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Phenomenology of sequestered mass generation

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I discuss aspects of the phenomenology of a novel class of two Higgs doublet models (2HDMs). One Higgs provides the bulk of the masses of the weak gauge bosons and the third generation fermions, while the second Higgs is responsible for the masses of the lighter fermion flavors. The phenomenology of this setup differs substantially from well studied 2HDMs with natural flavor conservation, flavor alignment, or minimal flavor violation. Flavor violating Higgs couplings generically arise in a controlled way. New production mechanisms and decay modes for the heavy scalar, pseudoscalar and charged Higgs involving second generation quarks can become dominant.

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1. Introduction

In the Standard Model (SM) of particle physics, the Higgs boson is the only source of electro-weak symmetry breaking and responsible for the masses of all other massive SM particles. Measurements of Higgs production and decay are overall in good agreement with SM predictions and indicate that the masses of the weak gauge bosons and also the third generation fermions are indeed largely due to the Higgs [1]. However, confirming the Higgs as the origin of the light flavors' mass is experimentally very challenging, due to the tiny Yukawa couplings involved. An alternative approach to uncover the origin of masses of the light flavors is to assume that it is *not* the Higgs and explore the implied phenomenology.

In [2] we proposed a framework, where the origin of the first and second generation fermions is not the Higgs boson, but an additional source of electro-weak symmetry breaking (see also [4, 5]). Arguably the simplest realization of this framework is a two Higgs doublet model (2HDM): one Higgs doublet couples to the fermions with rank 1 Yukawa couplings λ, providing mass only for the third generation, while the other Higgs also couples to first and second generation fermions with Yukawa couplings λ'. We will consider the following textures for the lepton Yukawa couplings

$$\lambda^\ell \sim \frac{\sqrt{2}}{v} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix} , \; \lambda'^\ell \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_e & m_e & m_e \\ m_e & m_\mu & m_\mu \\ m_e & m_\mu & m_\mu \end{pmatrix} , \tag{1.1}$$

where v and v' are the vacuum expectation values (vevs) of the two Higgs doublets. Analogous textures can be chosen for the up-quark Yukawas. To achieve quantitative agreement with the observed CKM mixing requires to adapt the corresponding down-quark Yukawa textures slightly (see [2, 3] for details).

Generically, such a framework leads to flavor changing neutral currents already at tree level. However, the rank 1 Yukawa couplings preserve a $SU(2)^5$ flavor symmetry acting on the first two generations of fermions. In the 2HDM setup the symmetry is only broken by the λ' Yukawa couplings of the second doublet and flavor transitions between the first and second generations are protected. Therefore, the most stringent flavor constraints from $\mu \to e$, $s \to d$, and $c \to u$ transitions can be controlled.

The outlined 2HDM setup shows very distinct phenomenology. In contrast to 2HDMs with natural flavor conservation [6], flavor alignment [7, 8], or minimal flavor violation [9], the couplings of the Higgs bosons to fermions are not proportional to the fermion masses. Non-standard production and decay modes of the heavy Higgs bosons involving light quark generations become relevant. Also flavor changing neutral Higgs couplings involving the third generation lead to interesting phenomenological implications. The following discussion is mainly based on [3] (see also [10, 11] for recent related studies).

2. Phenomenology of the 125 GeV Higgs

We identify the lightest neutral scalar h of the 2HDM with the 125 GeV Higgs boson. Its couplings are in general modified with respect to SM expectations, and measurements of Higgs rates at the LHC can be used to constrain the parameter space of the model.

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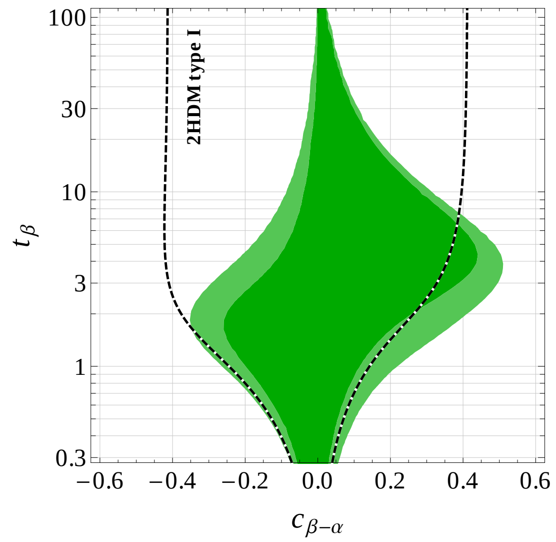

Figure 1: Allowed region in the $\cos(\beta-\alpha)$ vs. $\tan\beta$ plane from measurements of the 125 GeV Higgs rates at the LHC. The dark green and light green regions correspond to the 1σ and 2σ allowed regions, allowing the $O(m_{2\mathrm{nd}}/m_{3\mathrm{rd}})$ terms in the relevant Higgs couplings to float between $-3m_{2\mathrm{nd}}/m_{3\mathrm{rd}}$ and $+3m_{2\mathrm{nd}}/m_{3\mathrm{rd}}$. The dashed line corresponds to the 2σ contour in a 2HDM type 1.

As in any other 2HDM, the coupling of h to the weak gauge bosons W and Z is universally suppressed by a factor $\cos(\beta-\alpha)$, where α is the mixing angle of the two neutral scalar bosons and $\tan\beta = v/v'$ is the ratio of the vevs of the two Higgs doublets. The modifications to the couplings to third generation fermions read

$$\frac{Y_t}{Y_t^{\mathrm{SM}}} \simeq \frac{Y_b}{Y_b^{\mathrm{SM}}} \simeq \frac{Y_\tau}{Y_\tau^{\mathrm{SM}}} \simeq \frac{c_\alpha}{s_\beta}\ , \tag{2.1}$$

where $c_x = \cos x$, $s_x = \sin x$. In the above expression we show the leading term and neglect corrections of the order of m_{2nd}/m_{3rd}. The modification of the third generation couplings coincide with those in a 2HDM type 1. The couplings of the first and second generation are instead modified by

$$\frac{Y_c}{Y_c^{\mathrm{SM}}} \simeq \frac{Y_s}{Y_s^{\mathrm{SM}}} \simeq \frac{Y_\mu}{Y_\mu^{\mathrm{SM}}} \simeq \frac{Y_u}{Y_u^{\mathrm{SM}}} \simeq \frac{Y_d}{Y_d^{\mathrm{SM}}} \simeq \frac{Y_e}{Y_e^{\mathrm{SM}}} \simeq \frac{-s_\alpha}{c_\beta}\ , \tag{2.2}$$

where we neglected corrections of the order m_{2nd}/m_{3rd} (for second generation couplings) and m_{1st}/m_{3rd} (for first generation couplings). For $\alpha = 0$, i.e. in the absence of mixing between the scalar components of the two doublets, h does not couple to the first and second generation. Away from the decoupling limit, $\cos(\beta-\alpha) \neq 0$, the couplings can deviate substantially from SM values.

Fig. 1 shows the result of a χ^2 fit to the Higgs signal strengths from [1] combined with the bounds on $h \to \mu^+\mu^-$ from [12]. The dark (light) green region is allowed by the LHC results at the 1σ (2σ) level. Shown for comparison is also the 2σ constraint in a 2HDM type 1 (dashed contour).

Away from the decoupling limit, h generically also acquires flavor violating couplings. We generically expect lepton flavor violating Higgs decays of the order of

$$\mathrm{Br}(h\to\tau\mu) \sim \frac{m_\mu^2}{3m_b^2} \sim 10^{-3}\ , \ \mathrm{Br}(h\to\tau e) \sim \frac{m_e^2}{3m_b^2} \sim 10^{-7}\ , \ \mathrm{Br}(h\to\mu e) \sim \frac{m_e^2 m_\mu^2}{3m_\tau^2 m_b^2} \sim 10^{-10}\ . \tag{2.3}$$

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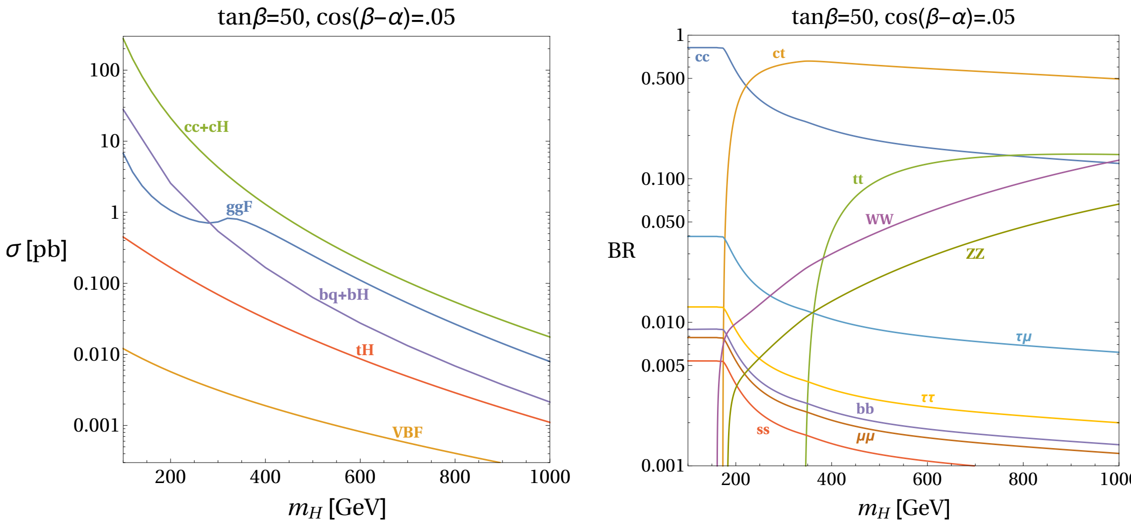

Figure 2: Left: Production cross sections of the heavy scalar H in 13 TeV proton-proton collisions as function of the scalar mass m_H for fixed $\tan\beta = 50$ and $\cos(\beta - \alpha) = 0.05$. Right: Branching ratios of the heavy scalar H as function of the scalar mass m_H for fixed $\tan\beta = 50$ and $\cos(\beta - \alpha) = 0.05$.

While the $h \to \tau e$ and $h \to \mu e$ decays are well below the foreseeable experimental sensitivities, $h \to \tau\mu$ can be at an experimentally accessible level.

3. Phenomenology of the Heavy Higgs Bosons

The couplings of the heavy Higgs bosons to fermions show a very pronounced flavor non-universal structure. For example, for the heavy scalar H we find

$$\frac{Y_t^H}{Y_t^{\rm SM}} \simeq \frac{Y_b^H}{Y_b^{\rm SM}} \simeq \frac{Y_\tau^H}{Y_\tau^{\rm SM}} \simeq \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta} , \tag{3.1}$$

$$\frac{Y_c^H}{Y_c^{\rm SM}} \simeq \frac{Y_s^H}{Y_s^{\rm SM}} \simeq \frac{Y_\mu^H}{Y_\mu^{\rm SM}} \simeq \frac{Y_u^H}{Y_u^{\rm SM}} \simeq \frac{Y_d^H}{Y_d^{\rm SM}} \simeq \frac{Y_e^H}{Y_e^{\rm SM}} \simeq t_\beta \frac{c_\alpha}{s_\beta} . \tag{3.2}$$

In these expressions we neglected corrections of the order m_{2nd}/m_{3rd} (for second and third generation couplings) and m_{1st}/m_{3rd} (for first generation couplings). Note that the third generation couplings are suppressed by $\tan\beta$, while the couplings to first and second generation are enhanced by $\tan\beta$. Correspondingly, the decays of H to the third generation (top, bottom, tau) are not necessarily dominant. For large and moderate $\tan\beta$, sizable branching ratios involving charm quarks and muons can be expected. Moreover, novel non-standard production modes of the heavy Higgs bosons involving second generation quarks can become relevant.

The left plot of Fig. 2 shows various production cross sections of H as function of its mass m_H for $\tan\beta = 50$ and $\cos(\beta - \alpha) = 0.05$. Production from charm quarks is dominant for large $\tan\beta$. The curve labeled "cc + cH" includes $c\bar{c} \to H$ production and production in association with a charm quark $cg \to cH$ and $\bar{c}g \to \bar{c}H$. Production from gluon fusion is sub-dominant. Production in association with bottom and top quarks is mainly induced by flavor violating couplings, e.g. $sg \to bH$ or $cg \to tH$. The corresponding cross sections can be at an interesting level. The vector

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boson fusion production cross section is tiny, as are the cross sections for production in association with vector bosons (not shown in the plot).

The branching ratios of H as function of its mass m_H are shown in the right plot of Fig. 2 for $\tan\beta = 50$ and $\cos(\beta-\alpha) = 0.05$. The dominant decay modes are $c\bar{c}$ and the flavor violating ct. The decay into $t\bar{t}$ can also be sizable. Decays into final states with taus and muons are at the level of few $\times 10^{-3}$ to few $\times 10^{-2}$. Note that the decay rates into $\tau^+\tau^-$ and $\mu^+\mu^-$ are comparable. This is in stark contrast to "un-flavored" 2HDMs where the ratio of these branching ratios is determined by the ratio of lepton masses $m_\tau^2/m_\mu^2 \simeq 300$. Decays into gauge bosons are typically sub-dominant. For the chosen value of $\cos(\beta-\alpha) = 0.05$, the WW and ZZ branching ratios can reach the 10% level for Higgs masses of around 1 TeV.

The production cross sections and branching ratios of the heavy pseudoscalar A show a very similar behavior. The main difference are the absence of vector boson fusion production and of production in association with vector bosons as well as the absence of decays into WW and ZZ. In contrast to the scalar H, the pseudoscalar A can be produced in association with the light Higgs h and can decay into Zh. The corresponding production cross section and branching ratio are typically too small to be of phenomenological relevance.

Given the distinct production and decay modes discussed above, the standard searches for heavy Higgs bosons at the LHC ($H/A \to \tau^+\tau^-$ and $H \to WW/ZZ$) have only weak sensitivity to our model. We find that the strongest constraints can currently be derived from searches for di-muon resonances. For $\tan\beta = 50$, such searches allow to exclude H and A with masses below ~ 300 GeV. For lower values of $\tan\beta$, the constraints are much weaker.

The discussed 2HDM setup predicts a set of novel signatures that can be searched for at the LHC. Among the most interesting signatures are flavor violating Higgs decays $pp \to H/A \to \tau\mu$ with cross sections up to 100 fb, and $pp \to H/A \to tc$ with cross sections as large as several pb. Another very interesting signature are multi top final states $pp \to tH/A \to ttc$. A significant fraction of this signature consists of two same sign tops, $cg \to tH/A \to tt\bar{c}$ or $\bar{c}g \to \bar{t}H/A \to \bar{t}\bar{t}c$, providing a very clean and distinct signature.

Also the charged Higgs boson shows distinct non-standard phenomenology. The dominant production mode is typically production from a cs initial state with cross sections as large as ~ 1 pb for a charged Higgs mass of $m_{H^\pm} \simeq 500$ GeV. Production in association with a top is typically several 10s of fb. The main decay mode is not necessarily $H^\pm \to tb$ but can be $H^\pm \to cb$ or $H^\pm \to cs$. The $H^\pm \to \tau\nu$ decay mode is suppressed, with branching ratios of few $\times 10^{-3}$. The $H^\pm \to \mu\nu$ decay has comparable branching ratio. Interesting novel signatures of the charged Higgs include production in association with a top followed by the decay into cb or cs: $pp \to tH^\pm \to tcb/s$. Searches for di-jet resonances with an associated top might have interesting sensitivities to the discussed framework.

4. Summary and Outlook

I discussed the distinct collider phenomenology of a novel class of 2HDMs. One Higgs doublet provides the dominant contribution of the masses of the weak gauge bosons and the third generation

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fermions, while the second Higgs doublet is responsible for the masses of the lighter fermion flavors.

The properties of the 125 GeV Higgs and the additional heavy Higgs bosons differ markedly from other well studied 2HDMs with natural flavor conservation, flavor alignment, and minimal flavor violation. Characteristic signatures include the lepton flavor violating decay $h \to \tau\mu$ with branching ratios possibly in reach of the LHC, as well as flavor violating decays of the heavy Higgs bosons $H/A \to tc$ and $H/A \to \tau\mu$. Other interesting collider signatures include same sign tops and di-jet resonances with an associated top. Further studies are required to determine the sensitivities of possible dedicated LHC searches for such signatures.

Acknowledgements

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