Charged Scalar Phenomenology in the Bilinear R–Parity Breaking Model†

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Abstract

We consider the charged scalar boson phenomenology in the bilinear R-parity breaking model which induces a mixing between staus and the charged Higgs boson. The charged Higgs boson mass can be lower than expected in the MSSM, even before including radiative corrections. The R-parity violating decay rates can be comparable or even bigger than the R-parity conserving ones. These features could have implications for charged supersymmetric scalar boson searches at future accelerators.

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A lot of emphasis has been put into the phenomenological study of the supersymmetric Higgs boson sector \([1]\). However, so far most of these phenomenological studies have been made in the framework of the Minimal Supersymmetric Standard Model with conserved R-parity \([2]\). Alternative supersymmetric scenarios where the effective low energy theory violates R-parity \([3]\) have recently received a lot of attention \([4, 5]\). The simplest version of these models, in which the violation of R-parity is effectively parametrized by a bilinear term \(\epsilon_3 \tilde{L}_i \tilde{H}_u\) is receiving growing attention \([6, 7]\). We focus on the phenomenology of the charged scalar bosonic sector. This complements a previous study of the electrically neutral sector \([8]\). We show that: 1) the mass of the charged Higgs boson can be lower than expected in the MSSM, even before including radiative corrections, 2) if the stau is the LSP it will only have R-parity violating decay channels into standard model fermions, while in the opposite case when it is heavier than the lightest neutralino one expects exotic high multiplicity events, 3) the branching ratios for the R-parity violating charged Higgs boson decays can be comparable or even bigger than the R-parity conserving ones.

The Lagrangian is specified by the superpotential \(W\) given by
\[
W = \varepsilon_{ab} \left[ h_{ij}^u \tilde{Q}^a_i \tilde{U}^b_j \tilde{H}^a_u + h_{ij}^d \tilde{Q}^a_i \tilde{D}^b_j \tilde{H}^a_d + h_{ij}^e \tilde{E}^b_i \tilde{\tau}^a_j \tilde{H}^a_d - \mu \tilde{H}_d^a \tilde{H}_u^b + \epsilon_3 \tilde{L}^a_i \tilde{H}_u^a \right]
\]
Supersymmetry breaking is parametrized by the set of soft supersymmetry breaking terms which do not introduce quadratic divergences to the unrenormalized theory. We will focus for simplicity on the case of one generation, namely the third \([8, 9]\). In contrast we keep in our discussion the theory as defined at low energies by the most general set of soft-breaking masses, trilinear and bilinear soft-breaking parameters, gaugino masses and the Higgs superfield mixing parameter \(\mu\). The electroweak symmetry is broken when the two Higgs doublets \(H_d\) and \(H_u\), and the third component of the left slepton doublet \(\tilde{L}_3\) acquire vacuum expectation values to minimize the scalar potential. Note that the \(W\) boson acquires a mass \(m_W^2 = \frac{1}{4} g^2 (v_u^2 + v_d^2 + v_d^2)\). In addition to the MSSM parameters, our model contains three new parameters, \(\epsilon_3\), \(v_\tau\) and \(B_2\), of which only two are independent, and these may be chosen as \(\epsilon_3\) and \(v_\tau\). An important feature of this model is that lepton number is also violated by the \(\epsilon_3\) term and by the presence of the sneutrino vacuum expectation value \(v_\tau\). This induces a mass for the tau neutrino, which turns out to be:
\[
m_{\nu_\tau} \approx \frac{(g^2 M + g'^2 M') (\mu v_\tau + \epsilon_3 v_d)^2}{-4MM' \mu^2 + 2\mu v_d v_u (g^2 M + g'^2 M') + \delta(\epsilon_3, v_\tau)}
\]
with \(\delta(\epsilon_3, v_\tau) = [2\epsilon_3 v_\tau (\mu v_d - M' v_u) + v_d^2 \mu^2 (g^2 + g'^2) + \epsilon_3^2 (g^2 v_u^2 + g'^2 v_d^2 - 4MM')]\) and it is naturally small in models with universality of soft mass parameters at the unification scale \([7]\). If the bilinear terms are rotated away the rotation will generate trilinear and bilinear R–parity violating couplings in the scalar potential which are proportional to \(\epsilon_3\). It has been claimed \([10, 11]\) that \(v_\tau\) terms are proportional to neutrino masses but in this basis may be possible to find light neutrinos with large \(\epsilon_3\) and \(v_\tau\) because \(m_{\nu_\tau} \sim (\mu v_\tau + \epsilon_3 v_d)^2\) and small neutrino masses requires that the combination \((\mu v_\tau + \epsilon_3 v_d)\) be small. Then we consider the possibility of large R–violation. In this paper we take the parameters at the
Figure 1: Tree level and one–loop charged Higgs boson mass as a function of the CP–odd Higgs mass \( m_A \).

weak scale independent (i.e. no universality assumption), and always impose \( m_{\nu_{\tau}} \lesssim 20 \) MeV. The charginos mix with the tau lepton forming a set of three charged fermions. The tau Yukawa coupling \( h_\tau \) can be fixed, such that one of the singular values is equal to the tau mass, through an exact tree level formula [7].

The 4 \times 4 mass matrix of the charged scalar sector has three components in the minimum of the potential:

\[
M_{S_{\pm}}^2 = M_{H_{d}}^2 + M_{H_{u}}^2 + M_\tau^2
\]

where \( M_{H_{d}}^2 \) is the 2 \times 2 MSSM charged Higgs block and \( M_\tau^2 \) is the 2 \times 2 MSSM stau block. The component not present in the MSSM which produces a mixing between the charged Higgs sector and the stau sector, \( M_\tau^2 \), is given by:

\[
\begin{pmatrix}
\frac{1}{2} h_\tau^2 v_\tau^2 & \frac{1}{2} (g^2 - g'^2) v_\tau^2 & \frac{1}{4} (g^2 - 2 h_\tau^2) v_\tau v_\tau & -\frac{1}{2} h_\tau (\epsilon_3 v_u + A_{\tau} v_\tau) \\
0 & \epsilon_3 + \frac{1}{4} (g^2 - g'^2) v_\tau^2 & -B_2 \epsilon_3 + \frac{1}{4} g^2 v_\tau v_\tau & -\frac{1}{2} h_\tau (\mu v_\tau + \epsilon_3 v_d) \\
\frac{1}{4} (g^2 - 2 h_\tau^2) v_\tau v_\tau & -B_2 \epsilon_3 + \frac{1}{4} g^2 v_\tau v_\tau & \epsilon_3^2 + \frac{1}{8} (g^2 + g'^2) v_\tau^2 & 0 \\
-\frac{1}{2} h_\tau (\epsilon_3 v_u + A_{\tau} v_\tau) & -\frac{1}{2} h_\tau (\mu v_\tau + \epsilon_3 v_d) & 0 & \frac{1}{2} h_\tau^2 v_\tau^2 - \frac{1}{4} g^2 v_\tau^2
\end{pmatrix}
\]

In our numerical study of the charged Higgs mass spectrum, we have varied the MSSM parameters over a wide range. Note that \( m_{H_{d}}, m_{H_{u}}, \) and \( B_2 \) are fixed through minimization. No big differences are observed if we change the sign of \( \mu \). We are interested in a relatively light charged Higgs, so we take \( |\mu|, |B| \leq 200 \) GeV. Similarly we are interested in relatively light staus, and that is why we take \( m_{R_3}, m_{L_3} \leq 300 \) GeV. The main point to note is that \( m_{H_{\pm}} \) can be lower than expected in the MSSM, even before including radiative corrections. This is due to negative contributions arising from the R-parity violating stau-Higgs mixing, controlled by the parameter \( \epsilon_3 \).

We now turn to a discussion of the charged scalar boson decays. In Fig. [2] we display the stau decay branching ratios below and above the neutralino threshold. We have fixed the parameters in such a way as to ensure that the lightest neutralino is about 80 GeV in mass and thus may be produced as a decay product of a stau produced at LEP II
energies. Below the neutralino threshold the stau is the LSP and will have only R-parity violating decays: $\nu_\tau \tau$, $c\bar{s}$ and $c\bar{b}$.

The charged Higgs boson branching ratios, Fig. 3, into supersymmetric channels can be comparable or even bigger than the R-parity conserving ones, even for relatively small values of $\epsilon_3$ and $v_3$. In the region of small $\tan \beta$, the R-parity violating Higgs boson decay branching ratios can exceed the conventional ones and may reach values close to 1. We have scanned the parameter space and we find that even for very small R–parity violating parameters the branching ratio $B(H^+ \rightarrow \tau^+ \tilde{\chi}^0)$ can be close to unity, and that in the region of $\tan \beta \gg 1$ the decay $H^+ \rightarrow \tau^+ \nu_\tau$ dominates.

If the stau is the LSP it will decay only through R-parity-violating interactions, to $c\bar{s}$ or $\tau\nu_\tau$. Then it leads to signatures identical to those of the charged Higgs boson in the MSSM. However, if it is not the LSP the $\tilde{\tau}_1^\pm$ is more likely to have standard R-parity-conserving decays such as neutralino plus $\tau$, leading to signals that can be drastically different from those expected in the MSSM and which would arise from $\tilde{\chi}^0 \rightarrow \nu_\tau Z^*$ or $\tilde{\chi}^0 \rightarrow \tau W^*$. Unless $\epsilon_3$ and $v_3$ are extremely small, the neutralino will decay inside the detector. For the case of stau pair production in $e^+e^-$ colliders, such as LEP II, this would imply a plethora of new high fermion-multiplicity events (multi-jets and/or multi-leptons). For example, $2\tau + 4j + \text{missing energy}$ if both neutralinos decay into jets through neutral currents, or $4\tau + 4j$ if both neutralinos decay into jets through charged currents. As for hadron colliders, we can also have very high leptonic multiplicity events such as six leptons of which at least two are taus, plus missing momentum. This should be easy to see at the LHC, due again to the negligible standard model background.

Another interesting feature of our model is the mixed production $e^+e^- \rightarrow H^+\tilde{\tau}^\mp$
Figure 3: Charged Higgs branching ratios possible in our model for a particular choice of parameters. The R–parity violating decay dominates at low tan β.

which is absent in the MSSM. If \( m_{\chi_1^0} < m_{\tilde{\tau}_1^\pm} \) then one can produce interesting signatures like di-tau + di-jets + missing energy. This is obtained when \( H^\pm \rightarrow \tau^\pm \nu_\tau \) and \( \tilde{\tau}^\mp \rightarrow \tau^\pm \chi_1^0 \rightarrow \tau^\pm q\bar{q} \nu_\tau \), and may have a non-negligible cross-section.

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