Measurement of the Higgs to EW bosons decays at low and intermediate CLIC energies

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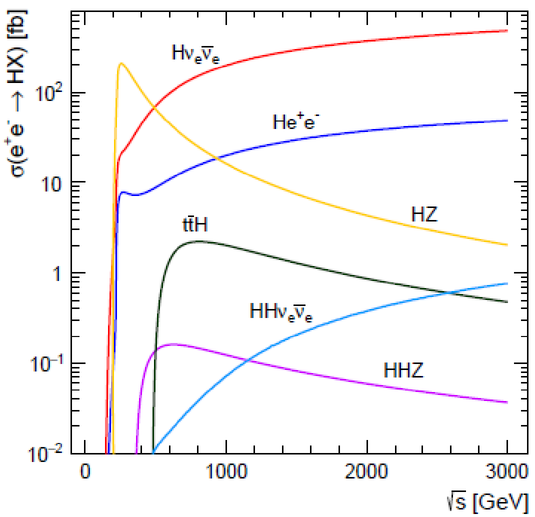
Overview

- A word of introduction - Higgs to EW bosons couplings at CLIC
- Simulation and reconstruction
- Signal signatures and samples
- Background for the measurements
- General strategy of the analyses
- H to WW decay at 350 GeV
- H to ZZ decay at 1.4 TeV
- Conclusion

Higgs to EW bosons couplings at CLIC

- **Energy staging – possibility to study wide span of physics program**
- **Higgs to EW bosons couplings at CLIC:**
  - ≥ 350 GeV, 500 fb^{-1}, $e^+e^- \rightarrow HZ$ model-independent measurement of g_{HZZ} (~0.8%), total ZH production x-section
  - Once g_{HZZ} is known, g_{HWW} can be determined from HZ and WW-fusion Higgs production and consequently Γ_H

$$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$



To exploit all the collected data, individual measurements are fitted in a model (in)dependent way

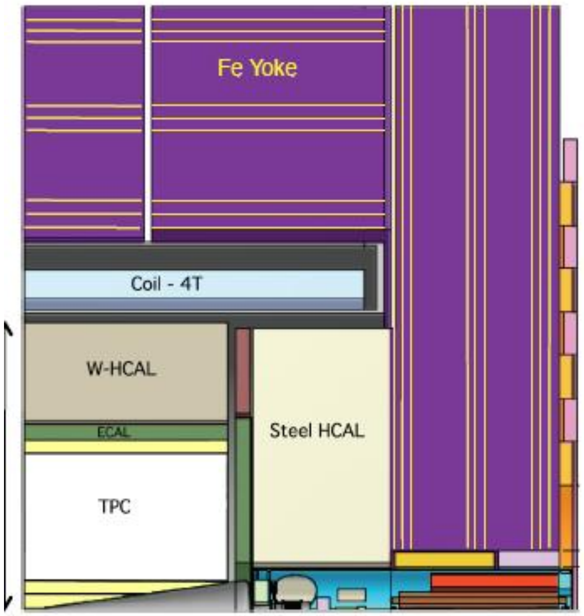
⇓

g_{HZZ}, g_{HWW} sub-percent precision – probe of the Higgs structure

Simulation and reconstruction

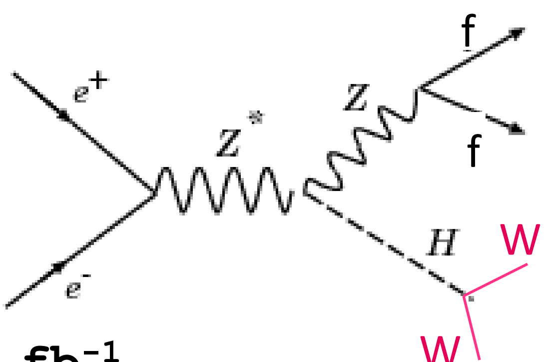
- Event generation: WHIZARD V1.95, PITHYA V6.4; ISR, realistic beam spectrum (GuineaPig 1.4.4)
  - EPA to describe processes with exchanged photon virtuality < 4 GeV;
  - Beam-recoil due to ISR;
- Full CLIC_ILD detector simulation
- Particle ID and reconstruction PandoraPFA - fully reconstructed signal and background
- Overlay of beam-induced $\gamma\gamma \rightarrow$ hadrons before digitization
- No beam polarization is considered

CLIC_ILD



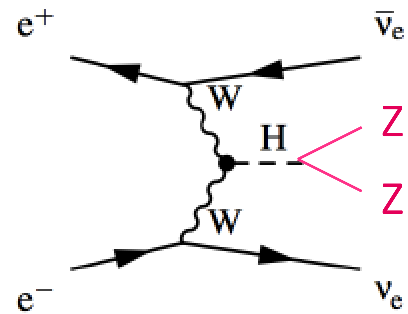
Signal signatures and samples

$(HZ@350GeV)\ H \to WW^*, W \to q_1 q_2$



- 500 fb^{-1}
- **Signature: 4-jet+2l or 6-jet**
- BR($H \to WW^* \to$4 jets)≈10%
- $Z \to ll$ ~700 events(~1%)
- $Z \to q\bar{q}$ ~5000 events (~7%)
- **4jets+2l events: $B/S \approx 10^3$**
- **6-jet events: $B/S \approx 10^2$**

$(H\nu_e\bar{\nu}_e@1.4TeV)\ H \to ZZ^*, Z \to q\bar{q} \vee Z \to ll$



- 1.5 ab^{-1}
- **Signature: E_{miss}** plus **(4-jet** or **2-jet+2l)**
- BR($H \to ZZ^* \to$4 jets)≈1.4%
- BR($H \to ZZ^* \to$2jets + 2l)≈0.4%
- ~ 5200 4-jet events
- ~ 1500 (2-jet + 2l) events
- **4-jet events: $B/S \geq 10^4$**
- **(2-jet+2l) events: $B/S \geq 10^5$**

Background for the measurements

$$(HZ@350GeV)\ H \to WW^*, W \to q_1 q_2$$
$$Z \to l^+ l^- \vee Z \to q\bar{q}$$

6-jet signal 9.16 [fb]			4-jet + 2l signal 0.91 [fb]
Common background [fb]			
	$e^+e^- \to qqqq$	5847.00	Preselection
Preselection	$e^+e^- \to qqll$	1704.00	
Preselection	$e^+e^- \to qql\nu$	5914.00	
	$e^+e^- \to HZ, H \to other$	92.60	
	$e^+e^- \to qq\nu_e\bar{\nu}_e$	325.00	Preselection
Preselection	$e^+e^- \to H\nu_e\bar{\nu}_e$	52.00	Preselection
	$e^+e^- \to t\bar{t}$	450.00	
	$e^+e^- \to WWZ$	10.00	

$$(H\nu_e\bar{\nu}_e@1.4TeV)\ H \to ZZ^*, Z \to q\bar{q} \vee Z \to ll$$

4-jet signal 3.45[fb]			2-jet + 2l signal 0.995[fb]	
Common background [fb]				
$e^+e^- \to qq\nu_e\bar{\nu}_e$		788.00		
$e^+e^- \to qqqq\nu_e\bar{\nu}_e$		24.70		
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to WW \to qqqq$		27.60		
$e^+e^- \to qq$		4009.50		
$e^+e^- \to qqqq$		1245.10		
$e^+e^- \to qqqqll$		71.70		
$e^+e^- \to qqql\nu$		115.30		
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to b\bar{b}$		136.94		
$e^+e^- \to H\nu_e\bar{\nu}_e$		19.02		
4-jet signal specific background[fb]			2-jet + 2l specific background[fb]	
	$e^+e^- \to qqqq\nu$	338.50	$e^+e^- \to qqll$	2725.80
Presel.	$\gamma\gamma \to qqqq$	30212.00	Presel $e\gamma \to qq\nu$	29873.50
Presel.	$e^+\gamma \to qqqqe$	2891.00	Presel $e\gamma \to qqe$	16898.80
			$\gamma\gamma \to qq$	76782.80
			$\gamma\gamma \to qqll$	13829.70
			$e^+e^- \to qql\nu$	4309.70

General strategy of the analyses

- Both leptons and jets can be present in signal signatures ⇒ **Lepton Isolation** ⇓ **Fast Jet**
- b-tagging applied to 2-jets to remove $H\rightarrow b\bar{b}$ bkg. ⇒ **Lcfi Vertexing**
- Reduce large x-section background ⇒ **Preselection**
- MVA approach to deal with more signal-like bkg. ⇒ **MVA selection**
- Extract (σxBR) uncertainty from the number of bkg and signal events ⇒ **Relative statistical uncertainty of $\sigma\times$BR**

$$\frac{\Delta(\sigma\times BR)}{(\sigma\times BR)} = \frac{\sqrt{S+B}}{S}$$

Higgs to ZZ decay at 1.4 TeV

- **PRESELECTION**

H→ZZ*→4jets	H→ZZ*→2jets + 2l
$45GeV < m_Z < 110GeV$	
$m_{Z'} < 65GeV$	
$90GeV < m_H < 165GeV$	
$-\log y_{34} < 3.5$	find 2 leptons
$-\log y_{23} < 3.0$	
$100GeV < E_{vis} < 600GeV$	$\varepsilon_{ff}(ll)$= 87%, l=e,μ → 62% with τ
$p^T_{jet} > 80GeV$	
$P_b^{jet1} < 0.95$	
$P_b^{jet2} < 0.95$	

Surviving background

$e^+e^- \to H\nu_e\bar{\nu}_e, H \to WW \to qqqq$

$e^+e^- \to qq\nu_e\bar{\nu}_e$

$e^+e^- \to qqqq\nu_e$

$e^+\gamma \to qq\nu_e$

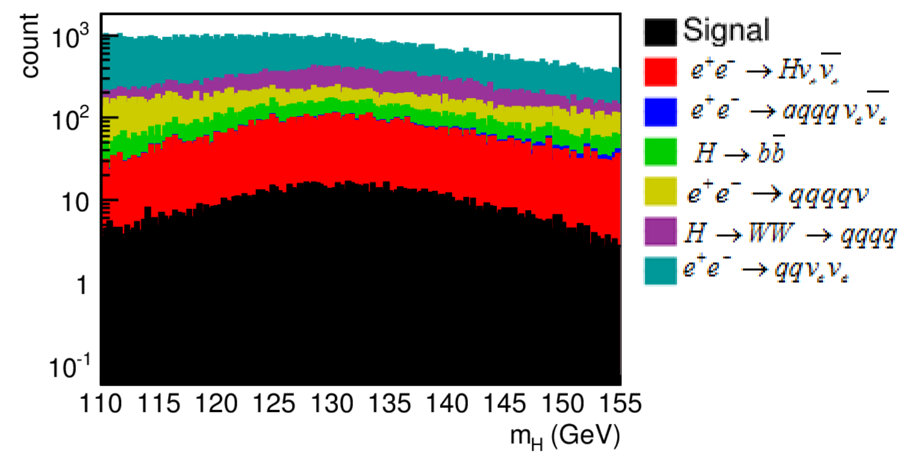
$e^+e^- \to qql\nu$

$e^+e^- \to qq$

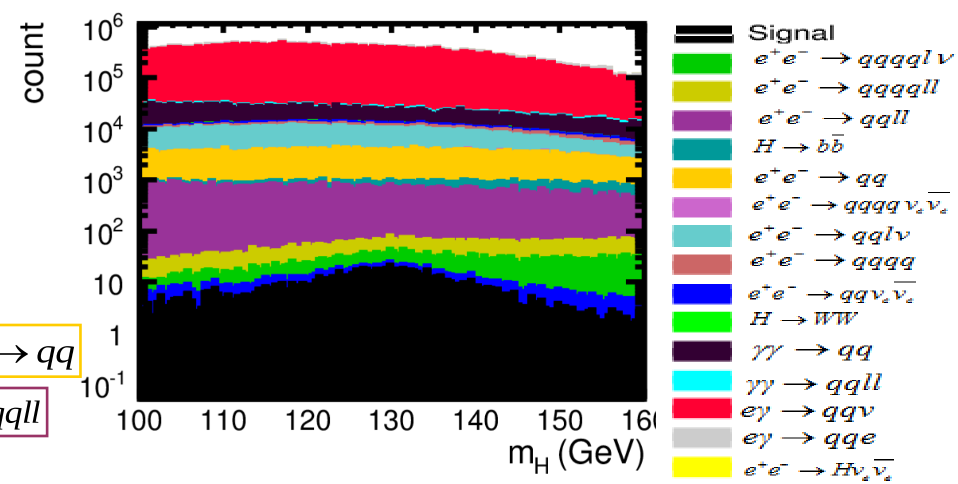
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to b\bar{b}$

$e^+e^- \to qqll$

H→ZZ*→4jets, **preselection** $\varepsilon_{ff}(S)$=32%

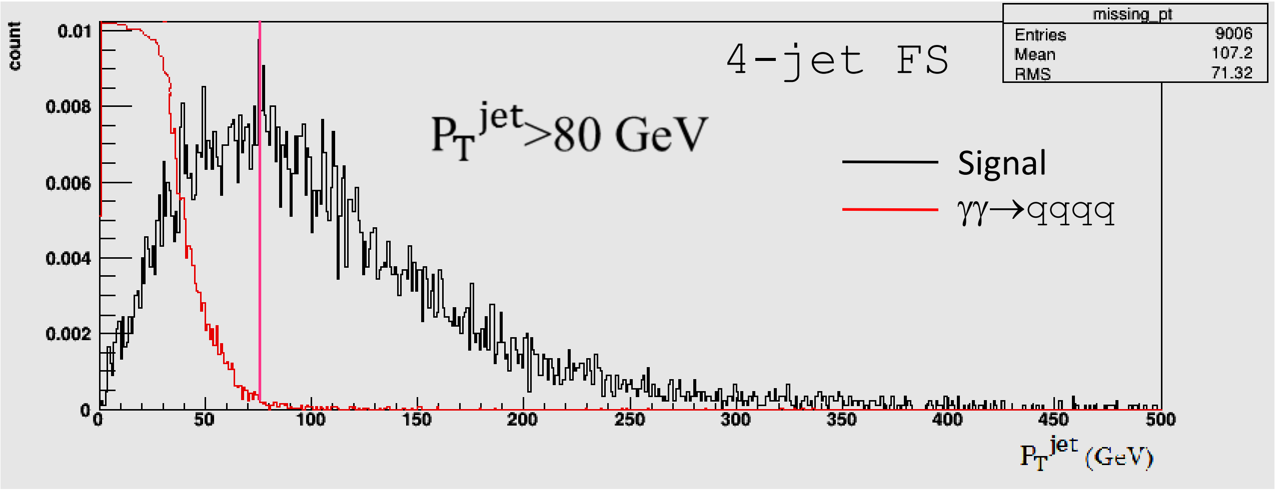


H→ZZ*→2jets + 2l, **preselection** $\varepsilon_{ff}(S)$=62%



Higgs to ZZ decay at 1.4 TeV

- Preselection dominantly reduces $e^{\pm}\gamma \rightarrow qqqqe$ and $\gamma\gamma \rightarrow qqqq$ background (for 4-jet final state) and $e^{\pm}\gamma \rightarrow qqe$ and $e^{\pm}\gamma \rightarrow qq\nu$, for 2jets+2l final state.



Higgs to ZZ decay at 1.4 TeV

MVA

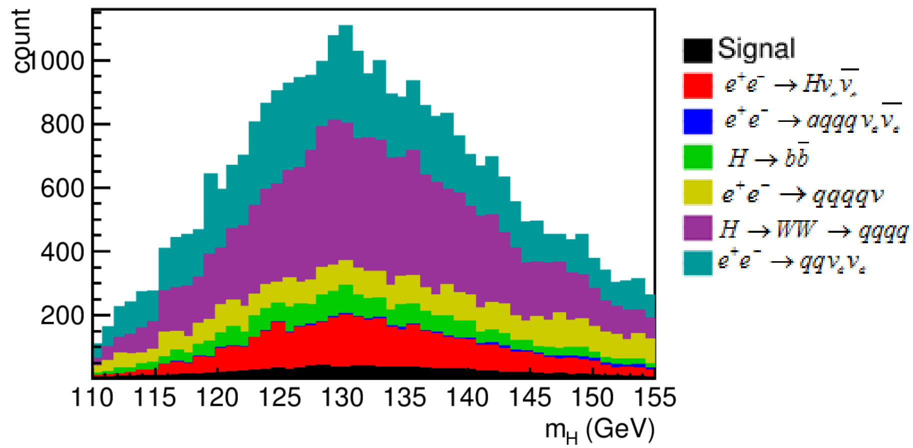
MVA signal efficiency ~60(45)% for 4jets(2jets+2l)

- Input variables:
  - Masses (Z,Z*,H)
  - Visible energy
  - Jet P_T
  - b,c-tag probabilities for jets
  - No. of jets (trans. variables $-\log(y_{23})$, $-\log(y_{34})$)

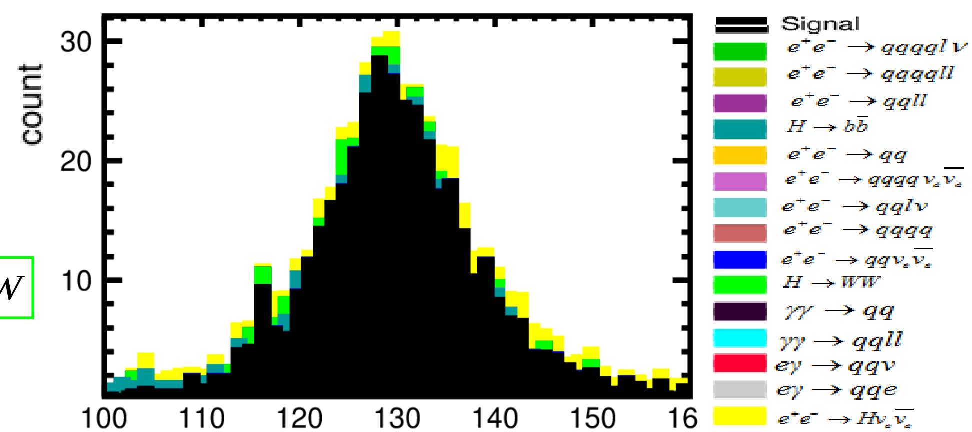
  + additional variables:

  N_{PFO}, θ_H, $(E_{vis}-E_H)$, m_{ll}, m_{qq}, and $-\log(y_{12})$ for 2jets+2l final state

H→ZZ*→4jets, overall $\varepsilon_{ff}(S)$=20%



H→ZZ*→2jets + 2l, overall $\varepsilon_{ff}(S)$=28%



Irreducible background
4 jets | 2 jets+2l
& resulting rejection

4 jets		2 jets+2l	
$e^+e^- \to H\nu_e\bar{\nu}_e$, $H \to WW \to qqqq$	19%	$e^+e^- \to H\nu_e\bar{\nu}_e, H \to WW$	0.04%
$e^+e^- \to H\nu\bar{\nu}, H \to other$	8.9%	$e^+e^- \to H\nu\bar{\nu}, H \to other$	0.15%
$e^+e^- \to qq\nu_e\bar{\nu}_e$	2.1%		

Higgs to ZZ decay at 1.4 TeV results

$ZZ \rightarrow qqqq$	$\sigma(H\nu_e\bar{\nu}_e)\times BR(H\rightarrow ZZ^*)$	$ZZ \rightarrow qqll$
20%	Signal efficiency	28%
1031	No. signal events	425
17.7%	$\frac{\Delta(\sigma\times BR)}{(\sigma\times BR)} = \frac{\sqrt{S+B}}{S}$	5.6%

- $\sigma_{prod.}\times$BR for Higgs to ZZ decay at 1.4 TeV can be measured with statistical uncertainty at ~6% in the semileptonic channel and ~18% in the hadronic channel.
- Result is dominated by irreducible (signal-like) background and by the limited signal efficiency for the hadronic channel (due to preselection cut on jet p_T).

Higgs to WW decay at 350 GeV

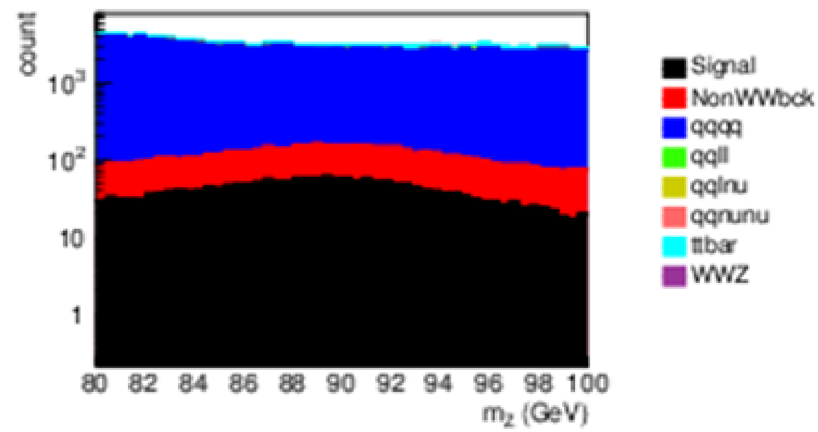
- **PRESELECTION**

H→WW*→6jets	H→WW*→4jets + 2l
$m_Z > 40GeV$ $E_{vis} > 250GeV$ $p_T^{jet} > 80GeV$ $-\log y_{12} < 2.0$ $-\log y_{23} < 2.6$ $-\log y_{34} < 3.0$ $-\log y_{45} < 3.2$ $-\log y_{56} < 4.0$ $N_{PFO} > 50$ $thrust < 0.9$ $P_b^{jet1} < 0.9$ $P_b^{jet2} < 0.9$	find 2 leptons $\varepsilon_{ff}(ll)\sim 90\%$ $70GeV < m_Z < 100GeV$

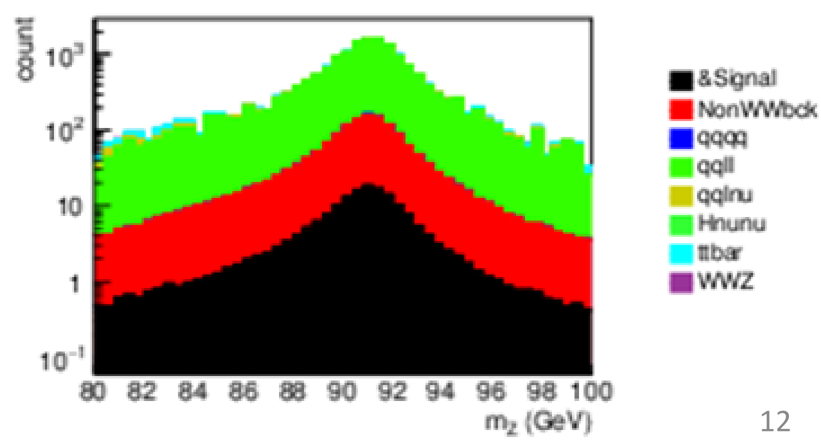
Surviving background

H→WW*→6jets	H→WW*→4jets + 2l
$e^+e^- \to HZ, H \to other$ $e^+e^- \to qqqq$ $e^+e^- \to t\bar{t}$	$e^+e^- \to HZ, H \to other$ $e^+e^- \to qqll$ $e^+e^- \to t\bar{t}$

H→WW*→6jets, preselection $\varepsilon_{ff}(S)$=71%



H→WW*→4jets + 2l, preselection $\varepsilon_{ff}(S)$=80(87)% for l=e(μ)

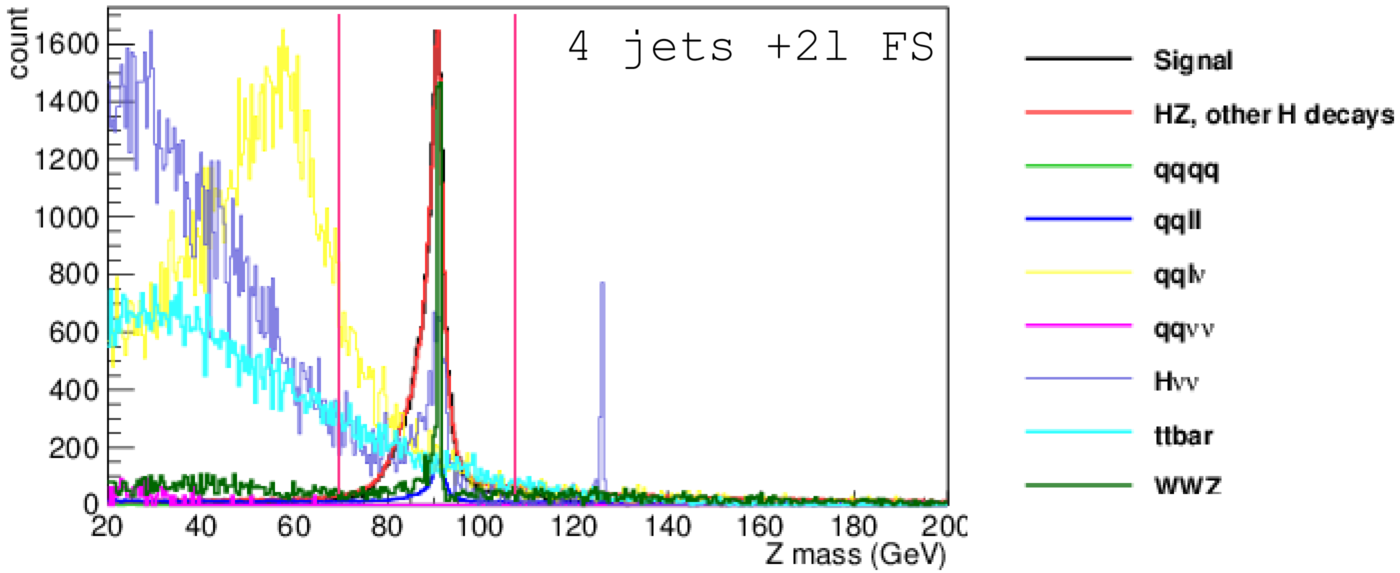


Higgs to WW decay at 350 GeV

- **Preselection dominantly reduces:**

  6 jets FS: $e^+e^- \to qql\nu$, $e^+e^- \to qqll$, $H\nu\nu$ background

  4 jets +2l FS: $e^+e^- \to qqqq$, $e^+e^- \to qq\nu\nu$, $H\nu\nu$ background



Higgs to WW decay at 350 GeV

MVA

MVA signal efficiency: ~40(63)% 6jets(4jets+2l)

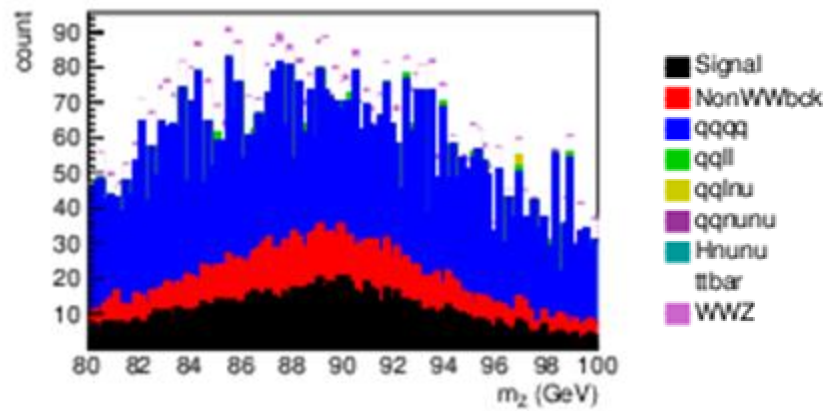
- **Input variables:**
  - N_{PFO}
  - Masses (W,W*,H,Z)
  - Visible energy
  - Jet P_T
  - b,c-tag probabilities for jets
  - No. of jets (transition variabl $-\log(y_{ij})$ i,j=1,6

  + additional variables:

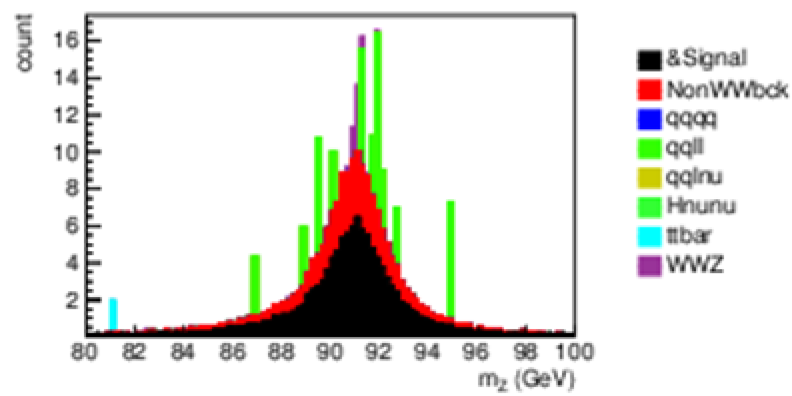
  $P_T(H)$, $\theta(W,W^*)$, thrust – for 6-jet FS

  θ_Z, for 4jets+2l final state

H→WW*→6jets, overall $\varepsilon_{ff}(S)$=29%



H→WW*→4jets + 2l, overall $\varepsilon_{ff}(S)$=42(55)% for l=e(μ)



Irreducible background
6 jets | 4 jets+2l
& resulting rejection

6 jets		4 jets+2l	
$e^+e^- \to HZ, H \to other$	0.29%	$e^+e^- \to HZ, H \to other$	3.0%
$e^+e^- \to qqqq$	0.15%	$e^+e^- \to qqll$	$<10^{-3}$%

Higgs to WW decay at 350 GeV results

$Z \to q\bar{q}$	$\sigma(HZ)\times BR(H \to WW^* \to qqqq)$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
29%	Signal efficiency	42%	55%
1328	No. signal events	95	125
5.9%	$\frac{\Delta(\sigma\times BR)}{(\sigma\times BR)} = \frac{\sqrt{S+B}}{S}$	16.1%	13.1%

- $\sigma_{prod.}\times BR$ for Higgs to WW decay at 350 GeV can be measured with statistical uncertainty at ≤16% in the semileptonic channel and ~6% in the hadronic channel.
- Result is dominated by irreducible (signal-like) backgrounds in the hadronic channel and by the limited signal statistics in the semileptonic decay channel.

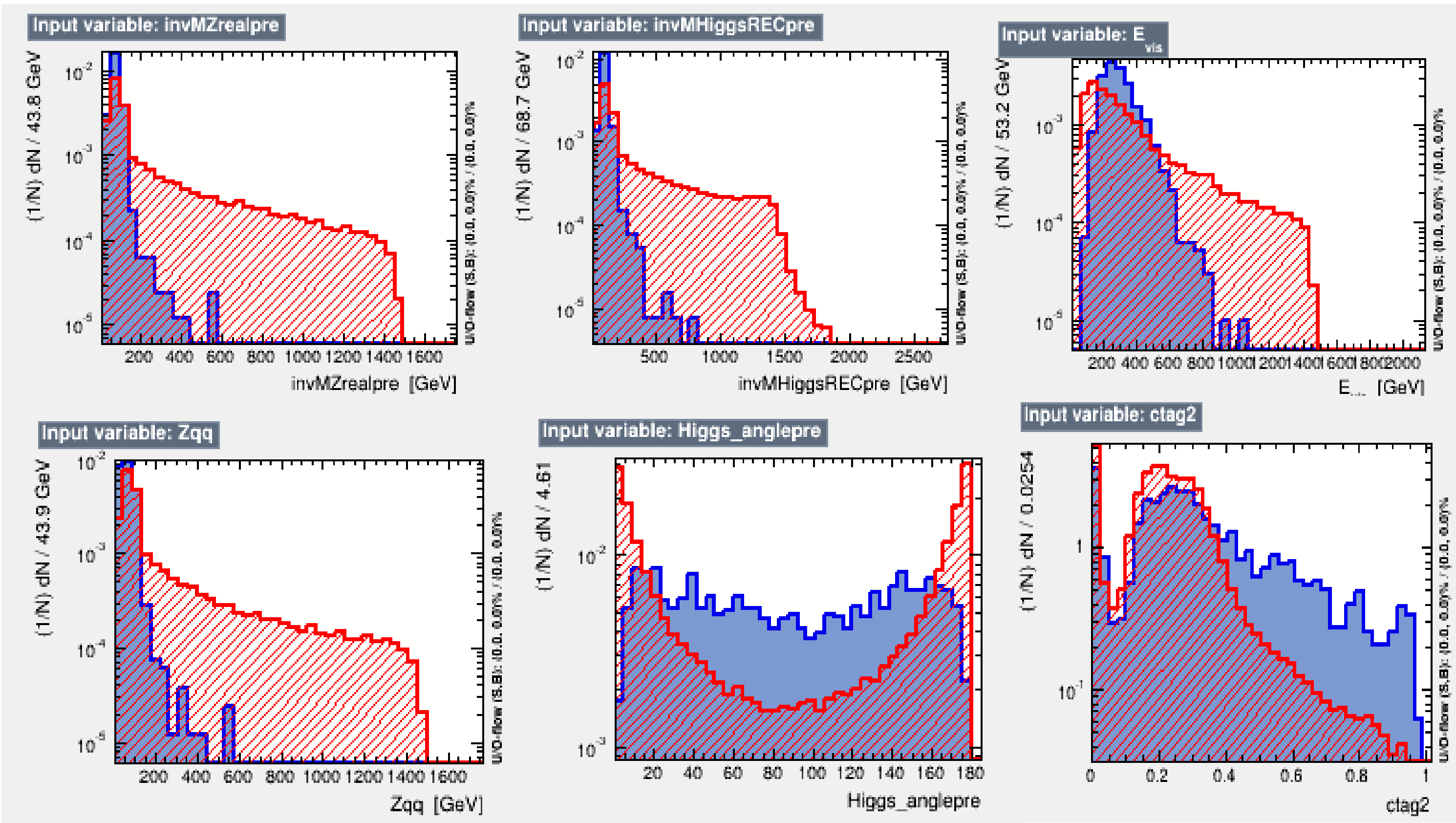
Conclusion

- $\sigma \times BR(H \to VV^*, V=W,Z)$ is observable to be measured at various CLIC energy stages;
- Its uncertainty affects the g_{HVV} precision obtained from the overall fit;
- $H \to WW^* \to$ 4jets is measured at 350 GeV in HZ, where Z is decaying hadronicly or leptonicly; Statistical uncertainties are: 5.9% ($Z \to qq$) and 13.1% ($Z \to \mu^+\mu^-$), 16.1%($Z \to e^+e^-$). The later result is being refined by ongoing optimization of lepton and Z reconstruction.
- $H \to ZZ^* \to$ 4jets (2jets+2l) is measured at 1.4 TeV in $H\nu\nu$; Statistical uncertainties are: 17.7% (5.6%);
- Both analyses are performed using the full detector simulation and reconstruction of physics and beam-induced processes.

Additional slides

- MVA observables -

MVA sensitive observables
H to ZZ



MVA sensitive observables
H to WW