LHCHXSWG3 - 2HDM benchmarking: A fermiophobic heavy Higgs scenario

D. López-Val[a]

[a] *Center for Cosmology, Particle Physics and Phenomenology CP3*
Université Catholique de Louvain
Chemin du Cyclotron 2, B-1348 Louvain–la–Neuve, Belgium

E-mail: david.lopezval@uclouvain.be

July 7, 2015

I. MOTIVATION & OVERVIEW

We propose a scenario based on the B5 benchmark studied in Ref. [1] in the context of Higgs–pair production. It describes a SM–like 125.03 GeV Higgs boson, along with a moderately heavier $\mathcal{CP}$–even companion H^0, which fully decouples from the fermionic sector. The latter condition can only be fulfilled in a **type–I** 2HDM with $\sin\alpha = 0$. The neutral $\mathcal{CP}$–odd and the charged Higgs scalars, in turn, have larger, almost degenerate masses in the $\mathcal{O}(500)$ GeV ballpark.

The parameter choice, as detailed below, is justified as follows:

- The fermiophobic limit for H^0 implies by construction $\sin\alpha = 0$ and a type–I setup.
- Departures from alignment are constrained by the measured signal strengths. Therefore the fermiophobic limit $\sin\alpha \simeq 0$ is only viable at large $\tan\beta$, so that $\sin(\beta-\alpha) \lesssim 1$.

  To restrict the allowed deviations from the SM, we tolerate a shift of up to $\mathcal{O}(10\%)$ in the Yukawa couplings, which in the 2HDM implies $|\cos(\beta-\alpha)| \lesssim 0.1$. In the fermiophobic scenario this means

$$\left|\frac{1}{\sqrt{1+\tan^2\beta}}\right| \lesssim 0.1 \qquad \text{and hence} \qquad \tan\beta \gtrsim 10. \tag{1}$$

- Finally, the Z_2 soft–breaking mass term m_{12}^2 must be fixed so that vacuum stability and unitarity bounds are satisfied – the latter become increasingly tight for large $\tan\beta$ values.

Compatibility with the available experimental constraints has been duly checked with a private interface of the public tools 2HDMC [2], HiggsBounds [3, 4], SuperIso [5, 6] and HiggsSignals [7, 8] along with complementary in–house routines. Experimental constraints include: i) mass bounds from direct searches; ii) LHC Higgs signal strength measurements; iii) Electroweak precision observables; iv) and flavor constraints from heavy flavor–meson physics. The exemplary parameter point given in Table I satisfies as well the conditions of vacuum stability, perturbativity and unitarity.

A systematic exploration of fermiophobic 2HDM configurations was initiated in [9, 10] and continued with the characterization of its trademark collider signatures [11–13] and its interplay with the additional heavy Higgs phenomenology [14]. On the experimental side, dedicated fermiophobic scalar searches were conducted in the past using LEP [15], Tevatron [16] and early LHC Run I data [17].

Fermiophobic $\mathcal{CP}$–even scalars are also welcome from a model–building perspective. They can for instance appear in non–minimal supersymmetric extensions of the SM [18] or in GUT–based constructions [19] – for which a fermiophobic 2HDM can be viewed as an effective low–energy parametrization. Other proposals for fermiophobic neutral $\mathcal{CP}$–odd or charged Higgs bosons have been suggested e.g. in Ref. [20, 21].

Such a fermiophobic 2HDM setup is particularly challenging from the experimental viewpoint. On the one hand, the relatively low–mass heavy $\mathcal{CP}$–even Higgs, which is by construction completely unlinked from the fermion sector, cannot couple to gluons via the usual heavy–fermion loop exchange. For the same reason, the s–channel H^0 interchange does not contribute to the light di–Higgs production via $gg \to H^0 \to h^0 h^0$ [1]. On the other hand, owing to the fact that $\cos(\beta-\alpha) \ll 1$, the H^0 state hardly couples to the gauge bosons, while it interacts very weakly with a light Higgs pair through the trilinear coupling $H^0 h^0 h^0$. More details on the collider phenomenology are discussed further down.

The fermiophobic limit should be read as a warning sign. The 2HDM, as a representative extended Higgs sector, allows for a relatively low–mass additional scalar, which is yet very elusive to direct collider searches. In this sense, lack of experimental signatures does not readily rule out the presence of additional heavy neutral Higgs companions.

II. BENCHMARK PLANES

Fermiophobic 2HDM configurations can be covered comprehensively by experimental analyses through benchmark planes, as we construct hereafter. To begin with, we single out the following relevant parameters:

- Mixing angle: it is fixed by construction to $\alpha = 0$ by the fermiophobic heavy Higgs condition;
- Distance to alignment: representative configurations can be explored by fixing $\cos(\beta-\alpha)$ to fiducial choices. Since α is already fixed, this is tantamount to specify a fiducial value for $\tan\beta$;
- Fermiophobic heavy Higgs mass, m_{H^0};
- A characteristic heavy Higgs mass splitting ΔM, which fixes the additional Higgs companion masses (assumed by simplicity to be degenerate) as $m_{A^0} \simeq m_{H^\pm} = m_{H^0} + \Delta M$.

There is large freedom to fix the Z_2 soft–breaking parameter m_{12}^2, as it barely influences the relevant phenomenology – it only impacts the Higgs self–interactions, and hence the heavy Higgs widths and branching fractions if Higgs–to–Higgs decay modes are kinematically available. A convenient criterion to define it is by using the vacuum stability and unitarity constraints. It particular, it can be proved that in the fermiophobic limit these constraints mostly rely on the combination

$$\tilde{\lambda} = \frac{1}{2v^2}\left[m_{12}^2\left(\frac{1-\tan^2\beta}{\sin\beta\,\cos\beta}\right) + \frac{m_{H^0}^2}{\cos^2\beta}\right], \tag{2}$$

which should generically fulfill $|\tilde{\lambda}| < 4\pi$. The above relation nicely illustrates the interplay between $\tan\beta$ and the mass scales $m_{H^0}^2, m_{12}^2$. Once a given choice is made for $\tan\beta$ and m_{H^0}, the condition $|\tilde{\lambda}| < 4\pi$ suggests a suitable choice for m_{12}^2. Notice that, in the limit of interest ($\tan\beta \gg 1$), we are left with the simple rule of thumb $m_{12}^2 \gtrsim \frac{m_{H^0}^2}{\tan\beta}$.

All in all, we can characterize the fermiophobic configurations by fixing the three independent parameters:

$$m_{H^0}, \qquad \Delta M; \qquad \tan\beta\,. \tag{3}$$

Notice that ΔM includes all possible mass hierarchies

$$\diamond\ \underline{\text{direct:}}\ (\Delta M > 0) \quad m_{H^0} < m_{A^0,H^\pm}; \quad \diamond\ \underline{\text{inverted}}\ (\Delta M < 0) \quad m_{H^0} > m_{A^0,H^\pm};$$
$$\diamond\ \underline{\text{degenerate}}(\Delta M = 0) \quad m_{H^0} = m_{A^0,H^\pm} \quad . \tag{4}$$

On the other hand, each of these quantities defines a relevant direction in the parameter space:

- Distance from alignment (variable $\tan\beta$)
- Heavy Higgs mass scale (variable m_{H^0})
- Heavy Higgs mass splitting (variable $\Delta\,M$)

$\tan\beta$	α/π	m_{H^0} [GeV]	m_{A^0} [GeV]	$m_{H^\pm}$ [GeV]	m^2_{12} [GeV^2]
20.00	0	200	500	500	2000

Table I. Input parameters (physical basis, in the notation and conventions of Ref. [2] and references therein) for the fermiophobic reference point

m_{H^0} [GeV]	$\cos(\beta-\alpha)$	$\tan\beta$	Z_4	Z_5	Z_7
200	4.994×10^{-2}	20	-3.465×10^{0}	-3.465×10^{0}	3.286×10^{-2}

Table II. Input parameters (hybrid basis, in the notation and conventions of Ref. [2] and references therein) for the fermiophobic reference point.

Representative benchmark planes can therefore be defined as slices in this 3–parameter subspace. We suggest to take $[m_{H^0}, \Delta M]$ as floating variables and fix $\tan\beta$ to fiducial values – e.g. increasingly departing from alignment as:

- ♭ $\tan\beta = 40$: small departure (coupling shifts of $\mathcal{O}(2\%)$)
- ♭ $\tan\beta = 20$: moderate departure (coupling shifts of $\mathcal{O}(5\%)$)
- ♭ $\tan\beta = 10$: strong departure (coupling shifts of $\mathcal{O}(10\%)$)

In Tables I-II we single out one particular reference point within these planes and discuss specific collider implications.

III. COLLIDER PHENOMENOLOGY

Experimental opportunities for this class of scenarios mostly rely on the complementarity between the H^0VV and the H^0A^0Z (resp. $H^0W^+H^-$) interactions. While the former are damped by a factor $\sim\cos(\beta-\alpha)\to 0$ as we approach the alignment limit, the latter behave like $\sin(\beta-\alpha)$ and thus remain unsuppressed. The total widths and BRs are obtained with 2HDMC [2] including leading QCD corrections. For the production we use MadGraph5 [22] along with an in–house modification of the public FeynRules model 2HDM_NLO [23]. Production rates and branching fractions include NLO QCD corrections.

A. Production:

The leading production mode for the fermiophobic H^0 state is in association with the $\mathcal{CP}$–odd partner A^0, via s–channel Z–boson exchange. At the reference point of Table I, the expected total rate at the LHC yields $\sigma(H^0A^0)\simeq 1.9$ fb for $\sqrt{S}=13$ TeV.

The associated production with a charged Higgs $H^0H^\pm$ falls a factor of 2 below, giving a total cross section of $\sigma(H^0H^\pm)\simeq 0.88$ fb for the same reference point.

Alternative mechanisms, such as e.g. $pp(bb)\to A^0\to H^0Z^0$ are not competitive (notice the suppressed Yukawa coupling at large $\tan\beta$) and contribute at the 0.1 fb level.

B. Decay

Decay patterns are of course critically dependent on the mass hierarchies between the different heavy Higgs fields.

- Direct hierarchy ($\Delta M > 0$): – Despite the strongly suppressed coupling to the gauge bosons, the H^0 state decays predominantly into W and Z pairs. The branching fractions for the reference point in Table I are

$$\mathrm{BR}(H^0\to W^+W^-) = 0.742; \qquad \mathrm{BR}(H^0\to Z^+Z^-) = 0.258, \tag{5}$$

while the loop–induced modes into γZ (resp. $\gamma\gamma$) contribute at (resp. below) $\mathcal{O}(10^{-4})$.

In view of its narrow width $\Gamma(\mathrm{H}^0) = 3.39 \times 10^{-3}$ GeV, the trademark decay signature of a fermiophobic H^0 state is a sharp resonance into WW/ZZ.

Additional signatures from the charged Higgs or the $\mathcal{CP}$–odd states are not competitive – their production rates being comparably suppressed by their heavier masses.

- Inverted hierarchy ($\Delta M < 0$): For $m_{\mathrm{H}^0} > m_{\mathrm{A}^0,\mathrm{H}^\pm}$, the additional decay modes $\mathrm{H}^0 \to \mathrm{A}^0\mathrm{Z}^0$ and $\mathrm{H}^0 \to \mathrm{H}^\pm\mathrm{W}^\pm$ can be open as well. In these configurations, though, the charged and the $\mathcal{CP}$–odd states will be more copiously produced as compared to H^0, and will then be less sensitive to the genuine features of the fermiophobic regime. Let us also recall the tight constraints on this region from recent CMS searches [24].

C. Electroweak precision observables

Finally, it is worth pointing out that Electroweak Precision analyses may offer a complementary pathway to probe the key couplings $\mathrm{H}^0\mathrm{A}^0\mathrm{Z}$ and $\mathrm{H}^0\mathrm{H}^\pm\mathrm{W}^\mp$, cf. e.g. [25].

IV. HIGGS COUPLINGS

For completeness, we provide numerical values for the relevant Higgs couplings (normalized to the SM Higgs coupling strengths, as explicitly indicated):

a. Higgs boson couplings to fermions All couplings are normalized to the SM.

	g_{htt}	g_{hbb}	$g_{h\tau\tau}$	g_{hVV}	g_{hgg}	$g_{h\gamma\gamma}$
h^0	1.001	1.001	1.001	0.999	1.001	0.9509
H^0	0.000	0.000	0.000	0.005	0.000	-0.344
A^0	0.05	-0.05	-0.05	0.000	-	-

b. Higgs boson self–couplings All couplings are normalized to the SM, $g^{\mathrm{SM}}_{\mathrm{HHH}} = -3m^2_{\mathrm{H}}/v$

$$\begin{array}{llllll} \mathrm{h}^0\mathrm{h}^0\mathrm{h}^0: & 0.9948 & \mathrm{H}^0\mathrm{h}^0\mathrm{h}^0: & 0.0427 & \mathrm{H}^0\mathrm{H}^0\mathrm{h}^0: & 0.8540 \\ \mathrm{H}^0\mathrm{H}^0\mathrm{H}^0: & 0.0000 & \mathrm{h}^0\mathrm{A}^0\mathrm{A}^0: & 9.7930 & \mathrm{H}^0\mathrm{A}^0\mathrm{A}^0: & 0.4471 \end{array} \qquad (6)$$

[1] B. Hespel, D. López-Val, and E. Vryonidou, JHEP **1409**, 124 (2014), 1407.0281.
[2] D. Eriksson, J. Rathsman, and O. Stål, Comput.Phys.Commun. **181**, 189 (2010), 0902.0851.
[3] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, Comput.Phys.Commun. **181**, 138 (2010), 0811.4169.
[4] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, Comput.Phys.Commun. **182**, 2605 (2011), 1102.1898.
[5] F. Mahmoudi, Comput.Phys.Commun. **178**, 745 (2008), 0710.2067.
[6] F. Mahmoudi, Comput.Phys.Commun. **180**, 1579 (2009), 0808.3144.
[7] P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, and G. Weiglein, Eur.Phys.J. **C74**, 2711 (2014), 1305.1933.
[8] O. Stål and T. Stefaniak, PoS **EPS-HEP2013**, 314 (2013), 1310.4039.
[9] L. Brucher and R. Santos, Eur.Phys.J. **C12**, 87 (2000), hep-ph/9907434.
[10] A. Barroso, L. Brucher, and R. Santos, Phys.Rev. **D60**, 035005 (1999), hep-ph/9901293.
[11] A. G. Akeroyd and M. A. Diaz, Phys.Rev. **D67**, 095007 (2003), hep-ph/0301203.
[12] A. Akeroyd, M. A. Diaz, and F. J. Pacheco, Phys.Rev. **D70**, 075002 (2004), hep-ph/0312231.
[13] J. Kumar, A. Rajaraman, and D. Yaylali, Phys.Rev. **D86**, 115019 (2012), 1209.5432.
[14] A. Akeroyd, M. A. Diaz, and M. A. Rivera, Phys.Rev. **D76**, 115012 (2007), 0708.1939.
[15] DELPHI, J. Abdallah *et al.*, Eur.Phys.J. **C35**, 313 (2004), hep-ex/0406012.
[16] CDF, T. Aaltonen *et al.*, Phys.Rev.Lett. **108**, 011801 (2012), 1109.4427.
[17] ATLAS, G. Aad *et al.*, Eur.Phys.J. **C72**, 2157 (2012), 1205.0701.

[18] E. Gabrielli, K. Kannike, B. Mele, A. Racioppi, and M. Raidal, Phys.Rev. **D86**, 055014 (2012), 1204.0080.
[19] J. Hetzel and B. Stech, Phys.Rev. **D91**, 055026 (2015), 1502.00919.
[20] V. Ilisie and A. Pich, JHEP **1409**, 089 (2014), 1405.6639.
[21] R. Enberg, J. Rathsman, and G. Wouda, (2013), 1311.4367.
[22] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, JHEP **1106**, 128 (2011), 1106.0522.
[23] C. Degrande, (2014), 1406.3030.
[24] CMS Collaboration, (2015), CMS-PAS-HIG-15-001.
[25] D. López-Val and J. Solà, Eur.Phys.J. **C73**, 2393 (2013), 1211.0311.