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On a reinterpretation of the Higgs field in supersymmetry and a proposal for new quarks

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ABSTRACT

In the framework of supersymmetry, when R-parity is violated the Higgs doublet superfield H_d can be interpreted as another doublet of leptons, since all of them have the same quantum numbers. Thus Higgs scalars are sleptons and Higgsinos are leptons. We argue that this interpretation can be extended to the second Higgs doublet superfield H_u, when right-handed neutrinos are assumed to exist. As a consequence, we advocate that this is the minimal construction where the two Higgs doublets can be interpreted in a natural way as a fourth family of lepton superfields, and that this is more satisfactory than the usual situation in supersymmetry where the Higgses are 'disconnected' from the rest of the matter and do not have a three-fold replication. On the other hand, in analogy with the first three families where for each lepton representation there is a quark counterpart, we propose a possible extension of this minimal model including a vector-like quark doublet representation as part of the fourth family. We also discuss the phenomenology of the associated new quarks.

1. Introduction

The Higgs particle in the framework of the standard model is intriguing, being the only elementary scalar in the spectrum, and introducing the hierarchy problem in the theory. Besides, whereas for the rest of the matter there is a three-fold replication, this does not seem to be the case of the Higgs since only one scalar/family has been observed. In the framework of supersymmetry, the presence of the Higgs is more natural: scalar particles exist by construction, the hierarchy problem can be solved, and the models predict that the Higgs mass must be $\lesssim 140$ GeV if perturbativity of the relevant couplings up to high-energy scales is imposed. In a sense, the latter has been confirmed by the detection of a scalar particle with a mass of about 125 GeV. However, in supersymmetry the existence of at least two Higgs doublets, H_d and H_u, is necessary, as in the case of the minimal supersymmetric standard model (MSSM) [1], and as a consequence new neutral and charged scalar particles should be detected in the future to confirm the theory. Similar to the standard model, no theoretical explanation is given for the existence of only one family of Higgs doublets.

In this work we want to contribute a new vision of the Higgs(es) in the framework of supersymmetry. We will argue that the well known fact that the Higgs doublet superfield H_d has the same gauge quantum numbers as the doublets of leptons L_i, where $i = 1, 2, 3$ is the family index, is a clue that the Higgses can be reinterpreted as a fourth family of lepton superfields. Thus Higgs scalars are sleptons and Higgsinos are leptons. This can be done only when R-parity (R_p) is violated, since the standard model particles and their superpartners have opposite R_p quantum numbers. Early attempts in this direction can be found in Refs. [2,3]. In particular, in the first paper it was pointed out that in theories with TeV scale quantum gravity, the scalar H_d can be a fourth family slepton. Since H_u is not present in that construction, with its role in the Lagrangian played by H_d through non-renormalizable couplings, H_d is proposed to be part of a complete standard model family in order to cancel anomalies. In the second paper, in the context of low-energy supersymmetry the scalar H_u was also included as a slepton as part of another complete family with opposite quantum numbers to the fourth family. Thus, four chiral families with standard model quantum numbers and one chiral family with opposite quantum numbers are present in that construction.

However, with the matter content of the MSSM, which is sufficient to cancel anomalies, this interpretation of H_d as another

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lepton superfield in the case of R_p violation cannot be extended to H_u in a natural way, as we will show in Section 2. Fortunately, as we will discuss in Section 3, when right-handed neutrino superfields are allowed in the spectrum, not only the violation of R_p turns out to be natural solving the μ problem and reproducing easily current neutrino data, but also the interpretation of H_u as part of the fourth family of lepton superfields is straightforward. Finally, we will argue in Section 4 that, as a consequence, a vector-like quark doublet representation might also be part of the new fourth family, and we will briefly discuss its phenomenology. Our conclusions are left for Section 5.

2. Supersymmetry without right-handed neutrinos

Unlike the standard model where only one Higgs doublet scalar (together with its complex conjugated representation) is sufficient to generate Yukawas couplings for quarks and charged leptons at the renormalizable level, in supersymmetry we need a vector-like Higgs doublet representation, with their superfields usually denoted as:

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \; H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}. \tag{1}$$

In addition, the matter sector of the supersymmetric standard model, in the absence of right-handed neutrinos, contains also the following three families of superfields:

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ - \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \; \begin{matrix} d_i^c \\ u_i^c \end{matrix}, \tag{2}$$

where we have defined u_i, d_i, ν_i, e_i, and u_i^c, d_i^c, e_i^c, as the left-chiral superfields whose fermionic components are the left-handed fields of the corresponding quarks, leptons, and antiquarks, antileptons, respectively.

With this matter content, the most general gauge-invariant renormalizable superpotential is given by:

$$W = \mu\, H_u\, H_d + Y_{ij}^e\, H_d\, L_i\, e_j^c + Y_{ij}^d\, H_d\, Q_i\, d_j^c - Y_{ij}^u\, H_u\, Q_i\, u_j^c \\ + \mu_i H_u\, L_i + \lambda_{ijk}\, L_i\, L_j\, e_k^c + \lambda'_{ijk}\, L_i\, Q_j\, d_k^c + \lambda''_{ijk}\, u_i^c\, d_j^c\, d_k^c, \tag{3}$$

where the summation convention is implied on repeated indexes, and our convention for the contraction of two $SU(2)$ doublets is e.g. $H_u\, H_d \equiv \epsilon_{ab} H_u^a\, H_d^b$, with ϵ_{ab} the totally antisymmetric tensor $\epsilon_{12} = 1$.

In the absence of the terms in the second line, the terms in the first line of Eq. (3) constitute the superpotential of the MSSM, where baryon (B) and lepton (L) numbers are conserved. This superpotential arises from imposing the Z_2 discrete symmetry R-parity [4], $R_p = (-1)^{2S}(-1)^{(3B+L)}$, which acts on the components of the superfields. Here S is the spin, and one obtains $R_p = +1$ for ordinary particles and -1 for their superpartners. Because of the different R_p quantum numbers, there can be no mixing between particles and superpartners.

If we allow the terms in the second line of Eq. (3) to be present, they violate R_p explicitly [4]. The first term $\mu_i H_u L_i$ which also violates lepton number, together with the superpotential of the MSSM, constitute the bilinear R-parity violation model (BRpV). This term contributes to the neutral scalar potential generating VEVs not only for the Higgses as in the MSSM, but also for the left sneutrinos, $\langle \widetilde{\nu}_{iL} \rangle \neq 0$. The other three terms are the conventional trilinear lepton- and baryon-number-violating couplings. The presence of the couplings $\mu_i, \lambda_{ijk}, \lambda'_{ijk}$, violating lepton number could have easily been argued, once the μ-term and the Yukawa couplings for d-type quarks and charged leptons are introduced in the first line of the superpotential (3), by noting that the superfields H_d and L_i have the same gauge quantum numbers. Actually, the latter fact might lead us to interpret the Higgs superfield H_d as a fourth family of lepton superfields L_4, in addition to the three families L_i of Eq. (2):

$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix} = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = H_d\,. \tag{4}$$

Notice that this is not possible in the case of the MSSM because the components of the superfields H_d and L_i have opposite quantum numbers under R_p. Unfortunately, we cannot interpret naturally the other Higgs superfield H_u in a similar way, given that it has no leptonic counterpart, in particular its neutral component. We will see in the next section that this counterpart is present when we enter right-handed neutrinos in our supersymmetric framework.

On the other hand, it is well known that the simultaneous presence of the couplings λ'_{ijk} and λ''_{ijk}, violating lepton and baryon number respectively, can be dangerous since they would produce fast proton decay. The usual assumption in the literature of the MSSM of invoking R_p to avoid the problem is clearly too stringent, since then the other couplings λ_{ijk}, and μ_i in the superpotential (3), which are harmless for proton decay, would also be forbidden. A less drastic solution, taking into account that the choice of R_p is *ad hoc*, is to use other Z_N discrete symmetries to forbid only λ''_{ijk}. This is the case e.g. of Z_3 Baryon-parity [5] which also prohibits dimension-5 proton decay operators, unlike R_p. In addition, this strategy seems reasonable if one expects all discrete symmetries to arise from the breaking of gauge symmetries of the underlying unified theory [6], because Baryon-parity and R_p are the only two generalized parities which are 'discrete gauge' anomaly free [5]. Discrete gauge symmetries are also not violated [6] by potentially dangerous quantum gravity effects [7].

Given the relevance of string theory as a possible underlying unified theory, a robust argument in favour of the above mechanism is that, in string compactifications such as e.g. orbifolds, the matter superfields have several extra $U(1)$ charges broken spontaneously at high energy by the Fayet–Iliopoulos D-term, and as a consequence residual Z_N symmetries are left in the low-energy theory. As pointed out in Ref. [8], the same result can be obtained by the complementary mechanism that stringy selection rules can naturally forbid the λ''_{ijk} couplings discussed above, since matter superfields are located in general in different sectors of the compact space. As a whole, some gauge invariant operators violating R_p can be forbidden, but others are allowed [9].

Let us finally remark that although the BRpV has the interesting property of generating through the bilinear terms μ_i that mix the left-handed neutrinos ν_{iL} and the neutral Higgsino $\tilde{H}_u^0$, one neutrino mass at tree level (and the other two masses at one loop), the μ problem [10] is in fact augmented with the three new supersymmetric mass terms which must be $\mu_i \lesssim 10^{-4}$ GeV, in order to reproduce the correct values of neutrino masses. This extra problem can be avoided imposing a Z_3 symmetry in the superpotential, which implies that only trilinear terms are allowed. Actually, this is what one would expect from a high-energy theory where the low-energy modes should be massless and the massive modes of the order of the high-energy scale. As pointed out in Ref. [11], this is what happens in string constructions, where the massive modes have huge masses of the order of the string scale and the massless ones have only trilinear terms at the renormalizable level. Thus one ends up with an accidental Z_3 symmetry in the low-energy theory.

To summarize the discussion, instead of the superpotential of Eq. (3), a more natural superpotential (in the sense of free of prob-