Moderately Light Charged Higgs in $\not{C}\not{P}$ MSSM and NMSSM.

- ♢ 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.

1) D.K. Ghosh, D.P. Roy and R.G., Phys. Lett. B.628,131 (2005) 2) D.P. Roy and R.G. (Contribution to the CPNSH report)

Introduction

Want to disucss 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 $\not{CP}$ SUSY.

Why study $\not{CP}$; why study $\not{CP}$ in SUSY?

The phenomenon still lacks a fundamental understanding

- CKM description vindicated by measurements of CP mixing in the B_0 sector.
- CKM $\not{CP}$ **not** sufficient to explain **quantitatively** why

$$\frac{N_b}{N_\gamma} \sim 6.1 \times 10^{-10} \qquad \frac{N_{\bar{b}}}{N_\gamma} \sim 0 \tag{1}$$

- **Sources of CP violation beyond the CKM?**

$\not{CP}$ 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 $\not{CP}$ phases in SUSY to zero.

Now:

Ibrahim et al 97,Brhlik et al 98,Bartl et al 99,Falk et al 98,99,.... Farzan, Ayazi 2006.

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 $\not{CP}$ in MSSM a Swan?

A few more things about $\not{CP}$:

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

2. The MSSM $\not{CP}$ 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 $\not{CP}$ 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 $\not{CP}$ on Higgs phenomenology

MSSM $\not{CP}$ phases $\Rightarrow$ $\not{CP}$ in the Higgs sector:

CP conserving MSSM Three Neutral Higgses h,H CP-even A CP-odd

CP violation : ϕ_1, ϕ_2, ϕ_3 no fixed CP property

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

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

(A. Mendez and A. Pomarol, PLB **272** (1991) 313. J.Gunion, H. Haber and J. Wudka, PRD **43** (1991) B.Grzadkowski, J.Gunion and J. Kalinowski, PRD **60** (1999) 075011)

$$g^2_{\phi_i WW} + g^2_{\phi_j WW} + g^2_{\phi_k WW} = g^2 m^2_W, i \neq j \neq k$$

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 $\not{CP}$ phases in the MSSM for this mixing.

Three types of effects on Higgs production rates

I] $\not{CP}$ phases in MSSM ⇒ $\not{CP}$ in $\tilde{q}\tilde{q}\phi$ couplings ⇒ affect the ggh_i coupling: A. Dedes and S. Moretti, PRL **84** (2000) 22,...

II] $\not{CP}$ phases in MSSM ⇒ *explicit* CP mixing for Higgses

A. Pilaftsis, PLB **435** (1998) 88, A. Pilaftsis, C. E. Wagner, NPB **553**, 3 (1999), S. Y. Choi, M. Drees and J. S. Lee, PLB **481**, 57 (2000)....

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

A few details of the mixing.

General two-Higgs-doublet Model:

Two complex $Y = 1$, $SU(2)_L$ doublet scalar fields, Φ_1 and Φ_2

Most general Higgs potential is:

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

$$
\text{Unitarity} \Rightarrow V \in \Re \Rightarrow \begin{cases} \{m_{11}, m_{22}, \lambda_{1-4}\} \in \Re \\ \{m_{12}, \lambda_{5-7}\} \in \mathcal{C} \end{cases}
$$

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

MSSM:

Higgs potential as 2HDM above with

$$\begin{array}{ll} m_{11}^2 = -m_1^2 - |\mu|^2 & \lambda_1 = \lambda_2 = -(g^2 + g'^2)/8 \\ m_{22}^2 = -m_2^2 - |\mu|^2 & \lambda_3 = -(g^2 - g'^2)/4 \\ m_{12}^2 = \mu B & \lambda_4 = g^2/2 \\ & \lambda_5 = \lambda_6 = \lambda_7 = 0 \end{array}$$

Vacuum expectation values:

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} e^{i\xi} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

At tree-level:

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

Rotate phase away with an appropriate choice of Φ_2

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

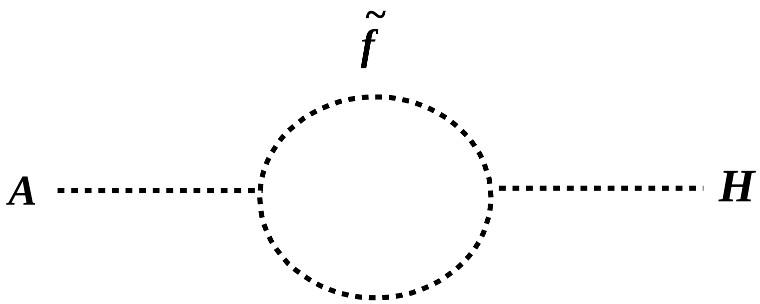
No CP-violation in tree-level Higgs sector

Higgs bosons are CP-eigenstates

At one-loop:

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

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



$$\propto \frac{m_f^2}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \Im m(A_f \mu)$$

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

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

Higgs bosons are NOT CP-eigenstates

The CPX Scenario

[Carena, Ellis, Pilaftsis & Wagner, Phys. Lett. **B495** (2000) 155]

"designed to showcase the effects of CP violation in the MSSM"

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\mathsf{SuSy}}$$

$$\mu = 4M_{\mathsf{SuSy}}, \quad |A_{t,b,\tau}| = 2M_{\mathsf{SuSy}}, \quad |M_3| = 1TeV$$

Allow the following parameters to vary:

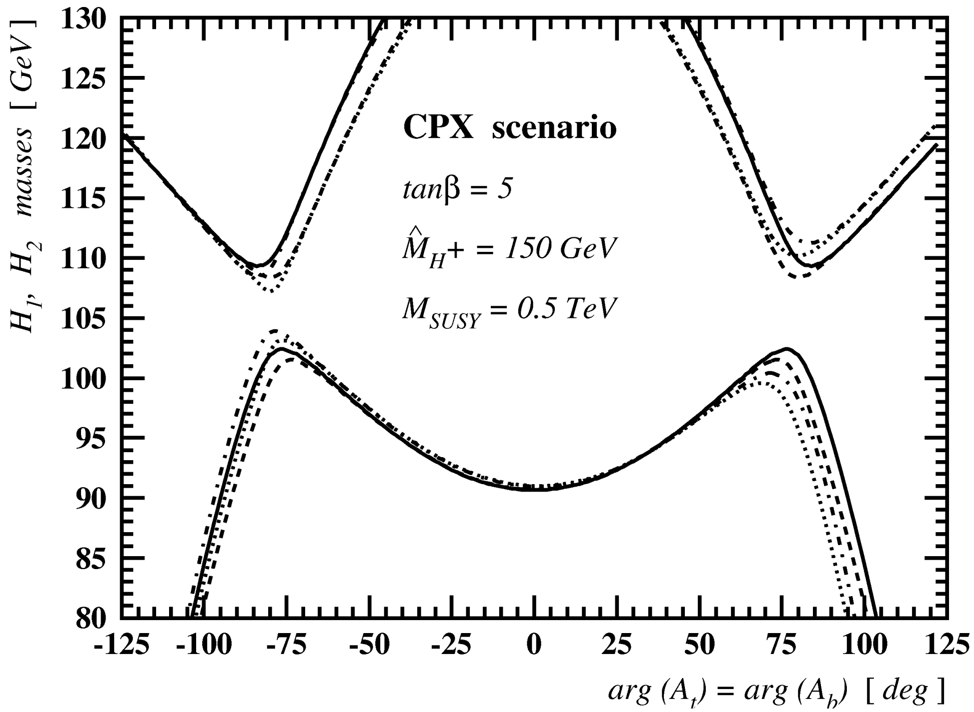
$\tan\beta$,	$M_{H^\pm}$,	M_{SuSy},
$\{\Phi_{A_t}, \Phi_{A_b}, \Phi_{A_\tau}\}$,	Φ_3,	Φ_μ

Masses and couplings

[Carena, Ellis, Pilaftsis & Wagner, Nucl. Phys. B **625** (2002) 345]

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

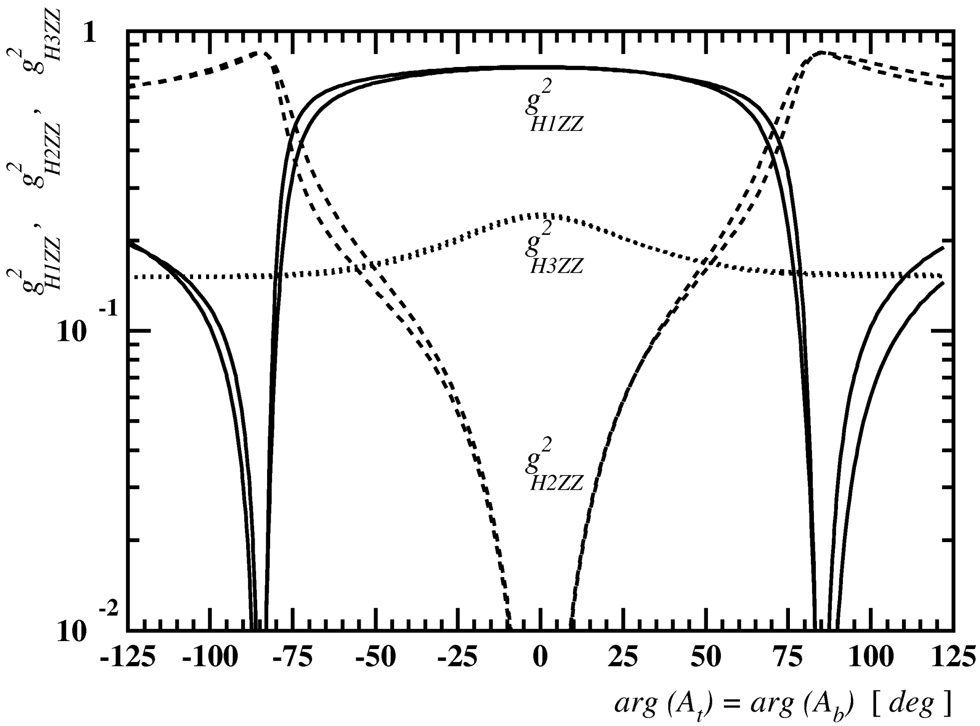
masses:



$M_{H_3} \sim 150$ GeV

$\Phi_{\tilde{g}}$ does not have a big effect (two-loop)

couplings to VV:



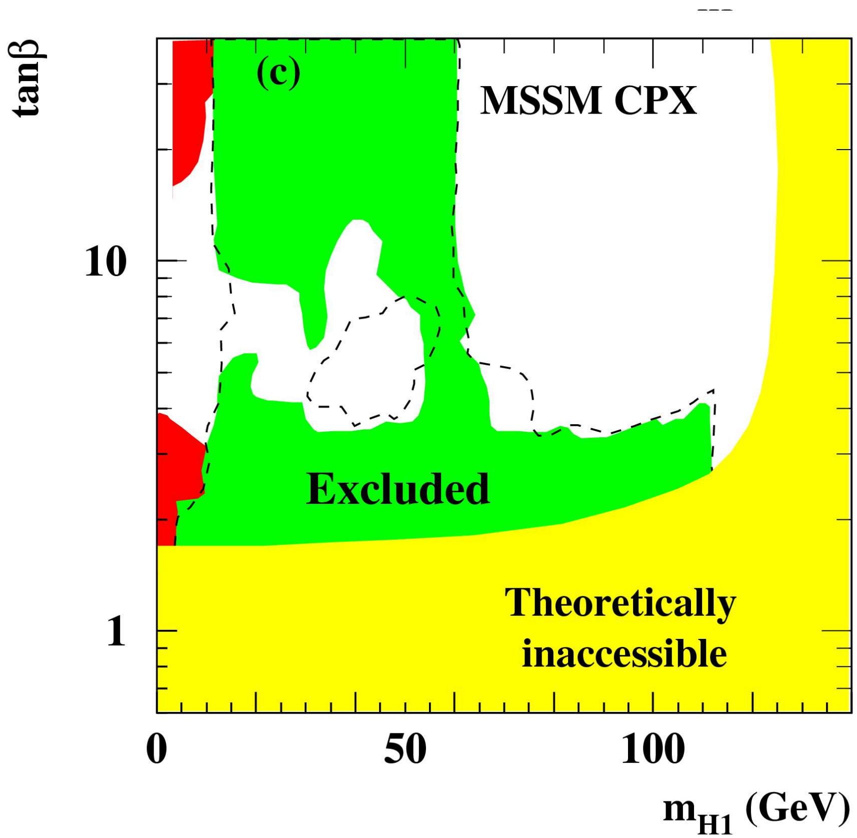
Sum rule for couplings

$$\sum_{i=1}^{3} g^2_{\phi_i VV} = g^2_{\phi_i VV\ (SM)}$$

Often $g_{\phi_i ZZ}$ vanishes!

$\Rightarrow$ light Higgs may have escaped LEP limits

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



$$\Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau} = \Phi_{\tilde{g}} = \frac{\pi}{2}$$

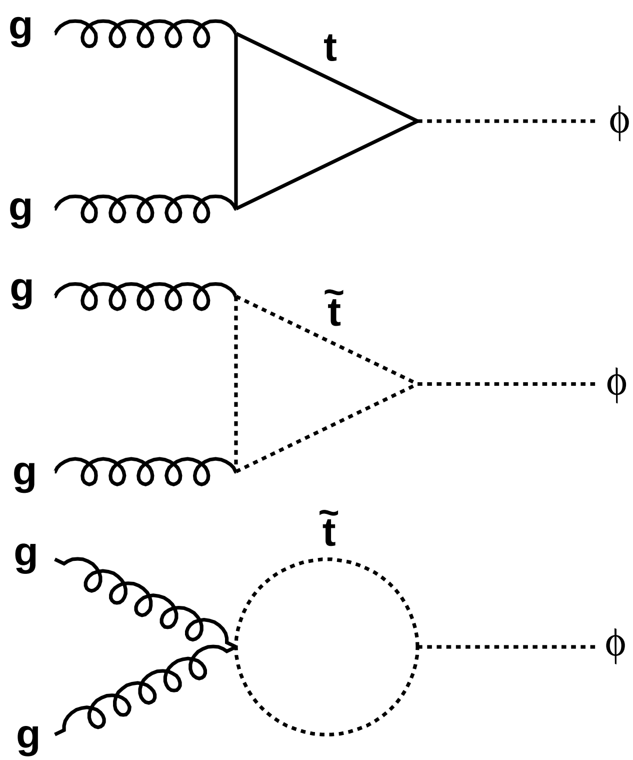
$$\Phi_\mu = 0$$

$$M_{\mathrm{SuSy}} = 500 \text{ GeV}$$

Even have gaps at 0–50 GeV!

$gg \to \phi$ cross-sections

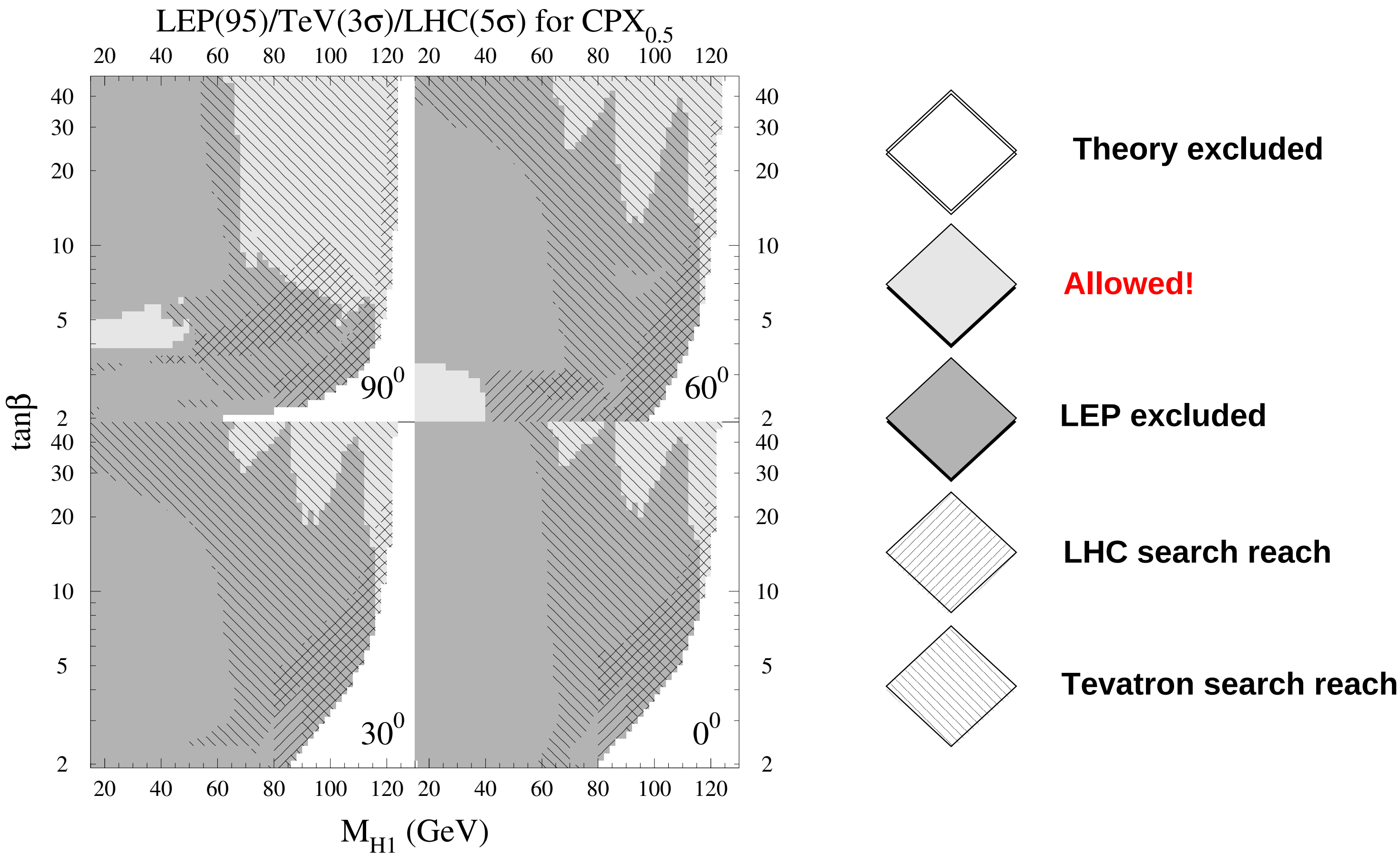
[Dedes, Moretti, Nucl. Phys. B **576** (2000) 29
Lee, Pilaftsis, Carena, Choi, Drees, Ellis & Wagner, Comput. Phys. Commun. **156** (2004) 283]



$$g_{h\tilde{t}_L\tilde{t}_R^*} = \frac{igm_t}{2M_W \sin\beta}(\mu^* \sin\alpha - A_t \cos\alpha)$$

$gg \to \phi$ cross-sections may be altered

[Carena, Ellis, Mrenna, Pilaftsis & Wagner, Nucl. Phys. B **659** (2003) 145]

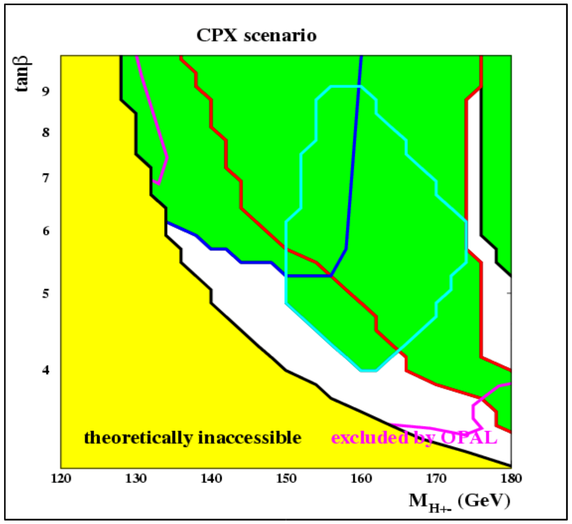


Gaps in coverage! Need to look at the light higgs searches again.

A few observations

- Small regions in $\tan\beta, M_{H^+}$ plane where LHC,TEVATRON will have no reach
- Caused by reduced ϕ_1 coupling to W/Z AND *top*.
- The $\phi_1 W H^\pm$ coupling remains large.
- A light ϕ_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.

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 $H^\pm W \phi_1$ coupling $\Rightarrow$ large $B.R.(H^+ \to \phi_1 W)$

$\Phi_{\rm CP} = 90°$.

$\tan\beta$	3.6	4	5
Br($H^+ \to \phi_1 W^+$)(%)	$> 90(87.45)$	$> 90(57.65)$	$> 90(46.57)$
Br($t \to bH^+$)(%)	~ 0.7	$.7 - 1.1$	$1.0 - 1.3$
M_{H^+} (GeV)	< 148.5 (149.9)	< 139 (145.8)	$< 126.2(134)$
M_{ϕ_1} (GeV)	< 60.62 (63.56)	< 49.51 (65.4)	$< 29.78(53.49)$

The BR ($H^\pm \to \phi_1 W > 47\%$ over the *entire* kinematic region in the light ϕ_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 ϕ_1 LEP window the $H^\pm$ can also be NOT searched for using the usual strategies for $\not{CP}$ case.

NMSSM: enlarge the Higgs sector of the MSSM by adding additional Higgs Singlets; try to solve the μ problem!

$$W = \lambda \widehat{S} \widehat{H}_1 \widehat{H}_2 - \frac{k}{3} \widehat{S}^3$$

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: $V_F = \mu^2 (v_1^2 + v_2^2) \Longrightarrow$

$\mu = \lambda x$

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 $\tan\beta$

Rleaxes then the limit on the doublet pseudoscalar mass parameter M_A hence on $M_{H^\pm}$.

$$M_{H^+}^2 = M_A^2 + M_W^2 (1 - \frac{2\lambda^2}{g^2})$$

A limit on $M_{H^\pm}$ is possible **only** a limit on λ is possible.

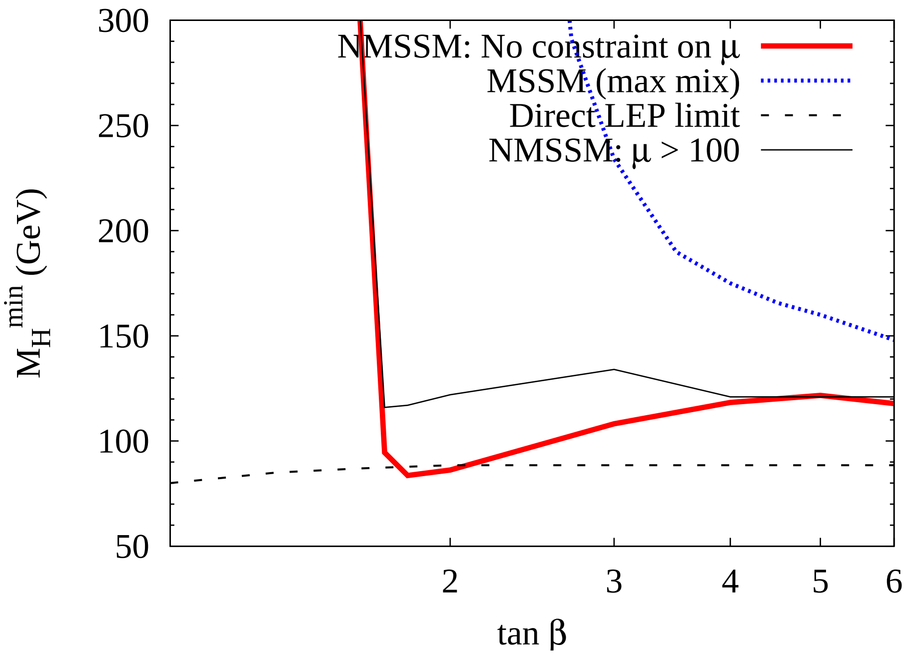
Such a limit obtained by demanding that all couplings remain perturbative upto some high scale.

Apart from λ, κ and x, one also has the sift SUSY breaking parameters: A_λ, A_κ.

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 GeV) one has a dominantly singlet H_1 with ($M_{H_1} \simeq$ 50 GeV). Thus this H_1 will evade LEP searches and will be difficult to produce at LHC as well. There is a light (50 GeV) pseudoscalar A_0 with significant doublet component. Such $H^{\pm}$ can be searched through $H^+ \to \tau^+ \nu$.

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

$\tan\beta$	M_{H^+} (GeV)	M_{A_1} (GeV)	B_{A_1} (%)	λ, κ	$x = v_s/\sqrt{2}, A_\lambda, A_\kappa$ (GeV)
2	147	38	94	.45,-.69	224,-8,2
3	159	65	83	.33,-.70	305,40,38
4	145	48	89	.28,-.70	563,170,85
5	150	10	91	.26,-.54	503,109,38

Look at

$$pp \to t \quad + \quad \bar{t} \quad + \quad X$$

$t \hookrightarrow b\,H^+$, $H^+ \hookrightarrow W\ H_1$, $W \hookrightarrow \ell\nu(q\bar{q})$, $H_1 \hookrightarrow b\bar{b}$

$\bar{t} \hookrightarrow \bar{b}\,W$, $W \hookrightarrow q\bar{q}(\ell\nu)$

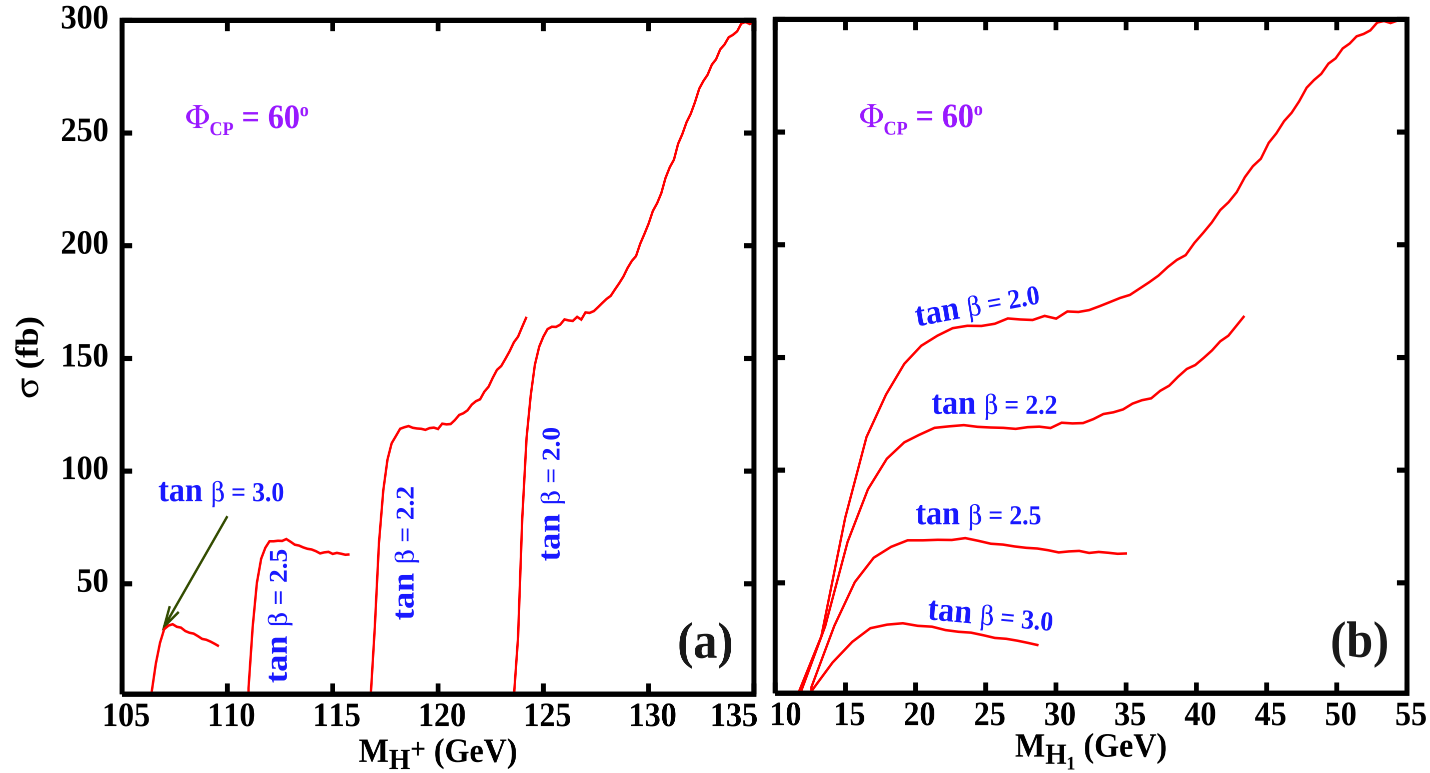
Process allows a probe of a light $H^{\pm}$ **and** light neutral Higgs.

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

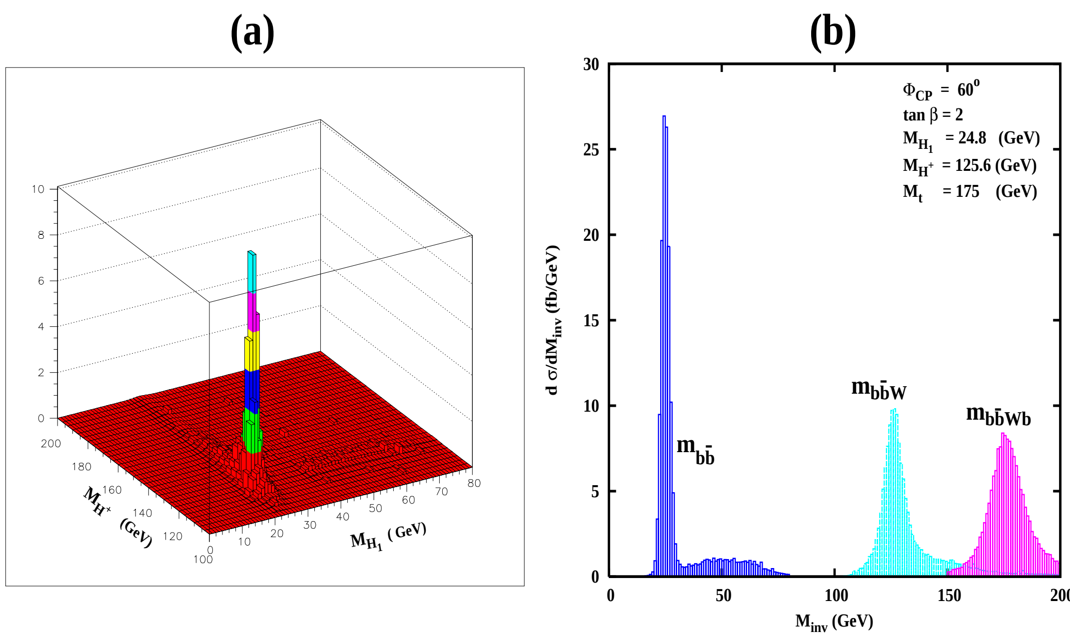
$t \to bH^+ \to b\phi_1 W \to bb\bar{b}W$ and $\bar{t} \to \bar{b}W$, with one W decaying leptonically the other hadronically. Hence both $W's$ can be reconstructed.

Look at the $WWbbbb$ events, demand three tagged $b's$.

The mass of the $b\bar{b}$ pair with the smallest value will cluster around m_{ϕ_1} and $b\bar{b}W$ around M_{H^+}.



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



LHC Signal : very clear clustering in the $b\bar{b}$, $b\bar{b}W$ invariant masses corresponding to m_{ϕ_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 bbbW mass within 25 GeV of m_t.

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

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 ($M_{H^{\pm}} > 130$ GeV) and moderate $\tan\beta$, the dominant decay via the $H^+ \to W^+ \ A_1^0$ channel provides a probe for not only a light H^+ but also a light A_1^0 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 $bb\bar{b}W$ 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 $\not{CP}$ SUSY at the LHC.