Two-Higgs doublet models

- The Higgs basis:

\[
\Phi_1 = \left[ \begin{array}{c} \frac{G^+}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} (v + S_1 + iG^0) \end{array} \right] \quad \Phi_2 = \left[ \begin{array}{c} \frac{H^+}{\sqrt{2}} \\ (S_2 + iS_3) \end{array} \right]
\]

- If \( \varphi_i^0(x) = \{h(x), H(x), A(x)\} \Rightarrow \varphi_i^0(x) = \mathcal{R}_{ij} S_j(x) \)

- When the potential is CP-conserving:

\[
\begin{pmatrix} h \\ H \\ A \end{pmatrix} = \begin{pmatrix} \cos \tilde{\alpha} & \sin \tilde{\alpha} & 0 \\ -\sin \tilde{\alpha} & \cos \tilde{\alpha} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix}
\]

- \( \tilde{\alpha} \equiv \alpha - \beta \), \( v = \sqrt{v_1^2 + v_2^2} \approx 246 \text{ GeV} \), \( \tan \beta \equiv v_2/v_1 \).
The general Yukawa Lagrangian in the Higgs basis:

\[
\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{Q}'_L (M'_d \Phi_1 + Y'_d \Phi_2) d'_R + \bar{Q}'_L (M'_u \Phi_1 + Y'_u \Phi_2) u'_R \\
+ \bar{L}'_L (M'_l \Phi_1 + Y'_l \Phi_2) l'_R \right\}
\]

with $M'_f$ and $Y'_f$ complex independent matrices (non simultaneously diagonalizable) ⇒ tree level FCNCs.

One usually imposes a discrete $\mathbb{Z}_2$ symmetry on the Higgs doublets: $\phi_1 \rightarrow \phi_1$, $\phi_2 \rightarrow -\phi_2$ (in a generic basis), etc.

However, a more general approach is to impose alignment in the flavour space: $Y'_f \sim M'_f$. 
Now we can simultaneously diagonalize both matrices and:

\[ Y_{d,l} = \varsigma_{d,l} M_{d,l} \quad \quad Y_u = \varsigma_u^* M_u \]

The Yukawa Lagrangian now reads:

\[
\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[ \varsigma_d V M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \varsigma_l \bar{\nu} M_l \mathcal{P}_R l \right\} \\
- \frac{1}{v} \sum_{\varphi_i^0,f} y_f^\varphi_i^0 \varphi_i^0 \left[ \bar{f} M_f \mathcal{P}_R f \right] + \text{h.c.}
\]

If the Higgs potential is CP-conserving then the neutral Yukawas read:

\[
y_{d,l}^h = \cos \tilde{\alpha} + \varsigma_{d,l} \sin \tilde{\alpha} \quad y_{d,l}^H = -\sin \tilde{\alpha} + \varsigma_{d,l} \cos \tilde{\alpha} \quad y_{d,l}^A = i \varsigma_{d,l} \\
y_{u}^h = \cos \tilde{\alpha} + \varsigma_u^* \sin \tilde{\alpha} \quad y_{u}^H = -\sin \tilde{\alpha} + \varsigma_u^* \cos \tilde{\alpha} \quad y_{u}^A = -i \varsigma_u^*
\]
The complex parameters still allow for new sources of CP-violation in the neutral Yukawa sector:

\[ m_f v \text{Re}(y_\phi f^i) + f^\dagger f \phi_0^i \gamma_5 m_f v \text{Im}(y_\phi f^i) \]

SM: \( \text{Re}(y_\phi f^i) = 1 \) and \( \text{Im}(y_\phi f^i) = 0 \).

For real \( \varsigma_f \) we can recover the usual \( Z_2 \) models:

<table>
<thead>
<tr>
<th>Model</th>
<th>( \varsigma_d )</th>
<th>( \varsigma_u )</th>
<th>( \varsigma_l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>( \cot \beta )</td>
<td>( \cot \beta )</td>
<td>( \cot \beta )</td>
</tr>
<tr>
<td>Type II</td>
<td>( - \tan \beta )</td>
<td>( \cot \beta )</td>
<td>( - \tan \beta )</td>
</tr>
<tr>
<td>Type X</td>
<td>( \cot \beta )</td>
<td>( \cot \beta )</td>
<td>( - \tan \beta )</td>
</tr>
<tr>
<td>Type Y</td>
<td>( - \tan \beta )</td>
<td>( \cot \beta )</td>
<td>( \cot \beta )</td>
</tr>
<tr>
<td>Inert</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
NEUTRAL SECTOR
If $h \rightarrow \gamma \gamma$ excess is "real"

- Complex yukawas
- Flipped sign yukawas

\[ y_u^h = \cos \tilde{\alpha} + \zeta_u^* \sin \tilde{\alpha} \]

\[ \mathcal{L}_{hH^+H^-} = -\nu \lambda_{hH^+H^-} hH^+H^- \]

[A.Pich, A.Celis, V.I. '13]
$\chi^2$ fit, CP-conserving potential & yukawas

- ATHDM and $Z_2$ types with Atlas + Tevatron + CMS: [A.Pich, A.Celis V.I. '13]
Flavour sector

- Flavour constraints on $\varsigma_u$: $R_b$, $\epsilon_K$, $\bar{B} - B$ mixing [A.Pich, M.Jung, P.Tuzon ’10]

- Flavour constraints on $(\varsigma_u, \varsigma_d)$: $B \rightarrow X_s \gamma$
Joining all the relevant constraints \( \text{LHC} + \text{Tevatron} + R_b + B \rightarrow X_s \gamma \), we obtain at 95 % CL:

\[ \text{95}\% \text{ CL} \]

[Victor Ilisie]

[95\% CL LHC, Tevatron, \( R_b \), \( B \rightarrow X_s \gamma \)]

[A.Pich, A.Celis, V.I. '13]
CHARGED SECTOR
Direct $H^\pm$ searches

- Atlas and CMS direct $H^\pm$ searches:

- Limits on: $BR(t \rightarrow H^+ b) \times BR(H^+ \rightarrow c\bar{s}, \tau^+ \nu)$

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Victor Ilisie

Bounds on Neutral and Charged Higgs from the LHC
For the di-quark final state searches, $H^+ \rightarrow c\bar{s}$ is assumed to be the dominant decay rate ($|V_{cb}| << |V_{cs}|$), however in the ATHDM:

$$\frac{\Gamma(H^+ \rightarrow c\bar{b})}{\Gamma(H^+ \rightarrow c\bar{s})} \approx \frac{|V_{cb}|^2 (|\varsigma_d|^2 m_b^2 + |\varsigma_u|^2 m_c^2)}{|V_{cs}|^2 (|\varsigma_d|^2 m_s^2 + |\varsigma_u|^2 m_c^2)}$$

for $|\varsigma_d| >> |\varsigma_u|$ the $H^+ \rightarrow c\bar{b}$ can also contribute.
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[A.Pich, A.Celis, V.I. ’13]

Victor Ilisie

Bounds on Neutral and Charged Higgs from the LHC
When $M_{H^\pm} > M_W + 2m_b$ there is an extra decay mode that can play an important role:

\[ H^+ \rightarrow t^* \bar{b} b \rightarrow W^+ b \bar{b} \]

- It has been previously analysed in MSSM and $\mathbb{Z}_2$ models → important contributions when $M_{H^\pm} \gtrsim 135 - 145$ GeV, depending on the model and on $\tan \beta$.
- In the ATHDM it can bring sizeable contributions $BR \sim 10 - 20\%$ already when $M_{H^\pm} \gtrsim 110$ GeV.
$H^\pm \rightarrow t^* b\bar{b} \rightarrow W^+ b\bar{b}$ decay

- Red: $BR(H^+ \rightarrow W^+ b\bar{b}) > 20\%$, Yellow: $BR(H^+ \rightarrow W^+ b\bar{b}) > 10\%$

Wide regions - partially overlap with the allowed parameter space region from direct searches. Therefore this decay mode should be included for a correct analysis and

The experimental searches should be enlarged by also including this channel!

[A.Pich, A.Celis, V.I. '13]
For a fermiophobic charged Higgs ($\zeta_f = 0$) therefore $H^\pm$ does not couple to fermions at tree level.

All experimental bounds are trivially satisfied; other production channels and decay rates would be needed to prove such a scenario.
BRs and total decay width

- Different mass configurations and couplings

![Graphs showing BRs and total decay width](image-url)
Dominating production modes.

+ QCD corrections
\[ \hat{\sigma}(q_u \bar{q}_d \to H^+ \varphi^0_i) = \frac{g^4 |V_{ud}|^2}{768 \pi N_c \hat{s}^2} \frac{(\mathcal{R}_{i2}^2 + \mathcal{R}_{i3}^2)}{(\hat{s} - M_W^2)^2} \chi^{3/2}(\hat{s}, M_{H^\pm}^2, M_{\varphi^0_i}^2) \]

LO production cross section \( \sigma(pp \to H^+ \varphi^0_i)/R^2 \) at \( \sqrt{s} = 14 \text{ TeV} \) (left), as function of \( M_{H^\pm} \), for different values of \( M_{\varphi^0_i} \). The QCD K factor is shown (right) for \( M_{\varphi^0_i} = 125 \text{ GeV} \) and different choices of \( \mu_R \) and \( \mu_F \).

\[ K_{\text{NLO}} \equiv \sigma_{\text{NLO}}/\sigma_{\text{LO}} \]
If $M_h = 125$ GeV $H$ can reach on-shell region $ightarrow$ estimate $\Gamma_H$

- $\Gamma_H \approx 400, 30 L H_{400,30} L$
- $\Gamma_H \approx 30 L H_{400,150} L$
- $\Gamma_H \approx 150 L H_{400,150} L$
- $\Gamma_H \approx 1 L H_{200,1} L$
- $\Gamma_H \approx 80 L H_{200,80} L$
- $\Gamma_H \approx 150 L H_{150,50} L$
- $\Gamma_H \approx 10^{-3} L H_{150,10^{-3}} L$

If $M_H = 125$ GeV both $h$ and $H$ are always off-shell.
Conclusions

- The $BR(H^\pm)$ depend sensitively on the chosen parameters.

- There are only a few decay channels to be analysed.

- The largest decay widths are the tree-level ones, (on-shell production of scalar bosons).

- Thus, the number of decay channels decreases as the number of neutral scalar bosons that are heavier than the charged Higgs (i.e., $M_{\phi^0_i} > M_{H^\pm}$) increases.

- The $W\gamma$ decay mode can bring sizeable contributions below and close to the the on-shell production threshold of a scalar boson $\phi^0_i$.

- $\tau_{H^\pm}$ is short, ranging from $10^{-11}$ to $10^{-23}$ s → its direct detection very compelling at the LHC.

- If a fermiophobic $H^\pm$ is discovered the precise value of its mass would provide priceless information about all other parameters.

- The masses of the remaining scalars would also be highly constrained by the electroweak oblique parameters.
Backup slides
The one loop corrections introduce some misalignment. Using the renormalization-group equations one finds FCNCs structures:

$$L_{\text{FCNC}} = \frac{C(\mu)}{4\pi^2 v^3} (1 + \zeta_u^* \zeta_d) \sum_i \varphi_i^0 \times$$

$$\times \left\{ (\mathcal{R}_{i2} + i \mathcal{R}_{i3})(\zeta_d - \zeta_u) \left[ \bar{d}_L V^\dagger M_u M_{u}^\dagger V M_d d_R \right] - (\mathcal{R}_{i2} - i \mathcal{R}_{i3})(\zeta_d^* - \zeta_u^*) \left[ \bar{u}_L V M_d M_{d}^\dagger V^\dagger M_u u_R \right] \right\} + \text{h.c.}$$

The leptonic coupling $\zeta_l$ does not introduce any FCNC interaction.

Assuming the alignment to be exact at some scale $\mu_0$ ($C(\mu_0) = 0$), a non-zero value is generated when running to another scale:

$$C(\mu) = -\log(\mu/\mu_0)$$

These effects are very suppressed by $m_q m'_q/v^3$ and by the quark mixing factors, avoiding the stringent experimental constraints.
The $\chi^2$ used for the fit is defined as:

$$
\chi^2 = \sum_{a \neq b} \left( \frac{(\mu_a - \hat{\mu}_a)^2}{\sigma_a^2} + \frac{(\mu_b - \hat{\mu}_b)^2}{\sigma_b^2} - 2\rho_{ab} \frac{(\mu_a - \hat{\mu}_a)(\mu_b - \hat{\mu}_b)}{\sigma_a \sigma_b} \right)
$$

$\hat{\mu}_a$ and $\sigma_a$ are the experimental signal strength and error; $\rho_{ab}$ is the correlation coefficient and:

$$
\mu_a = \frac{\sigma(pp \to \varphi^0_i)}{\sigma(pp \to h)_{SM}} \frac{Br(\varphi^0_i \to a)}{Br(h \to a)_{SM}}
$$

$$
\frac{Br(\varphi^0_i \to a)}{Br(h \to a)_{SM}} = \frac{1}{\rho(\varphi^0_i)} \frac{\Gamma(\varphi^0_i \to a)}{\Gamma(h \to a)_{SM}}
$$

$$
\Gamma(\varphi^0_i) = \rho(\varphi^0_i) \Gamma_{SM}(h) \quad (1)
$$
For THDMs with a general potential $\lambda_{\varphi^0 H^+ H^-}$ is a free parameter. When the potential is CP-conserving ($\lambda_i \in \mathbb{R}$):

$$\lambda_{hH^+ H^-} = \lambda_3 \cos \tilde{\alpha} + \lambda_7 \sin \tilde{\alpha}$$
$$\lambda_{HH^+ H^-} = -\lambda_3 \sin \tilde{\alpha} + \lambda_7 \cos \tilde{\alpha}$$

As it depends on yet unknown parameters we can calculate the one-loop correction:

$$(\lambda_{\varphi^0 H^+ H^-})_{\text{eff}} = \lambda_{\varphi^0 H^+ H^-} (1 + \Delta)$$

and impose $\Delta \leq 50\%$. 


