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The Discovery of Supersymmetry

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Abstract. Recent LHC searches have provided strong evidence for the Higgs, a boson whose gauge quantum numbers coincide with those of a SM fermion, the neutrino. This raises the question of whether Higgs and neutrino can be related by supersymmetry. I will show explicitly the implications of models where the Higgs is the sneutrino: from a theoretical point of view an R-symmetry, acting as lepton number, is necessary; on the experimental side, squarks exhibit novel decays into quarks and leptons, allowing to differentiate these scenarios from the ordinary MSSM.

1 Motivation

On the 4th of July 2012, CERN announced the discovery of a new particle [1]. Its couplings, it has often been said, resemble those of *the* SM Higgs boson. Indeed, the fact that its couplings to the $W^\pm$ (to the Z) electroweak gauge bosons is within 30% of $2m_W^2/v$ (of (m_Z^2/v)) [2–8], tells us that this scalar must be part of a doublet of $SU(2)_L$, with hypercharge 1/2 and that its vacuum expectation value (vev) is responsible for the $W^\pm, Z$ masses.

It strikes that the quantum numbers of these scalars are the same as the ones of the known leptons. So, the first question one is brought to ask is whether there can be an underlying symmetry connecting

$$\begin{pmatrix} h^0 \\ h^- \end{pmatrix} \leftrightarrow \begin{pmatrix} \nu^0 \\ l^- \end{pmatrix}. \qquad (1)$$

It is well known that the only such a symmetry, capable of relating bosons with fermions, is supersymmetry (SUSY). This observation brings a glimpse of hope in a moment in which all the supersymmetric particles, predicted in the minimal supersymmetric models (MSSM), are being pushed to higher and higher scales by the stringent LHC limits. Indeed, if the relation Eq. (1) were really due to a symmetry, then the implications would be fantastic: the first supersymmetric particle, has already been discovered!

In this note I explore this possibility further, to outline the low-energy behaviour of SUSY models that explain Eq. (1). This note is based mainly on Ref. [9], but similar ideas have been developed in [10–15].

2 One, Two or No Higgs doublet?

In the SM, the Higgs doublet H couples to down-type quarks through the Yukawa structure $\bar{Q}_L H d_R$ (and similarly for leptons). Up-type quarks, couple to the same Higgs. However, due to their different charge, they get masses through

$$\bar{Q}_L H^\dagger u_R. \qquad (2)$$

Supersymmetric theories need more structure than just a SUSY version of the SM model. First of all, a SUSY version of the SM with only one Higgs doublet is inconsistent, as a single higgsino induces non-vanishing anomalies that break the SM gauge group; an even number of Higgs-doublets is necessary. Furthermore, the couplings of Eq. (2) involving $H^\dagger$ are incompatible with unbroken SUSY. So, theories in which the Higgs is the partner of a lepton doublet are consistent from the point of view of anomalies (since there are no higgsinos), and they can successfully account for down-type quark masses through

$$\bar{Q}_L \tilde{L}\, d_R\ , \qquad (3)$$

but they need large supersymmetry breaking contributions in order to account for up-type masses.

Traditionally, this was considered unsatisfactory, as can be read in many books about early supersymmetric model-building " *An obvious possibility is to identify the Higgs $SU(2)$ doublet as the partner of a lepton doublet. However, this is not possible...*" [16]. Nevertheless, our point of view on SUSY has changed dramatically with the Higgs discovery at $m_H^2 = (125\,\text{GeV})^2$. Indeed, in unbroken SUSY, the Higgs mass is at most the mass of the Z boson $(m_H^{SUSY})^2 < m_Z^2 = 91^2\,\text{GeV}^2$, so that the remaining $\delta m_H^2 \approx (86\,\text{GeV})^2$ necessarily originate as SUSY breaking effects. This means that, if SUSY exists, it must be badly broken, at least in the Higgs sector. It is then not a big leap to imagine that the up-type quark Yukawas also originate from SUSY breaking effects, as necessary in theories where the Higgs is the SUSY partner of the lepton.

Interestingly and surprisingly, even in the presence of such large SUSY breaking effects, the Higgs mass-squared parameter is still protected from quadratic divergences. Indeed, although the up-type quark Yukawa breaks SUSY,

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quarks and squarks still run in the loop and their couplings to h are still identical due to the underlying supersymmetry [9].

3 *R*-parity or *R*-symmetry?

A further problem of realizing the symmetry Eq. (1) is lepton number. In the MSSM with R-parity, for example, lepton-number commutes with supersymmetry, so that sleptons carry lepton number and are odd under R parity. In such a framework, if the Higgs coincides with a slepton, its vev would break both lepton number and R- parity, leading to unacceptably large neutrino masses and huge proton-decay rates[1].

For these reasons, models where the Higgs is the partner of a lepton, must incorporate an R-symmetry (which by definition doesn't commute with SUSY) and this R-symmetry must coincide with a lepton number in the fermionic sector. Generic charge assignments are summarized in Table 1, where the Higgs doublet H can be the SUSY partner of any lepton doublet $L_3 \equiv L_e, L_\mu, L_\tau$.

	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_R$
Q	$(3,2)_{\frac{1}{6}}$	$1+B$
U	$(\bar{3},1)_{-\frac{2}{3}}$	$1-B$
D	$(\bar{3},1)_{\frac{1}{3}}$	$1-B$
$L_{1,2}$	$(1,2)_{-\frac{1}{2}}$	$1-L$
$E_{1,2}$	$(1,1)_1$	$1+L$
$H \equiv L_3$	$(1,2)_{-\frac{1}{2}}$	0
E_3	$(1,1)_1$	2
W_a^α	$(8,1)_0 + (1,3)_0 + (1,1)_0$	1
Φ_a	$(8,1)_0 + (1,3)_0 + (1,1)_0$	0

Table 1. *Superfield content and charge assignments under the SM gauge group and the $U(1)_R$ symmetry. The value of the R-charge (q_R) corresponds to the charge of the superfield and the scalar component, while the fermion component has charge $q_R - 1$. B and L are arbitrary charge assignments.*

The implications of this R-symmetry are diverse and have the biggest impact on the phenomenology of these models. First of all, Majorana masses for the gauginos, which are compatible with R-parity, are now forbidden: gauginos must obtain Dirac-type masses by pairing with other fermions (these additional superfields are denoted Φ_a in Table 1). Dirac-gauginos have the advantage of contributing via loop-effects only finitely to the Higgs mass-squared parameter, thus alleviating the hierarchy problem even if their mass is in the TeV range [17]. This is of particular importance for the naturalness of these models, since experimental constraints force their gaugino masses above about 2 TeV. Indeed, when the Higgs obtains its vev, the usual coupling between a wino, a lepton and a sneutrino (which in this models coincides with the Higgs) now induces a gaugino-lepton mixing which alters the $Z\bar{l}l$ couplings and implies a $M_{wino} \gtrsim 2$ TeV constraint from LEP I.

Another implication of the R-symmetry, is that A-terms are forbidden. Consequently, L and R sfermions do not mix and remain mass eigenstates. Sfermions belonging to the same $SU(2)_L$ doublet are then almost degenerate, since

$$m^2_{\tilde{b}_L} = m^2_{\tilde{t}_L} - m^2_t + m^2_b \, , \tag{4}$$

so that the strong bounds on $\tilde{b}_L$ (see below) also constrain $\tilde{t}_L$.

Finally, the absence of additional Higgs doublets, implies the absence of the infamous μ-term and of its inseparable μ-problem.

4 Phenomenology

The most important implications of this R-symmetry involve the squark phenomenology at the LHC. In fact, already in the MSSM, R-parity is a crucial ingredient for phenomenology. Its conservation implies that once a R-odd particle is produced, it will decay through a cascade that can only culminate in another R-odd particle; the latter must, therefore, be stable and escape the detector under the form of missing energy. In models where the R-symmetry coincides with lepton number, on the other hand, the lightest leptons (or the gravitino, if light enough) are the main final products of these cascade decays. We summarize this situation in Table 2, where we also report the Lagrangian interaction responsible for each decay (some of these decays are allowed by symmetries but their interaction is not present in the renormalizable part of the Lagrangian; in this case we have parametrized the strength of the interaction through Λ [18]).

Decay	Interaction
$\tilde{t}_L \to b_R \bar{l}^-_L$	$Y_d \, HQD\vert_{\theta^2}$
$\tilde{t}_L \to t_R \bar{\nu}_L$	$\frac{1}{\Lambda^2} \vert H\vert^2 \vert Q\vert^2 \vert_{\theta^4}$
$\tilde{t}_L \to t_L \tilde{G}$	$\frac{m_t^2 - m^2_{\tilde{t}_L}}{F} \, \tilde{t}^*_L \tilde{G} \, t_L$
$\tilde{b}_L \to b_R \bar{\nu}_L$	$Y_d \, QHD\vert_{\theta^2}$
$\tilde{b}_L \to b_L \tilde{G}$	$\frac{m_b^2 - m^2_{\tilde{b}_L}}{F} \, \tilde{b}^*_L \tilde{G} \, b_L$
$\tilde{t}_R \to t_L \nu_L$	$\frac{1}{\Lambda^2} \vert H\vert^2 \vert U\vert^2 \vert_{\theta^4}$
$\tilde{t}_R \to t_R \bar{\tilde{G}}$	$\frac{m_t^2 - m^2_{\tilde{t}_R}}{F} \, \tilde{t}^*_R \bar{\tilde{G}} \, \bar{t}_L$
$\tilde{b}_R \to b_L \nu_L$	$Y_d \, QHD\vert_{\theta^2}$
$\tilde{b}_R \to t_L \, l^-_L$	$Y_d \, QHD\vert_{\theta^2}$
$\tilde{b}_R \to b_R \bar{\tilde{G}}$	$\frac{m_b^2 - m^2_{\tilde{b}_R}}{F} \, \tilde{b}^*_R \bar{\tilde{G}} \, \bar{b}_L$

Table 2. *Decay modes for the (third family) squarks with the corresponding Lagrangian interaction.*

When the gravitino is light and the SUSY breaking scale is small $F \lesssim (2\,\text{TeV})^2$, decays into gravitinos typically dominate, especially at high squark masses, as illustrated by the solid lines in Figure 1. In the opposite case, however, decays into quarks and charged leptons have a larger branching ratio (BR).

Interestingly, many of these decay topologies are already covered by LHC searches. In particular, most of the

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[1] It is also important to realize that R-parity forbids proton decay only in the MSSM. Any new physics at sub-GUT scales can induce higher-dimension operators that lead to proton decay while respecting R-parity.

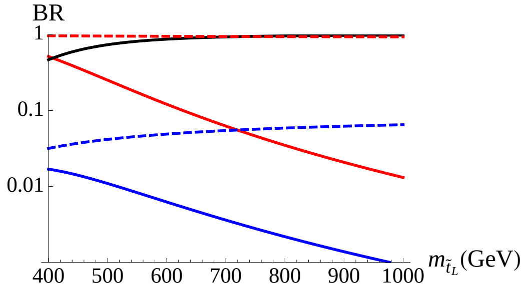

Figure 1. Branching ratios for $\tilde t_L \to b\bar l^-$ (red), $\tilde t_L \to t\bar\nu$ (blue) and $\tilde t_L \to t\tilde G$ (black). Solid: the case of a light gravitino and small SUSY breaking scale $F \lesssim (2\,\text{TeV})^2$. Dashed: when the gravitino is heavy.

decays involving neutrinos or gravitinos in the final state are captured by the usual searches for supersymmetry with *R*-parity, in the limit where the neutralino is massless. On the other hand, some of the decays involving quarks and charged leptons are addressed by leptoquark searches.

Bounds from leptoquark searches imply

$$m_{\tilde t_L} > \begin{cases} 660\,\text{GeV} & l_L^- = e_L \quad [19] \\ 1070\,\text{GeV} & l_L^- = \mu_L \quad [20] \\ 534\,\text{GeV} & l_L^- = \tau_L \quad [21] \end{cases}, \qquad (5)$$

while SUSY searches constrain [22],

$$m_{\tilde t_R} > 685\,\text{GeV} \qquad (6)$$

and (together with the relation Eq. (4)) [23],

$$m_{\tilde b_{L,R}} > 650\,\text{GeV} \quad \Rightarrow \quad m_{\tilde t_L} \gtrsim 670\,\text{GeV}\,. \qquad (7)$$

For second generation squarks the bounds lie at 830 GeV [23].

On the other hand, two-body decays of first generation squarks are chirality suppressed, so that decay topologies are typically three-body and involve quarks, leptons and gauge/Higgs bosons [9]. These are not been specifically looked for. Other channels that are not being addressed by the experiments are leptoquarks decays with a final state bottom and an electron/muon or top-quark and any lepton (or also τs and jets, as for charm-squark decays).

Finally, let me mention that, if the gravitinos are light enough, the coupling gravitino-slepton-lepton could induce Higgs invisible decays (such as in the case of light composite dark matter [24]) with $BR^{\text{inv}} \lesssim 10\%$. Unlike the MSSM and its extensions [25–27], no other deviations are expected in the Higgs couplings, which resemble much the SM ones.

5 Conclusions

In this era of agnosticism about physics above the multi-TeV scale, the traditional MSSM looses its role of ambassador for the general Supersymmetric framework. The discovery of a Higgs at 125 GeV shakes even more fundamentally the world of supersymmetric theories: if SUSY is part of Nature, then it is badly broken.

In this context, the class of models I've described in this note, naturally emerges (with the added-value of lacking a μ-problem). The question of whether the Higgs lies in the SUSY or in the SM part of the spectrum is of primary importance and I've explained how this question can be answered by searching for squarks with distinctive properties. The main point is that instead of *R*-parity, an *R*-symmetry is necessary, and it must coincide with lepton number. Searches for final states with quarks and charged leptons/neutrinos are capable to single out these models. Although a combination of leptoquark searches and SUSY searches (in the limit of massless neutralinos) cover most of the possibilities implied by these models, there remain a few channels which have received no experimental attention yet.

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