We investigate a mechanism for spontaneous R-parity breaking in a class of extensions of the minimal supersymmetric standard model with an extra Abelian gauge symmetry which is a linear combination of $B - L$ and weak hypercharge. Both $U(1)_X$ and R-parity are broken by the vacuum expectation value of the right-handed sneutrinos which is proportional to the soft SUSY masses. In these models the mechanism for spontaneous R-parity violation can be realized even with positive soft masses. In this context one has a realistic mechanism for generating neutrino masses as well as a realistic spectrum. We briefly discuss the possible collider signals which could be used to test the theory, the contributions to proton decay and the possibility of a gravitino as a dark matter candidate.

**I. INTRODUCTION**

There are several ideas in physics beyond the standard model for protecting the Higgs mass but Supersymmetry (SUSY) is perhaps the most appealing. It is well-known that in order to make predictions in the context of the minimal supersymmetric Standard Model (MSSM) one has to understand the origin of SUSY breaking and the R-parity violating terms. For a review on Supersymmetry see Ref. [1].

The so-called R-parity discrete symmetry is defined as $R = (-1)^{3(B - L) + 2S} = (-1)^{2S} M$, where the $B$, $L$, and $S$ stand for the baryon number, lepton number and spin, respectively. Here $M$ is the so-called matter parity which is $-1$ for any matter superfield and +1 for any Higgs or Gauge superfield. See Ref. [2] for the studies of R-parity conservation in SUSY models at the low-scale and Ref. [3] in the context of $SO(10)$ models. For studies of the phenomenological aspects of SUSY models with R-parity violation see Ref. [4].

In order to understand the origin of the R-parity violating operators present in the MSSM one has two possibilities: i) one can look for an extension of the MSSM where $B - L$ is a global symmetry [5], but one has to face the Majoron problem [6]. ii) study this issue in a framework where $B - L$ is a local symmetry. In this case the Majoron is eaten by the new gauge bosons in the theory and a simple consistent framework exists.

Recently, this latter option was studied in the context of left-right symmetric models [7] and in a simple extension of the MSSM where one has an extra $B - L$ Abelian gauge symmetry [8]. In this paper we want to study this approach to spontaneous R-parity breaking in the simplest most general extension of the MSSM where the new Abelian symmetry is a linear combination of the weak hypercharge and $B - L$. In this way all anomalies are canceled by adding only right-handed neutrinos. We discuss the full spectrum of the theory and the possible signals at the LHC. In this context the mechanism for spontaneous R-parity violation is possible even with positive soft-terms, in contrast with the results in Ref. [7] and Ref. [8] where one needs negative mass soft terms for the “right-handed” sneutrinos.

This paper is organized as follows: In Section II we discuss the mechanism for Spontaneous R-parity Breaking in a simple extension of the MSSM. In Section III we discuss the R-parity violating terms obtained and the full spectrum of the theory, while in Section IV the possible collider signals are pointed out. In Section V we discuss the possibility of gravitino cold dark matter and the proton decay constraints. Finally, we summarize our findings in Section VI.

**II. SPONTANEOUS R-PARITY BREAKING**

The well-known R-parity violating terms in the MSSM are

$$W_{Rpv} = \epsilon_i \hat{L}_i \hat{H}_u + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}^C_{ik} + \lambda''_{ijk} \hat{U}_i \hat{D}_j \hat{D}^C_k + \lambda''_i \hat{U}^C_i \hat{D}^C_j \hat{D}_k$$

(1)

where $\lambda''_{ijk} = -\lambda''_{ikj}$ and $\lambda_{ijk} = -\lambda_{ijk}$. In the above equation the first three interactions violate lepton number, while the last term violates baryon number.

The main goal of this paper is the investigation of the mechanism for spontaneous R-parity violation in simple local Abelian extensions of the MSSM, which contain $B - L$. Then, in this context the new hypercharge will be defined as

$$X = a \ Y + b \ (B - L),$$

(2)

where $Y$, $B$ and $L$ stand for the weak hypercharge, baryon number and lepton number, respectively. We stick to this simple linear combination since one can easily show that only three right-handed neutrinos are necessary for anomaly cancellation.

**II. A. Anomaly Cancellation**

As it is well-known once we extend the SM gauge group one introduces constraints on the particle charges based on anomaly cancelation. For the MSSM particle content with an $n_N$ additional right-handed neutrinos, the $(SU(2)_L, U(1)_Y, U(1)_X)$ charge assignment is:

$$\hat{Q} = \left( \begin{array}{c} \hat{U} \\ \hat{D} \end{array} \right) \sim (2, \frac{1}{3}, X_Q), \quad \hat{L} = \left( \begin{array}{c} \hat{N} \\ \hat{E} \end{array} \right) \sim (2, -1, X_L),$$


Therefore, \( n_N = 3 \), and this value will be used from now on. A similar substitution into Eq. (6) reveals no new constraints.

Further constraints are contributed from the couplings in the superpotential. Since
\[
W = W_{\text{MSSM}} + Y_u^D \, \hat{L}^T \, i \sigma_2 \, \hat{H}_u \, \hat{N}^C,
\]
where
\[
W_{\text{MSSM}} = Y_u \, \hat{Q}^T \, i \sigma_2 \, \hat{H}_u \, \hat{O}^C + Y_d \, \hat{Q}^T \, i \sigma_2 \, \hat{H}_d \, \hat{D}^C + Y_e \, \hat{L}^T \, i \sigma_2 \, \hat{H}_d \, \hat{E}^C + \mu \, \hat{H}_u^T \, i \sigma_2 \, \hat{H}_d,
\]
the Higgs X-charge is:
\[
X_H = \frac{1}{2} \left( X_E - X_N \right).
\]

All superpotential interactions are consistent with Eqs. (9) - (12) and (16). At this point it is illuminating to state all the conditions on the charges in terms of \( a \equiv X_H \) and \( b \equiv X_N \):
\[
X_Q = \frac{1}{3} a + \frac{1}{3} b, \\
X_L = -a - b, \\
X_U = -\frac{4}{3} a - \frac{1}{3} b, \\
X_D = \frac{2}{3} a - \frac{1}{3} b, \\
X_E = 2a + b,
\]
or simply stated: \( X = a \, Y + b \, (B - L) \). Since both \( Y \) and \( X \) will be separately conserved, \( B - L \) will also be conserved making R-parity an exact symmetry as well. Therefore, the most general charge assignment possible is also consistent with the goal discussed in the introduction.

Some interesting cases are: \( a = 0 \) and \( b = 1 \), which corresponds to \( B - L; a = 1 \) and \( b = -5/4 \) which is the GUT normalization for this group and allows it to be embedded in \( SO(10) \). Note that \( b = 0 \) is just a scaled version of hypercharge and does not constitute a new charge. It is possible to have different charges for the \( N \) [9], but here we are interested in the case where \( B - L \) is part of the symmetry.

II. B. Symmetry Breaking

The particle content, charge assignment and superpotential (Eq. (14)) where all given in the previous section. Symmetry breaking is achieved through the right-handed sneutrinos, which have a non-trivial \( X \)-charge. Once one of these fields acquire a vacuum expectation value (VEV), it spontaneously breaks both the gauge symmetry, \( U(1)_X \), as well as R-parity and forces left-handed sneutrino, through mixing terms, to acquire a VEV. Since \( B - L \) is part of the gauge symmetry the Majoron [6] (the Goldstone boson associated with spontaneous breaking of lepton number) becomes the longitudinal component of the \( Z' \) and does not pose a problem, thus allowing for a general, simple mechanism for spontaneous R-parity breaking.
In addition to the superpotential, the model is also specified by the soft terms:

\[
V_{\text{soft}} = M_{\tilde{N}C}^2 \tilde{N}^2 + M_L^2 \tilde{L}^2 + M_{EC}^2 \tilde{E}^2 + m_{\tilde{H}_L}^2 |H_U|^2 + m_{\tilde{H}_R}^2 |H_D|^2 + \frac{1}{2} M_X \tilde{B} \tilde{B}^c + A_{\tilde{L}} L \sigma_2 H_u \tilde{N}^c + B_{\tilde{H}_u} H_U^c \sigma_2 H_D + \text{h.c.} + \ldots
\]  

(22)

where the terms not shown here correspond to terms in the soft MSSM potential. Now, we are ready to investigate the predictions of this mechanism for spontaneous R-parity violation.

Here, symmetry breaking is achieved through the VEVs of sneutrinos \((\tilde{\nu}_i) = v_{\nu_i}/\sqrt{2}\) and \((\tilde{\nu}^c_i) = v_{\nu_i}/\sqrt{2}\) and the Higgs doublets \((H_u^0) = v_u/\sqrt{2}\) and \((H_d^0) = v_d/\sqrt{2}\).

The scalar potential in this theory is given by

\[
V = V_F + V_D + V_{\text{soft}}^S,
\]

(23)

where the relevant terms for \(V_{\text{soft}}^S\) are given in Eq. (22). Once one generation of sneutrinos, \(\tilde{\nu}\) and \(\tilde{\nu}^c\), and the Higgses, acquire a VEV, the potential reads

\[
\langle V_F \rangle = \frac{1}{4} (Y_{\nu}^D)^2 (v_{\nu}^2 + v_L^2 + v_{\nu}^2 v_L^2 + v_{\nu}^2)
\]

\[
+ \frac{1}{2} \mu^2 (v_{\nu}^2 + v_L^2) - \frac{1}{2} \sqrt{2} Y_{\nu}^D \mu v_{\nu} v_L v_d,
\]

(24)

\[
\langle V_D \rangle = \frac{1}{32} \left[ g_2^2 (v_{\nu}^2 - v_L^2 - v_{\nu}^2) + g_X^2 (v_{\nu}^2 - v_{\nu}^2) \right]
\]

\[
+ g_X^2 \left[ b v_{\nu}^2 - (a + b) v_L^2 + a v_{\nu}^2 - a v_{\nu}^2 \right]^2,
\]

(25)

\[
\langle V_{\text{soft}}^S \rangle = \frac{1}{2} M_{\tilde{N}C}^2 v_{\tilde{N}}^2 + \frac{1}{2} M_{\tilde{L}}^2 v_{\tilde{L}}^2 + \frac{1}{2} M_{\tilde{H}_u}^2 v_u^2 + \frac{1}{2} M_{\tilde{H}_d}^2 v_d^2
\]

\[
+ \frac{1}{2} \sqrt{2} \left( A_{\tilde{L}} + A_{\tilde{L}}^c \right) v_{\nu} v_L v_d,
\]

(26)

where \(g_1, g_2\) and \(g_X\) are the gauge couplings for \(SU(2)_L, U(1)_Y\) and \(U(1)_X\) respectively. Minimizing in the limit \(v_{\nu} v_L v_d \gg v_L:\)

\[
v_R = \sqrt{-8 m_{\tilde{N}C}^2 - a b g_X^2 (v_{\nu}^2 - v_d^2) / g_X^2 b^2},
\]

(27)

\[
v_L = \frac{M_{\tilde{L}}^2 - b v_{\nu}^2 - D_{\text{soft}}}{B_{\nu} v_{\nu}},
\]

(28)

\[
|\mu|^2 = \frac{1}{2} m_Z^2 - \frac{1}{8} g^2 g_X^2 (v_{\nu}^2 + v_L^2) - \frac{M_{\tilde{H}_u} \tan^2\beta - M_{\tilde{H}_d}}{\tan^2\beta - 1},
\]

(29)

\[
b = \frac{\sin 2\beta}{2} \left( 2 \mu^2 + m_{\tilde{H}_u}^2 + m_{\tilde{H}_d}^2 \right),
\]

(30)

where we make use of the following definitions:

\[
B_{\nu} = \frac{1}{\sqrt{2}} (Y_{\nu}^D \mu v_d - A_{\nu}^D v_u),
\]

(31)

\[
D_{\text{soft}}^2 = \frac{1}{8} (g_1^2 g_2^2 + a (a + b) g_X^2) (v_{\nu}^2 - v_d^2),
\]

(32)

\[
M_{\tilde{H}_u} = m_{\tilde{H}_u}^2 + \frac{1}{8} a b g_X^2 v_d^2,
\]

(33)

\[
M_{\tilde{H}_d} = m_{\tilde{H}_d}^2 - \frac{1}{8} a b g_X^2 v_d^2.
\]

(34)

Now, Eq. (27) indicates two possible scenarios for spontaneous R-parity violation:

- \(M_{\tilde{N}C}^2 < 0\). This case has been studied before in Ref. [7] and Ref. [8] in the context of left-right symmetric models and in the minimal gauged \(U(1)_{B-L}\) extension of the MSSM.

- \(M_{\tilde{N}C}^2\) very small and \(a b < 0\). In this case one should satisfy the condition

\[
|a b| g_X^2 (v_{\nu}^2 - v_d^2) > 8 M_{\tilde{N}C}^2.
\]

(35)

This is possible for a very small \(M_{\tilde{N}C}^2\), as may arise in gauge mediated supersymmetry breaking without \(X\)-charged messengers.

Using the constraint: \(M_Z^2 / g_X \geq 1\) TeV one arrives at the condition

\[
\frac{1}{2} |a b| v_{\nu} v_d \left( \frac{\tan^2\beta - 1}{1 + \tan^2\beta} \right)^{1/2} \geq 1\) TeV.
\]

(36)

Then, for large \(\tan\beta\), \(|b| \geq 66/|a|\). This is the main constraint that we find for this class of models. Notice that we are using the same normalization for both \(U(1)\) couplings in the theory and neglecting the mixing kinetic terms.

Therefore it is possible to realize this mechanism for spontaneous R-parity violation even with positive soft mass terms for the right-handed neutrinos. This possibility is quite appealing in our opinion.

III. RPV INTERACTIONS AND THE SPECTRUM

The effective MSSM-like theory will contain R-parity violating bilinear terms. For example, the \(Y_{\nu}^D \tilde{L} \sigma_2 H_u N^c\) term in the superpotential, leads to \(Y_{\nu}^D \tilde{H}_u v_{\nu} v_L / \sqrt{2}\) (the \(c_i\) term in Eq. (1)) and \(Y_{\nu}^D \tilde{H}_u v_{\nu} v_L / \sqrt{2}\). The kinetic term of the lepton doublet produces mixing between the neutrinos and neutral gauginos: \(W_{\nu}^0 v_{\nu} v_L / \sqrt{2}, B \nu v_L / \sqrt{2}\) and \(B' \nu v_L / \sqrt{2}\). While the kinetic term for right-handed neutrinos contains the term \(B' \nu v_L / \sqrt{2}\). Other R-parity violating interactions between the charged leptons and the charged components of the gauginos and Higgsinos can be found in a
similar fashion. It is important to emphasize that all the R-parity violating terms will be defined by two VEVs: \( v_L \) and \( v_R \), where \( v_R \gg v_L \). Notice that in this context one generates only bi-linear R-parity violating terms which violate lepton number.

### III. A. Mass Spectrum

#### III.A.1. Gauge Bosons

The gauge sector consists of the SM gauge bosons and an extra neutral gauge boson, the \( Z' \). In the gauge basis \((B, W^0, B')\), the mass matrix reads as

\[
M^2_0 = \begin{pmatrix}
\frac{1}{4} g_1^2 v^2 & -\frac{1}{2} g_1 g_2 v^2 & \frac{1}{2} a g_1 g_X v^2 \\
-\frac{1}{2} g_1 g_2 v^2 & \frac{1}{4} g_2^2 v^2 & -\frac{1}{2} a g_2 g_X v^2 \\
\frac{1}{2} a g_1 g_X v^2 & -\frac{1}{2} a g_2 g_X v^2 & \frac{1}{4} g_X^2 \left( b'^2 v_R^2 + a^2 v^2 \right)
\end{pmatrix}.
\]

Here \( v^2 = v_L^2 + v_R^2 = (246)^2 \text{GeV}^2 \). To satisfy the experimental constraint coming from the rho-parameter, \( \rho \sim 1 \), the \( Z \) mass should not be significantly modified from its MSSM expression. Therefore, aside from the zero eigenvalue corresponding to the photon, the eigenvalues of the above matrix are:

\[
m^2_Z = \frac{1}{4} \left( g_1^2 + g_2^2 \right) v^2 \left( 1 - \epsilon^2 \right) + O(\epsilon^4) \quad (38)
\]

\[
m^2_{Z'} = \frac{1}{4} b'^2 g_X^2 v^2 \left( 1 + \epsilon^2 \right) + O(\epsilon^4), \quad (39)
\]

where \( \epsilon^2 = \frac{g_X^2 a^2 v^2}{g_X^2 b' v_R^2 (g_1^2 + g_2^2) v^2} \ll 1 \). The most stringent bounds on the \( Z' \) mass comes from LEP2 and depend on its couplings to charged leptons. In this case then, it will depend on the value of \( a \) and \( b \). See Ref. 11 for a recent study of the \( Z' \) at the LHC and Ref. 12 for a review.

The \( Z-Z' \) mixing is also constrained and must be of order \( 10^{-3} \). Its value can be found by projecting out the zero-mode photon from Eq. (37) and is given by:

\[
\tan 2\xi = 2 \frac{M^2_{ZZ'}}{M^2_{Z'} - M^2_Z} \quad (40)
\]

where

\[
M^2_{ZZ'} = \frac{1}{4} a g_X \sqrt{g_1^2 + g_2^2} v^2 \quad (41)
\]

\[
M^2_Z = \frac{1}{4} \left( g_1^2 + g_2^2 \right) v^2 \quad (42)
\]

\[
M^2_{Z'} = \frac{1}{4} a^2 g_X^2 v^2 + \frac{1}{4} b'^2 g_X^2 v^2 \quad (43)
\]

Keeping up to first order in \( \frac{v^2}{v_R^2} \sim \epsilon^2 \) yields:

\[
\xi = \frac{a \sqrt{g_1^2 + g_2^2}}{b'^2 g_X} \frac{v^2}{v_R^2}, \quad (44)
\]

which can easily satisfy the bound.

#### III.A.2. Neutralinos and Neutrinos

Once R-parity is broken the neutralinos and neutrinos mix. Defining the basis \((\nu, \nu^c, \nu', B, \tilde{B}, \tilde{W}_L^0, \tilde{H}_d^0, \tilde{H}_u^0)\) their mass matrix is given by

\[
\mathcal{M}_N = \begin{pmatrix}
0 & \frac{1}{\sqrt{2}} Y^D_{\nu^c} v_u & -\frac{1}{2} (a + b) g_X v_L & -\frac{1}{2} a g_1 v_L & \frac{1}{2} g_2 v_L & \frac{1}{2} Y^D_{\nu^c} v_R \\
-\frac{1}{2} Y^D_{\nu^c} v_u & 0 & \frac{1}{2} a g_X v_R & 0 & 0 & 0 \\
\frac{1}{2} (a + b) g_X v_L & -\frac{1}{2} a g_X v_R & M_X & 0 & 0 & -\frac{1}{2} a g_X v_d \frac{1}{2} g_1 v_d \\
-\frac{1}{2} g_1 v_L & \frac{1}{2} g_2 v_L & 0 & M_1 & 0 & \frac{1}{2} g_2 v_d \\
0 & 0 & -\frac{1}{2} a g_X v_d & \frac{1}{2} g_1 v_d & \frac{1}{2} g_2 v_u & -\mu \\
0 & 0 & 0 & \frac{1}{2} g_1 v_u & -\frac{1}{2} g_2 v_u & 0
\end{pmatrix}.
\]

In order to understand the neutrino masses we focus on the simple case \( v_L \to 0 \) and \( Y^D_{\nu^c} \) small. Then, in this limit the neutrino mass matrix is given by

\[
M_\nu = M_\nu^I + M_\nu^R, \quad (46)
\]

where \( M_\nu^I \) is the type I seesaw contribution 13 and \( M_\nu^R \) is due to R-parity violation. These contributions are given by

\[
M_\nu^I = \frac{1}{2} Y^D_{\nu^c} M^{-1}_{\nu^c} \left( Y^D_{\nu^c} \right)^T v_u^2, \quad (47)
\]

\[
M_\nu^R = m M_{\tilde{\nu}_\nu}^{-1} m^T, \quad (48)
\]

where \( m = \text{diag} \left( 0, 0, 0, Y^D_{\nu^c} v_R / \sqrt{2} \right) \). Therefore, it is possible to generate the neutrino masses in a consistent way. Notice the possible strong mixing between \( B' \) and the Higgsinos.
III. A. 3. Higgses and Sleptons

Defining the basis $\sqrt{2} \text{Im} \left( \tilde{\nu}, \tilde{\nu}^c, H_1^0, H_2^0 \right)$ for CP-odd scalars, $\sqrt{2} \text{Re} \left( \tilde{\nu}, \tilde{\nu}^c, H_1^0, H_2^0 \right)$ for CP-even scalars and for the charged scalars $\left( \tilde{e}^c, \tilde{e}^c, H_1^{-}, H_2^{+} \right)$ the mass matrices are given by Eq. (49), Eq. (50) and Eq. (51), respectively. The mass matrix for the CP-odd neutral Higgses reads as

$$
\mathcal{M}_S^2 = \begin{pmatrix}
S^2_{\nu} & S^2_{eH} \\
(S^2_{eH})^T & S^2_{H}
\end{pmatrix}, \tag{50}
$$

where $S^2_{\nu}, S^2_{eH}$ and $S^2_{H}$ are given in the appendix. It is well-known that in the MSSM the tree level upper bound on the lightest CP-even Higgs is $M_Z$ and one can satisfy the experimental bound on the Higgs mass once the radiative corrections are included.

In the case of the charged Higgses the mass matrix is given by

$$
\mathcal{M}_C^2 = \begin{pmatrix}
C^2_{\tilde{e}} & C^2_{eH} \\
(C^2_{eH})^T & C^2_{H}
\end{pmatrix}, \tag{51}
$$

See the appendix for the definition of $C^2_{\tilde{e}}, C^2_{eH}$ and $C^2_{H}$. It is important to show that the spectrum of the theory is realistic and the expected Goldstone bosons exist. Here, we analyze the spectrum in the very illustrative limit of zero mixing between the left- and right-handed sneutrinos, i.e. $Y^D, A^D \to 0$. In this limit, Eq. (27) indicates that $v_L \to 0$ as well and $B_{\nu} \to 0$, by definition. In this limit, the $\nu$ component of the CP-even mass matrix decouples as does the same component in CP-odd mass matrix. This complex left-handed sneutrino then has the mass:

$$
m^2_{\tilde{\nu}} = M^2_{\tilde{\nu}} - \frac{1}{8} \left( a + b \right) g^2_X \left( b v_R^2 + a v_u^2 - a v_d^2 \right) - \frac{1}{8} \left( g_1^2 + g_2^2 \right) (v_u^2 - v_d^2). \tag{52}
$$

The remaining three-by-three CP-even mass matrix has potentially large mixing between the right-handed sneutrino and Higgses. An approximate solution can be attained in the limit of large $\tan \beta$. Here the heavier MSSM Higgs decouples leaving a mixing between the up-type Higgs and the right-handed sneutrino. The resulting trace and determinant are identical to those of the neutral gauge bosons, Eq. (37), demonstrating that the lightest Higgs in this case, as in the MSSM, is bounded by the $Z$ mass at tree-level. The mass of the mostly right-handed sneutrino in this limit is that of the $Z'$, Eq. (39).

III. A. 4. Charginos and Charged Leptons

Mixing between the charged leptons and the charginos will occur in the charged fermion sector, $\left( \tilde{e}^c, \tilde{e}^c, H_1^{-}, H_2^{+} \right)$ and

$$
\mathcal{M}_p^2 = \begin{pmatrix}
\frac{v_u}{\sqrt{2}} B_{\nu} & \frac{v_u}{\sqrt{2}} B_{\nu} \\
\frac{v_u}{\sqrt{2}} Y^D v_R & -\frac{1}{\sqrt{2}} Y^D v_L \\
-\frac{1}{\sqrt{2}} A^D v_R & -\frac{1}{\sqrt{2}} A^D v_L
\end{pmatrix} \begin{pmatrix}
B_{\nu} + \frac{Y^D v_R}{\sqrt{2} v_u} & B_{\nu} \\
-\frac{Y^D v_R}{\sqrt{2} v_u} & B_{\nu}
\end{pmatrix}
\begin{pmatrix}
\frac{v_u}{\sqrt{2}} B_{\nu} & \frac{v_u}{\sqrt{2}} B_{\nu} \\
\frac{v_u}{\sqrt{2}} Y^D v_R & -\frac{1}{\sqrt{2}} Y^D v_L \\
-\frac{1}{\sqrt{2}} A^D v_R & -\frac{1}{\sqrt{2}} A^D v_L
\end{pmatrix}, \tag{49}
$$

Applying the zero sneutrino mixing limit to the CP-odd and charged Higgs sector shows that those matrices decouple into three values: two eigenvalues representing the left- and right-handed slepton masses and the MSSM two-by-two mass matrix for the up- and down-type Higgs. We will focus on the former since the latter only reproduces the results of the MSSM.

Apart from the left-handed sneutrino mentioned above, the CP-odd matrix contains the Goldstone boson eaten by $Z'$ (the Majoron). It is completely made up of the imaginary part of the right-handed sneutrino, $\text{Im} \tilde{\nu}^c$. Finally, the masses of the charged sleptons are:

$$
m_{\tilde{\nu}^L}^2 = M_{\tilde{\nu}^L}^2 - \frac{1}{8} \left( a + b \right) g^2_X \left( b v_R^2 + a v_u^2 - a v_d^2 \right) + \frac{1}{8} \left( g_1^2 + g_2^2 \right) (v_u^2 - v_d^2), \tag{53}
$$

$$
m_{\tilde{\nu}^R}^2 = M_{\tilde{\nu}^R}^2 + \frac{1}{8} \left( 2a + b \right) g^2_X \left( b v_R^2 + a v_u^2 - a v_d^2 \right) + \frac{1}{4} g_1^2 (v_u^2 - v_d^2) + \frac{1}{2} Y^2 v_e v_d. \tag{54}
$$

A closer examination of these approximate masses for the MSSM fields indicates that these values are the MSSM mass values modified appropriately by the $X$ $D$-term contributions. All of these masses are realistic given $M_{\tilde{\nu}^L}^2 > \frac{1}{8} \left( a + b \right) g^2_X \left( b v_R^2 + a v_u^2 - a v_d^2 \right)$. Of further interest is the prediction of the degeneracy between the $Z'$ gauge boson and the physical right-handed sneutrino. Corrections to the approximate masses presented here would be suppressed by neutrino masses, making this discussion relevant even in the non-limit case.
\[ \mathcal{M}_C = \begin{pmatrix} -\frac{1}{\sqrt{2}} Y_{\nu_d} v_L & 0 & \frac{1}{\sqrt{2}} Y_{\nu_L} v_d \\ \frac{1}{\sqrt{2}} Y_{\nu_d} v_L & M_2 & \frac{1}{\sqrt{2}} g_2 v_u \\ \frac{1}{\sqrt{2}} Y_{\nu_d} v_R & \frac{1}{\sqrt{2}} g_2 v_u & \mu \end{pmatrix}. \] (55)

Since the mixing between the MSSM charginos and the charged leptons is proportional to \( v_L \) and \( Y_{\nu_d} \), small corrections to the charged lepton masses can exist once the charginos are integrated out. However, this contribution is always small once we impose the neutrino constraints.

### IV. COLLIDER SIGNALS

As a consequence of R-parity violation, the lightest neutralino will be unstable and will decay via lepton number violating interactions. These type of interactions will also exist for the charginos and the new gauge boson:

**Sleptons decays and production at the LHC:** It is important to emphasize the lepton number violating decays of sleptons:

\[ \tilde{\nu} \rightarrow \nu \nu, e^+ e^-, \tilde{e}_i \rightarrow e_j \nu_k, \tilde{\nu}_R \rightarrow \nu \nu, \] 

These decays are proportional to \( v_L \) or \( Y_{\nu_d} \) and are crucial for the test of the model.

The \( Z' \) allows for a new production mechanism for sleptons at the LHC:

\[ pp \rightarrow Z', Z' \rightarrow \tilde{\nu} \tilde{\nu}. \]

Therefore, channels with four sleptons in the final state are possible: \( ee\, ee, \mu \mu, ee\, \mu \mu, \mu \mu \mu \) and also with several tau’s. Then, one could test the existence of R-parity violation and lepton number violation in this way. See Ref. [14] for the study of this production mechanism at the LHC.

**\( Z' \) decays:** The \( Z' \) decays will be dependent on the values of \( a \) and \( b \). Determination of these values would be crucial to understanding the nature of the abelian symmetry. In addition to the typical \( Z' \) decays, new lepton number violating decays will be possible. These include \( Z' \rightarrow e^+_j \tilde{\chi}_{j} \) which are suppressed by \( v_L \). Also possible are the very interesting decays \( Z' \rightarrow \tilde{\nu} \tilde{\nu}, \nu \nu \), where the right-handed neutrinos can decay mainly to an electron and a selectron. These decays are lepton number violating and proportional to \( v_R \).

**Neutralino decays:** As it is well-known in the case of R-parity violation the lightest neutralino is unstable. These fields will decay as \( \tilde{\chi}_1^0 \rightarrow Z^0 \tilde{\nu} \) and \( \tilde{\chi}_2^0 \rightarrow W^+ e^\mp \). In the case when the neutralino is the up-like Higgsino, these decays are proportional to \( v_R \), while in the rest of the cases are suppressed by \( v_L \). For a recent study of these decays in SUSY models with R-parity violation see for example [13].

**\( L \)-violating Higgs decays:** The Higgses now has lepton number violating decay channels open such as MSSM-like Higgs into a slepton and a \( W \) or \( Z \) if kinematically allowed. More interesting is its mixing with the right-handed sneutrino. This could change the Higgs decay into two gammas branching ratio over its decay to matter branching ratio.

**Chargino decays:** In this case new decays into charged leptons and a \( Z \) or \( W \) exist. In this case all these decays are suppressed by \( v_L \) or \( Y_{\nu_d} \) once we impose the constraints coming from neutrino masses.

It is important to emphasize that in order to test this model at the LHC one should discover the \( Z' \), the right-handed neutrinos crucial to cancel anomalies, and understand the lepton number and R-parity violating decays of the sneutrinos.

### V. OTHER ASPECTS

As it is well-known in this context the gravitino can be a dark matter candidate. Here we discuss the issue of proton decay.

#### V.II. Proton Stability

Let us discuss the possible constraints coming from proton decay. See Ref. [17] for a review on proton decay. There are several operators which are relevant for proton decay in this context. One has the so-called LLLL dimension five contributions

\[ O_{LLL} = \alpha_{ijkl} \tilde{Q}_i \tilde{Q}_j \tilde{Q}_k \tilde{L}_l / \Lambda_B, \] (57)

and the RRRR contributions

\[ O_{RRRR} = \beta_{ijkl} \tilde{U}^C_i \tilde{D}^C_j \tilde{U}^C_k \tilde{E}^C_l / \Lambda_B. \] (58)

See Ref. [18] for the possibilities to suppress these contributions. Now, in this context one has an extra operator due to the existence of the right-handed neutrinos

\[ O_{\tilde{R}RRR} = \gamma_{ijkl} \tilde{U}^C_i \tilde{D}^C_j \tilde{D}^C_k \tilde{N}_l^C / \Lambda_B. \] (59)

Here \( \gamma_{ijkl} = -\gamma_{ikjl} \). In this case when the “right-handed” neutrino gets a VEV, baryon number violating interactions present in the MSSM are generated. Then, one finds \( U^C_i \tilde{D}^C_j \tilde{D}^C_k \tilde{V}_{RI} / \Lambda_B \), \( U^C_i \tilde{D}^C_j \tilde{D}^C_k \tilde{V}_{RI} / \Lambda_B \), and \( \tilde{U}^C_i \tilde{D}^C_j \tilde{D}^C_k \tilde{V}_{RI} / \Lambda_B \). Using the new interactions in the superpotential proportional to \( Y_{\nu_d} \) and the above operator one

\[ \gamma_{3/2} \sim 10^{26} s \left( \frac{\epsilon}{10^{-23}} \right)^{-2} \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^{-3}, \] (56)

where \( m_{3/2} \) is the gravitino mass. \( \epsilon \) defines the amount of R-parity violation, and it is proportional to the ratio between the R-parity violating coupling and the soft mass. See Ref. [19] for the study of gravitino dark matter in R-parity violating scenarios.

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1 It is a common misbelief that once R-parity in broken in supersymmetric theories one does not have a cold dark matter candidate. Fortunately, it is not always the case since if the gravitino is the lightest supersymmetric particle it still can be a good cold dark matter candidate since its decay rate will be suppressed by the Planck scale and the R-parity violating couplings. A naive estimation gives us

\[ \tau_{3/2} \sim 10^{26} s \left( \frac{\epsilon}{10^{-23}} \right)^{-2} \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^{-3}, \] (56)

where \( m_{3/2} \) is the gravitino mass. \( \epsilon \) defines the amount of R-parity violation, and it is proportional to the ratio between the R-parity violating coupling and the soft mass. See Ref. [19] for the study of gravitino dark matter in R-parity violating scenarios.
finds the following constraint coming from proton decay (as example we use \( p \rightarrow \pi^0e^+ \)):

\[
\gamma_{112i}\left(\frac{Y^D}{v_e}\right)_{1j}\frac{Y_i}{M_B} \lesssim 10^{-30} \text{ GeV}^{-2}.
\] (60)

Then, it is easy to show that if \( \Lambda_B \sim M_{pl} \) the coupling \( \gamma_{112i} \) can be of order one. See Ref. [19] for the constraints coming from different channels.

VI. SUMMARY AND OUTLOOK

We studied a consistent and general mechanism for spontaneous R-parity violation in a class of simple extensions of the minimal supersymmetric standard model (MSSM) with an extra Abelian gauge symmetry which is a linear combination of \( B - L \) and weak hypercharge. In this case we found that this mechanism can be realized even with positive soft masses for “right-handed” sneutrinos, whose VEV breaks both \( U(1)_X \) and R-parity. A realistic mechanism for generating neutrino masses exists as well as a realistic spectrum. We briefly discussed the possible collider signals which could be used to test the theory, contributions for proton decay and the gravitino as a dark matter candidate.

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APPENDIX: MASS MATRICES

Using the basis \( \sqrt{2} \text{ Re} (\tilde{\nu}, \tilde{\nu}^c, H^0_u, H^0_d) \) for CP-even scalars and for the charged scalars \( \left( \tilde{e}^*, \tilde{e}^c, H^*_d, H^*_u \right) \), the mass matrices for these two sectors are:

\[
M^2_S = \begin{pmatrix} S^2_v & S^2_v \\ (S^2_v)^T & S^2_H \end{pmatrix},
\] (61)

and

\[
M^2_C = \begin{pmatrix} C^2_v & C^2_v \\ (C^2_v)^T & C^2_H \end{pmatrix},
\] (62)

where:

\[
S^2_v = \begin{pmatrix} \left( \frac{1}{4} (g^2_1 + g^2_2 + a + b) g^2_X \right) v^2_u + \frac{\alpha}{v_u} B_{\mu} - \frac{1}{2} \left( (a + b) g^2_X - 4Y^D v_L v_R - B_{\nu} \right) \\
- \frac{1}{2} \left( (a + b) g^2_X - 4Y^D v_L v_R - B_{\nu} \right) v_L v_R - B_{\nu} \end{pmatrix},
\] (63)

\[
S^2_{\nu H} = \begin{pmatrix} \left( \frac{1}{4} (g^2_1 + g^2_2 + a + b) g^2_X \right) v^2_u - \frac{1}{\sqrt{2}} Y^D \mu v_R - \frac{1}{2} (g^2_1 + g^2_2 + a + b) g^2_X - 4Y^D v_L v_R + \frac{1}{\sqrt{2}} A_{\nu} v_L \\
- \frac{1}{2} \left( (a + b) g^2_X - 4Y^D v_L v_R - B_{\nu} \right) v_L v_R - B_{\nu} \end{pmatrix},
\] (64)

\[
S^2_H = \begin{pmatrix} \left( \frac{1}{4} (g^2_1 + g^2_2 + a^2 g^2_X) \right) v^2_u + \frac{\alpha}{v_u} B_{\mu} + \frac{Y^D \mu v_R}{\sqrt{2} v_u} - \frac{1}{2} (g^2_1 + g^2_2 + a^2 g^2_X) v_{\mu v_d} - B_{\mu} \\
- \frac{1}{2} \left( (a + b) g^2_X - 4Y^D v_L v_R - B_{\nu} \right) v_L v_R - B_{\nu} \end{pmatrix},
\] (65)

\[
C^2_v = \begin{pmatrix} C^2_1 & B_{\nu} \\
B_{\nu} & C^2_2 \end{pmatrix},
\] (66)

\[
C^2_{e H} = \begin{pmatrix} \frac{1}{4} g^2_2 v_{u v_L} - \frac{\sqrt{2}}{4} Y^D v_{u v_L} - \frac{1}{\sqrt{2}} Y^D \mu v_R + \frac{1}{\sqrt{2}} A_{\nu} v_L \\
\frac{1}{2} v_u v_L + \frac{1}{\sqrt{2}} A_{\nu} v_L \\
\end{pmatrix},
\] (67)

\[
C^2_H = \begin{pmatrix} \frac{1}{4} g^2_2 (v^2_u - v^2_d) + B_{\mu} v^2_u + \frac{1}{2} Y^2 v^2_u + \frac{Y^D \mu v_R}{\sqrt{2} v_u} \\
B_{\mu} + \frac{1}{2} g^2_2 v_{u v_d} \\
B_{\mu} + \frac{1}{2} g^2_2 v_{u v_d} + \frac{\alpha}{v_u} B_{\nu} + \frac{1}{2} Y^D v^2_d - \frac{A_{\nu} v_R}{\sqrt{2} v_u} \end{pmatrix},
\] (68)

In the above equations \( C^2_1 \) and \( C^2_2 \) are given by

\[
C^2_1 = \frac{1}{4} g^2_2 (v^2_u - v^2_d) + \frac{1}{2} Y^2 v^2_u + \frac{1}{2} Y^D v^2_d + \frac{v R}{v L} B_{\nu},
\] (69)
and

\[ C_{22}^2 = M_{E^c}^2 + \frac{1}{4} \bar{\nu}_1^2 (v_{1a}^2 - v_{1a}^2 - v_{1L}^2) + \frac{1}{8} (2a + b) g_X^2 (b v_{1R}^2 + a v_{1a}^2 - (a + b) v_{1L}^2) + \frac{1}{2} Y_e^2 (v_{e}^2 + v_{e}^2). \]

(70)

We also define for convenience:

\[ B_{\nu} = \frac{1}{\sqrt{2}} (Y_{\nu}^D \nu_d - A_{\nu}^D v_u), \text{ and } B_e = \frac{1}{\sqrt{2}} (Y_e \mu v_u - A_e \nu_d). \]

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