Cascade Decay of a Heavy Higgs at LHC

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Outline

- Motivation
- Analysis
  - Model Independent Approach
  - Model dependent Way
- Summary

Motivation

- Few months ago, we have celebrated 5th anniversary of Higgs discovery. **4th July 2012 : Higgs Discovery**
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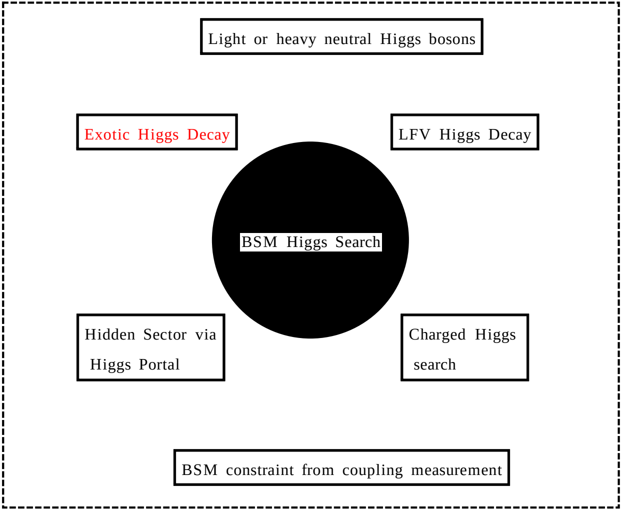
- Few months ago, we have celebrated 5th anniversary of Higgs discovery. **4th July 2012 : Higgs Discovery**
- But, We do not have a clear understanding whether this particle is entirely responsible for EWSB or not YET.
- Keeping this point in mind, the multi-Higgs models receive lot of attention among particle physics community.
- So it is worthy to revisit some of these multi-Higgs models because **the observation of additional scalar will be a clear indication of new physics.**

BSM Higgs Search Areas



BSM Higgs Search Via Exotic Higgs Decay

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- But the decay of type i.e. **Exotic $\rightarrow$ Exotic $\rightarrow$ SM** [Ref:1604.03108] is not explored much.

- Our main aim is to explore whether a heay Higgs is hidden inside the double new physics couplings suppression.

Process Considered

- We consider the production through gluon fusion and subsequent cascade decay of a heavy neutral scalar, $gg \to H_1 \to H_2 Z \to hZZ$, leading to the final state

  1. $2b\ 4\ell$ with $h \to b\bar{b}$ and $Z \to \ell\ell$.
  2. $4b\ 2\ell$ with $h \to b\bar{b}$, $Z \to \ell\ell$ and $Z \to b\bar{b}$. (Analysis is going on.)

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- In specific models like CP-conserving 2HDM, this could be $gg \to H \to AZ \to hZZ$. Here H and A are the scalar and pseudoscalar bosons arising in the model.

Benchmark Points

BP1: $m_{H_1} = 400$ GeV, $m_{H_2} = 250$ GeV, $m_h = 125$ GeV,
BP2: $m_{H_1} = 1000$ GeV, $m_{H_2} = 600$ GeV, $m_h = 125$ GeV,
BP3: $m_{H_1} = 1000$ GeV, $m_{H_2} = 250$ GeV, $m_h = 125$ GeV,
BP4: $m_{H_1} = 600$ GeV, $m_{H_2} = 400$ GeV, $m_h = 125$ GeV.

- The benchmark points are chosen to capture features of the distinct mass-splitting scenarios.
- BP1 is close to the threshold in both $H_1 \to ZH_2$, and the subsequent $H_2 \to hZ$, whereas BP2 provides the mass-differences sufficiently large so that both the decays are away from the threshold.

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- BP1 is close to the threshold in both $H_1 \to ZH_2$, and the subsequent $H_2 \to hZ$, whereas BP2 provides the mass-differences sufficiently large so that both the decays are away from the threshold.
- BP3 has a very large mass separation in the first decay, while the subsequent decay of H_2 is at the threshold.
- The last scenario, BP4 is a similar to BP2, but with reduced mass splitting.

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- Firstly, we will follow a model independent approach.
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- Thus the analysis is planned for an assumed cross section, which is expected to be in the ball park of a realisable model.
- SM backgrounds corresponding to a selected final state will determined.
- A cut and count analysis will be performed on detector level events.
- In the end, we will interpret these results in the context of our favourite models.

SM Backgrounds: 4l+2b

Background	Cross section $\times$ BR (fb)
$ZZb\bar{b}$	0.14
$t\bar{t}Z$	1.19
$WWZb\bar{b}$	1.16

Table: **Cross section of the background SM processes at 14 TeV LHC.**

Methdology

- The signal and background processes are generated through MADGRAPH5 with inbuilt parton level cuts.
- The showering and hadronisation is done through PYTHIA6 which is interfaced in MADGRAPH5.
- The events generated are then analysed with the help of MADANALYSIS5 using the inbuilt interface with DELPHES.

BP1 : Distributions

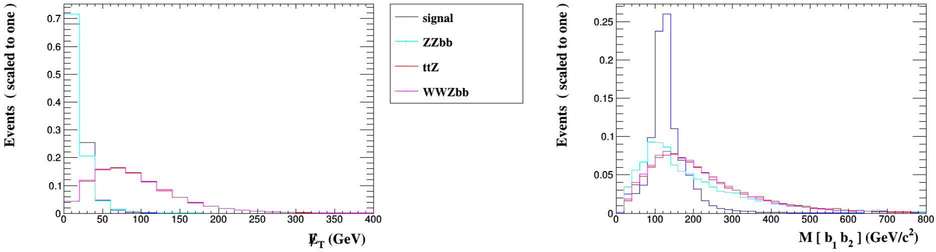

Figure: Normalised missing transverse energy ($\not{E}_T$ and $M_{b_1 b_2}$ distributions for the signal and selected backgrounds in the case of BP1 with $m_H = 400$ GeV, $m_A = 250$ GeV with final state $2b\ 2\ell^+\ 2\ell^-$.

p_T distributions:BP2

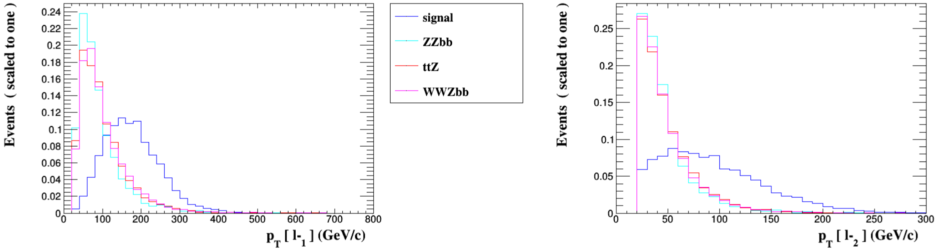

Figure: p_T distributions of lepton after applying $N(l^+)$=2,$N(l^-)$=2,$N(b)$=2 for BP2.

Cut Flow Table:4l+2b:N(b)=2

Selection Criterias	No. of Events (Lum. = 1000 fb^{-1})									
	Signal				Total Backgd	Efficiency				
	BP1	BP2	BP3	BP4		BP1	BP2	BP3	BP4	Backgd
Pre-Selection	5000	5000	5000	5000	13636					
$N(\ell^+) = N(\ell^-) = 2$	1993	2723	1979	2373	1992	0.39	0.54	0.39	0.47	0.14
$N(b) = 2$	206	490	260	340	231	0.10	0.18	0.13	0.14	0.12
$\not{E}_T < 50$	203	415	220	321	66	0.98	0.85	0.85	0.94	0.29
$90 < M_{bb} < 150$	160	344	174	257	16	0.79	0.82	0.79	0.80	0.24
$p_T(\ell_1) > 75$ GeV, $p_T(\ell_2) > 50$	NA	200	59	37	2	NA	0.58	0.34	0.14	0.12

Table: **Cut Flow and Efficiency Table in the case of $2b\ 2\ell^+\ 2\ell^-$ channel for $N(b) = 2$. For Background K-Factor = 2 considered.**

CutFlow Table for 4l+2b: N(b)=1

Selection Criterias	No. of Events (Lum. = 1000 fb^{-1})									
	Signal				Total Backgd	Efficiency				
	BP1	BP2	BP3	BP4		BP1	BP2	BP3	BP4	Backgd
Pre-Selection	5000	5000	5000	5000	13636					
$N(\ell^+) = N(\ell^-) = 2$	1993	2723	1979	2373	1992	0.39	0.54	0.39	0.47	0.14
$N(b) = 1$	884	1310	910	1115	818	0.44	0.48	0.45	0.47	0.41
$\not{E}_T < 50$	871	1122	782	1060	242	0.98	0.85	0.85	0.95	0.29
$p_T(\ell_1) > 75$ GeV, $p_T(\ell_2) > 50$	NA	650	296	163	20	NA	0.57	0.37	0.15	0.08

Table: **Cut Flow and Efficiency Table in the case of $2b\ 2\ell^+\ 2\ell^-$ channel for $N(b) = 1$. For Background K-Factor = 2 considered.**

Case 1: $N(b) = 2$

BPs	Significance		
	100 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
BP1	7.2	22.9	39.6
BP2	10.1	37.1	65.6
BP3	4.9	17.1	29.8
BP4	3.6	12.4	21.7

Case 2: $N(b) = 1$

BPs	Significance		
	100 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
BP1	12.9	40.7	70.5
BP2	18.2	58.3	101.0
BP3	10.6	33.9	58.8
BP4	6.9	22.0	38.1

Table: **Signal Significance with assumed systematic uncertainly of 10% for the background.**

Formula Used for signal significance:

$$\sigma = \sqrt{2} \times \left((S+B)\ \ln\left[\frac{(S+B)\ (B+x^2)}{B^2 + (S+B)\ x^2}\right] - \frac{B^2}{x^2} \ln\left[1 + \frac{x^2\ S}{B\ (B+x^2)}\right] \right)^{\frac{1}{2}} \quad (1)$$

Significance Vs. Systematics

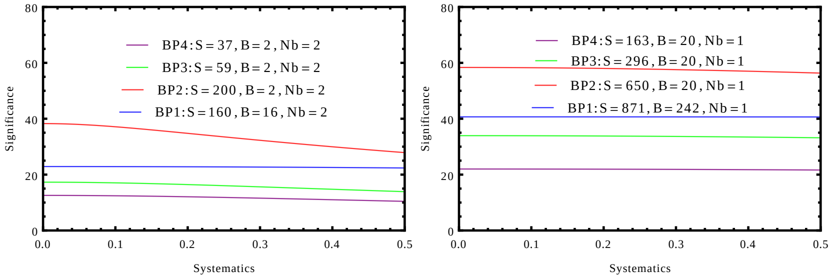

Figure: **Significance plotted against the systematic uncertainty for the two cases of (i) $N(b) = 2$ and (ii) $N(b) = 1$. Luminosity of 1000 fb^{-1} is considered.**

Significance Vs. Signal Events

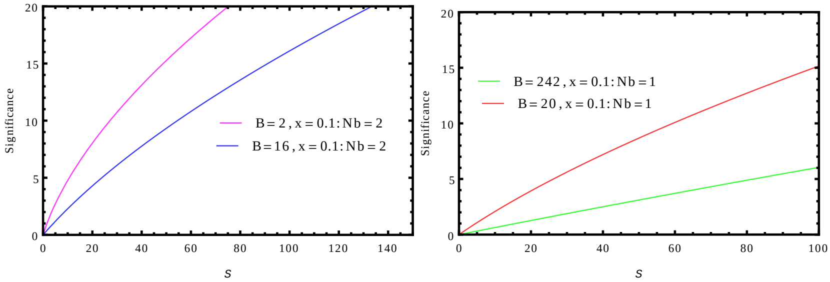

Figure: **Significance Vs. S. Systematic uncertainty of 10% on the background events is assumed.**

5σ Cross section Reach:

	Cross section(in fb) reach for 5σ significance	
	$2b4\ell$	$1b4\ell$
BP1	0.78	0.49
BP2	0.25	0.19
BP3	0.85	0.42
BP4	1.35	0.77

Table: 5σ **Cross section reach for BPs assuming systematic uncertainty of 10% at 1000 fb^{-1} luminosity.**

Model Implications

- We now turn to the issue of understanding the realizability of the quoted cross-sections in model dependent way.
- As an operating example, we choose the Type II 2HDM.
- Unlike the SM, the 2HDM has two Higgs fields (ϕ_1, ϕ_2) developing vacuum expectation values (vev) to break $SU(2) \times U(1)$ down to $U(1)_{\text{em}}$.

For details about 2HDM, see some of the Planery Talks(Example: Talks by Haber,Osland etc.).

Process and Relevant Couplings:

- The process we are considering, specifically, is $gg \to H \to AZ \to hZZ \to 2b + 4\ell$.
- A cascade decay of this sort is suppressed by two new physics couplings, viz., g_{HAZ} and g_{AhZ} - these are given by:

$$g_{HAZ} = \frac{g\sin(\beta - \alpha)}{2\cos\theta_w}(p_A - p_H)_\mu \qquad (2)$$

$$g_{AhZ} = \frac{g\cos(\beta - \alpha)}{2\cos\theta_w}(p_h - p_A)_\mu, \qquad (3)$$

Prod. Cross-section

$$\sigma(gg \to H) = \sigma_{\rm SM} \times \frac{\left| \left(\frac{\sin\alpha}{\sin\beta}\right) F^h_{1/2}(\tau_t) + \left(\frac{\cos\alpha}{\cos\beta}\right) F^h_{1/2}(\tau_b) \right|^2}{|F^h_{1/2}(\tau_t) + F^h_{1/2}(\tau_b)|^2}, \qquad (4)$$

where $\tau_f = 4m_f^2/m_H^2$ and the loop factor $F^h_{1/2} = -2\tau\left[1 + (1-\tau)f(\tau)\right]$ with

$$f(\tau) = \begin{cases} \left[\sin^{-1}(1/\sqrt{\tau})\right]^2 & \tau \geq 1, \\ -\frac{1}{4}\left[\ln(\eta_+/\eta_-) - i\pi\right]^2 & \tau < 1, \end{cases} \qquad (5)$$

with $\eta_\pm \equiv 1 \pm \sqrt{1-\tau}$.

Prod. Cross Section of H and Br Plot of $H \to AZ$

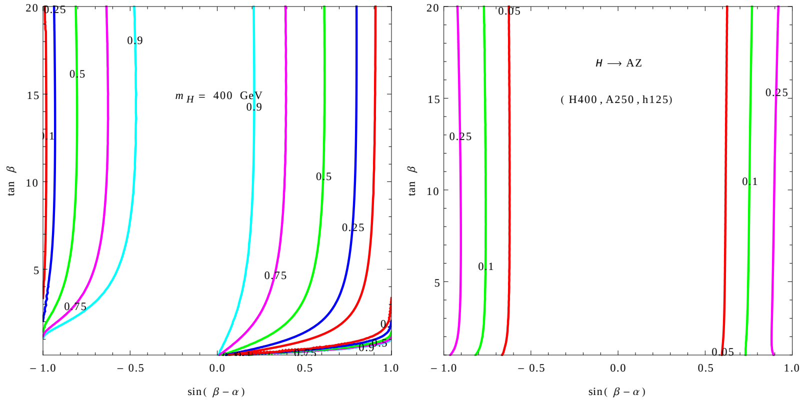

Figure: Normalized Prod. Cross section of H and Branching ratios for the decay $H \to AZ$ for BP1.

Br Plots: $A \to hZ$

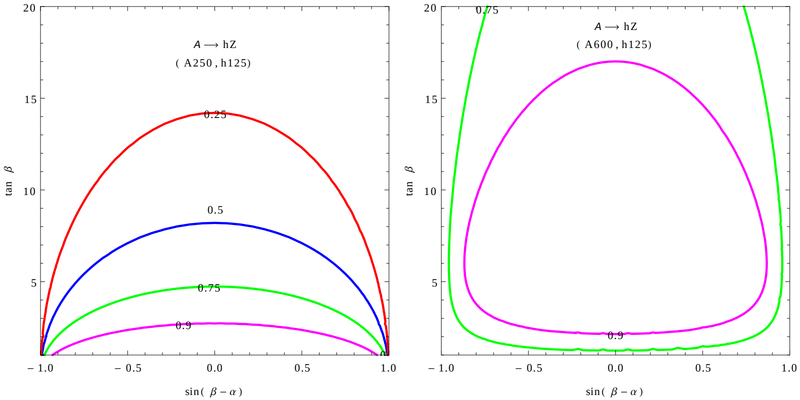

Figure: Branching ratios for the decay $A \to hZ$ for the benchmark points considered in this study.

Allowed Parameter Space

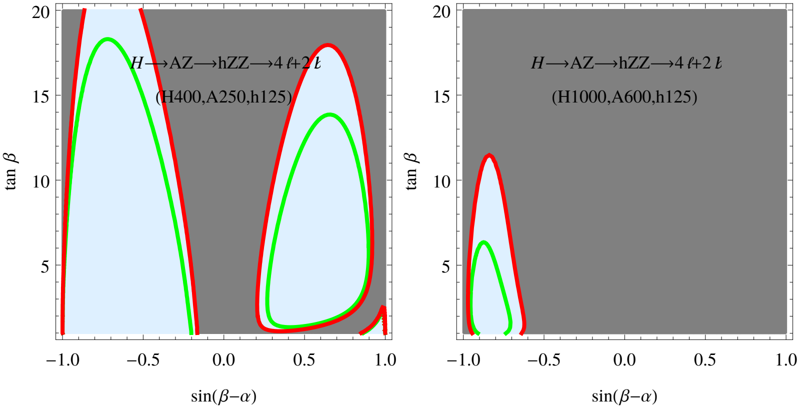

Figure: The extent of parameter space where discovery of the H^0 via the cascade decay. The light blue regions enclosed by the green contours correspond to the $4\ell + 2b$ case while the red ones correspond to the $4\ell + 1b$ scenario.

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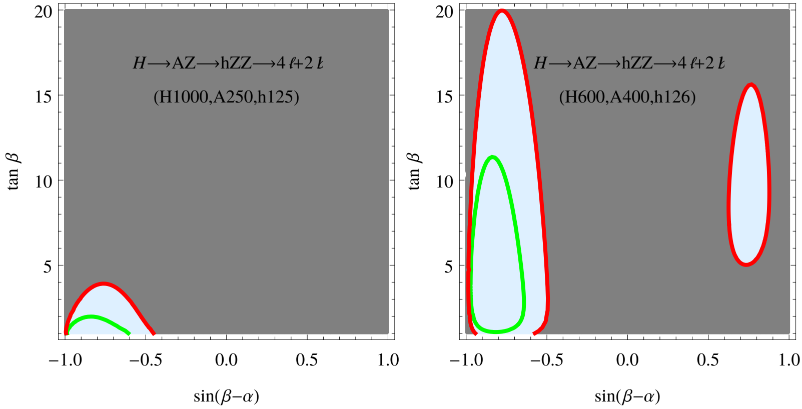

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Summary

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- We performed the collider analysis in a model independent way - without resorting to specific values of new physics couplings.
- Then we have interpreted the model independent results in the context of Type II 2HDM.
- BP1 understandably has the largest reach.
- BP4 offers another possibility but with $\sin(\beta - \alpha)$ range more restricted.
- The reach in BP2 and BP3, owing both to the large m_{H_2} and boosted b jets is limited.

Thank You!