

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

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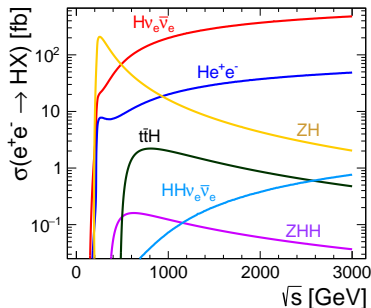
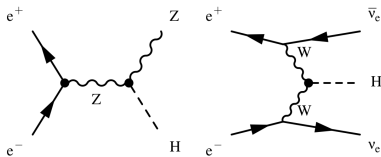
CLICdp physics session 2020

12.03.2020

# Higgs production

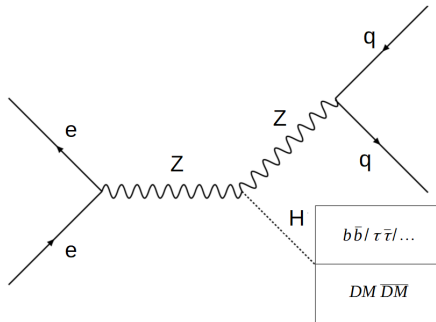
Sensitivity to search for invisible Higgs boson decays

→  $ZH$  production at 380 GeV



# Signal

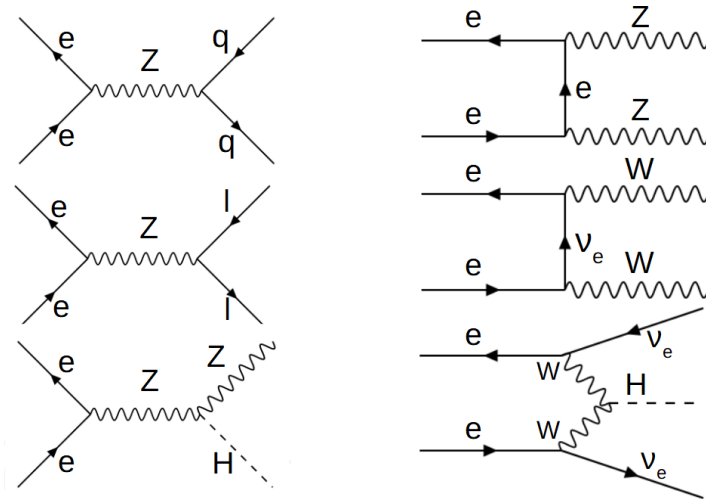
SM(-like) Higgs boson decay to invisible states (Dark Matter?)



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<sup>-1</sup> (unpolarised)
- detector simulation and event reconstruction with DELPHES, using modified<sup>1</sup> *CLICdet\_Stage1* cards

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

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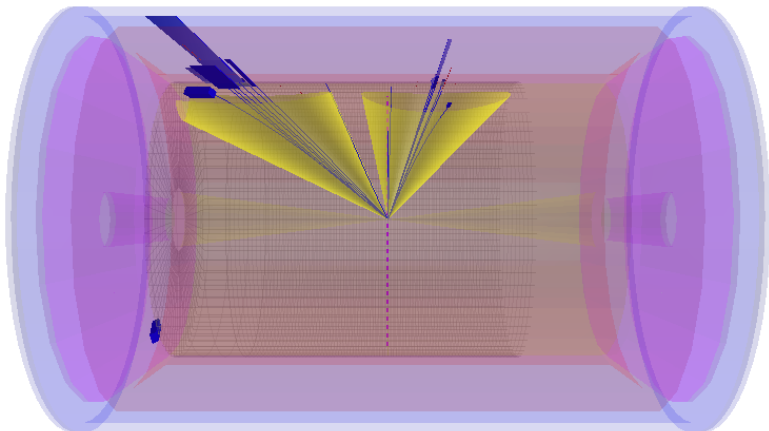
<sup>1</sup>required to make Higgs invisible in the detector

## Processes considered

<b>Final state</b>	<b><math>\sigma</math> [fb]</b>	<b><math>N_{GEN}</math></b>
$qq$	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

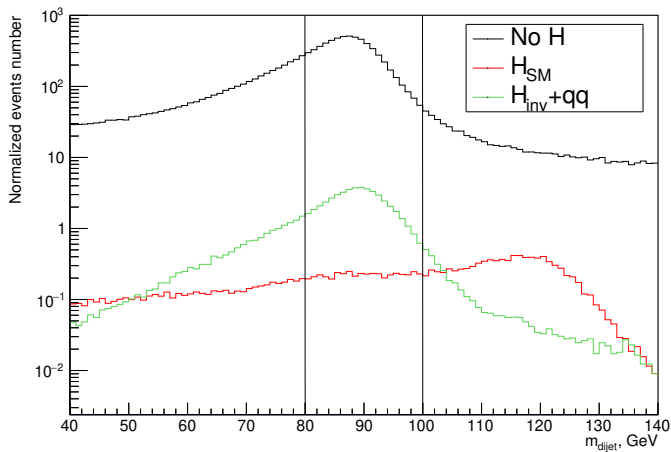
Preselection cuts were used to select events with proper signature and kinematics consistent with invisible Higgs boson decay:

- 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

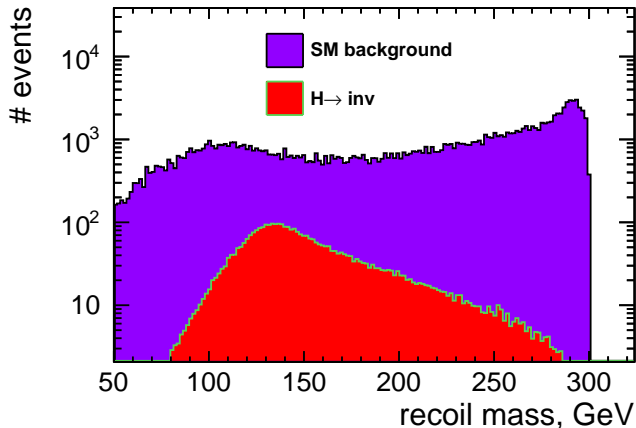
<i>Event class</i>	<i>Efficiency</i>
<b>Non-Higgs background</b>	<b>0.21%</b>
including $qq\nu\nu$	20.47%
$qq\nu\nu\nu\nu$	1.32%
$qq\nu$	0.60%
$qq$	0.08%
<b>SM Higgs decays</b>	<b>0.86%</b>
including $H + \nu\nu$	2.33%
<b><math>H + qq</math> invisible decays</b>	<b>43.56%</b>

# Preselection

Recoil mass distribution after preselection cuts

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

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



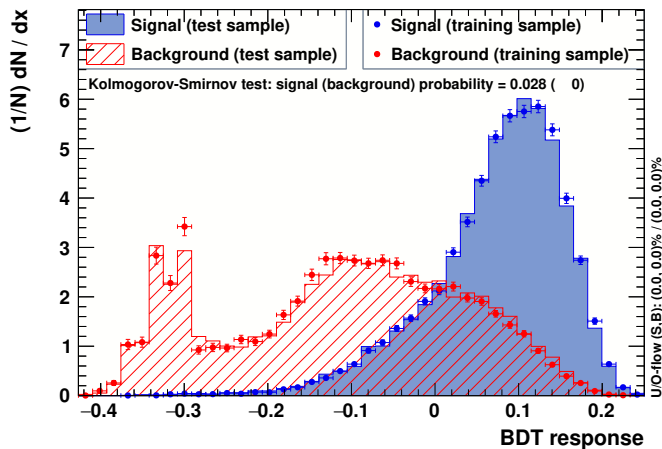
# Selection

Final event selection based on the multivariate analysis.

Variables used as input for Boosted Decision Tree (BDT):

- 1  $\alpha_{jj}$  – 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  $\sim 0.06$

# Results

95% C.L. limit expected for 1000 fb<sup>-1</sup> 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

# Results

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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<sup>-1</sup> collected at 350 GeV

M. A. Thomson, *The European Physical Journal C*, 76(2):72

for 350 GeV  $\sigma(e^+e^- \rightarrow HZ \rightarrow Hqq) = 93$  fb

for 380 GeV  $\sigma(e^+e^- \rightarrow HZ \rightarrow Hqq) = 82$  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:  $qq, ll, qqqq, qqll, qql\nu, qq\nu\nu, qql\nu\nu$



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

## Background processes – revisited

event samples generated with WHIZARD 2.7.0

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

## Results – revisited

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

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

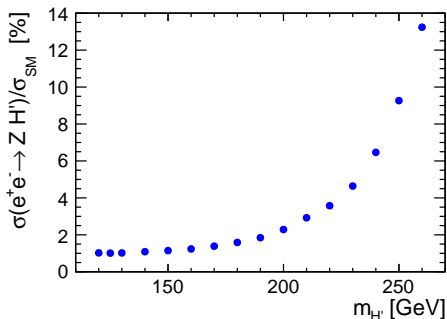
Assuming **no excess** above predicted SM background is observed

## Limits on new scalar production

Same approach can be used to search for production of  $H^0$  state in the process  $e^+e^- \rightarrow ZH^0 \rightarrow qq + inv$

( $H^0$  generated in WHIZARD as SM-Higgs particle of different mass)

Expected limits on the  $H^0$  production cross section, relative to SM, for  $1000 \text{ fb}^{-1}$  at 380 GeV assuming  $\text{BR}(H^0 \rightarrow inv) \approx 100\%$



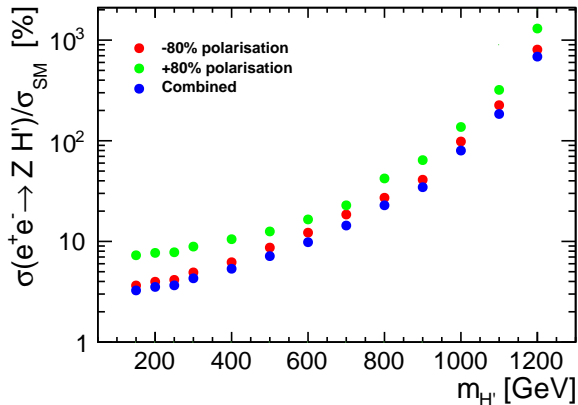
## CLIC at 1.5 TeV

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<sup>-1</sup> (for negative polarisation) and **500** fb<sup>-1</sup> (positive polarisation)

# Limits on new scalar production

Expected limits on the  $H^0$  production cross section, relative to SM,  
for  $2500 \text{ fb}^{-1}$  at  $1500 \text{ GeV}$  assuming  $\text{BR}(H^0 \rightarrow \text{inv}) \approx 100\%$



# Interpretation

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

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

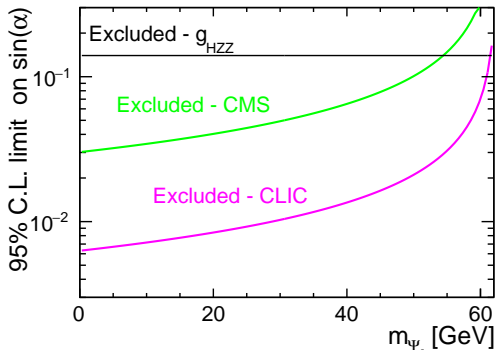
If  $\alpha \ll 1$ ,  $H$  is SM-like (the observed 125 GeV state), but it can also decay invisibly via  $\phi$  component ( $\text{BR} \sim \sin^2 \alpha$ )

If  $H^\theta$  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.

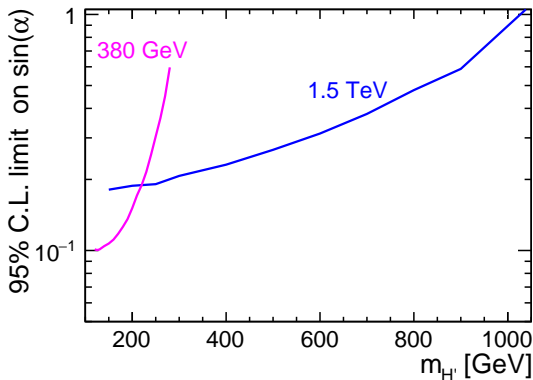


Based on WHIZARD calculations assuming  $g_\chi = 1$ .



# The VFDM model





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



# 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  $e\gamma$  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...

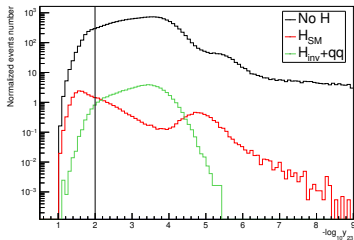
# References

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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.
-  K. Mekala, A.F. Żarnecki, B. Grzadkowski, and M. Iglicki.  
Sensitivity to new physics scenarios in invisible Higgs boson decays at CLIC.  
*In International Workshop on Future Linear Colliders (LCWS 2019) Sendai, Miyagi, Japan, October 28-November 1, 2019, 2020.*
-  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.  
*The European Physical Journal C*, 76(2):72, 2016.

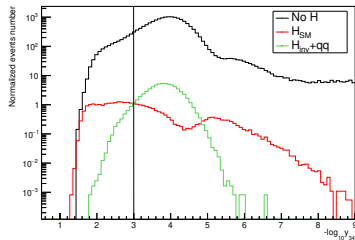
# BACKUP

## Preselection cuts on jet clustering results

2–3 separation (  $-\log_{10} y_{23}$  )



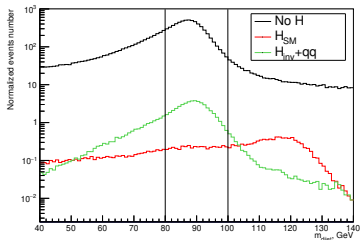
3–4 separation (  $-\log_{10} y_{34}$  )



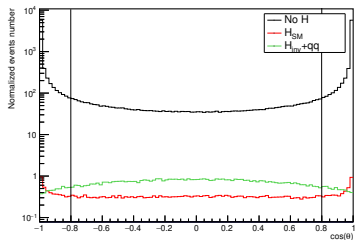
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## Preselection cuts on di-jet final state (Z boson)

Di-jet invariant mass



Di-jet emission angle



# BACKUP

<b>Channels</b>	$\sigma$ [fb]	$N_{GEN}$
$\gamma^{BS} \gamma^{BS} ! qq$	1914.43	200000
$\gamma^{BS} \gamma^{BS} ! qqll$	33.04	10000
$\gamma^{BS} \gamma^{BS} ! qq\nu$	0.72	10000
$\gamma^{BS} \gamma^{BS} ! qq\nu\nu$	0.03	10000
$\gamma^{BS} \gamma^{BS} ! qqqq$	1.84	10000
$\gamma^{BS} e ! qq\nu$	1418.31	300000
$\gamma^{BS} e^+ ! qq\nu$	1428.57	300000
$\gamma^{EPA} e ! qq\nu$	883.29	100000
$\gamma^{EPA} e^+ ! qq\nu$	883.41	100000

# BACKUP

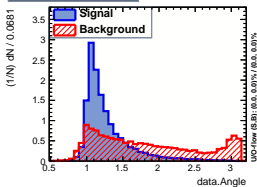
Efficiency of preselection cuts

<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%

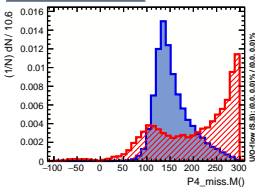
# BACKUP

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

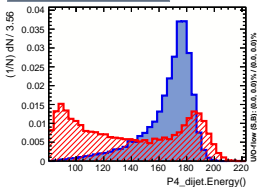
Input variable: data.Angle



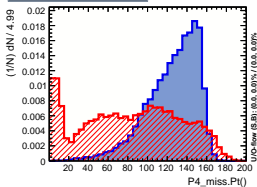
Input variable: P4\_miss.M()



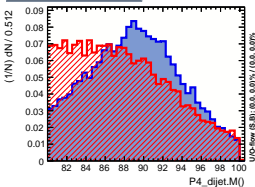
Input variable: P4\_dijet.Energy()



Input variable: P4\_miss.Pt()



Input variable: P4\_dijet.M()





# BACKUP

Considered processes for 1.5 TeV

<b>Final state</b>	$\sigma^{neg}$ [fb]	$\sigma^{pos}$ [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
$qq\nu$	7050.00	1710.00	1000000
$qq\nu\nu\nu$	40.10	5.39	100000
$\gamma^{BS}\gamma^{BS} ! qq$	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

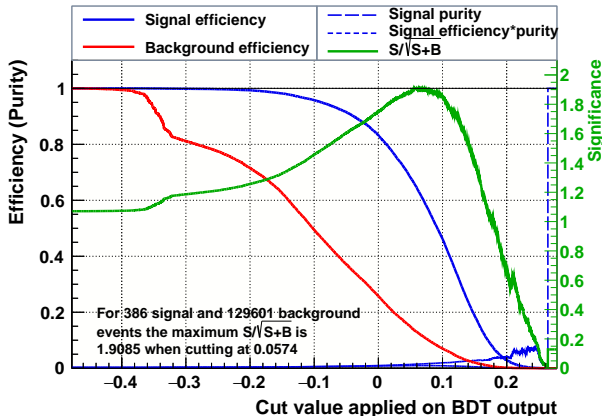
# BACKUP

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%
$\gamma^{BS}\gamma^{BS} ! qq$	0.21%	0.22%
<b>Total:</b>	1.48%	0.64%
with Higgs boson decays described in the Standard Model		
$H_{SM} + \nu\nu$	2.34%	2.50%
<b>Total:</b>	2.16%	1.65%
signal		
$H_{inv} + qq$	42.16%	42.04%

# BACKUP

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



# BACKUP

## BDT response distribution for negative and positive polarisation

