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Charged Higgs in the NMSSM

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The charged Higgs boson decays $H^\pm \to W^\pm A_1$ and $H^\pm \to W^\pm h_i$ are studied in the framework of the next-to Minimal Supersymmetric Standard Model (NMSSM). It is found that the decay rate for $H^\pm \to W^\pm A_1$ can dominate both below and above the top-bottom threshold. We suggest that $pp \to H^\pm A_1$ is a promising discovery channel for a light charged Higgs boson in the NMSSM with small or moderate $\tan\beta$ and dominant decay mode $H^\pm \to W^\pm A_1$ which leads to $W^\pm A_1 A_1$. This $W^\pm A_1 A_1$ signature can also arise from the Higgsstrahlung process $pp \to W^\pm h_1$ followed by the decay $h_1 \to A_1 A_1$. It is shown that there exist regions of parameter space where these processes can have comparable cross sections and we suggest that their respective signals can be distinguished at the LHC by using appropriate reconstruction methods.

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1. A charged Higgs boson ($H^{\pm}$) appears in any extension of the Standard Model with two hypercharge Y=1 doublets. Its phenomenology has been extensively studied in both the Two Higgs Doublet Model (2HDM) and MSSM. The presence of $H^{\pm}$ is also predicted in the Next-to MSSM (NMSSM) in which an additional singlet neutral complex scalar field S is added to the two Higgs doublets of the MSSM.

In the NMSSM, after electroweak symmetry breaking the Higgs spectrum consists of three neutral scalars (h_1, h_2, h_3), two pseudoscalars (A_1, A_2) and a pair of charged Higgs bosons $H^{\pm}$. In both the CP-odd and CP-even sector the physical eigenstates are ordered as $M_{h_1} \lesssim M_{h_2} \lesssim M_{h_3}$ and $M_{A_1} \lesssim M_{A_2}$. For detailed discussions of the Higgs sector of the NMSSM the reader is referred to [1, 2, 3, 4, 5]. The mass of $H^{\pm}$ at tree-level is given by [1], [6]:

$$M_{H^{\pm}}^2 = \frac{2\mu_{eff}}{\sin 2\beta}(A_{\lambda} + \kappa s) + M_W^2 - \lambda^2 v^2 \qquad (1)$$

where $\tan\beta = v_u/v_d$ and $v^2 = v_u^2 + v_d^2$. This differs from the corresponding MSSM expression in which M_A and $M_{H^{\pm}}$ are strongly correlated and become roughly equal for $M_A \geq 140$ GeV.
The CP-odd mass matrix can be obtained as follows: Firstly, as in MSSM one rotates the bare fields $(\Im\mathrm{mH_u}, \Im\mathrm{mH_d}, \Im\mathrm{mS})$ into a basis $(A, G, \Im\mathrm{mS})$ where G is a massless Goldstone boson. Then one eliminates the Goldstone mode and the remaining 2×2 CP-odd states are:

$$A_1 = \cos\theta_A A + \sin\theta_A \Im\mathrm{m(S)} \qquad , \qquad \mathrm{A_2} = -\sin\theta_1 \mathrm{A} + \cos\theta_\mathrm{A} \Im\mathrm{m(S)} \qquad (2)$$

Where $A = \cos\beta \Im\mathrm{mH_u} + \sin\beta \Im\mathrm{mH_d}$ is the CP-odd MSSM Higgs boson while $\Im\mathrm{mS}$ comes from the singlet S field.

In the MSSM the coupling $H^{\pm}AW$ (where A is the CP-odd neutral Higgs boson) contains no mixing angle suppression but the relation $M_A \sim M_{H^{\pm}}$ ensures that the decay $H^{\pm} \to AW$ is greatly suppressed in most of the parameter space. In the NMSSM, the relevant couplings for our study are described by the following Lagrangian:

$$\mathscr{L}_{VVH,VHH} = g m_W g_{VVh_i} W^{+\mu} W_{\mu}^{-} h_i - g W_{\mu}^{+} \left(\frac{i g_{W^+H^-h_i}}{2} h_i + \frac{P_{i1}}{2} A_i\right) \overset{\leftrightarrow}{\partial}{}^{\mu} H^- + h.c \qquad (3)$$

where $g_{VVh_i} = \sin\beta S_{i1} + \cos\beta S_{i2}$, $g_{W^+H^-h_i} = \cos\beta S_{i1} - \sin\beta S_{i2}$, $P_{11} = \cos\theta_A$ and $P_{21} = -\sin\theta_A$, S and P are orthogonal matrices which diagonalize respectively the CP-even and CP-odd scalar mass matrix. From the last term in eq. (3) one can see that the vertex $W^{\pm}H^{\mp}A_1$ is directly proportional to P_{11} i.e. the doublet component of the mass eigenstate A_1. Consequently, if A_1 is entirely composed of doublet fields this coupling is maximized and if A_1 is purely singlet the coupling vanishes.

Now we are ready to describe the phenomenology of the $H^{\pm}$ in the NMSSM and we summarize the results of our earlier work [7]. The phenomenology of $H^{\pm}$ in the NMSSM has many similarities with that of $H^{\pm}$ in the MSSM. This is to be expected since the fermionic couplings are identical in the two models. The main differences in their phenomenology originate from the possibility of large mass splittings among the Higgs bosons in the NMSSM which permits decay channels like $H^{\pm} \to A_1 W$ to proceed on-shell [8]. Moreover, in the NMSSM a light CP-even h_1 is also allowed and one can have the opening of the decay $H^{\pm} \to h_1 W$ both below and above the top-bottom threshold. This latter channel may change the NMSSM phenomenological predictions for the charged Higgs with respect to the MSSM [8]. In the MSSM the decay $H^{\pm} \to h_1 W$ is also open but the coupling $g_{W^+H^-h_1} \sim \cos^2(\beta - \alpha)$ is strongly suppressed when $M_{H^{\pm}} \gg m_{h_1} + m_W$ and thus its branching ratio is very small for such $M_{H^{\pm}}$. For $M_{H^{\pm}} < m_{h_1} + m_W$ and just above the threshold the branching ratio for this channel can reach 10% at most for small values of $\tan\beta$ [9], [10], [11].

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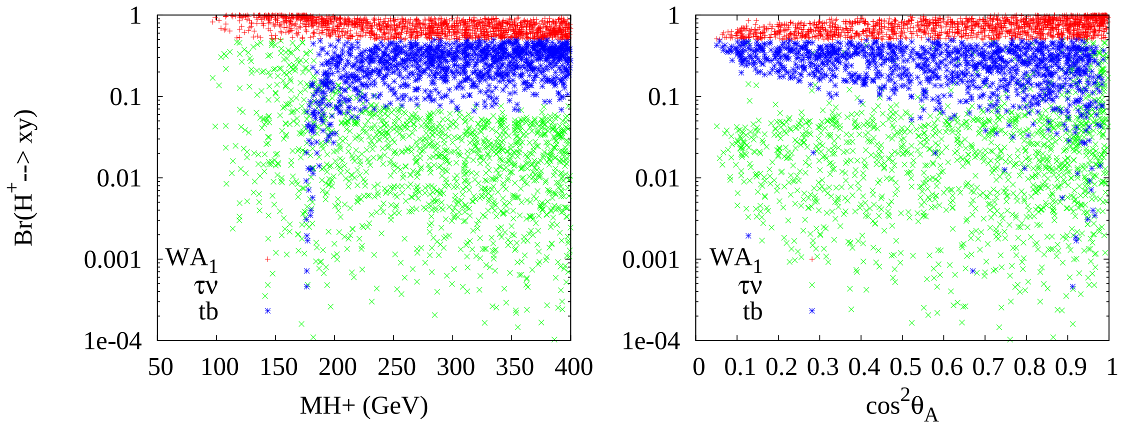

Figure 1: *Comparison of the branching ratios of* $H^{\pm} \to \{W^{\pm}A_1, \tau\nu, tb\}$ *as a function of* $M_{H^{\pm}}$ *(left),* $\cos\theta_A$ *(right). In all panels only points with* $Br(H^{\pm} \to W^{\pm}A_1) \geq 50\%$ *are selected.*

The decay $H^{\pm} \to AW$, where A is a CP-odd Higgs boson, may be sizeable in a variety of models with a non-minimal Higgs sector such as Two Higgs doublet models (Type I and II) [12, 13, 14] and in SUSY models with Higgs triplets [15]. Two LEP collaborations (OPAL and DELPHI) performed a search for a charged Higgs decaying to AW^* (assuming $m_A > 2m_b$) and derived limits on the charged Higgs mass [16] comparable to those obtained from the search for $H^{\pm} \to cs, \tau\nu$. In the MSSM the decay width for $H^{\pm} \to AW$ is very suppressed in most of the parameter space [9, 10] because the charged Higgs and the CP-odd Higgs are close to mass degeneracy. The importance of the decays $H^{\pm} \to A_1W$ and $H^{\pm} \to h_1W$ in the NMSSM was first pointed out in [8]. Their branching ratios may be close to 100% which can provide a clear signal at the LHC.

The decay width of $H^{\pm} \to A_1W$ is directly proportional to $\cos\theta_A$ which is the doublet component of A_1. This decay width can be substantially enhanced if A_1 is predominantly composed of doublet fields. However, even with small doublet (large singlet) component of A_1 it is possible that $H^{\pm} \to A_1W$ is the dominant decay mode. We perform a scan of the parameter space using the code NMSSM-Tools [17] in order to quantify the importance of $H^{\pm} \to A_1W$ and $H^{\pm} \to h_1W$.

Hereafter we assume that all scalar superparticles share the same soft mass term M_{SUSY}, and the ratios of gaugino masses satisfy $M_1 : M_2 : M_3 = 1 : 2 : 6$; the trilinear couplings are related to M_{SUSY} but the sign is not fixed, *i.e.* $A_{t,b} = \pm 2M_{SUSY}$. We scan the parameter space of the model by varying the free parameters within the following region:

$$\lambda = [0,1]\,,\ \ \kappa = [-1,1]\,,\ \ \tan\beta = [0.2,60]\,,\ \ \mu = [-1,1]\mathrm{TeV}\,,$$
$$A_\lambda = [-1.0,1.0]\mathrm{TeV}\,,\ \ A_\kappa = [-1.0,1.0]\mathrm{TeV}\,,\ \ M_{SUSY} = [0.2,3]\mathrm{TeV}\,,\ \ M_1 = [0.07,3]\mathrm{TeV}\,. \quad (4)$$

While varying these parameters, we take into account the experimental constraints on the MSSM spectrum e.g., charged Higgs mass ≥ 80 GeV, chargino and scalar fermions $\gtrsim 100$ 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, $Z2b2\tau$, $Z4\tau$, $2b2\tau$.

In Fig. (1) we display the branching ratios of $W^{\pm}A_1$, $\tau\nu$ and top-bottom modes. Before the opening of the $H^{\pm} \to tb$ channel, the full dominance of $W^{\pm}A_1$ over $\tau\nu$ requires light $M_{A_1} \lesssim 100\,GeV$, large doublet component of A_1 and $\tan\beta$ not too large. Note that at large $\tan\beta \approx 15-25$, the $W^{\pm}A_1$ and $\tau\nu$ channels become comparable in size. Once the decay $H^{\pm} \to tb$ is open, it competes strongly with $W^{\pm}A_1$ for $\tan\beta \lesssim 15$. As can be seen from Fig. (1) left, the branching

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ratio of $H^\pm \to W^\pm A_1$ is less than 90%. It is interesting to see also that for $\cos^2\theta_A \lesssim 0.05$ there is not a single point with $Br(H^\pm \to W^\pm A_1) \gtrsim 50\%$. Note also that at large $\tan\beta \gtrsim 25$, it is hard for $H^\pm \to W^\pm A_1$ to compete with $\tau\nu$ and top-bottom modes.

The most problematic region for $H^\pm$ discovery in the MSSM is for moderate values of $\tan\beta$, since the production mechanisms which rely on a large bottom quark or top quark Yukawa coupling (e.g. $gb \to H^\pm t$) are least effective. Hence alternative mechanisms which could offer good detection prospects for $H^\pm$ at moderate values of $\tan\beta$ are desirable. The cross sections for the pair production mechanisms $pp \to H^\pm A_1$ and $pp \to H^\pm h_1$ fall quickly with increasing scalar masses but for relatively light masses ($\lesssim 200$ GeV) they can provide promising signal rates which might enable their detection at the LHC (see [18] for studies in the context of the MSSM). One common feature is that the produced scalars enjoy large transverse momenta, which are crucial for the trigger and event selection.

In the NMSSM, if the coupling $H^\pm W^\mp A_1$ is sizeable, so will be the cross section for $pp \to W^\pm \to H^\pm A_1$ provided that $H^\pm$ and A_1 are not too heavy. The production mechanism $pp \to H^\pm A_1$ followed by the decay $H^\pm \to W^\pm A_1$ would give rise to a signal $W^\pm A_1 A_1 \to Wbbbb$ [19] or $W^\pm A_1 A_1 \to W\tau\tau\tau\tau$. The signature $W^\pm A_1 A_1 \to Wbbbb$ was simulated at the LHC in [20] in the context of the CP violating MSSM with the conclusion that a sizeable signal essentially free of background could be obtained. We use NMSSM-TOOLS1.1.1 to calculate the mass spectrum and couplings of the NMSSM Higgs bosons, and we link CTQ6.1M PDF distribution to this code in order to calculate the cross sections of $pp \to H^\pm A_1$, $pp \to H^\pm h_1$ and $pp \to W^\pm h_1$. All cross sections are evaluated at a scale which is the sum of the masses in the final states and do not include next-to-leading order QCD enhancement factors (K factors) of around $1.2 \to 1.3$ [18],[21].

Note that the process $pp \to H^\pm A_1 \to W^\pm A_1 A_1$ leads to the same signature as the process $pp \to Wh_1 \to WA_1A_1 \to Wbbbb$. The latter has been simulated in [22] and also offers very good detection prospects. We will compare the magnitude of these two distinct mechanisms which lead to the same $Wbbbb$ signature. In addition, the mechanism $pp \to H^\pm h_1$ followed by the decay $H^\pm \to W^\pm A_1$ would also lead to the same final state $W^\pm A_1 h_1 \to Wbbbb$.

Hence a numerical comparison of their cross sections is of particular interest and is shown in Fig. (2), where all points satisfy the following conditions:

$$\sigma(pp \to H^\pm A_1) > 0.1\ pb \qquad \text{and} \qquad \sigma(\mathrm{pp} \to \mathrm{W}^\pm \mathrm{h}_1) > 0.1\ \mathrm{pb}\,. \tag{5}$$

Superimposed on Fig. (2a) and Fig. (2b) are the main decay modes of the charged Higgs boson and the decay neutral Higgs boson H_1 respectively. We further impose the following conditions:

$$Br(H^\pm \to W^\pm A_1) > 0.5 \qquad \text{and} \qquad \mathrm{Br}(\mathrm{h}_1 \to \mathrm{A}_1\mathrm{A}_1) > 0.5\,, \tag{6}$$

and the surviving points are displayed in Fig. (2a). Importantly, there are many points where the two cross sections are of comparable size. We note that for these points in Fig. (2a) the pseudoscalar A_1 can be both R-axion like or a mixture of the three allowed basic axions. If the magnitude of the cross sections of both $pp \to H^\pm A_1$ and $pp \to Vh_1$ are similar then the interference of the two channels (i.e., the same $Wbbbb$ signature arising from distinct production mechanisms) should be taken into account. We have neglected such effects in the present study.

We now discuss whether the $Wbbbb$ signatures can be distinguished experimentally by comparing the strategies adopted in [20] (for $pp \to H^\pm A^0$) and [22] (for $pp \to W^\pm h_1$). In order to reconstruct the peak of the CP-even Higgs h_1, one can select events with a charged lepton and four tagged b quark jets as shown in [22]. This enables both a clean Higgs signal with high significance and a measurement of M_{h_1} given by the invariant mass of the four b quark jets, m_{4b}. The process

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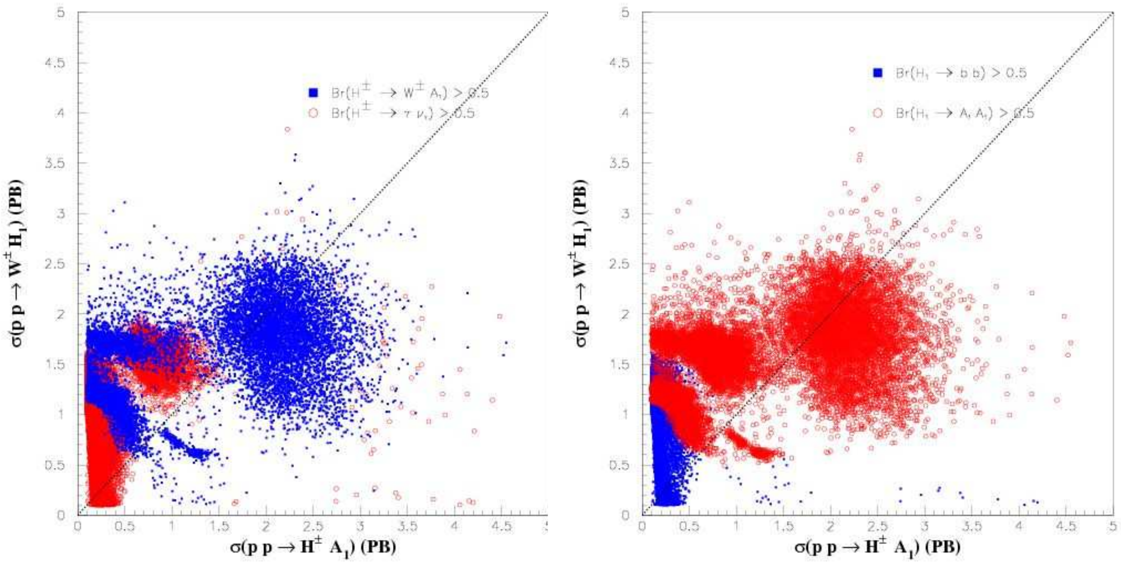

Figure 2: *Left panel: comparison of* $\sigma(pp \to H^\pm A_1)$ *and* $\sigma(pp \to W^\pm h_1)$ *with two* $H^\pm$ *decay modes. Right panel: comparison of* $\sigma(pp \to H^\pm A_1)$ *and* $\sigma(pp \to W^\pm h_1)$ *with two* h_1 *decay modes. The dotted line corresponds to* $\sigma(pp \to W^\pm h_1) = \sigma(pp \to H^\pm A_1)$.

$pp \to H^\pm A_1$ might be an irreducible background but presumably could be significantly suppressed with the aforementioned cut on m_{4b} e.g., $m_{h_1} - 15\text{GeV} < m_{4b} < m_{h_1} + 15\text{GeV}$.

Regarding detection of $pp \to H^\pm A^0$, it was demonstrated in [20] (for the analogous process $pp \to H^\pm H_1 \to W H_1 H_1$ in the CP violating MSSM) that the mass of $H^\pm$ can be reconstructed. This is achieved by defining a tranverse mass (M_T) which is a function of the momenta of the two secondary b jets (i.e., those originating from the decay $H^\pm \to A_1 W \to Wbb$) and the momenta of the lepton and missing energy coming from the W boson. It was shown that M_T is sensitive to the underlying charged Higgs mass and thus can be used for the determination of $M_{H^\pm}$. The pair of b jets from $pp \to W^\pm h_1$ might be an irreducible background but presumably could be suppressed with a cut on M_T

To reconstruct the peak of the light CP-odd neutral Higgs A_1 one can require events with four tagged b jets, construct the three possible double pairings of $b\bar{b}$ invariant masses, and then select the pairing giving the least difference between the two bb invariant masses values [20]. $W4b$ signatures from the process $pp \to W^\pm h_1$ also contribute constructively to the reconstruction of A_1. Thus we conclude that it is promising to reconstruct the peaks of the CP-even neutral Higgs (h_1), charged Higgs ($H^\pm$) and CP-odd neutral Higgs (A_1) and thus experimentally distinguish the $Wbbbb$ signatures arising from the two distinct production mechanisms. We defer a detailed simulation to a future work.

In summary, It was shown that $H^\pm \to W^\pm A_1$ can dominate over the standard decays $H^\pm \to \tau^\pm \nu$ and $H^\pm \to tb$ both below and above the top-bottom threshold. Large branching ratios for $H^\pm \to W^\pm A_1$ and $H^\pm \to W^\pm h_1$ would affect the anticipated search potential for $H^\pm$ at the LHC. We also studied the production process $pp \to H^\pm A_1$ and showed that sizeable cross sections (> 1 pb) are possible. It is known that intermediate values of $\tan\beta$ (e.g., $5 < \tan\beta < 20$) are most problematic for discovery of $H^\pm$ at the LHC [23] since the $H^\pm tb$ Yukawa coupling (which is

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employed in the conventional production processes) takes its lowest values. In such a region the process $pp \to H^{\pm}A_1$ can have a sizeable cross section if $m_{H^{\pm}} + m_{A_1} < 200$ GeV. Therefore we propose $pp \to H^{\pm}A_1$ as a unique mechanism to probe the parameter space of intermediate $\tan\beta$ and light charged Higgs boson in the NMSSM.

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