Charged Higgs boson phenomenology in Supersymmetric models with Higgs triplets

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**Outline**

- **Introduction**

- **One SUSY model beyond the MSSM**

  Two doublets and a complex Higgs Triplet (MSSM+1CHT)

  Some systematic studies of model

  - The Higgs spectrum and parameters of the model.
  - One-loop radiative corrections to the CP-even Higgs bosons masses and to the coupling $ZZH^0_i$.
    - The vertex $H+i\, fu\, fd$ and the decay $t \rightarrow Hi+b$.
  - Decays of charged Higgs bosons.
  - Direct charged Higgs production at the LHC.
  - Charged Higgs bosons event rates at the LHC.

- **Conclusions**
Introduction

EWSB dynamics in SM unsatisfactory:

Theory: Higgs boson mass is unstable under radiative corrections (hierarchy problem)

Experiment: no Higgs evidence so far

Hence, it is quite appropriate to explore implications of more complicated Higgs models!

Two major constraints to go beyond the SM:

1. The experimental fact that

\[ \rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \approx 1 \]

2. Limits on the existence of FCNCs

1&2 are not a problem in the SM and for any additional singlets!
Motivations

**Standard Model:** 1 doublet of scalar fields (spontaneous ew symmetry breaking)
→ 1 neutral scalar particle is predicted: the Higgs boson $H^0$

**Simple extension of the Higgs sector:** 2 doublets of scalar fields (SUSY)
→ 5 Higgs bosons are predicted
- 3 neutral ($h^0, H^0, A^0$)
- 1 pair of charged bosons $H^\pm$

at tree-level, Higgs sector defined by $(M_{A^0}, \tan \beta)$

**Observation of $H^\pm$:** important role in the proof of an extended SM Higgs sector

**MSSM Charged Higgs**
LEP limit: $M_{H^\pm} > 78.6$ GeV (model independent)
Electroweak $\rho$ parameter is experimentally close to 1 constraints on Higgs representations

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \approx 1,$$

$$V_{T,Y} = \langle \phi(T,Y) \rangle, \quad c_{T,Y} = \begin{cases} 1, & (T,Y) \in \text{complex representation} \\ \frac{1}{2}, & (T,Y) \in \text{real representation} \end{cases}$$

Real representation: consists of a real multiplet of fields with integer weak isospin and zero hypercharge

One can choose arbitrary Higgs representations and fine tune the Higgs potential parameters to produce $\rho \approx 1$.

Take a model with multiple `bad' Higgs representations and arrange `custodial' SU(2) symmetry among the copies (i.e., VEVs arranged suitably), so that $\rho=1$ at tree-level. This can be done for triplets.
Absence of (tree-level) FCNCs

In SM FCNC automatically absent as same operation diagonalising the mass matrix automatically diagonalises the Higgs-fermion couplings.

There are two ways:

Make Higgs masses large (1 TeV or more) so that tree-level FCNCs mediated by Higgs are suppressed to comply with experimental data.

Glashow & Weinberg theorem (more elegant): FCNCs absent in models with more than one Higgs doublet if all fermions of a given electric charge couple to no more than one Higgs doublet.

(MSSM is an example: $Y=-1(+1)$ doublet couples to down(up)-type fermions, as required by SUSY.)
• The Higgs spectrum of many extensions of SM include H+, whose detection would constitute a clear evidence of a Higgs sector beyond SM.

• A definitive test of the mechanism of EWSB will require further studies of complete Higgs spectrum.

• Probing the properties of H+ could help to find out whether they are associated with a weakly-interacting theory or with a strongly-interacting theory.

• Probing the symmetries of the Higgs potential could help to determine whether the H+ belong to a weak doublet or to some larger multiplet.

• The MSSM+1CHT is one of the simplest extensions of the MSSM that allows one to study phenomenological consequences of an explicit breaking of the custodial $SU(2)_c$ symmetry.
A. The Higgs potential of the model

The MSSM+1CHT model includes two Higgs doublets and a complex Higgs triplet given by

$$\Phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^- \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}, \quad \Sigma = \begin{pmatrix} \sqrt{\frac{1}{2}} \xi^0 & -\xi^+ \\ \xi^- & -\sqrt{\frac{1}{2}} \xi^0 \end{pmatrix}. \quad (1)$$

The Higgs triplet, of zero hypercharge, is described in terms of a $2 \times 2$ matrix representation: $\xi^0$ is the complex neutral field and $\xi^-, \xi^+$ denote the charged fields. The most general gauge invariant and renormalizable Superpotential that can be written for the Higgs Superfields $\Phi_{1,2}$ and $\Sigma$ is given by:

$$W = \lambda \Phi_1 \cdot \Sigma \Phi_2 + \mu_1 \Phi_1 \cdot \Phi_2 + \mu_2 \text{Tr}(\Sigma^2), \quad (2)$$

where we have used the notation $\Phi_1 \cdot \Phi_2 \equiv \epsilon_{ab} \Phi_1^a \Phi_2^b$. The resulting scalar potential involving only the Higgs fields is thus written as

$$V = V_{SB} + V_F + V_D,$$
where $V_{SB}$ denotes the most general soft-Supersymmetry breaking potential, which is given by

$$V_{SB} = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 + m_3^2 Tr(\Sigma^\dagger \Sigma)$$

$$+ [A\lambda\Phi_1 \cdot \Sigma\Phi_2 + B_1\mu_1 \Phi_1 \cdot \Phi_2 + B_2\mu_2 Tr(\Sigma^2) + h.c.], \quad (3)$$

$V_F$ is the SUSY potential from F-terms

$$V_F = \left| \mu_1 \phi_2^0 + \lambda \left( \phi_2^+ \xi_1^- - \frac{1}{\sqrt{2}} \phi_2^0 \xi_1^0 \right) \right|^2 + \left| \mu_1 \phi_1^0 + \lambda \left( \phi_1^- \xi_2^+ - \frac{1}{\sqrt{2}} \phi_1^0 \xi_1^0 \right) \right|^2$$

$$+ \left| \mu_1 \phi_2^+ + \lambda \left( \frac{1}{\sqrt{2}} \phi_2^0 \xi_0^0 - \phi_2^0 \xi_2^+ \right) \right|^2 + \left| \mu_1 \phi_1^- + \lambda \left( \frac{1}{\sqrt{2}} \phi_1^- \xi_0^0 - \phi_1^0 \xi_1^- \right) \right|^2$$

$$+ \left| 2\mu_2 \xi_0^0 - \frac{\lambda}{\sqrt{2}} \left( \phi_1^0 \phi_2^0 + \phi_1^- \phi_2^+ \right) \right|^2 + \left| \lambda \phi_1^0 \phi_2^+ - 2\mu_2 \xi_2^+ \right|^2 + \left| \lambda \phi_1^- \phi_2^0 - 2\mu_2 \xi_1^- \right|^2 \quad (4)$$
\[ V_D \text{ is the SUSY potential from D-terms} \]

\[ V_D = \frac{g^2}{8} \left[ |\phi_1^0|^2 - |\phi_1^-|^2 + |\phi_2^+|^2 - |\phi_2^0|^2 + 2|\xi_2^+|^2 - 2|\xi_1^-|^2 \right]^2 \]

\[ + \frac{g'^2}{8} \left[ |\phi_1^0|^2 + |\phi_1^-|^2 - |\phi_2^-|^2 - |\phi_2^0|^2 \right]^2 \]

\[ + \frac{g^2}{8} \left[ \phi_1^{0*} \phi_1^- + \phi_2^{+*} \phi_2^0 + \sqrt{2}(\xi_2^+ + \xi_1^-)\xi_0^* + h.c. \right]^2 \]

\[ - \frac{g^2}{8} \left[ \phi_1^{-*} \phi_1^0 + \phi_2^{0*} \phi_2^- + \sqrt{2}(\xi_2^- - \xi_1^-)\xi_0^* - h.c. \right]^2. \]

(5)

In turn, the full scalar potential can be split into its neutral and charged parts, i.e., \( V = V_{\text{charged}} + V_{\text{neutral}} \) [10, 11].


the physical charged Higgs bosons \( (H_1^+, H_2^+, H_3^+) \) and the
Goldstone boson \( G_0^+ \) (which gives mass to the \( W^+ \))
are related with the fields: \( \phi_2^+, \phi_1^{-*}, \xi_2^+ \) and \( \xi_1^{-*}, \)

\[
\begin{pmatrix}
\phi_2^+ \\
\phi_1^{-*} \\
\xi_2^+ \\
\xi_1^{-*}
\end{pmatrix}
= 
\begin{pmatrix}
U_{11} & U_{12} & U_{13} & U_{14} \\
U_{21} & U_{22} & U_{23} & U_{24} \\
U_{31} & U_{32} & U_{33} & U_{34} \\
U_{41} & U_{42} & U_{43} & U_{44}
\end{pmatrix}
\begin{pmatrix}
G^+ \\
H_1^+ \\
H_2^+ \\
H_3^+
\end{pmatrix}.
\]
\((H_1^0, H_2^0, H_3^0)\), the physical pseudoscalars \((A_1^0, A_2^0)\) and Goldstone boson \(G^0\) (which gives mass to the \(Z^0\)), with the real and imaginary parts of the fields \(\phi_1^0, \phi_2^0, \xi^0\), in the following way.

\[
\begin{pmatrix}
\sqrt{\frac{1}{2}} \text{Re}(\phi_1^0) \\
\sqrt{\frac{1}{2}} \text{Re}(\phi_2^0) \\
\sqrt{\frac{1}{2}} \text{Re}(\xi^0)
\end{pmatrix} = 
\begin{pmatrix}
V_{11}^S & V_{12}^S & V_{13}^S \\
V_{21}^S & V_{22}^S & V_{23}^S \\
V_{31}^S & V_{32}^S & V_{33}^S
\end{pmatrix}
\begin{pmatrix}
H_1^0 \\
H_2^0 \\
H_3^0
\end{pmatrix}.
\]

\[
\begin{pmatrix}
\sqrt{\frac{1}{2}} \text{Im}(\phi_1^0) \\
\sqrt{\frac{1}{2}} \text{Im}(\phi_2^0) \\
\sqrt{\frac{1}{2}} \text{Im}(\xi^0)
\end{pmatrix} = 
\begin{pmatrix}
V_{11}^{PS} & V_{12}^{PS} & V_{13}^{PS} \\
V_{21}^{PS} & V_{22}^{PS} & V_{23}^{PS} \\
V_{31}^{PS} & V_{32}^{PS} & V_{33}^{PS}
\end{pmatrix}
\begin{pmatrix}
A_1^0 \\
G^0 \\
A_2^0
\end{pmatrix}.
\]
We can combine the VEVs of the doublet Higgs fields through the relation
\[ v_D^2 \equiv v_1^2 + v_2^2 \] and define \( \tan \beta \equiv v_2/v_1 \). Furthermore, the parameters \( v_D, v_T, m_W^2 \) and \( m_Z^2 \) are related as follows:

\[
m_W^2 = \frac{1}{2} g^2 (v_D^2 + 4v_T^2),
\]
\[
m_Z^2 = \frac{1}{2} g^2 \frac{v_D^2}{\cos^2 \theta_W},
\]

which implies that the \( \rho \)-parameter is different from 1 at the tree level, namely,

\[
\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1 + 4R^2, \quad R \equiv \frac{v_T}{v_D}.
\] (6)

The bound on \( R \) is obtained from the \( \rho \) parameter measurement, which presently lies in the range 0.9993–1.0006, from the global fit reported in Refs. [6, 23]. Thus, one has \( R \leq 0.012 \) and \( v_T \leq 3 \) GeV. We have taken into account this bound in our numerical analyses.
MSSM+1CHT Higgs Sector

A total of 14 d.o.f to start with, minus 3 longitudinal modes for W’s & Z leaves 11 d.o.f which corresponds to:

- 3 CP-even neutral Higgs states
- 2 CP-odd neutral Higgs states
- 6 C.C. charged Higgs states (3 masses)

The parameters of the Higgs sector include:
- gauge: \( r = \frac{v_T}{v_D} \) and \( \tan \beta = \frac{v_2}{v_1} \)
- superpotential: \( \lambda, \mu_D, \mu_T \)
- soft: \( A, B_D, B_T \)

In our numerical analysis we shall fix:
\( r = 0.012, 1.5 < \tan \beta < 70 \), and
\( \lambda = 0.1, 0.5, 1. \) ,

Then we shall define several scenarios according to:
Scenario A: \( B_D = \mu_D = 0, B_T = -A, \mu_T = 100 \) GeV,
Scenario B: \( B_T = \mu_T = 0, B_D = -A, \mu_D = 100 \) GeV,
Scenario A. It is defined by considering $B_1 = \mu_1 = 0$, $B_2 = -A$ and $\mu_2 = 100$ GeV while for $\lambda$ we shall consider the values $\lambda = 0.1, 0.5, 1.0$. In this scenario it happens that the additional Higgs triplet plays a significant role in EWSB.

Scenario B. This scenario is defined by choosing: $B_2 = \mu_2 = 0$, $B_1 = -A$, while for $\lambda$ we shall consider again the values $\lambda = 0.1, 0.5, 1.0$. Most results will take $\mu_1 = 200$ GeV, though other values (such as $\mu_1 = 400, 700$ GeV) will also be considered. Here, the effects of the additional Higgs triplet are smaller, hence the behaviour of the model is similar to that of the MSSM.

One-loop radiative corrections to the CP-even Higgs bosons masses in the MSSM-1CHT

We study the radiative corrections to the neutral Higgs boson masses because of their appearance in charged Higgs decays.

In some scenarios, at tree level we have a very light CP-even Higgs boson, $O(0.1)$ GeV.

• However, in the MSSM, the inclusion of radiative corrections from top and stop loops can alter the neutral CP-even Higgs mass.

• Thus, we can expect that similar effects will appear in the MSSM-1CHT.

• Besides, a possible large correction from Higgs-chargino loops must be considered.

The radiative corrections to Supersymmetric Higgs boson masses can be evaluated using the effective potential technique [24], which at one-loop reads:

\begin{equation}
V_1(Q) = V_0(Q) + \Delta V_1(Q),
\end{equation}

\begin{equation}
\Delta V_1(Q) = \frac{1}{64\pi^2} \text{Str} M^4 \left( \log \frac{M^2}{Q^2} - \frac{3}{2} \right),
\end{equation}

where \( V_0(Q) \) is the tree-level potential evaluated with couplings renormalized at some scale \( Q \), \( \text{Str} \) denotes the conventional Supertrace and \( M^2 \) is the mass matrix for the CP-even sector.

It happens that the squared-mass matrix of the CP-even Higgs bosons only gets corrected along its (1, 1) and (2, 2) elements, given as follows:

\begin{equation}
(\Delta M^2_S)_{1,1} = \frac{3}{8\pi^2} \lambda_b^2 m_b^2 \log \frac{m_b^4}{m_b^4},
\end{equation}

\begin{equation}
(\Delta M^2_S)_{2,2} = \frac{3}{8\pi^2} \lambda_t^2 m_t^2 \log \frac{m_t^4}{m_t^4},
\end{equation}
the fermionic partner of the Higgs Superfields, which includes the Higgs-Higgsino triplets, because there is a potentially large effect emerging in the calculation of the squared-mass matrix of the CP-even Higgs bosons when the parameter $\lambda$ is large. Similarly to the top-stop and bottom-sbottom corrections, we estimate that the correction from the Higgs-Higgsino only modifies the element $(M_S^2)_{3,3}$

$$(\Delta M_S^2)_{3,3} = \frac{3}{8\pi^2} \lambda^2 m_{\chi^\pm}^2 \log \frac{m_{\chi^\pm}^4}{m_{H^\pm}^4},$$

where $\lambda$ is the Yukawa coupling that appears in the Superpotential of the Higgs Superfields.
corrections affect mainly the neutral Higgs bosons sector, in particular the production of the neutral scalar Higgs in $e^+e^-$ collisions, which is the Higgs-strahlung processes $e^+e^- \rightarrow H_i^0Z^0$, whose cross sections can be expressed in terms of the SM Higgs boson (herein denoted by $\phi_{SM}^0$) production formula and the Higgs-$Z^0Z^0$ coupling, as follows [26]:

$$\sigma_{H_i^0Z} = R_{H_i^0Z}^2 \sigma_{H_i^0Z}^{SM},$$

$$R_{H_i^0Z}^2 = \frac{g_{H_i^0Z}^2}{g_{\phi_{SM}ZZ}^2}, \quad (11)$$

where $g_{H_i^0Z}^2$ is the coupling $H_i^0Z^0Z^0$ in the MSSM+1CHT and $g_{\phi_{SM}ZZ}^2$ is the SM coupling $\phi_{SM}^0Z^0Z^0$, which obey the relation

$$\sum_{i=1}^3 g_{H_i^0Z}^2 = g_{\phi_{SM}ZZ}^2. \quad (12)$$
We define the scaling factor

\[ S_{95} = \sigma_{\text{max}} / \sigma_{\text{ref}}, \]  

(16)

where \( \sigma_{\text{max}} \) is the largest cross-section compatible with the data, at the 95% CL, and \( \sigma_{\text{ref}} \)

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<th>(b)</th>
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<th>( m_{H_1} ) (GeV/c^2)</th>
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Scenario A, $\lambda=0.1$

Two Higgs states below top mass

Scenario A, $\lambda=0.5$
We define the marginal regions those cases almost pass LEP2 bounds

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<th>$R^2_{H_1^0 Z^0 Z^0}$</th>
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<td>$\leq 77$</td>
<td>$79.8$ GeV $&lt; m_{H_1^\pm} &lt; 118$ GeV</td>
<td>$0.002 &lt; R^2_{H_1^0 Z^0 Z^0} &lt; 0.2$</td>
<td>$0.9 &lt; R^2_{H_2^0 Z^0 Z^0}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$12$ GeV $&lt; m_{H_1^0} &lt; 50$ GeV</td>
<td></td>
<td>Allowed by $R^2_{H_1^0 Z^0 Z^0}$, but marginal for $R^2_{H_2^0 Z^0 Z^0}$</td>
</tr>
<tr>
<td>1</td>
<td>$15 \leq \tan \beta$</td>
<td>$89$ GeV $&lt; m_{H_1^\pm} &lt; 187$ GeV</td>
<td>$R^2_{H_1^0 Z^0 Z^0} &lt; 0.01$</td>
<td>$0.9 &lt; R^2_{H_2^0 Z^0 Z^0}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$14$ GeV $&lt; m_{H_1^0} &lt; 89$ GeV</td>
<td></td>
<td>Allowed by $R^2_{H_1^0 Z^0 Z^0}$, but marginal for $R^2_{H_2^0 Z^0 Z^0}$</td>
</tr>
</tbody>
</table>
TABLE II: Analysis of $R_{H^0_i Z^0 Z^0}^2$ consistent with LEP. We consider experimental limits by LEP2 for charged and neutral Higgs bosons, for Scenario B with $A = 200, 300$ GeV and $\mu_1 = 200$ GeV.

| $\lambda = 0.1$ | $10 \leq \tan \beta \leq 100$ | $294$ GeV $< m_{H^\pm_1} < 532$ GeV  
$m_{H^0_1} \approx 110$ GeV  
$300$ GeV $< m_{H^0_2} < 538$ GeV | $0.99 < R_{H^0_1 Z^0 Z^0}^2$  
$R_{H^0_2 Z^0 Z^0}^2 < 0.001$ | Marginally allowed by $R_{H^0_1 Z^0 Z^0}^2$ |
| $\lambda = 0.5$ | $1 \leq \tan \beta \leq 100$ | $300$ GeV $< m_{H^\pm_1} < 1200$ GeV  
$100$ GeV $< m_{H^0_1} < 107$ GeV  
$290$ GeV $< m_{H^0_2} < 1200$ GeV | $0.99 < R_{H^0_1 Z^0 Z^0}^2$  
$R_{H^0_2 Z^0 Z^0}^2 < 0.001$ | Marginally allowed by $R_{H^0_1 Z^0 Z^0}^2$ |
| $\lambda = 1$ | $1 \leq \tan \beta \leq 100$ | $340$ GeV $< m_{H^\pm_1} < 1690$ GeV  
$104$ GeV $< m_{H^0_1} < 176$ GeV  
$252$ GeV $< m_{H^0_2} < 1700$ GeV | $0.99 < R_{H^0_1 Z^0 Z^0}^2$  
$R_{H^0_2 Z^0 Z^0}^2 < 0.001$ | Allowed by $R_{H^0_1 Z^0 Z^0}^2$ |
**TABLE III:** Same analysis of Table II, but taking $A = 0.1$ GeV.

| $\lambda = 0.1$ | $12 \leq \tan \beta < 100$ | $84$ GeV $< m_{H_1^\pm} < 95$ GeV  
$14$ GeV $< m_{H_1^0} < 50$ GeV  
$m_{H_2^0} \approx 110$ GeV | $R^2_{H_1^0 Z^0 Z^0} < 0.01$  
$0.99 < R^2_{H_2^0 Z^0 Z^0}$ | Allowed for $R^2_{H_1^0 Z^0 Z^0}$  
Marginal region for $R^2_{H_2^0 Z^0 Z^0}$ |
| $\lambda = 0.5$ | $4 \leq \tan \beta < 100$ | $121$ GeV $< m_{H_1^\pm} < 129$ GeV  
$16$ GeV $< m_{H_1^0} < 50$ GeV  
$m_{H_2^0} \approx 107$ GeV | $R^2_{H_1^0 Z^0 Z^0} < 0.01$  
$0.98 < R^2_{H_2^0 Z^0 Z^0}$ | Allowed for $R^2_{H_1^0 Z^0 Z^0}$  
Marginal region for $R^2_{H_2^0 Z^0 Z^0}$ |
| $\lambda = 1$ | $27 \leq \tan \beta < 100$ | $197$ GeV $< m_{H_1^\pm} < 200$ GeV  
$14$ GeV $< m_{H_1^0} < 46$ GeV  
$103$ GeV $< m_{H_2^0} < 105$ GeV | $R^2_{H_1^0 Z^0 Z^0} < 0.01$  
$0.99 < R^2_{H_2^0 Z^0 Z^0}$ | Allowed for $R^2_{H_1^0 Z^0 Z^0}$  
Marginal region for $R^2_{H_2^0 Z^0 Z^0}$ |

**TABLE IV:** Same analysis of Table II, but taking $A = 0$ GeV, $\mu_1 = 200, 400, 700$ GeV and $\lambda = 0.5$.

| $\lambda = 0.5$ | $1 < \tan \beta < 6$ | $121$ GeV $< m_{H_1^\pm} < 130$ GeV  
$10$ GeV $< m_{H_1^0} < 50$ GeV  
$97$ GeV $< m_{H_2^0} < 113$ GeV | $0.006 < R^2_{H_1^0 Z^0 Z^0} < 0.2$  
$0.76 < R^2_{H_2^0 Z^0 Z^0}$ | Allowed for $R^2_{H_1^0 Z^0 Z^0}$  
Marginal region for $R^2_{H_2^0 Z^0 Z^0}$ |
A. The Higgs boson coupling to fermions in the MSSM+1CHT

As in the MSSM, also in this model only the scalar doublets are coupled to the fermions, so that the Lagrangian of the Yukawa sector has the following expression:

$$
\mathcal{L}_{Yuk} = -\lambda_u [\bar{u} P_L u \phi_2^0 - \bar{u} P_L d \phi_2^+] - \lambda_d [\bar{d} P_L d \phi_1^0 - \bar{d} P_L u \phi_1^-] + h.c.,
$$

(15)

where the parameters $\lambda_{u,d}$ are related to the fermion masses via

$$
\lambda_u = \frac{\sqrt{2} m_u}{v D s_\beta}, \quad \lambda_d = \frac{\sqrt{2} m_d}{v D c_\beta}.
$$

(16)
The piece of Lagrangian containing the fermion couplings of the charged Higgs bosons is given by:

$$\mathcal{L}_{f f H^+_i} = -\frac{1}{\sqrt{2}v_D} \bar{u} \left[ \left( \frac{m_d (\phi^-_1)^*}{c_\beta} - \frac{m_u \phi_2^+}{s_\beta} \right) + \left( \frac{m_d (\phi^-_1)^*}{c_\beta} + \frac{m_u \phi_2^+}{s_\beta} \right) \gamma_5 \right] d + h.c. \tag{17}$$

where $(\phi^-_1)^*$, $\phi_2^+$ are related to the physical charged Higgs boson states $(H_1^+, H_2^+, H_3^+)$ as follows:

$$(\phi^-_1)^* = \sum_{j} U_{2,j+1} H_j^+, \quad \phi_2^+ = \sum_{j} U_{1,j+1} H_j^+,$$

$$H_j^+ = (H_1^+, H_2^+, H_3^+). \tag{18}$$

The $U_{jk}$'s denote the elements of the mixing-matrix that relates the physical charged Higgs bosons $(H_1^+, H_2^+, H_3^+)$ and the Goldstone boson $G^+$.
Then, the couplings $\bar{u}dH_i^+$, $\bar{\nu}_l lH_i^+$ are given by:

$$
\begin{align*}
g_{H_i^+\bar{u}d} &= -\frac{i}{v_D\sqrt{2}}(A_i^{ud} + V_i^{ud}\gamma_5), \\
g_{H_i^-\bar{u}d} &= -\frac{i}{v_D\sqrt{2}}(A_i^{ud} - V_i^{ud}\gamma_5), \\
g_{H_i^+\bar{\nu}_ll} &= -\frac{i}{v_D\sqrt{2}}A_i^l(1 + \gamma_5), \\
g_{H_i^-\bar{\nu}_ll} &= -\frac{i}{v_D\sqrt{2}}A_i^l(1 - \gamma_5),
\end{align*}
$$

(20)

where $A_i^{ud}$ and $V_i^{ud}$ are defined as:

$$
\begin{align*}
A_i^{ud} &= m_d t_\beta \frac{U_{2,i+1}}{s_\beta} - m_u \cot_\beta \frac{U_{1,i+1}}{c_\beta}, \\
V_i^{ud} &= m_d t_\beta \frac{U_{2,i+1}}{s_\beta} + m_u \cot_\beta \frac{U_{1,i+1}}{c_\beta}, \\
A_i^l &= m_l t_\beta \frac{U_{2,i+1}}{s_\beta}.
\end{align*}
$$

(21)

One can see that the formulae in Eq. (10) become the couplings $\bar{u}dH_i^+$, $\bar{\nu}_l lH_i^+$ of the MSSM when we replace $U_{2,i+1} \rightarrow s_\beta$ and $U_{1,i+1} \rightarrow -c_\beta$[2]. The vertex $\bar{u}dH_i^+$ induces at tree-level the decay $t \rightarrow H^+ b$, which will be studied in the next section.
B. The decay $t \to H_i^+ b$

In order to study this top quark BR we must consider both the decays $t \to H_i^+ b$ for $i = 1, 2$, because both modes could be kinematically allowed for several parameter configurations within our model. The decay width of these modes takes the following form:

$$
\Gamma(t \to H_i^+ b) = \frac{g^2}{64\pi(m_W^2 - 2g^2v_T^2)}m_t^3\lambda^{1/2}(1, q_{H_i^+}, q_b) \times \left[(1 - q_{H_i^+} + q_b)\left(\frac{U_{1,i+1}^2}{s_\beta^2} + q_b\frac{U_{2,i+1}^2}{c_\beta^2}\right) - 4q_b\frac{U_{1,i+1}U_{2,i+1}}{s_\beta c_\beta}\right] (22)
$$

where $\lambda$ is the usual kinematic factor $\lambda(a, b, c) = (a - b - c)^2 - 4bc$ and $q_{b,H^+} = m_{b,H^+}/m_t^2$. 
Experimental bound on the BR(t\rightarrow bH+) 

If the decay mode (H+ \rightarrow \tau^+ \nu) dominates the charged Higgs boson decay width, then BR(t \rightarrow H^+ b) is constrained to be less than 0.4 at 95 \% C.L.

However, if the decay mode (H+ \rightarrow \tau^+ \nu) is not dominant, then BR(t \rightarrow H^+ b) is constrained to be less than 0.91 at 95 \% C.L.

The combined LEP data excluded a charged Higgs boson with mass less than 79.3 GeV at 95 \% C. L.

Thus, we need to discuss all the charged Higgs decays.

FIG. 17: It is plotted: the $\text{BR}(t \rightarrow b H_1^+)$ vs. $\tan \beta$ (left), the $\tan \beta - m_{H_1^+}$ plane (right), in Scenario A taking $\lambda = 0.5$, for: $A = 200$ GeV (solid), $A = 300$ GeV (dashes), $A = 400$ GeV (dots).
FIG. 18: The figure shows the branching ratios of $H_1^+$ decaying into the principal modes in Scenario A, with $\lambda = 0.5$ and $\mu_2 = 100$ GeV, for: $A = 200$ GeV (left), $A = 300$ GeV (center), $A = 400$ GeV (right). The lines correspond to: (1) BR($H_1^+ \rightarrow \tau^+ \nu_\tau$), (2) BR($H_1^+ \rightarrow c\bar{s}$), (3) BR($H_1^+ \rightarrow c\bar{b}$), (4) BR($H_1^+ \rightarrow W^+ H_1^0$), (5) BR($H_1^+ \rightarrow W^+ A_1^0$).
FIG. 20: It is plotted: BR($t \rightarrow b \ H^{+}_{1}$) vs. tan $\beta$ (left), the tan $\beta - m_{H^{+}_{1}}$ plane (right), in Scenario B, taking $\lambda = 0.1$ for: $A = 200$ GeV (solid), $A = 300$ GeV (dashes), $A = 0.1$ GeV (dots).
FIG. 28: The figure shows the branching ratios of $H_1^+$ decaying into the principal modes in Scenario B considering the cases: $\lambda = 0.1$ (left), $\lambda = 0.5$ (right), with $A = 0.1$ GeV and $\mu_1 = 200$ GeV. The lines correspond to: (1) $\text{BR}(H_1^+ \rightarrow \tau^+\nu_\tau)$, (2) $\text{BR}(H_1^+ \rightarrow c\bar{s})$, (3) $\text{BR}(H_1^+ \rightarrow c\bar{b})$, (4) $\text{BR}(H_1^+ \rightarrow W^+H_1^0)$, (5) $\text{BR}(H_1^+ \rightarrow W^+A_1^0)$. 
B1. The point $\mu_2 = 10$ GeV, $\lambda = 0.1$, $A = 20$ GeV for say $\tan(\beta) = 30$ or 50 as represented in Fig. 1 (left panel). This is an interesting situation, in which one has both $MH^+/- (1)$ and both $MH^+/- (2)$ below $m_t$, so that one could have two charged Higgs decays of a top quark that may be accessible (see Fig. below) at Tevatron and/or LHC.
Decays of the charged Higgs

FIG. 26: The figure shows the branching ratios of $H_2^+$ (top) and $H_3^+$ (bottom) decaying into the principal modes in Scenario A, taking $\lambda = 0.5$ and $\mu_2 = 100$ GeV for $A = 200$ GeV (left), $A = 300$ GeV (center), $A = 400$ GeV (right). The lines correspond to: (1) BR($H_2^+ \rightarrow \tau^+ \nu_\tau$), (2) BR($H_2^+ \rightarrow t\bar{b}$), (3) BR($H_2^+ \rightarrow W^+H_1^0$), (4) BR($H_2^+ \rightarrow W^+A_1^0$), (5) BR($H_2^+ \rightarrow W^+Z^0$), (6) BR($H_3^+ \rightarrow t\bar{b}$), (7) BR($H_3^+ \rightarrow W^+H_1^0$), (8) BR($H_3^+ \rightarrow W^+H_2^0$), (9) BR($H_3^+ \rightarrow W^+A_1^0$), (10) BR($H_3^+ \rightarrow W^+Z^0$).
FIG. 32: The figure shows the branching ratios of $H_2^+$ (top) and $H_3^+$ (bottom) decaying into the principal modes in Scenario B, with $\lambda = 0.1$ and $\mu_1 = 200$ GeV, for: $A = 0.1$ GeV (left), $A = 200$ GeV (center), $A = 300$ GeV (right). The lines correspond to: (1) $\text{BR}(H_2^+ \to t\bar{b})$, (2) $\text{BR}(H_2^+ \to W^+H_1^0)$, (3) $\text{BR}(H_2^+ \to W^+H_2^0)$, (4) $\text{BR}(H_2^+ \to W^+A_1^0)$, (5) $\text{BR}(H_2^+ \to W^+Z^0)$, (6) $\text{BR}(H_3^+ \to t\bar{b})$, (7) $\text{BR}(H_3^+ \to W^+H_1^0)$, (8) $\text{BR}(H_3^+ \to W^+H_2^0)$, (9) $\text{BR}(H_3^+ \to W^+A_1^0)$, (10) $\text{BR}(H_3^+ \to W^+Z^0)$. 
Direct charged Higgs production at LHC in the MSSM-1CHT

• If $m_{H^+} < m_t - m_b$ the decay $t \rightarrow H^+ i \ b$ is the principal process for to produce charged Higgs. The following production channel is important

$$q\bar{q}, \ gg \rightarrow t\bar{t} \rightarrow t\bar{b}H_i^- + \text{c.c.}$$

• If the charged Higgs mass is above the threshold for $t \rightarrow H^+ i \ b$, the direct process

$$q\bar{q}, \ gg \rightarrow t\bar{b}H_i^- + \text{c.c.}$$
Direct charged Higgs production at LHC in the MSSM-1CHT

FIG. 38: The figure shows the cross sections of $H_{1,2,3}^+$ at the LHC through the channel $q\bar{q}, gg \rightarrow t\bar{t}H^- + \text{c.c.}$ in Scenario A with $\lambda = 0.5$ and for: $A = 200, 300, 400$ GeV, respectively.
TABLE V: Summary of LHC event rates for Scenario A with $\mu_2 = 100$ GeV for an integrated luminosity of $10^5$ pb$^{-1}$, for several different signatures.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$(A, \tan \beta)$</th>
<th>$m_{H_i^+}$ in GeV</th>
<th>$\sigma(pp \to H_2^+tb)$ in pb</th>
<th>Relevant BR's</th>
<th>Nr. Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>(200,5)</td>
<td>(118,740,790)</td>
<td>$1.6 \times 10^{-5}$</td>
<td>BR($H_2^+ \to tb$) $\approx 5.8 \times 10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+A_1^0$) $\approx 9.8 \times 10^{-1}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+Z^0$) $\approx 1.2 \times 10^{-2}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+H_1^0$) $\approx 4.2 \times 10^{-3}$</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>(200,20)</td>
<td>(114,390,470)</td>
<td>$1.2 \times 10^{-2}$</td>
<td>BR($H_2^+ \to tb$) $\approx 1.5 \times 10^{-1}$</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+A_1^0$) $\approx 7.5 \times 10^{-1}$</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+Z^0$) $\approx 1.0 \times 10^{-2}$</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+H_1^0$) $\approx 7.7 \times 10^{-2}$</td>
<td>92</td>
</tr>
<tr>
<td>0.5</td>
<td>(200,50)</td>
<td>(98,290,370)</td>
<td>$8.7 \times 10^{-1}$</td>
<td>BR($H_2^+ \to \tau^+\nu_\tau$) $\approx 8.2 \times 10^{-2}$</td>
<td>7134</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to tb$) $\approx 8.4 \times 10^{-1}$</td>
<td>73080</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+A_1^0$) $\approx 2.4 \times 10^{-2}$</td>
<td>2088</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+H_1^0$) $\approx 4.8 \times 10^{-2}$</td>
<td>4176</td>
</tr>
<tr>
<td>1.0</td>
<td>(200,5)</td>
<td>(191,1047,1087)</td>
<td>$3.4 \times 10^{-6}$</td>
<td>BR($H_2^+ \to \tau^+\nu_\tau$) $\approx 4.6 \times 10^{-6}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to tb$) $\approx 3.0 \times 10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+A_1^0$) $\approx 9.8 \times 10^{-1}$</td>
<td>0</td>
</tr>
<tr>
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<td></td>
<td>BR($H_2^+ \to W^+Z^0$) $\approx 1.3 \times 10^{-2}$</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>(200,20)</td>
<td>(185,545,610)</td>
<td>$4.5 \times 10^{-3}$</td>
<td>BR($H_2^+ \to tb$) $\approx 1.1 \times 10^{-1}$</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+A_1^0$) $\approx 7.7 \times 10^{-1}$</td>
<td>349</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+Z^0$) $\approx 1.1 \times 10^{-2}$</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BR($H_2^+ \to W^+H_1^0$) $\approx 1.0 \times 10^{-2}$</td>
<td>4</td>
</tr>
<tr>
<td>1.0</td>
<td>(200,50)</td>
<td>(153,400,450)</td>
<td>$3.6 \times 10^{-1}$</td>
<td>BR($H_2^+ \to \tau^+\nu_\tau$) $\approx 5.0 \times 10^{-2}$</td>
<td>1800</td>
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<tr>
<td></td>
<td></td>
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<td>BR($H_2^+ \to tb$) $\approx 8.4 \times 10^{-1}$</td>
<td>30240</td>
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<td>BR($H_2^+ \to W^+A_1^0$) $\approx 2.6 \times 10^{-2}$</td>
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<td></td>
<td></td>
<td>BR($H_2^+ \to W^+H_1^0$) $\approx 7.9 \times 10^{-2}$</td>
<td>2844</td>
</tr>
</tbody>
</table>
B2. The point $\mu_2=100$ GeV, $\lambda=0.5$, $A=200$ GeV for $\tan(\beta)=50$, see Fig. below. Here, there seems to be scope to access $H^+/-(1)$ in top decays as well as $H^+/-(2)$ in either $tb$ or $W^+/A_0(1)/H_0(1)$ or both, see row 3 of Tab. below, at least for the LHC.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$(A, \tan\beta)$</th>
<th>$m_{H^\pm}$ in GeV</th>
<th>$\sigma(pp \rightarrow H^\pm tb)$ in pb</th>
<th>Relevant BR's</th>
<th>Nr. Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>(200,50)</td>
<td>(98,290,370)</td>
<td>$8.7 \times 10^{-1}$</td>
<td>$\text{BR}(H^\pm \rightarrow \tau^{\pm} \nu_\tau) \approx 8.2 \times 10^{-2}$</td>
<td>7134</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\text{BR}(H^\pm \rightarrow tb) \approx 8.4 \times 10^{-1}$</td>
<td>73080</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\text{BR}(H^\pm \rightarrow W^\pm A_0^0) \approx 2.4 \times 10^{-2}$</td>
<td>2068</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\text{BR}(H^\pm \rightarrow W^\pm H_0^0) \approx 4.8 \times 10^{-2}$</td>
<td>4176</td>
</tr>
</tbody>
</table>
FIG. 40: The figure shows the cross sections of $H_{1,2,3}^+$ at the LHC through the channel $q\bar{q}, gg \to \bar{t}bH^- + \text{c.c.}$ in Scenario B with $\lambda = 0.1$ and for: $A = 200, 300, 0.1$ GeV, respectively.
TABLE VI: Summary of LHC event rates for Scenario B with $\mu_1 = 200$ GeV for an integrated luminosity of $10^5$ pb$^{-1}$, for several different signatures.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$(A, \tan \beta)$</th>
<th>$m_{H_1^+}$ in GeV</th>
<th>$\sigma(pp \to H_1^+ \bar{t}b)$ in pb</th>
<th>Relevant BR's</th>
<th>Nr. Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>(200,5)</td>
<td>(473,1304,1305)</td>
<td>$1.8 \times 10^{-2}$</td>
<td>$\text{BR}(H_1^+ \to \tau^+ \nu_{\tau}) \approx 1.7 \times 10^{-2}$</td>
<td>31</td>
</tr>
<tr>
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<td>$\text{BR}(H_1^+ \to \bar{t}b) \approx 9.8 \times 10^{-1}$</td>
<td>1764</td>
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<tr>
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<td>$\text{BR}(H_1^+ \to W^+ Z^0) \approx 4.2 \times 10^{-6}$</td>
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<td>(200,20)</td>
<td>(906,1223,1225)</td>
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<td>(921,1724,1738)</td>
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<td>1.0</td>
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<td>(1434,1699,1713)</td>
<td>$6.2 \times 10^{-3}$</td>
<td>$\text{BR}(H_1^+ \to \tau^+ \nu_{\tau}) \approx 3.8 \times 10^{-2}$</td>
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Conclusions

• We have studied the fermion-charged Higgs bosons vertices in the MSSM-1CHT.

• We have analyzed the decay $t \rightarrow H^+ i b$.

• We have found some plausible scenarios for MSSM-1CHT that forbidden in the MSSM. Is possible to have a charged Higgs boson with mass $\approx 90$ GeV forbidden in the MSSM, which is not excluded by any of the current data.

• If the mass of the charged Higgs is larger than the mass of the quark mass, the direct charged Higgs production can be through the mode

$$q\bar{q}, \, gg \rightarrow t\bar{b}H_i^- + c.c.$$  

• The detection at LHC of charged Higgs bosons in the regions of parameter space accessible in the MSSM (or THDM) would not contradict the MSSM-1CHT hypothesis.

• The observation of several charged Higgs bosons would correspond to a model with a more elaborate Higgs sector, such as the MSSM-1CHT.