Sensitivity to new physics scenarios in invisible Higgs boson decays at CLIC

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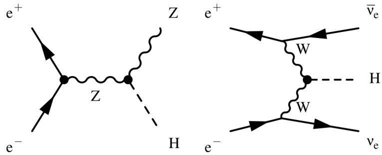
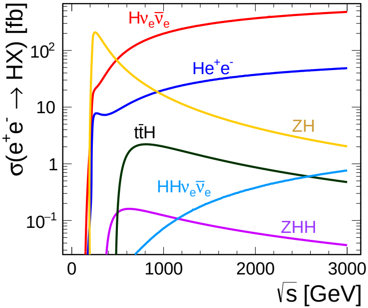
Higgs production

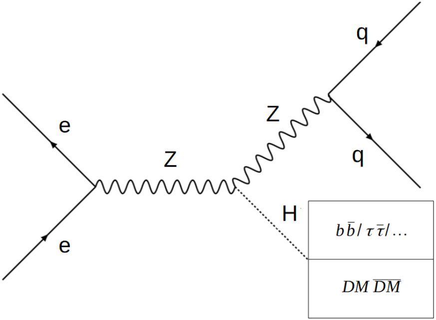
Sensitivity to search for invisible Higgs boson decays
→ *ZH* production at 380 GeV





Signal

SM(-like) Higgs boson decay to invisible states (Dark Matter?)

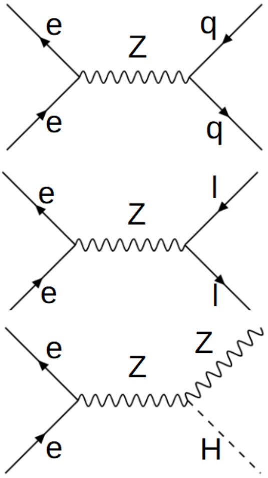


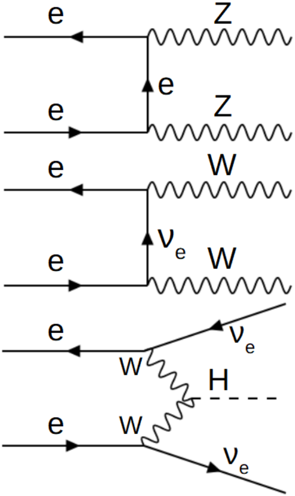
Signature of invisible Higgs decay:

- two jets consistent with hadronic Z decay
- missing energy-momentum consistent with production of invisible massive state of 125 GeV

higher statistics

Background processes considered





Simulation framework

- event samples generated with WHIZARD 2.7.0
  - Non-Higgs background: qq, ll, $qqqq$, $qqll$, $ql\nu$, $qq\nu\nu$, $qql\nu\nu\nu$
  - SM Higgs boson production:
    $H + qq$, $H + ll$, $H + \nu\nu$ (with 100% SM decays)
  - Signal: $H + qq$ production with Higgs defined as stable

- CLIC energy spectra for **380** GeV
- CLIC integrated luminosity of **1000** fb^{-1} (unpolarised)
- detector simulation and event reconstruction with DELPHES, using modified[1] *CLICdet_Stage1* cards

Two jets reconstructed with VLC algorithm ($R = 1.5$, $\beta = \gamma = 1$)

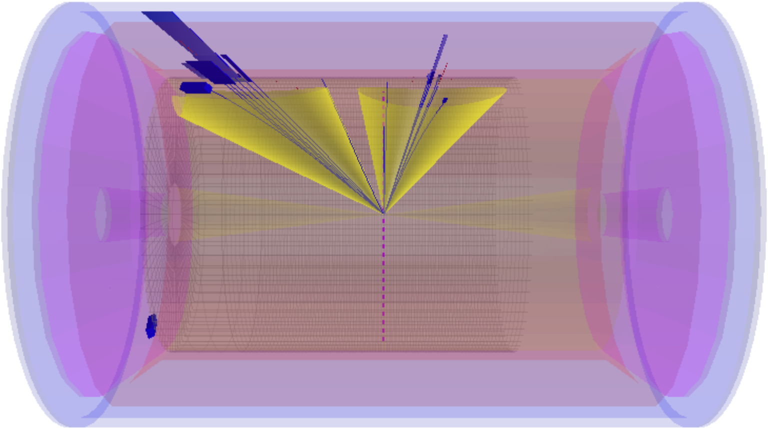
[1] required to make Higgs invisible in the detector

Processes considered

Final state	σ **[fb]**	**N**$_{GEN}$
qq	22200.0	2000000
ll	19900.0	1000000
$qqqq$	5080.0	500000
$qqll$	1730.0	200000
$qq\nu\nu$	317.0	300000
$qql\nu$	5560.0	500000
$qql\nu\nu\nu$	1.37	100000
$H_{SM} + qq$	82.3	100000
$H_{SM} + ll$	15.5	100000
$H_{SM} + \nu\nu$	54.5	100000
$H_{inv} + qq$	82.3	100000

Signature of $e^+e^- \to HZ \to jj + inv$

Two-jet events without electrons, muons, or isolated photons...



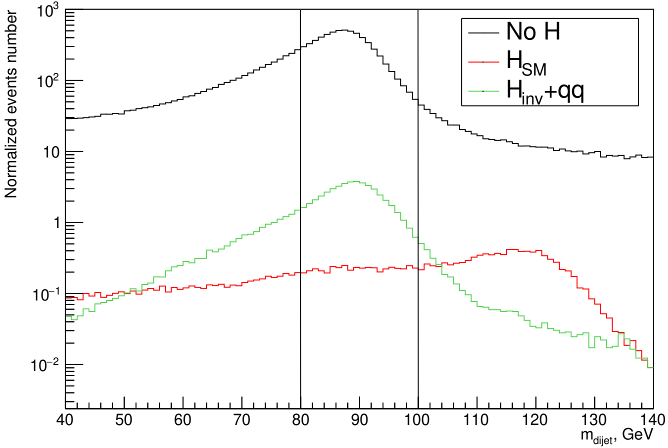
Preselection

Preselection cuts were used to select events with proper signature and kinematics consistent with invisible Higgs boson decay:

- Remove events with isolated electrons, muons or photons with energy above 2 GeV, 3 GeV and 5 GeV respectively
- Energy "lost" in jet clustering below 10 GeV
- At least 2 charged particles
- Two-jet topology: $y_{23} < 0.01$ and $y_{34} < 0.001$
- Jet invariant mass: $80 < M_{jj} < 100\,\text{GeV}$ (Z mass)
- Dijet emision angle: $|\cos\Theta_{jj}| < 0.8$ (Z direction)

Preselection cut example

Di-jet invariant mass distribution with preselection cut indicated



Preselection

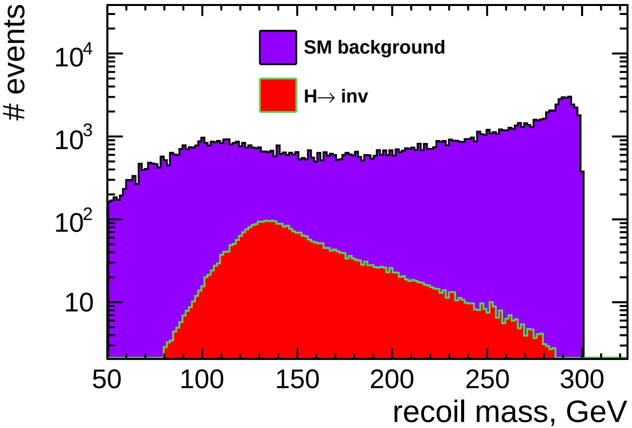
Efficiency of preselections cuts

Event class	*Efficiency*
Non-Higgs background	**0.21%**
including $qq\nu\nu$	20.47%
$qql\nu\nu\nu$	1.32%
$qql\nu$	0.60%
qq	0.08%
SM Higgs decays	**0.86%**
including $H + \nu\nu$	2.33%
$H + qq$ **invisible decays**	**43.56%**

Preselection

Recoil mass distribution after preselection cuts

For 1000 fb^{-1} collected at 380 GeV   assuming BR(H→inv) = 10%

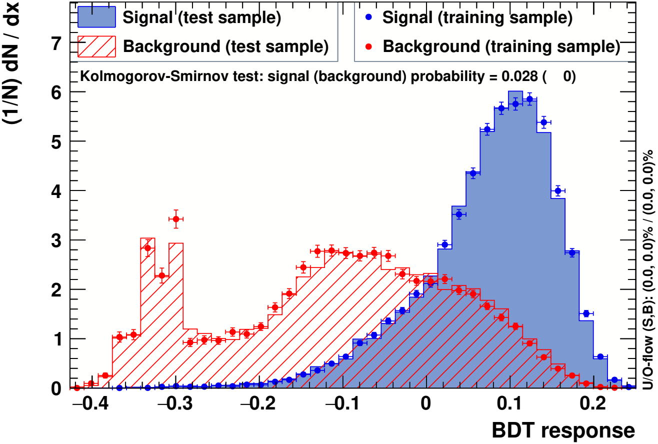


Selection

Final event selection based on the multivariate analysis.
Variables used as input for Boosted Decision Tree (BDT):

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

Selection



Highest significance for invisible Higgs decays for BDT cut $\sim$ 0.06

Results

95% C.L. limit expected for 1000 fb^{-1} collected at 380 GeV:

$$BR(H \rightarrow inv) \ < \ 0.89\%$$

Assuming **no excess** above predicted SM background is observed

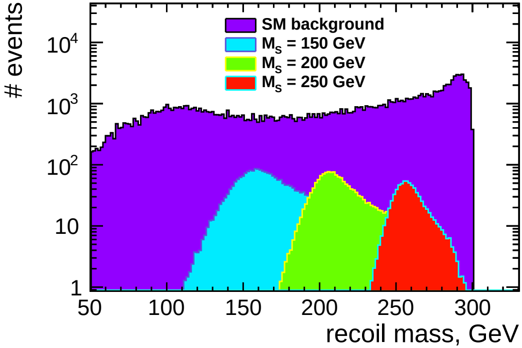
Result consistent with the old study:
$BR(H \rightarrow inv) < 0.94\%$ expected for 500 fb^{-1} collected at 350 GeV
M. A. Thomson, The European Physical Journal C, 76(2):72

for 350 GeV $\sigma(e^+e^- \rightarrow HZ) = 134$ fb
for 380 GeV $\sigma(e^+e^- \rightarrow HZ) = 82$ fb

Limits on new scalar production

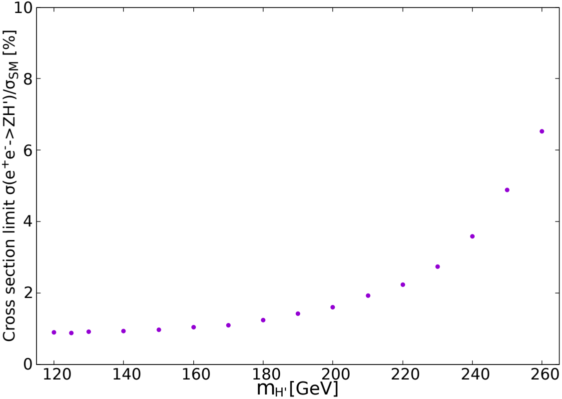
Same approach can be used to search for production of H' state in the process $e^+e^- \rightarrow ZH' \rightarrow qq + inv$

(H' generated in WHIZARD as SM-Higgs particle of different mass)



Limits on new scalar production

Expected limits on the H' production cross section, relative to SM, for $1000\,\mathrm{fb}^{-1}$ at $380\,\mathrm{GeV}$ assuming $\mathrm{BR}(H' \to inv) \approx 100\%$



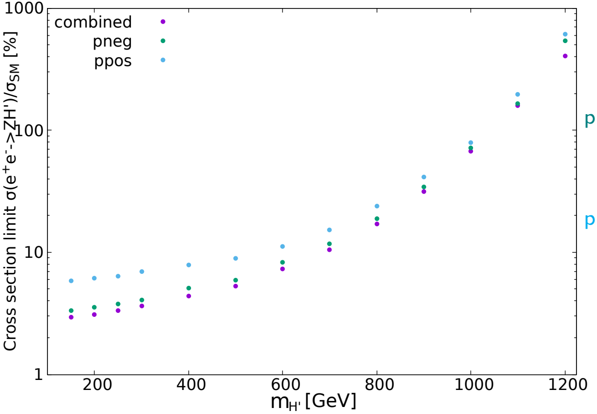
CLIC at 1.5 TeV

At 1.5 TeV, cross section for ZH_{SM} production is smaller but it is possible to produce much heavier hypothetical Higgs-like particles.

- additional jet energy smearing
- polarised e^{-} beam – CLIC integrated luminosity of **2000** fb^{-1} (for negative polarisation) and **500** fb^{-1} (positive polarisation)
- new background channel $\gamma^{BS}\gamma^{BS} \to qq$ (the simplest beamstrahlung photons interactions included)

Limits on new scalar production

Expected limits on the H' production cross section, relative to SM, for $2500\,\mathrm{fb}^{-1}$ at $1500\,\mathrm{GeV}$ assuming $\mathrm{BR}(H' \to inv) \approx 100\%$



pneg:
$P(e^-) = -80\%$
$2000\ \mathrm{fb}^{-1}$

ppos:
$P(e^-) = +80\%$
$500\ \mathrm{fb}^{-1}$

Interpretation

In Higgs-portal models, new scalars fields ϕ coupling to dark matter particles can mix with the SM Higgs field h resulting in two mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

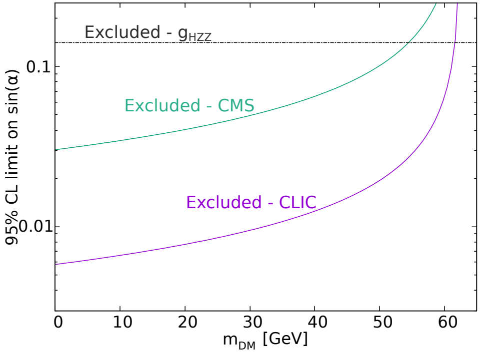
If $\alpha \ll 1$, h_1 is SM-like (the observed 125 GeV state), but it can also decay invisibly via ϕ component (BR $\sim \sin^2\alpha$)

If h_2 is also light, it can be produced in e^+e^- collisions in the same way as the SM-like Higgs boson; invisible decays dominate.

We consider Vector-fermion dark matter model (VFDM) [arXiv:1710.01853]

Interpretation

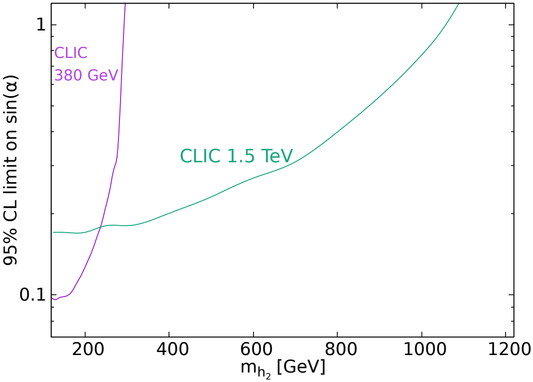
Limit on the invisible decays of the 125 GeV Higgs boson (H) can be interpreted in terms of the VFDM mixing angle limits.



Based on WHIZARD calculations assuming $g_X = 1$.

The VFDM model

Expected limits on the production cross section can be translated within the VFDM model into limits on the mixing angle α.



Conclusions

1. Search for invisible Higgs boson decays based on the WHIZARD event generation and fast simulation with DELPHES.
2. CLIC running at 380 GeV can constrain the invisible decays of the SM Higgs boson to below 1%.
3. Results consistent with the previous study based on full simulation.
4. The study can be extended to search for extra scalars at CLIC operating at 380 GeV and 1.5 TeV.
5. Backgrounds due to the photon-photon and electron-photon interactions still to be studied in more details.
6. Write-up of the analysis in preparation...

References

A. Ahmed, M. Duch, B. Grzadkowski, and M. Iglicki.
Multi-component dark matter: the vector and fermion case.
The European Physical Journal C, 78(11):905, Nov 2018.

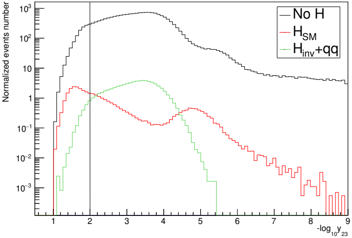
D.Azevedo, M.Duch, B.Grzadkowski, D.Huang, M.Iglicki, and R.Santos.
Testing scalar versus vector dark matter.
Phys. Rev., D99(1):015017, 2019.

M. A. Thomson.
Model-independent measurement of the $e^+e^- \to HZ$ cross section at a future e^+e^--linear collider using hadronic Z decays.
The European Physical Journal C, 76(2):72, 2016.

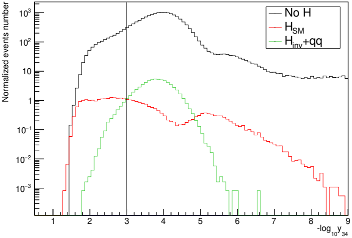
BACKUP

Preselection cuts on jet clustering results

2–3 separation ($-\log_{10} y_{23}$)



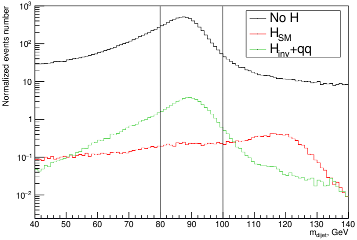
3–4 separation ($-\log_{10} y_{34}$)



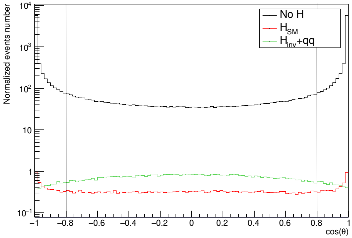
BACKUP

Preselection cuts on di-jet final state (Z boson)

Di-jet invariant mass



Di-jet emission angle



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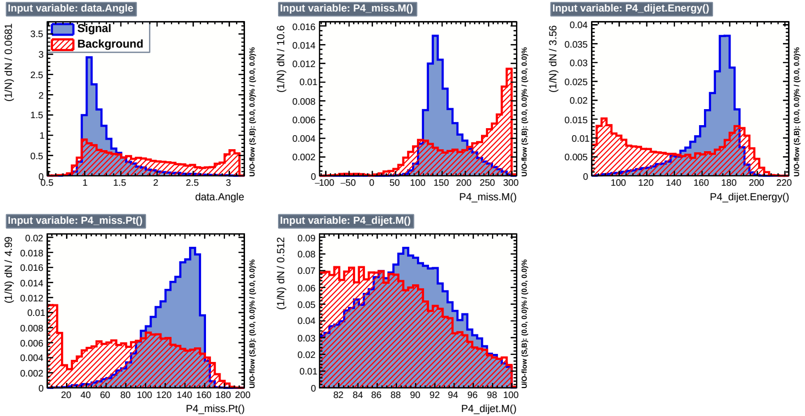
Input variables for multivariate analysis, for invisible decays of 125 GeV Higgs



BACKUP

Considered processes for 1.5 TeV

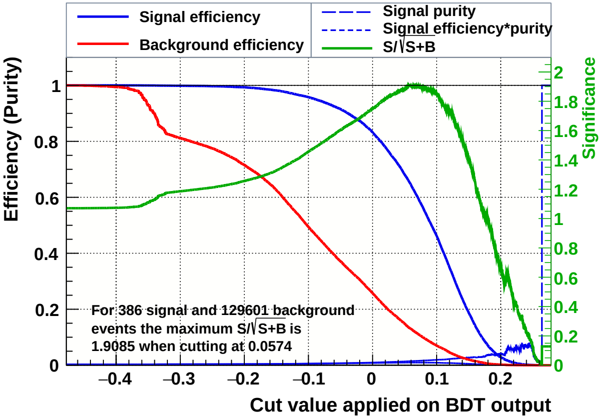
Final state	σ^{neg} **[fb]**	σ^{pos} **[fb]**	$\mathbf{N}_{GEN}$
qq	2870.00	1810.00	1000000
ll	1400.00	1220.00	1000000
$qqqq$	1970.00	265.00	1000000
$qqll$	2740.00	2570.00	1000000
$qq\nu\nu$	1520.00	187.00	1000000
$qql\nu$	7050.00	1710.00	1000000
$qql\nu\nu\nu$	40.10	5.39	100000
$\gamma^{BS}\gamma^{BS} \to qq$	6030.00	6030.00	1000000
$H_{SM} + qq$:	9.42	6.59	100000
$H_{SM} + ll$	31.60	22.10	100000
$H_{SM} + \nu\nu$	468.00	53.50	100000
$H_{inv} + qq$	9.42	6.59	100000

BACKUP

Preselection efficiency for 1.5 TeV

Final state	**Efficiency - p. neg.**	**Efficiency - p. pos.**
without Higgs boson		
qq	0.07%	0.08%
$qq\nu\nu$	13.53%	12.73%
$ql\nu$	1.47%	2.30%
$qql\nu\nu\nu$	1.24%	2.07%
$\gamma^{BS}\gamma^{BS} \to qq$	0.21%	0.22%
Total:	1.48%	0.64%
with Higgs boson decays described in the Standard Model		
$H_{SM} + \nu\nu$	2.34%	2.50%
Total:	2.16%	1.65%
signal		
$H_{inv} + qq$	42.16%	42.04%

Signal significance as a function of the BDT cut
assuming BR(H→inv) = 1%



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BDT response distribution for negative and postivie polarisation