The Minimal Supersymmetric Standard Model with a Bilinear R–Parity Violating Term

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Abstract

Some aspects of bilinear R-Parity violation, the simplest extension of the MSSM which does not conserve R–Parity, are reviewed in comparison with the MSSM. We put special emphasis on the effect of quantum corrections.

† Talk given at the International Workshop on Quantum Effects in the Minimal Supersymmetric Standard Model, 9–13 September 1997, Barcelona, Spain.
1 Introduction

The simplest extension of the Minimal Supersymmetric Standard Model (MSSM) that violates R–Parity is the “$\varepsilon$–model”, which includes only bilinear R–Parity violation. In this model, a term of the form $\varepsilon_i \hat{L}_a^i \hat{H}_2^b$ is introduced explicitly in the superpotential [1]. This is motivated by models that break spontaneously R–Parity and lepton number through vacuum expectation values of right handed sneutrinos [2]. Here, as we said, the $\varepsilon_i$ term is introduced explicitly and we assume for simplicity that only $\varepsilon_3$ is different from zero. The presence of $\varepsilon_3$ induces a non–zero v.e.v. of the left handed tau sneutrino $\langle \tilde{\nu}_\tau \rangle = v_3/\sqrt{2}$ which contribute to the $W$ mass according to $m_{W}^2 = \frac{1}{4} g^2 (v_1^2 + v_2^2 + v_3^2)$ with $v_1$ and $v_2$ being the v.e.v.’s of the Higgs fields.

2 Bilinear R–Parity Violation

Bilinear R–Parity violation is characterized by the following superpotential

$$ W = \varepsilon_{ab} \left[ h_t Q_3^a \tilde{H}_2^b + h_b Q_3^b \tilde{D}_1^a + h_\tau \tilde{L}_3^a \tilde{H}_2^a - \mu \tilde{H}_1^a \tilde{H}_2^b + \varepsilon_3 \tilde{L}_3^a \tilde{H}_2^b \right] $$

where the first four terms correspond to the MSSM and the last term is the explicit violation of R–Parity and tau–lepton number.

The $\varepsilon_3$–term is physical and cannot be rotated away by the redefinition of the fields

$$ \mu' \tilde{H}_1^a = \mu \tilde{H}_1^a - \varepsilon_3 \tilde{L}_3, \qquad \mu' \tilde{L}_3 = \varepsilon_3 \tilde{H}_1^a + \mu \tilde{L}_3, $$

with $\mu^2 = \mu^2 + \varepsilon_3^2$. The reason is that, although the bilinear term disappear from the superpotential after performing that rotation, a trilinear R–Parity violating term is reintroduced in the Yukawa sector, which is proportional to the bottom quark Yukawa coupling $h_b$.

At the same time, bilinear terms which induce a non–zero vacuum expectation value of $\tilde{\nu}_\tau'$ reappear in the soft terms, therefore, $\langle \tilde{\nu}_\tau' \rangle = v'_3 \neq 0$. These terms in the rotated basis are

$$ V_{soft} = (B_2 - B) \frac{\varepsilon_3 \mu'}{\mu'} \tilde{L}_3^a \tilde{H}_2 + (m_{H_1}^2 - M_{L_3}^2) \frac{\varepsilon_3 \mu'}{\mu'} \tilde{L}_3^a \tilde{H}_1' + h.c. + ... $$

where $B$ and $B_2$ are the bilinear soft breaking terms associated to the next-to-last and last terms in eq. (1), and $m_{H_1}$ and $M_{L_3}$ are the soft mass terms associated to $H_1$ and $\tilde{L}_3$.

The presence of $\varepsilon_3$ and $v_3$ induce a mixing between the neutralinos and the tau neutrino. As a consequence, a tau neutrino mass is generated which satisfy $m_{\nu_\tau} \sim (\varepsilon_3 v_3 + \mu v_3)^2$. The quantity inside the brackets is proportional to $v'_3$, thus a non–zero vev of $\tilde{\nu}_\tau'$ is crucial for the generation of a mass for the tau neutrino.
3 Charginos in the MSSM and in the $\epsilon$–Model

At $e^+e^-$ colliders within the MSSM charginos are produced in the $s$–channel with the interchange of $Z$–gauge bosons or photons, and in the $t$–channel with the interchange of neutralinos. Quantum corrections to the total cross section $\sigma(e^+e^- \rightarrow \tilde{\chi}_a^+ \tilde{\chi}_b^-)$, with $a, b = 1, 2$, have been calculated recently \cite{3} in the approximation where top and bottom quarks and squarks are included in the loops. These corrections are important in order to extract the parameters of the theory from the experimental measurements \cite{4}. In Fig. 1 we plot the radiatively corrected cross section as a function of $\tan \beta$ for different values of the squark mass parameters. We compare the tree level with the one–loop cross section and we see that corrections are positive and typically of 10% to 15% if the squark mass parameters are of the order of 1 TeV. These quantum corrections have not been calculated in the $\epsilon$–model.

In the chargino sector, the main difference between the MSSM and bilinear R–Parity violation is that the two charginos mix with the tau lepton, forming a set of three charged fermions. Due to this mixing, in $e^+e^-$ colliders it is possible the mixed production $e^+e^- \rightarrow \tilde{\chi}_i^\pm \tau^\mp$ which is forbidden in the MSSM.
4 The $\epsilon$–Model in Minimal Supergravity

The large number of independent parameters in the MSSM can be greatly reduced when this model is embedded into a supergravity inspired model (MSSM–SUGRA) and universality of soft parameters at the unification scale is assumed. In addition, in MSSM–SUGRA the breaking of the electroweak symmetry can be achieved radiatively due to the large value of the top quark Yukawa coupling.

Radiative breaking of the electroweak symmetry can be achieved also in models with bilinear R–Parity violation embedded into supergravity with the universality assumption [5]. Using the RGE’s we impose the correct electroweak symmetry breaking. In order to do that, we impose that the one–loop tadpole equations are zero, and find the three vacuum expectation values. This tadpole method is equivalent to use the one–loop effective potential [5]. The solutions we find are displayed as scatter plots. In Fig. 2 we show an interesting effect of quantum corrections. In this figure we plot the neutrino mass $m_{\nu_e}$ as a function of the parameter $\xi \equiv (\epsilon_3 v_1 + \mu v_3)^2 = \mu' v'_3$. As we can see, it is easy to find solutions with $m_{\nu_e} < 30 \text{ MeV}$. This is so because the neutrino mass is radiatively generated. Indeed, the tadpole equation for $v'_3$ is

$$t'_3 = (m^2_{H_1} - M^2_{L_3}) \frac{\epsilon_3 \mu}{\mu^2} v'_1 + (B_2 - B) \frac{\epsilon_3 \mu}{\mu^2} v'_2 + \frac{m^2_{H_1} \epsilon_3^2 + M^2_{L_3} \mu^2}{\mu^2} v'_3 + \frac{1}{8} (g^2 + g'^2) v'_3 (v_1^2 - v_2^2 + v_3^2) = 0$$

(4)
and considering that the RGE solution for the differences
\[ m_{H_u}^2 - M_{L_3}^2 \approx -\frac{3h_b^2}{8\pi^2} \left( m_{H_1}^2 + M_Q^2 + M_D^2 + A_D^2 \right) \ln \frac{M_{GUT}}{m_{weak}} \]
\[ B_2 - B \approx \frac{3h_b^2}{8\pi^2} A_D \ln \frac{M_{GUT}}{m_{weak}} \]
are proportional to the square of the bottom quark Yukawa coupling through the factor \( h_b^2/(8\pi^2) \), then it is easy to see from eq. (4) that \( v_3^\prime \), and therefore \( m_{\nu_\tau} \), are small and generated by radiative corrections [9].

In Fig. 3 we see the correlation between the bottom quark Yukawa coupling at the GUT scale with \( \tan \beta \). For large values of \( \tan \beta \), \( h_b \) is large and allows unification with the top and tau Yukawa couplings [8].

5 Neutral Scalar Sector

The neutral scalar sector of the \( \epsilon \)-model differs from the MSSM in that the Higgs bosons mix with the tau sneutrinos. The CP–even sector is a mixture of the two Higgs bosons and the real part of the tau sneutrino field. Similarly, the CP–odd sector is a mixture between the Higgs bosons and the imaginary part of the tau sneutrino, with one linear combination being the unphysical Goldstone boson. Within bilinear R–Parity violation embedded into Supergravity, we calculate the lightest neutral CP–even scalar mass, including radiative corrections proportional to \( m_t^4 \). In Fig. 4 we plot the ratio between this mass and the
Figure 4: Ratio between the lightest CP-even scalar mass in bilinear R–Parity violation and the lightest CP–even Higgs boson mass in the MSSM as a function of $v_3$.

The lightest Higgs mass $m_h$ in the MSSM, as a function of the sneutrino v.e.v. $v_3$. We observe that the $\epsilon$–model approaches to the MSSM result when $v_3$ approaches zero.

Due to its mixing with the tau sneutrino, the decays of the lightest neutral scalar $h$ in this model include some decays that violates R–Parity. For example, the decay $h \rightarrow \tilde{\chi}_1^0 \nu_\tau$ can be substantially large, and even with its branching ratio close to one, specially if its mass is near to $m_{\tilde{\nu}_\tau}$, so the mixing is large [9].

6 Charged Scalar Sector

In bilinear R–Parity violation, the charged Higgs bosons mix with the left and right staus. Due to this mixing, the lower limit of the charged Higgs mass is lowered. In the MSSM, the one–loop renormalized charged Higgs mass is given by [10, 11]

$$m_{H^\pm}^2 = m_W^2 + m_A^2 + \text{Re}[A_{H^+ H^-} (m_{H^\pm}^2) - A_{WW} (m_W^2) - A_{AA} (m_A^2)], \quad (7)$$

We approximate the radiative corrections to the charged Higgs mass in the $\epsilon$–model by the corrections in eq. (7). We perform a scan over parameter space and in Fig. 5, each curve corresponds to the lower limit below where no solutions are found. Four curves are shown according to the range of variation of the R–Parity violating parameters $\epsilon_3$ and $v_3$. The allowed region lies above each curve. We observe that in this bilinear R–Parity
6.1 Charged Scalar Production

Charged Higgs boson pairs are produced at $e^+e^-$ colliders through intermediate $Z$–bosons and photons in the $s$–channel. Within the MSSM, radiative corrections to the total cross section are important \[12\]. In Fig. 6 we plot the tree level and the one–loop corrected cross section as a function of $\tan \beta$, for three representative choices of parameters. Curves are truncated when the CP-odd Higgs mass is too low. Corrections vary between 50% and $-20\%$ for the choice of parameters in Fig. 6.

In the $\epsilon$–model the effect of radiative corrections to the cross section $\sigma(e^+e^- \rightarrow H^+H^-)$ is unknown. In Fig. 7 we plot at tree level (a) the charged Higgs and (b) the stau pair production cross section as a function of the corresponding mass. The scan was made with $4 \times 10^4$ points in parameter space. Most of the points fall into the MSSM curves, but there are some deviations due to charged Higgs fields mixing with right–stau. In the case of stau production cross section, the upper (lower) region where the points are concentrated corresponds to left (right) staus.

As opposed to the MSSM, bilinear R–Parity violation makes possible the mixed pro-
Figure 6: Tree level (dashes) and radiatively corrected (solid) total production cross section of a pair of charged Higgs bosons at LEP2 as a function of $\tan \beta$ in the MSSM.

Figure 7: Total production cross section of a pair of (a) charged Higgs and (b) light staus, as a function of their mass. The center of mass energy is 192 GeV.
Figure 8: Stau branching ratios possible in our model, for certain choice of parameters. Below the neutralino threshold, the stau has R–Parity violating decay modes with 100%.

The production of charged Higgs bosons and staus. The total cross section \( \sigma(e^+e^- \rightarrow H^+\tilde{\tau}_1^+) \equiv \sigma(e^+e^- \rightarrow H^+\tilde{\chi}_1^0) + \sigma(e^+e^- \rightarrow H^-\tilde{\tau}_1^+) \) can reach values up to 0.13 pb.

### 6.2 Charged Scalar Decays

Decay modes of charged scalar particles are modified with respect to the MSSM for two reasons. First, there are new R–parity violating channels like \( H^+ \rightarrow \tilde{\chi}_1^0 \nu_r \) and \( H^+ \rightarrow \tilde{\chi}_1^0 \nu_r \) for the charged Higgs, and \( \tilde{\tau}_i^+ \rightarrow \nu_r \tau^+ \) and \( \tilde{\tau}_i^+ \rightarrow c\bar{s} \) for the staus. And second, the lightest supersymmetric particle is not stable. In the case of the neutralino as the LSP, its decay modes are \( \tilde{\chi}_1^0 \rightarrow \nu_r Z^* \rightarrow \nu_r q\bar{q}(l\bar{l}) \) and \( \tilde{\chi}_1^0 \rightarrow \tau W^* \rightarrow \tau q\bar{q}(l\bar{l}) \). Furthermore, the LSP need not to be the lightest neutralino, and if the LSP is the lightest stau, it can have R–parity violating decays \( \tilde{\tau}_1^+ \rightarrow \nu_r \tau^+(c\bar{s}) \) with a 100% branching ratio [13].

In Fig. 8 we see this effect. We have chosen arbitrary values for the parameters except for the fact that the stau can be the lightest supersymmetric particle. In addition, the R–Parity violating parameters \( \epsilon_3 \) and \( v_3 \equiv v \cos \theta \) are chosen to be small. Below the neutralino threshold the R–Parity violating decay \( \tilde{\tau}_1^+ \rightarrow \nu_r \tau^+ \) occurs with probability close to one. Note also that the decay mode \( \tilde{\tau}_1^+ \rightarrow c\bar{b} \) cannot be neglected in front of \( \tilde{\tau}_1^+ \rightarrow c\bar{s} \).

In Fig. 9 we plot the branching ratios of the charged Higgs boson decays as a
function of $\tan \beta$. R–Parity violating parameters are chosen to be small just in order to appreciate that large effects can be obtained with small parameters. Besides that, the choice of parameters is arbitrary. In the region of small $\tan \beta$ the decay $H^+ \rightarrow \chi^0_1 \tau^+$, which violates R–Parity, is the dominant. This decay cannot compete with $H^+ \rightarrow \nu_\tau \tau^+$ at large $\tan \beta$ because the last one grows with $\tan^2 \beta$. The existence of a region of parameter space where the R–Parity violating decay mode of the charged Higgs is dominant, does not depend on the particular choice of parameters made in Fig. 9. To prove this we make a scan over parameter space and plot in Fig. 10 curves that represent the boundary beyond which no solutions are found. The parameters are varied arbitrarily with the exception of the R–Parity violating parameters $\epsilon_3$ and $v_3$, which are varied as indicated in the Figure. We observe that even for small values of $\epsilon_3$ and $v_3$, solutions with $B(H^+ \rightarrow \chi^0_1 \tau^+)$ close to unity are found, and only for large $\tan \beta$, $B(H^+ \rightarrow \nu_\tau \tau^+)$ dominates all the time. Also interesting to notice is the fact that large values of R–Parity violating parameters are allowed by the model.

7 Conclusions

We have reviewed some aspects of the MSSM and its simplest extension that violates R–Parity. This extension corresponds to bilinear R–Parity violation, sometimes called “$\epsilon$–model”, and introduces in the superpotential a term $\epsilon_i \tilde{L}_i \tilde{H}_2^l$, which violates lepton number as well as R–Parity. In its simplest version, the violation occurs only in the third
generation. The $\epsilon_3$ term induces a v.e.v. to the tau sneutrino and generates a mass for the tau neutrino. In models with universality of soft masses $m_{\nu_\tau}$ is generated radiatively at one–loop and turns up to be proportional to $h_b^2/(8\pi^2)$, where $h_b$ is the bottom quark Yukawa coupling. The neutral (charged) Higgs sector mixes with the tau sneutrino (stau) sector, and the phenomenology of the $\epsilon$–model turns out to be very different from the MSSM.

We have discussed some effects of one–loop radiative corrections, within the MSSM, to masses and production cross sections. We have shown that in order to have a correct interpretation of the experimental data, it is important to include quantum corrections. In this sense, much work needs to be done in models with bilinear R–Parity violation, where much of the analysis has been done at tree level.

**Acknowledgments**

The author is indebted to his collaborators A. Akeroyd, J. Ferrandis, M.A. Garcia–Jareño, A. Joshipura, J.C. Romão, and J.W.F. Valle for their contribution to the R–Parity violating section of this talk, and H.E. Haber, S.F. King, D.A. Ross, and T. ter Veldhuis for their contribution to the R–Parity conserving section. The author was supported by a DGICYT postdoctoral grant of the Spanish Ministerio de Educación y Ciencias.
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