Aspects of Charged Higgs Boson in the 2HDM Doppelganger

The talk is based on arXiv:2011:10926

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The Experimental Limit


- The tree-level vertex $H^+W^-Z$

\[
\mathcal{L}_{H^\pm W^\mp Z} = -g m_Z \xi [W^+_{\mu} Z^{\mu} H^- + \text{h.c.}]
\]

with, \( \xi^2 = \frac{g^2}{4m_W^2} \{ \sum_{T,Y} Y^2 [4T(T+1) - Y^2] |V_{T,Y}|^2 \} - \frac{1}{\rho^2} \) where \( \rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \) and \( V_{T,Y} \) defines the v.e.v of neutral Higgs field.

Ref: The Higgs Hunter’s Guide
The model is a minimal extension of the Standard Model with an extra $SU(2)$ gauge group with the coupling $g_1$.

The symmetry breaking is engineered via two scalar doublets $\Phi_1, \Phi_2$ and a non-linear sigma field $\Sigma$. 
Symmetry Breaking Pattern:

\[ \Sigma = \exp \left( \frac{i\Pi \sigma}{F} \right) \]

\[ \Phi_i = \begin{pmatrix} (f_i + H_i + i\Pi_i^0) / \sqrt{2} \\ i\Pi_i^- \end{pmatrix} \]

\[ \mathcal{L}_{gauge} = \frac{F^2}{2} \text{Tr}[D_\mu \Sigma^\dagger D^\mu \Sigma] + D_\mu \Phi_1^\dagger D_\mu \Phi_1 + D_\mu \Phi_2^\dagger D_\mu \Phi_2 \]
Scalar Sector

- The most general potential for the scalar fields consistent with the gauge symmetries:

\[ V(\Phi_1, \Phi_2, \Sigma) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Sigma \Phi_2 + \text{h.c.}) + \frac{\beta_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\beta_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \beta_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \beta_4 (\Phi_1^\dagger \Sigma \Phi_2)(\Phi_2^\dagger \Sigma^\dagger \Phi_1) + \left[ \frac{\beta_5}{2} (\Phi_1^\dagger \Sigma \Phi_2)^2 + \text{h.c.} \right] \]

- The CP-even Higgs obtain their mass terms from the $\Phi_i^\dagger \Phi_i$ terms.

- On the other hand, the charged Higgs $H^\pm$ mass term solely comes from the $m_{12}^2$, $\beta_4$ and $\beta_3$ term in the potential, while $\beta_5$ terms only contain the interaction terms of pions. The physical charged Higgs boson eigenstate takes the following form

\[ H^\pm = \frac{f}{\sqrt{2v}} \Pi^\pm_1 - \frac{F}{\sqrt{2v}} \Pi^\pm_1 + \frac{f}{\sqrt{2v}} \Pi^\pm_2 \]
Fermion Sector

<table>
<thead>
<tr>
<th></th>
<th>$\psi_{L0}$</th>
<th>$\psi_{L1}$, $\psi_{R1}$</th>
<th>$u_{R2}, d_{R2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SU}(2)_0$</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\text{SU}(2)_1$</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$\text{U}(1)$</td>
<td>$\frac{1}{6}$</td>
<td>$\frac{1}{6}$</td>
<td>$\frac{2}{3}$ or $-\frac{1}{3}$</td>
</tr>
</tbody>
</table>

$$
\mathcal{L}_{\text{fermion}} = -\lambda_{u0}^{ij} \bar{\psi}_{L0} \Phi_1 u_{R2} - \lambda_{d0}^{ij} \bar{\psi}_{L0} \tilde{\Phi}_1 d_{R2} - \lambda_{uR}^{ij} \bar{\psi}_{L1} \Phi_2 u_{R2} - \lambda_{dR}^{ij} \bar{\psi}_{L1} \tilde{\Phi}_2 d_{R2}
$$

$$
\quad - \lambda_L \bar{\psi}_{L0} \Sigma \psi_{R1} - M_D \bar{\psi}_{L1} \psi_{R1} + \text{h.c.}
$$

In leading order, $\lambda_{u0} = \frac{\sqrt{2} m_u}{v \sin \beta}$, which shows that the light fermion couplings to the neutral scalars follow a Type-I 2HDM pattern with appropriate scaling factor w.r.t SM.
<table>
<thead>
<tr>
<th>Vertex</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^\pm W'^{\mp} Z_V$</td>
<td>$\frac{-ie^2 v x^2 \cos \beta \sin \beta}{32 \cos^3 \theta_w}$</td>
</tr>
<tr>
<td>$H^\pm W^{-}_\mu Z_V$</td>
<td>$\frac{-ie^2 v \sin 2\beta \sec \theta_w}{4 \sin^2 \theta_w} \left[1 + \frac{x^2}{4}\right]$</td>
</tr>
<tr>
<td>$H^\pm W'^{-}_\mu Z_V$</td>
<td>$\frac{ie^2 v \sin 2\beta}{4 \sin^2 \theta_w} \left[1 + \frac{x^2}{16} (3 + \cos 2\theta_w) \sec^2 \theta_w\right]$</td>
</tr>
<tr>
<td>$H^\pm W'^{-}_\mu Z'_V$</td>
<td>$\frac{-ie^2 v \tan^2 \theta_w \sin 2\beta}{8 \sin^2 \theta_w} \left[1 + \frac{x^2}{4} \sec^2 \theta_w\right]$</td>
</tr>
<tr>
<td>$H^\pm W^{-}_\mu h$</td>
<td>$\frac{ie \sin \alpha}{8 \sin \theta_w} \left[(4 \cos \beta + \sqrt{2} \sin \beta) + \frac{x^2}{8} (8 \cos \beta - \sqrt{2} \sin \beta)\right] (p_{H^\pm} - p_h)_\mu$</td>
</tr>
<tr>
<td>$H^\pm t\bar{b}$</td>
<td>$-i\lambda_t \cos \beta (1 - \frac{x}{4}) + i\lambda_b \cos \beta (1 - \frac{x^2}{4})$</td>
</tr>
</tbody>
</table>
In the following figure, we display the branching ratio of the Heavy charged Higgs \((m_{H^\pm} > 300\text{GeV})\) into dominant channels for different values of the \(\sin \beta\) with \(\sin \alpha\) fixed at -0.7 and the \(M_{W'}\) fixed at 400 GeV. The choice of the parameter is allowed by the recent Higgs discovery data.
Our model utilizes the aspects of ideal fermion delocalisation to satisfy the precision electroweak bound like the traditional "Higgsless" models. As a result the heavy gauge bosons masses is allowed to be in sub-TeV region.

Due to the low mass value of the heavy gauge bosons, charged Higgs boson reveal cascade kind of decays with multiple gauge bosons in the final state.

As a result, the final state topology of the charged Higgs signature will contain multiple hard leptons and b-quarks.