Probing super light neutral Higgs boson at the LHC in CP violating MSSM Higgs sector

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1-2 September, 2010

Plan

- **CP violating ($\not{C}P$) MSSM Higgs sector**
- **General feature of the phenomenology of the CP violating ($\not{C}P$) MSSM Higgs sector**
- **Study of ultra light Higgs boson ($m_H \leq 60$ GeV) at LHC in Four possible scenarios**
- **Summary**

CP violation in Higgs sector

- **CP violation arises naturally in the three generation SM (Phase in the CKM matrix)**

- **The CP violation has been first measured in neutral K-meson decays. [J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay , *Phys. Rev. Lett.*13, 138 (1964)]**

- **CP non-conservation provides a key ingredient for cosmological baryogenesis**

- **It is possible to have CP violation in Multi-Higgs models**

- **MSSM contains an extended Higgs sector : may realize CP violation**

General frame work

- **Higgs potential of the MSSM is invariant under CP at the tree level**
- **Two CP-even neutral Higgs bosons :**h^0, H^0 $(M_{H^0} > M_{h^0})$
- **One CP-odd neutral Higgs boson :**A^0
- **One charged Higgs boson :**$H^\pm$
- $M_A, \tan\beta, \mu$ **and** $A_{t,b}$ **control the MSSM Higgs spectrum**
- **The tree level CP invariance of the MSSM Higgs potential may be violated sizeably by loop effects involving soft CP-violating trilinear couplings** $A_{t,b}$ **[A. Pilaftsis, PRD58,096010 (1998) and PLB435,88 (1998)]**

CP violation in MSSM

- **After radiative corrections to the tree level Higgs potential: CP violation induced through loop effects via 3 generation sfermion and gaugino mass parameters**

- **From the one loop effective potential Higgs boson mass matrix is calculated [J.Ellis et al'90, Y.Okada et al '90, E.Haber et al'90,..M.Carena et al'95...A.Demir'99, A.Pilaftsis et al'99... S.Y.Choi et al'99]**

$$M_N^2 = \begin{pmatrix} M_S^2 & M_{SP}^2 \\ M_{PS}^2 & M_P^2 \end{pmatrix}$$

- M_S^2, M_P^2 **and** M_{SP}^2 **denote the** 2×2 **matrices of the scalar, pseudoscalar and scalar-pseudoscalar squared mass terms of the neutral Higgs bosons.**

$$M_{PS}^2 \simeq \mathcal{O}\left(\frac{m_t^4}{v^2}\frac{|\mu||A_t|}{32\pi^2 M_S^2}\right)\sin\phi_{CP}\left(1, \frac{|A_t|^2}{M_S^2}, \frac{|\mu|^2}{\tan\beta M_S^2}, \frac{|\mu||A_t|}{M_S^2}\right)$$

- M_S **is stop mass average,** $\phi_{CP} = Arg(A_{t,\mu})$

CP violation in MSSM Higgs sector

- **In CP conserving MSSM:** $M_{SP} = 0$: **2 CP-even h, H and one CP-odd A.**
- $\mathrm{Diag}(M^2_{H_1}, M^2_{H_2}, M^2_{H_3}) = O^T M^2_N O$, with $M_{H_1} < M_{H_2} < M_{H_3}$
- **After diagonalization the Physical mass eigenstates are mixed states of CP,** $H_{1,2,3}$ **have undefined CP properties.**
- **To get sizeable CP violation, large** $\mid \mu \mid, \mid A_{t,b} \mid$ **and large** $\sin\phi_{CP}$ **are needed**
- m_A **no longer a physical parameter, but the** $m_{H^\pm}$ **can be used as a physical parameter**
- **Elements of matrix** O **are similar to** $\cos\alpha$ **and** $\sin\alpha$ **in the CP-conserving case. But** 3^{rd} **row and column are zero in the non-diagonal elements in such a case**
- **Large** $m_{H^\pm}$ **implies** $H_1 \to H_{sm}$

The interaction between Higgs and gauge bosons

$$\mathcal{L}_{H_iVV} = g m_W \sum_{i=1}^{3} g_{H_iVV} \, [H_i W_\mu^+ W^{-,\mu} + \frac{1}{2c_W^2} H_i Z_\mu Z^\mu]$$

$$\mathcal{L}_{H_iH_jZ} = \frac{g}{2c_W} \sum_{j>i=1}^{3} g_{H_iH_jZ} \, (H_i \overleftrightarrow{\partial}_\mu H_j) Z^\mu$$

$$\mathcal{L}_{HH^\mp W^\pm} = \frac{g}{2c_W} \sum_{i=1}^{3} g_{H_iH^-W^+} \, (H_i \overleftrightarrow{\partial}_\mu H^-) W^{+,\mu}$$

$$g_{H_iVV} = O_{1i} \cos\beta + O_{2i} \sin\beta,$$

$$g_{H_iH_jZ} = O_{3i}(\cos\beta O_{2j} - \sin\beta O_{1j}) - (i \leftrightarrow j)$$

$$g_{H_iH^+W^-} = O_{2i} \cos\beta - O_{1i} \sin\beta + iO_{3i}$$

$$g_{H_kVV} = \epsilon_{ijk} g_{H_iH_jZ}$$

- **We have the following Sum rules:**

$$\sum_{i=1}^{3} g_{H_iVV}^2 = 1,$$

The CPX Scenario

(Carena, Ellis, Pilaftsis & Wagner, PLB495(2000) 155)

- **Designed to showcase the effects of CP violation in the MSSM Higgs sector**

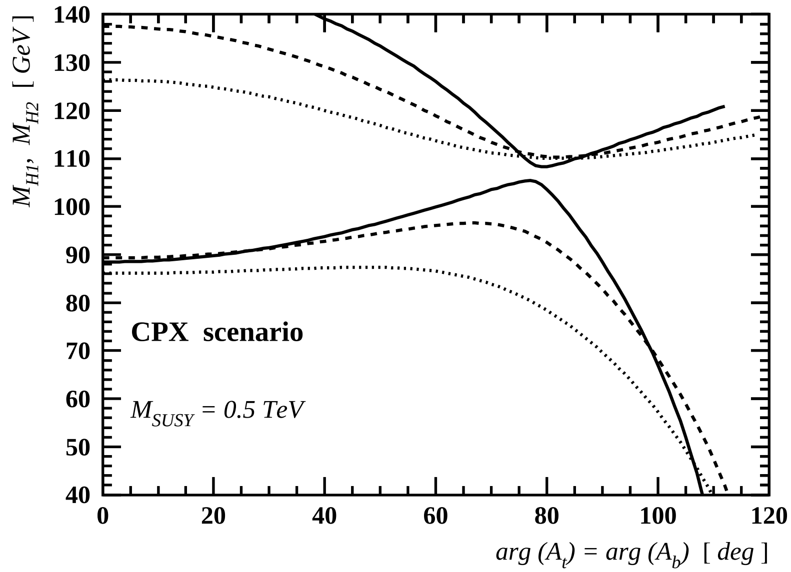
$$M_{\tilde{t}} = M_{\tilde{b}} = M_{\tilde{\tau}} = M_{\rm SUSY}$$
$$\mu = 4M_{\rm SUSY}, \mid A_{t,b,\tau} \mid = 2M_{\rm SUSY}, \mid M_{\tilde{g}} \mid = 1{\rm TeV}$$

- **Allows the following parameters to vary:**

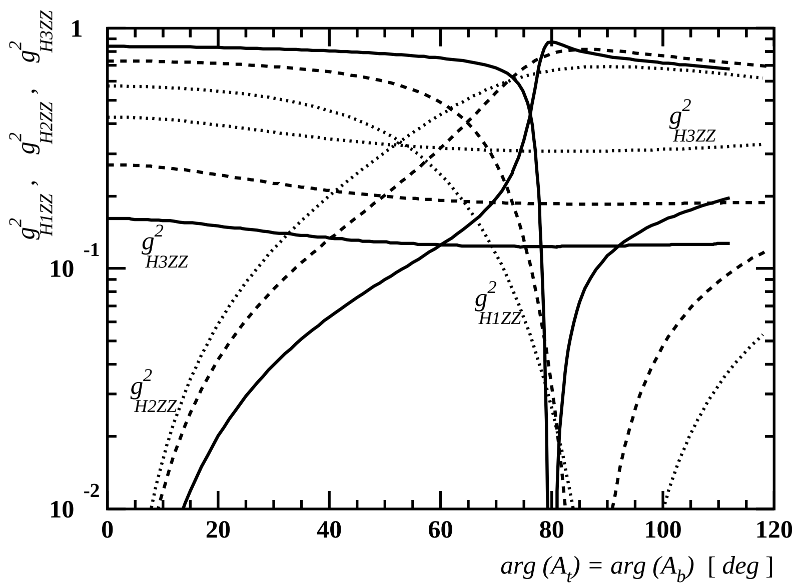
$$\tan\beta, M_{H^\pm}, M_{\rm SUSY}$$
$$\Phi_{A_t}, \Phi_{A_b}, \Phi_{A_\tau}, \Phi_{\tilde{g}}, \Phi_\mu$$

- **The spectrum is generated by CPSUPERH code**
  [J. S. Lee etal, Comput.Phys.Commun. 156,283(2004), hep-ph/0307377]

Implications of CP violating phases on Higgs searches



(a)



(b)

- (a) M_{H_1}, M_{H_2} **and** (b) $g^2_{H_iZZ}$ **as functions of** $\mathrm{Arg}(A_t)$**, in the CPX scenario for** $M_{\mathrm{SUSY}} = 1$ **TeV and for the following choices of** $(M_{H^\pm}, \tan\beta)$**: (160 GeV, 4)(solid lines), (150 GeV, 5) (dashed lines) and (140 GeV, 6) (dotted lines)**

Implications of CP violating phases on Higgs searches

- **In CPC MSSM**, we have access only **two neutral Higgses** h, H in **Higgsstrahlung** /**WW fusion process**

- **In CPV MSSM**, the three neutral Higgs mass eigenstates H_i **(i=1,2,3)** do not have well defined CP quantum numbers.

- Each of them can be produced in the Higgs-Strahlung process: ($e^+e^- \to ZH_i$) and/or in the **WW fusion** ($e^+e^- \to H_i\nu_e\bar{\nu}_e$)

- Also in pair $(e^+e^- \to H_iH_j(i \neq j))$

- The relative rates depend of the choice of the parameters describing the CP-odd/even mising. **[A.Akeroyd & A. Arhrib, PRD64,095018 (2001)]**

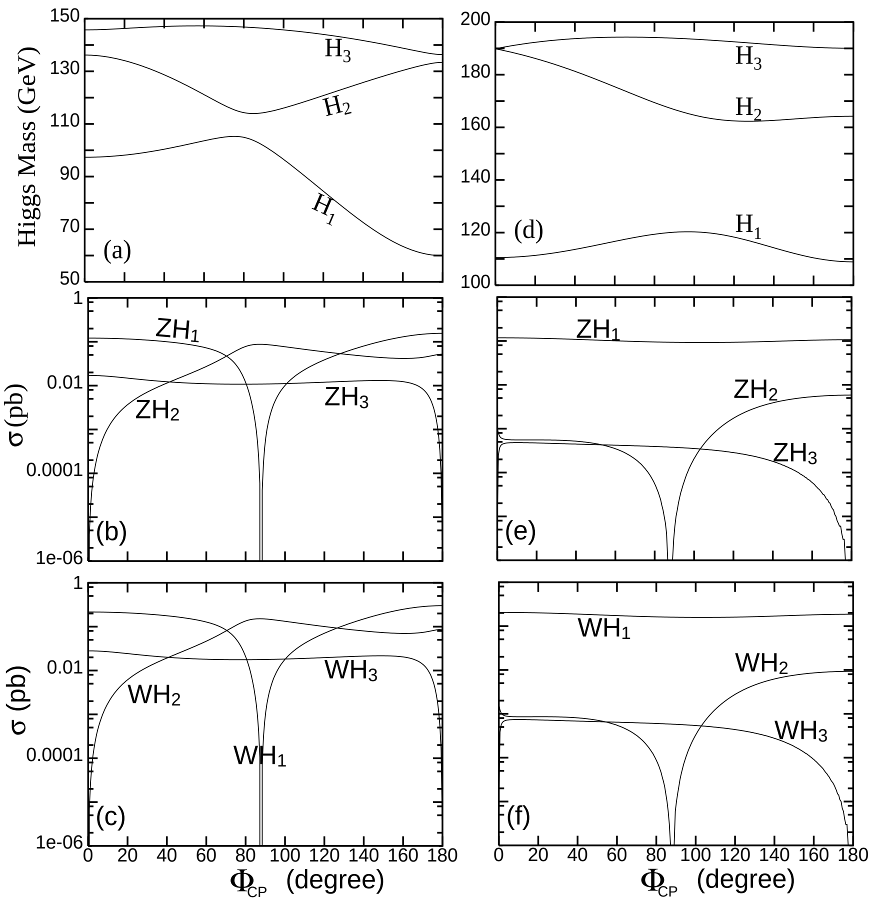
Higgs production in CP violating MSSM

- We studied WH_i **and** $ZH_i, (i = 1, 2, 3)$ pair production at Tevatron ($p\bar{p}$) Run II and LHC (pp) Collider.
  [Arhrib,Ghosh & Kong,PLB'2002]

- Our parameters are fixed as:
  Set A:
  $\widetilde{M}_Q = \widetilde{M}_t = \widetilde{M}_b = 1\text{TeV}$, $|\mu| = 4\text{TeV}$,
  $|A_t| = |A_b| = 2\text{TeV}$, $\text{Arg}(A_t) = \text{Arg}(A_b)$,
  $\tan\beta = 6$
  Set B:
  $\widetilde{M}_Q = \widetilde{M}_t = \widetilde{M}_b = 0.5\text{TeV}$, $|\mu| = 2\text{TeV}$,
  $|A_t| = |A_b| = 2\text{TeV}$, $\text{Arg}(A_t) = \text{Arg}(A_b)$,
  $\tan\beta = 15$

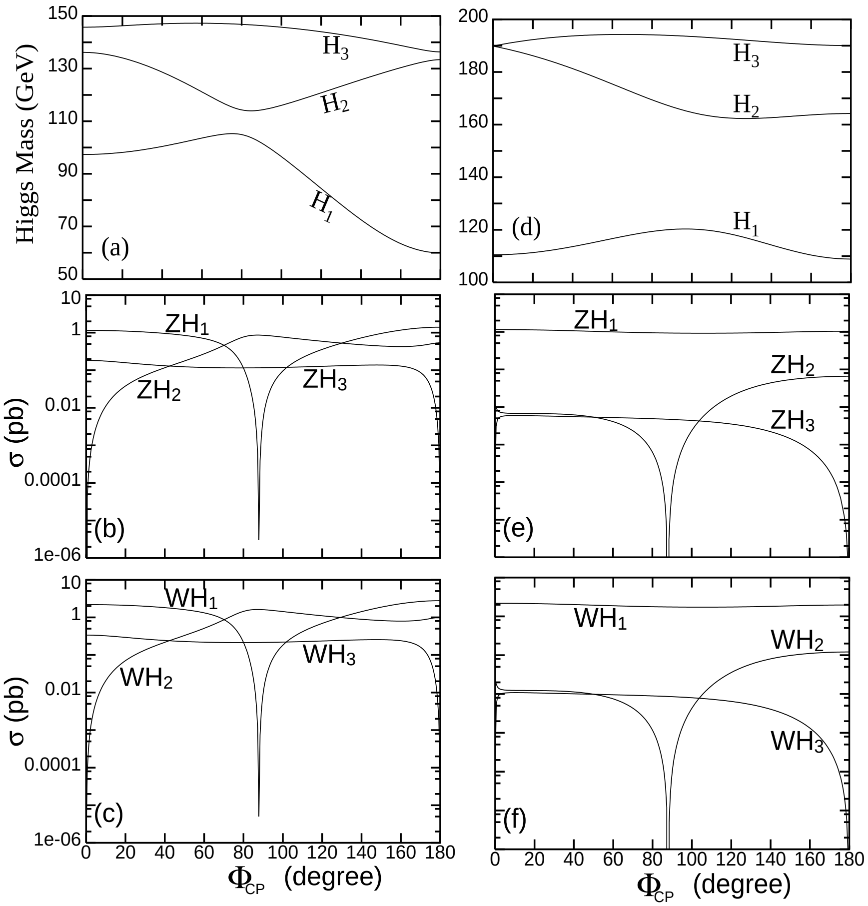
- Interested in $M_{H^\pm} \lesssim 300$ **GeV**
  $M_{H^\pm} > 300$ is the decoupling scenario and H_1 is SM like
  $VVH_1 = 1, VVH_2 = VVH_3 = 0$

Higgs production in CP violating MSSM



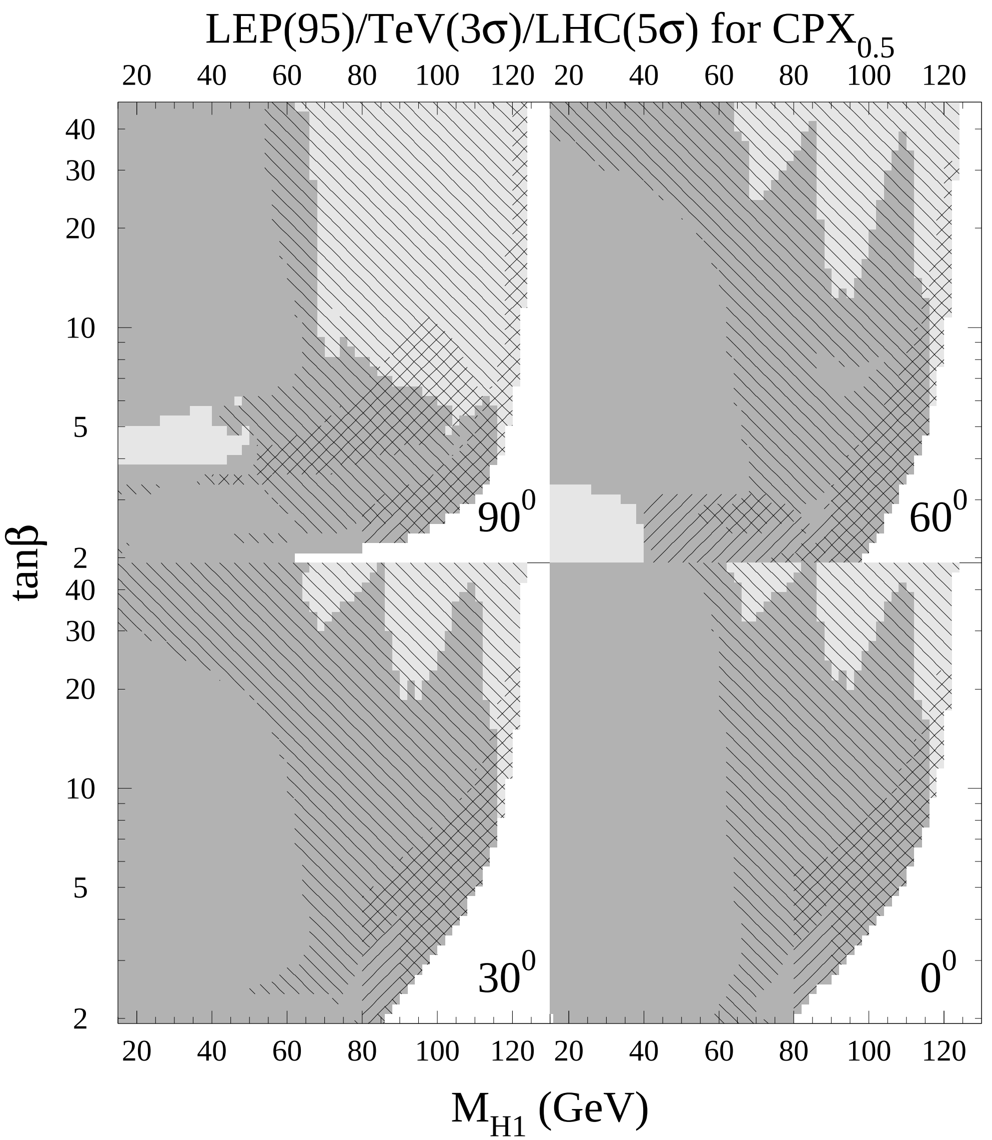
- **Tevatron Run II energy.** $M_{H^\pm} = 150$**(left pannel) and 200 GeV (right pannel). Other MSSM parameters correspond to set** A**.**

Higgs production in CP violating MSSM



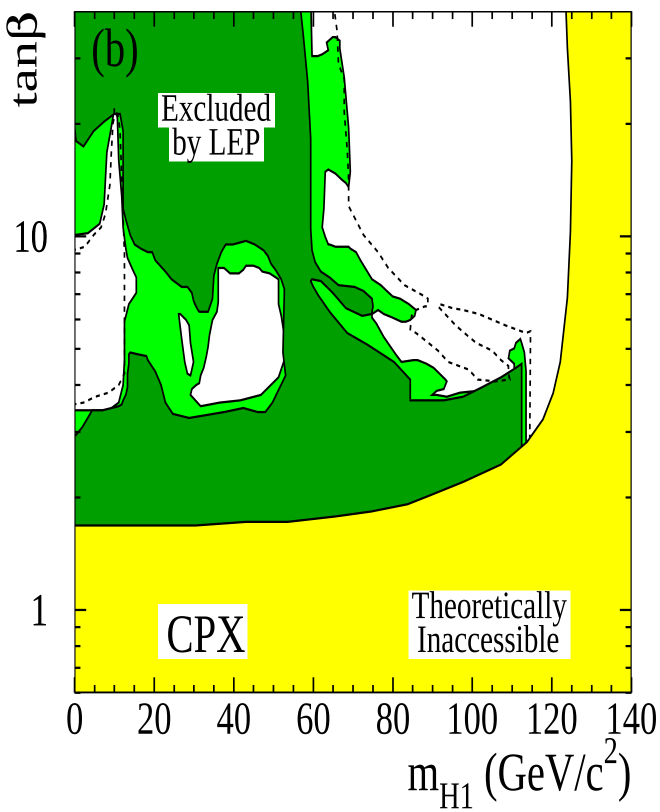
- **LHC energy. $M_{H^\pm} = 150$(left pannel) and 200 GeV (right pannel). Other MSSM parameters correspond to set A.**

Higgs search in CP violating MSSM Higgs sector



- **M. Carena etal. [NPB659,145 (2003)] looked for several channels for Higgs boson H_i searches at hadron colliders**
- 45° **line: Tevatron:** $W/ZH_i(\to b\bar{b})$.
- 135° **line: LHC:** $gg \to H_i \to \gamma\gamma(\ 100\ \mathrm{fb}^{-1})$, $t\bar{t}H_i(\to b\bar{b})(\ 100\ \mathrm{fb}^{-1})$, $WW/ZZH_i(\to \tau^+\tau^-)(\ 100\ \mathrm{fb}^{-1})$.
- **dark grey $\to$ LEP exclusion.**
- **Gaps at $M_{H_1} \leq 50$ GeV for 90° and 60°**

LEP-2 exclusion



- **Exclusions, at 95%CL(light-green) and the 99.7%CL(dark-green)**
- **Two main channels LEP studied : (a) $e^+e^- \to H_1Z(H_2Z)$ and (b) $e^+e^- \to H_1H_2$**
- **For low M_{H_1}, LEP looked at $e^+e^-H_1H_2 \to H_1(H_1H_1) \to 6b$ jets,and 6τ leptons**

[Eur.Phys.J.C47, 547 (2006)]

Light Higgs window : Scenario I

- **LEP can not exclude the light Higgs mass in these two regions of parameter space:**

- $\Phi_{\rm CP} = 90^\circ$, $\tan\beta \sim 4-5$,
  $M_{H^\pm} \sim 125 - 140$ **GeV**, $M_{H_1} \lesssim 60$ **GeV**

- $\Phi_{\rm CP} = 60^\circ$, $\tan\beta \sim 2-3$,
  $M_{H^\pm} \sim 105 - 130{\rm GeV}, M_{H_1} \lesssim 40$ **GeV**

- **Suppressed $H_1 ZZ$ coupling and also the $H_1 t\bar{t}$.**

- **Tevatron also can not probe this because of suppressed W/ZH_1 coupling.**

- **No hope at the LHC through $t\bar{t}H_1$ and W/ZH_1.**

[with D. P. Roy and R. M. Godbole, PLB628,131(2005)]

Light Higgs window : Scenario I

- H_1ZZ **coupling** **is suppressed,** $H^+W^-H_1$ **coupling** **remains large**
- **Large** $H^{\pm}WH_1$ **coupling** $\Rightarrow$ **large Br** $(H^{\pm} \to H_1W^{\pm})$
- **Small** $\tan\beta$**, light** $H^{\pm}, (M_{H^+} < M_t) \Rightarrow H^{\pm}$ **can be produced in the top decay.**

$\tan\beta$	3.6	**5**
$\mathrm{Br}(H^+ \to H_1W^+)(\%)$	> 90**(87.45)**	> 90**(46.57)**
$\mathrm{Br}(t \to bH^+)(\%)$	$\sim$ **0.7**	**1.0 – 1.3**
M_{H^+} **(GeV)**	< 148.5 **(149.9)**	< 126.2**(134)**
M_{H_1} **(GeV)**	< 60.62 **(63.56)**	< 29.78**(53.49)**

The BR $(H^{\pm} \to H_1W) > 0.47$ **over the entire kinematic region in the light** H_1 **window still allowed by LEP. BR** $(H^{\pm} \to \tau\nu_\tau)$ **is suppressed by over an order of magnitude.**

Light Higgs window : Scenario I

$$
\begin{array}{llllll}
pp \to t & & + & \bar{t} & + & X \\
\quad \hookrightarrow b\,H^+ & & & \hookrightarrow \bar{b}\,W & & \\
\qquad \hookrightarrow W & H_1 & & \quad \hookrightarrow q\bar{q}(\ell\nu) & & \\
\qquad\quad \hookrightarrow \ell\nu(q\bar{q}) & \hookrightarrow b\bar{b} & & & &
\end{array}
$$

- **Process allows a probe of a light $H^{\pm}$ and light neutral Higgs.**
- **Use $t\bar{t}$ production with:**
  $t \to bH^+ \to bH_1W \to bb\bar{b}W$ and $\bar{t} \to \bar{b}W$, with one W decaying leptonically the other hadronically.
- **Look for $WWbbbb$ events, demand 3 or more tagged b's.**
- **The mass of the $b\bar{b}$ pair with the smallest value will cluster around M_{H_1} and $b\bar{b}W$ around M_{H^+}**

Light Higgs window : Scenario I

As a basic selection criteria we require

- $\mid \eta_{j,\ell} \mid < 2.5$ **:**

- $p^i_{T_{\rm jets}}(i = 1, 2, 3) > 30$ **GeV**

- p_T **of all the other jets, lepton** > 20 **GeV,**

- $\Delta R_{jj,\ell j} > 0.4$

- **Three or more tagged** b**-jets in the final state,** $\epsilon_b = 0.5$**.**

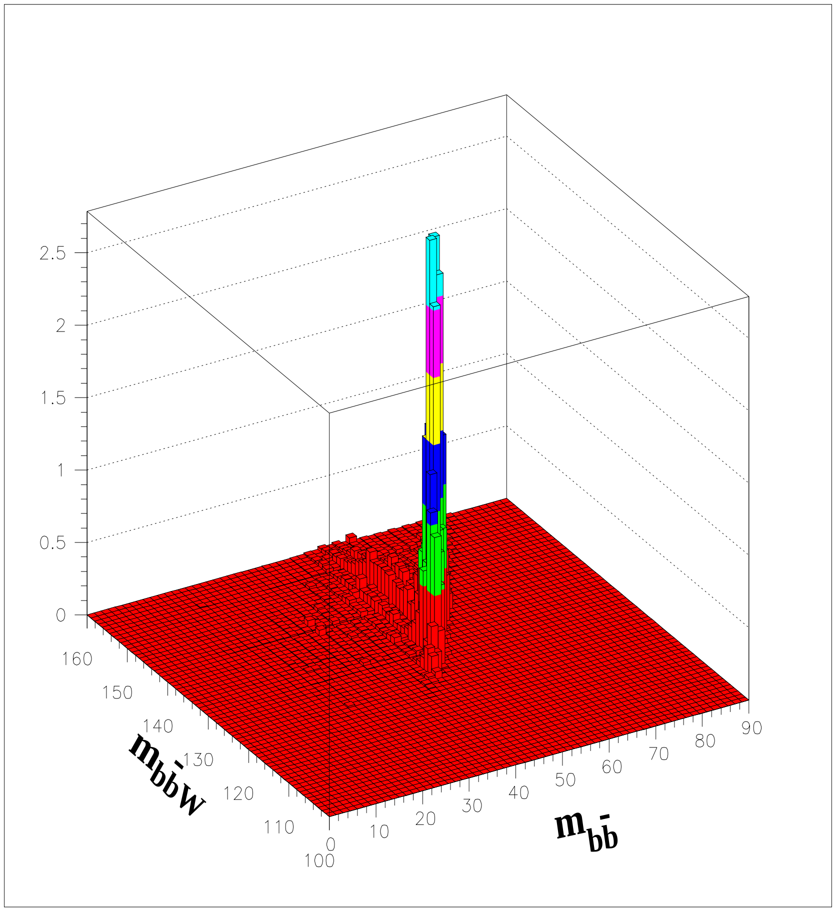
- **Signal cross-section varies between 20-150 fb for the range of light Higgs mass 20-50 GeV**

- **The main SM background** $\sigma(pp \rightarrow t\bar{t}b\bar{b}) \sim 0.5$ **fb after all cuts**

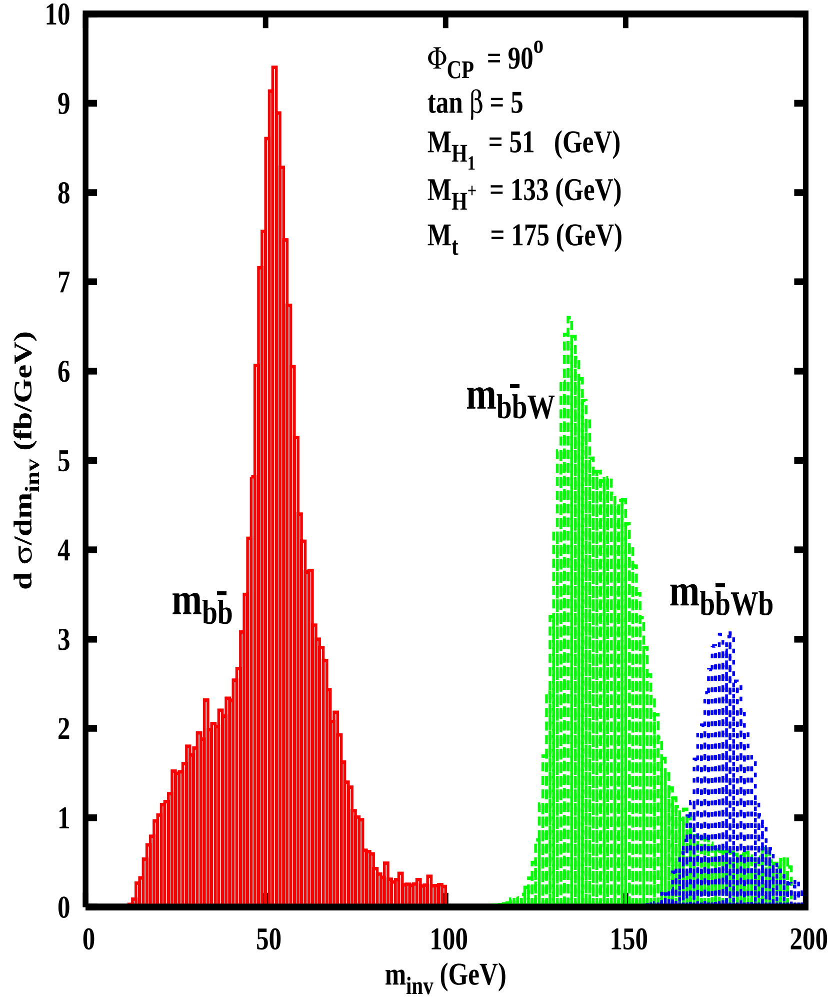
- **With** 30 fb^{-1} **data one expects upto** ~ 4500 **events after all cuts**

Light Higgs window : Scenario I

(a)



(b)



Light Higgs window : Scenario II

- Use the same fact that $W^{\pm}H^{\mp}H_1$ coupling is enhanced
- We look at $pp \to H^{\pm} + H_1 \to (H_1 W^{\pm}) + (b\bar{b}) \to (b\bar{b})(\ell\nu) + (b\bar{b})$
- Signal will be $4b + \ell^{\pm}$ with missing energy
- Important feature : Two pairs of b-jets reconstruct at light Higgs mass
- The signal cross-section is not large (production process is a weak interaction)
- **After all cuts $\sigma_{\rm signal}$ can reach up to 1.6 fb for $M_{H_1} \sim 45$ GeV**

[with S. Moretti, EPJC42,341 (2005)]

Light Higgs window : Scenario II

- **Following SM backgrounds were generated using MADGRAPH :**

- **We used same set of basic cuts as in Scenario I**

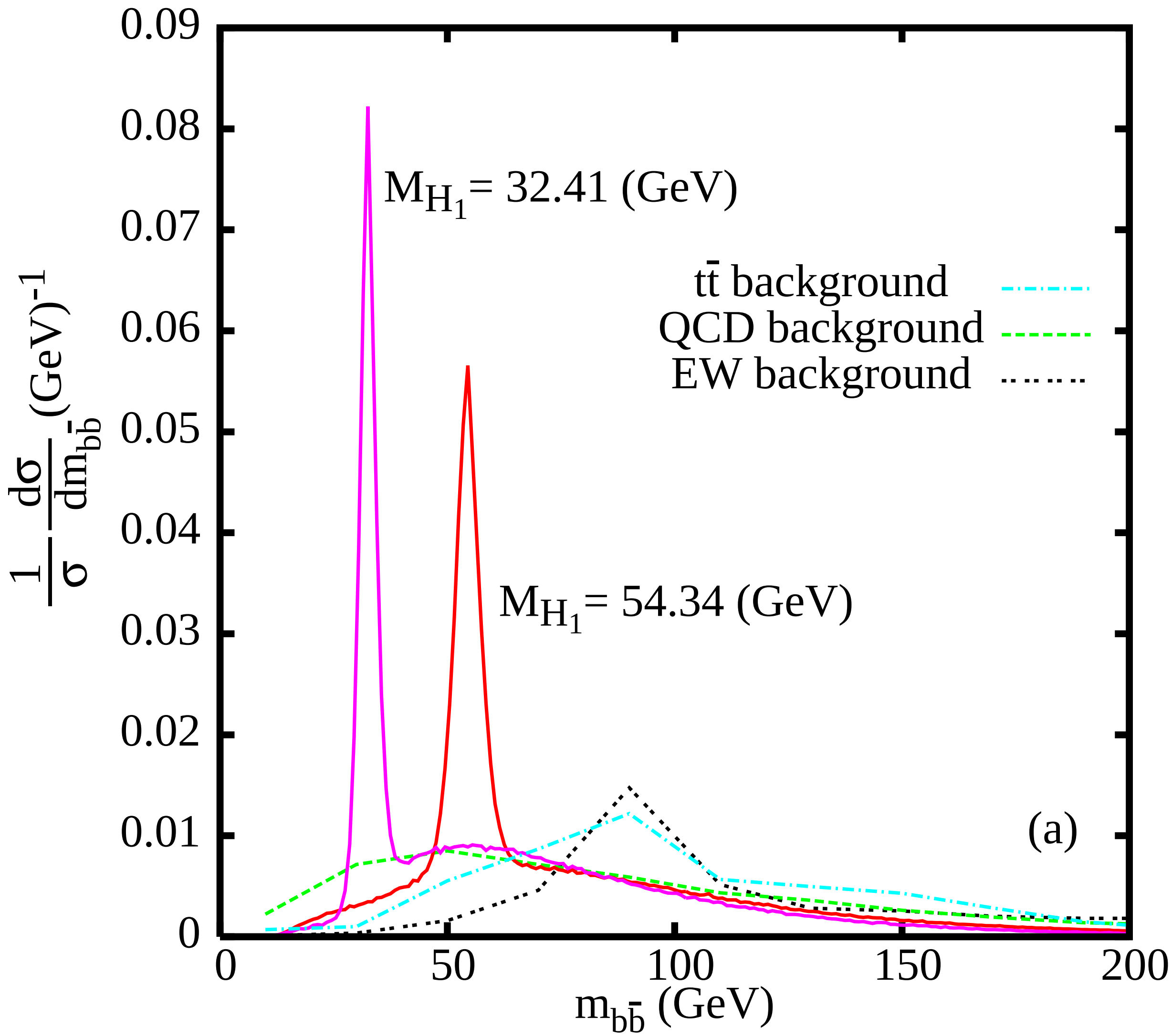
- $(a) \quad \sigma(gg \to b\bar{b}jj\ell\nu) \lesssim 2.2 \times 10^{-3}$ **fb**

- $(b) \quad \sigma(q\bar{q}' \to ZZW^{\pm} \to b\bar{b}jj\ell\nu) \lesssim 4.0 \times 10^{-3}$ **fb;**

- $(c) \quad \sigma(gg \to t\bar{t} \to b\bar{b}jj\ell\nu) \lesssim 2.9 \times 10^{-2}$ **fb**

- **We have assumed the b-tagging efficiency $\epsilon_b = 0.5$ (for each b-jet) and the appropriate light-quark rejection factors ($R_{u,d,s} = 1/50$ and $R_c = 1/25$).**

Light Higgs window : Scenario II



Light Higgs window : Scenario III

- **Use $\tilde{t}_1\tilde{t}_1^* h_1$ coupling**

- $\sigma(\tilde{t}_1\tilde{t}_1^* h_1)$ **is large in CPV scenario, due to large value of A_t. Large $A_t \Longrightarrow$ lighter stop. In addition, both h_2 and h_3 also couple favorably to the $t\bar{t}$ pair can add modestly to the signal**

- **Typical masses (GeV) :**$m_{h_i} = (48.9, 103.3, 135.7); m_{\tilde{t}_i} = (322, 664); m_{\tilde{\chi}^0_{1,2}} = (99.6, 198.4); m_{\tilde{\chi}^\pm_1} = 198.4; m_{\tilde{g}} = 1000$

- **Cross-sections(fb):** $\sigma_{\tilde{t}_1\tilde{t}_1^* h_1} = 440; \sigma_{\tilde{t}_1\tilde{t}_1^* h_2} = 6; \sigma_{\tilde{t}_1\tilde{t}_1^* h_3} = 4; \sigma_{t\bar{t}h_1} = 8; \sigma_{t\bar{t}h_2} = 198; \sigma_{t\bar{t}h_3} = 135; \sigma_{\tilde{g}\tilde{g}} = 134$

- **Typical Branching fractions:** $\mathrm{Br}(\tilde{t}_1 \to b\tilde{\chi}^+_1) = 0.81; \mathrm{Br}(\tilde{t}_1 \to t\tilde{\chi}^0_1) = 0.19; \mathrm{Br}(h_1 \to b\bar{b}) = 0.91; \mathrm{Br}(h_2 \to h_1 h_1) = 0.71; \mathrm{Br}(h_3 \to h_1 h_1) = 0.82; \mathrm{Br}(\tilde{g} \to t\tilde{t}^*_1) = 0.16$

[P. Bandyopadhyay, PRD78, 015017 (2008)]

Light Higgs window : Scenario III

- **They looked at** $pp \to \tilde{t}_1 \tilde{t}_1^* h_1$ **and** $pp \to t\bar{t}h_{2,3}$
- h_1 **and both top (stop) dominantly decay to** b **quarks**
- **For the signal, the associate** W**s (or** $\tilde{\chi}_1^\pm$**) produced in the decay of** t **(or** $\tilde{t}_1$**) are required to decay leptonically**
- **These decay lead to** $4b + 2\ell + \text{missing } p_T$ **final state**
- **Low** m_{h_1} **give rise to softer** b**-jet (less than 40 GeV)**
- **This forced them to look for** $3 \text{ tagged } b + 2\ell + \text{ other untagged jets } + \text{missing } p_T$
- **Backgrounds: Two sources : CPC MSSM, & SM**
- **CPC MSSM :** $pp \to \tilde{g}\tilde{g}, pp \to t\bar{t}h$
- **SM :** $pp \to t\bar{t}, t\bar{t}Z, t\bar{t}b\bar{b}, t\bar{t}h$

Light Higgs window : Scenario III

- **Decisive cuts:**

  1. **Missing** $p_T \geq 110$ **GeV**
  2. $p_T^{jet} \leq 300$ **GeV**
  3. $N_j \leq 5$

- **Cut (1) remove mainly SM** $t\bar{t}h$

- **Cut (2) & (3) remove ther CPC** $(pp \to \tilde{g}\tilde{g})$ **and rest of the SM backgrounds**

- **Assuming** $\mathcal{L} = 30\ \mathrm{fb}^{-1}$**, they expect** $S/\sqrt{B} \sim 7$

Light Higgs window : Scenario IV

- **Look for** $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1$
- $\mathrm{Br}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1) \sim 0.79$ **and** $\mathrm{Br}(\tilde{g} \to \tilde{\chi}_2^0 q\bar{q}) \sim 0.17$ **in the region where a light Higgs is unexcluded by the present data**
- **Consider the SUSY cascade decay chain starting with a gluino:**
- $\tilde{g} \to \tilde{\chi}_2^0 q\bar{q} \to \tilde{\chi}_1^0 h_1 q\bar{q} \to \tilde{\chi}_1^0 q\bar{q} b\bar{b}(\tau^+\tau^-)$
- $\sigma_{\tilde{g}\tilde{g}} \approx 8.5$ **pb for** $M_{\tilde{g}} = 500$ **GeV**
- **Around** 13% **gluinos produced in this scenario will decay into** h_1
- **More detailed analysis (even parton level) is required to establish their claims**

[A.C. Fowler and G. Weiglein, arXiv:0909.5165]

Summary

- **CP violation in the MSSM Higgs sector can be generated at loop level leading to very interesting phenomenology in the MSSM Higgs sector**

- **LEP-2 still allows very light Higgs in the CP violating MSSM Higgs sector, due to strong suppression of the H_1ZZ coupling**

- **No hope from Tevatron and LHC either through conventioanl channel: $H_1W^{\pm}W^{\mp}$ and $H_1t\bar{t}$ couplings are suppressed in the same parameter space**

- **At LHC the light Higgs window scenario may be closed through:**
  - $pp \to t\bar{t} \to (bW^+)(\bar{b}H^-) \to (b\ell\nu)(bH_1W^-) \to (b\ell\nu)(bb\bar{b})(jj)$
  - $pp \to H^{\pm}H_1 \to (H_1W^{\pm}) + (b\bar{b}) \to (b\bar{b}\ell\nu) + (b\bar{b})$

- **Other possible channels:**
  - $pp \to \tilde{t}_1\tilde{t}_1^*h_1$, **followed by** 3 tagged $b + 2\ell +$ other untagged jets $+$missing p_T
  - **Look for** $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + h_1$ **decay**

Summary

– $\sigma_{\tilde{g}\tilde{g}}$ **is large.** $\tilde{g} \to \tilde{\chi}_2^0 q\bar{q} \to \tilde{\chi}_1^0 h_1 q\bar{q} \to \tilde{\chi}_1^0 q\bar{q} b\bar{b} (\tau^+\tau^-)$

- **So far no dedicated analysis using B decays**

- **Question : Can $B \to \mu^+\mu^-, X_s\gamma, \tau\nu_\tau$ close this light Higgs window ?**