IS THE STANDARD MODEL SCALAR THE FIRST DISCOVERED SUSY PARTICLE?

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The scalar particle recently discovered at the LHC has the same gauge quantum numbers as the neutrino, so they could be one the superpartner of the other. We discuss the conditions that should be satisfied in order to realize such identification and present a model where this is realized. This model possesses an interesting phenomenology that we present here.

1 Introduction

On July 4th 2012, at CERN, it was announced the discovery of a new particle, at a mass of $(125.9 \pm 0.4)$ GeV, compatible with the Standard Model (SM) scalar boson. In October 2013 the Nobel Prize for physics was assigned to François Englert and Peter W. Higgs “for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”. This discovery completes the picture of the SM particles and, for the first time, a scalar is discovered with the same gauge quantum numbers of an already discovered fermion, the neutrino. Indeed in the SM both the scalar and the neutrinos belong to SU(2) doublets and have the same hypercharge. Then a natural question arises, if they can be one the superpartner of the other. Were this the case, the SM scalar discovery would also represents the discovery of supersymmetry (SUSY). It is then clear that it is worth to check whether this is feasible or not. This has been studied in details in Ref. 1, of which in the following I will give a short review.

In order to identify the SM scalar with a sneutrino few conditions have to be satisfied. Since we are dealing with a SUSY theory, we could think of starting from the Minimal Supersymmetric Standard Model (MSSM). In order to avoid fast proton decay, in the MSSM a parity symmetry, called R-parity, is usually imposed, under which all SM particles are even, while SUSY partners are odd. Additionally, this ensures the absence of large neutrino masses, that would be generated if the R-parity were broken. If we now identify a sneutrino with the SM scalar, once the latter acquires vev, the R-parity and Lepton Number (LN), under which the sneutrino is charged, will be broken and large neutrino masses will be generated, thus excluding the model. We therefore immediately come to the first condition: in order to identify the SM scalar with a sneutrino the R-parity should be replaced by a $U(1)_{R}$ symmetry, which plays the rôle of LN and prevents the generation of large $\nu$ masses.

$U(1)_{R}$ symmetries are well-known in the literature, since they have the interesting feature that, in models respecting them, gauginos have Dirac masses, and this offers a further protection mechanism to the SM scalar mass known as “supersoft SUSY breaking” 2. In this framework
it is therefore possible to identify a slepton doublet with the SM scalar doublet and indeed this possibility has been explored in the literature. However, in order to obtain all the SM Yukawa Lagrangian terms and therefore all the fermion masses, a second chiral superfield, \( H_u \) is usually introduced, since a term containing the hermitian conjugate of the SM scalar, like in the up-quark Yukawa coupling in the SM, is forbidden in SUSY theories, since the superpotential must be analytic. Then, in the previously mentioned models, the sneutrino plays the rôle of the SM scalar only in the down quark and charged lepton sectors, while \( H_u \) provides the masses of the up-type quarks. Once \( H_u \) is introduced, a new superfield has to be added to cancel the anomaly induced by the presence of \( H_u \) alone. Moreover, the \( \mu \)-term is still there in this case, with all the problematics associated to it.

Here we would like to explore the viability of a model where no chiral superfield is introduced, a part from the ones associated to leptons and quarks, and where a sneutrino plays the rôle of the SM scalar, giving mass to all the fermions. This would have the additional benefits that no superfield must be added in order to cancel any anomaly and moreover the \( \mu \)-problem would be solved, since no \( \mu \)-term would be present in the theory. The price one has to pay in order to realize this is that at least the Yukawa coupling of up-type quarks must come from the Kähler potential, i.e. from higher-dimensional SUSY-breaking operators.

In the following I will discuss the main features of the model and the interesting phenomenology associated to it.

### 2 The Higgsinoless MSSM

Since the only chiral superfields present in this model are the ones associated to quarks and leptons, no chiral Higgs superfields are present and hence no Higgsinos, from which the name of the model. In table 1 the superfield content of this model, as well as their charge assignments, are shown. From there one can see that a certain freedom on the charges is possibile. In the following we will not enter into the details of such charge assignment, for which we remand to Ref.\(^1\), but just assume that \( L \neq 1 \) (i.e. the SM scalar is identified with \( L_3 \)) and \( B \neq 1/3 \) (in order to prevent proton decay). It follows that the only possible superpotential terms, at the renormalizable level, are:

\[
W = Y_d H Q D + Y_{e_{ij}} H L_i E_j ,
\]

where indexes \( i, j = 1, 2 \) are summed over (\( i, j = 3 \) is forbidden by the antisymmetry of SU(2) contracted indexes) and \( Y_d \) is a matrix in flavor space. As it stands, this superpotential does not generate up-type quark masses, gaugino masses, nor a mass for the charged lepton contained in \( L_3 \), whose scalar partner plays the rôle of the SM scalar. These must originate as SUSY breaking
effects. If we introduce a spurion field $X$, whose $F$-component is nonzero, $X = \theta^2 F$, and breaks SUSY, in a SUSY-preserving notation the masses of the up-type quarks can be written as

$$\int d^4 \theta \ y_u \frac{X^\dagger H^\dagger Q U}{M} = \int d^2 \theta \ Y_u H^\dagger Q U,$$

where $y_u$ are dimensionless couplings and $Y_u \equiv y_u F/(M \Lambda)$ are the Yukawa couplings of the up-type quarks. Here $\Lambda$ is the scale at which the effective operator is generated, while $M$ is the SUSY mediation scale.

In a similar fashion we can write the masses for $\ell_3$ and the gauginos

$$\int d^4 \theta \ y_3 \frac{X^\dagger X F \alpha D_\alpha}{M^2} \frac{H^\dagger D_\alpha}{\Lambda^2} E_3,$$

$$\int d^2 \theta \ D_\alpha \frac{X^\dagger X}{M} W^a_\alpha \Phi_a,$$

where $D_\alpha$ are superspace derivatives, as well as an additional quartic coupling for the SM scalar:

$$\int d^4 \theta \ \lambda_h \frac{X^\dagger X |H|^4}{M^2} \frac{H^\dagger}{\Lambda^2} = \delta \lambda_h h^4 + \ldots.$$  

This last term is needed in order to obtain a SM scalar mass $\sim 126$ GeV, since in this model A-terms are forbidden by the R-symmetry and, for naturalness, we would like to have light stops.

Eqs. (1)-(5) are the necessary and sufficient ingredients we need to build a realistic model without any additional chiral superfield. Moreover, from Eq. (2) we derive the first interesting consequence of our approach: since $Y_t \sim 1$, and $F/M$ is the scale of scalar superpartners that we would like not to be heavier than the TeV, we obtain $\Lambda \sim y_u F/M \lesssim 4\pi$ TeV. That is, this model is an effective theory valid up to few tens of TeV.

A nice feature of this model is that, thanks to the R-symmetry, the SUSY breaking corrections to the SM scalar mass are suppressed, and EWSB is realized without fine tuning. Moreover, for the same reason, a naturally splitted spectrum is possible. In particular, gauginos must be heavier then the TeV, due to the modifications they can induce in the $Z$ coupling to charged leptons, with whom they mix, while stops and sbottoms can be just around the corner in LHC searches. We will not enter here into these technical details, that can be found in Ref. 1, while we will now focus on the interesting phenomenology proper of this model.

3 Phenomenology

Let’s start with the SM scalar. At tree level, its couplings are identical to the SM ones, but at the loop level deviations can occur. In particular, light stops circulating in the loops can induce corrections to the scalar couplings to gluons and photons, modifying the branching ratios and especially the production cross section.

An even more interesting feature is given by the possibility of having an invisible branching fraction. Indeed, since the scalar is the partner of the neutrino and they couple to the goldstino, if the gravitino is light, the scalar can decay into gravitino and neutrino, which manifest themselves in missing transverse energy ($E_T$). For $F \sim 1$ TeV, the invisible branching fraction can be as large as 10%.

In this model squarks and sleptons can be light. In particular, for naturalness reasons, we expect the third generation squarks to be lighter than the TeV scale. Notice that, thanks to the R-symmetry, left and right sfermions do not mix. This permits us to make a nice prediction on quark masses:

$$m_{b_L}^2 = m_{t_L}^2 - m_t^2 + m_b^2.$$  

(6)
The possible decays are shown. These are summarized in Table 2, where the squarks can decay into a quark and a neutralino. In particular the \( \tilde{b}_L \) can decay into a b and a charged lepton, while the \( \tilde{b}_R \) can decay into a t and a \( \ell \). The branching ratios into these channels depend on several variables, in particular on the gravitino mass: if the gravitino is light the decay into it and a quark dominates, while if it is heavy the above leptoquark decays can occur. As for the decay \( \tilde{t}_L \to b_R \tilde{l}_L^- \), one can adapt leptoquark searches at the LHC and put a bound on the stop mass. On the other hand, the decay \( \tilde{b}_R \to t_L \tilde{l}_L^- \) has not yet been searched for.

The prediction on the mass relation, the fact that leptoquark decays exist with predictable branching ratios and that the final state helicity is fixed in this model, render it distinguishable from the MSSM. Indeed, suppose a final state composed by a b-jet and missing transverse energy is observed: it can be the \( \tilde{b}_R \) of this model only if a leptoquark decay into top-lepton is observed at the same mass, or it can be the \( \tilde{b}_L \) if the \( \tilde{t}_L \) is observed at a slightly higher mass. On the other hand suppose that a top and missing \( E_T \) are observed: it can be the \( \tilde{t}_L \) if a lighter \( \tilde{b}_L \) and decays into b and leptons are observed, but it can be also the \( \tilde{t}_R \). In this case, in order to distinguish from the MSSM one should look at the top helicity and, even if not trivial, this is in principle feasible.

As for the 1\(^{st}\) and 2\(^{nd}\) generation squarks, bounds coming from the searches of final states with jets and missing \( E_T \) are quite strong, namely \( > 830 \text{ GeV} \). In principle also for these sparticles leptoquark decays can occur, like for stops and sbottoms, but, since they come from superpotential terms, the corresponding branching ratios are proportional to the Yukawa couplings that, in this case, are small. Therefore, an interesting thing can happen: 3-body decays can be dominant over the 2-body ones. In Table 3 the possible decays are shown. These constitute another interesting and peculiar signal of this model.

In the slepton sector the situation is quite similar: indeed also in this case the Yukawa couplings are small and it can happen that 3-body decays dominate. The possible decays for the charged sleptons, in the case where the gravitino is heavy, are shown in Table 4.

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

| Decay | Interaction |
|-------|-------------|
| \( t_L \to b_R \tilde{l}_L^- \) | \( Y_d H Q D \mid \theta^2 \) |
| \( t_L \to t_R \nu_L \) | \( \frac{1}{2} \mid H \mid (\mid Q \mid)^2 \mid \theta^2 \) |
| \( \tilde{t}_L \to \tilde{t}_L \tilde{G} \) | \( \frac{m_t^2 - m_{\tilde{t}_L}^2}{F} \tilde{t}_L \tilde{G} \tilde{t}_L \) |
| \( b_L \to b_R \nu_L \) | \( Y_d Q H D \mid \theta^2 \) |
| \( \tilde{b}_L \to \tilde{b}_L \tilde{G} \) | \( \frac{m_b^2 - m_{\tilde{b}_L}^2}{F} \tilde{b}_L \tilde{G} \tilde{b}_L \) |

### Table 3: Dominant decay modes for first and second family squarks when the gravitino is heavy or \( \sqrt{F} \gg \text{TeV} \).

| Decay | Interaction |
|-------|-------------|
| \( \tilde{u}_L \to d + \tilde{l}_L^- + Z \) | \( \tilde{c}_L \to s + \tilde{l}_L^- \) (for \( m_{\tilde{c}_L} \lsim 500 \text{ GeV} \)) |
| \( d_L \to u + \nu_L + W^- \) | \( \to s + \tilde{l}_L^- + Z \) |
| \( \tilde{u}_R \to u + \tilde{l}_L^- + W^- \) | \( \tilde{s}_L \to s + \tilde{\nu}_L \) (for \( m_{\tilde{s}_L} \lsim 300 \text{ GeV} \)) |
| \( d_R \to d + \tilde{l}_L^- + W^- \) | \( \to c + \tilde{\nu}_L + W^- \) |

The decay modes of sfermions are dictated by symmetries and, for the third generation squarks, are summarized in Table 2. Notice that in many cases stops and sbottoms decay into a quark plus a neutralino or a neutrino, i.e. missing energy. Therefore, the MSSM searches for a squark decaying into a quark plus a neutralino can be adapted here by taking \( m_{\chi^0} = 0 \) and used to place bounds on the masses of squarks. However, at difference with the MSSM and due to the absence of the R-parity, here the squarks can decay into a quark and a lepton. In particular the \( \tilde{t}_L \) can decay into a b and a charged lepton, while the \( \tilde{b}_R \) can decay into a t and a \( \ell \). The branching ratios into these channels depend on several variables, in particular on the gravitino mass: if the gravitino is light the decay into it and a quark dominates, while if it is heavy the above leptoquark decays can occur. As for the decay \( \tilde{t}_L \to b_R \tilde{l}_L^- \) one can adapt leptoquark searches at the LHC and put a bound on the stop mass. On the other hand, the decay \( \tilde{b}_R \to t_L \tilde{l}_L^- \) has not yet been searched for.
Table 4: Dominant decay modes for sleptons when the gravitino is heavy or $\sqrt{F} \gg$ TeV. We assume that the slepton masses are larger than 500 GeV.

| $\tilde{e}_L$ | $\nu_e + \nu_L + W^-$ | $\tilde{\mu}_L$ | $\nu_\mu + \nu_L + W^-$ | $\tilde{\tau}_L$ | $\tau + \nu_L$ |
|------------|----------------------|-----------------|----------------------|-----------------|----------------|
| $\tilde{e}_R$ | $e + l_L^- + W^+$ | $\tilde{\mu}_R$ | $\nu_\mu + l_L^- (50\%)$ | $\tilde{\tau}_R$ | $\tau + \nu_L (50\%)$ |
| $\tilde{\nu}_e$ | $e + l_L^- + Z$ | $\nu_\tau$ | $\tau + l_L^-$ (50%) | \text{not shown} | \text{not shown} |

We have discussed here the phenomenology of a model which shows peculiar features with respect to the MSSM. In particular we stress that this model is testable at the LHC, distinguishable from the MSSM in case of a discovery, and moreover falsifiable at the LHC running at 14 TeV, since, being it an effective theory valid up to few TeV, almost all its parameter space will be explored in the next LHC run.

4 Conclusions

We have answered the question of the title and shown that it is indeed possible for the SM scalar to be the superpartner of the neutrino. For this to be realized, few conditions have to be satisfied, which lead to a model which is an effective theory valid up to few TeVs. This model has an interesting collider phenomenology that permits to test it at the LHC and, in case SUSY is discovered, to distinguish it from the MSSM or other SUSY models.

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