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ON HIGGS-EXTENDED MSSM MODELS

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Motivated by the LHC results revealing the SM scalar sector as well as by its possible revision, we consider an MSSM scalar extension consisting of two Higgs triplets generating the observed neutrino and Higgs masses. The latter constrains their suppressed vevs and sizable couplings, which slightly influences the extended neutralino sector and the LSP emergence.

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1. INTRODUCTION

Despite the undeniable success of the SM of particle physics in describing the matter building blocks and their interactions below the weak scale [1, 2], it is now known to be rather complicated and incomplete. The past and the recent data continue to brighten the spectrum and dynamics of the electroweak symmetry breaking sector responsible for major problems in the SM, mostly the Higgs mass hierarchy problem. The supersymmetry is the well-known simple model curing the Higgs problem without fine tuning. In the MSSM, the mass of the lightest Higgs boson is close the Z-boson mass at tree level, but could be raised to the value best motivated theoretically and experimentally by considering large radiatve corrections.

Recently, with the LHC observation of a new scalar boson around 125–126 GeV with a diphoton rate excess [3, 4], the consideration of MSSM extended models has become appealing. In particular, the extended Higgs sector could reproduce such a result by generating sizeable tree-level correction to the Higgs mass as well as enhancement of its diphoton decay rate through charged new degrees of freedom, whose possible detection would be a clear evidence of a Higgs sector beyond that of the MSSM [5–7]. The most considered scalar extended models often include extra singlets or triplets, which have been seen to affect the Higgs sector phenomenology, thereby providing a large landscape where, in addition to the observed Higgs results, more famous open questions in the SM can be studied, due to the new involved parameters. Indeed, the associated parameters of the extra singlets or triplets, such as coupling constants and vevs present in the superpotential of the model within new mass and interaction terms, might be helpful in discussing more known problems such as neutrino masses and the dark matter sector in the large parameter space. However, models with an extended Higgs boson are strongly constrained by the electroweak precision tests, in particular by the ρ parameter [8], imposing constraints on the extra scalar vevs that affect the model phenomenology.

In the light of the recent Higgs observation and the deployed theoretical efforts, we consider a Higgs-triplet-extended MSSM and discuss its phenomenological implications for the mass spectrum. Specifically, we study the contribution of two extra $Y = \pm 2$ complex triplets $\Delta_{u,d}$ to the neutrino and Higgs masses by means of their vevs $v_{\Delta_{u,d}}$ and coupling parameters $\lambda_{u,d}$, which are constrained from the known and the electroweak precision data. We then investigate the neutralino sector extended by the fermionic triplet neutral states and discuss its compositeness and the LSP emergence according to the scale of the triplet parameters.

2. MODEL AND CONSTRAINTS

Signals for physics beyond the SM, mostly neutrinos and dark matter sectors [9–12], have been largely

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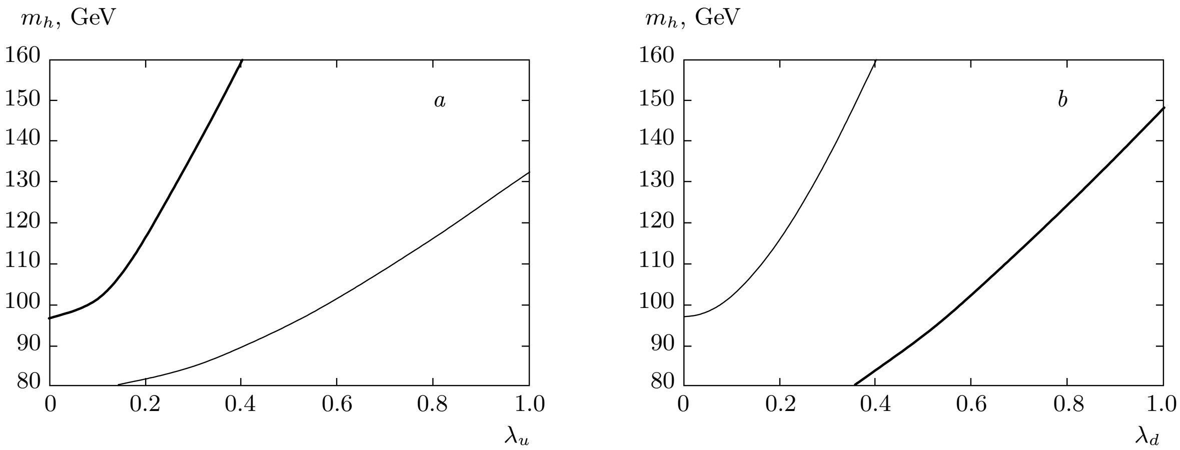

Plots of the m_h as a function of λ_u. a — $\mathrm{tg}\,\beta = \sqrt{3}$, $\lambda_d = 0.8$ (thick line) and for $\mathrm{tg}\,\beta = \sqrt{3}/3, \lambda_d = 0.2$ (thin line). b — $\mathrm{tg}\,\beta = \sqrt{3}$, $\lambda_u = 0.1$ (thick line) and for $\mathrm{tg}\,\beta = \sqrt{3}/3, \lambda_u = 0.8$ (thin line)

investigated and led to several extensions of the SM. Most of them are based on the supersymmetry and/or extended scalar sectors. Recently, with the discovered resonance at 125.5 GeV [3, 4], the hunt for one or more Higgs boson(s) has given a big boost to the search for such directions where most studied models involve extra scalar fields. Here, for the aforementioned reasons, we extend the MSSM Higgs sector by two $Y = \pm 2$ triplets given by

$$\Delta_d = \begin{pmatrix} \delta^+/\sqrt{2} & \delta_d^{++} \\ \delta_d^0 & -\delta^+/\sqrt{2} \end{pmatrix}, \qquad \Delta_u = \begin{pmatrix} \delta_u^-/\sqrt{2} & \delta_u^0 \\ \delta_u^{--} & -\delta_u^-/\sqrt{2} \end{pmatrix}. \tag{1}$$

The scalar triplets are described in terms of a 2×2 matrix representations: $\delta^0_{u,d}$ are the complex neutral fields and δ^{++}, δ^+, δ^-, δ^{--} denote the charged fields. This is one of the MSSM extensions that allows realizing some of its outstanding fragments. An implication of this emerges in the superpotential extension

$$W = W^{MSSM} + W^{\Delta}, \tag{2}$$

where W^{Δ} comprises all possible new mass and an interaction terms involving the triplet fields. Indeed, roughly, the most general gauge-invariant and renormalizable superpotential that can be written for the extra scalars is given by

$$W^{\Delta} = \lambda_L^{ij} L_i \Delta_d L_j + \mu_\Delta \,\mathrm{Tr}\,(\Delta_u \Delta_d) + \lambda_u H_u \Delta_u H_u + \lambda_d H_d \Delta_d H_d, \tag{3}$$

where $H_u = (h_u^+, h_u^\circ), \quad H_d = (h_d^\circ, h_d^-)$, and L_i are the MSSM Higgs and lepton doublets, and $i = 1, 2, 3$ is the generation index. The first piece is a neutrino-generated mass term and the others are the scalar-sector interaction terms. After the electroweak symmetry breaking, when the triplet Δ_d acquires a vacuum expectation value v_{Δ_d} in its neutral compenent, the neutrinos acquire Majorana masses, restricting the value of v_{Δ_d}. In fact, for $\lambda_L^{ij} \le 1$ and neutrino masses ≤ 0.1 eV, v_{Δ_d} is expected to be

$$v_{\Delta_d} = \frac{m_v}{\lambda_L} \le 10^{-10}\ \mathrm{GeV}, \tag{4}$$

which is more than 12 orders of magnitude less than the electroweak symmetry breaking scale

$$v = \sqrt{v_u^2 + v_d^2} \sim 10^2\ \mathrm{GeV}.$$

Moreover, strong constraints on models with triplets comes from the electroweak precision tests. Due to the addition of the triplets, the full Higgs kinetic Lagrangian is given by

$$L = |D_\mu H_\mu| + |D_\mu H_d| + \mathrm{Tr}\,[|D_\mu \Delta_u|] + \mathrm{Tr}\,[|D_\mu \Delta_d|], \tag{5}$$

from which we can derive the contribution of these extra fields to the gauge bosons. In particular, the Z- and W-bosons receive the masses

$$M_Z^2 = \frac{g_1^2 + g_2^2}{2}\left(v^2 + 4v_{\Delta_u}^2 + 4v_{\Delta_d}^2\right), \qquad M_W^2 = \frac{g_2^2}{2}\left(v^2 + 2v_{\Delta_u}^2 + 2v_{\Delta_d}^2\right), \tag{6}$$

and hence would redefine the ρ parameter [8] as

$$\rho = \frac{1 + \dfrac{2\left(v_{\Delta_u}^2 + v_{\Delta_d}^2\right)}{v^2}}{1 + \dfrac{4\left(v_{\Delta_u}^2 + v_{\Delta_d}^2\right)}{v^2}}. \tag{7}$$

Because the experimental value of the ρ parameter is near unity, the factor $\left(v_{\Delta_u}^2 + v_{\Delta_d}^2\right)/v^2$ is required to be much smaller than unity at the tree level. This constraint with (4) means that the Δ_u-triplet vev v_{Δ_u} should also be much smaller than the electroweak scale $\sim v$, whence such a deviation is found to be $\delta\rho \le 10^{-24}$, thus keeping the experimental ρ parameter near unity. We finally obtain the scalar vev bound

$$v_{\Delta_{u,d}} \ll v \sim 10^2 \text{ GeV}. \tag{8}$$

We now turn to the Higgs boson sector, which consists of four states, with two from the ordinary doublets $H_{u,d}$ and the other two from the triplets $\Delta_{u,d}$. For that, we need to write the scalar potential of the model. Gathering all the contributions from F, D and soft terms, the neutral part of the scalar potential can be written as

$$\begin{aligned} V_H = {} & \left(m_{H_d}^2 + |\mu|^2\right)|H_d^0|^2 + \left(m_{H_u}^2 + |\mu|^2\right)|H_u^0|^2 + \\ & + (b_H H_d^0 H_u^0 + \text{H.c.}) + (b_\Delta \delta_u^0 \delta_d^0 + \text{H.c.}) + \\ & + m_{\Delta_d}^2 |\delta_d^0|^2 + m_{\Delta_u}^2 |\delta_u^0|^2 + \\ & + \left(A_u \left|H_u^0\right|^2 \delta_u^0 - A_d \left|H_d^0\right|^2 \delta_d^0 + \text{H.c.}\right) + \\ & + 4\mu\lambda_u H_d^0 H_u^0 \delta_u^0 - 4\mu\lambda_d H_d^0 H_u^0 \delta_d^0 + \\ & + 4\lambda_u^2 \left|H_u^0\right|^2 \left|\delta_u^0\right|^2 + 4\lambda_d^2 \left|H_d^0\right|^2 \left|\delta_d^0\right|^2 + \mu_\Delta^2 \left|\delta_d^0\right|^2 + \\ & + \mu_\Delta^2 \left|\delta_u^0\right|^2 + \lambda_d^2 \left|H_d^0\right|^4 + \lambda_u^2 \left|H_u^0\right|^4 + 2\mu_\Delta \lambda_u \delta_d^0 \left|H_u^0\right|^2 - \\ & - 2\mu_\Delta \lambda_d \delta_u^0 \left|H_d^0\right|^2 + \frac{g_1^2 + g_2^2}{8}\left[\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right]^2 + \\ & + \frac{g_1^2 + g_2^2}{2}\left[\left|\delta_d^0\right|^2 - \left|\delta_u^0\right|^2\right]^2 + \frac{g_1^2 - g_2^2}{2} \times \\ & \times \left[\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right]\left[\left|\delta_d^0\right|^2 - \left|\delta_u^0\right|^2\right]. \end{aligned} \tag{9}$$

The triplets are expected to nearly decouple from the doublets because their mixings are induced by the triplet vevs, which however should be much smaller than a few GeVs, because otherwise the ρ parameter would deviate from unity beyond the experimentally allowed level [8]. In this picture, ignoring the insignificant effects, the SM-like Higgs boson mass can be expressed as

$$m_h \approx \\ \approx \sqrt{m_Z^2 \cos^2(2\beta) + 6v^2\left(\lambda_u^2 \sin^4(\beta) + \lambda_d^2 \cos^4(\beta)\right)}, \tag{10}$$

which is slightly above the MSSM tree-level mass owing to the new contributions of the triplets parameterized by their coupling constants $\lambda_{u,d}$. Thus, a sufficiently large tree-level Higgs boson mass requires sizable strengths of the $\lambda_{u,d}$ for each value of the angle β $(0 < \beta < \pi/2)$ defined by

$$\operatorname{tg}\beta = \frac{v_u}{v_d},$$

which is not fixed by present experiments. We illustrate this by plotting the Higgs mass m_h as a function of $\lambda_{u,d}$ in the Figure.

As we can see from the Figure, the constraint $m_h = 125$–126 GeV requires small $\lambda_u \sim 0.1$–0.25 and large $\lambda_d \sim 0.8$ for large $\operatorname{tg}\beta$ values, while large $\lambda_u \sim 0.8$–0.9 and small $\lambda_d \sim 0.2$–0.25 for small $\operatorname{tg}\beta$ values. Therefore, regardless of $\operatorname{tg}\beta$, one of the two Higgs triplets $\Delta_{u,d}$ has to be significantly coupled to the MSSM Higgs sector $\lambda_u(\lambda_d) \sim 1$. This scenario, on top of raising the SM-like Higgs boson mass, can at the same time enhance the Higgs decay width to the diphoton [8, 13, 14] and the Higgsino mixing in the neutralino sector.

3. NEUTRALINO AND LSP

In the present model, after the electroweak symmetry breaking, the neutral gauginos $\widetilde{B}$ and $\widetilde{W}^0$ combine with the two neutral MSSM Higgsinos $\widetilde{h}_u^0$, $\widetilde{h}_d^0$, and the neutral Higgsino triplets (triplinos) $\widetilde{\delta}_u^0$, $\widetilde{\delta}_d^0$ to form six mass eigenstates, called neutralinos. We let them be denoted by $\widetilde{N}_{i=1,2,\ldots,6}$, conventionally labeled in the ascending order, such that $m_{\widetilde{N}_i} < m_{\widetilde{N}_{i+1}}$. In the gauge-eigenstate basis

$$\widetilde{\psi}^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{h}_d^0, \widetilde{h}_u^0, \widetilde{\delta}_d^0, \widetilde{\delta}_u^0),$$

the neutralino-mass part of the Lagrangian is

$$L_{\widetilde{N}} = -\frac{1}{2}(\widetilde{\psi}^0)^T M_{\widetilde{N}} \widetilde{\psi}^0 + \text{H.c.}, \tag{11}$$

where the neutralino mass matrix takes the form[1)]

[1)] We use the abbreviations $s_\alpha = \sin\alpha$ and $c_\alpha = \cos\alpha$ for $\alpha = \beta, \theta_W$.

$$M_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_w & M_Z s_\beta s_w & 0 & 0 \\ 0 & M_2 & M_Z c_\beta c_w & -M_Z s_\beta c_w & 0 & 0 \\ -M_Z c_\beta s_w & M_Z c_\beta c_w & 0 & -\mu & \lambda_d v c_\beta & 0 \\ M_Z s_\beta s_w & -M_Z s_\beta c_w & -\mu & 0 & 0 & -\lambda_u v s_\beta \\ 0 & 0 & \lambda_d v c_\beta & 0 & 0 & \mu_\Delta \\ 0 & 0 & 0 & -\lambda_u v s_\beta & \mu_\Delta & 0 \end{pmatrix}. \qquad (12)$$

The entries M_1 and M_2 in this matrix come directly from the MSSM soft Lagrangian, while the entries $-\mu$ are the supersymmetric Higgsino mass terms. The terms proportional to M_Z are the result of Higgs–Higgsino–gaugino couplings, with the Higgs scalars replaced by their vevs $v_{u,d}$ after some rearranging, and the zero entries refer to the neglegted terms $M_Z v_{\Delta_{u,d}} s_w/v$ and $M_Z v_{\Delta_{u,d}} c_w/v$ proportional the suppressed triplet vevs $v_{\Delta_{u,d}}$ as constrained by the electroweak data [7].

The analytic analysis of the resulting neutralino mass matrix (12) is very difficult, unless we assume a space parameter configuration where the matrix is simplified or reduced, something which affects the model phenomenology. However, in the present model, we can derive the neutralino sector properties just from the corresponding matrix structure (12). Indeed, we can easily infer that the upper left four-by-four submatrix is nothing but the usual MSSM neutralino matrix, while the remaining components invloving $\lambda_{u,d}$ and μ_Δ parameterize the Higgs triplet extension effect. In this picture, we can assume that there is negligibile mixing between the neutral triplinos $\widetilde{\delta}_d^0$, $\widetilde{\delta}_u^0$ and the MSSM gauginos $\widetilde{B}$, $\widetilde{W}^0$, and large mixing occurs between the neutral MSSM Higgsinos $\widetilde{h}_d^0$, $\widetilde{h}_u^0$ and the neutral triplinos as well as between the two triplinos, respectively characterized by their coupling constants $\lambda_{u,d}$ and the triplino mass terms μ_Δ. Thus, the gaugino content of the neutralino remains practically intact, whereas the Higgsino content is enhanced with the triplet scalars. This could be interesting in the research of the widely studied dark matter candidate, i. e., mostly the lightest neutralino $\widetilde{N}_1$, LSP, which is usually assumed to be the potential particle that can produce dark matter unless there is a lighter gravitino or R-parity is not conserved [15]. In fact, a neutralino LSP is in general a mixture of all six gauge eigenstates. However, the character is normally dominated by only one or two constituents. In that context, we can here distinguish the cases listed in the Table.

Therefore, a neutralino LSP can have four different natures (bino, wino, Higgsino, triplino) in contrast to only three possibilities in the MSSM. Now, to be more predictive, we have the nice prediction $M_1 \approx M_2/2$ at the electroweak scale as expected from renormalization group equations [16]. If so, then the neutralino masses depend on only three unknown mass parameters, e. g., the bino mass M_1 and the supersymmetric Higgsino and triplino large masses μ and μ_Δ, and thus with the most likely mass parameter hierarchy

$$M_1 \ll M_2, \mu, \mu_\Delta,$$

the LSP has a tendency to be dominated by the lightest mass parameter M_1, bino-like, as often emerges from the large region of the MSSM parameter space [17, 18].

In the discussed extended model, although the effect of the Higgs triplets is not large enough to cause a large mixing between the usual MSSM-like states and the new ones, thus keeping an MSSM-like LSP, we expect that the prospects of its productions and detections could be dramatically affected. This can provide interesting features in the context of dark matter, where such a neutralino LSP must have the correct electroweak interaction strength and mass. Indeed, the decays of the produced particles result in final states with two neutralino LSPs. Some of the LSPs pair-annihilate into final states containing ordinary particles. In this model, we restrict ourselves to the relevant channel

$$\begin{gathered} \widetilde{N}_1 \widetilde{N}_1 \to (h^0, \delta^0, \dots) \to f\overline{f}, \\ f = t, b, \tau, \quad \overline{f} = \overline{t}, \overline{b}, \overline{\tau}, \end{gathered} \qquad (13)$$

involving intermediate Higgs and triplet scalars of the model, particulary the lightest Higgs h^0. In this picture, the dominance of a Higgs-intermediate annihilation processes depends on the LSP mass range, relying on its mixture state. We discuss the important extreme states. For a triplino-like LSP state, all the annihilation processes through the Higgs scalars are possible with a tendency to the process through the neutral triplet scalars δ^0, while for the recurring bino-like LSP, only the annihilation process through the MSSM Higgses is possible, probably with a tendency to the process with the lightest Higgs h^0. In this picture, $2m_{\widetilde{N}_1}$ should be greater than or equal to the lightest Higgs mass, leading to

Table. The neutralino LSP state according to the scale of the mass parameters of the model

Mass parameter	$M_1 \ll M_2, \mu, \mu_\Delta$	$M_2 \ll M_1, \mu, \mu_\Delta$	$\mu \ll M_1, M_2, \mu_\Delta$	$\mu_\Delta \ll M_1, M_2, \mu$
LSP state	Bino-like	Wino-like	Higgsino-like	Triplino-like

$$m_{\tilde{N}_1} \geqslant 62 \text{ GeV}. \tag{14}$$

Such an approach is interesting in the sense that it does not exclude a possible low-scale LSP, which is experimentally important.

4. CONCLUSION

Although the MSSM solves the hierarchy problem by providing a technical solution to the existence of a grand hierarchy between the GUT and the electroweak scales, in view of the actual Higgs-like discovery at the LHC provided by the ATLAS and CMS experiments, it seems to require an amount of fine tuning to interpret the observed 125.5 GeV Higgs-like mass. The appealing possibility is to introduce an extra sector of triplet chiral superfields coupled to the MSSM Higgs sector in the superpotential, which can increase the mass of the Higgs boson as well as its diphton production rate as recently confirmed.

In this paper, we have elucidated that the developed supersymmetric triplet Higgs model constitutes a simple alternative as regards generating neutrino masses and increasing the tree-level Higgs mass. This typically requires the triplet scalars with vevs much smaller than the electroweak symmetry breaking scale $v_{v_{\Delta_{u,d}}} \ll\sim 10^2$ GeV for $\sim$ eV-scale neutrino masses and from the elctroweak precision data, and one of the Higgs triplets with large coupling constants $\lambda_u(\lambda_d) \sim 1$ for an observed Higgs mass $\sim$ 125.5 GeV. Under these restrictions, we have determined the neutralino sector extended by the Higgs triplet neutral compenents and then discussed its compositeness according to the allowed range of the constrained parameters crucial for the LSP state whose nature is found to be MSSM-like, while its behavior is expected to be decisive for all experimental supersymmetric scalar signatures.

We have only briefly discussed one of the possible Higgs-triplet MSSM extensions, partly due to the experimental uncertainties, which are currently still being too large. However, a dedicated study, both theoretical and experimental, covering this region is worth attempting in the future, when more data concerning the Higgs sector is accumulated at the LHC.

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