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Neutrino masses from R-parity violation with a Z_3 symmetry

E. Peinado*

AHEP Group, Instituto de Física Corpuscular—C.S.I.C./Universitat de València, Edificio de Institutos de Paterna, Apartado 22085, E-46071 València, Spain

A. Vicente†

Laboratoire de Physique Théorique, CNRS—UMR 8627, Université de Paris-Sud 11, F-91405 Orsay Cedex, France

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We consider a supersymmetric model where the neutrino mass matrix arises from bilinear and trilinear R-parity violation, both restricted by a Z_3 flavor symmetry. Assuming flavor-blind soft supersymmetry breaking conditions, corrected at low energies due to running effects, we obtain a neutrino mass matrix in agreement with oscillation data. In particular, a large θ_{13} angle can be easily accommodated. We also find a correlation between the reactor and atmospheric mixing angles. This leads in some scenarios to a clear deviation from $\theta_{23} = \pi/4$. The lightest supersymmetric particle decay, dominated by the trilinear couplings, provides a direct way to test the model at colliders.

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I. INTRODUCTION

Supersymmetry (SUSY) is one of the most popular extensions of the Standard Model (SM) [1,2]. The main advantage with respect to non-SUSY models is the technical solution that it provides to the hierarchy problem [3–6]. In addition, other theoretical and phenomenological issues can be addressed in the context of supersymmetric models; for example, questions such as the radiative origin of the electroweak symmetry breaking [7–9] and the unification of the gauge couplings at high energies [10–14].

However, despite these appealing theoretical motivations, no experimental evidence of supersymmetry has been found so far at the Large Hadron Collider (LHC) [15,16]. This might be telling us that we are adopting a wrong search strategy. In fact, most searches are based on the assumption of conserved R-parity [17], thus including a lower cut on the amount of missing transverse energy. This should encourage the search for nonminimal supersymmetric scenarios with a departure from the usual signatures, such as those with R-parity violation [18].

In the minimal supersymmetric Standard Model (MSSM) there are renormalizable terms, perfectly allowed under all symmetries of the theory, that break either baryon or lepton number [18]. These new interactions, that involve SM particles and their superpartners, are highly constrained by the nonobservation of baryon- or lepton-number-violating processes.[1] In fact, if baryon- and lepton-number-breaking interactions were present at the same time, they would induce proton decay. For these reasons, these dangerous terms are usually forbidden by an *ad hoc* additional symmetry, such as R-parity.

However, in order to stabilize the proton it is sufficient to forbid one of these terms, namely the baryon-number-violating one. In this case, the lepton-number-violating interactions would contribute to the generation of Majorana neutrino masses [18,27], an open issue not addressed in the MSSM, while problems due to proton decay are evaded. This well-motivated framework is one of the few scenarios where the mechanism behind neutrino mass generation can be directly tested in accelerator experiments; see, for example, Refs. [28–35].

Furthermore, the presence of R-parity-violating couplings opens up good perspectives for a richer phenomenology. Although the smallness of the R-parity-violating couplings implies that the standard decay chains are not affected, the decay of the lightest supersymmetric particle (LSP) dramatically changes the final signatures at the LHC [36]. In fact, the LSP decay reduces the amount of missing transverse energy in the final state. Instead, one expects events with large lepton and/or jet multiplicity. This has been recently used by different authors [34,37] to relax the stringent bounds on the squark and gluino masses, otherwise pushed to values clearly above the TeV.

Regarding neutrino oscillation experiments, the intense activity over the last few years has led to an increasing accuracy in the determination of the oscillation parameters. In particular, the θ_{13} mixing angle has been finally measured, with a surprisingly large result. Indeed, Double-Chooz [38], T2K [39], MINOS [40], Daya-Bay [41] and RENO [42] have completely ruled out the possibility of a vanishing θ_{13}, consistently pointing towards a value in the $\sin^2 2\theta_{13} \sim \mathcal{O}(0.1)$ ballpark. Updated global fits to all available experimental data have also appeared recently [43–45].

*epeinado@ific.uv.es
†avelino.vicente@th.u-psud.fr

[1] Many detailed studies regarding bounds on R-parity-violating couplings have been written. These are obtained from baryon- or lepton-number-violating processes as well as from several (unobserved) flavor-violating processes. See, for example, Refs. [19–26] and references therein.

The aforementioned measurement of θ_{13} has also ruled out the popular tribimaximal neutrino mixing pattern [46] and led to an explosion of papers where different flavor symmetries are used to accommodate a large θ_{13}. Concerning supersymmetric models with R-parity violation, a flavor model for bilinear R-parity violation was introduced in Ref. [47]. The requirement of an exact A_4 flavor symmetry in the superpotential couplings led to the known neutrino mixing pattern at the price of a higher complexity of the scalar sector of the model. Here we present another example, based on a simple Z_3 symmetry, of a flavored R-parity-violating model. In addition to the bilinear term, the trilinear ones play a fundamental role in the generation of neutrino masses. The flavor symmetry strongly restricts the allowed terms, and only a few remain in the model. However, it still allows for the required interplay that leads to the observed neutrino masses and mixings.

The paper is organized as follows. In Sec. II we define the model and the basic assumptions followed throughout the paper. In Sec. III we describe the origin of the different contributions to the neutrino mass matrix, and we analyze the resulting neutrino mixing pattern in Sec. IV. Finally, we briefly comment on collider phenomenology in Sec. V, and conclude in Sec. VI.

II. DEFINITION OF THE MODEL

We consider the MSSM particle content with the following charge assignment under an additional Z_3 symmetry:

In addition, all quark superfields are singlets under Z_3. The most general superpotential in the leptonic sector allowed by the gauge and flavor symmetries is

$$\mathcal{W} = Y_e^i \hat{L}_i \hat{E}_i \hat{H}_d + \epsilon \hat{L}_1 \hat{H}_u + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k + \lambda'_{jk} \hat{L}_1 \hat{Q}_j \hat{D}_k, \quad (1)$$

where the only nonzero λ_{ijk} couplings allowed by Z_3 are λ_{122}, λ_{133} and λ_{231}. The flavor symmetry also implies that only one ϵ parameter is nonzero, $\epsilon \equiv \epsilon_1$, the other two being forbidden due to the μ and τ charges under Z_3. We do not specify the superpotential terms without lepton fields for brevity, since they do not play any role in the following discussion. We also impose the conservation of baryon number. This forbids the superpotential term $\lambda''_{ijk} U_i D_j D_k$ and stabilizes the proton.

We allow for a soft breaking of the Z_3 flavor symmetry in the scalar potential, and thus general terms of the type

$$V_{\rm soft} \sim m^2_{L_i H_d} \tilde{L}_i^* H_d + B_\epsilon^i \tilde{L}_i H_u \quad (2)$$

are considered.

Finally, in the following discussion we will make two important assumptions about the parameters of the model. First, we will assume that the ϵ parameter is a small dimensionful parameter and thus it plays a negligible role in neutrino mass generation. This will allow us to drop some contributions to the neutrino mass matrix, as required to obtain the correct neutrino mixing pattern. In the next section we will estimate how small ϵ must be for our discussion to be unaltered. Second, we will consider universal soft SUSY-breaking terms at the grand unification scale, $m_{\rm GUT}$. This implies that generation-dependent couplings are exactly the same for all families and, in particular, one has $m^2_{L_1 H_d} = m^2_{L_2 H_d} = m^2_{L_3 H_d}$ and $B^1_\epsilon = B^2_\epsilon = B^3_\epsilon$ at $m_{\rm GUT}$. However, this equality is no longer valid at the SUSY scale due to the effect of the running of renormalization group equations. In fact, in constrained MSSM-like scenarios, like the one considered here, third-family sfermion soft terms depart from universality at low energies due to their larger Yukawa couplings.[2] Therefore, we will simply make use of this departure from universality and consider independent third-family sfermion soft terms at the SUSY scale.[3]

III. NEUTRINO MASS GENERATION

The breaking of lepton number induces nonzero Majorana masses for the neutrinos which, in this model, are generated by both bilinear and trilinear R-parity-violating couplings. As a result of this, the neutrino mixing pattern requires the correct interplay between those two sources. In this section we will describe the different contributions to the neutrino mass matrix and estimate their sizes.

The interplay between different $\not{R}_p$ couplings is not a new idea. For example, a similar approach was followed in Ref. [51], where the combination of bilinear and trilinear R-parity violation, together with a properly chosen flavor symmetry, also led to the required structure for the neutrino mixing matrix. However, the construction of the model and the resulting neutrino mass matrix are different in our work. The use of flavor symmetries to restrict the allowed $\not{R}_p$ couplings has also been discussed in Refs. [52–55] and, in particular, the Z_3 group has also been considered in Refs. [56,57]. Furthermore, many discrete symmetries have been used as a substitute for R-parity; see, for example, the recent [58,59].

Finally, before we proceed to describe the different contributions to the neutrino mass matrix we note that the charge assignment in Table I leads to a diagonal charged lepton mass matrix.

[2]Another possibility that takes nonuniversality in the soft terms as a starting point is the so-called *natural supersymmetry*, where the first and second generation sfermions are much heavier than the third one; see, for example, Refs. [48,49].

[3]Approximate formulas for the third-family soft terms are known in the literature; see Ref. [50]. However, their complexity (and dependence on unknown parameters such as $\tan\beta$) does not allow for simple estimates. Therefore, we will treat the departure from universality as a free phenomenological parameter.

TABLE I. Charge assignment of the model. We use the standard notation $\omega = e^{i2\pi/3}$.

	$\hat{L}_1$	$\hat{L}_2$	$\hat{L}_3$	$\hat{E}_1$	$\hat{E}_2$	$\hat{E}_3$	$\hat{H}_d$	$\hat{H}_u$
Z_3	1	ω	ω^2	1	ω^2	ω	1	1

A. Bilinear *R*-parity violation

A precise determination of the one-loop corrections to neutrino masses in bilinear *R*-parity-violating supersymmetry requires the consideration of several types of diagrams. We will follow closely the results presented in the pioneer references on this topic [60–63].

The Z_3 flavor symmetry implies that only one bilinear ϵ parameter is allowed in the superpotential, $\epsilon \hat{L}_1 \hat{H}_u$. This would in principle lead to one nonzero entry in the tree-level neutrino mass matrix, $m_\nu^{11} \propto \epsilon^2$. However, we will assume that the smallness of the ϵ parameter makes this contribution negligible.

Therefore, the dominant bilinear *R*-parity-violating (BRpV) contributions to neutrino masses come from one-loop diagrams without the ϵ coupling (see Ref. [64] for a similar scenario). Examples of such possibilities are presented in Figs. 1 and 2. We note however that they require relatively large B_ϵ^i and $m^2_{L_i H_d}$ (see below for an estimate); otherwise, these one-loop contributions would be too small to account for neutrino masses. This would generate large sneutrino vacuum expectation values, v_L^i, and lead to tree-level contributions to neutrino masses that are too large. Therefore we are forced to impose a fine-tuning of the parameters so that the relative contributions to v_L^i coming from B_ϵ^i and $m^2_{L_i H_d}$ cancel each other. This fine-tuning relation can be easily obtained from the potential in Eq. (2),

$$m^2_{L_i H_d} v_d + B_\epsilon^i v_u \simeq 0, \tag{3}$$

which implies that the approximate relation $m^2_{L_i H_d} \simeq \tan\beta B_\epsilon^i$ must hold.

We proceed now to estimate the size of the different diagrams. If the scale of lepton number violation in the soft terms is denoted as B_ϵ^i, $m^2_{L_i H_d} \sim m^2_{\not{R}_p}$, one obtains[4]

$$m_\nu^{\rm BRpV}(\text{one-loop}) \sim \frac{g^2}{16\pi^2}\frac{m^4_{\not{R}_p}}{m^3_{\rm SUSY}}. \tag{4}$$

For $m_{\rm SUSY} = 100$ GeV one finds that $m_{\not{R}_p} \sim 1$ GeV leads to $m_\nu^{\rm BRpV} \sim 0.1$ eV, in the correct range. On the other hand, the tree-level contribution to the neutrino mass matrix can be roughly estimated to be $m_\nu^{\rm BRpV}(\text{tree}) \sim \epsilon^2/m_{\rm SUSY}$, and thus for $m_{\rm SUSY} = 100$ GeV one needs $\epsilon \gtrsim 100$ KeV to be competitive with the one-loop contributions. We will therefore assume in the following that ϵ is below that scale.

[4]In fact, this definition of $m^2_{\not{R}_p}$ actually corresponds to $m^2_{L_j H_d}$. That is why Eq. (4) does not include a $\tan^2\beta$ enhancement (see Refs. [62,63]) since that factor is absorbed in $m^2_{\not{R}_p}$.

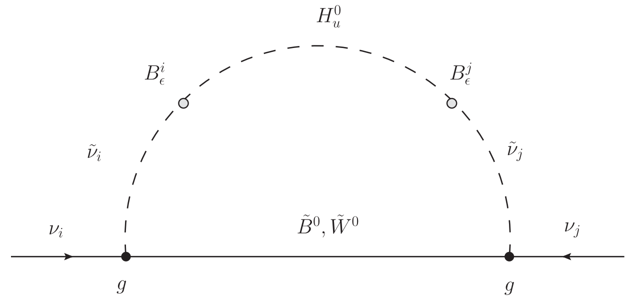

FIG. 1. One-loop neutrino masses from bilinear *R*-parity violation. B_ϵ contribution.

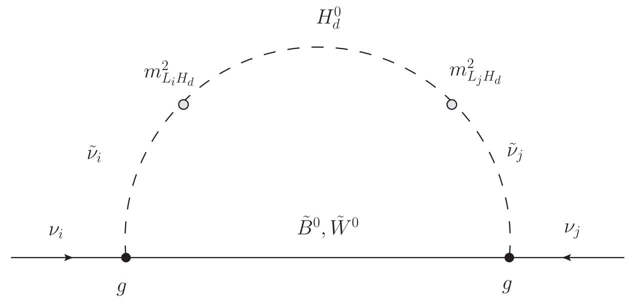

FIG. 2. One-loop neutrino masses from bilinear *R*-parity violation. $m^2_{LH_d}$ contribution.

It is important to notice that these contributions require a nonvanishing mass splitting between the real and imaginary components of the sneutrinos, $\Delta m^2_{\tilde{\nu}}$, as discussed in Ref. [60] and previously deduced from general considerations in Ref. [65].

Concerning the flavor structure of these one-loop contributions, note that by assumption the soft SUSY-breaking potential is flavor-universal for the first and second generations, with a (little) departure in the third generation soft terms. Therefore, we obtain the sum of two terms, a democratic structure plus a deviation from universality:

$$m_\nu^{\rm BRpV} = a\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + d\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 2 \end{pmatrix}. \tag{5}$$

Here a is given by the estimate in Eq. (4). The dimensionful coefficient d follows from a similar expression, where the corresponding soft terms $m^2_{\not{R}_p}$ have been properly replaced by $m^2_{\not{R}_p} + \delta m^2$. The mass squared parameter δm^2 is the result of the deviation from universality, expected to be sizable for the third generation. Terms of order $(\delta m^2)^2$ have been neglected in Eq. (5).

Before we move on to the discussion of the contributions from trilinear *R*-parity-violating couplings, we would like to emphasize that the deviation from universality provided

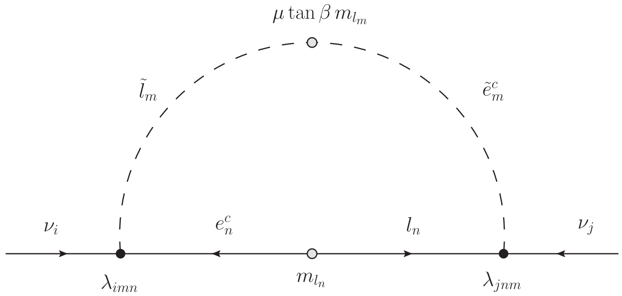

FIG. 3. One-loop neutrino masses from trilinear R-parity violation.

by the second term in Eq. (5) is phenomenologically required. As we will see below, this is the only term that breaks μ-τ invariance in the neutrino sector. Its absence would imply a vanishing reactor mixing angle and maximal atmospheric mixing; see, for instance, Ref. [66]. This would be in contradiction with recent data, which clearly indicates $\theta_{13} \neq 0$. Therefore, one can interpret the departure from universality in the soft terms, quite general in supersymmetric models, as the origin of the nonzero reactor angle in our model.[5]

B. Trilinear *R*-parity violation

As previously explained, the flavor symmetry implies that the only nonzero λ_{ijk} couplings are λ_{122}, λ_{133} and λ_{231}. Therefore, the usual one-loop diagrams in trilinear R-parity violation (see Fig. 3) can only fill the 11 and 23–32 entries of the neutrino mass matrix, leading to

$$m_\nu^{\text{TRpV}} = \begin{pmatrix} b & 0 & 0 \\ 0 & 0 & c \\ 0 & c & 0 \end{pmatrix}. \qquad (6)$$

Similarly, the λ' couplings can also contribute to neutrino masses, but only to the 11 element of the matrix, here denoted by b. We can now estimate the size of this family of one-loop contributions. For example, in the case of the c element in the previous matrix one has

$$(m_\nu^{\text{TRpV}})_{23} = c \sim \frac{1}{16\pi^2}\lambda_{231}^2 \mu \tan\beta \frac{m_e m_\tau}{m_{\text{SUSY}}}. \qquad (7)$$

The element b has a similar generic expression, although more couplings are involved (and for the λ' diagrams quark masses appear instead). Equation (7) shows that $\mathcal{O}(0.1\ \text{eV})$ contributions can be obtained for $\mu \sim m_{\text{SUSY}} = 100$ GeV and $\tan\beta = 10$ if $\lambda_{231} \sim 0.05$. This value is close to the experimental limit, but it can be easily lowered by using $\mu > m_{\text{SUSY}}$ or a larger $\tan\beta$. See Table III and Refs. [21,23] for more details.

Summing up the two contributions one obtains the texture

$$m_\nu = m_\nu^{\text{BRpV}} + m_\nu^{\text{TRpV}} = \begin{pmatrix} a+b & a & a+d \\ a & a & a+c+d \\ a+d & a+c+d & a+2d \end{pmatrix}. \qquad (8)$$

In the following section we will show how the mass matrix in Eq. (8) can accommodate the observed pattern of neutrino mixing. However, we already observe that the coefficient d, which can be traced back to the departure from universality in the soft SUSY-breaking terms, is the only source of μ-τ invariance breaking. In fact, in the limit $d = 0$, one recovers an exactly μ-τ-symmetric neutrino mass matrix that implies θ_{13} and a maximal atmospheric angle.[6] In conclusion, $d \neq 0$ is required. This will induce a nonzero reactor angle and a deviation from maximal atmospheric mixing. Since the same parameter is at the root of both deviations, we expect a tight correlation between θ_{13} and θ_{23}.

IV. NONZERO θ_{13} AND DEVIATIONS FROM MAXIMAL ATMOSPHERIC MIXING

The mass matrix in Eq. (8) has only four parameters. Therefore, since it must be able to accommodate the pattern of neutrino mixing measured in oscillation experiments, some connections between the parameters must appear. Although we cannot give definite predictions for the oscillation parameters, clear correlations between them exist. Similarly, the absolute scale of neutrino masses, determinant for neutrinoless double-beta decay experiments, is linked to the other parameters. This allows one to test the model with neutrino phenomenology.

In our analysis we assumed real parameters,[7] so the number of free parameters in the neutrino sector is four, namely, a, b, c, and d in Eq. (8), to explain six observables, namely, two squared mass differences Δm^2_{atm} and Δm^2_{sol}, the neutrinoless double-beta decay effective mass m_{ee}, and the three mixing angles. Therefore we have two predictions: the neutrinoless double-beta decay effective mass and a correlation between the reactor mixing angle and the atmospheric mixing angle.

[5]As already explained, the μ-τ invariance can also be broken *by hand* by introducing a small difference between the soft SUSY-breaking terms B_ϵ^2 and B_ϵ^3 (or, analogously, $m^2_{L_2 H_d}$ and $m^2_{L_3 H_d}$). Similarly, one can relax the conditions given by the Z_3 symmetry by allowing the existence of T_λ couplings whose corresponding superpotential terms are forbidden. For example, $T_{\lambda_{233}}$ would induce a high-order breaking of the μ-τ invariance of the neutrino mass matrix. However, we consider the breaking by the Yukawa couplings, transferred to the soft SUSY-breaking terms by renormalization group equations running, which is the simplest solution.

[6]We remind the reader that we are working in a basis where the charged lepton sector is diagonal.

[7]This assumption will be lifted below when the general CP-violating case is considered.

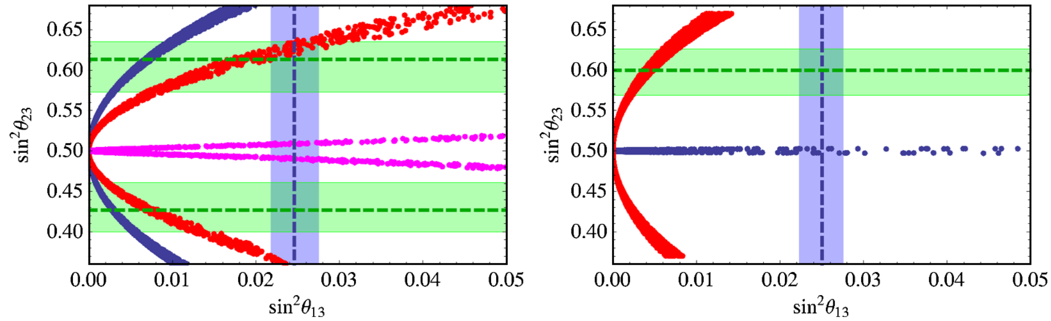

FIG. 4 (color online). $\sin^2\theta_{23}$ as a function of $\sin^2\theta_{13}$ for normal (left side) and inverted (right side) neutrino spectra. The numerical scan is based on the results of the global fit of Ref. [43]. The dashed lines represent the best-fit values for $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$, whereas the shaded regions correspond to 3σ (in the case of $\sin^2\theta_{13}$) and 1σ (in the case of $\sin^2\theta_{23}$) allowed regions. Different colors correspond to different *CP* branches: η_1 (blue), η_2 (red) and η_3 (purple).

We have performed a detailed scan over the parameter space fixing $\Delta m^2_{\rm atm}$, $\Delta m^2_{\rm sol}$, $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$ within the 3σ range given in Ref. [43]. Large deviations from the measured value of θ_{13} have been allowed in order to clearly see potential correlations between this parameter and the other mixing angles. Correct fits[8] have been found for both normal and inverted neutrino spectra without a particular preference. However, the results clearly favor a quasidegenerate spectrum with large neutrino masses.

The mass matrix in Eq. (8) would be μ-τ-symmetric in the absence of the d parameter, thus leading to $\sin^2\theta_{23} = 1/2$ and $\sin^2\theta_{13} = 0$ with a free θ_{12}. Interestingly, deviations from this scheme typically affect simultaneously θ_{13}, which departs from zero, and θ_{23}, which departs from maximality. This generic prediction, present in many flavor models (see, for instance, Ref. [67]), is especially relevant in our model, since it is caused by a single parameter, d, which leads to a tight correlation. Our numerical results confirm this expectation; see Fig. 4, where $\sin^2\theta_{23}$ is shown as a function of $\sin^2\theta_{13}$ for normal (left side) and inverted (right side) neutrino spectra. The atmospheric mixing angle is restricted to be within the 3σ allowed region found in Ref. [43], whereas the vertical shaded band represents the 3σ allowed region for $\sin^2\theta_{13}$, as given by the same analysis.

Figure 4 deserves some comments. In addition to the aforementioned correlation, one clearly observes distinct regions in the θ_{13}–θ_{23} plane. These regions, or *branches*, correspond to different cases of intrinsic *CP* charges of the neutrinos, η [68]. There are four possible cases: $\eta_1 = (-,+,+)$, $\eta_2 = (+,-,+)$, $\eta_3 = (+,+,-)$ and $\eta_4 = (+,+,+)$. Other choices can be reduced to one of these by means of an unphysical global sign. In Fig. 4, different colors are given for these *CP* cases: blue for η_1, red for η_2 and purple for η_3. No valid fits were found for the η_4 case.

[8] In the following, we will use the expressions "valid fit" or "correct fit" to denote a set of values for the parameters a, b, c and d that leads to $\Delta m^2_{\rm atm}$, $\Delta m^2_{\rm sol}$, $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$ within the 3σ range given in Ref. [43].

Similarly, for inverted hierarchy we could only find correct points for cases η_1 and η_2.

For normal hierarchy, the η_1 case leads to very large deviations in θ_{23}, which clearly departs from maximality, even for small values of θ_{13}. In fact, from our results in Fig. 4 one can conclude that the η_1 branch is ruled out by oscillation data since it cannot accommodate θ_{13} and θ_{23} simultaneously. In contrast, cases η_2 and η_3 can reproduce the measured mixing angles, although with different predictions. On the one hand, η_2 leads to big deviations in θ_{23}, which gives a region in excellent agreement with oscillation data. On the other hand, η_3 leads to small deviations, at most $\Delta\sin^2\theta_{23} \sim 0.2$, which is in agreement at 3σ. For inverted hierarchy the results are slightly different. First, it is now η_2 that is ruled out due to the large deviations induced in θ_{23}. And second, for η_1 one finds very small departures from maximal atmospheric mixing, at most $\Delta\sin^2\theta_{23} \sim 0.03$.

So far we have based our discussion on the results of the global fit of Ref. [43]. In their analysis, the authors of that work found two regions with similar ($\sim 1\sigma$) significance for the atmospheric mixing angle in the normal hierarchy case and one region, above $\sin^2\theta_{23} = 0.5$, in the inverse hierarchy case. A similar result is found in the analysis of

TABLE II. Comparison between the results of Refs. [43–45] regarding $\sin^2\theta_{23}$. In the case of Forero *et al.* [43] and Fogli *et al.* [44] the upper row corresponds to normal hierarchy and the lower row to inverse hierarchy. We show the two approximately equivalent best-fit regions found in the analysis by Forero *et al.* [43] and González-García *et al.* [45].

Analysis	Best-fit $\pm 1\sigma$	3σ range
Forero *et al.* [43]	$0.427^{+0.034}_{-0.027}$ $0.613^{+0.022}_{-0.04}$	0.36–0.68
	$0.600^{+0.026}_{-0.031}$	0.37–0.67
Fogli *et al.* [44]	$0.386^{+0.024}_{-0.021}$	0.331–0.637
	$0.392^{+0.039}_{-0.022}$	0.335–0.663
González-García *et al.* [45]	$0.41^{+0.037}_{-0.025}$ $0.59^{+0.021}_{-0.022}$	0.34–0.67

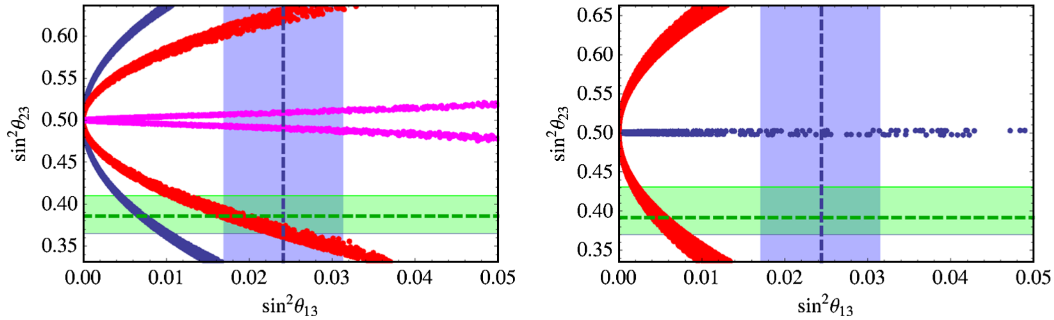

FIG. 5 (color online). $\sin^2\theta_{23}$ as a function of $\sin^2\theta_{13}$ for normal (left side) and inverted (right side) neutrino spectra. The numerical scan is based on the results of the global fit of Ref. [44]. The dashed lines represent the best-fit values for $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$, whereas the shaded regions correspond to 3σ (in the case of $\sin^2\theta_{13}$) and 1σ (in the case of $\sin^2\theta_{23}$) allowed regions. Different colors correspond to different CP branches: η_1 (blue), η_2 (red) and η_3 (purple).

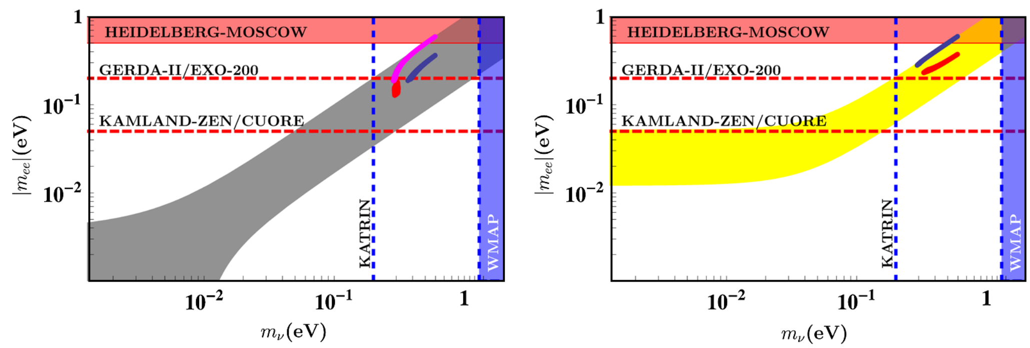

FIG. 6 (color online). Effective neutrinoless double-beta decay parameter m_{ee} as a function of the lightest neutrino mass for normal (left side) and inverted (right side) neutrino spectra. The grey and yellow shaded regions correspond to the *flavor-generic* normal and inverse (gray) hierarchy neutrino spectra, respectively. For a discussion see the text.

Ref. [45]. However, the analysis [44] finds a slight preference for $\theta_{23} < \pi/4$. The results of this analysis show a $\lesssim 2\sigma$ deviation from maximal mixing in the case of normal hierarchy, with a best-fit value of $\sin^2\theta_{23} = 0.386$, and a $\lesssim 3\sigma$ deviation in the case of inverse hierarchy, with a best-fit value of $\sin^2\theta_{23} = 0.392$. A brief compilation of these results is given in Table II.

Due to the impact that such a deviation from maximal atmospheric mixing would have on our model because of the correlation with the reactor angle, we have repeated our numerical scans using the input parameters given by Refs. [44,45]. The results for the case of Ref. [44] are shown in Fig. 5. Qualitatively, the results do not differ very much from those presented in Fig. 4. Again, there is a little preference for the η_2 case and a neutrino spectrum with normal hierarchy. We do not show the analogous figures for Ref. [45], since they lead to very similar conclusions.

We have also investigated the predictions that our model can make regarding neutrinoless double-beta decay ($0\nu 2\beta$). The results are shown in Fig. 6, where the effective neutrinoless double-beta decay parameter m_{ee} is given as a function of the lightest neutrino mass. We present the results for normal hierarchy on the left side and the results for inverse hierarchy on the right side. The shaded bands (in grey and yellow) correspond to the well-known *flavor-generic* predictions, which are much more spread than the predictions given by our model. In fact, one can easily see that our model is restricted to lie on a very small portion of the plane. This is due to the fact that only solutions with quasidegenerate spectra were found in our scan.

Again, different CP-intrinsic charges for the neutrinos lead to different regions in Fig. 6. The color code is as in Fig. 4. Future experimental sensitivities are also included in this figure, as well as the region excluded by the Heidelberg-Moscow collaboration [69]. Since our model favors quasidegenerate spectra, most of the points have large values for the lightest neutrino mass and the effective m_{ee} $0\nu 2\beta$ parameter. This implies that they are at the reach of experiments such as KATRIN [70], GERDA-II [71] and EXO-200 [72].[9] Only η_2 in the case of normal hierarchy

[9]Recently, the EXO-200 collaboration made public new results [73], not included in Fig. 6, which allow one to set a lower limit on the $0\nu 2\beta$ half-time in ^{136}Xe of about $T_{1/2} > 1.6 \times 10^{25}$ yr (90% CL). This corresponds to $m_{ee} < 140$–380 meV, the broad range being caused by the theoretical uncertainty in the nuclear matrix element calculation. Similarly, the KamLAND-Zen collaboration also reported new limits [74], although slightly less stringent.

predicts low values for m_{ee}, out of reach for GERDA-II and EXO-200, but still with sufficiently large neutrino masses so that KATRIN is able to measure them. In conclusion, both $0\nu 2\beta$ and absolute neutrino mass experiments offer good perspectives to probe our model.

Finally, let us briefly discuss the general *CP*-violating case, where all four parameters in the neutrino mass matrix are allowed to be complex. We have generalized our numerical scan to include all *CP* phases: the Dirac phase, δ, and Majorana phases, α and β. The main result is that the regions between branches in Figs. 4 and 5 are filled with points where at least one of the (physical) *CP* phases do not vanish. Therefore, the conclusions drawn in the previous paragraphs should be regarded as valid only in the *CP*-conserving case. For example, our model would not be ruled out if the θ_{13} and θ_{23} angles are precisely measured to lie outside the $\eta_{1,2,3}$ branches. That would point towards a *CP*-violating scenario, which would be something to be probed by experiments such as T2K [75] and NOνA [76] (see Ref. [77]).

V. SOME COMMENTS ON COLLIDER PHENOMENOLOGY

Since *R*-parity is broken the LSP is no longer stable, and it decays.[10] The decays can go via bilinear (ϵ, B_ϵ^i and $m^2_{L_i H_d}$) or trilinear (λ_{122}, λ_{133}, λ_{231} or λ'_{jk}) $\not{R}_p$ couplings. In the bilinear case, only ϵ can mediate the decay at tree level, and thus its small size reduces the relevance of this possibility. We are thus left with decays mediated by trilinear couplings, and we conclude that gauge-mediated LSP decays are suppressed.

By studying the size of the different λ and λ' couplings one could go further and find the dominant LSP decay signatures that particular scenarios would predict. For example, a simple estimate based on the one-loop-generated masses that come from λ_{231} shows that this coupling must be of order 0.05. On the other hand, the other two λ parameters (λ_{122} and λ_{133}) are strongly constrained by flavor physics [21], and thus they are less relevant for the LSP decay. However, the relative importance of λ_{231} and the λ'_{jk} couplings cannot be determined. Table III shows the relevant experimental bounds for our model, as obtained in Refs. [21,23]. However, we cannot know *a priori* the relative importance of the different couplings, and general predictions concerning the LSP decay cannot be made (apart from the aforementioned trilinear dominance).

Nevertheless, we emphasize that independent tests of the model and its underlying flavor structure should be performed. In addition to the aforementioned correlations among neutrino mixing angles, unfortunately present in many flavor models, collider tests are fundamental in order to disentangle the dynamics behind the observed flavor pattern in neutrino mixing. Reference [81] addresses this issue by studying how one may discriminate between different $\not{R}_p$ flavor operators leading to the decays of a neutralino LSP at the LHC. Similar works exist in the case of b-$\not{R}_p$ [28–31,33,35], where one can find a strong correlation between LSP decays and neutrino mixing angles. Finally, it is also possible to distinguish between bilinear and trilinear violation of *R*-parity if the LSP is a slepton. In that case, its decay properties can be used to determine the relative importance of the $\not{R}_p$ couplings, as shown in Ref. [32].

TABLE III. Experimental bounds for trilinear *R*-parity-violating couplings. These limits were obtained by setting all SUSY masses to 100 GeV. For the λ' couplings the extreme cases are shown, with the most and least constrained couplings for each case. For more details see Refs. [21,23].

Coupling	Bound	The bound comes from
λ_{122}	2.7×10^{-2}	Neutrino masses [21]
λ_{133}	1.6×10^{-3}	Neutrino masses [21]
λ_{231}	0.05	Leptonic τ decay [23]
λ'_{jk} $(j \neq k)$	0.02–0.47	Several processes [21]
λ'_{jk} $(j = k)$	3.3×10^{-4}–0.02	$\beta\beta 0\nu$ and m_ν [21]

VI. CONCLUSIONS

We studied a simple extension of the MSSM assuming an Abelian Z_3 flavor symmetry. Neutrino masses arise at one-loop from bilinear and trilinear *R*-parity-breaking operators. If the soft SUSY-breaking terms were flavor-blind, one would obtain a μ-τ-invariant neutrino mass structure, thus implying a vanishing reactor angle. However, this is cured by renormalization group running effects, which are naturally present in supersymmetric theories. We have shown how this model can accommodate a neutrino mixing pattern in accordance with data. In particular, we have studied the correlations between mixing angles that allow us to link different deviations from tribimaximal mixing. The model also predicts large values for the lightest neutrino mass and the effective m_{ee} $0\nu 2\beta$ parameter, both of which are at the reach of current and future experiments. Finally, since the LSP decays one in principle has a rich phenomenology at the LHC. Due to the structure of the model, we predict a clear dominance of the trilinear couplings in the LSP decay.

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[10]This implies that the usual neutralino LSP is lost as a dark matter candidate. However, it is well-known that a relatively light gravitino provides a valid alternative; see, for example, the recent references [78–80].

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