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How to spontaneously break R parity

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We demonstrate explicitly that R parity (R_p) can break spontaneously in a simple extension of the minimal supersymmetric standard model (MSSM) proposed previously. For suitable values of the parameters of the low energy theory, consistent with observation, the energy is minimum when both R parity and electroweak symmetries are spontaneously broken. The R-parity breaking scale typically lies in the phenomenologically interesting range ~ 10 GeV–1 TeV.

1. Introduction

The minimal supersymmetric standard model (MSSM) assumes a discrete symmetry called R parity [1] related to the spin (S), lepton number (L), and baryon number (B) according to $R_p = (-1)^{(3B+L+2S)}$. Clearly under this symmetry all standard model particles are R-even while their superpartners are R-odd. Also B and L conservation lead to R-parity conservation and imply that SUSY particles must always be pair-produced, the lightest of them being absolutely stable.

Whether or not R parity is a good symmetry, and to what extent, is ultimately a dynamical question, which is sensitive to physics at a more fundamental scale. It is therefore of great interest to investigate alternative scenarios where the effective low energy theory does not exhibit this symmetry. This interest is further enhanced in view of the fact that the associated effects may well be accessible to experimental verification [2–6].

Explicit R-parity violating interactions $u^c u^c d^c$, lle^c or Qld^c may arise as residual effects from physics at a higher mass scale [7]. They involve many arbitrary low energy constants generically denoted λ, some of which induce proton decay and are highly constrained [8]. Additional restrictions may follow from cosmological arguments related to the baryon asymmetry of the universe [9]. Indeed, these interactions mediate $B-L$ violating decays of squarks and sleptons such as $\tilde{u} \to \bar{d}\bar{d}$, $\tilde{u} \to \bar{l}d$, and $\bar{\tilde{l}} \to l\nu$. At temperatures T above $O(m_W/\alpha_{weak})$, B- and L-violating transitions will occur rapidly [10] and may erase any primordial B-asymmetry, unless an excess of the anomaly-free $B-L$ symmetry existed at very early times. However, in this case it is crucial that this $B-L$

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asymmetry not be eliminated through R_p violating interactions in the early universe, leading to a very stringent limit $\lambda \leqslant O(10^{-7})(\tilde{m}/\mathrm{TeV})^{1/2}$ [9]. Barring the existence of additional symmetries that may protect this erasure of the primordial $B-L$ asymmetry by appropriate restrictions on the flavour structure of the R_p violating couplings [11] (and/or the possibility of generating the baryon asymmetry at low energy [12]) this bound holds generically and substantially restricts the prospects of detectability of effects associated to *explicit* R-parity violating interactions at collider experiments.

On the other hand it seems reasonable to assume that, as all fundamental symmetries, R parity should be a manifest symmetry at the lagrangian level broken only by the ground state [13,14]. This provides a *systematic* way to include R-parity violating effects, that automatically respects low energy *baryon number conservation*. Moreover, it naturally *evades* the baryogenesis restrictions discussed above, to the extent that the breaking of R parity sets in only as an electroweak scale phenomenon. As a result these models naturally allow for the possibility of sizeable R parity violating effects [2,15].

There are two ways to spontaneously break R_p. If *lepton number is part of the gauge symmetry* there is a new gauge boson Z' which acquires mass via the Higgs mechanism at a scale related to that which characterizes R-parity violation [15,16]. On the other hand, if spontaneous R-parity violation occurs *in absence of an additional gauge symmetry*, there is a physical massless Goldstone boson, called majoron (J) [13]. Consistency with LEP measurements of the invisible Z width requires that R-parity breaking be driven by *isosinglet* slepton vacuum expectation values (VEVs) [14]. In this case the majoron is mostly singlet and the Z does not decay by majoron emission. Both mechanisms above require the existence of additional singlet leptons and lead to distinctive *dynamical consequences*, such as the existence of a new Z' boson or of the majoron, absent in the simplest explicit breaking models.

In this letter we consider in detail the question of spontaneous R-parity breaking in the simple extension of the minimal SUSY standard model proposed in ref. [14]. First we determine the extremum conditions of the scalar potential and devise a strategy to search for the corresponding minima. We calculate explicitly the scalar mass matrices in the model and show that they are positive definite in all directions in field space, except for that corresponding to the majoron. This shows that, for a wide range of effective low energy parameters in the scalar potential these extrema are local minima and not saddle points. Moreover we evaluate explicitly the potential for these VEV configurations and show that it attains a value lower than that which would correspond to configurations where R parity and/or electroweak symmetries are unbroken. This establishes that R-parity breaking can take place. Its characteristic scale can naturally lie anywhere in the phenomenologically interesting range

$$v_R = O(10\ \mathrm{GeV}\text{–}1\ \mathrm{TeV})\ , \tag{1}$$

with a correspondingly small v_L in the range

$$v_L \leqslant O(10\text{–}100\ \mathrm{MeV})\ . \tag{2}$$

There is a marked hierarchy in the values of v_R and v_L, because v_L is related to a Yukawa coupling h_ν and vanishes as $h_\nu \to 0$. This naturally suppresses stellar energy loss via majoron emitting processes [17] and leads to an explanation of the solar neutrino deficit [3], absent in the MSSM. Although minima will depend on parameters of the effective low energy theory, we conclude that for a wide range of suitably chosen values the energy is minimum when both R parity and electroweak symmetry are spontaneously broken. Moreover this symmetry breaking is consistent with all observational restrictions such as those that follow from SUSY searches at LEP as well as neutrino physics.

2. The model and the scalar potential

We consider the $SU(2)\otimes U(1)$ model proposed in ref. [14] that is defined by the superpotential terms

$$h_u u^c Q H_u + h_d d^c Q H_d + h_e e^c l H_d + \hat{\mu} H_u H_d + (h_0 H_u H_d - \epsilon^2)\Phi + h_\nu \nu^c l H_u + h\Phi\nu^c S + M\nu^c S + M_\Phi \Phi\Phi + \lambda\Phi^3 . \quad (3)$$

The first five terms are the usual ones that define the R_p-conserving MSSM. The fifth term ensures that electroweak symmetry breaking can take place at the tree level [18]. The last four terms involve isosinglet superfields that arise in several extensions of the standard model [19,20] and may lead to interesting phenomenological signatures of their own [19,21]. For our present purposes their presence is essential in order to drive the spontaneous violation of R parity and electroweak symmetries in a phenomenologically acceptable way [14].

The superpotential in eq. (3) conserves *total* lepton number as well as R parity. The superfields (Φ, ν_i^c, S_i) are singlets under $SU(2)\otimes U(1)$ and carry a conserved lepton number assigned as $(0, -1, 1)$ respectively (all couplings h_u, h_d, h_e, h_ν, h are described by arbitrary matrices in generation space). Note that we have added some new terms that were not included in ref. [14] because they are allowed by our symmetries. The bilinear $H_u H_d$ term plays an important role in giving more flexibility in the minimization of the Higgs potential while at the same time obeying all experimental constraints, especially the chargino mass limit from LEP. The bare singlet mass terms $\Phi\Phi$ and $\nu^c S$ allow us to give an approximate treatment of the neutral fermion sector but since they do not play any important role for our present considerations, they will be ignored. Similarly, we also take λ to be zero in our study.

In order to find the minima of the potential we assume that colour and electric charge are not broken, in analogy with what has been verified to hold for a suitable range of parameters in the corresponding R-parity conserving model [18]. We also assume that the coupling matrices $h_{\nu ij}$ and h_{ij} are nonzero only for the third generation and set $h_\nu \equiv h_{\nu 33}$ and $h \equiv h_{33}$. With this assumption we are studying effectively a one-generation model. We are well aware that a phenomenologically consistent model requires the presence of flavour nondiagonal couplings such as $h_{\nu 23}$, needed in order to ensure that the massive ν_τ decays fast enough [22] so as to obey cosmological limits. This has been shown to be the case due to the existence of the majoron emission decay channel $\nu_\tau \to \nu_\mu + J$. However for our present purposes the effective one-generation model approach will be enough. To further specify the model we give the form of the soft SUSY breaking terms. The most general form of these terms in a spontaneously broken $N=1$ supergravity model is

$$\begin{aligned} V_{\rm soft} &= \tilde{m}_0(-Ah_0\Phi H_u H_d - B\epsilon^2\Phi + Ch_\nu \tilde{\nu}^c\tilde{\nu}H_u + Dh\Phi\tilde{\nu}^c\tilde{S} + E\hat{\mu}H_u H_d + \text{h.c.}) \\ &\quad + \tilde{m}_u^2|H_u|^2 + \tilde{m}_d^2|H_d|^2 + \tilde{m}_L^2|\tilde{\nu}|^2 + \tilde{m}_R^2|\tilde{\nu}^c|^2 + \tilde{m}_S^2|\tilde{S}|^2 + \tilde{m}_\Phi^2|\Phi|^2 , \end{aligned} \quad (4)$$

where we just considered the neutral scalars. Our soft breaking terms have the form expected in models with minimal $N=1$ supergravity theories which, at the unification scale, are characterized by a universal, diagonal supersymmetry-breaking mass for the scalars (the gravitino mass) and by the proportionality of the trilinear scalar terms to a single dimensionless parameter A

$$C = D = A, \quad E = A - 1 , \quad (5)$$

$$\tilde{m}_u^2 = \tilde{m}_d^2 = \tilde{m}_L^2 = \tilde{m}_R^2 = \tilde{m}_S^2 = \tilde{m}_\Phi^2 . \quad (6)$$

Moreover in this case the coefficient B appearing in the linear term in Φ is proportional to $A-2$. At low energies, however, these conditions are not expected to hold when renormalization group evolution from the unification scale down to the electroweak scale is taken into account. In our study we allowed the values of the soft breaking masses to be different from their unification scale value $\tilde{m}_0$. We have kept however the values of B, C, D and E related as above. Moreover for simplicity we assume all parameters in the potential to be real.

With the definitions above the full scalar potential along neutral directions is given by

$$\begin{aligned} V_{\rm total} &= |h\Phi\tilde{S} + h_\nu\tilde{\nu}H_u|^2 + |h_0\Phi H_u + \hat{\mu}H_u|^2 + |h\Phi\tilde{\nu}^c|^2 \\ &\quad + |-h_0\Phi H_d - \hat{\mu}H_d + h_\nu\tilde{\nu}\tilde{\nu}^c|^2 + |-h_0 H_u H_d + h\tilde{\nu}^c\tilde{S} - \epsilon^2|^2 + |h_\nu\tilde{\nu}^c H_u|^2 \\ &\quad + \tilde{m}_0[-A(-h\Phi\tilde{\nu}^c\tilde{S} + h_0\Phi H_u H_d - h_\nu\tilde{\nu}H_u\tilde{\nu}^c) + (1-A)\hat{\mu}H_u H_d + (2-A)\epsilon^2\Phi + \text{h.c.}] \\ &\quad + \sum_i \tilde{m}_i^2|z_i|^2 + \alpha(|H_u|^2 - |H_d|^2 - |\tilde{\nu}|^2)^2 , \end{aligned} \quad (7)$$

where $\alpha=\frac{1}{8}(g^2+g'^2)$ and z_i denotes any neutral scalar field in the theory.

We now state the symmetry breaking scenario outlined in ref. [14]. Electroweak breaking is driven by the isodoublet VEVs $v_u=\langle H_u\rangle$ and $v_d=\langle H_d\rangle$, assisted by the VEV v_F of the scalar in the singlet superfield Φ. The combination $v^2=v_u^2+v_d^2$ is fixed by the W mass,

$$m_W^2=\tfrac{1}{2}g^2(v_u^2+v_d^2+v_L^2)\ , \tag{8}$$

while the ratio of isodoublet VEVs determines the parameter

$$\tan\beta=v_u/v_d\ . \tag{9}$$

With this pattern we will basically recover the standard tree level spontaneous breaking scenario of SU(2)⊗U(1) in a SUSY version of the standard model.

On the other hand the spontaneous breaking of R parity is driven by nonzero VEVs for the scalar neutrinos. The scale characterizing R-parity breaking is set by the isosinglet VEVs

$$v_R=\langle\tilde\nu_\tau^c\rangle\ , \tag{10}$$

$$v_S=\langle\tilde S_\tau\rangle\ , \tag{11}$$

where $V=\sqrt{v_R^2+v_S^2}$ can lie anywhere in the range ~ 10 GeV–1 TeV. Here we define the angle δ as $\tan\delta=v_R/v_S$. A necessary ingredient for the consistency of this model is the presence of a small seed of R parity breaking in the SU(2) doublet sector,

$$v_L=\langle\tilde\nu_{L\tau}\rangle\ . \tag{12}$$

We will now sharpen the analysis of the minimization of the potential energy in this theory, starting from the extremization equations.

The stationarity equations obtained by differentiating V_{total} with respect to all six independent variables v_d, v_u, v_L, v_R, v_S and v_F, where these denote the VEVs of the neutral scalar fields H_d, H_u, $\tilde\nu$, $\tilde\nu^c$, $\tilde S$, Φ respectively. One obtains

$$\begin{aligned}\frac{\partial V}{\partial v_d}&=-(Ah_0\tilde m_0v_F+hh_0v_Rv_S-h_0\epsilon^2)v_u\\&\quad-[2\alpha(v_u^2-v_d^2-v_L^2)-h_0^2v_u^2-\tilde m_d^2-(h_0v_F+\hat\mu)^2]v_d-h_\nu v_Lv_R(h_0v_F+\hat\mu)+(1-A)\hat\mu\tilde m_0v_u=0\ ,\end{aligned} \tag{13}$$

$$\begin{aligned}\frac{\partial V}{\partial v_u}&=-(Ah_0\tilde m_0v_F+hh_0v_Rv_S-h_0\epsilon^2)v_d+2\alpha(v_u^2-v_d^2-v_L^2)v_u\\&\quad-[-h_0^2v_d^2-\tilde m_u^2-h_\nu^2v_L^2-h_\nu^2v_R^2-(h_0v_F+\hat\mu)^2]v_u+h_\nu hv_Lv_Fv_S+A\tilde m_0h_\nu v_Lv_R+(1-A)\mu\tilde m_0v_d=0\ ,\end{aligned} \tag{14}$$

$$\frac{\partial V}{\partial v_L}=[-2\alpha(v_u^2-v_d^2-v_L^2)+h_\nu^2v_u^2-h_\nu v_Rv_d(h_0v_F+\hat\mu)+h_\nu^2v_R^2+\tilde m_\nu^2]v_L+A\tilde m_0h_\nu v_uv_R+h_\nu hv_uv_Fv_S=0\ , \tag{15}$$

$$\begin{aligned}\frac{\partial V}{\partial v_R}&=(A\tilde m_0hv_F-hh_0v_dv_u-h\epsilon^2)v_S+(h^2v_S^2+h^2v_F^2+h_\nu^2v_L^2+h_\nu^2v_u^2+\tilde m_R^2)v_R\\&\quad+A\tilde m_0h_\nu v_uv_L-h_\nu h_0v_dv_Fv_L-h_\nu\hat\mu v_dv_L=0\ ,\end{aligned} \tag{16}$$

$$\frac{\partial V}{\partial v_S}=(A\tilde m_0hv_F-hh_0v_uv_d-h\epsilon^2)v_R+(h^2v_R^2+h^2v_F^2+\tilde m_S^2)v_S+h_\nu hv_uv_Fv_L=0\ , \tag{17}$$

$$\frac{\partial V}{\partial v_{\mathrm{F}}}=[h_0^2(v_u^2+v_d^2)+h^2(v_{\mathrm{R}}^2+v_S^2)+\tilde{m}_{\mathrm{F}}^2]v_{\mathrm{F}}-\tilde{m}_0[Ah_0v_uv_d-Ahv_{\mathrm{R}}v_S+(A-2)\epsilon^2]$$
$$+h_\nu v_{\mathrm{L}}(hv_uv_S-h_0v_dv_{\mathrm{R}})+h_0\hat{\mu}(v_u^2+v_d^2)=0\,. \tag{18}$$

In order to find determine these VEVs one has in general to solve these equations for each set of input low energy parameters, make sure that their solutions are in fact minima and not saddle points, and that their energy is lower than that of other trivial solutions where either R parity or electroweak symmetry are unbroken.

3. Strategy to find minima

Instead of directly solving the above extremization equations, which are nonlinear in the VEVs, we prefer to evaluate the squared mass matrices of the neutral scalars and study their positivity in the low energy parameter space. They are given in general by

$$M_{\mathrm{R}ij}^2=\frac{1}{2}\left(\frac{\partial^2 V}{\partial z_i\,\partial z_j}+\mathrm{c.c.}\right)+\frac{\partial^2 V}{\partial z_i\,\partial z_j^*}\,, \tag{19}$$

$$M_{\mathrm{I}ij}^2=-\frac{1}{2}\left(\frac{\partial^2 V}{\partial z_i\,\partial z_j}+\mathrm{c.c.}\right)+\frac{\partial^2 V}{\partial z_j\,\partial z_j^*}\,, \tag{20}$$

where

$$z_i=\frac{1}{\sqrt{2}}\left[\mathrm{Re}(z_i)+\mathrm{i}\,\mathrm{Im}(z_i)\right]. \tag{21}$$

As we assume CP conservation, the real and imaginary parts do not mix, so that the mass part of the potential energy reads

$$V_{\mathrm{mass}}=\tfrac{1}{2}\,\mathrm{Re}(z_i)\,M_{\mathrm{R}ij}^2\,\mathrm{Re}(z_j)+\tfrac{1}{2}\,\mathrm{Im}(z_i)\,M_{\mathrm{I}ij}^2\,\mathrm{Im}(z_j)\,. \tag{22}$$

The matrices obtained this way are 6×6 matrices with complicated entries, that we choose not to write explicitly here. In this model there are six CP-even and five CP-odd scalars, the last ones including the massless majoron, given by the imaginary part of

$$\frac{v_{\mathrm{L}}^2}{Vv^2}\,(v_uH_u-v_dH_d)+\frac{v_{\mathrm{L}}}{V}\,\tilde{\nu}_\tau-\frac{v_{\mathrm{R}}}{V}\,\tilde{\nu}_\tau^{\mathrm{c}}+\frac{v_S}{V}\,\tilde{S}_\tau\,. \tag{23}$$

Although the explicit expressions for the masses in terms of the input parameters defining the low energy theory are quite involved, a fairly simple mass formula can be derived. From eq. (19) and eq. (20) we have

$$\mathrm{Tr}\,M_{\mathrm{R}}^2=\mathrm{Tr}\,M_{\mathrm{I}}^2+\sum_{i=1}^{6}\left(\frac{\partial^2 V}{\partial z_i\,\partial z_j}+\mathrm{h.c.}\right). \tag{24}$$

Using the explicit form of the potential we get the last term in eq. (24) is just m_Z^2, so that

$$\mathrm{Tr}\,M_{\mathrm{R}}^2=\mathrm{Tr}\,M_{\mathrm{I}}^2+m_Z^2\,, \tag{25}$$

which nicely generalizes the corresponding sum rule of the MSSM.

In order for a solution of the extremization equations to be a minimum the eigenvalues of the matrices M_{I}^2 and M_{R}^2 must all be positive, with the exception of the would-be Goldstone boson associated to the breaking of $\mathrm{SU(2)}\otimes\mathrm{U(1)}$ symmetry and of the majoron, which remains massless. In order to discriminate against trivial solutions (section 4) with no electroweak and/or no R-parity breaking we need to devise a good strategy to search for the interesting solutions, avoiding the trivial ones. We adopt the following criteria:

(1) We restrict the values of v_u and v_d so that they give the correct W-mass equation (8) and choose a definite fixed value for their ratio, eq. (9).

(2) For each set of parameters

$$h, h_0, h_\nu, \epsilon^2, A, \tilde{m}_0, \tan\beta\,, \tag{26}$$

we take random values for

$$v_{\mathrm{R}}, v_S, v_{\mathrm{L}}, v_{\mathrm{F}} \tag{27}$$

in a reasonable range.

(3) With these VEV values we then solve the extremization equations for the soft SUSY breaking mass-squared parameters

$$\tilde{m}_u^2, \tilde{m}_d^2, \tilde{m}_{\mathrm{L}}^2, \tilde{m}_{\mathrm{R}}^2, \tilde{m}_S^2, \tilde{m}_\Phi^2\,. \tag{28}$$

This is easy because these equations are all linear in these parameters. Of course with this method we cannot ensure that these masses are all equal to the universal $\tilde{m}_0^2$ parameter as in eq. (6). However, as we mentioned, universality is not expected to hold when renormalization group evolution from the unification scale down to the electroweak scale is taken into account. As a practical criterium we can adopt the view of accepting values where the spread in these parameters is restricted to any given reasonable level.

(4) After a solution to the extremization equations is found, we determine the eigenvalues of the matrices M_{I}^2 and M_{R}^2 at the extremum. If all six eigenvalues of M_{R}^2 and all four nontrivial eigenvalues of M_{I}^2 are positive we have found a minimum.

(5) The eigenvalues of the matrices M_{I}^2 and M_{R}^2 should also be restricted by experiments such as LEP [23]. Pending a more detailed study [24] we will adopt the conservative criterium of imposing on our model the same limit that applies to the MSSM, knowing that we may be excluding some of the interesting solutions.

(6) Finally we must check if the minimum that breaks R parity is lower than the trivial minima. We also do this as discussed in the next section.

If all the above conditions are verified for a given set of parameters and VEVs then a minimum that breaks R parity spontaneously has been found.

4. The trivial minima

By inspecting the extremization equations one notes that the last of them is linear in v_{F} and one can see that v_{F} is easily nonzero. However, the set of extremization equations admits many trivial solutions where some of the other VEVs are zero. These are either unphysical (no electroweak breaking) or uninteresting for our purposes (no R-parity breaking). We now consider these trivial minima in more detail.

First note that there is always the possibility of having an R-parity conserving minimum. This minimum exists when $v_u \neq 0$, $v_d \neq 0$ and $v_{\mathrm{F}} \neq 0$, with $v_{\mathrm{L}} = v_{\mathrm{R}} = v_S = 0$. In this case only electroweak symmetry is broken. Then three of the extremum equations are automatically satisfied while the others have to be solved for v_u, v_d and v_{F}. We define variables

$$\Sigma_1 = v_u^2 + v_d^2, \quad \Delta_1 = v_u^2 - v_d^2\,, \tag{29}$$

in terms of which the potential to be minimized becomes

$$\begin{aligned} V_{\mathrm{SU(2)}}(\Sigma_1, \Delta_1, v_{\mathrm{F}}) = {} & +\alpha\Delta_1^2 + \tfrac{1}{4}\,(\Sigma_1^2 - \Delta_1^2)h_0^2 + (h_0 v_{\mathrm{F}} + \hat{\mu})^2\Sigma_1 + \epsilon^4 + \tfrac{1}{2}(\tilde{m}_u^2 + \tilde{m}_d^2)\Sigma_1 + \tfrac{1}{2}(\tilde{m}_u^2 - \tilde{m}_d^2)\Delta_1 + \tilde{m}_\Phi^2 v_{\mathrm{F}}^2 \\ & - 2\tilde{m}_0(A-2)\epsilon^2 v_{\mathrm{F}} + [(-\tilde{m}_0 A h_0 v_{\mathrm{F}} - h_0\epsilon^2) + (1-A)\hat{\mu}\tilde{m}_0]\,\sqrt{\Sigma_1^2 - \Delta_1^2}\,, \end{aligned} \tag{30}$$

so that one can solve for Δ_1 to find

$$\Delta_1 = \frac{(\tilde{m}_d^2 - \tilde{m}_u^2)\Sigma_1}{\tilde{m}_u^2 + \tilde{m}_d^2 + 2(h_0 v_F + \hat{\mu})^2 + 4\alpha\Sigma_1} . \tag{31}$$

This shows that indeed $v_u = v_d$ if $\tilde{m}_u^2 = \tilde{m}_d^2$. It is not possible to solve analytically the other equations for Σ_1 and v_F, so we have done it numerically. Having found a set of values $(\Sigma_1, \Delta_1, v_F)$ that solves the extremum equations we must check that the corresponding second derivative matrix has positive eigenvalues and we have done this numerically. The points that obey this condition are local minima that break $SU(2)\otimes U(1)$. This is the situation in the model discussed in ref. [18] where the electroweak symmetry breaks at the tree level. The value of the potential at this minimum $V_{SU(2)}(\Sigma_1, \Delta_1, v_F)$ has to be compared with the values found for the other solutions, such as the interesting one where both $SU(2)\otimes U(1)$ and R parity are broken.

Apart from the above R-parity conserving minimum there may also be unphysical minima. For example there is a minimum that occurs for $v_u = v_d = v_L = v_R = v_S = 0$ with only $v_F \neq 0$. In this case neither electroweak nor R-parity symmetries are broken. The extremum equations are satisfied for

$$v_F = \frac{\tilde{m}_0 (A-2)\epsilon^2}{M_\Phi^2} , \tag{32}$$

and the corresponding value of the potential is

$$V_0 = \epsilon^4 \left(1 - \frac{\tilde{m}_0^2 (A-2)^2}{M_\Phi^2} \right) . \tag{33}$$

This may be minimum if the corresponding second derivative matrix are positive.

Another trivial minimum exists corresponding to the choice $v_u = v_d = v_L = 0$ with $v_R \neq 0$, $v_S \neq 0$ and $v_F \neq 0$. In this case only R parity is broken. It is convenient to define variables

$$\Sigma_2 = v_R^2 + v_S^2, \quad \Delta_2 = v_R^2 - v_S^2 , \tag{34}$$

we can write the potential as

$$\begin{aligned} V_{R_p}(\Sigma_2, \Delta_2, v_F) &= \Sigma_2 h^2 v_F^2 + \tfrac{1}{2}(\tilde{m}_R^2 + \tilde{m}_S^2)\Sigma_2 + \tfrac{1}{2}(\tilde{m}_R^2 - \tilde{m}_S^2)\Delta_2 + \tfrac{1}{4}(\Sigma_2^2 - \Delta_2^2)h^2 \\ &\quad + \epsilon^4 + \tilde{m}_\Phi^2 v_F^2 - 2\tilde{m}_0 (A-2)\epsilon^2 v_F + (\tilde{m}_0 A h v_F - h\epsilon^2)\sqrt{\Sigma_2^2 - \Delta_2^2} , \end{aligned} \tag{35}$$

so that one finds

$$\Delta_2 = \frac{(\tilde{m}_S^2 - \tilde{m}_R^2)\Sigma_2}{\tilde{m}_S^2 + \tilde{m}_R^2 + 2h^2 v_F^2} , \tag{36}$$

showing again that if $\tilde{m}_R^2 \neq \tilde{m}_S^2$ then $v_R \neq v_S$. The minima are found by checking that the corresponding second derivative matrix has positive eigenvalues. The corresponding value of the potential $V_{R_p}(\Sigma_2, \Delta_2, v_F)$ will be compared with the values found for the other solutions.

5. Results

Following the strategy outlined in section 3 we have varied randomly the parameters in the following interesting ranges

$$10^{-6} \leqslant |h_\nu| \leqslant 10^{-1}, \quad 10^{-2} \leqslant |h|, \quad |h_0| \leqslant 1, \quad 10^3 \leqslant |\epsilon^2/\mathrm{GeV}| \leqslant 10^6 ,$$

$$250 \leqslant \tilde{m}_0 \leqslant 1500\ \mathrm{GeV}, \quad -3 \leqslant A \leqslant 3, \quad 10 \leqslant |v_R|, |v_S| \leqslant 1000\ \mathrm{GeV} . \tag{37}$$

For each value of $\tan\beta$, v_u and v_d are determined by the W mass, eq. (8). We then determine v_F and v_L by solving eq. (8) and eq. (16) approximately. We find

$$v_F \simeq \frac{Ah_0 v_u v_d - Ahv_R v_S + (A-2)\epsilon^2}{\tilde{m}_0^2 + h_0^2(v_u^2+v_d^2) + h^2(v_R^2+v_S^2)}, \tag{38}$$

$$v_L \simeq -\frac{h_\nu(A\tilde{m}_0 v_u v_R + hv_F v_u v_S - v_d v_R(h_0 v_F + \hat{\mu})}{\tilde{m}_0^2 + h_\nu^2(v_u^2+v_R^2) - 2\alpha(v_u^2-v_d^2)}. \tag{39}$$

For given values of v_R, v_S, v_L, v_u, v_d, v_F we solve the extremum equations for the soft SUSY breaking mass-squared parameters. For $\tan\beta \neq 1$ these mass parameters are necessarily different. If one wants to have them as close as possible to the canonical value $\tilde{m}_0$ at unification we can choose solutions in some given range around $\tilde{m}_0$.

For illustration purposes we choose among a large variety of possible minima where both SU(2)⊗U(1) and R parity break the point defined by the following choice of parameters:

$$h_\nu = 8.59\times10^{-3},\quad h=-0.351,\quad h_0=0.140,\quad A=1.196,$$

$$\epsilon^2 = -3.715\times10^5\ \mathrm{GeV}^2,\ \tilde{m}_0 = 355.6\ \mathrm{GeV},\quad \hat{\mu}=-23.8\ \mathrm{GeV},\ \mu_{\mathrm{eff}} = \hat{\mu}+h_0 v_F = 94.1\ \mathrm{GeV},$$

$$\tilde{m}_d = 426.9\ \mathrm{GeV},\quad \tilde{m}_u = 205.0\ \mathrm{GeV},\quad \tilde{m}_L = 386.8\ \mathrm{GeV},$$

$$\tilde{m}_F = 355.7\ \mathrm{GeV},\quad \tilde{m}_R = 409.7\ \mathrm{GeV},\quad \tilde{m}_S = 409.7\ \mathrm{GeV}, \tag{40}$$

and the corresponding VEVs

$$v_d = 81.65\ \mathrm{GeV},\quad v_u = 153.77\ \mathrm{GeV},\quad v_L = -35.9\ \mathrm{MeV},\quad v_R = v_S = 50.00\ \mathrm{GeV},\quad v_F = 840.89\ \mathrm{GeV}. \tag{41}$$

This minimum is illustrated in figs. 1, 2. In all of these we represent the shape of the potential around the minimum as a function of pairs of VEVs, keeping all the others fixed at the minimum. More precisely, we represent the relative difference to the minimum, i.e. $[V(v_1, v_2) - V_{\min}]/V_{\min}$ where v_1 and v_2 are the chosen VEVs. Their corresponding values are shown relative to their values at the minimum. We have checked this

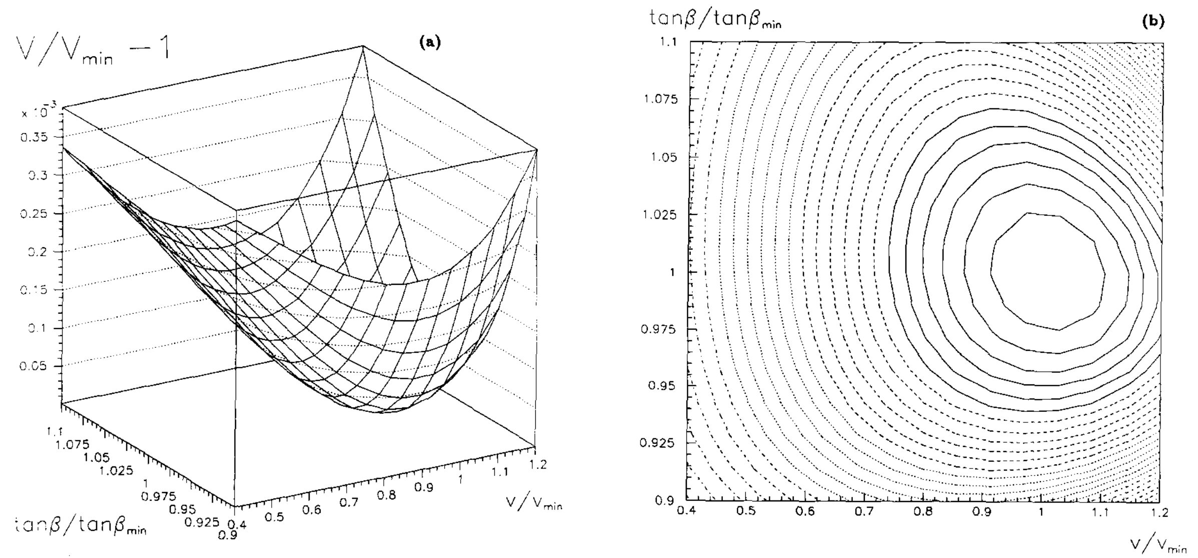

Fig. 1. (a) Profile of the potential around the minimum as a function of $\tan\beta = v_u/v_d$ and $v=\sqrt{v_u^2+v_d^2}$ for the parameters given in the text. (b) Contour plot of the potential around the minimum as a function of $\tan\beta$ and v for the parameters given in the text.

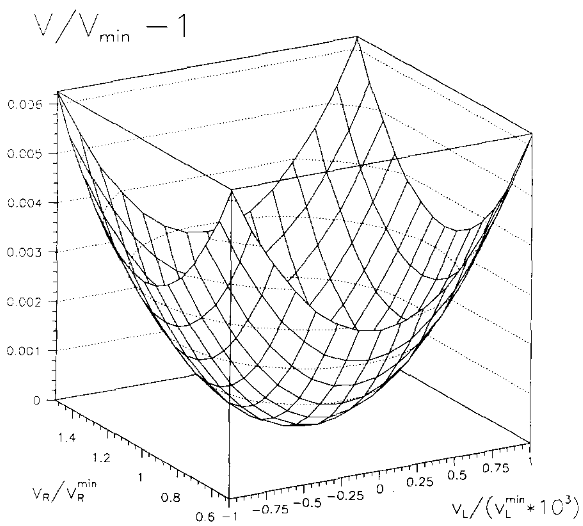

Fig. 2. Profile of the potential around the minimum as a function of v_L and v_R for the parameters given in the text.

minimum with respect to all relevant variables but chose to represent here only the most interesting ones. For example, in fig. 1a we display the profile of the potential function as a function of $(\tan\beta, v)$, illustrating the breaking of $SU(2)\otimes U(1)$ symmetry. In fig. 1b we see the corresponding lines of constant $\tan\beta$, v. These level curves show a rather well behaved pattern indicative of a minimum. In fig. 2 we see how the potential behaves as v_L, v_R vary, illustrating the need a small amount of R parity breaking in the isodoublet sector. We have also checked that the contour plot of the potential around the minimum as a function of v_L and v_R corresponding to fig. 2 is well behaved.

Last, but not least, we have verified that over the entire range ~ 10 GeV–1 TeV it is possible to find true $SU(2)\otimes U(1)$ and R-parity breaking minima which are consistent with experimental constraints imposed by Higgs boson physics as well as SUSY searches at LEP.

6. Discussion

In conclusion we have demonstrated that for suitable values of the low energy parameters, consistent with observation, it is energetically favourable to spontaneously break R parity in the supersymmetric extension of the standard model defined in section 2 at a scale which typically lies in the range ~ 10 GeV–1 TeV. The major seed of R-parity violation lies in an isosinglet sector (v_R, v_S) so that the majoron is mainly singlet. The subdominant isodoublet breaking of R parity by v_L is controlled by the Yukawa parameter h_ν, thus naturally implying a hierarchy between v_L and v_R, required by astrophysics. This has, in addition, interesting implications for the neutrino mass spectrum, leading to an explanation of the solar neutrino deficit [3] that can, on the other hand, be probed in accelerator experiments. New effects include large rates for single chargino and neutralino production at LEP [2] and hadron colliders [5] as well as experimentally measurable rates for rare muon and tau decays by majoron emission [6]. Note that in this discussion it is crucial to keep *finite* values of the parameters v_L and h_ν. If h_ν is taken to be strictly zero a conserved R parity can be assigned to the scalars in ν^c and S so that R_p never breaks, irrespective of whether or not a nonzero VEV is induced for v_R, a trivial but crucial point missed in ref. [25].

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