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Baryonic violation of R parity from anomalous $U(1)_H$

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Supersymmetric scenarios with R-parity conservation are becoming very constrained due to the lack of missing energy signals associated to heavy neutral particles, thus motivating scenarios with R-parity violation. In view of this, we consider a supersymmetric model with R-parity violation and extended by an anomalous horizontal $U(1)_H$ symmetry. A self-consistent framework with baryon-number violation is achieved along with a proper suppression for lepton-number violating dimension-five operators, so that the proton can be sufficiently stable. With the introduction of right-handed neutrinos, both Dirac and Majorana masses can be accommodated within this model. The implications for collider physics are discussed.

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I. INTRODUCTION

In contrast to the standard model (SM), its supersymmetric version (SSM) does not have accidental lepton (L) and baryon-number (B) symmetries, and this can lead to major phenomenological problems, like fast proton decay. The standard solution to forbid all dangerous operators is the imposition of a discrete symmetry, like R parity, and only in this minimal version (MSSM) the lightest supersymmetric particle (LSP), generally the neutralino, is stable, providing a good dark matter candidate. However, the recent results on searches for supersymmetry by CMS [1] and ATLAS [2] experiments have raised the bound on scalar and gluino masses, when they are approximately equal, to the order of 1.4 TeV for scenarios such as the R-parity conserving constrained minimal supersymmetric standard model. These searches are mainly based on missing transverse momentum carried by the LSP. A high mass scale for scalars and gluinos represents a potential chink in the initial proposal of the SSM as a possible solution to the hierarchy problem.

However, these mass limits can be avoided in alternative supersymmetric models such as the R-parity violating SSM [3–8], in which the LSP is usually assumed to be the gravitino that also provides a good decaying dark matter candidate [9,10]. The next-to-the-lightest supersymmetric particle decays to standard model particles, and thus the missing transverse momentum may be considerably reduced [11–18]. In addition, if the involved couplings are small enough, the presence of displaced vertices may reduce the efficiency of the standard searches at the LHC [11,18]. In particular, R-parity breaking scenarios with operators that violate B lead to the most difficult signals to be searched at hadron colliders [12–17,19]. The *ad hoc* choice of a discrete symmetry, like lepton parity, to forbid all the L-violating operators gives rise to several issues. First, the size of the R-parity breaking couplings must be chosen precisely by hand in order to avoid constraints from flavor physics observables and other precision physics observables [8]. Second, dimension-five L-violating operators are automatically forbidden, and lepton-number violating neutrino mass terms cannot be generated at the renormalizable and nonrenormalizable levels [20,21].

Thus, it will be desirable to build a general framework for supersymmetric models with baryonic violation of R parity rather than from *ad hoc* choices as it was done in Refs. [22–33]. This is the purpose of this work.

We address this issue by considering the SSM extended with an anomalous horizontal $U(1)_H$ symmetry *à la* Froggatt-Nielsen (FN) [34]. In these kinds of models, the standard model particles and their superpartners do not carry an R-parity quantum number and carry a horizontal charge (H charge) instead. In addition, these kinds of models involve new heavy FN fields and, in the simplest realizations, an electroweak singlet superfield S of H charge -1, called the flavon. For a recent discussion, see Ref. [35].[1] In the case of supersymmetric models based on an anomalous $U(1)_H$ flavor symmetry with a single flavon, the quark masses, the quark mixing angles, the charged lepton masses, and the conditions of anomaly cancellation constrain the possible H-charge assignments. Since the number of constraints is always smaller than the number of H charges, some of them are necessarily unconstrained, and apart from theoretical upper bounds on their values, they can be regarded as free parameters that should be determined by additional

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[1] In models in which two flavons are used to explain the charged fermion hierarchy, it is possible to obtain lepton parity as a remnant from a horizontal symmetry [23].

phenomenological input (for a review, see Ref. [36]). This freedom can be used to set the order of magnitude of the R-parity violating couplings. Along these lines, consistent models have been built in which neutrino oscillation data can be explained [36–41]. Also, by using the reported anomalies in cosmic-ray electron/positron fluxes, a consistent model with tiny R-parity breaking couplings was built with decaying leptophilic-neutralino dark matter [35].

We adopt a new approach here by assuming a set of H charges that give rise to a self-consistent model of R-parity breaking and baryon-number violation. As a consequence of our H-charge assignments, it is not possible to generate a Majorana mass term for left-handed neutrinos. However, a neutrino Dirac matrix can be built after the introduction of right-handed neutrinos with proper H charges. We also show that by adding a second flavon field with fractional charge, it is possible to build a Majorana neutrino mass matrix. In both cases an anarchical matrix [42–45] is obtained, which is supported by the recent results of a large value for θ_{13} [46–49].

As a consequence of H-charge assignments, the λ''_{323} coupling dominates over the other couplings, and the third-generation quarks are expected to be present at the final states of LSP decays. Moreover, the horizontal symmetry predicts a precise hierarchy of B-violating couplings, which can be translated into relations between different branching ratios that could be measured at e^+e^- colliders.

In the next section, the required conditions to obtain one R-parity breaking SSM with B violation are shown, also taking into account dimension-five operators. The generation of neutrino masses by introducing right-handed neutrinos is discussed in Sec. III. In Sec. IV the consequences for collider physics are mentioned, and then Sec. V ends with the conclusions. In the appendices the horizontal charges of the dimension-four and dimension-five R-parity breaking operators are detailed.

II. HORIZONTAL MODEL WITH BARYON-NUMBER VIOLATION

To solve the charged fermion mass hierarchy in the SSM, it is used to invoke the FN mechanism [34]. In the simplest scenario, the $U(1)_H$ symmetry is spontaneously broken at one scale close to Planck mass, M_P, by the vacuum expectation value of a SM singlet scalar, the flavon field S, with H charge -1, which allows us to define the expansion parameter $\theta = \langle S\rangle/M_P \approx 0.22$ [39,50]. The fermion masses and mixings are determined by factors of the type θ^n, for which n is fixed by the horizontal charges of the fields involved. In supersymmetric scenarios, the order of magnitude of the R-parity violating couplings can also be fixed by the FN mechanism [36–39,51–55].

The most general renormalizable superpotential respecting the gauge invariance of the standard model is given by [7,8]

$$\begin{aligned} W = {} & h^u_{ij}\hat{H}_u\hat{Q}_i\hat{u}_j + h^d_{ij}\hat{L}_0\hat{Q}_i\hat{d}_j + h^l_{ij}\hat{L}_0\hat{L}_i\hat{l}_j + \mu_\alpha\hat{L}_\alpha\hat{H}_u \\ & + \tfrac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{l}_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{d}_k + \tfrac{1}{2}\lambda''_{ijk}\hat{u}_i\hat{d}_j\hat{d}_k, \end{aligned} \tag{1}$$

where $i, j, k = 1, 2, 3$; $\alpha = 0, \ldots, 3$, and the down-type Higgs superfield $\hat{H}_d$ is denoted by $\hat{L}_0$. Lepton number is explicitly broken by the bilinear couplings μ_i and trilinear couplings λ_{ijk} and λ'_{ijk}, whereas the couplings λ''_{ijk} are responsible for the B violation. The factor of $1/2$ is due to the antisymmetry of the corresponding operators [8]. The H charges for the fields determines whether or not a particular term in the second line of Eq. (1) can be present in the superpotential.

Before proceeding we will fix our notation: following Ref. [38] we will denote a field and its H charge with the same symbol, i.e., $H(f_i) = f_i$, H-charge differences as $H(f_i - f_j) = f_{ij}$ [56], and bilinear H charges as $n_\alpha = L_\alpha + H_u$. In what follows we will constrain the H charges to satisfy the condition $|H(f_i)| < 10$, which leads to a consistent prediction of the size of the suppression factor θ in the context of string theories [36,51]. To properly account for the hierarchy of charged fermions with a single flavon, the symmetry $U(1)_H$ needs to be anomalous. With three theoretical restrictions coming from anomaly cancellation through the Green-Schwarz mechanism [57], eight phenomenology conditions from mass ratios and mixings of the charged fermionic sector, and two more conditions corresponding to the absolute value of the third-generation fermion masses, we obtain a set of 13 conditions. Hence, 13 out of 17 H charges are constrained and can be expressed in terms of the remaining four charges that have been chosen to be the lepton-number violating bilinear H charges n_i, and x [38], where $x = L_0 + L_3 + e_3 = L_0 + Q_3 + d_3$ takes integer values from 0 to 3 in order to obtain the allowed range for $\tan\beta = \theta^{x-3}$. With all these restrictions, there is only a possible set of charge differences, which is displayed in Table I. This self-consistent solution includes the Guidice-Masiero mechanism to solve the μ problem because $n_0 = -1$, and therefore the μ term is absent from the superpotential [38].

The H charges of the R-parity breaking couplings can be written as

TABLE I. Standard model fields H-charge differences with $n_0 = -1$ (from Ref. [38]). Here $\mathcal{L}_{i3} = L_{i3} + l_{i3}$.

Q_{13}	Q_{23}	d_{13}	d_{23}	u_{13}	u_{23}	$\mathcal{L}_{13}$	$\mathcal{L}_{23}$
3	2	1	0	5	2	5	2

$$
\begin{aligned}
H(\lambda''_{ijk}) &= \tfrac{1}{3}\mathcal{N} + [x + \mathcal{I}''(i,j,k)] \quad (j<k)\\
H(\lambda'_{ijk}) &= n_i + [x + \mathcal{I}'(i,j,k)]\\
H(\lambda_{ijk}) &= n_i + n_j - n_k + n_0 + [x + \mathcal{I}(i,j,k)] \quad (i<j)\\
&= \begin{cases} n_{i(\text{or } j)} + n_0 + [x + \mathcal{I}(i,j,k)] & \text{if } i = k (\text{or} j = k)\\ \mathcal{N} - 2n_k + [x + \mathcal{I}(i,j,k)] & \text{if } i \neq k \text{ and } j \neq k \end{cases},
\end{aligned}
\tag{2}
$$

where

$$
\mathcal{N} = \sum_{\alpha=0}^{3} n_\alpha = n_0 + n_1 + n_2 + n_3 = n_1 + n_2 + n_3 - 1 \tag{3}
$$

is the sum of the bilinear H charges. The terms inside the brackets in Eq. (2) are the integer part of the corresponding H charges, with the $\mathcal{I}$'s being functions of the coupling indices returning *integer* values. They are given explicitly in Eq. (A1).

From Eq. (2) it is straightforward to see the possible scenarios in the context of an anomalous horizontal Abelian symmetry with a single flavon, reviewed in the introduction. The MSSM is obtained when $\mathcal{N}/3$; each individual n_i and $\mathcal{N} - 2n_k$ are fractional [39,41]. Bilinear R-parity violation[2] is obtained when $\mathcal{N}/3$ is fractional and each n_i is a negative integer [38,40]. Another self-consistent R-parity breaking model with L violation can be obtained if $\mathcal{N}/3$ and each individual n_i are fractional, but some of the $\mathcal{N} - 2n_k$ are integers. In such a case, the decays of the LSP are leptophilic [35].

In this work we want to explore the last self-consistent possibility, consisting in the R-parity breaking model with B violation. It is clear from Eq. (2) that if $\mathcal{N}$ is an integer and multiple of 3, and each n_i is fractional but not a half-integer, then only the 9 λ''_{ijk} are generated. The specific horizontal charges are

$$
H\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312}\\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313}\\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \begin{pmatrix} 6 & 3 & 1\\ 6 & 3 & 1\\ 5 & 2 & 0 \end{pmatrix} + n_{\lambda''}\mathbf{1}_3, \tag{4}
$$

where $\mathbf{1}_3$ is a 3×3 matrix filled with ones, and $n_{\lambda''}$ is defined by

$$
n_{\lambda''} = x + \frac{1}{3}\mathcal{N}. \tag{5}
$$

For positive $n_{\lambda''}$ values, the third-generation couplings dominate with fixed ratios between them:

$$
\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312}\\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313}\\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} \approx \theta^{n_{\lambda''}} \begin{pmatrix} \theta^6 & \theta^3 & \theta\\ \theta^6 & \theta^3 & \theta\\ \theta^5 & \theta^2 & 1 \end{pmatrix} n_{\lambda''} \geq 0. \tag{6}
$$

[2]See, for example, Ref. [58] and references therein.

For negative values some of the couplings start to be forbidden in the superpotential by holomorphy, and for $n_{\lambda''} < -6$ all of them must be generated from the Kähler potential with additional Planck mass suppression, so that the LSP may be a decaying dark matter candidate as in the case of L violation studied in Ref. [35]. We will not pursue this possibility in this work because in that case the phenomenology at colliders should be the same as that in the MSSM.

Below, the allowed range for $n_{\lambda''}$ and their consequences at present and future colliders will be checked.

A. Constraints from $\Delta B \neq 0$ processes

Several experimental constraints are found on B-violating couplings both for individual and quadratic products of couplings [8]. For individual couplings, the stronger constraints are for λ_{11k}. Because in our model the predicted order of magnitude for the coupling λ''_{113} is the same as that for λ''_{112}, the most restrictive constraint is that obtained for the later and comes from the dinucleon $NN \to KK$ width, which according to Refs. [26,59] is

$$
\Gamma \sim \rho_N \frac{128\pi\alpha_s^2 |\lambda_{112}|^4 (\tilde{\Lambda})^{10}}{m_N^2 m_{\tilde{g}}^2 m_{\tilde{q}}^8}, \tag{7}
$$

where $\rho_N \approx 0.25\ \text{fm}^{-3}$ is the nucleon density, $m_N \approx m_p$ is the nucleon mass, and $\alpha_s \approx 0.12$ is the strong coupling. Note that this kind of matter instability requires only B violation and is suppressed by the tenth power of $\tilde{\Lambda}$, which parametrizes the hadron and nuclear effects. For this quantity, order of magnitude variation is expected around the Λ_{QCD} scale of 200 MeV. However, $\tilde{\Lambda}$ is roughly expected to be smaller than Λ_{QCD} because of the repulsion effects inside the nucleus [26]. From general experimental searches of matter instability [60], lower bounds similar to the proton lifetime should be used for this specific dinucleon channel [59], and therefore additional suppression from λ_{112} could be required. In fact, the first lower bound on dinucleon decay to kaons has been recently obtained from Super-Kamiokande data [61],

$$
\tau_{NN\to KK} = \frac{1}{\Gamma} > 1.7 \times 10^{32}\ \text{yr}.
$$

From this value, we can obtain a constraint for the B-violating coupling:

$$|\lambda_{112}| \lesssim 3.2 \times 10^{-7}\left(\frac{1.7\times 10^{32}\ \mathrm{yr}}{\tau_{NN\to KK}}\right)^{1/4}\left(\frac{m_{\tilde{g}}}{300\ \mathrm{GeV}}\right)^{1/2} \times\left(\frac{m_{\tilde{q}}}{300\ \mathrm{GeV}}\right)^{2}\left(\frac{75\ \mathrm{MeV}}{\tilde{\Lambda}}\right)^{5/2}, \tag{8}$$

where a conservative value for $\tilde{\Lambda}$, as in Ref. [8], has been used. Large values of $\tilde{\Lambda}$ give rise to even smaller upper bounds for $|\lambda_{112}|$. In Fig. 1, we illustrate the effect of varying gluino and squark masses. We can see that the constraint still holds strong for large values of the relevant supersymmetric masses, especially for low-mass gluinos.

For $\tilde{m} = m_{\tilde{g}} = m_{\tilde{q}}$, we can obtain the lower bound

$$\tilde{m} \gtrsim (279\ \mathrm{GeV})\theta^{(-8+2n_{\lambda''})/5}\left(\frac{\tau_{NN\to KK}}{1.7\times 10^{32}\ \mathrm{yr}}\right)^{1/10} \times\left(\frac{\tilde{\Lambda}}{75\ \mathrm{MeV}}\right), \qquad n_{\lambda''} \geq -6. \tag{9}$$

The excluded supersymmetric masses as function of $n_{\lambda''}$ are illustrated with the yellow (light-gray) bands in Fig. 2. The important restrictions appear for negative powers of θ in Eq. (9), corresponding to $n_{\lambda''} \leq 4$. If $\tilde{\Lambda}$ is increased to 150 GeV, stronger restrictions are obtained, as illustrated in the dashed bands of Fig. 2. We can see that for the full range of equal gluino and squark masses displayed in Fig. 2, the constraint is strong enough to forbid all the negative solutions of $n_{\lambda''}$ and also some of the positive solutions depending of the chosen $\tilde{\Lambda}$ value.

It is also possible to exclude the negative solutions if we use the available quadratic coupling product bounds. For our model the most important constraint is obtained from the penguin decays $B \to \phi\pi$ [8,62]. Updating the limit with the last result from *BABAR* [63][3] to $\mathrm{Br}(B^+ \to \phi\pi^+) < 2.4\times 10^{-7}$, we obtain from Fig. 3 of Ref. [62]

$$|\lambda''_{i23}\lambda''^{*}_{i12}| < 2\times 10^{-5}\left(\frac{m_{\tilde{u}_{iR}}}{100\ \mathrm{GeV}}\right)^{2}. \tag{10}$$

The excluded right-handed up-squark masses are shown in the green (dark gray) bands of Fig. 2, with the specific generation of up squark labeled inside the band. The solutions with the additional "*" label have the quoted λ''_{i23} coupling absent from the superpotential. However, it is regenerated at order θ through a Kähler rotation [51] from the dominant coupling still present in the superpotential. As a result, again the negative solutions are excluded for the full range of squark masses displayed in the figure. Moreover, the first two positive solutions are also excluded. In the figure, the gray region for $n_{\lambda''} \leq -7$ is also shown. In this case, the holomorphy of the superpotential forbids all the λ'' terms, and although they will be generated after $U(1)_H$ symmetry breaking via the Kähler potential [65], these terms are suppressed by the additional factor $m_{3/2}/M_P$ [35]. Therefore, the LSP is very long-lived, and the phenomenology at colliders is expected to be the same as that in the MSSM.

Therefore, by demanding a B-violating model and imposing the constraints on the R-parity breaking couplings, only positive solutions for $n_{\lambda''}$ remain allowed, giving rise to a clear hierarchy between λ'' couplings, which have a direct impact on the phenomenology of the LSP. The dominant coupling turns out to be λ''_{323}, a feature shared with Refs. [26,27].

[3]The limit from Belle is $\mathrm{Br}(B^+ \to \phi\pi^+) < 3.3\times 10^{-7}$ [64].

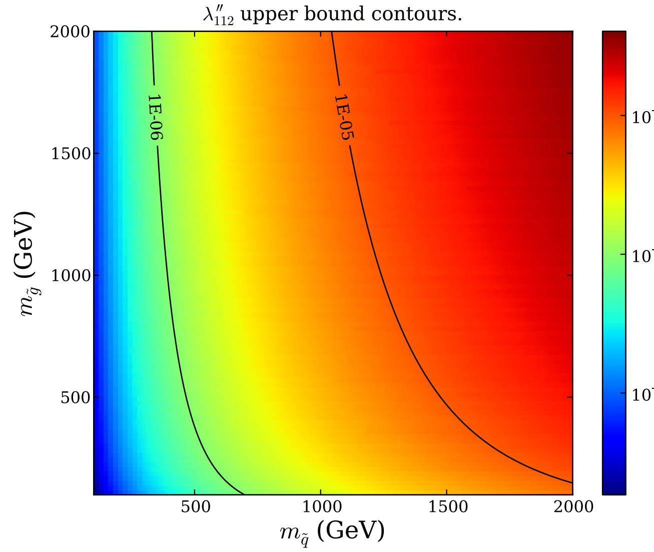

FIG. 1 (color online). λ''_{112} constraint as a function of squark and gluinos mass, for $\tilde{\Lambda} = 75$ GeV and $\tau_{NN\to KK} = 1.7\times 10^{32}$ yr.

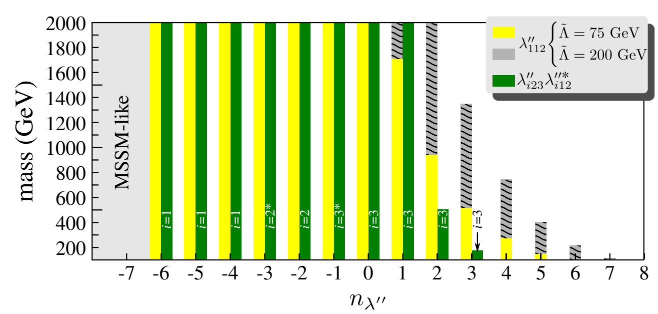

FIG. 2 (color online). The yellow bands (green bands) display the excluded range for $\tilde{m}$ ($\tilde{u}_{iR}$) as a function of the possible $n_{\lambda''}$ solutions from the constraints in $|\lambda''_{112}|$ ($|\lambda''_{i23}\lambda''^{*}_{i12}|$). The gray dashed bands show the effect of increasing $\tilde{\Lambda}$ in the $|\lambda''_{112}|$ constraint. The affected $\tilde{u}_{iR}$ is indicated for each value of $n_{\lambda''}$. For $n_{\lambda''} < -6$ the phenomenology at colliders is expected to be the same as in the MSSM.

B. Dimension-five operators and proton decay

So far, the $U(1)_H$ symmetry has been used to forbid dimension-four lepton-number violating couplings in order to keep proton decay to a safe limit. However, proton decay mediated by λ'' couplings alone can occur in scenarios with a gravitino lighter than a proton [66], leading to strong bounds on these couplings. Thus, by ensuring gravitino masses greater than 1 GeV, in these scenarios there will be no contribution to the proton decay coming from a gravitino, which being the LSP can be also a dark matter canditate [9,10,26,67,68].

On the other hand, there are also dimension-five lepton-or/and baryon-number violating couplings, which can induce proton decay. Hence, it is also necessary to check if these terms are also banned or suppressed enough.

The nonrenormalizable dimension-five operators in the superpotential W_{5D} and Kähler potential V_{5D} are given by [7,8,20,69]

$$\begin{aligned} W_{D5} = {} & \frac{(\kappa_1)_{ijkl}}{M_P}\hat{Q}_i\hat{Q}_j\hat{Q}_k\hat{L}_l + \frac{(\kappa_2)_{ijkl}}{M_P}\hat{u}_i\hat{u}_j\hat{d}_k\hat{e}_l \\ & + \frac{(\kappa_3)_{ijk}}{M_P}\hat{Q}_i\hat{Q}_j\hat{Q}_k\hat{H}_d + \frac{(\kappa_4)_{ijk}}{M_P}\hat{Q}_i\hat{H}_d\hat{u}_j\hat{e}_k \\ & + \frac{(\kappa_5)_{ij}}{M_P}\hat{L}_i\hat{H}_u\hat{L}_j\hat{H}_u + \frac{(\kappa_6)_i}{M_P}\hat{L}_i\hat{H}_u\hat{H}_d\hat{H}_d, \end{aligned} \tag{11}$$

$$\begin{aligned} V_{5D} = {} & \frac{(\kappa_7)_{ijk}}{M_P}\hat{u}_i\hat{d}_j^*\hat{e}_k + \frac{(\kappa_8)_i}{M_P}\hat{H}_u^*\hat{H}_d\hat{e}_i + \frac{(\kappa_9)_{ijk}}{M_P}\hat{Q}_i\hat{L}_j^*\hat{u}_k \\ & + \frac{(\kappa_{10})_{ijk}}{M_P}\hat{Q}_i\hat{Q}_j\hat{d}_k^*. \end{aligned} \tag{12}$$

A review of the effect of these operators in the destabilization of the proton is given in Ref. [30]. In the present case of B violation, we would guarantee a sufficiently stable proton if the B- and L-violating operators with couplings $\kappa_{1,2}$ and the L-violating operators with coupling $\kappa_{4,7,8,9}$ are forbidden.[4] The operator with coupling κ_5, LH_uLH_u, is not constrained by proton decays because it violates the lepton number by two units.

The horizontal charges for all the dimension-five operators are given in Appendix B. Given the fractional values needed for n_i in order to get rid of the dimension-four L-violating operators in Eq. (1), it turns out that all dimension-five L-violating operators are also automatically forbidden by the $U(1)_H$ symmetry [see Eqs. (B3)–(B5)]. At this stage the $U(1)_H$ symmetry plays the same role as that of a lepton-parity discrete symmetry [7,20,21,69].

[4]The constraints on the operator with coupling κ_6 are mild [30].

III. GENERATION OF NEUTRINO MASSES

Although it is not required that the LH_uLH_u operator be forbidden by $U(1)_H$ symmetry to ensure proton stability, it is unavoidably prohibited because the bilinear charges n_i are not half-integers. Thus, the Majorana mass terms $\nu_L\nu_L$ are automatically forbidden. The same happens with lepton-parity symmetry and also within the more general approach of gauge discrete symmetries [20,21,69], for which the solutions that allow the UDD operator automatically forbid Majorana neutrinos. The proposed solution in these kinds of frameworks is just to introduce right-handed neutrinos N with their Majorana mass terms NN forbidden, while keeping the Yukawa operators containing left- and right-handed neutrinos still allowed, generating in this way Dirac neutrino mass matrices [25]. When these ideas are applied to our case of horizontal symmetries, it is also necessary to explain the smallness of the neutrino Yukawa couplings. The introduction of three right-handed neutrinos N_i ($i = 1, 2, 3$) allows us to give Dirac masses to neutrinos by assigning fractional and not half-integer H charges to N_i, such that the NN terms remain forbidden.

Let us paramatrize the bilinear H charges as $n_2 = n_1 + \alpha$, $n_3 = n_1 + \beta$ and for right-handed neutrinos: $N_2 = N_1 + \epsilon$ and $N_3 = N_1 + \rho$. The neutrino Dirac mass matrix reads

$$M_\nu \sim v_u\theta^{\beta+\rho+n_1+N_1}\begin{pmatrix} \theta^{-\beta-\rho} & \theta^{\epsilon-\beta-\rho} & \theta^{-\beta} \\ \theta^{\alpha-\beta-\rho} & \theta^{\alpha+\epsilon-\beta-\rho} & \theta^{\alpha-\beta} \\ \theta^{-\rho} & \theta^{\epsilon-\rho} & 1 \end{pmatrix}, \tag{13}$$

where v_u is the vacuum expectation value developed by the up-type Higgs field. From Eq. (5) we obtain $n_1 = \frac{1}{3}\times(1-\alpha-\beta+3n_{\lambda''}-3x)$. Motivated by the recent results of a large value for θ_{13} [46–49], which support those models based on a anarchical neutrino mass matrix [42–45], it is convenient to choose $\alpha=\beta=\epsilon=\rho=0$ and $\beta+\rho+n_1+N_1=n_{Y_\nu}$, with n_{Y_ν} being an integer and $n_{Y_\nu}\geq 16$ in order to generate a neutrino Yukawa coupling $Y_\nu \lesssim 10^{-11}$. It is worth stressing that since n_1 cannot be an integer, the $\mu\tau$ anarchical texture with $\alpha = \beta = -1$ [39,70–72] is not allowed. However, other textures can be accommodated in our model [72], such as pseudo-$\mu\tau$ anarchy ($\alpha=\beta=\epsilon=\rho=-2$) and the hierarchical texture ($\alpha=\epsilon=-1$, $\beta=\rho=-2$). An immediate consequence of the anarchy assumption is that the bilinear charges are equal and are set to $n_i = n_{\lambda''} - x + \frac{1}{3}$, being clearly noninteger numbers. The H charges that allow us to obtain a self-consistent framework with the requirements mentioned above are shown in Table II. It is remarkable that when explaining the neutrino Yukawa couplings Y_ν, a lower bound on $n_{\lambda''}\geq 6$ emerges, which leads to deep implications on the phenomenology of the model (see the next section).

TABLE II. Some sets of H charges allowing a self-consistent framework of R-parity breaking with B violation and Dirac neutrinos.

x	0	0	0	0	1	0	1	2
$n_{\lambda''}$	6	7	8	9	9	10	10	10
n_i	19/3	22/3	25/3	28/3	25/3	31/3	28/3	25/3
N_i	29/3	26/3	29/3	26/3	29/3	23/3	26/3	29/3

TABLE III. Sets of H charges that allow having Majorana neutrinos with $H(N_i) = 7/2$. For this scenario there is no lower bound on $n_{\lambda''}$.

x	1	1	1	2	2	2	3	3
$n_{\lambda''}$	5	6	7	6	7	8	8	9
n_i	13/3	16/3	19/3	13/3	16/3	19/3	16/3	19/3
ψ	−47/6	−53/6	−59/6	−47/6	−53/6	−59/6	−53/6	−59/6

A. Majorana neutrinos

It is worth mentioning that it is also possible to have Majorana neutrinos if, in addition to the right-handed neutrinos, we include in the model a second flavon,[5], ψ with fractional[6] H charge and with a vacuum expectation value approximately equal to θ. The horizontal charges of these superfields are fixed by new invariant diagrams coming from Dirac and Majorana mass terms.

In this way, the H charge of ψ must be such that it does not get coupled to L-violating operators. Therefore, the respective total H charge of the full L-violating operator would be either fractional, and therefore forbidden, or negative and sufficiently suppressed.

The introduction of an additional flavon field could spoil the proton stability since H-invariant terms can be obtained by coupling a large number of ψ flavons to dangerous operators. Therefore, it is mandatory to ensure that L-violating bilinear, dimension-four and dimension-five operators are generated through the Giudice-Masiero mechanism or have a large Froggatt-Nielsen suppression. The H charges that allow us to obtain Majorana neutrinos with the requirements mentioned above are shown in Table III. To illustrate this point, let us consider the first solution given in Table III. For that set of H charges, we have found that the minimum suppression that is achieved for dimension-four and dimension-five operators is $\hat{L}_1\hat{Q}_1\hat{D}_1{:}m_{3/2}\theta^{21}/M_P$ and $\hat{u}_1\hat{u}_2\hat{d}_1\hat{e}_1{:}m_{3/2}\theta^2/M_P^2$, which is enough to satisfy the constraints coming from proton decay.

Henceforth, we will combine the solutions allowed by the experimental constraints on R-parity breaking couplings discussed in Sec. II, with the restrictions to obtain Dirac neutrinos, and therefore we will only consider solutions with $n_{\lambda''} \geq 6$.

[5]For a model with several flavons, see Ref. [73].

[6]A scenario with Majorana neutrinos and nonanomalous $U(1)_H$ symmetry, which is spontaneously broken by two flavons with opposite H charges $+1$ and -1, was obtained in Ref. [23].

IV. IMPLICATIONS ON COLLIDER SEARCHES

From a collider physics point of view, there are two main differences between the models with and without R-parity conservation. When R-parity conservation is assumed, the production of supersymmetric particles is in pairs, and the LSP is stable leading to missing energy signatures in the detectors. On the other hand, R-parity violation allows for the single production of supersymmetric particles and the decay of the LSP involving jets or/and leptons. The R-parity breaking and B-violating operators induce LSP decay directly or indirectly to quarks, including the top if LSP is sufficiently massive.[7] Given that the LSP is no longer stable due to R-parity violation, in principle, the LSP can be any supersymmetric particle [6,8,74]. For recent phenomenological studies in supersymmetric scenarios with R-parity breaking through B violating, see, e.g., Refs. [13–17,67,74–86] and, in particular, Refs. [26,27].

The phenomenology of the model at the LHC is basically the same studied in the SSM with minimal flavor violation (MFV) [26] and partial compositeness [27]. In fact, in Ref. [26] C. Csaki *et al.* also get a hierarchy in which the third-generation couplings dominate with fixed ratios between them. Fixing the expansion parameter as $\theta = 0.22$, their set of R-parity breaking parameters can be written as

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} \approx \tan^2\beta_{\mathrm{MFV}} \begin{pmatrix} \theta^{24} & \theta^{18} & \theta^{13} \\ \theta^{19} & \theta^{14} & \theta^{12} \\ \theta^{16} & \theta^{13} & \theta^{11} \end{pmatrix}$$
$$= \theta^{n_{\mathrm{MFV}}} \begin{pmatrix} \theta^{13} & \theta^{7} & \theta^{2} \\ \theta^{8} & \theta^{3} & \theta \\ \theta^{5} & \theta^{2} & 1 \end{pmatrix}, \qquad (14)$$

with $\theta^{n_{\mathrm{MFV}}} = \theta^{11}\tan^2\beta_{\mathrm{MFV}}$. Comparing with Eq. (6), we can see that the set of predicted couplings until order $\theta^{n_{\mathrm{MFV}}+3}$ is basically the same as in our case (with the exception of their λ''_{312}, which has an additional suppression factor of θ). Therefore, the phenomenology of both theories for R-parity violation should be the same at the LHC. In fact, the phenomenology of Ref. [26] for the leading couplings was analyzed in detail at the LHC with the results presented as function of $\tan\beta_{\mathrm{MFV}}$. The specific values at $\tan\beta_{\mathrm{MFV}} \approx (44.5, 20.7, 9.7, 4.6, 2.1)$ in several plots of Ref. [26] correspond to the discrete set of solutions $n_{\lambda''} = (6, 7, 8, 9, 10)$, respectively, in our model. In particular, in several plots there, they explore the decay length ($c\tau$) for LSP masses in the range of 100–800 GeV. When the stop is

[7]If a supersymmetric partner of some SM particle is the next-to-the-lightest supersymmetric particle with the gravitino as the LSP, our phenomenological results would not change.

the LSP, for example, displaced vertices (DV) are expected for $n_{\lambda''} = 10$. For a sbottom LSP, it is possible to have DV for $n_{\lambda''} = 9, 10$, while the three-body decays of a LSP neutralino could generate DV for $n_{\lambda''} = 8, 9, 10$. In the same vein, because decays of the stau LSP involves four particles in the final state, DV are expected for $n_{\lambda''} \geq 6$.

Recent phenomenological analysis in R-parity breaking trough UDD operators has focused on prompt decay for stops and sbottoms [26,32,79,87]. However, the experimental results about DV at the LHC are, in general, not directly applicable to these kinds of models because high p_T leptons are required to trigger the events [88–90] and to be part of the DV [89,90]. We assume in the discussion below that pure hadronic DV are still compatible with light squarks and gluinos.

Regarding collider searches, a pair produced gluino with a prompt decay to three jets has been searched by CDF [91], CMS [92,93], and ATLAS [94].[8] CMS results constrain the gluino mass to be in the ranges $144 < m_{\tilde{g}} < 200$ GeV or $m_{\tilde{g}} > 460$ GeV. However, ATLAS already excludes gluino masses up to $m_{\tilde{g}} \lesssim 666$ GeV. In general, these bounds do not apply when the gluino is not the LSP [26,87]. On the other hand, CDF [95], ATLAS [96,97], and CMS [98] also have performed searches for pair production of dijet resonances in four-jet events without putting appreciable constraints on stops decaying to dijets. Therefore, the already analyzed data at the LHC still allow for low squarks and gluinos in scenarios with R-parity breaking through B-violating couplings [75,87].

We have seen that both this single-flavon horizontal (SFH) and the MFV models, lead to a realistic and predictive framework which could be more easily probed at LHC than some *ad hoc* version or R-parity breaking with B violation. In fact, recently in [86] the CMS results on searches for new physics in events with same-sign dileptons and b jets [99] have been recasting in a simplified version of the R-parity breaking MFV model where it is assumed one spectrum with only two light states: a gluino and a stop. All other SUSY particles are assumed to be either too heavy or too weakly coupled to be relevant at the LHC. Furthermore, the stop is assumed to be the LSP, and $m_{\tilde{g}} > m_{\tilde{t}} + m_t$.[9] Under these conditions they are able to set a lower bound on the gluino mass about 800 GeV at 95% of confidence level.[10] The same bound could apply to the SFH model with R-parity breaking presented in this work.

In order to really probe this single-flavon horizontal (or the MFV) R-parity breaking model, the full textures in Eq. (4) or (14) should be probed. However, relations between different branching ratios could be measured only in e^+e^- colliders. In a stop LSP scenario, it can decay directly into two down quarks of different generations through the λ''_{3jk} coupling. In this case, the hierarchy between λ'' couplings allows for estimate several fractions of branchings, e.g., $\mathrm{Br}(\tilde{t} \to \bar{s}\,\bar{b})/\mathrm{Br}(\tilde{t} \to \bar{d}\,\bar{s})/ \sim \theta^2$. A sbottom LSP, with a mass larger than the top mass, may show the clear hierarchy $\mathrm{Br}(\tilde{b} \to \bar{t}\,\bar{s})/\mathrm{Br}(\tilde{b} \to \bar{c}\,\bar{s})/ \sim \theta^4$. For a neutralino LSP with $m^0_{\tilde{\chi}} > m_t$, the dominant coupling λ''_{323} entails $\mathrm{Br}(\tilde{\chi} \to tdb)/\mathrm{Br}(\tilde{\chi} \to tsb) \sim \mathrm{Br}(\tilde{\chi} \to tds)/\mathrm{Br}(\tilde{\chi} \to tsb) \sim \theta^2$ and $\mathrm{Br}(\tilde{\chi} \to csb)/\mathrm{Br}(\tilde{\chi} \to tsb) \sim \theta^4$. For the case $m_{\tilde{\chi}} < m_t$ the main neutralino decay is then controlled by λ''_{223}, and will produce charm quarks with ratios of branching ratios given by $\mathrm{Br}(\tilde{\chi} \to cdb)/\mathrm{Br}(\tilde{\chi} \to csb) \sim \mathrm{Br}(\tilde{\chi} \to cds)/\mathrm{Br}(\tilde{\chi} \to csb) \sim \theta^2$.

V. CONCLUSIONS

We have obtained a supersymmetric R-parity breaking model with B violation by considering the most general supersymmetric standard model allowed by gauge invariance and extending it with a SFH $U(1)_H$ symmetry. The generated effective theory at low energy has only the particle content of the SSM. After imposing existing constraints in both single and quadratic R-parity violating (RPV) couplings, only one precise hierarchy remains depending on a global suppression factor $\theta^{n_{\lambda''}}$ ($n''_\lambda > 1$) with λ''_{323} as the dominant coupling and very suppressed couplings for the first two generations. Additional suppression is required in order to obtain Dirac neutrino masses in the model, and only solutions with $n''_\lambda \geq 6$ remain allowed. In this way, the resulting RPV and B-violating model also explaining neutrino masses is powerful enough to satisfy all the existing constraints on RPV. In particular, the $U(1)_H$ symmetry also ensures that dimension-five L-violating operators are sufficiently suppressed so that the decay of the proton is above the experimental limits.

The resulting underlying theory for the RPV operators is quite similar to that obtained after imposing the MFV hypothesis on a general RPV model (at least until couplings of order $\theta^{n_{\lambda''}+3}$), and therefore the predictions of both models are the same at the LHC.

The phenomenology at colliders depends strongly on the nature and decay length of the LSP. Specific searches at the LHC for the RPV with B violation have reported restrictions only in the case of prompt decays of the gravitino when it is the LSP. Several analyses of CMS and ATLAS involving leptons have been reanalyzed to constrain the gluino as a function of the stop mass (see Ref. [86] and references therein) within a special spectrum guaranteeing that $\mathrm{BR}(\tilde{g} \to \tilde{t}\,\bar{t}) = 1$ and with prompt decays of the corresponding LSP stop. In both cases bounds in the gluino mass around 600 GeV have been obtained. Therefore, the parameter space of the RPV/SFH scenario (or the RPV/MFV one) have still plenty of room to accommodate a low-energy supersymmetric spectrum.

[8]In this analysis all the superpartners except for the gluinos are decoupled, and some reinterpretation would be needed to apply the results to a more generic SUSY spectrum.

[9]As a consequence the gluino branching to stop-top is equal to 1.

[10]The obtained lower bound only applies if the gluino is a Majorana particle.

There is a number of open issues that could be more easily studied within this realistic and predictive framework, for example, the constraints on the couplings from low-energy observables and indirect dark matter experiments or the restrictions in the parameter space from other collider signatures like the displaced vertices searches already implemented by ATLAS [89] and CMS [90].

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APPENDIX A: INTEGER PART OF *R*-PARITY BREAKING *H* CHARGES

Functions of the trilinear R-parity breaking coupling indices returning integer values are

$$\begin{aligned} \mathcal{I}''(ijk) &= -2i + p''_i + p''_j + p''_k \quad (j<k) \\ \mathcal{I}'(ijk) &= \frac{1}{2}(j + k + p'_j + p'_k) - 2\delta_{j3} \\ \mathcal{I}(ijk) &= i - 2k + p_i + p_j + p_k, \quad (i<j) \end{aligned} \tag{A1}$$

where the several p_i's are shown in Table IV.

APPENDIX B: *H* CHARGES OF DIMENSION-FIVE OPERATORS

The horizontal charges for the dimension-five operators that violate only B are given by

$$\begin{aligned} H[(\kappa_3)_{1jk}\hat{Q}_1\hat{Q}_j\hat{Q}_k\hat{H}_d] &= A_3 + (2x + 4 - n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_3)_{2jk}\hat{Q}_2\hat{Q}_j\hat{Q}_k\hat{H}_d] &= A_3 + (2x + 3 - n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_3)_{3jk}\hat{Q}_3\hat{Q}_j\hat{Q}_k\hat{H}_d] &= A_3 + (2x + 1 - n_{\lambda''})\mathbf{1}_3, \end{aligned} \tag{B1}$$

$$\begin{aligned} H[(\kappa_{10})_{ij1}\hat{Q}_i\hat{Q}_j\hat{d}_1^*] &= A_3 + (x - n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_{10})_{ij2}\hat{Q}_i\hat{Q}_j\hat{d}_2^*] &= A_3 + (x + 1 - n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_{10})_{ij2}\hat{Q}_i\hat{Q}_j\hat{d}_3^*] &= H[(\kappa_{10})_{ij3}\hat{Q}_i\hat{Q}_j\hat{d}_2^*]. \end{aligned} \tag{B2}$$

For the lepton- and baryon-number violating operators, we have that

TABLE IV. Integer values required to obtain the horizontal charges of dimension-four RPV operators.

i	1	2	3
p_i	3	2	2
p'_i	4	1	0
p''_i	3	2	2

$$\begin{aligned} H[(\kappa_1)_{1jkl}\hat{Q}_1\hat{Q}_j\hat{Q}_k\hat{L}_l] &= A_1 + (5 + 2x + n_l - n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_1)_{2jkl}\hat{Q}_2\hat{Q}_j\hat{Q}_k\hat{L}_l] &= A_1 + (4 + 2x + n_l - n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_1)_{3jkl}\hat{Q}_3\hat{Q}_j\hat{Q}_k\hat{L}_l] &= A_1 + (2 + 2x + n_l - n_{\lambda''})\mathbf{1}_3, \end{aligned} \tag{B3}$$

$$\begin{aligned} H[(\kappa_2)_{ij11}\hat{u}_i\hat{u}_j\hat{d}_1\hat{e}_1] &= A_2 + (6 - n_1 + n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_2)_{ij21}\hat{u}_i\hat{u}_j\hat{d}_2\hat{e}_1] &= A_2 + (5 - n_1 + n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_2)_{ij31}\hat{u}_i\hat{u}_j\hat{d}_3\hat{e}_1] &= H[(\kappa_2)_{ij21}\hat{u}_i\hat{u}_j\hat{d}_2\hat{e}_1], \\ H[(\kappa_2)_{ij12}\hat{u}_i\hat{u}_j\hat{d}_1\hat{e}_2] &= A_2 + (3 - n_2 + n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_2)_{ij22}\hat{u}_i\hat{u}_j\hat{d}_2\hat{e}_2] &= A_2 + (2 - n_2 + n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_2)_{ij32}\hat{u}_i\hat{u}_j\hat{d}_2\hat{e}_2] &= H[(\kappa_2)_{ij22}\hat{u}_i\hat{u}_j\hat{d}_3\hat{e}_2] \\ H[(\kappa_2)_{ij13}\hat{u}_i\hat{u}_j\hat{d}_1\hat{e}_3] &= A_2 + (1 - n_3 + n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_2)_{ij23}\hat{u}_i\hat{u}_j\hat{d}_2\hat{e}_3] &= A_2 + (-n_3 + n_{\lambda''})\mathbf{1}_3, \\ H[(\kappa_2)_{ij33}\hat{u}_i\hat{u}_j\hat{d}_2\hat{e}_3] &= H[(\kappa_2)_{ij23}\hat{u}_i\hat{u}_j\hat{d}_3\hat{e}_3]. \end{aligned} \tag{B4}$$

Finally, for the lepton-number violating terms, we have found

$$\begin{aligned} H[(\kappa_4)_{ij1}\hat{Q}_i\hat{H}_d\hat{u}_j\hat{e}_1] &= A_4 + (5 - n_1 + x)\mathbf{1}_3, \\ H[(\kappa_4)_{ij2}\hat{Q}_i\hat{H}_d\hat{u}_j\hat{e}_2] &= A_4 + (2 - n_2 + x)\mathbf{1}_3, \\ H[(\kappa_4)_{ij3}\hat{Q}_i\hat{H}_d\hat{u}_j\hat{e}_3] &= A_4 + (-n_3 + x)\mathbf{1}_3, \\ H[(\kappa_5)_{ij}\hat{L}_i\hat{H}_u\hat{L}_j\hat{H}_u] &= \begin{pmatrix} 2n_1 & n_1+n_2 & n_1+n_3 \\ n_1+n_2 & 2n_2 & n_2+n_3 \\ n_1+n_3 & n_2+n_3 & 2n_3 \end{pmatrix}, \\ H[(\kappa_6)_i\hat{L}_i\hat{H}_u\hat{H}_d\hat{H}_u] &= -1 + n_i, \\ H[(\kappa_7)_{ij1}\hat{u}_i\hat{d}_j^*\hat{e}_1] &= A_7 + (4 - n_1)\mathbf{1}_3, \\ H[(\kappa_7)_{ij2}\hat{u}_i\hat{d}_j^*\hat{e}_2] &= A_7 + (1 - n_2)\mathbf{1}_3, \\ H[(\kappa_7)_{ij3}\hat{u}_i\hat{d}_j^*\hat{e}_3] &= A_7 + (-1 - n_3)\mathbf{1}_3, \\ H[(\kappa_8)_1\hat{H}_u^*\hat{H}_d\hat{e}_1] &= 5 - n_1 + x, \\ H[(\kappa_8)_2\hat{H}_u^*\hat{H}_d\hat{e}_2] &= 2 - n_2 + x, \\ H[(\kappa_8)_3\hat{H}_u^*\hat{H}_d\hat{e}_3] &= -n_3 + x, \\ H[(\kappa_9)_{i1k}\hat{Q}_i\hat{L}_j^*\hat{u}_k] &= A_9 + (-n_j)\mathbf{1}_3. \end{aligned} \tag{B5}$$

In the above expressions, we have defined

$$A_1 = A_3 = \begin{pmatrix} 6 & 5 & 3 \\ 5 & 4 & 2 \\ 3 & 2 & 0 \end{pmatrix}, \qquad A_2 = \begin{pmatrix} 10 & 7 & 5 \\ 7 & 4 & 2 \\ 5 & 2 & 0 \end{pmatrix},$$
$$A_4 = A_9 = \begin{pmatrix} 8 & 5 & 3 \\ 7 & 4 & 2 \\ 5 & 2 & 0 \end{pmatrix}, \qquad A_7 = \begin{pmatrix} 5 & 6 & 6 \\ 2 & 3 & 3 \\ 0 & 1 & 1 \end{pmatrix}. \tag{B6}$$

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