The neutrino mass and other possible signals of lepton-number violation in supersymmetric theories

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We review a recently proposed framework in which the neutrino mass is a signal of supersymmetry breaking and is suppressed dynamically. In addition, we briefly comment on some possible consequences of general lepton-number violation in supersymmetric theories, e.g., dijet and multijet signals and $jj \rightarrow ll\gamma\gamma$.

1. Lepton number violation in supersymmetric models is only mildly constrained (see, e.g., Bhattacharyya’s contribution), allowing for the generation of a tree-level neutrino mass at the weak scale (see Section 2), and leading to non trivial signatures of supersymmetry (see Section 3). We discuss a few examples, stressing model-building and phenomenological aspects.

2. It has been pointed out by Hall and Suzuki [1] that by explicitly introducing a $\Delta L = 1$ (where $L$ is the lepton number) mass term in the superpotential, i.e.,

$$W = \mu H_1 H_2 + \mu_L LH_2 + \text{Yukawa terms},$$  (1)

one mixes the neutrinos and neutralinos, leading to a tree-level mass for one neutrino species. (Here $L$ is a lepton doublet and $H_{1,2}$ are the hypercharge $Y = \mp 1$ Higgs doublets.) The Higgs-lepton mixing is sufficient to generate a expectation value for the scalar neutrino (sneutrino) once electroweak symmetry is broken, leading to additional gaugino-neutrino mixing. The two sources for the mixing, the $\mu$ parameter and the expectation value, are, in fact, four-vectors in field space. They explicitly and spontaneously break the $SU(4)$ symmetry of $[H_1, L_{\tau, \mu, e}]$ rotations (in field space) down to a residual $SU(2)$. Thus, two

(neutrino) states remain massless at tree-level. (However, Yukawa and Yukawa-gauge loops explicitly break the residual $SU(2)$, and all states are massive at the loop level.)

Here, we outline a realization of that idea within a framework of a spontaneously broken $U(1)_R$ symmetry, and, in which the neutrino mass is suppressed dynamically. A detailed discussion, additional examples, and a comprehensive reference list, can be found in Ref. [2].

2.1. The $U(1)_R$ framework: A spontaneously broken $U(1)_R$ is often present in models of dynamical supersymmetry breaking, and thus, it is a natural candidate to set the selection rules for nonrenormalizable operators in the low-energy superpotential. We will further assume that supersymmetry, as well as the $U(1)_R$, are broken in the hidden sector (e.g., in gaugino condensation models) at a scale $\Lambda = O(10^{11})$ GeV. The $R$-axion in this case could be, for example, invisible, or heavy due to a possible anomaly with respect to the hidden QCD group.

Operators in the effective theory are suppressed by inverse powers of the Planck mass, $M_P$. The possible “non-singlet” operators are the $\mu$ parameters with $R(\mu_H) = 2$ and $R(\mu_L) = 1$, and the lepton and baryon number violating Yukawa couplings with $R(h_{\text{LNV}}, h_{\text{BNV}}) = -1$. (We define $R = 3B + L$ for the chiral superfields, and adopt the normalization $R(W) = 2$. $B$ and $L$ are baryon and lepton number, respectively, and $R = L$ for

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The superpotential (1) contains only non-baryonic chiral superfields.) Dimensional arguments suggest that the latter are given by, e.g., $h^{LNV} \sim |\mu_L/M_P| \to 0$. For example, consider a hidden superfield $Z = (z, \tilde{z}, F_Z)$ and $R(Z) = 1$. Then, $\mu_H = (z)^2/M_P$ and $\mu_L = F_Z^2/M_P$ are of the same order of magnitude $\sim \Lambda^2/M_P$, and the holomorphicity of the superpotential implies that $h^{L(D)NV}$ are suppressed, as promoted above.

The models\(^3\) contain a very restricted form of lepton number violation, i.e., only in the supersymmetric mass terms. Since $U(1)_R$ and the field-rotation $SU(4)$ do not commute, it cannot be simply rotated (at high energies) from the mass to the Yukawa operators. Thus, there is a distinction between the high and low-energy lepton number definitions. The former is defined by the superpotential (e.g., by the term $h_D H_1 Q D$). The latter is defined, after weak-scale rotations, e.g., by requiring $\langle L_i \rangle = 0$ (the caret denotes rotated fields). Note that once (low-energy) rotations are performed (i) baryon number violation is still absent and (ii) the lepton number violating Yukawa couplings are proportional to the ordinary Yukawa couplings. Therefore, the lepton number conserving and violating Yukawa couplings are diagonalized simultaneously, suppressing new contributions to FCNC’s. Furthermore, the $h^{LNV}$ are naturally small (and, in general, satisfy all constraints). The superpotential (1) and the corresponding $U(1)_R$ framework outlined above are quite striking. The only new supersymmetric mass is that of the neutrino superfield, and it is generated naturally. In general, supersymmetric mass parameters (which are not $O(M_P)$) represent a small perturbation at high energy and parameterize the high-energy physics. The neutrino mass, which results here from such a parameter, is also a signal of that physics and, in particular, of supersymmetry breaking.

2.2 Dynamical suppression on the neutrino mass: The neutrino mass is constrained (from energy density) $m_\nu \leq O(100)$ eV $\sim 10^{-9} M_Z$ (while we expect $\mu = O(M_Z)$). Yet, there is no need to encode the $O(10^{-9})$ suppression factor in the superpotential, i.e., in the ratio $\mu_L/\mu_H$. The tree-level neutrino mass vanishes if the $\mu$ and expectation value four-vectors are aligned in field space (see also Ref. \(^3\)). In this case, the $SU(4)$ is broken down to only $SU(3)$, leaving all three neutrinos massless. The alignment also enables one to consistently define the Standard-Model (SM) lepton number (since $\mu_L$ and $\langle L \rangle$ would be rotated away simultaneously).

The merit of the above mechanism is that one need not impose the alignment. It can be achieved dynamically. Let us assume (a) universal soft scalar masses $m_0^2 \phi_i \phi_j^* \delta_{ij}$ at the grand scale (in fact, we need to require universality only of lepton and Higgs masses\(^4\)) and (b) the proportionality of the soft scalar mass terms $m_0^2 \phi_i \phi_j + h.c.$ to the respective $\mu$ parameters (i.e., "$B$ proportionality"). It is a straightforward exercise to renormalize the model and solve the minimization equations. However, the resulting alignment can also be understood intuitively. Given our boundary conditions, the $\mu$-vector is the only direction in field space up to perturbations proportional to $h_D^2/8\pi^2$ (from scaling). Thus, the expectation value must align in this direction. The small perturbations, however, create a tiny misalignment that permits a small neutrino mass.

The alignment (i.e., the (output) expectation value ratio $\langle L \rangle/\langle H_1 \rangle \equiv \nu_L/\nu_H$ vs. the (input) $\mu_L/\mu_H$ ratio) in the models is shown in Fig. 1 for large $\tan \beta \equiv \langle H_2 \rangle/\langle H_1 \rangle = 5, 15, 30$. (For simplicity, we considered the one generation case.) It is excellent for small $\tan \beta$ and can have different values for large $\tan \beta$. (The dependence of $m_\nu$ on $\tan \beta$ is not trivial and is explored in Ref. \(^5\).) We find that, typically, 10 eV $\leq m_\nu \leq 10$ MeV. The neutrino mass is sufficiently suppressed due to the smallness of the radiative corrections (to the universal boundary conditions). The corrections only slightly perturb the dynamical alignment, lifting the degeneracy by a small amount, and allowing for a neutrino mass of the correct

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\(^3\) The superpotential (1) contains only $L$ and $B$ conserving "Yukawa terms" $-\lambda U H_2 Q + h_D H_1 Q D + h_E H_1 L E$ (where $U$, $D$, and $E$ are the quark and lepton singlets, respectively, $Q$ are the quark doublets, and we suppress family indices).

\(^4\) Note that this condition is difficult to satisfy in unified models \(^4\).

\(^5\) A similar mechanism could operate in low-energy supersymmetry breaking models (if $B$-proportionality holds – see Pomarol’s contribution).
3. In the remainder of this contribution we would like to comment on some possible signatures of supersymmetric models with (low-energy) $h^{\text{LNV}} \neq 0$ (i.e., models with the $LQD$ and/or $LLE$ operators). (Section 2 represents a special case.) Typical signals, e.g., like-sign dileptons, are well studied (see, e.g., V. Barger in these proceedings). Here, we will comment on two (unusual) examples: The lightest supersymmetric particle (LSP) is the photino and it decays radiatively, or it is the sneutrino and it decays to $2j$. (Note that quite generally the LSP is not a dark matter candidate once lepton number is violated.) Our purpose is to stress the wealth of new phenomena once lepton number is not conserved, and to motivate further investigation.

3.1 Radiative decay of the photino: The photino LSP decays $\tilde{\gamma} \rightarrow f \bar{f} \rightarrow 2j + l$ (where the tilde denotes superpartner, $j$ is a hadronic jet, and we assumed dominance of the $LQD$ operator) at tree level and $\tilde{\gamma} \rightarrow \gamma \nu$ radiatively. The former is expected to dominate unless it is forbidden kinematically (i.e., $M_{\tilde{\gamma}} < 2m_\nu$ if the $LQD$ operator is dominant) or the photino is extremely light. The tree level decay is, however, absent if the source of lepton number violation is mainly the sneutrino expectation value $\tilde{\nu}$. There could also be a situation in which the leading tree-level signal is hidden in the SM backgrounds while the radiative decay produces a spectacular signature. Of particular interest is the case $jj \rightarrow l^+l^- \rightarrow l^+l^-\gamma2\nu$. (The tree level multijet signal is $l^+l^-2\nu_{1j}$, where $2\nu_{1j}$ is a like-sign dilepton or neutrino $E_T$.) Such a scenario may be able to provide a valid interpretation to the $e^+e^-2\gamma+E_T$ event observed by CDF (see contributions by Thomas and by Kane).

3.2 The sneutrino decay to $2j$: If the sneutrino is the LSP, it would be singly produced by either leptons or jets, and decay (assuming dominance of the $LQD$ operator) to $2j$. The general enhancement of the dijet signal is discussed in [2]. It is $O(10\%)$ of the QCD signal (at the threshold) [6]. However, most probably the charged $SU(2)$ partner of the sneutrino (and possibly other scalars) would decay similarly, leading to a larger (and smeared) enhancement of the dijet signal. Cascade decays lead, in this scenario, to multijet signals.

4. In conclusion, the supersymmetric extension may not conserve lepton number. In particular, if the neutrino mass is (naturally) generated at low-energies (e.g., from supersymmetric mass parameters). The wealth of possible signals of supersymmetry, in this case, requires further investigation.

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