Charged Higgs at the LHC in minimal flavor violation and beyond

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A theory named SUSY
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- Charged Higgs at the ’Ring of Fire’
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- Come to where the flavor is
- Charged Higgs + Jet
Minimal Supersymmetric Standard Model

Model: R-parity conserving MSSM
MSSM: Minimal gauge group and particle content

SUSY explicitly broken

Relevant soft-breaking Lagrangian:

\[ \mathcal{L}_{soft} = - M_{Q_i}^2 \tilde{Q}_i \tilde{Q}_i - M_{\tilde{u}_i}^2 |\tilde{u}_R|^2 - M_{\tilde{d}_i}^2 |\tilde{d}_R|^2 \\
- \left[ A_{ij}^u \tilde{u}_R^* H_2 \cdot \tilde{Q}_j + A_{ij}^d \tilde{d}_R^* H_1 \cdot \tilde{Q}_j \right] \]

Often imposed Minimal Flavor Violation (MFV) assumption [D’Ambrosio, Giudice, Isidori, Strumina 2002]
Up-type squark matrix in MFV and NMFV:

\[ M_{\text{mfv}}^u = \begin{pmatrix}
(M_u^2)_{\text{LL}}^u & 0 & 0 & \Delta_{LR,11}^u & 0 & 0 \\
0 & (M_u^2)_{\text{c,LL}}^t & 0 & \Delta_{LR,22}^u & 0 & 0 \\
0 & 0 & (M_u^2)_{\text{LR,RR}}^u & 0 & \Delta_{LR,33}^u & 0 \\
\text{h.c.} & \Delta_{LL,12}^u & \Delta_{LL,13}^u & \Delta_{LR,11}^u & \Delta_{LR,12}^u & \Delta_{LR,13}^u \\
(M_u^2)_{\text{LL}}^c & (M_u^2)_{\text{c,LL}}^t & (M_u^2)_{\text{c,LR,RR}}^u & (M_u^2)_{\text{c,LR,RR}}^c & (M_u^2)_{\text{c,LR,RR}}^t & (M_u^2)_{\text{c,LR,RR}}^c \\
\end{pmatrix} \]

\[ M_{\text{nmfv}}^u = \begin{pmatrix}
(M_u^2)_{\text{LL}}^u & \Delta_{LL,12}^u & \Delta_{LL,13}^u & \Delta_{LR,11}^u & \Delta_{LR,12}^u & \Delta_{LR,13}^u \\
\Delta_{LL,12}^u & (M_u^2)_{\text{c,LL}}^t & \Delta_{LL,23}^u & \Delta_{LR,21}^u & \Delta_{LR,22}^u & \Delta_{LR,23}^u \\
\Delta_{LL,13}^u & \Delta_{LL,23}^u & (M_u^2)_{\text{c,LR,RR}}^u & \Delta_{LR,31}^u & \Delta_{LR,32}^u & \Delta_{LR,33}^u \\
\Delta_{LR,11}^u & \Delta_{LR,21}^u & \Delta_{LR,31}^u & (M_u^2)_{\text{c,LR,RR}}^c & \Delta_{RR,12}^u & \Delta_{RR,13}^u \\
\Delta_{LR,12}^u & \Delta_{LR,22}^u & \Delta_{LR,32}^u & \Delta_{RR,12}^u & (M_u^2)_{\text{c,RR}}^t & \Delta_{RR,23}^u \\
\Delta_{LR,13}^u & \Delta_{LR,23}^u & \Delta_{LR,33}^u & \Delta_{RR,13}^u & \Delta_{RR,23}^u & (M_u^2)_{\text{c,RR}}^c \\
\end{pmatrix} \]

\[
(M_u^2)_q^{\text{LL}} = M_{Q,q}^2 + m_q^2 + (T_3^q - Q_q \sin^2 \theta_w) m_Z^2 \cos 2\beta
\]

\[
(M_u^2)_q^{\text{RR}} = M_{u,q}^2 + m_q^2 + Q_q \sin^2 \theta_w m_Z^2 \cos 2\beta
\]

\[
\Delta_{LR,ii}^u = \langle H_2^0 \rangle A_{ii}^u - m_{q_i} \mu^* \cot \beta
\]

\[
\Delta_{LL,ij}^u = M_{Q,q}^2, i \neq j
\]

\[
\Delta_{RR,ij}^u = M_{u,q}^2, i \neq j
\]
In general the squark mass matrix has to be diagonalized

\[ Z^u M^u Z^{u\dagger} = \text{diag}(m_{\tilde{u}_1}^2, m_{\tilde{u}_2}^2) \]

Mass Insertion Approximation can be used if off-diagonal entries are small compared to \( \tilde{m}_q \) (average squark mass)

\[ \delta^q_{AB,ij} = \frac{\Delta^q_{AB,ij}}{\tilde{m}_q^2} \]

\[ \langle \tilde{q}_A^i \tilde{q}_B^{j*} \rangle = i(k^2 \mathbf{1} - \tilde{m}_q^2 \mathbf{1} - \Delta^q_{AB})^{-1}_{ij} \]

\[ = i\delta_{ij} - i\Delta^q_{AB,ij} (k^2 - \tilde{m}_q^2) + O(\Delta^2) \]

\[ Z_{ia} \quad - \quad - \quad Z_{aj}^{\dagger} = \quad - \quad - \quad + \quad - \quad \times \quad - \quad + \quad \ldots \]
Charged Higgs at the LHC

- Charged Higgs is a signature for 'New Physics'

- Studying a light neutral Higgs alone is not sufficient to identify an extended Higgs sector

- Tedious Task: No $H^\pm W^\mp Z$ interaction at tree-level. In the two Higgs doublet model not the $H^\pm$ but the Goldstone boson $G^\pm$ couples to $W^\pm Z$.

$\Rightarrow$ Most promising strategy of finding a charged Higgs at LHC: Couple it to a bottom quark in the large tan $\beta$ regime:

- Light $H^\pm$: $M_{H^\pm} \leq m_t - m_b \approx 170\text{GeV}$
  
  
  \[ pp \rightarrow t\bar{t} \rightarrow H^\pm tb \]

- Heavy $H^\pm$: $M_{H^\pm} \geq 170\text{GeV}$

  \[ pp \rightarrow H^- tb \]
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$\Rightarrow$ Leaving a hole for $\tan \beta \leq 20$ \ [CMS TDR, 2007]
Single Higgs in non-minimal flavor violation

- Direct production without phase-space suppression
- But what about the Background?

\[
\frac{C_{H^+}}{C_{W^+}} = \frac{m_d \tan \beta}{m_W} \approx 10^{-4}
\]

\[\mathcal{L}_{H^\pm q\bar{q}'} \supset -\frac{g m_W}{\sqrt{2}} \sin 2\beta + \frac{g m_d^2 \tan \beta}{\sqrt{2} m_W} + \frac{g m_u^2 \cot \beta}{\sqrt{2} m_W} \tilde{d}_L^\dagger \tilde{u}_L H^-
\]

\[+ \left[ \frac{g \tan \beta}{\sqrt{2} m_W} \langle H_1^0 \rangle A^d + \frac{g}{\sqrt{2} m_W} m_d \mu^* \right] \tilde{d}_R^\dagger \tilde{u}_L H^-
\]

\[+ \left[ \frac{g \cot \beta}{\sqrt{2} m_W} \langle H_2^0 \rangle A^{u*} + \frac{g}{\sqrt{2} m_W} m_u \mu \right] \tilde{d}_L^\dagger \tilde{u}_R H^-
\]

- In MFV all contributions suppressed by small Yukawa-Couplings
  \(\Rightarrow\) in \(m_q \to 0\) amplitude strictly zero
- NMFV circumvents Yukawa-Coupling suppression.
  Especially for small \(\tan \beta\)
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Relevant Bounds

No severe bounds for the production of a charged Higgs!

\[ \mathcal{M}_{sq}^u = \begin{pmatrix}
(M_u^2)_{LL}^u & \Delta_{LL,12}^u & \Delta_{LL,13}^u & \Delta_{LR,11}^u & \Delta_{LR,12}^u & \Delta_{LR,13}^u \\
(M_u^2)_{LL}^c & (M_u^2)_{LL}^t & (M_u^2)_{RR}^u & (M_u^2)_{RR}^c & (M_u^2)_{RR}^t & \text{h.c.}
\end{pmatrix} \]

- \( B_d - B_d^\bar{d} \) and \( B_s - B_{s}^\bar{d} \) mixing
- \( B \rightarrow X_s \gamma \) and \( B \rightarrow \rho \gamma \)
- \( B \rightarrow X_s ll \) and \( B \rightarrow \pi ll \)
- Corrections to quark masses
- \( m_{\bar{q}_i} > 200 \text{ GeV} \) – exp. constraint

Green entries give main contributions to Charged Higgs production.
Working Assumptions:

- All soft-breaking parameters are real
- Just flavor violation in up-squark sector
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Parameters:

\[
\begin{align*}
\tan \beta &= 7 & m_A &= 170 \text{ GeV} & \mu &= -300 \text{ GeV} \\
 m_{\text{diag}} &= 600 \text{ GeV} & m_{\tilde{g}} &= 500 \text{ GeV} & M_2 &= 700 \text{ GeV} \\
 A^{u,c} &= 0 & A^{d,s,b} &= 0 & A^t &= 1400 \text{ GeV}
\end{align*}
\]

\[\Rightarrow m_{h^0} = 119 \text{ GeV} \quad \text{(at 2 Loop)} \quad m_{H^+} = 188 \text{ GeV} \quad \text{(at Tree Level)}\]
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- All soft-breaking parameters are real
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Parameters:
- $\tan \beta = 7$
- $m_A = 170$ GeV
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- $A^{d,s,b} = 0$
- $A^t = 1400$ GeV

$\Rightarrow m_{h^0} = 119$ GeV (at 2 Loop) $m_{H^+} = 188$ GeV (at Tree Level)

Flavor bounds at 90% C.L.
- $0.63 \cdot 10^{-6} < BR(B \rightarrow \rho \gamma) < 1.24 \cdot 10^{-6}$
- $2.94 \cdot 10^{-4} < BR(B \rightarrow X_s \gamma) < 4.14 \cdot 10^{-4}$
- $B_s - B_{\bar{s}} : 0.56 < \frac{\Delta m_s}{\Delta m_{s}^{\text{SM}}} < 1.44$
- $B_d - B_{\bar{d}} : 0.46 < \frac{\Delta m_d}{\Delta m_{d}^{\text{SM}}} < 1.54$
- $2.8 \cdot 10^{-6} < BR(B \rightarrow X_s ll) < 6.2 \cdot 10^{-6}$
- $BR(B \rightarrow \pi ll) < 9.1 \cdot 10^{-8}$
Points outside rainbow-coded area forbidden:

- **Blue**: Violates radiative and semileptonic decays
- **Green**: Violates rad. and semilep. decays and exp. squark mass bounds
- **Grey**: Negative squark mass square
- **Orange**: Violates BB-Mixing bounds and rad. and semilep. decays
- **Black**: Violates BB-Mixing bounds, rad. and semilep. decays and exp. squark mass bounds
Points outside rainbow-coded area forbidden:

- **Yellow**: Violates experimental squark mass bounds
- **Blue**: Violates radiative and semileptonic decays
- **Green**: Violates radiative and semileptonic decays and experimental squark mass bounds
- **Grey**: Negative squark mass square
Results of single Higgs production

- Flavor-mixing can strongly enhance charged Higgs production cross-section
- Largest contribution from $\delta_{LR,31}^u$

- Tree-Level value for hadr. cross-section with $M_{H^+} = 188$ GeV:
  $\sigma_{\text{tree}}(pp \rightarrow H^+ + X) = 41$ fb
- Unfortunately,
  $\sigma(pp \rightarrow W^+ + X) \approx 90$ nb
  $\Rightarrow$ bad signal to background ratio $H^+$
Considered process: $\sigma(pp \rightarrow H^+ + \text{Jet})$

- Even with $m_q \rightarrow 0$ (just D-Terms) and in MFV the cross-section is finite
- Just SUSY-QCD corrections
  Expected to cause the largest enhancement
- We require a hard jet, $p_{T,j} \geq 100$ GeV, to handle collinear divergencies
- Background:
  $\sigma(pp \rightarrow W^+ + \text{Jet}) \approx 1.1\text{nb}$
Results for $m_q \rightarrow 0$ in MFV

- For $m_q \rightarrow 0$ just D-Term couplings present
- Cross-sections are very small because the D-Terms decouple with $1/M_{SUSY}^4$ on the amplitude level (Large mass expansion)
- D-Term contributions to the Amplitude are proportional to $\sin(2\beta)$
Diagrams for 1 of 18 partonic processes - $ug \rightarrow H^+ b$:

$$u \ g \rightarrow H \ b$$
Results: $H^+ + \text{Jet}$

<table>
<thead>
<tr>
<th>$m_{H^+}$</th>
<th>$\tan \beta$</th>
<th>$\sigma_{2HDM}$</th>
<th>$\sigma_{2HDM}^{(m_s=0)}$</th>
<th>$\sigma_{MFV}$</th>
<th>$\sigma_{MFV}^{(m_s=0)}$</th>
<th>$\sigma_{MFV}^{(m_q=0)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>188 GeV</td>
<td>3</td>
<td>$2.5 \cdot 10^{-1}$</td>
<td>$1.9 \cdot 10^{-1}$</td>
<td>$2.6 \cdot 10^{-1}$</td>
<td>$2.0 \cdot 10^{-1}$</td>
<td>$6.7 \cdot 10^{-4}$</td>
</tr>
<tr>
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<td>$6.0 \cdot 10^{-1}$</td>
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<th>$m_{H^+}$</th>
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</tr>
<tr>
<td>400 GeV</td>
<td>7</td>
<td>0.79</td>
<td>0.73</td>
<td>0.54</td>
</tr>
</tbody>
</table>

- $\sigma_{SUSY}$ corresponds to $\delta_{LR,31}^u = 0.5$
- Light-flavor and bottom Yukawa have roughly the same impact ($m_b V_{cb} \sim m_s V_{cs}$)
- The D-Term couplings are numerically irrelevant
- NMFV can enhance cross-section by one order of magnitude for small $\tan \beta$
Two loop induced $H^+$ production mechanisms were studied in MFV and NMFV:

Can we detect a charged Higgs in this channel although Signal to Background Ratio quite small?
Conclusions

Two loop induced $H^+$ production mechanisms were studied in MFV and NMFV:

Can we detect a charged Higgs in this channel although Signal to Background Ratio quite small?

- Viable process to detect a charged Higgs for small $\tan \beta$, yielding a clear signal for physics beyond the standard model
- It is possible to rule out the MFV assumption
- It is possible to constrain the free parameters $A_{LR,3(1,2)}^u$ and $M_{RR,3(1,2)}^u$ which is not possible by flavor physics
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Intersectional field of flavor and collider physics might give interesting results for LHC
The dominant Operators are:

\[
H_{\Delta B=2}^{\text{eff}} = \sum_{i=1}^{5} C_i(\mu) O_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{O}_i(\mu)
\]

\[
O_1 = \bar{d}^\alpha_L \gamma_\mu b^\alpha_L \bar{d}^\beta_L \gamma_\mu b^\beta_L, \quad O_2 = \bar{d}^\alpha_R b^\alpha_L \bar{d}^\beta_R b^\beta_L,
O_3 = \bar{d}^\alpha_R b^\beta_L \bar{d}^\beta_R b^\alpha_L, \quad O_4 = \bar{d}^\alpha_R b^\alpha_L \bar{d}^\beta_R b^\beta_L, \quad O_5 = \bar{d}^\alpha_R b^\beta_L \bar{d}^\beta_R b^\alpha_L
\]

The operators \(\tilde{O}_{1,2,3}\) are obtained from \(O_{1,2,3}\) by exchanging \(L \leftrightarrow R\)

- Light quark masses are neglected \(\Rightarrow\) just \(O_1\) and \(\tilde{O}_3\) at high scale
- Main contributions from \(\delta^u_{LL,13}\) and \(\delta^u_{LR,13}\)
\( B \rightarrow X_s \gamma \) and \( B \rightarrow \rho \gamma \)

Operators:

\[
O_2 = \bar{s}_L \gamma_\mu c_L \gamma^\mu b_L \\
O_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R \\
O_8 = \frac{g s}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} G^{\mu\nu}_{\alpha} t_\alpha b_R
\]

The Operators \( \tilde{O}_7 \) and \( \tilde{O}_8 \) are obtained by interchanging L and R.

Exp. Values for \( BR(b \rightarrow s\gamma) \):

\[
355 \pm 24^{+9}_{-10} \pm 3 \cdot 10^{-6}
\]

Exp. Values for \( BR(B \rightarrow \rho\gamma) \):

BaBar: \( 0.79^{0.22}_{-0.20} \pm 0.06 \cdot 10^{-6} \)

Belle: \( 1.25^{0.37+0.07}_{-0.33-0.06} \cdot 10^{-6} \)
Gluino corrections to quark masses:

\[ \delta m_i \propto -\frac{\alpha_s}{4\pi} m_{\tilde{g}} \text{Re}(\delta_{ii}^q)_{LR} I(x) \]

Assumption: \( \delta m_i \) smaller than the values of the absolute value of the quark masses
The Operators $\tilde{O}_7$ and $\tilde{O}_8$ are obtained by interchanging $L$ and $R$. 

$$O_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F_{\mu\nu} b_R$$

$$O_8 = \frac{gs}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} G^{\mu\nu}_a t_a b_R$$

$$O_9 = \frac{e^2}{16\pi^2} \bar{s}_L \gamma^\mu b_L \bar{l} \gamma_\mu l$$

$$O_{10} = \frac{e^2}{16\pi^2} \bar{s}_L \gamma^\mu b_L \bar{l} \gamma_\mu \gamma_5 l$$