initial preselection step, all events which were not consistent with this

⁵ This procedure is different from the one implemented in DELPHES cards for CLICdet [32], where the jet mass is neglected in the jet energy smearing

signature were rejected. In particular, events with isolated leptons (electrons or muons) or isolated energetic photons (with energy greater than 5 GeV) were excluded. For a significant fraction of events, the difference between the energy sum of the reconstructed jets and the energy sum of all identified particles in the event was sizable, indicating an incomplete event reconstruction (e.g. additional jet with transverse momentum below the required threshold of 20 GeV or deposits removed by the VLC algorithm run in exclusive mode due to the small beam distance). To avoid such events, we required this difference to be less than 10 GeV.

In the next steps, quantities describing event topology were considered. First, we analysed the distributions of parameters y_{23} and y_{34} describing the results of jet clustering with VLC algorithm. While the algorithm was forced to reconstruct two jets in each event, these distributions allowed us to distinguish actual two-jet events from events with a larger number of underlying jets in the final state. The distributions of $-\log_{10}y_{23}$ and $-\log_{10}y_{34}$ are shown in Fig. 1a and b, respectively. The double-peak structure, clearly visible in the background sample of SM Higgs boson decays (H_{SM}), corresponds to pure two- and four-jet events. The distribution for the other background channels is more uniform. For the signal sample, with two hadronic jets, we expect values of y_{23} and y_{34} to be relatively small. We selected events for which $y_{23} < 0.01$ ($-\log_{10}y_{23} > 2.0$) and $y_{34} < 0.001$ ($-\log_{10}y_{34} > 3.0$).

The next quantity considered for the preselection of signal events was the invariant mass of the two-jet final state— m_{jj} . It should correspond to the mass of the Z boson, so only events for which this value was in the range of 80–100 GeV were selected for further analysis. The distribution of the invariant masses for different event samples is shown in Fig. 1c. For e^+e^- SM background events (SM bg), dijet mass distribution is also peaked at the mass of the Z boson, so only the tails of the distribution can be rejected. However, photon-induced backgrounds ($\gamma\gamma$ and $e^\pm\gamma$) are dominated by hadronic decays of the W boson and significant suppression is possible with the dijet mass cut. The peak visible in the channel of SM Higgs boson decays (H_{SM}) around 120 GeV corresponds to the process $e^+e^- \rightarrow HZ \rightarrow qq\nu\nu$ which, considering only its topology (two jets and missing energy), is indistinguishable from the signal.⁶ We also studied the distribution of the dijet emission angle, θ , defined as the angle between the beam axis and a sum of the jet four-momenta (the emission angle of the Z boson for the signal events). For the majority of background events, small emission angles are reconstructed, while for signal events the distribution is almost flat (angles close to 90° are slightly preferred). Therefore, events for which $|\cos(\theta)|$ was greater than 0.8 were excluded from the analysis. The distribution of cosine of the angle θ is shown in Fig. 1d.

The results of the preselection are presented in Tables 3 and 4. Shown in Fig. 2 is the distribution expected for CLIC running at 380 GeV of the so-called recoil mass, the invariant mass of the Higgs boson produced together with the Z boson, after preselection cuts, reconstructed from the energy–momentum conservation (missing mass). For the background sample, the distribution has two maxima: at around 300 GeV, which is the maximum recoil mass allowed (as we require two jets to have an invariant mass of at least 80 GeV), and at around 90 GeV, which is mainly due to invisible Z boson decays. For signal events, normalised in Fig. 2 to $\text{BR}(H \rightarrow \text{inv}) = 1\%$, the expected recoil mass distribution is consistent with the SM Higgs boson mass of 125 GeV. The slight shift of the maxima and longer tail in the reconstructed recoil mass distribution towards higher mass values is most likely due to the influence of the beam energy spectra, which is not accounted for in the recoil mass reconstruction.

⁶ The observed shift in the peak position can be attributed to the missing energy carried out by neutrinos from b-quark decays.

Fig. 1 Distributions of variables used for event preselection: jet clustering parameters, y_{23} (a) and y_{34} (b), dijet invariant mass, m_{jj} (c) and the cosine of the dijet emission angle, $\cos(\theta)$ (d). Compared are distributions for different event samples: 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. For easier shape comparison, the signal sample is normalised to $\text{BR}(H \rightarrow \text{inv}) = 100\%$. Black vertical lines indicate preselection cuts, see text for details

3.2 Final selection

The second stage of the analysis was based on multivariate analysis and machine learning. The boosted decision tree (BDT)[35] algorithm, as implemented in TMVA framework[36], was used, with 1000 trees and 5 input variables. The following parameters were selected as the BDT input variables:

1. E_{jj} —dijet energy,
2. m_{jj} —dijet invariant mass,
3. m^{miss} —reconstructed recoil mass,
4. p_t^{miss} —missing transverse momentum,
5. α_{jj} —angle between the two reconstructed jets in the LAB frame.

Table 3 Efficiency and expected event numbers after preselection, N_{pre} , corresponding to the integrated e^+e^- luminosity of 1000fb^{-1} collected at 380GeV , for each considered sample or events. Results for the signal sample were calculated for SM Higgs boson production cross section and $\text{BR}(H \rightarrow \text{inv}) = 100\%$

Final state	Efficiency (%)	N_{pre}
<i>Without Higgs boson</i>		
qq	0.08	16,864
ll	< 0.01	20
qqqq	< 0.01	51
qqll	0.02	415
qq $\nu\nu$	20.47	64,965
qq $\ell\nu$	0.60	33,065
qq $\ell\nu\nu$	1.32	18
Total:	0.21	115,398
<i>With Higgs boson decays described in the Standard Model</i>		
$H_{\text{SM}} + \text{qq}$	< 0.01	41
$H_{\text{SM}} + \text{ll}$	0.01	1
$H_{\text{SM}} + \nu\nu$	2.33	1271
Total:	0.86	1313
<i>Photon interactions</i>		
$\gamma^{\text{BS}}\gamma^{\text{BS}} \rightarrow \text{qq}$	0.78	3412
$\gamma^{\text{BS}}\gamma^{\text{BS}} \rightarrow \text{qqll}$	0.03	2
$\gamma^{\text{BS}}\gamma^{\text{BS}} \rightarrow \text{qq}\ell\nu$	1.59	3
$\gamma^{\text{BS}}\gamma^{\text{BS}} \rightarrow \text{qq}\nu\nu$	0.06	1
$\gamma^{\text{BS}}\gamma^{\text{BS}} \rightarrow \text{qqqq}$	0.03	1
$\gamma^{\text{BS}}e^- \rightarrow \text{qq}\nu$	6.73	42,707
$\gamma^{\text{BS}}e^+ \rightarrow \text{qq}\nu$	6.68	42,823
$\gamma^{\text{EPA}}e^- \rightarrow \text{qq}\nu$	6.32	56,054
$\gamma^{\text{EPA}}e^+ \rightarrow \text{qq}\nu$	6.20	56,489
Total:	5.11	201,492
<i>Signal</i>		
$H_{\text{inv}} + \text{qq}$	43.56	35,920

This choice of parameters was selected as optimal, resulting in the most efficient event classification, from a large number of different parameter sets considered. Distributions of the selected variables for the signal and the background samples are shown in Fig. 3.

Distributions of the BDT algorithm response for considered signal and background event samples (after preselection cuts) are shown in Fig. 4a. Most of the background events can be easily distinguished from the signal, but there is also a significant contribution of background events for which BDT response values are positive, consistent with the response expected for signal events. This indicates that it is not possible to achieve full separation between the signal and the background processes. One should note that about 0.1% of SM Higgs boson decays result in fact in the invisible final state ($H \rightarrow ZZ^* \rightarrow \nu\nu\nu\nu$), which is included in the background simulation.

Table 4 Efficiency and expected event numbers after preselection, N_{pre} , corresponding to the integrated e^+e^- luminosity of 2000fb^{-1} (negative polarisation) and 500fb^{-1} (positive polarisation) collected at 1.5GeV , for each considered sample of events. Results for the signal were calculated for SM Higgs boson production cross section and $\text{BR}(H \rightarrow inv) = 100\%$

Final state	Efficiency - p. neg. (%)	$N_{\text{pre}}^{\text{neg}}$	Efficiency - p. pos. (%)	$N_{\text{pre}}^{\text{pos}}$
<i>Without Higgs boson</i>				
qq	0.07	4005	0.08	679
ll	< 0.01	14	< 0.01	2
qqqq	< 0.01	99	< 0.01	7
qqll	0.04	2208	0.04	455
qq $\nu\nu$	13.30	396,177	12.73	11,925
qql ν	1.47	206,227	2.29	19,594
qql $\nu\nu\nu$	1.23	985	2.10	57
Total:	1.76	609,715	0.84	32,719
<i>With Higgs boson decays described in the Standard Model</i>				
$H_{\text{SM}} + \text{qq}$	0.02	3	< 0.01	0
$H_{\text{SM}} + \text{ll}$	0.11	69	0.11	12
$H_{\text{SM}} + \nu\nu$	2.34	21,877	2.50	669
Total:	2.16	21,949	1.65	681
<i>Photon interactions</i>				
$\gamma_{\text{BS}}\gamma_{\text{BS}} \rightarrow \text{qq}$	0.21	16,627	0.22	4182
$\gamma_{\text{BS}}\gamma_{\text{BS}} \rightarrow \text{qqll}$	0.04	1464	0.04	375
$\gamma_{\text{BS}}\gamma_{\text{BS}} \rightarrow \text{qql}\nu$	0.32	27,529	0.32	6689
$\gamma_{\text{BS}}\gamma_{\text{BS}} \rightarrow \text{qq}\nu\nu$	0.38	32	0.37	8
$\gamma_{\text{BS}}\gamma_{\text{BS}} \rightarrow \text{qqqq}$	< 0.01	0	< 0.01	0
$\gamma_{\text{BS}}e^- \rightarrow \text{qq}\nu$	4.04	1,711,301	3.91	47,133
$\gamma_{\text{BS}}e^+ \rightarrow \text{qq}\nu$	4.02	943,061	4.03	23,627
$\gamma_{\text{EPA}}e^- \rightarrow \text{qq}\nu$	3.17	418,210	3.16	11,615
$\gamma_{\text{EPA}}e^+ \rightarrow \text{qq}\nu$	3.20	235,400	3.21	58,972
Total:	2.93	3,353,624	2.24	152,601
<i>Signal</i>				
$H_{\text{inv}} + \text{qq}$	42.16	8023	42.04	1388

In the final step of the analysis, we select the cut on the BDT response which gives the highest significance for the expected signal. The dependence of the signal significance at 380GeV on the BDT algorithm response cut is shown in Fig. 4b, for the signal sample normalised to $\text{BR}(H \rightarrow inv) = 1\%$. The highest significance for invisible Higgs decays at 380GeV CLIC is obtained for a BDT response cut of about 0.14, corresponding to a BDT selection efficiency for signal events of about 50% and background rejection efficiency of about 95%. The background remaining after the BDT cut is dominated by contributions from $e^+e^- \rightarrow \text{qq}\nu\nu$ (68% of expected background events), $e^+e^- \rightarrow \text{qql}\nu$ (14%) and $\gamma e^\pm \rightarrow \text{qq}\nu$ (17%). While we do not discuss systematic uncertainties of the measurement here, one has

Fig. 2 Distributions of the reconstructed invariant mass of the invisible Higgs boson decay products 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 $\text{BR}(H \rightarrow \text{inv}) = 1\%$

to note that they can be significantly constrained based on measurements of $e^+e^- \rightarrow ZZ$ and $e^+e^- \rightarrow WW$ processes in other decay channels (data-driven approach).

The same analysis procedure was applied for signal and background samples generated for CLIC running at 1.5 TeV, separately for two considered electron beam polarisation settings. Distributions of the BDT algorithm response for considered signal and background event samples (after preselection cuts) are shown in Fig. 5.

A similar level of signal–background separation is obtained for each polarisation. The background remaining after the BDT cut is again dominated by $qq\nu\nu$ contribution (about 74%) and $\gamma e^\pm$ processes (17%), while contribution from $qq\ell\nu$ channel decreases and is at the level of about 7%.

The analysis procedure developed to discriminate between the background of different SM processes and the signal of invisible scalar decays, described above for the case of the 125 GeV SM-like Higgs boson, was used to estimate the expected sensitivity of CLIC experiment to production and invisible decays of a new scalar state. Same preselection cuts and same set of input BDT variables were used for each scenario, and the BDT algorithm was trained separately for each considered scalar mass (each generated signal sample). With the BDT response cut optimised for signal significance, one can extract an expected limit on the cross section for the production of the new scalar H' as a function of its mass, assuming its invisible decays, $\text{BR}(H' \rightarrow \text{inv}) = 100\%$.

For the scalar mass of 125 GeV, expected numbers of background events and efficiency of signal event selection can also be translated into a constraint on the invisible branching ratio of the SM-like Higgs boson. For the first stage of the CLIC accelerator, assuming that the measured event distributions are consistent with the predictions of the Standard Model,

Fig. 3 Distributions of the input variables selected for the BDT algorithm: dijet energy, E_{jj} (a), dijet invariant mass, m_{jj} (b), reconstructed recoil mass, m^{miss} (c), missing transverse momentum, p_t^{miss} (d) and angle between the two reconstructed jets, α_{jj} (e). Expected signal (thick blue line) and background (thin red line) event distributions for CLIC running at 380 GeV are normalised to 1000 fb^{-1} and $\text{BR}(H \rightarrow \text{inv}) = 1\%$ for signal events

the expected 95% C.L. limit⁷ is:

$$\text{BR}(H \rightarrow \text{inv}) < 1.0\% \quad (0.5\%)$$

for the integrated luminosity of 1000 fb^{-1} (4000 fb^{-1}).⁸ A significance above 5σ , necessary to confirm the discovery of a new decay channel (and therefore also existence of new, invisible particles), is expected for an invisible Higgs boson branching ratio above 3.0% (1.5%). Presented results seem to be consistent with previous estimates presented by CLICdp Collab-

⁷ Assuming that one-side confidence limit of 95% corresponds to significance of 1.64.

⁸ It was verified that the expected limits scale with the integrated luminosity L as $1/\sqrt{L}$.

Fig. 4 Distribution of BDT response for the signal (thick blue line) and the background (thin red line) events (left) and the expected significance of signal observation as a function of the BDT response cut (right), for 1000 fb^{-1} collected at 380 GeV and $\text{BR}(H \rightarrow \text{inv}) = 1\%$ for signal events

Fig. 5 Distribution of BDT response for the signal (thick blue line) and the background (thin red line) for CLIC running at 1.5 TeV , with electron beam polarisation of -80% (left) and $+80\%$ (right)

oration, $\text{BR}(H \rightarrow \text{inv}) < 0.69\%$ (0.34%) at 90% C.L. [29,30]. However, direct comparison is not possible, as these estimates are based on the study assuming CLIC running at 350 GeV [22,23], with higher expected Higgs production cross section and lower cross sections for main background channels. Beamstrahlung and EPA photon interactions were also not taken into account in [22,23]. Presented results on searches for invisible Higgs boson decays at 380 GeV CLIC show that even for 4000 fb^{-1} of integrated luminosity the expected sensitivity is weaker than at other Higgs factories, running at energies of $240\text{--}250\text{ GeV}$, where the exclusion limits of the order of $0.22\text{--}0.27\%$ are expected (for first stages of FCC-ee, ILC and CEPC) [6]. That is why we focus on the search for production of new scalars in the following.

4 Results

In Fig. 6a and b presented are 95% C.L. limits on the cross section for the production of the new scalar H' in association with the Z boson, relative to the expected cross section for the production of the SM-Higgs boson (for given mass), as a function of the assumed scalar mass. The results shown in Fig. 6a and b are obtained for CLIC running at 380 GeV and 1.5 TeV , respectively.

Fig. 6 Expected 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). New scalar is assumed to have only invisible decay channels, $\text{BR}(H' \rightarrow \text{inv}) = 100\%$

Fig. 7 Expected sensitivity of CLIC running at 380 GeV and 1.5 TeV compared to the existing limit from LEP [37] and the expected sensitivity of ILC running at 250 GeV and 500 GeV [24]. 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, new scalar is assumed to have invisible decay channel only, $\text{BR}(H' \rightarrow \text{inv}) = 100\%$, while LEP and ILC results are decay-mode independent

Decays of the new scalar are assumed to be dominated by invisible channels, $\text{BR}(H' \rightarrow \text{inv}) = 100\%$. The results indicate that the experiment at CLIC will be able to exclude new scalar production with rate of about 1% of the SM production cross section for masses up to about 200 GeV, assuming 4000 fb^{-1} of data collected at 380 GeV. For higher masses the experimental sensitivity decreases mainly due to the decreasing production cross section.

For the second CLIC stage, sensitivity to production and invisible decays of the light Higgs-like scalars is smaller than at 380 GeV, mainly due to the decreasing signal cross section and higher background levels. The expected limit on the invisible decays of SM Higgs boson is about 3%. Assuming the production cross section given by the SM predictions, the second stage of CLIC will be sensitive to the new ‘invisible’ scalars up to about 1 TeV.

In Fig. 7, the expected sensitivity of CLIC running at 380 GeV and 1.5 TeV is compared to the existing limit from LEP [37] and the expected sensitivity of ILC for 2000 fb^{-1} collected at 250 GeV and 4000 fb^{-1} collected at 500 GeV [24]. LEP and ILC limits were evaluated in a

decay-mode independent approach, based on the reconstruction of leptonic Z boson decays ($Z \rightarrow e\bar{e}$ and $Z \rightarrow \mu\bar{\mu}$). The two approaches are complementary. Stronger limits can be obtained when considering hadronic Z boson decays, if we can assume that invisible decay channels dominate for H' . Production of new scalars with masses below 125 GeV was not considered in the presented study, as signal–background separation becomes more difficult in this range and fast detector simulation with DELPHES could be not detailed enough to model this correctly.

5 Interpretation

The expected limits on 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 different BSM scenarios. We demonstrate the possibility of constraining parameters of the Higgs-portal models taking the VFDM model [18, 19] as an example. The Standard Model (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 employed in the dark sector. Dark matter candidates are the massive vector boson X_μ and two Majorana fermions $\psi_\pm$. The spontaneous symmetry breaking in the dark sector results in an additional scalar state ϕ . This state can mix with the SM Higgs field h implying 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 ($\text{BR}(H \rightarrow \text{inv}) \sim \sin^2 \alpha$). If H' is also light, it can be produced in e^+e^- collisions in the same way as the SM-like Higgs boson. We assume in the following that invisible decays to dark matter sector particles dominate for H' ($\text{BR}(H' \rightarrow \text{inv}) \approx 100\%$). If this is the case,⁹ the cross section for new scalar production corresponding to the limits presented in the previous section can be written as:

$$\sigma_{H'} = \sigma_{\text{SM}}^{m_{H_{\text{SM}}} = m_{H'}} \cdot \sin^2(\alpha),$$

where $\sigma_{H'}$ is the cross section for the production of a new scalar of mass $m_{H'}$, and $\sigma_{\text{SM}}^{m_{H_{\text{SM}}} = m_{H'}}$ is the cross section for the production of the Higgs boson in the Standard Model with the same mass. Limits on the sine of the mixing angle, $\sin \alpha$, resulting from the cross section limits presented in Fig. 6, are shown in Fig. 8.

The mixing angle in the VFDM model can also be constrained by analysing the limit on the invisible branching ratio for the SM-like Higgs boson $\text{BR}(H \rightarrow \text{inv})$. When the contribution of the $H'H'$ decay channel can be neglected, the invisible partial width of the Higgs boson, Γ_{inv} , is proportional to $\sin^2(\alpha)$, but depends also on other model parameters, in particular on the dark sector coupling constant, g_X , the mass of the vector dark matter, m_X , and the masses of the fermionic dark matter particles, m_{ψ_-} and m_{ψ_+} .¹⁰ Constraints on the scalar sector mixing angle, resulting from the limits on the invisible decays of the SM-like Higgs boson expected at 380 GeV CLIC, are shown in Fig. 9. Expected limits on $\sin \alpha$, plotted as a

⁹ This assumption is a good approximation in a wide range of model parameters, although a small part of the new scalar decays must also be visible because otherwise the scalar would not be produced.

¹⁰ The two fermionic states are defined in such a way that $m_{\psi_-} \leq m_{\psi_+}$.

Fig. 8 Expected limits on the sine of the scalar sector mixing angle, $\sin \alpha$, as a function of the H' mass, for CLIC running at 380 GeV (left and right plots) and 1.5 TeV (right plot)

function of the Ψ_- particle mass, are based on the invisible decay widths¹¹ calculated with WHIZARD, for $g_X = 1$ and $m_X = m_{\Psi_+} = 200$ GeV.¹² Also indicated in Fig. 9 are the indirect limits on the mixing angle, which can be set at CLIC from the analysis of the Higgs coupling measurements. Due to the mixing with the ϕ state, all couplings of the SM-like Higgs boson to SM particles are scaled by $\cos(\alpha)$. In particular, the coupling of the Higgs boson to the Z bosons, g_{HZZ} , is given by:

$$g_{HZZ} = g_{HZZ}^{(\text{SM})} \cdot \cos(\alpha).$$

It is expected that the experiment at 380 GeV CLIC will be able to measure g_{HZZ} in a model-independent approach with an accuracy of 0.6% [29]. If no deviations from SM are observed, the corresponding 95% C.L. limit on the mixing angle in the VFDM model is:

$$|\sin(\alpha)| < 0.14.$$

If the Higgs coupling fit is performed with the assumption that the Higgs boson couplings to all SM particles scale by the same factor, κ , much stronger constraints can be set [38]. After three CLIC running stages, the overall scaling of the Higgs boson couplings should be known to

$$\Delta\kappa = 0.06\%.$$

This corresponds to 95% C.L. limit on the mixing angle in the VFDM model of:

$$|\sin(\alpha)| < 0.044.$$

Also indicated in Fig. 9 are constraints resulting from the ATLAS and CMS limits on invisible Higgs boson decays, $\text{BR}(H \rightarrow \text{inv}) < 13\%$ [4] and $< 19\%$ [5], respectively. For masses of dark matter particles up to about 60 GeV, direct search for invisible Higgs boson decays will allow to set much better constraints on the mixing angle in the scalar sector than it will be possible with indirect methods.

¹¹ The scaling of SM (visible) decay width with factor $\cos^2(\alpha)$ was neglected for the considered range of $\sin \alpha$.

¹² For other parameter values, limits on $\sin(\alpha)$ presented in Fig. 9 scale as $\frac{m_X}{200 \text{ GeV} \cdot g_X}$, assuming $m_{\Psi_+} \gg m_{\Psi_-}$.

Fig. 9 Expected upper limits on the sine of the scalar sector mixing angle, $\sin \alpha$, as a function of the Ψ -particle mass of the VFDM model, for 1 ab^{-1} (magenta) and 4 ab^{-1} (green) of integrated luminosity collected at 380 GeV CLIC. Indicated by blue and red curves are limits corresponding to the direct limits from ATLAS [4] and CMS [5] experiments, respectively. The horizontal lines indicate the indirect limits expected from the measurement of the g_{HZZ} and κ couplings [29,38]

6 Summary

We studied the sensitivity to invisible Higgs boson decays and the possibility of constraining production of new scalar particles at CLIC running at 380 GeV and 1.5 TeV. We assumed associated production of Higgs-like neutral scalar with Z boson and invisible scalar decays. The analysis was based on the WHIZARD event generation and fast simulation of the CLIC detector response with DELPHES, taking into account beam energy profile as well as background contributions from photon-photon and electron-photon interactions. An approach consisting of a two-step analysis, with multivariate analysis methods employed at the second step, was used to optimise separation between signal and background processes. 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. For 1000 fb^{-1} of data collected at initial CLIC stage invisible Higgs boson decays at the level of 1.0% can be excluded at 95% C.L. The limits obtained in the model-independent approach can also be used to set limits on the different extensions of the Standard Model. Constraints at the percent level can be set on the scalar sector mixing angle in Higgs-portal models.

Acknowledgements The work was carried out in the framework of the CLIC detector and physics (CLICdp) collaboration. We thank collaboration members for fruitful discussions, valuable comments and suggestions. The work was partially supported by the National Science Centre (Poland) under OPUS research Projects Nos. 2017/25/B/ST2/00496 (2018–2021) and 2017/25/B/ST2/00191 and a HARMONIA Project under contract UMO-2015/18/M/ST2/00518 (2016–2019).

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