Prospects of light charged scalars in a three Higgs doublet model with Z_3 symmetry

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Overview

Motivation

- 2HDMs are a minimal extension to the SM
- QFV processes motivate the study of NFC models
- Experimental observations keep pushing the NP scale upwards
  - Are light (charged) scalars still plausible?

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NFC Models

	2HDM				3HDM
fermion	Type-I	Type-II	Type-X	Type-Y	Democratic
u	ϕ_3	ϕ_3	ϕ_3	ϕ_3	ϕ_3
d	ϕ_3	ϕ_2	ϕ_3	ϕ_2	ϕ_2
ℓ	ϕ_3	ϕ_2	ϕ_2	ϕ_3	ϕ_1

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The Z3HDM: A Z_3-symmetric 3HDM

Z_3 transformations ($\omega = e^{2i\pi/3}$)

$$\phi_1 \to \omega\,\phi_1\,, \qquad \phi_2 \to \omega^2\phi_2\,, \qquad \ell_R \to \omega^2\ell_R\,, \qquad n_R \to \omega\,n_R\,,$$

Yukawa Lagrangian

$$\mathcal{L} = -Y_\ell \overline{L}_L \phi_1 \ell_R - Y_d \overline{Q}_L \phi_2 n_R - Y_u \overline{Q}_L \widetilde{\phi}_3 p_R + \text{h.c.}\,,$$

- Democratic Structure ⇒ No tree-level FCNCs

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(Softly Broken) Scalar Potential

$$\begin{aligned} V \;=\; & m_{11}^2(\phi_1^\dagger\phi_1) + m_{22}^2(\phi_2^\dagger\phi_2) + m_{33}^2(\phi_3^\dagger\phi_3) \\ & - \left(m_{12}^2(\phi_1^\dagger\phi_2) + m_{23}^2(\phi_2^\dagger\phi_3) + m_{13}^2(\phi_1^\dagger\phi_3) + \text{h.c.}\right) \\ & + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_3^\dagger\phi_3)^2 \\ & + \lambda_4(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_5(\phi_1^\dagger\phi_1)(\phi_3^\dagger\phi_3) + \lambda_6(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) \\ & + \lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda_8(\phi_1^\dagger\phi_3)(\phi_3^\dagger\phi_1) + \lambda_9(\phi_2^\dagger\phi_3)(\phi_3^\dagger\phi_2) \\ & + \left[\lambda_{10}(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_3) + \lambda_{11}(\phi_2^\dagger\phi_1)(\phi_2^\dagger\phi_3) + \lambda_{12}(\phi_3^\dagger\phi_1)(\phi_3^\dagger\phi_2) + \text{h.c.}\right] \end{aligned}$$

Symmetry Basis $\rightarrow$ Mass Basis (Assume $\lambda_{10\rightarrow 12} \in \mathbb{R}$)

$$\phi_k = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, w_k^+ \\ v_k + h_k + i z_k \end{pmatrix}, \quad k = 1, 2, 3, \qquad \begin{aligned} v_1 &= v\, c_{\beta_1} c_{\beta_2} \\ v_2 &= v\, s_{\beta_1} c_{\beta_2} \\ v_3 &= v\, s_{\beta_2} \end{aligned}$$

$$\begin{pmatrix} w^\pm \\ H_1^\pm \\ H_2^\pm \end{pmatrix} = \mathcal{O}_{\gamma_2} \mathcal{O}_\beta \begin{pmatrix} w_1^\pm \\ w_2^\pm \\ w_3^\pm \end{pmatrix}, \quad \begin{pmatrix} \zeta \\ A_1 \\ A_2 \end{pmatrix} = \mathcal{O}_{\gamma_1} \mathcal{O}_\beta \begin{pmatrix} z_1 \\ z_2 \\ z_3 \end{pmatrix}, \quad \begin{pmatrix} h \\ H_1 \\ H_2 \end{pmatrix} = \mathcal{O}_\alpha \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

$$\mathcal{O}_{\gamma_i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\gamma_i} & -s_{\gamma_i} \\ 0 & s_{\gamma_i} & c_{\gamma_i} \end{pmatrix}, \qquad \mathcal{O}_\beta = \begin{pmatrix} c_{\beta_2} c_{\beta_1} & c_{\beta_2} s_{\beta_1} & s_{\beta_2} \\ -s_{\beta_1} & c_{\beta_1} & 0 \\ -c_{\beta_1} s_{\beta_2} & -s_{\beta_1} s_{\beta_2} & c_{\beta_2} \end{pmatrix}$$

$$\mathcal{O}_\alpha = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_1} c_{\alpha_3} & -c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_3} & c_{\alpha_1} s_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

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Alignment Limit:

$$\alpha_1 = \beta_1, \qquad \alpha_2 = \beta_2$$

$$\mathcal{O}_\alpha = \begin{pmatrix} c_{\beta_1} c_{\beta_2} & s_{\beta_1} c_{\beta_2} & s_{\beta_2} \\ c_{\beta_1} s_{\beta_2} s_{\alpha_3} & s_{\beta_1} s_{\beta_2} s_{\alpha_3} + c_{\beta_1} c_{\alpha_3} & -c_{\beta_2} s_{\alpha_3} \\ -c_{\beta_1} s_{\beta_2} c_{\alpha_3} - s_{\beta_1} s_{\alpha_3} & c_{\beta_1} s_{\alpha_3} - s_{\beta_1} s_{\beta_2} c_{\alpha_3} & c_{\beta_2} c_{\alpha_3} \end{pmatrix}$$

Charged-Higgs Yukawa Couplings

Z3HDM

$$\mathcal{L}^{Q}_{H_1^{\pm}} = -\frac{\sqrt{2}H_1^{+}}{v}\,\overline{u}\left[\frac{c_{\beta_2}}{s_{\beta_2}}s_{\gamma_2}(D_u V)P_L + \frac{s_{\beta_2}}{c_{\beta_2}}\left(\frac{c_{\beta_1}c_{\gamma_2}}{s_{\beta_1}s_{\beta_2}} + s_{\gamma_2}\right)(V D_d)P_R\right] d + \text{h.c.}$$

$$\mathcal{L}^{Q}_{H_2^{\pm}} = \frac{\sqrt{2}H_2^{+}}{v}\,\overline{u}\left[\frac{c_{\beta_2}}{s_{\beta_2}}c_{\gamma_2}(D_u V)P_L - \frac{s_{\beta_2}}{c_{\beta_2}}\left(\frac{c_{\beta_1}s_{\gamma_2}}{s_{\beta_1}s_{\beta_2}} - c_{\gamma_2}\right)(V D_d)P_R\right] d + \text{h.c.}$$

2HDM-II

$$\mathcal{L}^{\text{2HDM-II}}_{H^{\pm}} = \frac{\sqrt{2}H^{+}}{v}\overline{u}\left[\frac{c_{\beta}}{s_{\beta}}\,(D_u\,V)\,P_L + \frac{s_{\beta}}{c_{\beta}}\,(V\,D_d)\,P_R\right] d + \text{h.c.},$$

Charged-Higgs Yukawa Couplings

Z3HDM: $\tan\beta_1 \gg 1$

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Z3HDM: a Relaxation of 2HDM-II

$\tan\beta_1 \gg 1$

$$\mathcal{L}_{H_1^\pm} \approx -\frac{\sqrt{2}H_1^+}{v}\overline{u}\, s_{\gamma_2} \left[\frac{c_{\beta_2}}{s_{\beta_2}}\,(D_u\,V)\,P_L + \frac{s_{\beta_2}}{c_{\beta_2}}\,(V\,D_d)\,P_R\right] d + \text{h.c.},$$

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$$\mathcal{L}^{\text{II}}_{H^\pm} = \frac{\sqrt{2}H^+}{v}\overline{u} \left[\frac{c_\beta}{s_\beta}\,(D_u\,V)\,P_L + \frac{s_\beta}{c_\beta}\,(V\,D_d)\,P_R\right] d + \text{h.c.},$$

Z3HDM as a relaxed type-II 2HDM

ΔM_{B_q} and $b \to s\gamma$: Decoupling One Charged-Scalar

Parameters of Interest

At the 1-loop level, the relevant parameters for meson oscillations (ΔM_{B_q}) and $b \to s\gamma$ are: $\left(\tan\beta_1, \quad \tan\beta_2, \quad \gamma_2, \quad m_{H_1^+}, \quad m_{H_2^+}\right)$.

- $\tan\beta_1 \gg 1$ $(\tan\beta_1 = 10\ )$
  (relaxed 2HDM-II limit)

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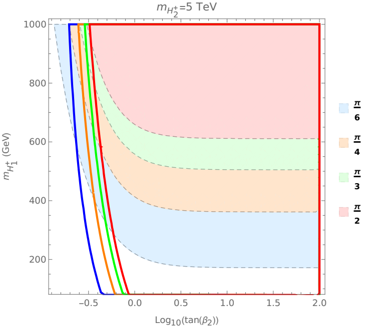

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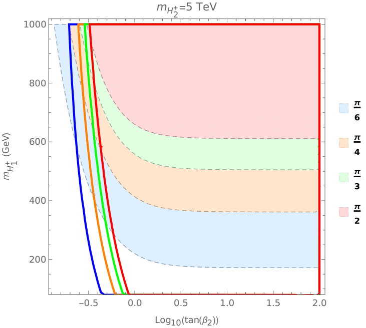
- $\tan\beta_1 \gg 1$ ($\tan\beta_1 = 10$) (relaxed 2HDM-II limit)
- $\tan\beta_2 \gtrsim 1$ (compliance with ΔM_{B_q})
- $\gamma_2 \in [0, \pi/2]$



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  (relaxed 2HDM-II limit)
- $\tan\beta_2 \gtrsim 1$
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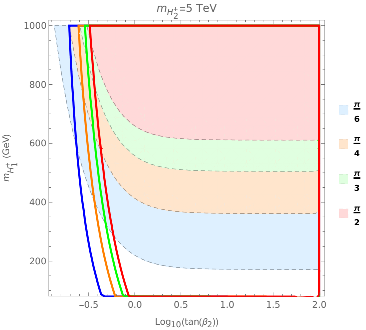
- $\gamma_2 \in [0, \pi/2]$
- Prospects for $m_{H_1^\pm}$, $m_{H_2^\pm}$?

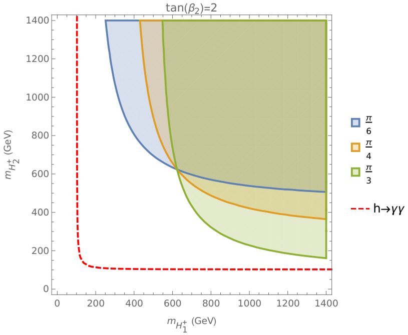


ΔM_{B_q} and $b \to s\gamma$: Charged Scalars Mass Plane

Benchmarks

$$\tan\beta_1 = 10, \quad \tan\beta_2 = 2, \quad \gamma_2 = \pi/3,\, \pi/4,\, \pi/6$$

- Region of Interest in agreement with ΔM_{B_q}
- Safeguarded against $h \to \gamma\gamma$ (using pair-wise degeneracy)
- Relaxed bounds for the charged-scalar masses



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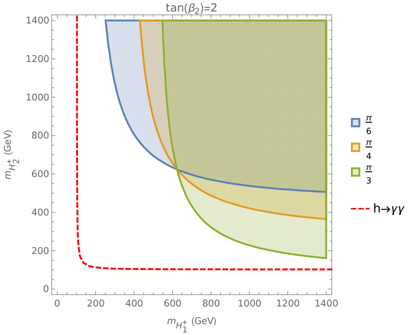


Prospects of Light Charged Scalars

Neutral Nonstandard Masses

Oblique Parameters

In the limit $\gamma_1 = \gamma_2 = -\alpha_3 = \alpha$, we find:

$$\Delta\rho = \frac{g^2}{64\pi^2 m_W^2}\Big\{F\left(m^2_{H_1^+}, m^2_{A_1}\right) + F\left(m^2_{H_2^+}, m^2_{A_2}\right) + F\left(m^2_{H_1^+}, m^2_{H_1}\right) + F\left(m^2_{H_2^+}, m^2_{H_2}\right) - F\left(m^2_{A_1}, m^2_{H_1}\right) - F\left(m^2_{A_2}, m^2_{H_2}\right)\Big\}$$

$$F(x,y) \equiv \begin{cases} \dfrac{x+y}{2} - \dfrac{xy}{x-y}\ln\dfrac{x}{y} & \text{for } x \neq y \\ 0 & \text{for } x = y \end{cases}$$

$$m_{H_i^\pm} \approx M_{H_i} \approx M_{A_i} = M_i \quad \Rightarrow \quad \Delta\rho = 0$$

A Simplified Analysis

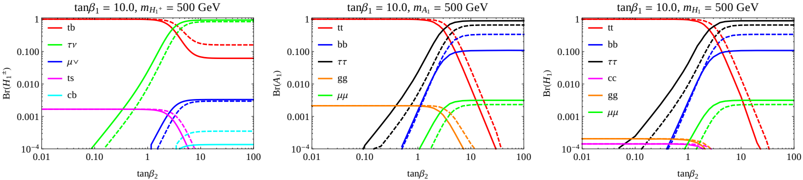
We can impose tier degeneracy, along with $\gamma_1 = \gamma_2 = -\alpha_3$ to easily avoid any constraints from electroweak ρ-parameter constraints.
As a proof-of-concept, we can choose $m_{12}^2, m_{13}^2, m_{23}^2$ in such a way we arrive at:

$$\begin{aligned} V &= m_{11}^2(\phi_1^\dagger\phi_1) + m_{22}^2(\phi_2^\dagger\phi_2) + m_{33}^2(\phi_3^\dagger\phi_3) \\ &\quad - \left(m_{12}^2(\phi_1^\dagger\phi_2) + m_{23}^2(\phi_2^\dagger\phi_3) + m_{13}^2(\phi_1^\dagger\phi_3) + \text{h.c.}\right) \\ &\quad + \lambda(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3)^2 \end{aligned}$$

which is SM-like in its quartic couplings, thus avoiding unitarity and BFB constraints

Direct Searches

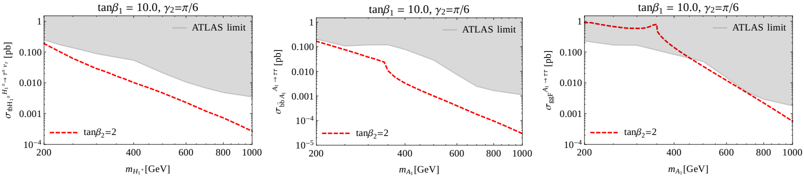
- Assume $m_{H_i} = m_{A_i} = m_{H_i^\pm} = M_i$, and decoupling the heavy states ($M_2 = 5$ TeV)



$\tau\nu$ and $\tau\tau$ are the relevant production channels for the studied parametric space

Direct Searches

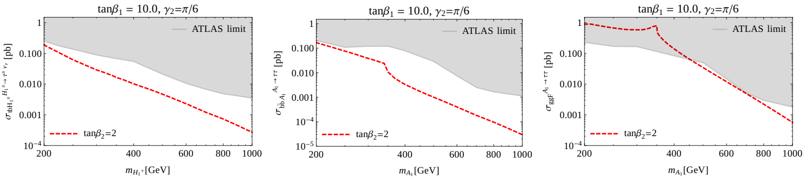
- Assume $m_{H_i} = m_{A_i} = m_{H_i^{\pm}} = M_i$, and decoupling the heavy states ($M_2 = 5$ TeV)
- Given $\tan\beta_1 \gg 1$, the relevant decay channels are $S \to \tau\tau$.
- The most stringent constraints come from $A_1 \to \tau\tau$.



Direct Searches already exclude $M_1 \lesssim 450$ GeV

Direct Searches

- $\Delta\rho = 0$ can be accomodated by other means
- Lifting the tier-wise degeneracy will open new channels $(A_1 \to H_1 Z)$
- Extra channels could be present in extended models (*e.g.*, dark singlets)



Direct Searches bounds can be relaxed!

Summary

Motivation

Z3HDM has a 2HDM-II like yukawa couplings, in the $\tan\beta_1 \gg 1$ limit

Prospects

- Flavour Constraints can be accomadated while evading the $\mathcal{O}(600$ GeV$)$ 2HDM-II limit.
- Direct Searches already start constraining the parameter space
- Extreme values of γ_2 decouple the charged scalars, effectively keeping the flavour constraints in check, while allowing light scalars.

Thank You

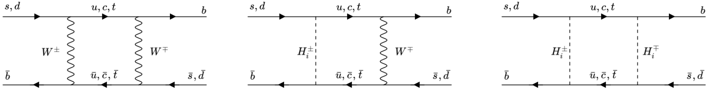
Back Up

$b \to s\gamma$ in NFC Models

$$\frac{\mathrm{Br}\,(b \to s\gamma)}{\mathrm{Br}\,(b \to ce\overline{\nu})} = \frac{6\alpha}{\pi B}\left|\frac{V_{ts}^* V_{tb}}{V_{cb}}\right|^2 \left[\left|C_{7L}^{\mathrm{eff}}\right|^2 + \left|C_{7R}^{\mathrm{eff}}\right|^2\right]$$

$$\begin{aligned}
X_1 &= -\cot\beta_2 \sin\gamma_2,\\
Y_1 &= -\tan\beta_2 \left(\frac{\cot\beta_1 \cos\gamma_2}{\sin\beta_2} + \sin\gamma_2\right),\\
X_2 &= \cot\beta_2 \cos\gamma_2,\\
Y_2 &= -\tan\beta_2 \left(\frac{\cot\beta_1 \sin\gamma_2}{\sin\beta_2} - \cos\gamma_2\right).
\end{aligned}$$

ΔM in NFC Models



$$\mathcal{L}_{\text{eff}}^{\Delta F=2} = \frac{G_F^2 M_W^2}{16\pi^2} \sum_{\substack{a,b=u,c,t \\ i,j=H_1^\pm,H_2^\pm}} \lambda_a \lambda_b \; \omega_a \omega_b \Bigg(\frac{S(y_a, y_b)}{4} + \\ + X_{ia} X_{ib} \Big[I_1(y_a, y_b, y_i) + X_{ja} X_{jb} I_2(y_a, y_b, y_i, y_j) \Big] \Bigg) O_F .$$

$$\lambda_a = \left(V^*_{a\,q_2} V_{a\,q_1} \right), \qquad O_F = (\overline{q}_1 \gamma^\mu P_L q_2)^2 .$$

$$\Delta M_P = 2|M_{12}^P|, \qquad M_{12}^P = -\frac{1}{2M_P} \langle P^0 | \mathcal{L}_{\text{eff}}^{\Delta F=2} | \overline{P}^0 \rangle,$$

$$\langle P^0 | O_F^P | \overline{P}^0 \rangle = \frac{2}{3} f_P^2 M_P^2 B_P,$$