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Higgs, chargino and neutralino mass spectra in RPV $U(1)'$ model

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Summary. — We examine the sensitivity of the particle spectrum to the parameters of the $U(1)'$-extended MSSM with R-parity violation. This model provides a simultaneous solution to both the μ-problem and the proton decay problem which plague the MSSM. We focus on variations of neutralino, chargino and Higgs boson masses in various lepton number violations couplings, scanning over all the space to find allowed regions of the parameter space consistent with the experimental constraints for these masses.

1. – Introduction

SUSY still appears to be the leading candidate of physics beyond the SM. Unfortunately, there are no signs of SUSY at the LHC (yet), and not for lack of trying. The experimental searches have imposed the following constraints on the parameters of MSSM: i) the Higgs mass at 125 GeV requires heavy scalar top and/or large left-right stop mixing, although new D- or F-terms in the superpotential could reduce the constraints, ii) gluinos and first and second generation scalar quarks must be heavier than ~ 1 TeV, and iii) charginos and neutralinos have masses heavier than 500 GeV or so.

These bounds can be avoided if R-parity is broken, and thus, the fate of R-parity may hold the key to discovering supersymmetry. We use this motivation to explore the effects of breaking R-parity on the spectrum of supersymmetry (SUSY). SUSY has the attractive feature that it provides the lightest supersymmetric particle (LSP) as the dark matter candidate. Breaking R-parity spoils this, as the LSP can now decay. However, in models with bilinear R-parity breaking, it has been shown that the gravitino or the axino can be the LSP and still provide a dark matter candidate. Here we select an extended

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supersymmetric scenario to highlight the effect of R-parity violation on the scalar sector and the fermionic sector. We choose the so-called $U(1)'$ model because: i) it provides a solution to the μ problem in supersymmetry [1], by generating it dynamically, though the VEV of the Higgs singlet needed to break the extra $U(1)'$, and ii) it forbids terms that violate baryon number from coexisting with lepton violating terms (unlike in the MSSM), making the proton stable [2]. In models with broken R-parity, if lepton number is also broken, the neutral (charged) Higgs mix with the sneutrinos (sleptons). The neutralinos mix with the neutrinos (providing a mass mechanism for the neutrinos, whether Majorana or Dirac), and the charginos mix with the leptons. Higgs and collider phenomenology would be significantly affected. We present an analysis of the spectrum in sect. **3**, after introducing the model in the sect. **2**.

2. – $U(1)'$ model with bilinear and trilinear R-parity violations

In the $U(1)'$ model [3-5], the symmetry of the MSSM is augment by an abelian $U(1)$ group, and the particle spectrum is enlarged by an additional neutral gauge boson and at least one additional singlet Higgs representation, needed to break the extra symmetry. The VEV of the singlet Higgs field $\langle S\rangle = \frac{v_S}{\sqrt{2}}$ breaks the abelian gauge symmetry $U(1)'$ at higher scales. This VEV also yields an effective μ term dynamically, $\mu_{eff} = h_s\langle S\rangle$. The $SU(2)_L \times U(1)_Y$ symmetry is broken as usual by the VEVs of the Higgs doublets, H_u and H_d. R-parity induces additional terms in the Lagrangian. In $U(1)'$, R-parity can be broken in two different ways, as the Lagrangian can contain bilinear *or* explicit R-parity–breaking terms as in [2], for lepton number violation (L) and baryon number violation (B)

$$(1)\quad \widehat{W} = \widehat{W}_{MSSM}(\mu \to 0) + \sum_{r=1}^{2}\left[h_r \widehat{S}_r \widehat{H}_d \cdot \widehat{H}_u + \frac{h_{\tau N_\tau}}{M_R}\widehat{S}_r \widehat{N}_\tau \widehat{H}_u \cdot \widehat{L}_\tau\right] + \widehat{W}_L + \widehat{W}_B,$$

where

$$(2)\qquad \widehat{W}_L = \sum_{r=1}^{2} h'_{r\tau}\widehat{S}_r \widehat{H}_u \cdot \widehat{L}_\tau + \frac{1}{2}\lambda_{i\tau k}\widehat{L}_i \cdot \widehat{L}_\tau \widehat{E}^c_k + \lambda'_{\tau jk}\widehat{L}_\tau \cdot \widehat{Q}_j \widehat{D}^c_k,$$

and

$$(3)\qquad \widehat{W}_B = \frac{1}{2}\lambda''_{ijk}\widehat{U}^c_i \widehat{D}^c_j \widehat{D}^c_k.$$

Here the couplings λ_{ijk} and λ''_{ijk} are antisymmetric with respect to ij and jk, respectively. The first term in eq. (2) is the so-called bilinear term $\mu''_i H_u L_i$, but here $\mu''_{i\,eff}$ is promoted to a dynamical variable when $U(1)'$ is broken, $\mu''_{i,eff} = Y'_{s,i}\langle S\rangle$. As shown before [2], in $U(1)'$, unlike in the minimal model, one can have *either* explicit lepton *or* explicit baryon number violating interactions, but *not both*, thus forbidding proton decay. Additionally $U(1)'$ symmetry disallows higher-dimensional proton decay inducing operators, otherwise expected to appear at a higher scale. Thus, in $U(1)'$ models with R-parity violation, the μ problem is solved, and the proton is stable. In what follows, we concentrate on trilinear lepton-violating and on bilinear R-parity breaking effects as in eq. (2). The effect of the latter on Higgs phenomenology is particularly interesting, as the bilinear term induces mixings between Higgs and sleptons/sneutrinos. We use the superpotential for the effective $U(1)'$ model with bilinear and R-parity as in eq. (1) and eq. (2), and assume that all Yukawa couplings except for Y_t and Y_b are negligible.

In addition to the superpotential, the Lagrangian includes soft supersymmetry-breaking terms containing additional terms with respect to the MSSM as given below:

$$\begin{aligned}(4)\quad & \mathcal{L}^{Soft}_{U(1)'} = \mathcal{L}^{Soft}_{MSSM}(\mu \to 0) - m^2_{S_1} S_1^\dagger S_1 - m^2_{S_2} S_2^\dagger S_2 - (m^2_{S_1S_2} S_1^\dagger S_2 + \text{h.c.}) \\ & - m^2_{\widetilde{L}_\tau} |\widetilde{L}_\tau|^2 - m^2_{\widetilde{N}_\tau} |\widetilde{N}_\tau|^2 + \Bigg(\sum_r h_r A_r S_r H_u \cdot H_d + \sum_r h'_{r\tau} A_\tau S_r H_u \cdot \widetilde{L}_\tau \\ & + \sum_r A_{N_\tau} \frac{h_{\tau N_\tau}}{M_R} S_r (\widetilde{L}_\tau \cdot H_u) \widetilde{N}_\tau + \frac{1}{2} A_{ijk} \widetilde{L}_i \cdot \widetilde{L}_j \widetilde{E}^c_k + \frac{1}{2} A'_{ijk} \widetilde{L}_i \cdot \widetilde{Q}_j \widetilde{D}^c_k + \text{h.c.} \Bigg).\end{aligned}$$

2·1. *The Higgs-Slepton sector of the model.* – The additional singlet fields S_r, and third generation slepton doublet from R-parity breaking, can be expanded around their VEVs as

$$\begin{aligned}(5)\quad & \langle S_1 \rangle = \frac{1}{\sqrt{2}} (v_{S_1} + \phi_{S_1} + i\varphi_{S_1}), \quad \langle \widetilde{L}_\tau \rangle = \begin{pmatrix} \frac{1}{\sqrt{2}} (v_{\nu_\tau} + \phi_{\nu_\tau} + i\varphi_{\nu_\tau}) \\ \widetilde{L}^-_\tau \end{pmatrix}, \\ & \langle S_2 \rangle = \frac{1}{\sqrt{2}} (v_{S_2} + \phi_{S_2} + i\varphi_{S_2}), \quad \langle \widetilde{N}_\tau \rangle = \left(\frac{1}{\sqrt{2}} (v_{\nu_R} + \phi_{\nu_R} + i\varphi_{\nu_R}) \right),\end{aligned}$$

where $v^2 = v_u^2 + v_d^2 + v_\tau^2 \simeq v_u^2 + v_d^2 = (246\,\text{GeV})^2$. Here v_{ν_R} is the VEV of the right-handed tau neutrino. We define $\tan\beta = v_u/v_d$, and we adopt the convention that all the parameters of the model are real. The spectrum of physical Higgs bosons consists of 6 neutral scalars, 4 CP-odd pseudoscalars (A_i^0), and 3 charged Higgs bosons $H_j^\pm$. We denote the CP-even neutral Higgs fields by, $\Phi^{0\,T}_{even} = (\phi_u, \phi_d, \phi_{S_1}, \phi_{S_2}, \phi_{\widetilde{\nu}_\tau}, \phi_{\widetilde{\nu}_R})$, diagonalized by $\mathcal{L}_{even} = -\Phi^{0\,\dagger} \mathcal{M}^2_{even} \Phi^0$. And we denote the CP-odd neutral Higgs fields by, $\Phi^{0\,T}_{odd} = (\varphi_u, \varphi_d, \varphi_{S_1}, \varphi_{S_2}, \varphi_{\widetilde{\nu}_\tau}, \varphi_{\widetilde{\nu}_R})$. For charged Higgs-slepton sector, we work in the basis: $S^- = (H_u^-, H_d^-, \widetilde{\tau}_L^-, \widetilde{\tau}_R^-)$, $S^+ = (H_u^+, H_d^+, \widetilde{\tau}_L^+, \widetilde{\tau}_R^+)^T$ and where $\mathbf{M}^2_{S^\pm}$ is the mass of the charged Higgs in this basis.

2·2. *Chargino and neutralino sector of the model.* – The charged leptons mix with charginos, and neutrinos with neutralinos. In the basis $(\tau_R^+, \widetilde{W}^+, \widetilde{H}_u^+)$, $(\tau_L^-, \widetilde{W}^-, \widetilde{H}_d^-)^T$, the mass matrix is

$$(6)\quad \mathcal{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} \frac{h_\tau v_d}{\sqrt{2}} & \frac{g_2 v_{\nu_\tau}}{\sqrt{2}} & \sum_{r=1}^{2} \left[\frac{h'_{r_\tau} v_{S_r}}{\sqrt{2}} + \frac{h_{\tau N_\tau} v_{\nu_R} v_{S_r}}{2M_R} \right] \\ 0 & M_{\tilde{W}} & \frac{g_2 v_u}{\sqrt{2}} \\ \frac{h_\tau v_{\nu_\tau}}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & \sum_{r=1}^{2} \frac{h_r v_{S_r}}{\sqrt{2}} \end{pmatrix}.$$

The lightest eigenstate of this mass matrix will be the tau lepton.

In the basis $\Phi^{0\,T} = (\widetilde{B}, \widetilde{W}, \widetilde{H}_d, \widetilde{H}_u, \widetilde{S_1}, \widetilde{Z}', \widetilde{S_2}, \nu_\tau, N_\tau)$, the Lagrangian responsible for the mixing of neutralinos with one neutrino generation is $\mathcal{L}_{\tilde{\chi}_i^0} = -\frac{1}{2} \Phi^{0\,T} \mathcal{M}_{\tilde{\chi}^0} \Phi^0$ [6]. One

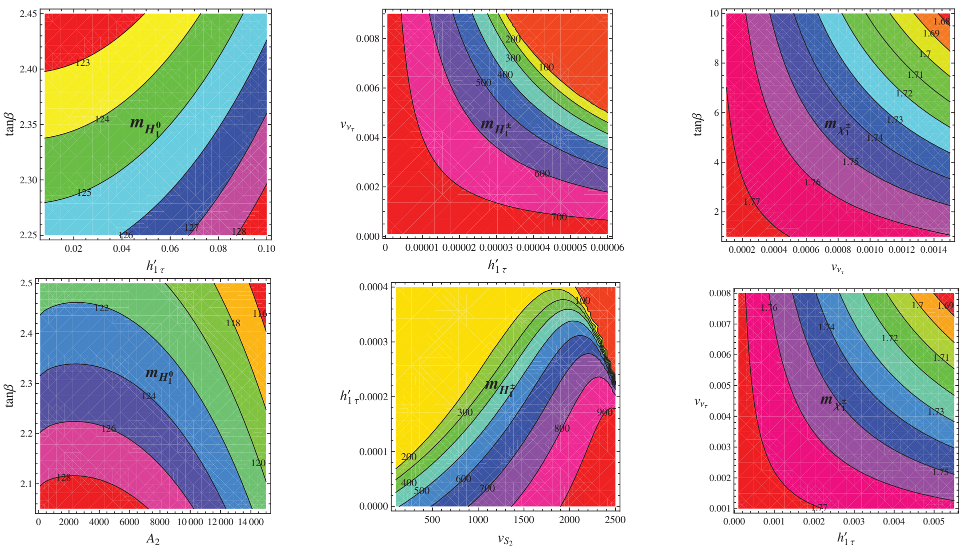

Fig. 1. – (Color online) Contour plots for the variation of the mass (in GeV) of the H_1^0 lightest CP-even Higgs in the $h'_{1\tau} - \tan\beta$ and in the $A_2 - \tan\beta$ planes (left-hand column); the contours of $m_{H_1^\pm}$ in the $h'_{1\tau} - v_{\nu_\tau}$ and in the $v_{S_2} - h'_{1\tau}$ planes (middle column); and contours of $m_{\tilde{\chi}^\pm}$ in the $v_{\nu_\tau} - \tan\beta$ and in the $h'_{1\tau} - v_{\nu_\tau}$ planes (right-hand column).

type of neutrinos obtains mass from the mixing at tree level, which in our choice is the τ-neutrino.

3. – Numerical analysis

We chose to plot graphs with either parameters that yield significant variations in the mass (such as $\tan\beta$, $h'_{1\tau}$) or to highlight some typical parametric dependence, such as the contours in the $h'_{1\tau} - v_{\nu_{\tau,R}}$ planes. We scan over all parameters to find allowed regions of the space consistent with theoretical and experimental constraints. Some of the particle masses are far more sensitive to some parameters than others. In fig. 1 we show contour plots for the variations of the mass of the lightest CP-even Higgs ($m_{H_1^0}$), the mass of the lightest charged Higgs ($m_{H_1^\pm}$), and the mass of the lightest chargino ($m_{\tilde{\chi}^\pm}$). Here v_{ν_τ} is the VEV of the left-handed tau neutrino, and v_{S_2} is the VEV of the singlino $\widetilde{S_2}$ (VEVs are in GeV).

4. – Interpreting the results

Although many parameters are involved, small variations of only a few affect Higgs and chargino masses significantly. Neutralino masses are almost independent of R-parity–violating parameters. Figure 1 shows the parameters which maximally affect the masses of the Higgs, charginos and neutralinos. The contours shown indicate regions of the parameter space for which the constraints from the experimental data are satisfied. These results are being used for an exploration of the collider signals of the model [6].

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