Unusual signals of charged scalars

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Motivation

Motivation for NHDM:

- Simple extension of the SM that allows for CP violation.
- Possibility for Dark Matter.
- Large portions of parameter space testable at LHC.

We considered models with two charged scalars.

- Zee model

  $\Rightarrow$ Type-II 2HDM with a complex charged singlet scalar.
- Type-Z 3HDM

  $\Rightarrow$ Each scalar couples to a fermion of different electric charge.

Constraints on a Model

The restrictions to consider when performing parameter scans for a given model include,

- the S matrix must satisfy perturbative unitarity, [Bento et al., 2017] for NHDMs;
- the Higgs potential must be bounded from below (BFB),
  - $\Rightarrow$ Derived sufficient conditions for the $\mathbb{Z}_3$ 3HDM
  - $\Rightarrow$ Set of necessary for the Zee model [Barroso, Ferreira, 2005];
- Agreement with the S, T and U electroweak parameters [Grimus et al., 2008];
- Coupling modifiers and cross section ratios μ_{if}^h from [The ATLAS Collaboration, 2020],

$$\mu_{if}^h = \left(\frac{\sigma_i^{\text{3HDM}}(pp \to h)}{\sigma_i^{\text{SM}}(pp \to h)}\right)\left(\frac{\text{BR}^{\text{3HDM}}(h \to f)}{\text{BR}^{\text{SM}}(h \to f)}\right); \tag{1}$$

- HiggsBounds-5 [Bechtle et al., 2020] that uses the experimental cross section limits from the LEP, the Tevatron and the LHC (at 95% C.L).

We built a FORTRAN program that numerically calculates all the necessary quantities for a randomly generated set of parameters and then tests the restrictions implemented.

Constraints from BR($B \to X_s\gamma$)

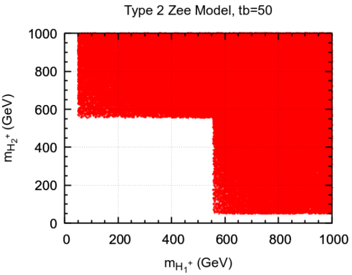
The experimental limits on the BR($B \to X_s\gamma$) put important constraints in the parameter space of models with charged the scalars. The bound

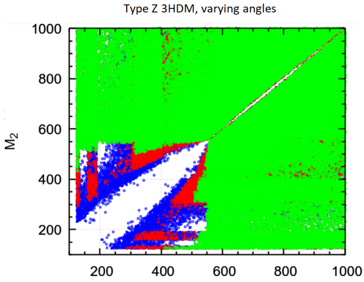
$$m_{H^+} > 580\,\text{GeV} \quad (2)$$

was derived for the Type-II 2HDM at 95% CL (2σ) [Misiak, Steinhauser, 2017].
Both models studied can have at least one small charged Higgs mass.

In the Zee model, we find that eq. (2) can be relaxed for one of the charged scalars.

We find the possibility of cancellation of the contributions from H_1^+ and H_2^+ in the type-Z 3HDM.





Type-Z Z_3 3HDM

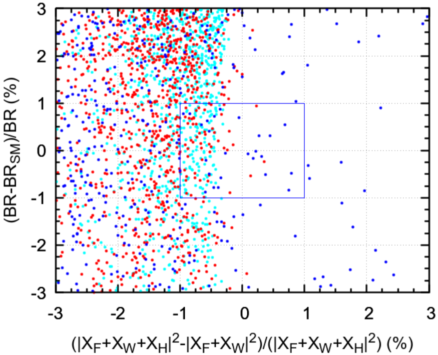
We set our focus on a model that is able to yield a Type-Z Yukawa coupling,

$$\text{Type-Z} : \Phi_u \neq \Phi_d, \quad \Phi_d \neq \Phi_l, \quad \Phi_l \neq \Phi_u \, . \tag{3}$$

The choice made is a 3HDM that respects a $\mathbb{Z}_3$ symmetry, through the representation,

$$S_{\mathbb{Z}_3} = \text{diag}(1, e^{i\frac{2\pi}{3}} e^{-i\frac{2\pi}{3}}). \tag{4}$$

We follow the parametrization of [Das, Saha, 2020] and consider all parameters and vevs to be real, with the addition of quadratic soft-breaking terms.



Points with significant approximate cancellation in both $h \to \gamma\gamma$ (horizontal axis) and $B \to X_s\gamma$ (vertical), which pass all theoretical and experimental bounds.

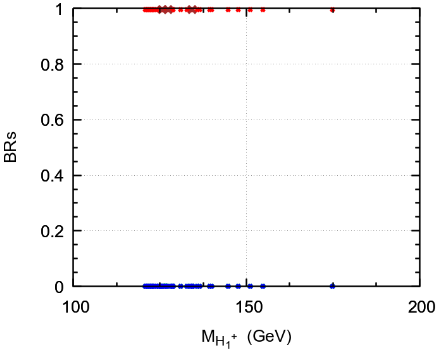
With an extensive scan of the 18 parameter space we find the possibility of large cancellations between the two charged Higgs in $B \to X_s\gamma$ and $h \to \gamma\gamma$.
We find points with this property where H_2^+ does not decay primordially into quarks or leptons, but rather as $H_2^+ \to H_1^+ h_j$, with $h_j = h_1, h_2, A_1$.

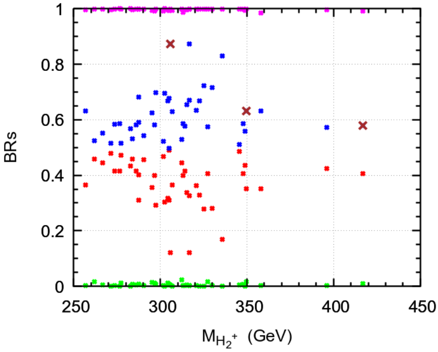
Benchmark points for type-Z 3HDM

Type-Z	BP1	BP2	BP3
m_{h_2}	158.70	162.28	156.16
m_{h_3}	421.87	370.19	295.44
m_{A_1}	178.54	186.06	173.48
m_{A_2}	385.60	330.43	274.96
$m_{H_1^\pm}$	127.32	134.25	125.72
$m_{H_2^\pm}$	416.74	349.55	305.82
(m_{12}^2)	44978	24497	19072
(m_{13}^2)	-23603	-22718	-15156
(m_{23}^2)	-36356	-28653	-15156
α_1	0.3645	0.4216	0.3907
α_2	1.175	1.179	1.262
α_3	0.6670	0.6675	0.6381
γ_1	-0.5370	-0.5823	-0.6275
γ_2	-0.5930	-0.5281	-0.5337
β_1	0.5119	0.4323	0.3784
β_2	1.215	1.132	1.234
BR($H_1^+ \to \nu_\tau + \tau^+$)	0.9783	0.9484	0.9526
BR($H_2^+ \to \nu_\tau + \tau^+$)	0.0003	0.0002	0.0003
BR($H_2^+ \to t + \bar{b}$)	0.4050	0.3502	0.1202
BR($H_2^+ \to H_1^+ h_1$)	0.0039	0.0122	0.0057
BR($H_2^+ \to H_1^+ h_2$)	0.0922	0.2444	0.5998
BR($H_2^+ \to H_1^+ A_1$)	0.4822	0.3757	0.2688
BR($H_2^+ \to W^+ h_1$)	0.00001	0.0022	0.0002
BR($H_2^+ \to W^+ h_2$)	0.0094	0.0134	0.0035

Benchmark points with approximate cancellation in both $h \to \gamma\gamma$ and $B \to X_s\gamma$.

Benchmark points for type-Z 3HDM





- $BR(H_2^+ \to \nu_\tau + \tau^+)$
- $BR(H_2^+ \to t + \bar{b})$

- $BR(H_2^+ \to \nu_\tau + \tau^+)$
- $BR(H_2^+ \to t + \bar{b})$
- $BR(H_2^+ \to H_1^+ + h_j)$
- Sum of the BRs

The Zee model

Scalars denoted by

$$\phi_{1,2} = \begin{pmatrix} \phi_{1,2}^{+} \\ \phi_{1,2}^{0} \end{pmatrix}, \qquad \chi^{+} \tag{5}$$

Impose $\mathbb{Z}_2$ symmetry where ϕ_2 and the up type quarks u_R transform as $\psi \to -\psi$.
The Higgs potential, with all parameters real and after minimization, has 12 parameters,

$$m_C^2, \lambda_C, \mu_4, m_{12}^2, k_1, k_2, k_{12}, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \tag{6}$$

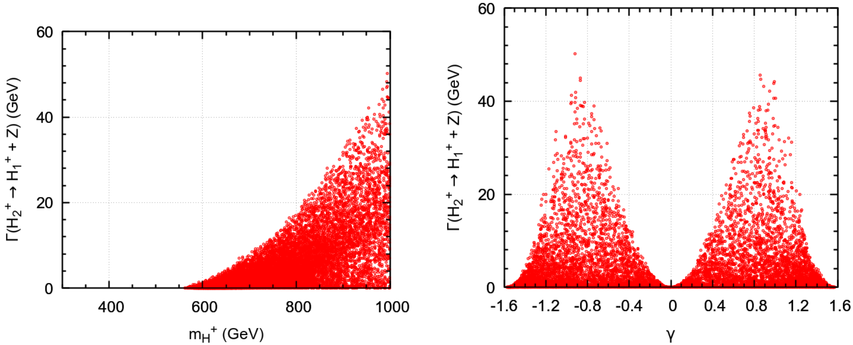
There is a "flavour" changing $Z\, H_1^+ H_2^-$ coupling due to the cubic term with μ_4,

$$V \supset \mu_4 \phi_1 i\sigma_2 \phi_2 \chi^- + h.c. \tag{7}$$

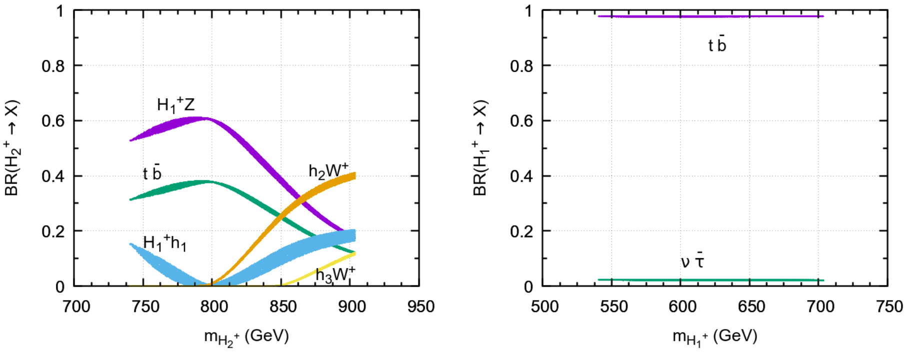
We have studied the impact on the loop decay $h \to Z\gamma$ and the now possible decay $H_2^+ \to H_1^+ + Z$. We find benchmark points with this decay having the largest branching ratio.

Decays for the Zee model

This model has the unique signal $H_2^+ \to H_1^+ + Z$.



Benchmark P_1 for Zee model



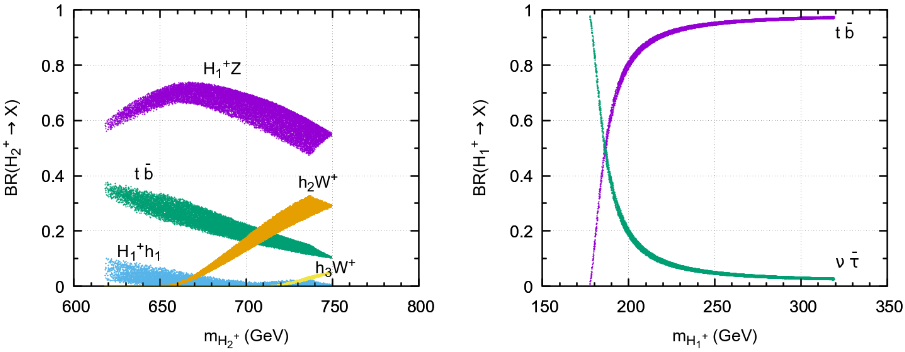
$$m_{h_1} = 125\,\text{GeV} \qquad m_{h_2} = 714.98\,\text{GeV} \qquad m_{h_3} = 767.42\,\text{GeV} \tag{8a}$$

$$m_{H_1^+} = m_{H_2^+} - 200\,\text{GeV} \qquad \alpha = 1.391 \qquad \gamma = 0.894 \tag{8b}$$

$$m_{12}^2 = 8.828\times 10^4\,\text{GeV}^2 \qquad \lambda_c = 0.4363 \qquad k_1 = 0.4633 \tag{8c}$$

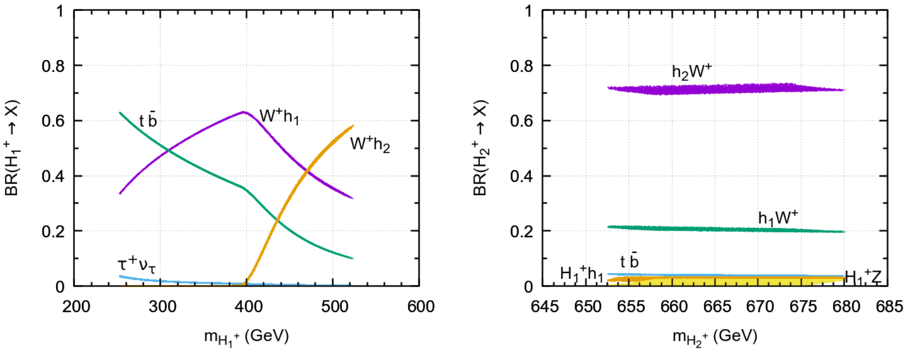
$$k_2 = 0.4633 \qquad k_{12} = 5.427\times 10^{-2} \tag{8d}$$

Benchmark P_2 for Zee model



$$
\begin{aligned}
&m_{h_1} = 125\ \text{GeV} && m_{h_2} = 580.7\ \text{GeV} && m_{h_3} = 633.7\ \text{GeV} && \text{(9a)}\\
&m_{H_1^+}, m_{H_2^+} \text{GeV, scanned as shown} && \alpha = 1.398 && \gamma = 1.089 && \text{(9b)}\\
&m_{12}^2 = 5.77 \times 10^4\ \text{GeV}^2 && \lambda_c = 4.473 && k_1 = 1.082 && \text{(9c)}\\
&k_2 = 3.98 \times 10^{-3} && k_{12} = -1.266 \times 10^{-3} && && \text{(9d)}
\end{aligned}
$$

Benchmark P_4 for Zee model



$$m_{h_1} = 125\,\text{GeV} \qquad m_{h_2} = 314.9\,\text{GeV} \qquad m_{h_3} = 651.3\,\text{GeV} \tag{10a}$$

$$m_{H_1^+}, m_{H_2^+}\ \text{GeV, scanned as shown} \qquad \alpha = -1.402 \qquad \gamma = -1.421 \tag{10b}$$

$$m_{12}^2 = 1.85 \times 10^4\,\text{GeV}^2 \qquad \lambda_c = 2.00 \times 10^{-2} \qquad k_1 = 1.422 \times 10^{-2} \tag{10c}$$

$$k_2 = 0.432 \qquad k_{12} = -9.597 \times 10^{-3} \tag{10d}$$

Summary

- We have discussed the possibility of uncovering a second charged scalar via uncommon decays.
- In Type Z 3HDM, we found many points with the uncommon decay

$$H_2^+ \to H_1^+ + h_j, \qquad \text{with } h_j = h_1, h_2, A_1 \tag{11}$$

- In Zee model we found many points with the uncommon decay

$$H_2^+ \to H_1^+ + Z \qquad \text{and} \qquad H_1^+ \to t + \bar{b} \tag{12}$$

$$H_{1,2}^+ \to W^+ + h_j, \qquad \text{with } h_j = h_1, h_2 \tag{13}$$

The End

Extra Slides

Neutral Higgs into photons

The formula for the width $h_j \to \gamma\gamma$ reads,

$$\Gamma(h_j \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} (|X_F^{\gamma\gamma} + X_W^{\gamma\gamma} + X_H^{\gamma\gamma}|^2), \tag{14}$$

where, noticing that for scalars the Y terms in vanish,

$$X_F^{\gamma\gamma} = -\sum_f N_c^f 2a_j^f Q_f^2 \tau_f [1 + (1 - \tau_f) f(\tau_f)], \tag{15}$$

$$X_W^{\gamma\gamma} = C_j \left[2 + 3\tau_W + 3\tau_W (2 - \tau_W) f(\tau_W)\right], \tag{16}$$

$$X_H^{\gamma\gamma} = -\sum_{k=1}^{2} \frac{\lambda_{jkk} v^2}{2m^2_{H_k^\pm}} \tau_{jk}^\pm \left[1 - \tau_{jk}^\pm f\left(\tau_{jk}^\pm\right)\right]; \tag{17}$$

We used

$$\tau = 4m^2 / m^2_{h_j}, \tag{18}$$

where m is the mass of the relevant particle while m_{h_j} is the Higgs boson to decay. The function $f(\tau)$ is defined in the Higgs Hunter's Guide,

$$f(\tau) = \begin{cases} \left[\sin^{-1}(\sqrt{1/\tau})\right]^2, & \text{if } \tau \geq 1 \\ -\frac{1}{4}\left[\ln\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2, & \text{if } \tau < 1 \end{cases}. \tag{19}$$