Introduction.

CP mixing induced in the Higgs sector due to CP violation in soft SUSY breaking parameters. Light charged and neutral Higgs allowed by LEP data.

Moderately light charged Higgs in the NMSSM

Searching for the light charged (and neutral) Higgs in the top decay at the LHC and plugging the “hole” in tan $\beta - m_{H^+}$ plane for $m_{\phi_1} < 50$ GeV.

Conclusions and Summary.

Want to discuss the phenomenology of a light charged Higgs \( \sim 150 GeV \) at low and moderate values of \( \tan \beta \), which is still allowed in the NMSSM and in \( CP \) SUSY.

Why study \( CP \); why study \( CP \) in SUSY?

The phenomenon still lacks a fundamental understanding

- CKM description vindicated by measurements of CP mixing in the \( B_0 \) sector.

- CKM \( CP \) not sufficient to explain quantitatively why

\[
\frac{N_b}{N_\gamma} \sim 6.1 \times 10^{-10} \quad \frac{N_{\bar{b}}}{N_\gamma} \sim 0
\]  

\( \text{Sources of CP violation beyond the CKM?} \)
CP and SUSY

CP violation in SUSY: Ugly Duckling to Swan!

Large # (44 to be precise) of phases of the SUSY parameters \( e.g., \mu, A_f, M_i, i = 1, 3 \) can not be rotated away by a simple redefinition of the fields.

Older days:

These generate unacceptably large electric dipole moments for fermions. Fine tune all the \( CP \) phases in SUSY to zero.

Now:


It is possible for some combination of phases to be \( O(1) \) and yet satisfy all the constraints on EDM’s.

Why does that make \( CP \) in MSSM a Swan?
A few more things about $\mathcal{P}$ :

1. $\mathcal{P}$ SUSY offers the possibility of explaining the Baryon Asymmetry quantitatively unlike the SM which does not have enough $\mathcal{P}$.

2. The MSSM $\mathcal{P}$ phases induce CP mixing in the Higgs sector (which has no CP mixing at the tree level) of the MSSM through loop effects Pilaftsis 98, Choi et al 00, Carena et al 00

3. CP mixing in the Higgs sector, one way for $\mathcal{P}$ in SUSY to manifest itself: can affect production rates at LHC as well. Dedes et al 99, Choi et al 01. Can affect Higgs phenomenology profoundly.
Effect of SUSY $\mathcal{CP}$ on Higgs phenomenology

MSSM $\mathcal{CP}$ phases $\Rightarrow \mathcal{CP}$ in the Higgs sector:

**$CP$ conserving MSSM** Three Neutral Higgses $h, H, A$

$\mathcal{CP}$-even $h, H$

$\mathcal{CP}$-odd $A$

$\mathcal{CP}$ violation: $\phi_1, \phi_2, \phi_3$

no fixed $\mathcal{CP}$ property

$m_{\phi_1} < m_{\phi_2} < m_{\phi_3}$

Sum rules exist for $\phi_i f\bar{f}$, $\phi_i VV$


$$g_{\phi_i WW}^2 + g_{\phi_j WW}^2 + g_{\phi_k WW}^2 = g^2 m_W^2, i \neq j \neq k$$

First proposed in a model independent way.

The $h, H, A$ now all mix and share the couplings with vector boson pair $VV$. Will affect production rates.

Predictions in terms of SUSY $\mathcal{CP}$ phases in the MSSM for this mixing.
Three types of effects on Higgs production rates

I] $\mathcal{CP}$ phases in MSSM $\Rightarrow$ $\mathcal{CP}$ in $\bar{q}q\phi$ couplings $\Rightarrow$ affect the $ggh_i$ coupling: A. Dedes and S. Moretti, PRL 84 (2000) 22,...

II] $\mathcal{CP}$ phases in MSSM $\Rightarrow$ explicit CP mixing for Higgses


III] Effects on the couplings with $b$

Enhanced production cross-sections through $b$-fusion: hep-ph 0401024, F. Borzmuati, J.S. Lee and W. Y. Song

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A few details of the mixing.

**General two-Higgs-doublet Model:**

Two complex $Y = 1$, $SU(2)_L$ doublet scalar fields, $\Phi_1$ and $\Phi_2$

Most general Higgs potential is:

\[
V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.] \\
+ \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
+ \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[ \lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right] \Phi_1^\dagger \Phi_2 + h.c. \right\}
\]

Unitarity $\Rightarrow V \in \mathbb{R} \Rightarrow \left\{ \begin{array}{l}
\{m_{11}, m_{22}, \lambda_{1-4}\} \in \mathbb{R} \\
\{m_{12}, \lambda_{5-7}\} \in \mathbb{C}
\end{array} \right.$

Notice that with one Higgs doublet, we can have no CP violation.
**MSSM:**

Higgs potential as 2HDM above with

\[ m_{11}^2 = -m_1^2 - |\mu|^2 \quad \lambda_1 = \lambda_2 = -(g^2 + g'^2)/8 \]
\[ m_{22}^2 = -m_2^2 - |\mu|^2 \quad \lambda_3 = -(g^2 - g'^2)/4 \]
\[ m_{12}^2 = |\mu|B \quad \lambda_4 = g'^2/2 \]
\[ \lambda_5 = \lambda_6 = \lambda_7 = 0 \]

Vacuum expectation values:

\[ \langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} e^{i\xi} \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \]
At tree-level:

Minimisation conditions $\Rightarrow \arg (m_{12}^2 e^{i\xi}) = 0$

Rotate phase away with an appropriate choice of $\Phi_2$

$\Phi_2 \rightarrow e^{-i\xi}\Phi_2 \Rightarrow \arg (m_{12}) = 0$

No CP-violation in tree-level Higgs sector

Higgs bosons are CP-eigenstates
At one-loop:

Now have $\text{arg}(m_{12}^2 e^{i\xi}) \neq 0$

Potentially have CP-violation from soft-susy breaking terms $A_{t,b,\tau}$, $M_3$

\[
\begin{align*}
\tilde{f} & \quad \sim H \\
A & \quad \sim \alpha \frac{m_f^2}{m_{f_1}^2 - m_{f_2}^2} \text{Im}(A_f \mu)
\end{align*}
\]

write $A_f = |A_f|e^{i\Phi_f}$, $M_3 = |M_3|e^{i\Phi_3}$ and $\mu = |\mu|e^{i\Phi_\mu}$

CP-violation parameterised by $\{\Phi_f, \Phi_3, \Phi_\mu\}$

Higgs bosons are NOT CP-eigenstates
The CPX Scenario


“designed to showcase the effects of CP violation in the MSSM”

\[ M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = M_{\text{SuSy}} \]

\[ \mu = 4M_{\text{SuSy}}, \quad |A_{t,b,\tau}| = 2M_{\text{SuSy}}, \quad |M_3| = 1\text{TeV} \]

Allow the following parameters to vary:

\[
\begin{align*}
\tan \beta, & \quad M_{H^+}, \quad M_{\text{SuSy}}, \\
\{\Phi_A, \Phi_B, \Phi_C\}, & \quad \Phi_3, \quad \Phi_\mu
\end{align*}
\]
Moderately light charged Higgs in $\mathcal{CP}$ MSSM and NMSSM.

Masses and couplings


CPX scenario with $\tan\beta = 5$, $M_{H^\pm} = 150\text{GeV}$, $M_{\text{SuSy}} = 500\text{GeV}$, $\Phi_\mu = 0$, $\Phi_{\tilde{g}} = 0$ and $\pi/2$.

masses:

$M_{H_3} \sim 150\text{ GeV}$

$\Phi_{\tilde{g}}$ does not have a big effect (two-loop)
Moderately light charged Higgs in \( \mathcal{P} \) MSSM and NMSSM.

**Couplings to VV**

Sum rule for couplings

\[
\sum_{i=1}^{3} g_{\phi,VV}^2 = g_{\phi,VV}^2 (SM)
\]

Often \( g_{\phi,ZZ} \) vanishes!

\[ \Rightarrow \text{light Higgs may have escaped LEP limits} \]
Moderately light charged Higgs in $\mathcal{F}$P MSSM and NMSSM.

**LEP Limits**

Preliminary OPAL results: hep-ex/0406057, EJPC 37, 2004,49; LHWG-Note 2004-01

\[
\begin{align*}
\Phi_{A_t} &= \Phi_{A_b} = \Phi_{A_r} = \Phi_{\bar{g}} = \frac{\pi}{2} \\
\Phi_{\mu} &= 0 \\
M_{\text{Susy}} &= 500 \text{ GeV}
\end{align*}
\]

Even have gaps at 0–50 GeV!
**Moderately light charged Higgs in $\mathcal{P}$MSSM and NMSSM.**

**LEP Allowed Window**

$gg \rightarrow \phi$ cross-sections


\[ g \bar{h}_L \bar{t}_R = \frac{igm_t}{2M_W \sin \beta} (\mu^* \sin \alpha - A_t \cos \alpha) \]

$gg \rightarrow \phi$ cross-sections may be altered
Moderately light charged Higgs in $\mathcal{CP}$ MSSM and NMSSM.


Gaps in coverage! Need to look at the light higgs searches again.

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A few observations

- Small regions in $\tan \beta, M_{H^+}$ plane where LHC, TEVATRON will have no reach

- Caused by reduced $\phi_1$ coupling to $W/Z$ AND $\text{top}$.

- The $\phi_1 W H^\pm$ coupling remains large.

- A light $\phi_1$ always accompanied by a 'light' $H^\pm$ too!
What happens to plots of our experimentalist friends at the LHC?

preliminary results presented by M. Schumacher at the meeting on 'CP violation and nonstandard Higgs' //http://kraml.home.cern.ch/kraml/CPstudies/

Warning by M.S.: NOT the official ATLAS results.

A hole in the tan $\beta - M_{H^+}$ plane: for $m_{\phi_1} < 50$, $100 < m_{\phi_2} < 110$ and $130 < m_{\phi_3} < 180$.

The results of theory analysis verified.
Moderately light charged Higgs in \( \mathcal{CP} \) MSSM and NMSSM.

A 'light' \( H^\pm \)

Small \( \tan \beta \), light \( H^\pm \), \( (M_{H^+} < M_t) \Rightarrow H^\pm \) can be produced in the top decay

The sum rules on couplings means large \( H^\pm W_1 \phi_1 \) coupling \( \Rightarrow \) large \( B.R.(H^+ \to \phi_1 W) \)

\[ \Phi_{CP} = 90^\circ. \]

<table>
<thead>
<tr>
<th>( \tan \beta )</th>
<th>3.6</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Br}(H^+ \to \phi_1 W^+)(%) )</td>
<td>( &gt; 90(87.45) )</td>
<td>( &gt; 90(57.65) )</td>
<td>( &gt; 90(46.57) )</td>
</tr>
<tr>
<td>( \text{Br}(t \to bH^+)(%) )</td>
<td>( \sim 0.7 )</td>
<td>( .7 - 1.1 )</td>
<td>( 1.0 - 1.3 )</td>
</tr>
<tr>
<td>( M_{H^+} ) (GeV)</td>
<td>( &lt; 148.5 ) (149.9)</td>
<td>( &lt; 139 ) (145.8)</td>
<td>( &lt; 126.2 ) (134)</td>
</tr>
<tr>
<td>( M_{\phi_1} ) (GeV)</td>
<td>( &lt; 60.62 ) (63.56)</td>
<td>( &lt; 49.51 ) (65.4)</td>
<td>( &lt; 29.78 ) (53.49)</td>
</tr>
</tbody>
</table>

The \( \text{BR}(H^\pm \to \phi_1 W) > 47\% \) over the entire kinematic region in the light \( \phi_1 \) window still allowed by LEP. The BR of \( H^\pm \) in the usual \( \tau \nu_\tau \) channel discussed yesterday by Dr. Hashemi suppressed by over an order of magnitude.

In the light \( \phi_1 \) LEP window the \( H^\pm \) can also be NOT searched for using the usual strategies for \( \mathcal{CP} \) case.

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Moderately light charged Higgs in \( \mathcal{O} \) MSSM and NMSSM. Light \( H^\pm, H_1 \) in NMSSM too!

**NMSSM:** enlarge the Higgs sector of the MSSM by adding additional Higgs Singlets; try to solve the \( \mu \) problem!

\[
W = \lambda \tilde{S} \tilde{H}_1 \tilde{H}_2 - \frac{k}{3} \tilde{S}^3
\]

The resulting \( F \) term of the Higgs potential is

\[
V_F = \lambda^2 x^2(v_1^2 + v_2^2) + \lambda^2 v_1^2 v_2^2 + k^2 x^4 - 2\lambda k x^2 v_1 v_2,
\]

where \( x = \langle S \rangle, \ v_{1,2} = \langle H_{1,2}^0 \rangle \) and \( \tan \beta = v_2/v_1 \).

The \( D \)-term same as in MSSM, i.e.

\[
V_D = \frac{1}{8}(g^2 + g'^2)(v_1^2 - v_2^2)^2 + \frac{1}{2}g^2 v_1^2 v_2^2.
\]

\( F \)-term of the MSSM: \( V_F = \mu^2(v_1^2 + v_2^2) \implies \mu = \lambda x \)

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The upper limit on the lightest Higgs mass is now:

\[ M_{H_1}^2 \leq M_Z^2 \cos^2(2\beta) + \frac{2\lambda^2 M_W^2}{g^2} \sin^2(2\beta) + \epsilon, \]

The NMSSM relaxes the LEP bound on \( M_{H_1} \). Due to the second term in red above.

Effect pronounced at moderate \( \tan \beta \)

Relaxes then the limit on the doublet pseudoscalar mass parameter \( M_A \) hence on \( M_{H^+} \).

\[ M_{H^+}^2 = M_A^2 + M_W^2 \left( 1 - \frac{2\lambda^2}{g^2} \right) \]
A limit on $M_{H^\pm}$ is possible only a limit on $\lambda$ is possible.

Such a limit obtained by demanding that all couplings remain perturbative up to some high scale.

Apart from $\lambda, \kappa$ and $x$, one also has the sift SUSY breaking parameters: $A_\lambda, A_\kappa$.

We obtain a limit by varying all these parameters of the NMSSM potential, imposing LEP constraints.

Direct LEP bound is also shown.

For $\tan \beta \leq 6(4)$ $M_{H^+} > 150(175)$ GeV for MSSM. In NMSSM a $H^\pm$ with mass less than 120 GeV allowed over this range.
1. If \((M_{H^+} \simeq 120 \text{ GeV})\) one has a dominantly singlet \(H_1\) with \((M_{H_1} \simeq 50 \text{ GeV})\). Thus this \(H_1\) will evade LEP searches and will be difficult to produce at LHC as well. There is a light \((50 \text{ GeV})\) pseudoscalar \(A_0\) with significant doublet component. Such \(H^\pm\) can be searched through \(H^+ \rightarrow \tau^+\nu\).

2. \((M_{H^+} > 130 \text{ GeV})\), (in this \(\tan\beta\) range), decays dominantly via the \(H^+ \rightarrow W^+ A_1^0\). This is a good channel for the \(H^\pm\) as well as \(A_1^0\) search.

<table>
<thead>
<tr>
<th>(\tan\beta)</th>
<th>(M_{H^+}) (GeV)</th>
<th>(M_{A_1}) (GeV)</th>
<th>(B_{A_1}) (%)</th>
<th>(\lambda, \kappa)</th>
<th>(x = v_s/\sqrt{2}, A_{\lambda}, A_{\kappa}) (GeV)</th>
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</thead>
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<td>38</td>
<td>94</td>
<td>.45,-.69</td>
<td>224,-8,2</td>
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<td>563,170,85</td>
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<tr>
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<td>150</td>
<td>10</td>
<td>91</td>
<td>.26,-.54</td>
<td>503,109,38</td>
</tr>
</tbody>
</table>
Moderately light charged Higgs in P MSSM and NMSSM. 'Light' $H^\pm \rightarrow W + \phi_1(A^0_1)$

Look at

\[
pp \rightarrow t \hspace{1cm} + \hspace{1cm} \bar{t} \hspace{1cm} + \hspace{1cm} X
\]

\[
\downarrow bH^+ \hspace{1cm} \downarrow W \hspace{1cm} \hspace{1cm} \downarrow \ell\nu(q\bar{q}) \hspace{1cm} \downarrow b\bar{b}
\]

\[
\downarrow H_1 \hspace{1cm} \downarrow \bar{b}W \hspace{1cm} \downarrow q\bar{q}(\ell\nu)
\]

Process allows a probe of a light $H^\pm$ and light neutral Higgs.

Use $t\bar{t}$ production with:

$t \rightarrow bH^+ \rightarrow b\phi_1W \rightarrow b\bar{b}\bar{W}$ and $\bar{t} \rightarrow \bar{b}W$, with one $W$ decaying leptonically the other hadronically. Hence both $W$'s can be reconstructed.

Look at the $WWb\bar{b}bb$ events, demand three tagged $b$'s.

The mass of the $b\bar{b}$ pair with the smallest value will cluster around $m_{\phi_1}$ and $b\bar{b}W$ around $M_{H^+}$.

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Moderately light charged Higgs in \( \mathcal{O} \) MSSM and NMSSM.

'Light' \( H^\pm \rightarrow W + \phi_1(A^0) \)

Cross-sections substantial. With 30 fb\(^{-1}\) data one expects upto \( \sim \) 4500 events after all the cuts.

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LHC Signal: very clear clustering in the $b\bar{b}$, $b\bar{b}W$ invariant masses corresponding to $m_{\phi_1}$, $M_{H^+}$ also in $b\bar{b}bW$ invariant mass at $m_t$. So detectability controlled by mainly the signal size.

The QCD bkgd can be removed by demanding that $b\bar{b}bW$ mass within 25 GeV of $m_t$.

Need experimental analyses of this signal. ATLAS has done a preliminary analysis.

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Conclusions

- In CPX scenario a light neutral Higgs $\phi_1 < 50$ GeV could have been missed at LEP for $3 < \tan \beta < 5, 125 < M_{H^+} < 140$ GeV. LHC and Tevatron can not see such a (pseudo)scalar either. The $H^{\pm}$ in this 'mass window' will dominantly decay into $W \phi_1$.

- In NMSSM the lower limit on $H^{\pm}$ mass as well as $H^0, A^0$ mass are relaxed. For ($M_{H^+} > 130$ GeV) and moderate $\tan \beta$, the dominant decay via the $H^+ \to W^+ A^0_1$ channel provides a probe for not only a light $H^+$ but also a light $A^0_1$ via its decay into a $b\bar{b}$ final state.

- Such a light charged $H^+$ decaying dominantly into the $WH_1$ channel, giving rise to a striking $t\bar{t}$ signal at the LHC, where one of the top quarks decays into the $b\bar{b}W$ channel, via $t \to bH^\pm, H^\pm \to WH_1$ and $H_1 \to b\bar{b}$.

- The characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $bb\bar{b}W$ invariant mass peaks helps reduce the SM background, drastically.

- We have pointed out some novel features of the phenomenology of a light charged Higgs a light neutral Higgs, still allowed by the LEP data in the NMSSM and CP SUSY at the LHC.

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