Charged Higgs Phenomenology in the NMSSM

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A. A, K. Cheung, T. J. Hou and K. W. Song, JHEP'07

Outline

- Short review of Next-to MSSM (NMSSM)
- Very light CP-odd pseudoscalar A_1
- Higgs-gauge bosons couplings in NMSSM and sum rules
- $H^\pm \to W^\pm A_1, W^\pm h_{1,2}$ in NMSSM
- $pp \to H^\pm h_1$, $pp \to H^\pm A_1$ vs $pp \to W^\pm h_1$
- Conclusions

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NMSSM=MSSM + an extra singlet scalar field S

- The presence of S provides an elegant solution to the μ problem of the MSSM $\lambda \hat{S}\, \hat{H}_u\, \hat{H}_d \rightarrow \underbrace{\lambda v_s}_{\mu_{eff}} \hat{H}_u\, \hat{H}_d$.

- Within the NMSSM, the fine-tune problem (little hierarchy) can be relieved [Dermisek and Gunion'05]

- To evade LEPII bound $m_H \gtrsim 114$ GeV: reduce $\mathcal{B}(h \rightarrow \{b\bar{b}, \tau^+\tau^-\})$ or ZZh coupling.

  In NMSSM, the decay $h_1 \rightarrow A_1 A_1$ can dominate over $h_1 \rightarrow b\bar{b}$ in regions of parameters space. For $m_{A_1} \lesssim 2m_b$ and $h_1 \rightarrow A_1 A_1 \rightarrow \{4\tau, 4j\}$, scenarios with $m_h \approx 82 - 100$ GeV are not ruled out by LEP. [Dermisek et al'05, U. Ellwanger et al'05]

NMSSM Superpotetial

$$W = Y_u \hat{Q}_L \hat{H}_u \hat{U}^c - Y_d \hat{Q}_L \hat{H}_d \hat{D}^c - Y_l \hat{L}_L \hat{H}_d \hat{E}^c + \lambda \hat{S}\, \hat{H}_u\, \hat{H}_d + \frac{1}{3}\kappa\, \hat{S}^3$$

$$V_{\rm soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + [\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3]$$

Free parameters: λ, κ, A_λ, A_κ, $\tan\beta$ and $\mu_{eff} = \lambda v_s$

After electroweak symmetry breaking: 3 CP-even $h_{1,2,3}$, 2 CP-odd $A_{1,2}$ and a pair of charged Higgs $H^\pm$.

$$M_{H^\pm}^2 = \frac{2\mu_{eff}}{\sin 2\beta}(A_\lambda + \kappa v_s) + M_W^2 - \lambda^2 (v_u^2 + v_d^2) \quad , \quad \underbrace{M_{H^\pm}^2 = M_W^2 + M_A^2}_{MSSM}$$

In NMSSM, the indirect lower bound on $H^\pm$ following from LEP limits on the neutral Higgs is $m_{H^\pm} \geq 120$ GeV , $\tan\beta \geq 1.5$.

In MSSM $m_{H^\pm} \geq 150$ GeV for $\tan\beta \geq 6$ [Godbole, Roy'05]

After rotating $(\Im m\Phi_{\rm u}^0, \Im m\Phi_{\rm d}^0, \Im m S)$ into $(A^{\rm MSSM}, G^0, \Im m S)$. Then one eliminate the G^0 Goldstone mode and the remaining 2×2 CP-odd mass matrix in $(A^{\rm MSSM}, \Im m S)$ basis:

$$\begin{aligned}
\mathcal{M}^2_{P,11} &= \frac{\lambda v_s}{\sin\beta\cos\beta}(A_\lambda + \kappa v_s), \\
\mathcal{M}^2_{P,22} &= (2\lambda\kappa + \frac{\lambda A_\lambda}{2v_s})\sin 2\beta(v_u^2 + v_d^2) - 3\kappa A_\kappa v_s, \\
\mathcal{M}^2_{P,12} &= \lambda\sqrt{v_u^2 + v_d^2}(A_\lambda - 2\kappa v_s).
\end{aligned}$$

$A_1 = \cos\theta_A A + \sin\theta_A \Im m(S)$, $A_2 = \cos\theta_A A - \sin\theta_A \Im m(S)$ with $m_{A_1} < m_{A_2}$.

$h_i = S_{i1}\Re e(\Phi_{\rm u}^0) + {\rm S}_{\rm i2}\Re e(\Phi_{\rm d}^0) + {\rm S}_{\rm i3}\Re e({\rm S})$

How to get light CP-odd in NMSSM

$$\mathrm{Det}\mathrm{M}_{\mathrm{P}}^2 = -\frac{3\kappa\lambda \mathrm{v_s}}{\sin 2\beta}\left(2\kappa \mathrm{v_s^2} \mathrm{A}_\kappa + 2\mathrm{v_s}\mathrm{A}_\kappa \mathrm{A}_\lambda - 3\lambda \mathrm{A}_\lambda(\mathrm{v_u^2}+\mathrm{v_d^2})\sin 2\beta\right) \approx 0$$

1. $\kappa \to 0$ ($U(1)_{PQ}$ symmetry)

$$m_{A_1}^2 = 3s\kappa(-A_\kappa \sin^2\theta_A + \frac{6}{\sin 2\beta}\lambda s \cos^2\theta_A) + O(\kappa^2)$$

2. $A_\lambda \to 0$ and $A_\kappa \to 0$ ($U(1)_R$ symmetry)
[Dobrescu and Matchev'2000]

$$m_{A_1}^2 = 3s(-\kappa A_\kappa \sin^2\theta_A + \frac{3}{2\sin 2\beta}\lambda A_\lambda \cos^2\theta_A) + O(\kappa^2 A_\kappa^2, \lambda^2 A_\lambda^2)$$

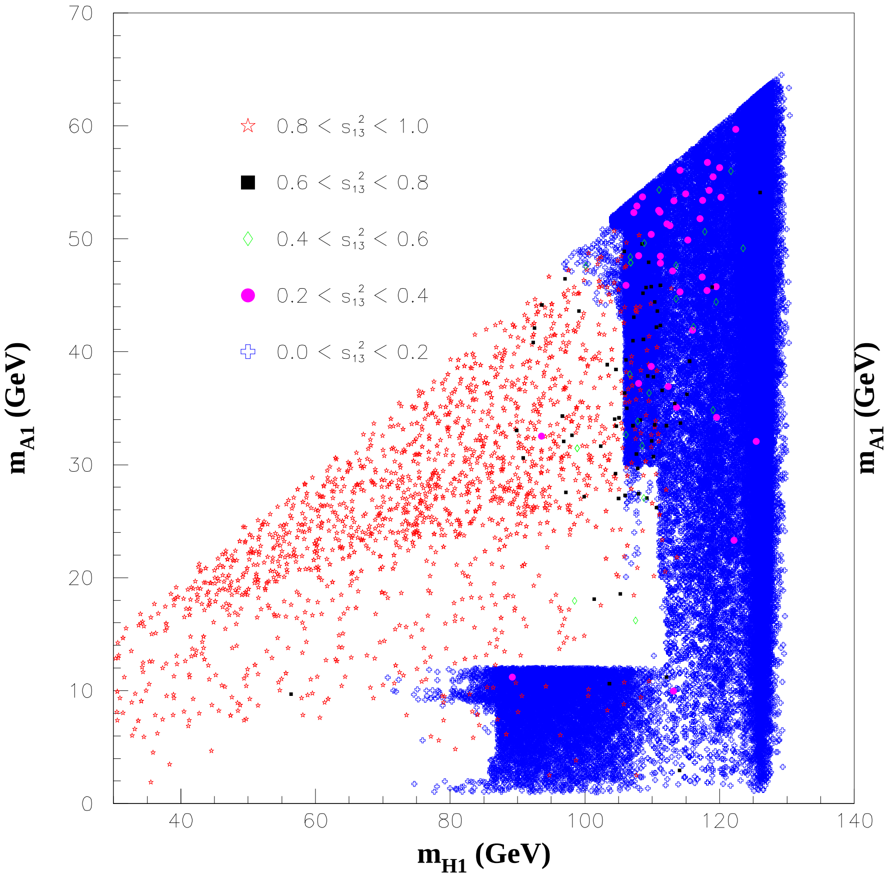
3. $\lambda \to 0$, $v_s \to 0$ (small $\mu_{eff} = \lambda v_s$ ruled out by chargino bound)

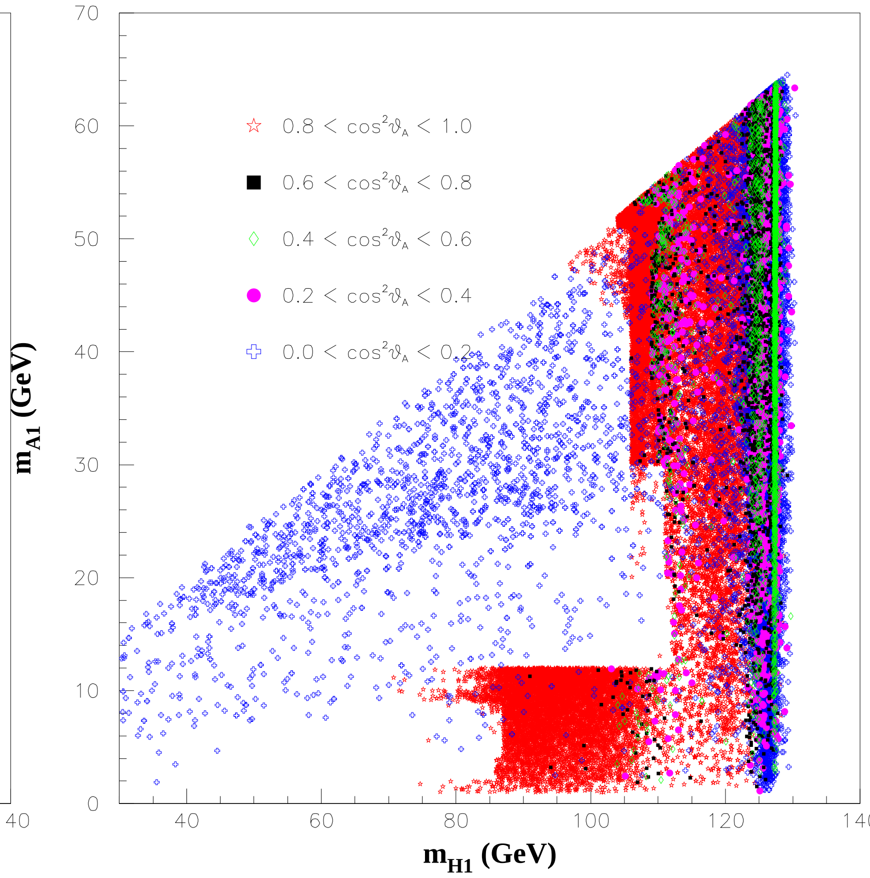
- Very light A_1 is natural in NMSSM due to small explicit breaking of Peccei-Quinn symmetry and also to $U(1)_R$ symmetry.
- A light A_1 can be:

  i) singlet dominated: $\cos\theta_A \approx 0$

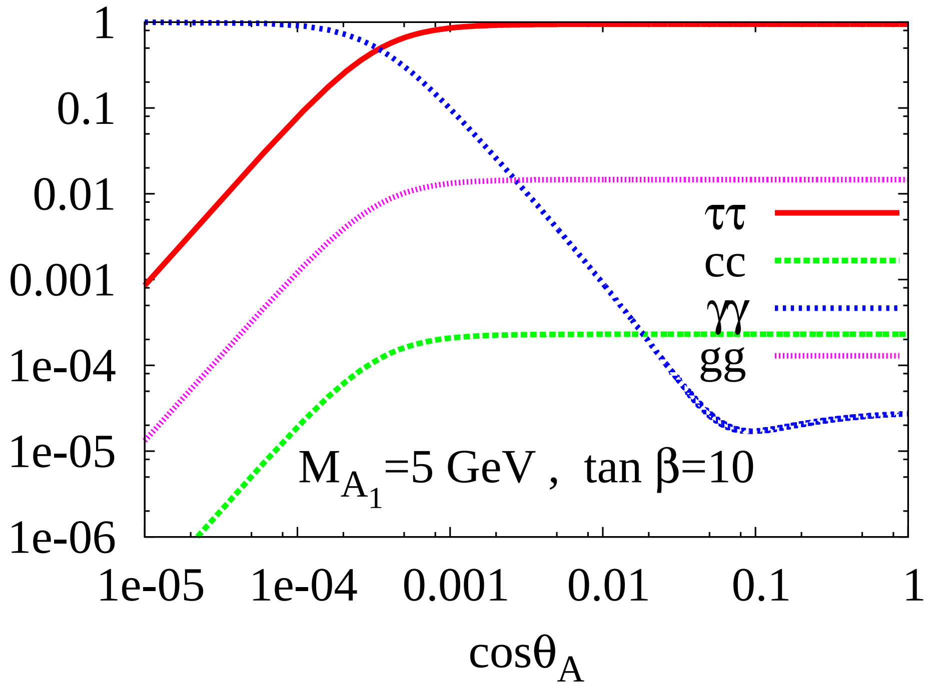
  ii) doublet dominated: large doublet component $\cos\theta_A \approx 1$ leads to large $W^{\pm}H^{\mp}A_1$ coupling
  [Drees,Guchait,Roy'98,99, Godbole,Roy'05]

$\mathrm{Br}(h_1 \to A_1 A_1) \gtrsim 50\%$: s_{13} is the singlet component of h_1





Light A_1: Branching ratios



Higgs bosons - gauge bosons couplings in NMSSM

$$\mathcal{L} = g m_W g_{WWh_i} W^{+\mu} W^-_\mu h_i - g W^+_\mu (i g_{W^+H^-h_i} h_i \overleftrightarrow{\partial}^\mu H^- + \cos\theta_A A_1 \overleftrightarrow{\partial}^\mu H^-)/2$$

$A_1 = \cos\theta_A A + \sin\theta_A \Im m(S)$, $g_{WWh_i} = \sin\beta S_{i1} + \cos\beta S_{i2}$, $g_{W^+H^-h_i} = \cos\beta S_{i1} - \sin\beta S_{i2}$. S is 3×3 orthogonal matrix.

As in the MSSM one can easily derive the following sum rules:

$$\sum_{i=1}^{3} g^2_{WWh_i} = 1 \quad , \quad h_i = S_{i1}\Re\mathrm{e}(\Phi^0_\mathrm{u}) + \mathrm{S_{i2}}\Re\mathrm{e}(\Phi^0_\mathrm{d}) + \mathrm{S_{i3}}\Re\mathrm{e}(\mathrm{S})$$

$$\underbrace{g^2_{WWh_i} + g^2_{W^+H^-h_i} = 1}_{MSSM} - S^2_{i3} \quad , \quad i = 1,2,3$$

If $S^2_{i3} \approx 0$ (h_i mainly doublet), MSSM sum rule is recovered

If $S^2_{i3} \approx 1$ (h_i mainly singlet), $g^2_{WWh_i} \approx g^2_{W^+H^-h_i} \approx 0$: Difficult scenario for LHC

Charged Higgs decays in NMSSM

- $H^{\pm}$ phenomenology in NMSSM and MSSM has many similarities: Because the fermionic couplings are identical in the two models.

- In MSSM, $H^{\pm} \to AW$ is open only for extreme choices of certain SUSY parameters [Akeroyd et al'02, D. Eriksson et al'06]

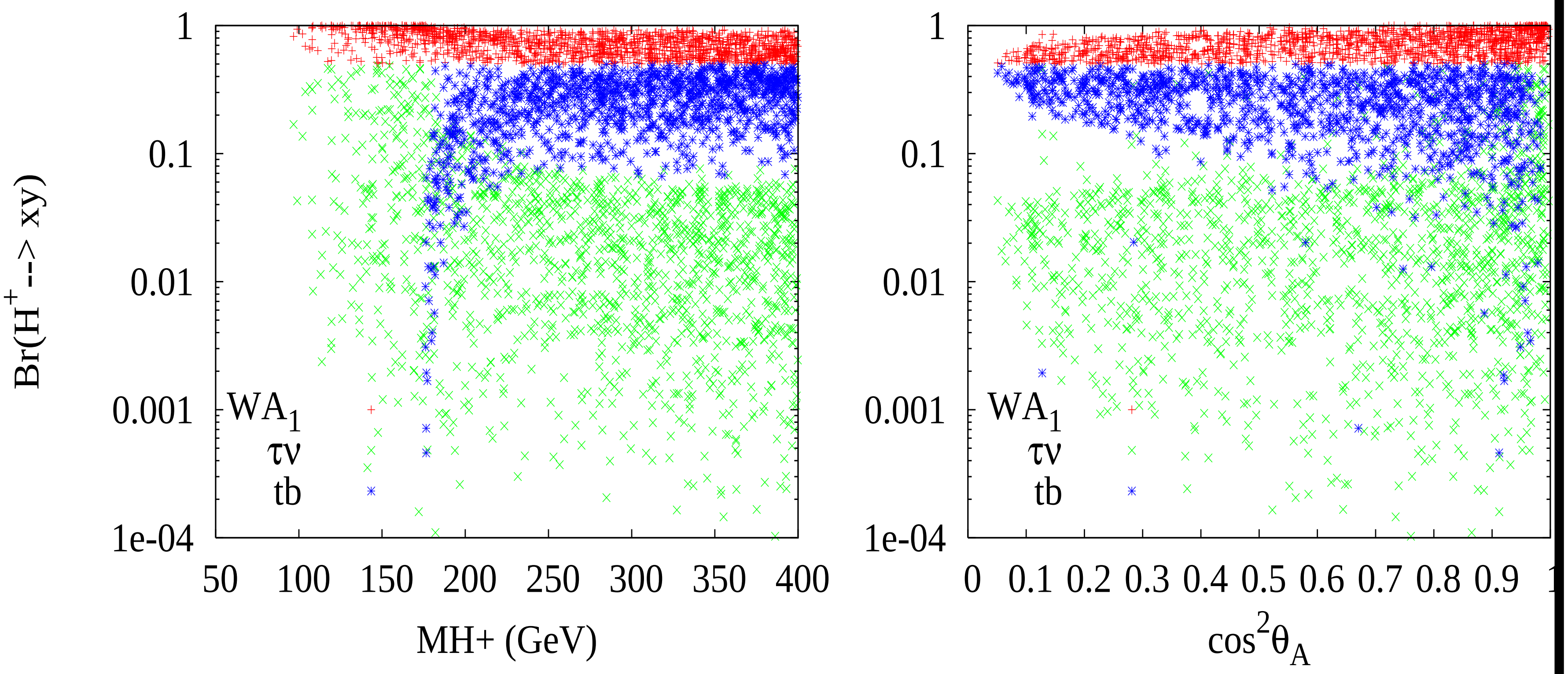
- In MSSM $H^{\pm} \to hW$ can be open but the coupling $g_{W^+H^-h} \sim \cos^2(\beta - \alpha) \to 0$ when $M_{H^{\pm}} \gg m_h + m_W$.
  In the best cases $\mathrm{Br}(H^{\pm} \to hW)$ can reach 10%

- In NMSSM, its possible to have large mass splittings among the Higgs which permits $H^{\pm} \to A_1 W$ and $H^{\pm} \to h_{1,2} W$ to proceed on-shell and dominate below and above top-bottom threshold.

- In NMSSM, $H^{\pm} \to \widetilde{\chi}_1^{\pm} \widetilde{\chi}_1^0$ can dominate in some cases

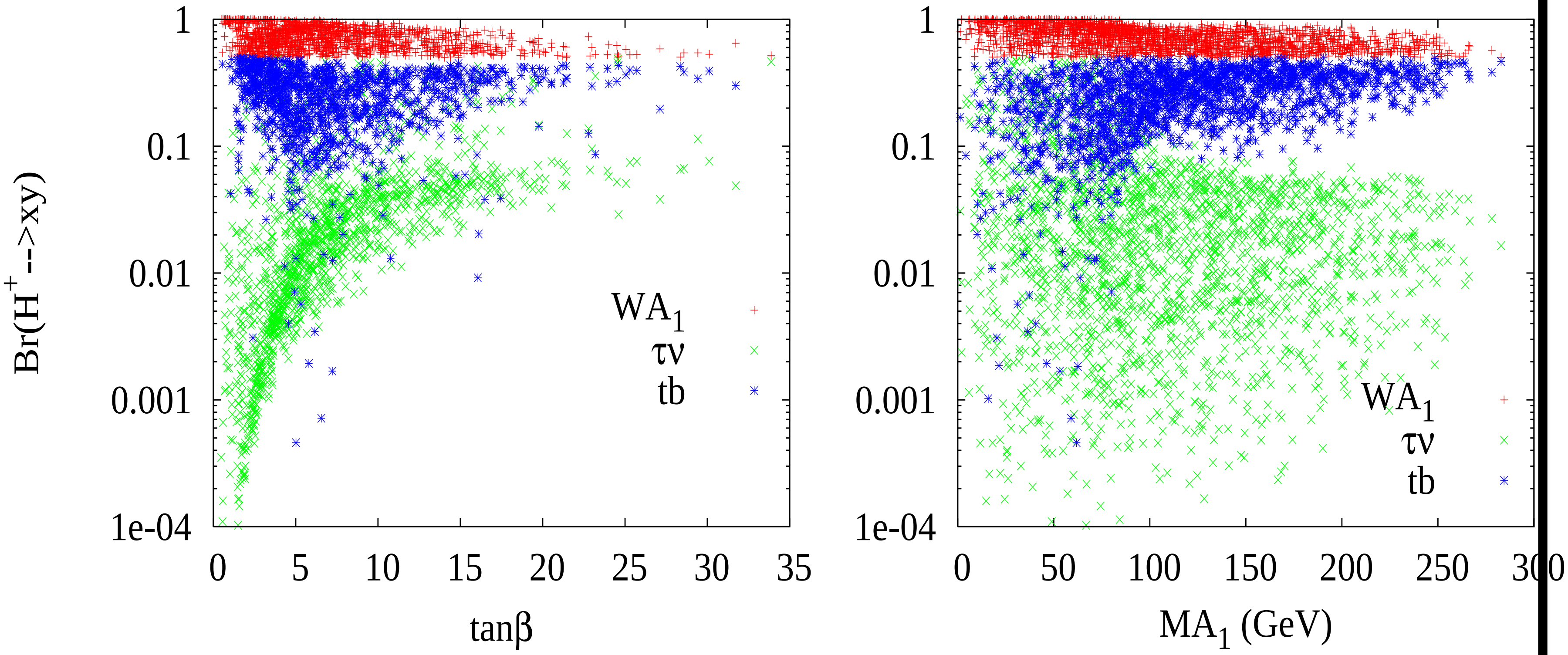
$\mathrm{Br}(H^{\pm} \to W^{\pm} A_1) \gtrsim 50\%$

$WA_1, \tau\nu, tb$



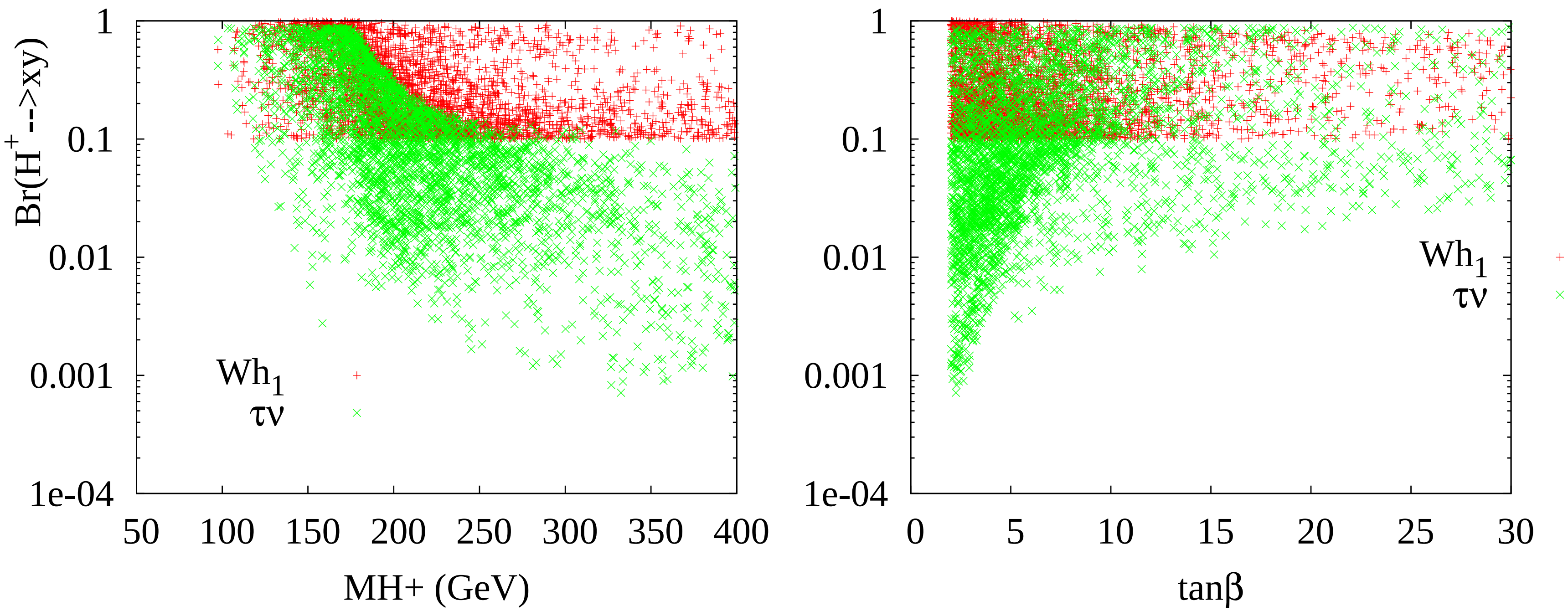
$\mathrm{Br}(H^{\pm} \to W^{\pm} A_1) \gtrsim 50\%$

$W A_1, \tau\nu, tb$



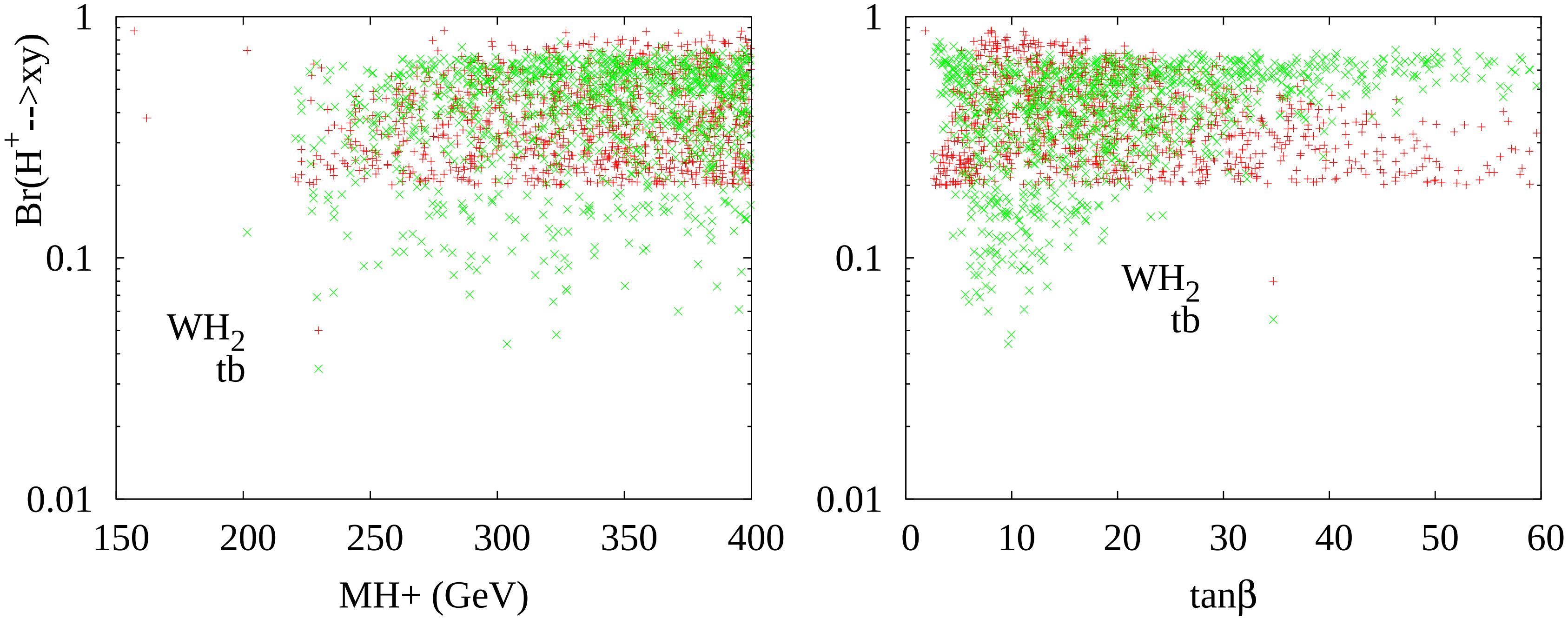
$\text{Br}(H^{\pm} \to W^{\pm} h_1) \gtrsim 10\%$

$W h_1, \tau\nu$

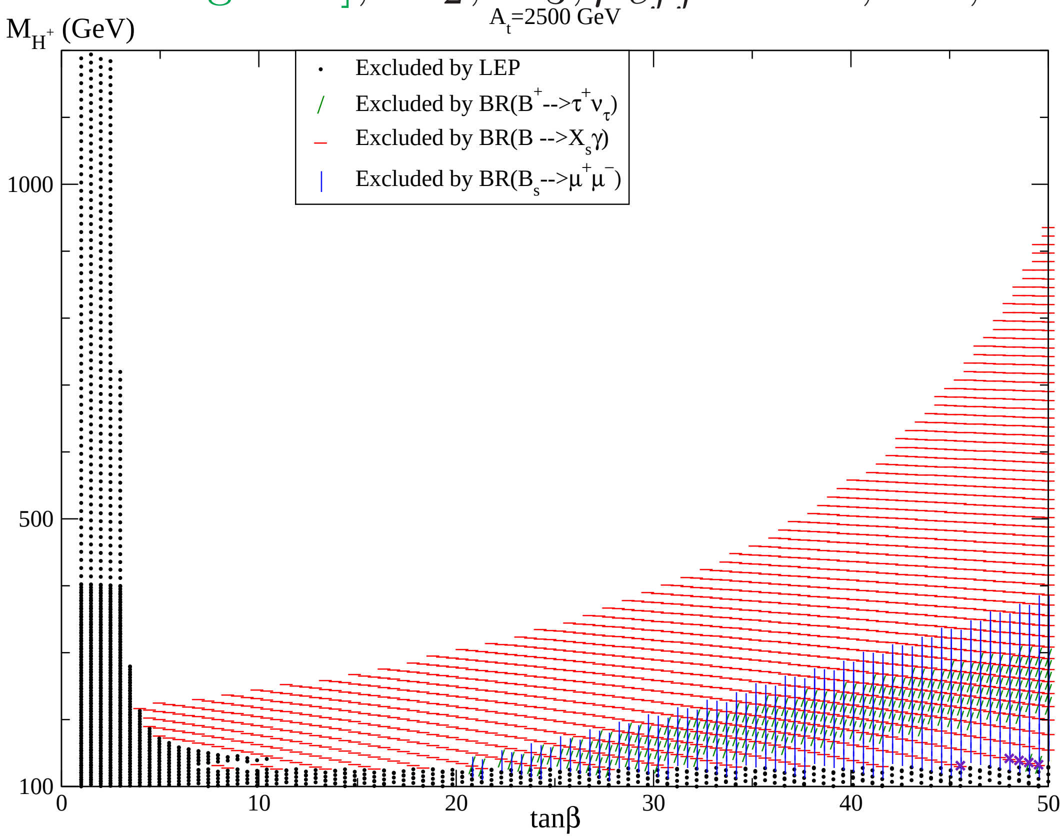


$\mathrm{Br}(H^\pm \to W^\pm h_2) \gtrsim 20\%$

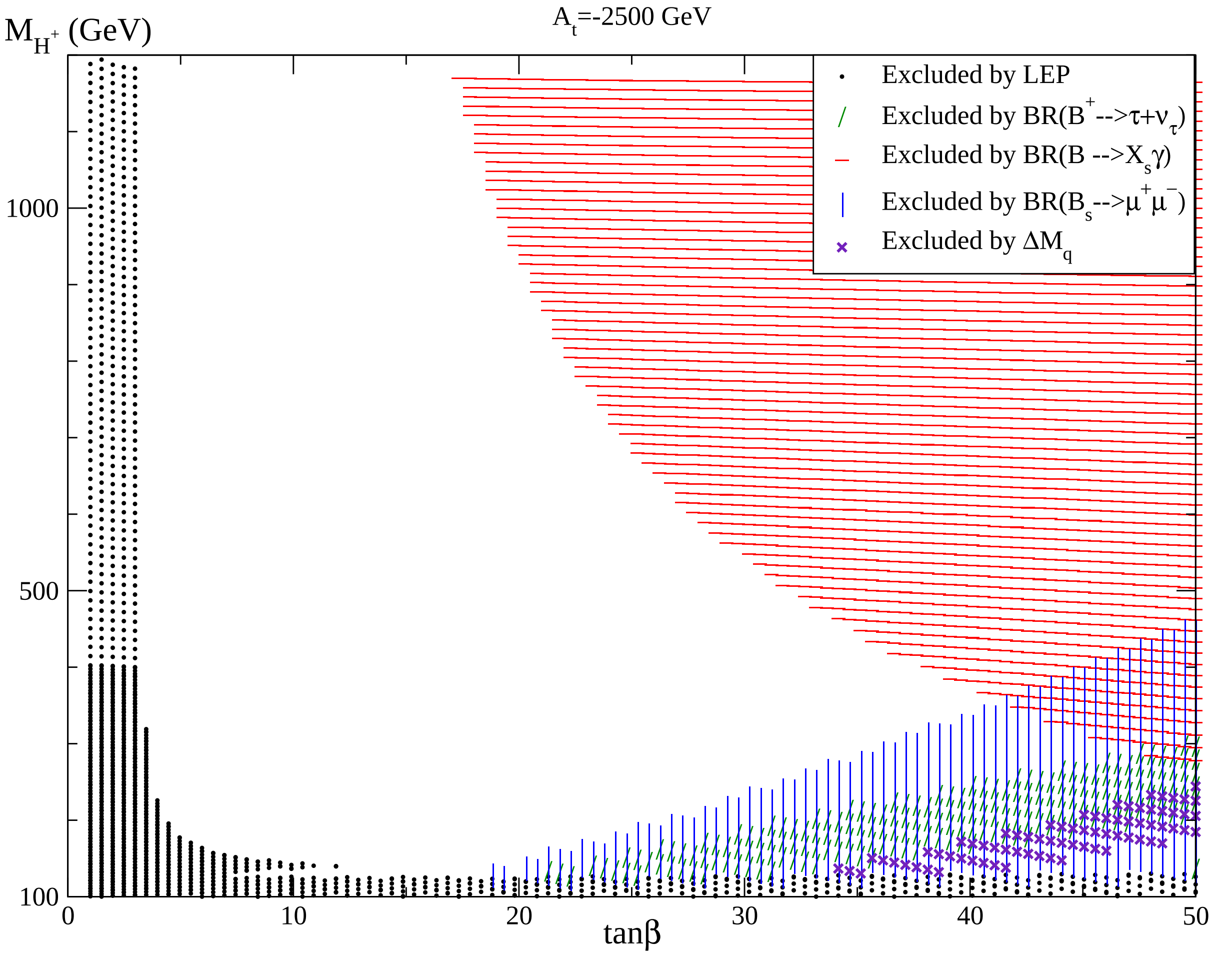
$W h_1, tb$



Light charged Higgs and B physics constraints [F. Domingo and U.Ellwanger'07], $M_2, M_3, \mu_{eff} = 300, 900, 300$ GeV and $\lambda, \kappa \leq 0.1$



Light $H^{\pm}$ in the NMSSM is compatible with $b \to s\gamma$, ΔM_q, $B^{\pm} \to \tau^{\pm}\nu$, $B_s \to \mu^+\mu^-$ even without invoking extra sources of flavour violation from gluinos.



M_{H^+} (GeV)
A_t=-2500 GeV
Excluded by LEP
Excluded by BR(B^+-->$\tau+\nu_\tau$)
Excluded by BR(B -->$X_s\gamma$)
Excluded by BR(B_s-->$\mu^+\mu^-$)
Excluded by ΔM_q
1000
500
100
0
10
20
30
40
50
tanβ

Production mechanisms: $pp \to h_1 H^\pm$ and $pp \to A_1 H^\pm$ vs $pp \to W h_1$

- $gb \to tH^+$, $gg \to tbH^+$ [Kidonakis talk]
- $t\bar{t} \to tH^+ b \to tbWh$: [S. Moretti'2000 (MSSM), Ghosh, Moretti'05(Complex MSSM)]
- The strength of $H^\pm A_1 W$ can have an application to $pp \to H^\pm A_1$ [S. Kanemura et al'02, Q.H. Cao et al'02, A. Belyaev et al'06 (MSSM), A. Akeroyd'03, D. Ghosh et al'05 (Complex MSSM)]
- If Br($H^\mp \to W^\pm A_1$) is large then, $pp \to A_1 H^\pm$ leads to $W A_1 A_1$.
- If Br($h_1 \to A_1 A_1$) is large then, $pp \to W h_1$ leads to same final state $W A_1 A_1$ as $pp \to A_1 H^\pm \to W A_1 A_1$ [$pp \to V h_1 \to V A_1 A_1 \to V 4b$: K. Cheung et al'07, M. Carena et al'07]
- Is it possible to have simultaneously $Br(H^\mp \to W^\pm A_1) \gtrsim 0.5$ and $Br(h_1 \to A_1 A_1) \gtrsim 0.5$?
- If yes, is $pp \to A_1 H^\pm$ comparable to $pp \to W h_1$?

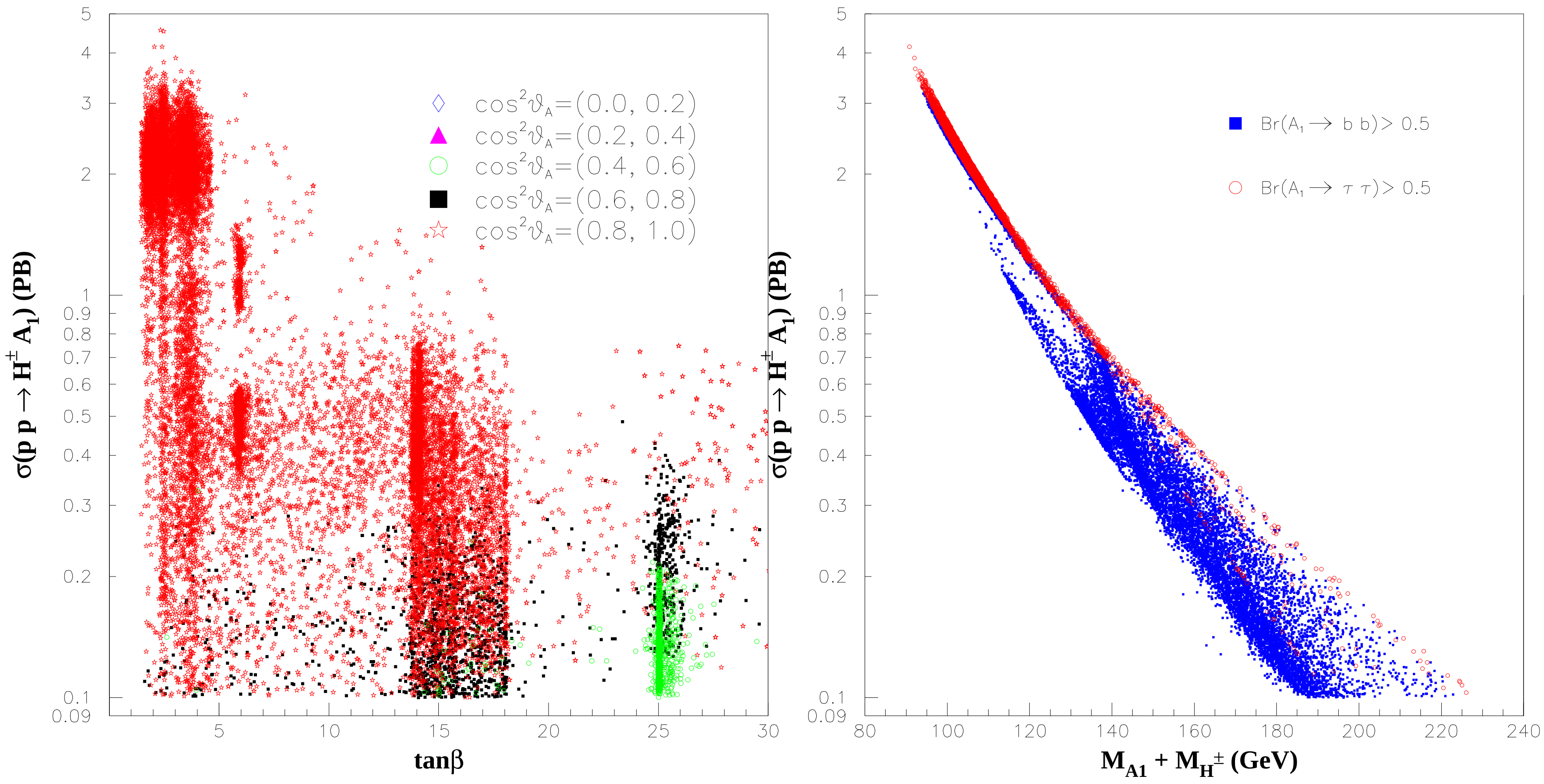
We use the NMSSM Tools

http://www.th.u-psud.fr/NMHDECAY/nmssmtools.html

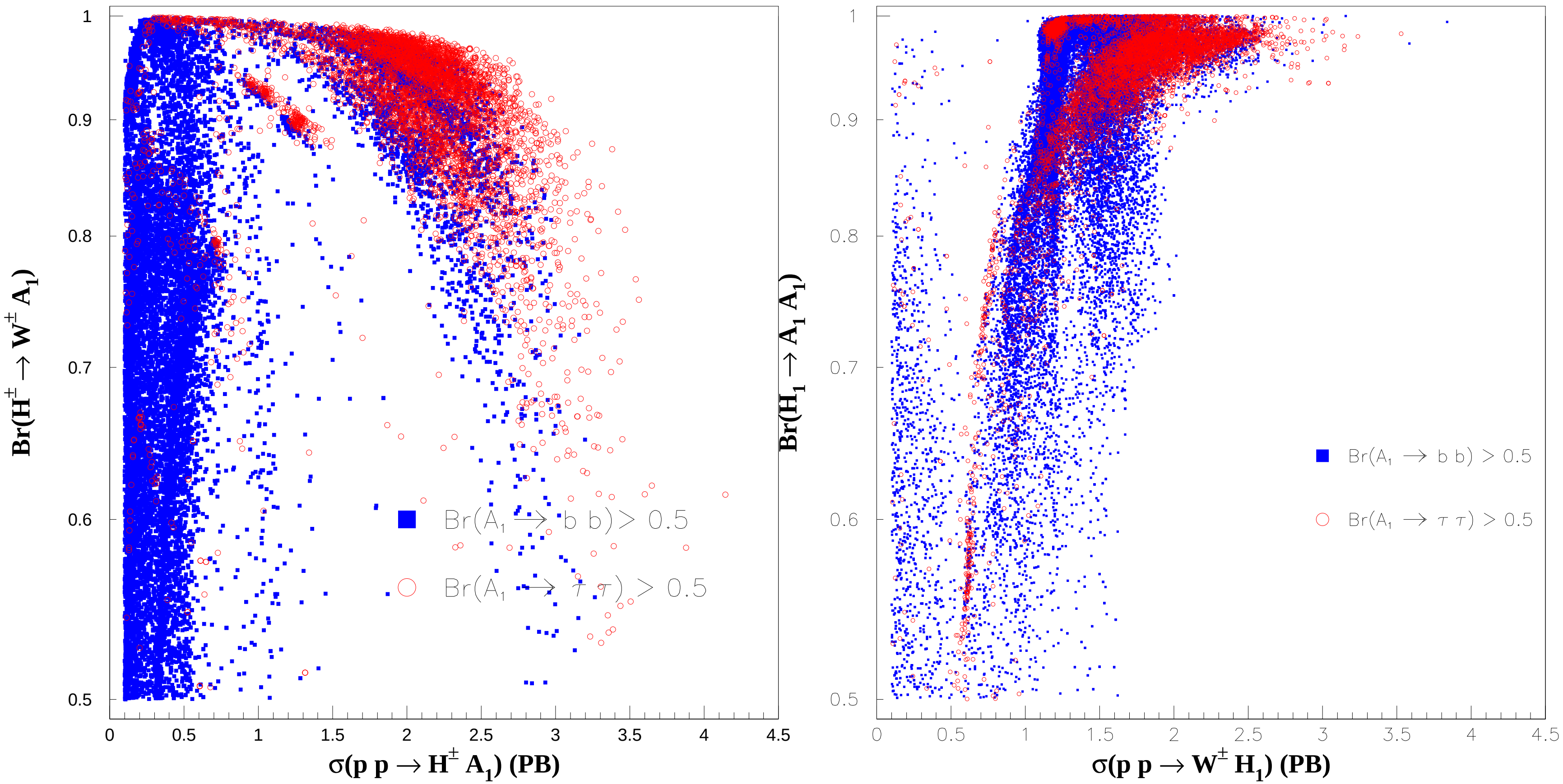
$$\lambda = [0,1]\,, \quad \kappa = [-1,1]\,, \quad \tan\beta = [0.2,60]\,, \quad \mu = [-1,1]\text{TeV}\,,$$
$$A_\lambda = [-1.0,1.0]\text{TeV}\,, \quad A_\kappa = [-1.0,1.0]\text{TeV}\,,$$
$$M_{SUSY} = [0.2,3]\text{TeV}\,, \quad M_1 = [0.07,3]\text{TeV}\,.$$

- We take into account the experimental constraints on the MSSM spectrum: $M_{H\pm} \geq 80$ GeV, $m_{\tilde{\chi}_1}, m_{\tilde{t}_1}, m_{\tilde{b}_1} \gtrsim 100$ GeV.
- We also apply the full set of LEP constraints obtained from searches for neutral Higgs bosons decaying to final states like $Z2b$, $Z4b$, $6b$, 6τ, $Z2b2\tau$, $Z4\tau$, $2b2\tau$.
- We suppose that the threshold of observability at LHC is 0.1 pb: only cross sections $\gtrsim 0.1$ pb are shown.

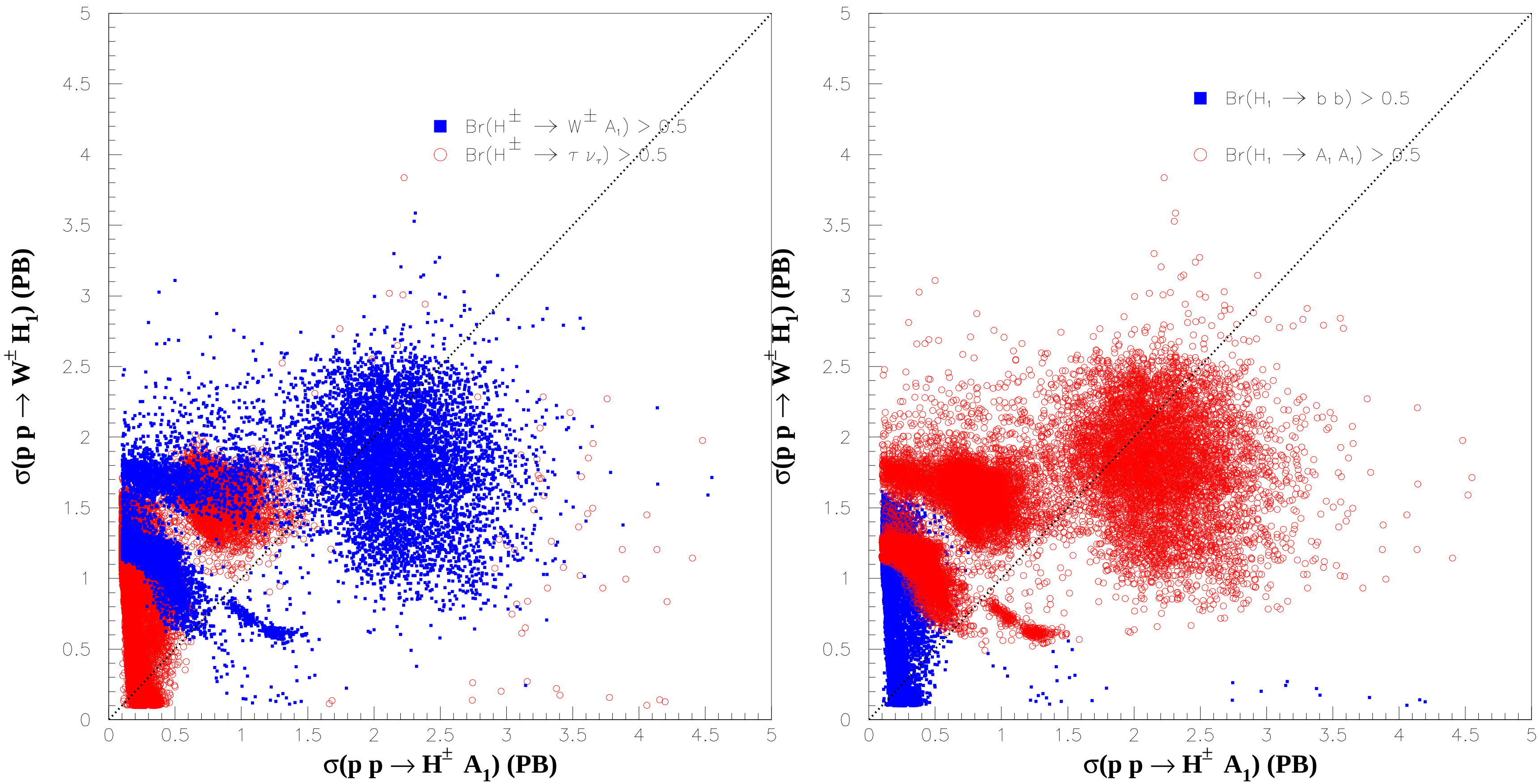
Large $pp \to H^{\pm} A_1$ needs: $\tan\beta \lesssim 15$, large doublet component for A_1 and $M_{H^\pm} + M_{A_1} \lesssim 200$ GeV



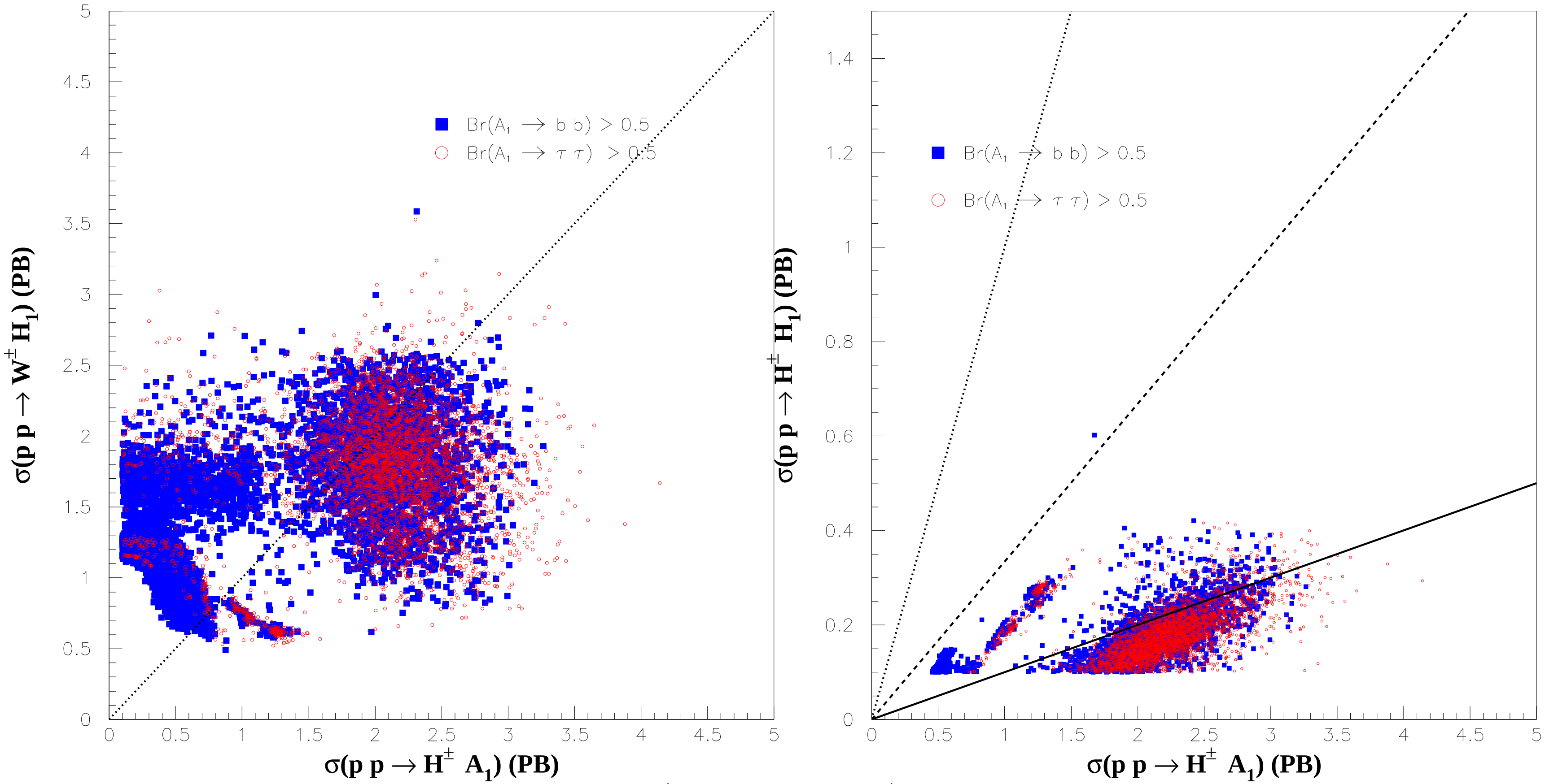
Large $pp \to H^{\pm} A_1$ (resp large $pp \to W^{\pm} h_1$) with large $Br(H^{\pm} \to W^{\pm} A_1) \gtrsim 90\%$ (resp large $Br(h_1 \to A_1 A_1) \gtrsim 90\%$) is possible with $Br(A_1 \to b\bar{b}) \gtrsim 50\%$ or $Br(A_1 \to \tau^+\tau^-) \gtrsim 50\%$



(Left) $\mathrm{Br}(H^{\pm} \to W^{\pm} A_1) \gtrsim 0.5$, (Right) $\mathrm{Br}(h_1 \to A_1 A_1) \gtrsim 0.5$



$\mathrm{Br}(H^{\pm} \to W^{\pm} A_1)$ and $\mathrm{Br}(h_1 \to A_1 A_1) \gtrsim 50\%$



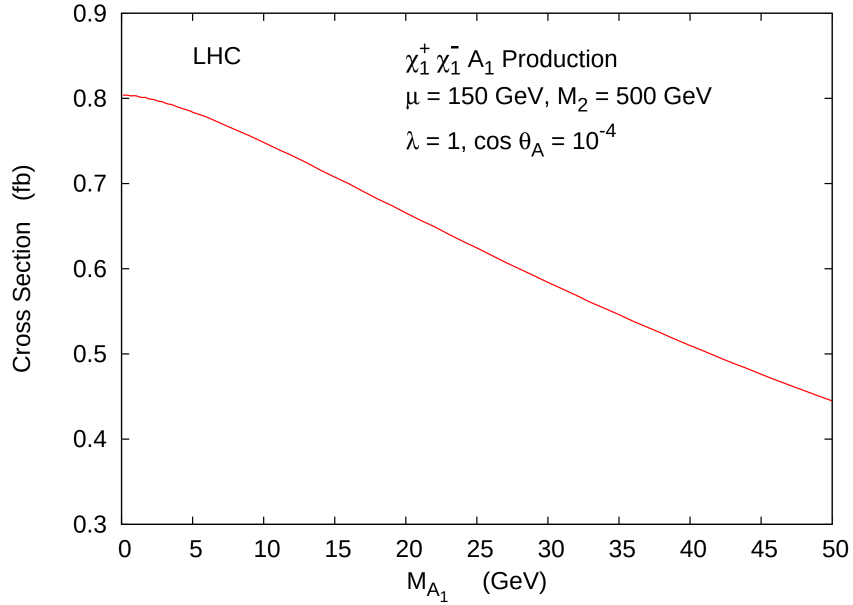
It is possible to have $pp \to H^{\pm} A_1 \to W^{\pm} A_1 A_1 \to \{W4b, W4\tau\}$ and $pp \to W^{\pm} h_1 \to W^{\pm} A_1 A_1 \to \{W4b, W4\tau\}$ with sizeable cross sections.

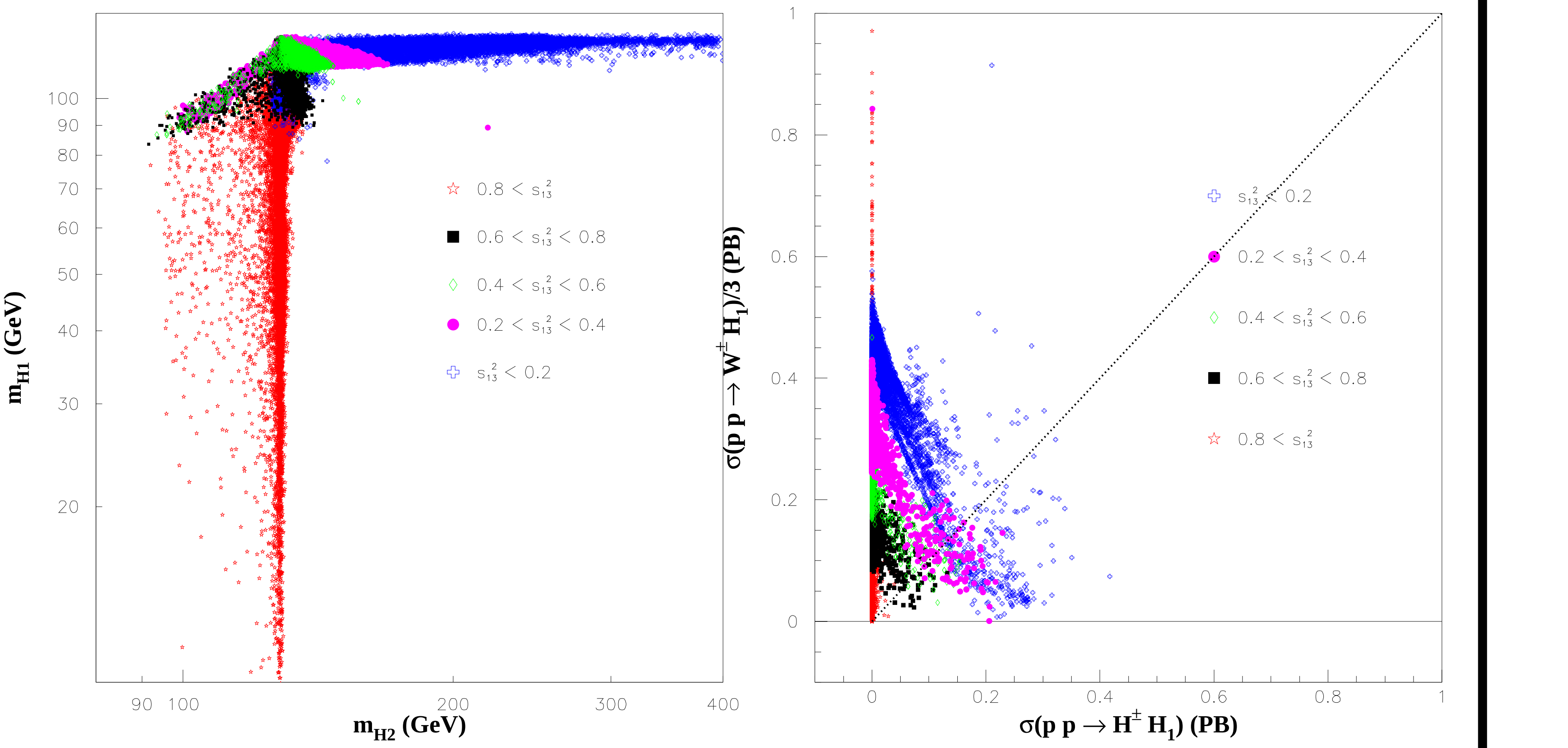
Conclusions

- In the NMSSM, $H^\pm \to W^\pm A_1, W^\pm h_1$ dominate over $\tau^\pm\nu$ and tb channels both below and above the top-bottom threshold.
- $pp \to H^\pm A_1$ with $H^\pm \to W^\pm A_1$ can be used to search for light charged Higgs with small to moderate $\tan\beta$.
- $pp \to H^\pm A_1$ with $H^\pm \to W^\pm A_1$ and $pp \to W^\pm h_1$ with $h_1 \to A_1 A_1$ leads to same signal $W A_1 A_1 \to \{W4b, W4\tau\}$ which can be distinguished at the LHC by applying appropriate reconstruction methods.
- The interference term for $W4b$ and $W4\tau$ might not be negligible and should be taken into account in any simulation study.

Light A_1 production

- If A_1 is pure Singlet: difficult to produce in conventional channels
- $\mathrm{Br}(h_1 \to A_1 A_1)$ can be large, A_1 can be produced in h_1 decay $pp \to h_1 \to A_1 A_1 \to 4\gamma, 4\tau$. Photons are difficult to resolve
- $pp \to \widetilde{\chi}_i^+ \widetilde{\chi}_j^- A_1$: A_1 radiated off the charginos legs
- A_1 pure Singlet ($\cos\theta_A \approx 0$): $\widetilde{\chi}_1^+ \widetilde{\chi}_1^- A_1 \propto \lambda \sin\theta_A U_{12}^* V_{12}^*$





100
90
80
70
60
50
40
30
20
m_{H1} (GeV)
90 100
200
300
400
m_{H2} (GeV)
$0.8 < s_{13}^2$
$0.6 < s_{13}^2 < 0.8$
$0.4 < s_{13}^2 < 0.6$
$0.2 < s_{13}^2 < 0.4$
$s_{13}^2 < 0.2$
1
0.8
0.6
0.4
0.2
0
$\sigma(p\,p \to W^\pm H_1)/3$ (PB)
0
0.2
0.4
0.6
0.8
1
$\sigma(p\,p \to H^\pm H_1)$ (PB)
$s_{13}^2 < 0.2$
$0.2 < s_{13}^2 < 0.4$
$0.4 < s_{13}^2 < 0.6$
$0.6 < s_{13}^2 < 0.8$
$0.8 < s_{13}^2$