

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

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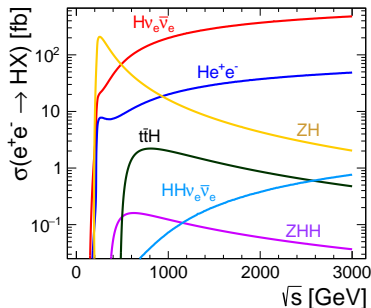
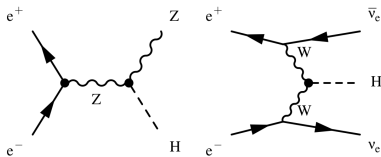
CLICdp physics session 2020

12.03.2020

Higgs production

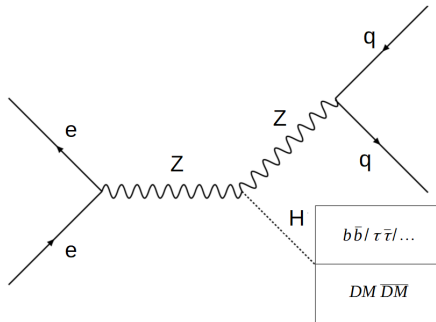
Sensitivity to search for invisible Higgs boson decays

→ ZH production at 380 GeV



Signal

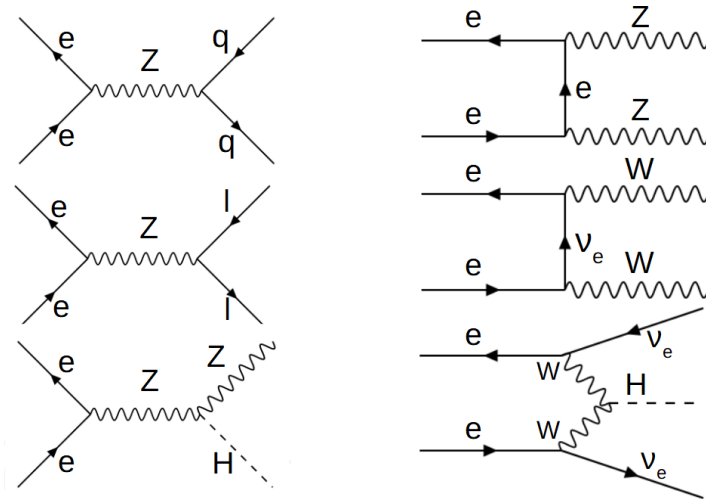
SM(-like) Higgs boson decay to invisible states (Dark Matter?)



Signature of invisible Higgs decay:

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

Background processes considered



Simulation framework

- event samples generated with WHIZARD 2.7.0
 - signal: $H + qq$ production with Higgs defined as stable
 - SM Higgs boson production:
 - $H + qq$, $H + ll$, $H + \nu\nu$ (with 100% SM decays)
 - non-Higgs background: qq , ll , $qqqq$, $qqll$, $qq\nu\nu$, $qq\nu\nu\nu$
- CLIC energy spectra for **380** GeV
- CLIC integrated luminosity of **1000** fb⁻¹ (unpolarised)
- detector simulation and event reconstruction with DELPHES, using modified¹ *CLICdet_Stage1* cards

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

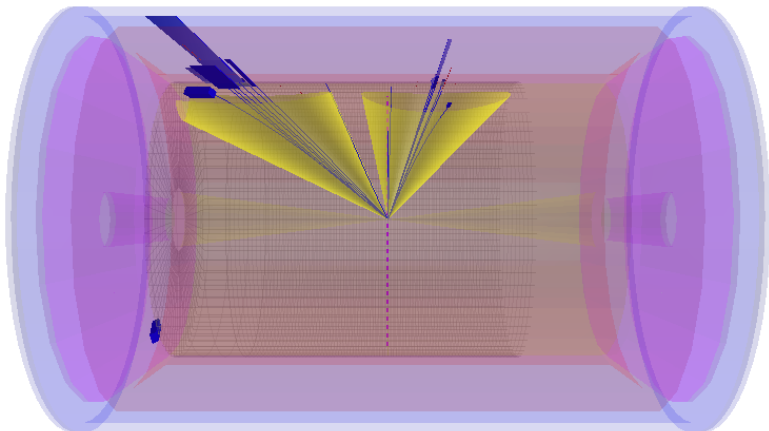
¹required to make Higgs invisible in the detector

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
$qq\nu l$	5560.0	500000
$qq\nu\nu\nu$	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 $e^+e^- \rightarrow HZ \rightarrow jj + inv$

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



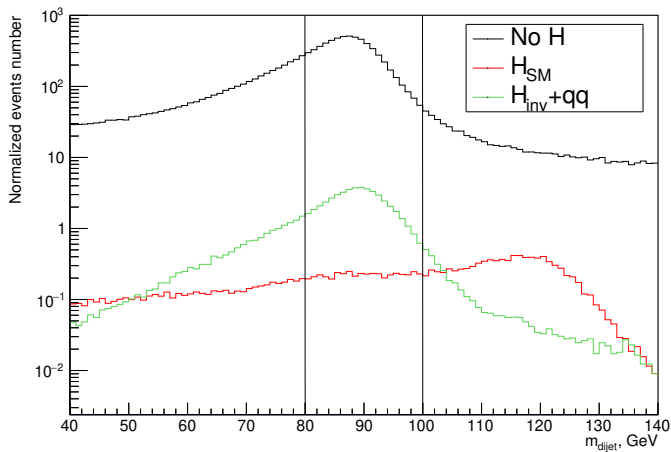
Preselection

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: $80 < M_{jj} < 100$ GeV (Z mass)
- Dijet emission angle: $|\cos \Theta_{jj}| < 0.8$ (Z direction)

Preselection cut example

Di-jet invariant mass distribution with preselection cut indicated



Preselection

Efficiency of preselection cuts

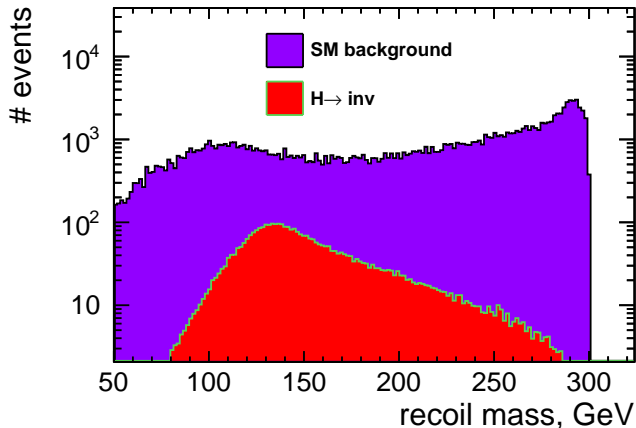
<i>Event class</i>	<i>Efficiency</i>
Non-Higgs background	0.21%
including $qq\nu\nu$	20.47%
$qq\nu\nu\nu\nu$	1.32%
$qq\nu$	0.60%
qq	0.08%
SM Higgs decays	0.86%
including $H + \nu\nu$	2.33%
$H + qq$ invisible decays	43.56%

Preselection

Recoil mass distribution after preselection cuts

For 1000 fb^{-1} collected at 380 GeV

assuming $\text{BR}(H \rightarrow \text{inv}) = 10\%$



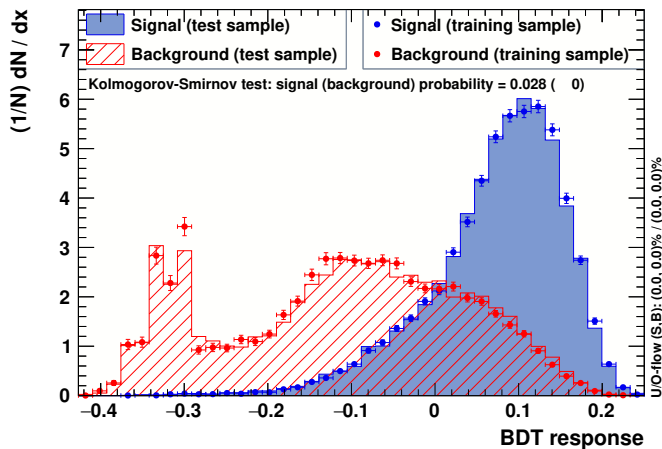
Selection

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 the LAB frame
- 2 m_{jj} – dijet invariant mass
- 3 m^{miss} – reconstructed missing mass
- 4 E_{jj} – dijet energy
- 5 p_t^{miss} – missing transverse momentum

Selection



Highest significance for invisible Higgs decays for BDT cut ~ 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

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

K. Mekala, A.F. Żarnecki, B. Grzadkowski, M. Iglicki, arXiv:2002.06034

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

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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 $\sigma(e^+e^- \rightarrow HZ \rightarrow Hqq) = 93 \text{ fb}$

for 380 GeV $\sigma(e^+e^- \rightarrow HZ \rightarrow Hqq) = 82 \text{ fb}$

Background processes – revisited

event samples generated with WHIZARD 2.7.0

- signal: $H + qq$ production with Higgs defined as stable
- SM Higgs boson production:
 $H + qq, H + ll, H + \nu\nu$ (with 100% SM decays)
- non-Higgs background: $qq, ll, qqqq, qqll, qql\nu, qq\nu\nu, qql\nu\nu$

Background processes – revisited

event samples generated with WHIZARD 2.7.0

- signal: $H + qq$ production with Higgs defined as stable
- SM Higgs boson production:
 $H + qq, H + ll, H + \nu\nu$ (with 100% SM decays)
- non-Higgs background: $qq, ll, qqqq, qqll, qql\nu, qq\nu\nu, qql\nu\nu$
- new beamstrahlung background: $\gamma^{BS} e^\pm \rightarrow qq\nu,$
 $\gamma^{BS} \gamma^{BS} \rightarrow qq/qql\nu/qqll/qq\nu\nu/qqqq$

Background processes – revisited

event samples generated with WHIZARD 2.7.0

- signal: $H + qq$ production with Higgs defined as stable
- SM Higgs boson production:
 $H + qq, H + ll, H + \nu\nu$ (with 100% SM decays)
- non-Higgs background: $qq, ll, qqqq, qqll, qql\nu, qq\nu\nu, qql\nu\nu$
- new beamstrahlung background: $\gamma^{BS} e^\pm \rightarrow qq\nu,$
 $\gamma^{BS} \gamma^{BS} \rightarrow qq/qql\nu/qqll/qq\nu\nu/qqqq$
- new Effective Photon Approximation background:
 $\gamma^{EPA} e^\pm \rightarrow qq\nu$ (new generation with WHIZARD 2.8.3)

Results – revisited

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

$$BR(H \rightarrow inv) < 1.01\%$$

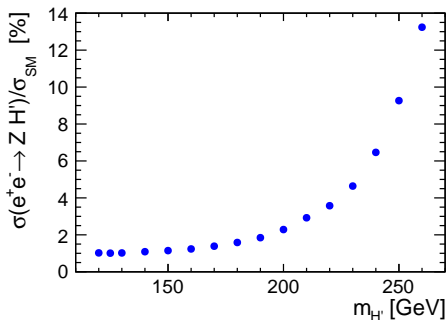
Assuming **no excess** above predicted SM background is observed

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)

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



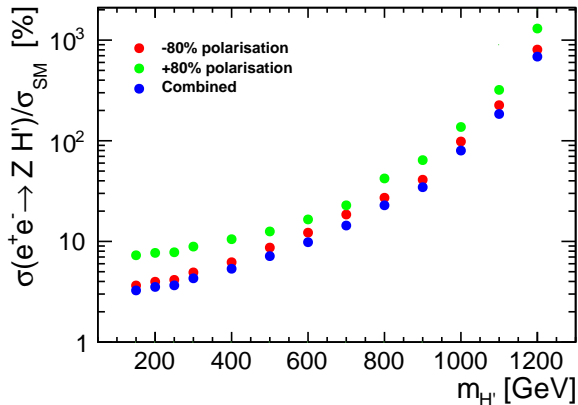
CLIC at 1.5 TeV

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)

Limits on new scalar production

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



Interpretation

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

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

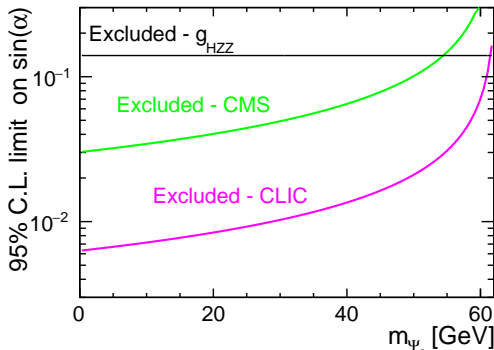
If $\alpha \ll 1$, H is SM-like (the observed 125 GeV state), but it can also decay invisibly via ϕ component ($\text{BR} \sim \sin^2 \alpha$)

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

We consider Vector-fermion dark matter model (VFDM) [[arXiv:1710.01853](https://arxiv.org/abs/1710.01853)]

Interpretation

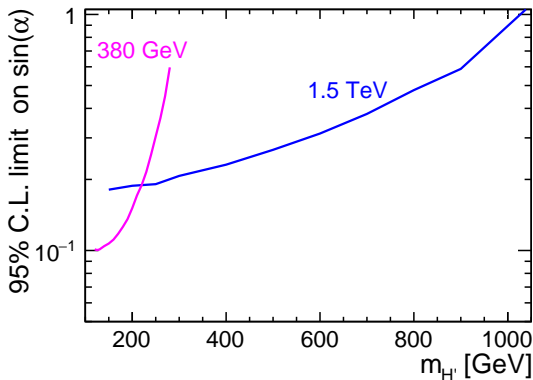
Limit on the invisible decays of the 125 GeV Higgs boson (H) can be interpreted in terms of the VFDM mixing angle limits.



Based on WHIZARD calculations assuming $g_{\chi} = 1$.

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 Updated results including $\gamma\gamma$ and $e^\pm\gamma$ backgrounds.
- 3 CLIC running at 380 GeV can constrain the invisible decays of the SM Higgs boson to 1%.
- 4 Results consistent with the previous study based on full simulation.
- 5 The study can be extended to search for extra scalars at CLIC operating at 380 GeV and 1.5 TeV.
- 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.



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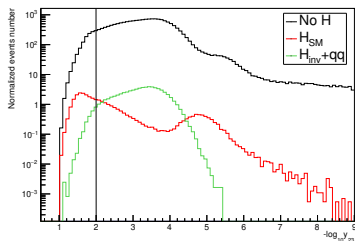


M. A. Thomson.
Model-independent measurement of the $e^+e^- \rightarrow HZ$ cross section at a future e^+e^- -linear collider using hadronic Z decays.
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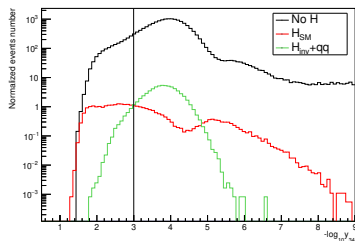
BACKUP

Preselection cuts on jet clustering results

2–3 separation ($-\log_{10} y_{23}$)



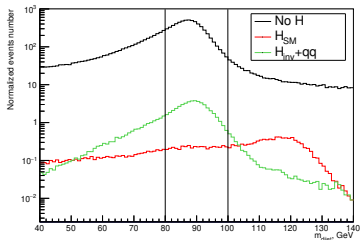
3–4 separation ($-\log_{10} y_{34}$)



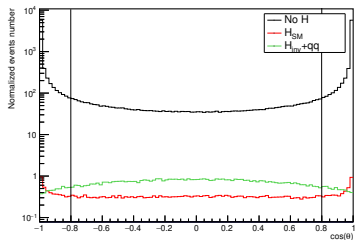
BACKUP

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

Di-jet invariant mass



Di-jet emission angle



BACKUP

Channels	σ [fb]	N_{GEN}
$\gamma^{BS} \gamma^{BS} \rightarrow qq$	1914.43	200000
$\gamma^{BS} \gamma^{BS} \rightarrow qqll$	33.04	10000
$\gamma^{BS} \gamma^{BS} \rightarrow qq\nu$	0.72	10000
$\gamma^{BS} \gamma^{BS} \rightarrow qq\nu\nu$	0.03	10000
$\gamma^{BS} \gamma^{BS} \rightarrow qqqq$	1.84	10000
$\gamma^{BS} e^- \rightarrow qq\nu$	1418.31	300000
$\gamma^{BS} e^+ \rightarrow qq\nu$	1428.57	300000
$\gamma^{EPA} e^- \rightarrow qq\nu$	883.29	100000
$\gamma^{EPA} e^+ \rightarrow qq\nu$	883.41	100000

BACKUP

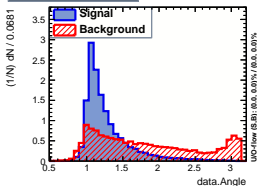
Efficiency of preselection cuts

<i>Event class</i>	<i>Efficiency</i>
Non-Higgs background	0.21%
SM Higgs decays	0.86%
$\gamma^{BS} \gamma^{BS} \rightarrow qq$	0.78%
$\gamma^{BS} \gamma^{BS} \rightarrow qqll$	0.03%
$\gamma^{BS} \gamma^{BS} \rightarrow qq\nu$	1.59%
$\gamma^{BS} \gamma^{BS} \rightarrow qqqq$	0.03%
$\gamma^{BS} e^- \rightarrow qq\nu$	6.73%
$\gamma^{BS} e^+ \rightarrow qq\nu$	6.68%
$\gamma^{EPA} e^- \rightarrow qq\nu$	6.41%
$\gamma^{EPA} e^+ \rightarrow qq\nu$	6.31%
$H + qq$ invisible decays	43.56%

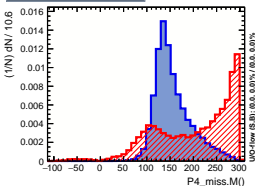
BACKUP

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

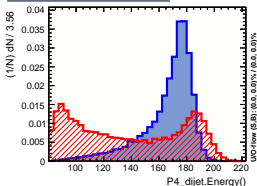
Input variable: data.Angle



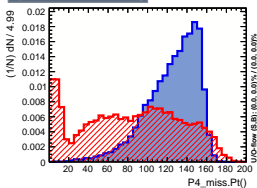
Input variable: P4_miss.M()



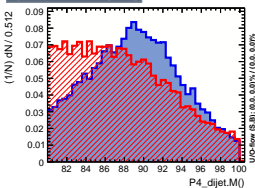
Input variable: P4_dijet.Energy()



Input variable: P4_miss.Pt()



Input variable: P4_dijet.M()



BACKUP

Considered processes for 1.5 TeV

Final state	σ^{neg} [fb]	σ^{pos} [fb]	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
$\gamma^{BS}\gamma^{BS} \rightarrow qq$	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

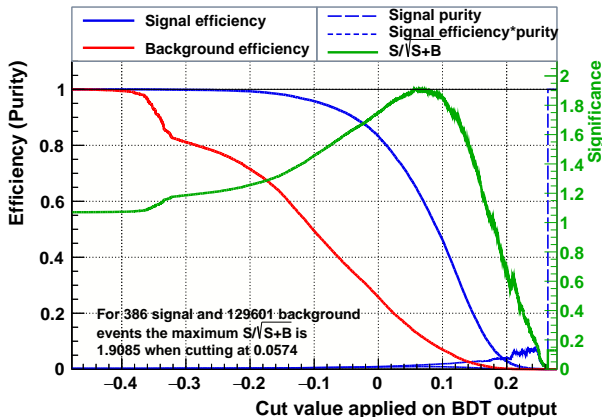
BACKUP

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%
$qql\nu$	1.47%	2.30%
$qql\nu\nu\nu$	1.24%	2.07%
$\gamma^{BS}\gamma^{BS} \rightarrow qq$	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%

BACKUP

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



BACKUP

BDT response distribution for negative and positive polarisation

