Charged Higgs and Yukawa Textures

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Plan

1. Multi-Higgs models: Motivations
2. MSSM Higgs sector - THDMII
3. The THDM-III (with Textures)
4. Charged Higgs and top decays
5. Production of $H^\pm$ at Colliders
6. Conclusions.

(Based on Diaz-Cruz et al., PRD09)
1.1 SM Higgs

- Minimal Model: $\Phi = (\phi^+, \phi^0)$,
- SSB induce $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$,
- $W^\pm, Z$ and fermions acquire their masses (Yukawa),
- Remnant of SSB: $\Phi \rightarrow h$, the Higgs boson.
- Rad. Corrs. prefer a light Higgs, with a mass of order of the EW scale ($m_{\phi_{SM}} \simeq v$), LEP limits: $m_h > 114$ GeV.
- LHC will probe the Higgs sector soon,
1.2 Scenarios of New Physics

Open problems in the SM suggest the need for New Physics:

- Large/Little hierarchy problem,
- Neutrino masses,
- Strong CP problem,
- Dark Matter,
- Cosmological constant (Dark energy),
- Some deviations from the SM (a few std. dev.), e.g. $\Delta a_\mu$, etc.
- Aesthetical questions,
1.2b Scenarios of New Physics

Models of New Physics often → Multi-Scalar models:

• Hierarchy problem  
  → SUSY → Two-Higgs doublet model

• Neutrino masses  
  → Radiative → Higgs triplets  
  → LR models → Higgs triplets, doublets and bi-doublets

• Strong CP problem  
  → PQ → Two-Higgs doublet model

• Dark Matter  
  → MDM → Scalar DM,
1.3 Proposals to understand EWSB-Hierarchy problem

- **Weakly interacting EWSB:**
  
  Need a symmetry to stabilize elementary Higgs boson

  e.g. SUSY $\rightarrow$ MSSM $\rightarrow$ mSUGRA, ...

- **Strongly Interacting EWSB:**

  Composite $W^\pm, Z^0$ $\rightarrow$ e.g. Technicolor, ETC,WTC...

  Composite Higgs models $\rightarrow$ e.g. PGB Higgs (4D)

  Another possibility: Accidental Cancellacion,

  $$\lambda = y_t^2 - \frac{1}{8} [3g^2 + g'^2]$$ (1)
2.1 SUSY

Why is SUSY attractive?

• Offers the possibility to stabilize the Higgs mass and EWSB,
• Improves Unification and o.k. with proton decay,
• Favors a light Higgs boson, in agreement with EWPT, i.e. $m_h \leq 180$ GeV,
• New sources of flavor and CP violation may help to get the right BAU,
• LSP is stable and Dark matter candidate.
2.2 The MSSM

The minimal extension of the SM consistent with SUSY, is based on:

- SM Gauge Group (→ gauge bosons and gauginos),
- 3 families of fermions and sfermions,
- Two Higgs doublets,
- Soft-breaking of SUSY,
- R-parity distinguish SM and their superpartners → LSP is stable and DM candidate.
### 2.3 The MSSM particle content

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>Superpartners</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SM Bosons</strong></td>
<td>$W^\pm, Z, \gamma$</td>
<td>Wino, Zino, Photino</td>
</tr>
<tr>
<td></td>
<td>gluon</td>
<td>gluino</td>
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<tr>
<td></td>
<td>Higgs bosons</td>
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<tr>
<td><strong>SM Fermions</strong></td>
<td>quarks</td>
<td>squarks</td>
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<tr>
<td></td>
<td>leptons</td>
<td>sleptons</td>
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<tr>
<td></td>
<td>neutrinos</td>
<td>sneutrinos</td>
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</tbody>
</table>

Mixing of gauginos and Higgsinos →
Charginos ($\chi_i^{\pm}, i = 1, 2$) and
Neutralinos ($\chi_j^0, j = 1, 4$),

Gravitino may also play a role.
2.4 The MSSM-THDM2 sector

At tree-level MSSM Higgs sector is of type-II, i.e. each doublet couples only to one type (u or d) quark.

- CP-even neutral Higgs bosons $h^0, H^0$,
  Stop-top loops needed for: $m_h > m_Z$ (LEP limits),
- CP-odd neutral Higgs $A^0$ with $m_H^2 = m_A^2 + m_Z^2 \sin^2 2\beta$,
- Charged Higgs $H^{\pm}$, with $m_{H^+}^2 = m_A^2 + m_W^2$,
- Masses and mixing angles fixed with:
  $m_A$ and $\tan\beta = v_2/v_1$,
- When $m_A \leq \tilde{m}$, Higgs search uses SM techniques.
- But $H^0, A^0, H^\pm$ may decay into SUSY modes; LHC search gets more complicated!
2.5 MSSM neutral Higgs couplings:

- \((hvV)\) : \(\frac{2m_V^2}{v} \cos(\beta - \alpha)\), \(v^2 = v_1^2 + v_2^2\),

- \((huu)\) : \(\frac{m_u}{v} \left(\frac{\cos \alpha}{\sin \beta}\right)\),

- \((hdd)\) : \(\frac{m_d}{v} \left(\frac{\sin \alpha}{\cos \beta}\right)\),

- \((hll)\) : \(\frac{m_l}{v} \left(\frac{\sin \alpha}{\cos \beta}\right)\),

- \((hhh)\) : \(\sim \lambda v\), \(\lambda = \frac{g^2 + g'^2}{8}\),

- \((hhhh)\) : \(\sim \lambda\).

Similar expressions hold for \(H^0, A^0\).
2.6 Charged Higgs-Fermions coupling

- **MSSM charged state** $H^\pm$ has $m_{H^\pm} > m_W$
- Its couplings with fermions is given by:

$$\mathcal{L}_{H^+ \bar{u}_i d_j} = -\frac{ig}{2\sqrt{2}M_W} (S_{ij} + P_{ij} \gamma_5),$$

where:

$$S_{ij} = (V_{CKM})_{il} m_{di} X_{lj} + m_{ui} Y_{il} (V_{CKM})_{lj}$$

$$P_{ij} = (V_{CKM})_{il} m_{di} X_{lj} - m_{ui} Y_{il} (V_{CKM})_{lj}.$$ 

with

$$X_{lj} = \tan \beta \delta_{lj}, \quad Y_{il} = \cot \beta \delta_{il}.$$
Rare B decays have been used to constrain the Neutral and Charged Higgs sector in SUSY (and BSM)

- $B.R. (B \to X_s + \gamma)_{\text{exp.}} = (3.55 \pm 0.24) \times 10^{-4}$:
  (SM prediction: $B.R. = (3.15 \pm 0.23) \times 10^{-4}$)

- $B.R. (B_s \to \mu\mu)_{\text{exp.}} \leq 5.8 \times 10^{-8}$:
  (SM prediction: $B.R. (B_s \to \mu\mu) = 3 \times 10^{-9}$)

- $B \to \tau\nu$, $B \to \mu\nu$,

- $B \to D\tau\nu$

- $\tau \to \mu\nu\nu$
2.8 Flavor and Higgs

![Graph showing 95% CL excluded regions for various decay modes.]

- $\beta\tan(10)$ in [GeV]
- LEP 95% CL exclusion
- 95% CL excluded regions
- Combined fit (toy MC)
2.9 Charged Higgs at Colliders

- Tevatron has searched for the decay $t \to bH^+$, its non-observation implies $m_{H^\pm} > m_t - m_b$, which is satisfied for some regions of MSSM params.,
- More recently, Tevatron has searched for $qq' \to H^+ \to tb$, but its sensitivity only probes some region of params.
- LHC will be able to search for a charged Higgs,
- Interesting to study how to distinguish MSSM charged Higgs from THDM-II,
2.9b Top decay to $H^\pm + b$ at Tevatron

![Graph showing the exclusion limits for $H^\pm + b$ decay](image)
2.9c Charged Higgs search at Tevatron

95% CL Upper Limit on 2HDM Type-II $H^+$ Production

Expected limit (all $\tan \beta$)

Observed limit (all $\tan \beta$)

Theory $\sigma(q\bar{q}\rightarrow H^+\rightarrow tb)$
($\tan \beta = 0.1$)

DØ preliminary $0.9 \text{ fb}^{-1}$
2.10 Charged Higgs search at LHC

![Graph showing charged Higgs search at LHC](image)

**CMS, 100 fb^{-1}**

- Maximal stop mixing
- $H,A \rightarrow \tau \tau \rightarrow l+\tau \text{ jet}+X$, 30 fb^{-1}

**Excluded by LEP**

$m_A (GeV)$ vs. $\tan \beta$
3.1 Charged Higgs within the THDM-III

In THDM-III $\Phi_{1,2}$ couple to both d- and u-type quarks:

- FC Neutral Higgs interactions are induced at tree-level,
- Fermion mass textures keep under control FCNC,
  A four-texture THDM3 satisfies all constraints, i.e.
  Higgs-fermion coupling $Y_{ij} \sim \frac{(m_i m_j)^{1/2}}{v}$ (Cheng-Sher)
- Interesting to study Charged Higgs III (flavor and LHC),
  because MSSM-THDM2 becomes a THDM3 after rad. corrs.
3.1b The THDM-III

THDM3 is useful, cheap, economical.....and takes you almost everywhere.
### 3.2 THDM-III Lagrangian

When both $\Phi_{1,2}$ couple to u- and d-type quarks, the charged Higgs-fermion interaction becomes:

$$\mathcal{L} = Y^u_1 \bar{Q}_L \tilde{\Phi}_1 u_R + Y^u_2 \bar{Q}_L \tilde{\Phi}_2 u_R + Y^d_1 \bar{Q}_L \Phi_1 d_R + Y^d_2 \bar{Q}_L \Phi_2 d_R,$$

where

$\Phi_{1,2} = (\phi_{1,2}^+, \phi_{1,2}^0)^T$ refer to the two Higgs doublets,

$\tilde{\Phi}_{1,2} = i \sigma_2 \Phi_{1,2}^*$;

$Q_L$ is the left-handed fermion doublet, $u_R$ and $d_R$ are the right-handed singlets,

$Y^{u,d}_{1,2}$ denote the $(3 \times 3)$ Yukawa matrices.
3.2b THDM-III Lagrangian

Consider Yukawa matrices with four-Hermitic-texture form (Fritzsch-Xing):

\[
M^q = \begin{pmatrix}
0 & C_q & 0 \\
C_q^* & \tilde{B}_q & B_q \\
0 & B_q^* & A_q
\end{pmatrix}
\] (q = u, d),

(2)

To diagonalize them, use matrices \(O_q\) and \(P_q\):

\[
\bar{M}^q = O_q^T P_q M^q P_q^T O_q
\]

(3)

Then, write \(\tilde{Y}_n^q = O_q^T P_q Y_n^q P_q^T O_q\), in the form,

\[
\begin{pmatrix}
\tilde{Y}_n^q
\end{pmatrix}_{ij} = \sqrt{\frac{m_i^q m_j^q}{v}} \begin{pmatrix}
\tilde{\chi}_n^q
\end{pmatrix}_{ij} = \frac{1}{v} \sqrt{\frac{m_i^q m_j^q}{v}} \begin{pmatrix}
\chi_n^q
\end{pmatrix}_{ij} e^{i\varphi_{ij}^q}
\]

(4)
3.2c THDM-III Lagrangian

Then, $\bar{u}_i d_j H^+$ and $u_i \bar{d}_j H^-$ couplings are written in terms of:

\[
S_{ij} = (V_{CKM})_{il} m_{d_l} X_{lj} + m_{u_i} Y_{il} (V_{CKM})_{lj}
\]

\[
P_{ij} = (V_{CKM})_{il} m_{d_l} X_{lj} - m_{u_i} Y_{il} (V_{CKM})_{lj}.
\]

\[
X_{lj} = \left[ \tan \beta \delta_{lj} - \frac{\sec \beta}{\sqrt{2}} \sqrt{\frac{m_{d_l}}{m_{d_l}}} \tilde{\chi}_{dlj} \right],
\]

\[
Y_{il} = \left[ \cot \beta \delta_{il} - \frac{\csc \beta}{\sqrt{2}} \sqrt{\frac{m_{u_l}}{m_{u_l}}} \tilde{\chi}_{uil} \right].
\]

The 33 elements are the parameters $X = X_{33}, Y = Y_{33}$, and $Z = Z_{33}$, used in literature.
3.3 THDM-III Lagrangian

- Based on the analysis of $B \to X_s \gamma$ (Borzumati and Greub), it is claimed that $X \leq 20$ and $Y \leq 1.7$ for $m_{H^+} > 250$ GeV (Xiao-Guo), while for a lighter charged Higgs boson mass $m_{H^+} \sim 200$ GeV, one gets: $(X, Y) \leq (18, 0.5)$.

- Next Figure shows $(X, Y)$ as a function of $\tan \beta$ within our model.

- Then, we find the bounds: $|\chi_{33}^{u,d}| \leq 1$ for $0.1 < \tan \beta \leq 70$.

- In summary, we find that low energy constraints still allow to have $\tilde{\chi}_{ij}^q = O(0.1 - 1)$.
3.4 THDM-III Lagrangian

\[ \begin{align*}
X_{33} & \quad \chi_{33} = 1 \\
& \quad \chi_{33} = 0.1 \\
& \quad \chi_{33} = -0.1 \\
& \quad \chi_{33} = -1 \\
Y_{33} & \quad \tan \beta
\end{align*} \]

\[ \begin{align*}
X_{23} & \quad \chi_{23} = 1 \\
& \quad \chi_{23} = 0.1 \\
& \quad \chi_{23} = -0.1 \\
& \quad \chi_{23} = -1 \\
Y_{23} & \quad \tan \beta
\end{align*} \]
4.1 Charged Higgs decays

We shall refer to four benchmark scenarios, namely.

- **Scenario A**: $\tilde{\chi}^u_{ij} = 1, \tilde{\chi}^d_{ij} = 1;$
- **Scenario B**: $\tilde{\chi}^u_{ij} = 0.1, \tilde{\chi}^d_{ij} = 1;$
- **Scenario C**: $\tilde{\chi}^u_{ij} = 1, \tilde{\chi}^d_{ij} = 0.1;$
- **Scenario D**: $\tilde{\chi}^u_{ij} = 0.1, \tilde{\chi}^d_{ij} = 0.1.$

For the numerical results of $H^\pm$ decays we take:

- $\tan \beta = 0.1, 1, 15, 70,$
- $100 \text{ GeV} \leq m_{H^\pm} \leq 1000 \text{ GeV},$ and fixing
- $m_{h^0} = 120 \text{ GeV}, m_{A^0} = 300 \text{ GeV}$ and the mixing angle $\alpha = \pi/2.$
4.2a Charged Higgs decays
4.2b Charged Higgs decays

![Graphs showing charged Higgs decays](image)
4.3c Top decay into $H^+$
4.3d Top decay into $H^+$
4.3e Top decay into $H^+$

![Graph showing the branching ratio (BR) of top decay into $H^+$ as a function of $m_{H^+}$ for different values of $\tan\beta$. The graphs show the BR (t → $H^+b$) and BR (t → $H^+s$) for $m_{H^+}$ ranging from 100 to 160 GeV. Different lines represent different values of $\tan\beta$: $\tan\beta = 0.1$, $\tan\beta = 1$, $\tan\beta = 15$, and $\tan\beta = 70$.]

Charge Higgs and Yukawa Textures – p. 31
5.1 s-channel Charged Higgs production

- Because in THDM3 the coupling Hcb can be enhanced, it can affect the reaction $c b \rightarrow H^+$. 
- This reaction has been searched at Tevatron, with $H^+ \rightarrow t b$, 
- We have studied this s-channel reaction at LHC, 
- At LHC other decay modes could be searched, e.g. $H^+ \rightarrow W h$. 
5.2 Charged Higgs search at Tevatron

95% CL Upper Limit on 2HDM Types-I & -III $H^+$ Production

$\sigma(p\bar{p}\rightarrow H^+\rightarrow tb)$
($\tan\beta = 30$)

Type-I
Type-III

Expected limits

Observed limits

$D\emptyset$ preliminary 0.9 fb$^{-1}$
5.3 s-channel Charged Higgs production at LHC

\[ \sigma \left( pp \rightarrow H^+ + X \right) \text{(pb)} \]

- \( \tan \beta = 0.1 \)
- \( \tan \beta = 1 \)
- \( \tan \beta = 15 \)
- \( \tan \beta = 70 \)

s=14 TeV

\[ m_{H^+} \text{(GeV)} \]
5.2b s-channel Charged Higgs production at LHC

\[ \sigma \left( \mathrm{pp} \rightarrow H^+ + X \right) (\text{pb}) \]

- \[ \tan \beta = 0.1 \]
- \[ \tan \beta = 1 \]
- \[ \tan \beta = 15 \]
- \[ \tan \beta = 70 \]

\( s = 14 \text{ TeV} \)

\( m_{H^+} \) (GeV)
5.3 Associated Charged Higgs production at LHC

- if the charged Higgs boson mass $m_{H^\pm}$ satisfies $m_{H^\pm} < m_t - m_b$, $H^\pm$ could be produced in the decay of on-shell (i.e., $\Gamma_t \rightarrow 0$) top (anti-)quarks $t \rightarrow bH^\pm$,

- We denote such a $H^\pm$ production channel as $q\bar{q}$, $gg \rightarrow tt \rightarrow t\bar{b}H^- + \text{c.c.}$ (i.e., if due to (anti-)top decays) whilst we use the notation $q\bar{q}$, $gg \rightarrow t\bar{b}H^- + \text{c.c.}$

- Charged Higgs bosons could also be produced at and beyond the kinematic top decay threshold.
5.4a Associated Charged Higgs production at LHC

![Graph showing the cross-section (σ) as a function of charged Higgs mass (m_{H^\mp}) for different tanβ values.](image)
5.4b Associated Charged Higgs production at LHC
5.bc Associated Charged Higgs production at LHC

![Graph showing charged Higgs production cross-section as a function of $m_{H^+}$ (GeV) for different values of $\tan\beta$. The graph includes curves for $\tan\beta = 0.1$, $\tan\beta = 1$, $\tan\beta = 15$, and $\tan\beta = 70$. The cross-section is given in pb (picobarns).]
5.4d Associated Charged Higgs production at LHC
5. Conclusions

- Worth studying $H^\pm$ within THDM-III.
- Rare B decays have been used to constrain the Neutral and Charged Higgs sector in SUSY (and BSM).
- Charged Higgs and top decays were evaluated,
- Very interesting signal: $cb \rightarrow H^+ \rightarrow W + h^0$ THDM-III rates can be very large, and thus the discovery potential in ATLAS and CMS can be substantial.
- Associated production of $H^\pm$ within THDM3 can be different from THDM2,
- Realistic simulations are to be studied.