Searches for Extra Higgs Doublets in the ZZh Final State

Work in progress, in collaboration with:
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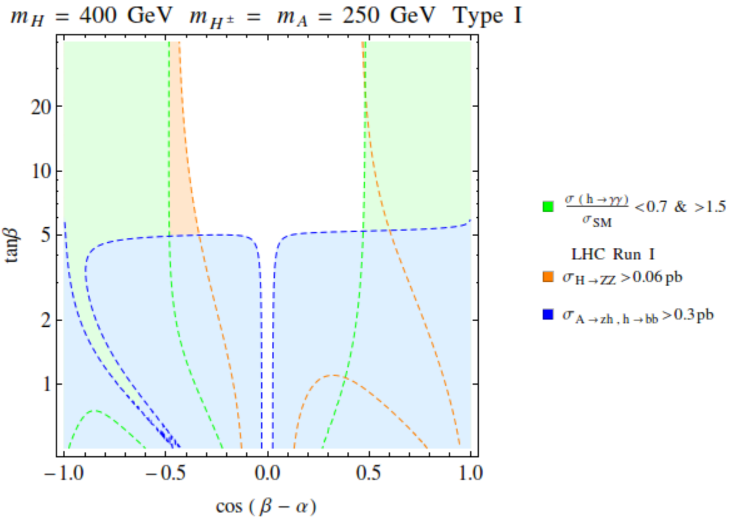
Extended Higgs sector?

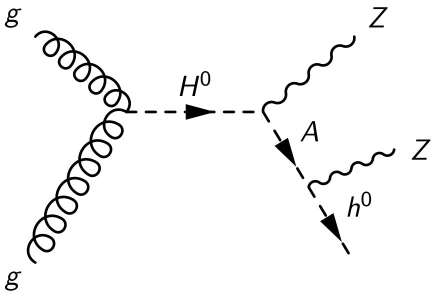
- New Physics in the Higgs sector?
- If there are additional Higgs boson there are two approaches:
  - **Precision tests**
    They are universal and can probe very high masses.
    Disadvantage: We have a deviation but we don't know what it corresponds to.
  - **Direct searches**
    They give a lot more information, more stringent bounds.
    Disadvantage: inefficient for heavy Higgses.

Precision tests and direct searches are *complementary*.

LHC Run-I Bounds



Our search: ZZh final state



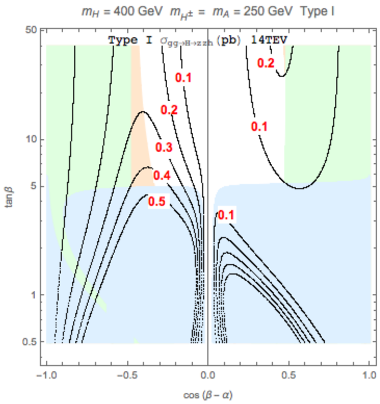
Benchmark

$m_H = 400$ GeV,
$m_A = m_{H^\pm} = 250$ GeV

Final states we considered so far:

h	Z	Z
$b\bar{b}$	$\ell\ell$	$\ell\ell$
$b\bar{b}$	$\ell\ell$	jj
$b\bar{b}$	$\nu\nu$	$\ell\ell$
$\gamma\gamma$	$\ell\ell$	$\ell\ell$
$\gamma\gamma$	$\ell\ell$	jj
$\gamma\gamma$	$\nu\nu$	jj
$\gamma\gamma$	$\nu\nu$	$\ell\ell$
$\ell\nu\ell\nu$	$\ell\ell$	all
$llll$	$\nu\nu$	all

$H \to ZA \to ZZh$ cross-section estimation



- We put LHC Run-I bounds together with contour lines for $\sigma(gg \to H \to ZZh)$ in the 2HDM type I.
- From here, the optimal cross-section in the allowed region is:

$$\sigma_{MAX}(gg \to H \to ZZh) \approx 0.43 \text{ pb}$$

Analysis

For the signal and background simulation we used MadGraph 5, PYTHIA and Delphes 3, for matrix element generation, hadronization/showering and detector simulation, respectively.

h	Z	Z	comments
$b\bar{b}$	$\ell\ell$	$\ell\ell$	Clean, ideal for reconstruction
$b\bar{b}$	$\ell\ell$	jj	Relatively large signal xsec but large background
$b\bar{b}$	$\nu\nu$	$\ell\ell$	Overwhelmed by $t\bar{t}$ background
$\gamma\gamma$	$\ell\ell$	$\ell\ell$	Signal xsec too small
$\gamma\gamma$	$\ell\ell$	jj	Relatively clean at the cost of small signal xsec
$\gamma\gamma$	$\nu\nu$	jj	Hard to reconstruct
$\gamma\gamma$	$\nu\nu$	$\ell\ell$	Clean but very small cross section
$\ell\nu\ell\nu$	$\ell\ell$	all	Relatively clean after placing high $\not{E}_T$ cut

Table : Summary of the final states of ZZh studied so far.

Most sensitive channel: $ZZh \to llllb\bar{b}$

- Main background: $t\bar{t}Z$, $ZZb\bar{b}$ (ZZ + jets negligible for 1.5% b-tagging fake rate.)
- Pre-selection:
  - 2 b-tagged jets.
  - 2 pairs of same flavor and oppositely charged leptons.
  - $p_T(l_1) > 20$ GeV, $p_T(l_2) > 15$ GeV, $p_T(l_3), p_T(l_4) > 10$ GeV.

Optimized cuts

- $m_{b\bar{b}} \in [70, 160]$ GeV
- $\not{E}_T < 70$ GeV.
- $|m_{ll} - m_Z| < 20$ GeV.
- $|m_{llbb} - m_A| < 50$ GeV.
- $|m_{llllbb} - m_H| < 60$ GeV.

# Cuts	0 Initial	1 llllbb	2 $m_{b\bar{b}}$	3 m_{ll}	4 $\not{E}_T$	5 m_A	6 m_H
Signal	337	36.1	30.9	29.0	25.6	25.1	21.2
ttZ	643	37.5	14.3	3.77	1.30	1.11	0.52
ZZbb	81.6	6.09	2.18	2.06	1.81	1.35	0.75
Total backgrounds	402	43.6	16.5	5.83	3.11	2.46	1.27

Table : Cut flows after each selection at the benchmark $m_H = 400$ GeV and $m_A = 250$ GeV, @14 TeV, 300 fb^{-1}

After the cuts the significance is

$$Z = \sqrt{2((s+b)(1+ln(1+\frac{s}{b}) - s)} \approx 9.32\sigma \qquad (1)$$

(8.74σ without the the m_A and m_H cuts).

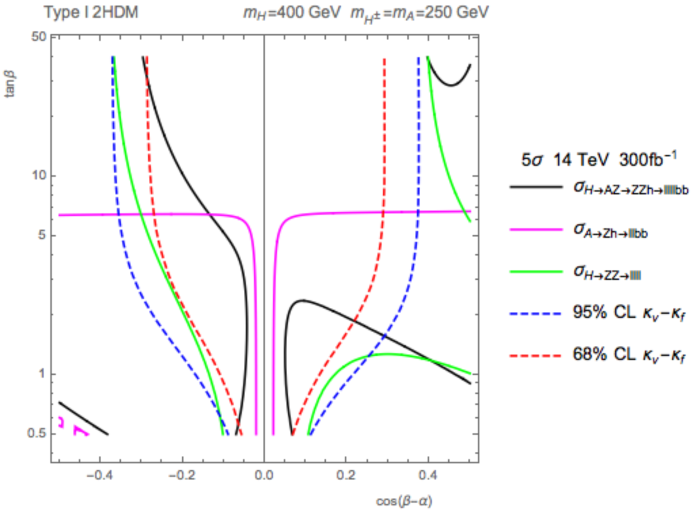
Summary: Most sensitive channels

Channel	14 TeV 300 fb^{-1}			14 TeV 3000 fb^{-1}		
	Sig Yields	Bkg Yields	Sign.	Sig Yields	Bkg Yields	Sign.
$\ell\ell\ell\ell bb$	27.3	3.11	9.2 σ	273	31.1	29 σ
$\ell\ell\ell\ell + \not{E}_T$	6.76	3.22	3.0 σ	67.6	32.2	9.5 σ
$\ell\ell jjbb$	633	4.57×10^4	2.9 σ	6330	4.57×10^5	9.3 σ
$\gamma\gamma\nu\nu\ell\ell$	2.01	0.225	2.5 σ	2.25	20.1	7.9 σ
$\gamma\gamma\ell\ell jj$	1.80	0.694	1.7 σ	18.0	6.94	5.3 σ

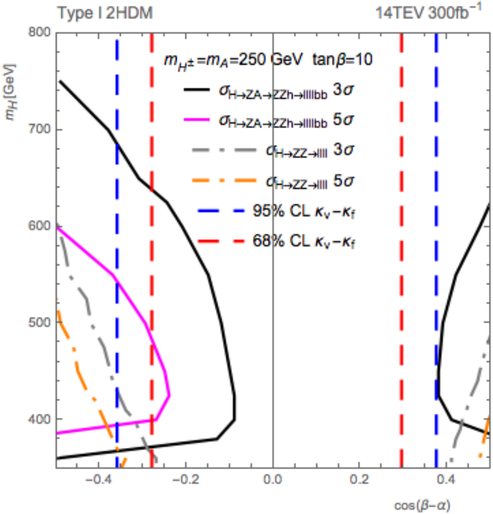
Table : Summary of the most sensitive channels of the $H \to ZA$, $A \to Zh$ cascade search.

For example, for $llllb\bar{b}$ we reach 3 σ (5σ) significance at x fb^{-1} (x fb^{-1}).

5σ cross-section and ATLAS projected bounds @14 TeV, 300 fb^{-1}



H Cascade Search - Mass Reach @14 TeV, 300 fb^{-1}



Summary and Conclusions

- We proposed the Higgs cascade search $H \to AZ$, $A \to Zh$, considering different final states.
- From the different final states considered, we found that $\ell\ell\ell\ell bb$ performs the best; the four-lepton requirement provides a clean signal, and $h \to bb$ has a relatively large branching ratio.
- Considering the bounds from the LHC Run-I and projected bounds at 14 TeV, we found that for large $\tan\beta$ this search is competitive with future H direct searches.
- We show that this can be the most sensitive probe of new physics in a Type I 2HDM at large $\tan\beta$.

Thanks for your attention!

Two Higgs Doublet Model (2HDM)

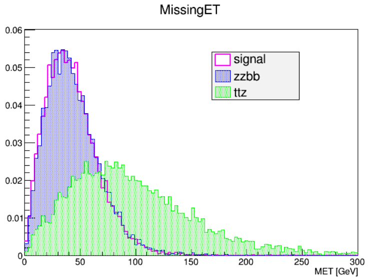
In the *Higgs basis*, where only one of the doublets gets a vacuum expectation value (VEV):

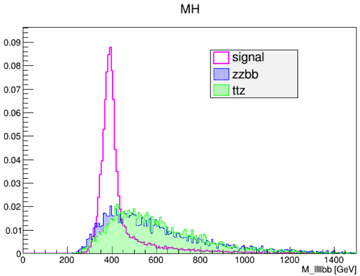
$$H_1 = \begin{pmatrix} G^{\pm} \\ \frac{1}{\sqrt{2}}(v + \phi_1^0 + iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^{\pm} \\ \frac{1}{\sqrt{2}}(\phi_2^0 + iA) \end{pmatrix}, \qquad (2)$$

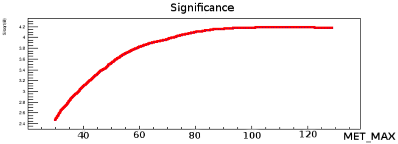
where $v^2 = v_1^2 + v_2^2$ and $\tan\beta \equiv v_2/v_1$. ϕ_1^0 and ϕ_1^0 mix to give two CP-even neutral Higgs bosons:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos(\beta-\alpha) & -\sin(\beta-\alpha) \\ \sin(\beta-\alpha) & \cos(\beta-\alpha) \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}. \qquad (3)$$

Example of cut optimization







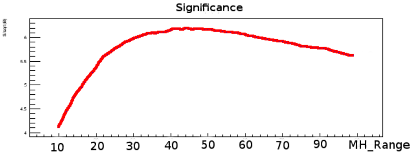


Table 1: SM predictions of the Higgs boson production cross sections and decay branching ratios and their uncertainties for $m_H = 125.36$ GeV, obtained by linear interpolations from those at 125.3 and 125.4 GeV from Ref. [11] except for the tH production cross section which is obtained from Refs. [23, 26]. The uncertainties of the cross sections are the sum in quadrature of the uncertainties resulting from variations of QCD scales, parton distribution functions and α_s. The uncertainty on the tH cross section is calculated following the procedure in Refs. [11, 23].

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Decay channel	Branching ratio [%]
ggF	15.0 ± 1.6	19.2 ± 2.0	$H \to b\bar{b}$	57.1 ± 1.9
VBF	1.22 ± 0.03	1.57 ± 0.04	$H \to WW^*$	22.0 ± 0.9
WH	0.573 ± 0.016	0.698 ± 0.018	$H \to gg$	8.53 ± 0.85
ZH	0.332 ± 0.013	0.412 ± 0.013	$H \to \tau\tau$	6.26 ± 0.35
bbH	0.155 ± 0.021	0.202 ± 0.028	$H \to c\bar{c}$	2.88 ± 0.35
ttH	0.086 ± 0.009	0.128 ± 0.014	$H \to ZZ^*$	2.73 ± 0.11
tH	0.012 ± 0.001	0.018 ± 0.001	$H \to \gamma\gamma$	0.228 ± 0.011
			$H \to Z\gamma$	0.157 ± 0.014
Total	17.4 ± 1.6	22.3 ± 2.0	$H \to \mu\mu$	0.022 ± 0.001

[Atlas: 1507.04548]