2HDM Benchmarks

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(Dated: May 22, 2015)

I. DESCRIPTION OF THE SCAN: PROCESS $h \to ZA$

We have investigated the 2HDM with type I and type II Yukawa couplings looking for the decay pattern

$$h \to ZA \to Z\mu^+\mu^-/Z\tau^+\tau^-/Zb\bar{b} \tag{1}$$

with variable mass of the pseudoscalar A.

We have scanned the 2HDM in the physical basis over the following range of parameters

$$\begin{aligned} &m_h = 122, 128 \text{ GeV} \quad m_H = 150, 900 \text{ GeV} \quad m_A = 1, 100 \text{ GeV} \quad m_{H^+} = 150, 900 \text{ GeV} \\ &\tan_\beta = 1.5, 50 \quad \lambda_6 = \lambda_7 = 0 \quad m_{12}^2 = -10^4, 10^4 \text{ GeV}^2 \quad \sin(\beta - \alpha) = -1, 1 \end{aligned} \tag{2}$$

that is focusing on a region where h is the SM like Higgs.

We have used the following tools

- 2HDMC[1], that has been used to generate 2HDM spectra and decay tables as well as checking Unitarity, Perturbativity and Stability constraints.

- HiggsSignals[2] and HiggsBounds[3], linked with 2HDMC, in order to check constraints arising from the current measurements of the Higgs boson properties as well as from the non-observation of further scalar states in addition to the 125 GeV Higgs.

- SuperISO[4], that has been used to check constraints arising from flavour measurements.

A. Benchmark choice for 2HDM type I

In Fig. 1 we plot the product of $BR(h \to ZA) \cdot BR(A \to \mu\mu)$ (left panel), $BR(h \to ZA) \cdot BR(A \to \tau\tau)$ (central panel) and $BR(h \to ZA) \cdot BR(A \to b\bar{b})$ (right panel) as function of the pseudoscalar mass. Red, yellow and blue points correspond to different values of the p-value computed by HiggsSignal and among the blue points we choose two representative benchmarks, one with a ~ 20 GeV A and one with a ~ 65 GeV A, maximizing the rates into the selected final states. We call this benchmarks A and B, respectively. In the table we also indicate the reduced Higgs to gluon gluon coupling, that is the ratio of the 2HDM coupling with respect to the SM one, which has been computed by taking the ratio of $\Gamma(h \to gg)$ in the 2HDM and in the SM (obtained from the 2HDM limit with $\sin(\beta - \alpha) = 1$ and the masses of all the extra Higgs states set at 1 TeV).

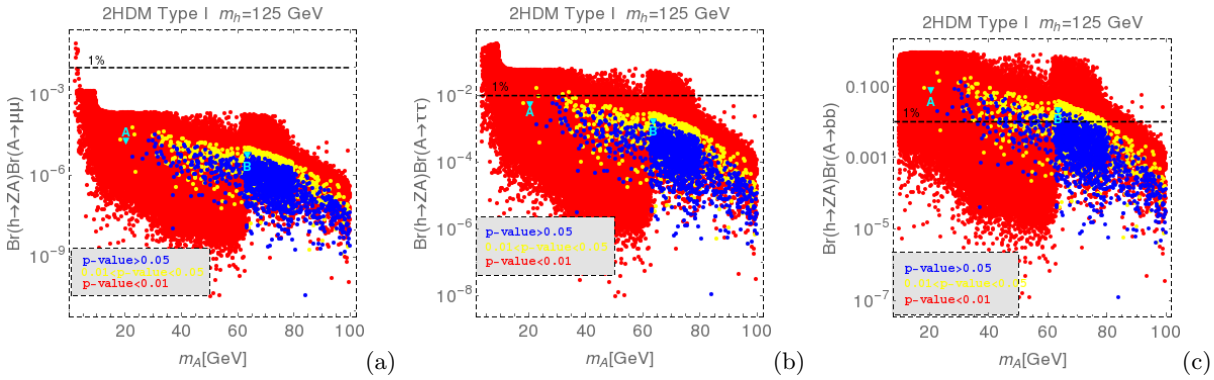

FIG. 1: Combination of $BR(h \to ZA)$ with (a) $BR(A \to \mu\mu)$, (b) $BR(A \to \tau\tau)$, (c) $BR(A \to b\bar{b})$ as function of the mass of the pseudoscalar. Red, yellow and blue points correspond to different p-values computed by HiggsSignal. All points satisfied the flavour constraints implemented in SuperISO.

#	m_h	m_H	m_A	m_{H^+}	$\tan\beta$	$\lambda_{6,7}$	m_{12}^2	$s_{\beta-\alpha}$	$BR(h \to ZA)$	$BR(A \to \mu\mu)$	$BR(A \to \tau\tau)$	$BR(A \to b\bar{b})$	r_{hgg}
A	125.97	165.50	20.25	444.72	1.86	0	3891.45	-0.99	0.0971	0.0002101	0.0585	0.8496	0.93
B	125.93	153.38	63.42	257.71	6.20	0	2793.34	-0.85	0.0268	0.0002318	0.0655	0.7908	0.77

TABLE I: Benchmark points for type I 2HDM. Dimensionfull parameter are in GeV, except m_{12}^2 which is GeV^2. The reduced coupling r_{hgg} is relative to a SM Higgs boson with the same mass as the A's.

B. Benchmark choice for 2HDM type II

We perform the same exercise for the type II 2HDM showing the product of branching ratios in Fig. 2 and again we choose benchmarks in order to maximize the rates into the chosen final states focusing now on three region, the first where A is under the $b\bar{b}$ threshold, the second with $A \sim 20$ GeV and the third one where $A \sim 65$ GeV. We call these benchmarks C, D and E, respectively.

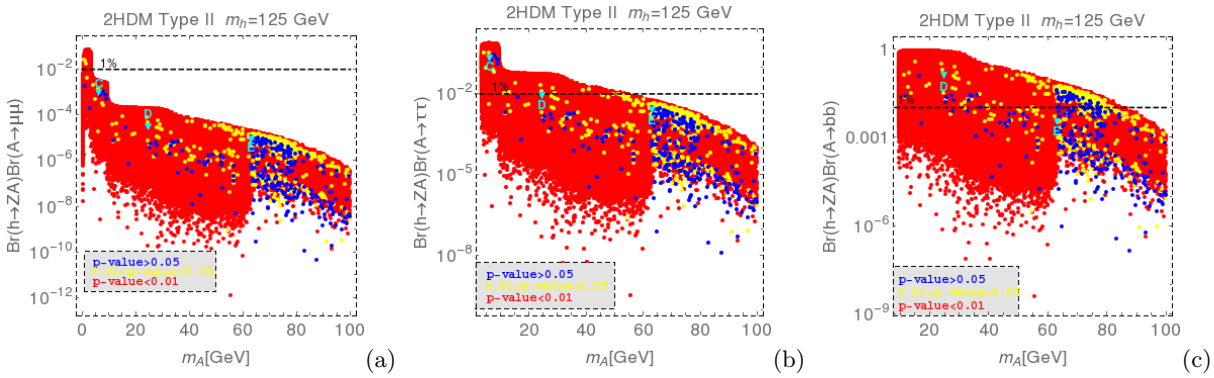

FIG. 2: Combination of $BR(h \to ZA)$ with (a) $BR(A \to \mu\mu)$, (b) $BR(A \to \tau\tau)$, (c) $BR(A \to b\bar{b})$ as function of the mass of the pseudoscalar. Red, yellow and blue points correspond to different p-values computed by HiggsSignal. None of the points satisfied the flavour constraints implemented in SuperISO.

#	m_h	m_H	m_A	m_{H^+}	$\tan\beta$	$\lambda_{6,7}$	m_{12}^2	$s_{\beta-\alpha}$	$BR(h \to ZA)$	$BR(A \to \mu\mu)$	$BR(A \to \tau\tau)$	$BR(A \to b\bar{b})$	r_{hgg}
C	125.85	263.67	6.28	308.25	1.89	0	2737.40	0.99	0.3063	0.003348	0.7813	0	1.09
D	126.27	227.08	24.71	226.80	1.76	0	3406.77	0.99	0.1526	0.000224	0.0627	0.9175	1.10
E	125.19	210.17	63.06	333.50	2.38	0	4791.92	0.7	0.03818	0.000265	0.0747	0.9191	1.15

TABLE II: Benchmark points for type II 2HDM. Dimensionfull parameter are in GeV, except m_{12}^2 which is GeV^2. The reduced coupling r_{hgg} is relative to a SM Higgs boson with the same mass as the A's.

II. COMMENTS

- Numbers in the tables are rounded to a reduced number of digits for reason of space: please find attached the definition of the benchmarks with a higher precision.

- No strong correlations with the model parameters were found for both Yukawa type models, apart from a slight preference for small $\tan\beta$ and, naturally, $\sin(\beta-\alpha) \sim -1,1$: this signals that our choice is not fine tuned in any particular way though we did not seek to quantify this.

- In the type II case all points violate at least one flavour constraint: a view should be taken by the WG as to what extent such bounds should be adhered to.

III. EXPERIMENTAL PERSPECTIVE

The search for $h(125) \to ZA$ is novel within both CMS and ATLAS; previous Higgstrahlung searches have only focused upon decays of a heavier Higgs to states including the discovered $h(125)$ [5–7].

For scenarios A, C and D, where the Z is on-shell, one can trigger on the Z decay to two muons. Scenario C involves a very light A boson and thus its decay products will be heavily boosted (and distributed borderline with the jet p_T thresholds in case of $b\bar{b}$ decays). Both CMS and ATLAS have analyses [8, 9] that tackle boosted pair production of μ/τ from light boson decays. Scenarios A and D by comparison have a heavier A boson, with $m_A \sim 20$ GeV. The decay products from this boson will be slightly boosted and therefore, if one focuses on the $A \to b\bar{b}$ decay channel (which has by far the largest $\sigma \times BR$), then standard reconstruction of b-jets would prove inefficient. Instead, one could utilise jet-substructure techniques.

Scenarios B and E utilise an off-shell Z decay. Previous Higgstrahlung searches have only focused on scenarios where the Z boson is on-shell, limiting their available mass range. Whilst an off-shell Z does not allow one to reconstruct a clean Z peak, it is still possible to trigger on one or both muons from the Z. Unlike scenarios A, C and D, the A boson in these scenarios B and E will not be heavily boosted, and thus its decay products will be well separated in the detector. However, there are substantial backgrounds from $b\bar{b}$ and Drell-Yan processes to be considered.

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