PHENOMENOLOGICAL ASPECTS OF NONSTANDARD SUPERSYMMETRY BREAKING TERMS.

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In realistic supersymmetric models, very small hard supersymmetry breaking terms generally appear. Some of them violate baryon and/or lepton number. We discuss their possible applications to proton decay and generation of neutrino masses.

1 Introduction.

The aim of the present talk which is based on the recent paper ¹ is to discuss possible observable effect of hard supersymmetry breaking terms which are too small to destroy attractive features of supersymmetry but reveal themselves in rare processes, in particular, those with violation of baryon and lepton number.

In realistic models of broken supersymmetry, two scales usually appear. One is the scale of SUSY breaking in the hidden sector which is parameterized by the vacuum expectation value (vev) $F$ of the auxiliary component of some hidden sector field, another is the scale $M$ at which SUSY breaking is transferred to the visible sector.

In the gravity mediated scenario, $M \sim 10^{18}$ GeV. Various supersymmetry breaking terms appear in the low energy lagrangian after integrating out the hidden sector. Soft supersymmetry breaking terms of MSSM (masses of scalar fields and trilinear scalar couplings) are of order $F/M$, and thus $F/M \sim 1$ TeV to explain gauge hierarchy by radiative electroweak symmetry breaking. However, this is not the whole story and other renormalizable gauge invariant terms could be generated in the low energy lagrangian. The case of dimension $m^1$ terms (e.g., non-holomorphic trilinears) is well-known. They could be “hard” if global singlets are present (these terms were listed in the original work on MSSM, ref. ², and were also discussed in ³). As was emphasized recently in ref. ⁴, dimensionless couplings may be generated too. These are hard supersymmetry breaking terms, and such couplings do induce quadratic divergencies in scalar masses. This is not dangerous, however, because all these terms are suppressed by $F/M^2 \sim 10^{-15}$ or even by $F^2/M^4$ (would-be-hard dimensionful terms are suppressed by $F^2/M^3$). Quadratic divergencies do not destroy the hierarchy because corrections to mass scales are highly suppressed and the effective Lagrangian approach can only be seen with an implicit cutoff. Phenomenological relevance of such tiny couplings is doubtful, and they are usually ignored. In ref. ⁴, these terms were exploited to stabilize (otherwise) flat directions. Here, we note that such terms are relevant for observable effects – neutrino masses and rare processes. Characteristic dimensionful scale of these terms is of order

$$F^2/M^3 \sim 10^{-3} \text{eV}. \quad (1)$$

This scale determines, for example, Majorana neutrino masses and proton width.
We consider the Minimal Supersymmetric Standard Model (MSSM) with usual matter content, that is not necessary including right handed neutrinos. We use standard notations for MSSM scalar fields: $H_U$ and $H_D$ are Higgs fields, $\tilde{L}$ is the left-handed slepton doublet, $\tilde{E}$ is the superpartner of $e^+_L$ (or $e^-_R$), $\tilde{Q}$ is the squark doublet, and $\tilde{U}$ and $\tilde{D}$ are up and down antisquark singlets. We allow for the presence of all renormalizable $SU(3) \times SU(2) \times U(1)$ gauge invariant terms which are (at least naively) suppressed by $F^2/M^3$ or $F/M^2$, or weaker (naive suppression factors can be read out from ref.4). These terms include scalar couplings (quartics and non-holomorphic trilinears) listed in the following table:

| term                          | breaks R parity | breaks lepton number | breaks baryon number |
|-------------------------------|-----------------|----------------------|----------------------|
| $H_U^* \tilde{Q} \tilde{U}$  | no              | no                   | no                   |
| $H_U^* \tilde{Q} \tilde{D}$  | no              | no                   | no                   |
| $H_U^* \tilde{L} \tilde{E}$  | no              | no                   | no                   |
| $(H_U^* H_D)^2$              | no              | no                   | no                   |
| $\tilde{E} \tilde{L} \tilde{Q} \tilde{U}$ | no     | no                   | no                   |
| $(\tilde{L} H_U)^2$          | no              | yes                  | no                   |
| $\tilde{Q} \tilde{Q} \tilde{Q} \tilde{L}$ | no       | yes                  | yes                  |
| $\tilde{U} \tilde{U} \tilde{D} \tilde{E}$ | no     | yes                  | yes                  |
| $E^* H_U H_D$                 | yes             | yes                  | no                   |
| $H_U^* \tilde{E} H_D$         | yes             | yes                  | no                   |
| $D^* \tilde{E} \tilde{U}$     | yes             | yes                  | no                   |
| $H_U H_D H_U \tilde{L}$       | yes             | yes                  | no                   |
| $\tilde{Q} \tilde{Q} \tilde{H} D$ | yes   | no                   | yes                  |
| $L^* \tilde{Q} \tilde{U}$    | yes             | yes                  | yes                  |
| $\tilde{E} H_D \tilde{Q} \tilde{U}$ | yes | yes                  | yes                  |

In what follows, we require $R$ parity conservation since once $R$ parity is imposed, only highly suppressed dimensionless couplings can violate lepton or baryon number. Thus, of particular interest are three couplings, $(\tilde{L} H_U)^2$, $(\tilde{Q} \tilde{Q} \tilde{L})$ and $(\tilde{U} \tilde{U} \tilde{D} \tilde{E})$.

2 Majorana neutrino masses.

Since a Majorana neutrino mass is not invariant under $SU(2) \times U(1)$, it can be generated only with broken electroweak symmetry, and thus this term cannot appear at the scale $M$. However, if highly suppressed couplings violate lepton number, Majorana masses could be generated radiatively at the electroweak symmetry breaking scale (at the possible cost of some extra suppression). While the value of neutrino mass is currently unknown ($m_{\nu_e} < \text{a few eV}$), mass differences as low as $\delta m^2 = 10^{-10} \text{ eV}^2$ are expected for the vacuum oscillation solution of the solar neutrino problem.

The $(\tilde{L} H_U)^2$ term can be used to generate Majorana mass. It can be generated in the low energy lagrangian after integrating out the supersymmetry breaking sector, for example, from the operator $\frac{1}{M^2} (XLH_U L H_U) \mid_F$, where $\mid_F$ denotes an $F$-term. When the auxiliary component of the $X$ superfield develops a vev $(X) \mid_F \sim F$, this generates the desired coupling, see ref.4.

So, consider the effect of the $SU(2)$ invariant term

$$ h (\tilde{L}_i H_{ij} \epsilon_{ij})^2, $$

where $h$ is the coupling constant of order $F/M^2$ and $\epsilon_{ij}$ is the usual antisymmetric tensor, $i$ and $j$ are $SU(2)$ indices. Slepton doublets $\tilde{L}$ have the same gauge quantum numbers as $H_D$, so this coupling is easily seen to be gauge invariant. It is also $R$-even, but breaks lepton number (by a small amount).
The important observation for us is that, when associated to electroweak symmetry breaking and non-zero gaugino masses (from soft supersymmetry breaking), this new term is responsible for the appearance of Majorana masses for neutrinos. The diagram of Fig. 1 can be readily evaluated to yield

$$\frac{h}{32\pi^2} \frac{g^2 \langle H_U \rangle^2}{m_\tilde{Z} m_\tilde{\nu}} f\left(\frac{m_\tilde{Z}^2}{m_\tilde{\nu}^2}\right),$$

where $h$ is the small coupling constant defined in (2), $m_\tilde{Z}$ and $m_\tilde{\nu}$ are masses of zino and sneutrino, respectively, $g$ is the $SU(2)$ coupling constant, $\theta_w$ is the electroweak angle, and

$$f(x) = \frac{\sqrt{x(x - 1 - \log x)}}{(x - 1)^2},$$

$0.6 > f(x) > 0.2$ for $0.01 < x < 100$. The diagram was evaluated in the case of diagonal $\tilde{Z}$. We expect this evaluation to be representative even in the case where $\tilde{Z}$ mixes with the other neutralinos (normally decoupled from neutrino). As Higgs vev and sneutrino mass are both of order $F/M$, eq. (3) indeed gives neutrino masses as estimated in eq. (1). As expected, the loop integration implies an extra suppression, here by a factor $16\pi^2$ included in (3), which somewhat reduces the result.

The actual value of the mass depends crucially on the unknown hard coupling $h$ which cannot be determined unless a specific calculable mechanism of supersymmetry breaking is chosen.

It must be stressed that this contribution appears only as the result of electroweak symmetry breaking; Majorana mass for the electron is not gauge invariant and is not generated.

We must now study possible divergent contributions to neutrino masses. They could appear in higher orders in perturbation theory and require explicit counterterms for Majorana neutrino masses. This would signal that the physical masses are sensitive to unknown dynamics at high energies, so bare mass terms should be regarded as free parameters of the theory instead of predictions (a similar problem occurs for MSSM gauginos, see Ref. 5). This is fortunately not the case for neutrino masses generated in the way discussed above.

Indeed, we now show that all diagrams contributing to Majorana mass have negative superficial degree of divergence. As already noted, $SU(2)$ breaking is required and thus the contribution must be proportional to $v$. Because the Majorana mass term has weak hypercharge 2, and the corresponding diagram has to be gauge invariant before breaking, at least one extra factor of $v$ is required. (In practice, we also need to reverse the fermionic flow, which involves either a gaugino mass or some other dimensionful chirality breaking).

Possible subdivergencies are removed by renormalization of other parameters of the lagrangian. Note that the (innocuous, as this merely modify the new coupling $h$) renormalization of $h$ implied by Fig. 2 only appears if an explicit Dirac mass term for the neutrino exists (which requires also $\nu_R$ to be included from the start).

For massless neutrinos, the terms considered here could thus account for (very small) masses of neutrinos, reminiscent of the vacuum oscillation solution of the solar neutrino problem. If other contributions to the neutrino mass exist, these terms could generate a splitting, $\delta m_i \lesssim 10^{-5}$ eV, the resulting $\delta m_i^2$ becomes of order $m_i \delta m_i$. For a “common” neutrino mass around 1 eV (a welcome
contribution to the dark mass of the Universe) this effect could contribute also to other cases of oscillation.

To summarize, the mechanism which generates the hierarchy \( \frac{M_{EW}}{M_{Pl}} \) can as well generate the hierarchy \( \frac{m_\nu}{M_{EW}} \sim \frac{M_{EW}}{M_{Pl}} \). We present here an explicit realization of this phenomena in the Minimal Supersymmetric Standard Model without additional fields (even right handed neutrinos) or mass scales. Of course, the idea to relate the two hierarchies can work in different frameworks. For instance, neutrino masses of order \( M_{EW} \cdot \frac{M_{EW}}{M_{Pl}} \) can be generated by extra dimensions with localized gravity, see estimate of Ref. 6. This is however completely different from the present approach, which relies on supersymmetry breaking and gaugino masses.

Our approach results in reasonable neutrino mass values which are evocative of the vacuum oscillations explanation of solar neutrino anomaly. It is worth pointing out that the interaction (3) is flavour-dependent, so the coupling \( h \) is in fact a matrix \( h_{ij} \) in the flavour space. The hierarchy of neutrino masses and mixings in our scenario is completely defined by this matrix and by the sneutrino masses, and is thus not directly related to the mass hierarchy of charged leptons (cf. ref. 7).

3 Baryon number violation and other effects.

We now consider baryon number violation and other dimensionless supersymmetry breaking terms. Among such couplings are two \( R \)-even terms which violate baryon number, namely, \((\tilde{Q}\tilde{Q}\tilde{Q}\tilde{L})\) and \((\tilde{U}\tilde{U}\tilde{D}\tilde{E})\) (\( SU(3) \) indices are contracted antisymmetrically in both terms). Such terms can of course be excluded from the onset by requiring baryon number conservation. It is however interesting to evaluate their physical impact. These terms contribute to proton decay through the diagram Fig. 3(a). This should be compared to the usual SUSY GUT contribution from dimension 5 operators induced by triplet higgsino (the coloured part of the \( SU(5) \) 5-plet Higgs superpartner) exchange, Fig. 3(b). The contribution from hard terms, Fig. 3(a), is suppressed by \( \frac{E}{M^2} \frac{1}{m_\lambda} \), which is numerically of the same order as the GUT contribution, Fig. 3(b), which is estimated as \( 1/m_{\psi_{H_3}} \sim (10^{17} \, \text{GeV})^{-1} \). Note,
however, that proton decay takes place here via hard supersymmetry breaking terms already in the MSSM, i.e. without Grand Unification.

In a different context, the effect of nonstandard supersymmetry breaking terms may also be substantial in models where supersymmetry breaking is transmitted to the visible sector at lower energies. There, $F/M$ is of order 100 TeV with $M$ much lower than the Planck scale. This could lead to larger effects in neutrino masses and rare processes, thus imposing very strong lower bounds on $M$.

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