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# Extended Higgs sector at the LHC

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**Summary.** — We present an extension of the Minimal Supersymmetric Standard Model with a $Y = 0$ $SU(2)$ triplet superfield and a Standard Model gauge singlet superfield. We present some of the relevant features of the model, dubbed TNMSSM, together with the most important results for the simulations of the decay of the 125 GeV Higgs in a pseudoscalar pair at the LHC and the pair production of light charged Higgs bosons at the LHC.

## 1. – Introduction

The success of the Standard Model (SM) in explaining the gauge structure of the fundamental interactions has reached its height with the discovery of a scalar particle with most of the properties of the SM Higgs boson —such as a 125 GeV mass resonance— at the LHC [1]. With this discovery, the mechanism of spontaneous symmetry breaking of the gauge symmetry, which in a gauge theory such as the SM is mediated by a Higgs doublet, has been confirmed, but the possible existence of an extended Higgs sector, at the moment, cannot be excluded.

In fact the SM is not a completely satisfactory theory, even with its tremendous success, since it does not provide an answer to long-standing issues, most prominently the gauge-hierarchy problem. This is instead achieved by the introduction of supersymmetry, which, among its benefits, allows gauge coupling unification and, in its $R$-parity conserving version, also provides a neutral particle as a dark-matter candidate.

In the current situation, extensions of the Higgs sector with the inclusion of one or more electroweak doublets and/or of triplets of different hypercharges —in combination with SM gauge singlets— are still theoretical possibilities in both supersymmetric and non-supersymmetric extensions of the SM.

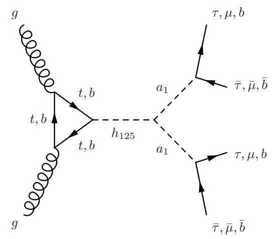



Fig. 1. – A pair of light pseudoscalars produced from a Higgs boson and their fermionic decays.

## 2. – Extended Higgs sector at the LHC

As detailed in [2], the TNMSSM contains a $SU(2)$ triplet $\hat{T}$ of zero hypercharge ($Y = 0$) together with a SM gauge singlet $\hat{S}$ added to the superfield content of the MSSM. The superpotential of the model is

$$\begin{aligned}\mathcal{W} &= y_t \hat{U} \hat{H}_u \cdot \hat{Q} - y_b \hat{D} \hat{H}_d \cdot \hat{Q} - y_\tau \hat{E} \hat{H}_d \cdot \hat{L} \\ &\quad + \lambda_T \hat{H}_d \cdot \hat{T} \hat{H}_u + \lambda_S \hat{S} \hat{H}_d \cdot \hat{H}_u + \frac{\kappa}{3} \hat{S}^3 + \lambda_{TS} \hat{S} \mathrm{Tr}[\hat{T}^2],\end{aligned} \tag{1}$$

whereas the potential is obtained from $F$-terms and $D$-terms togheter with the soft supersymmetry-breaking terms [2]. In the limit when the trilinear soft breaking parameters $A_i$ go to zero, the discrete $Z_3$ symmetry of the Lagrangian is promoted to a continuos $U(1)$ symmetry given by

$$(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S}) \to e^{i\phi} (\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S}). \tag{2}$$

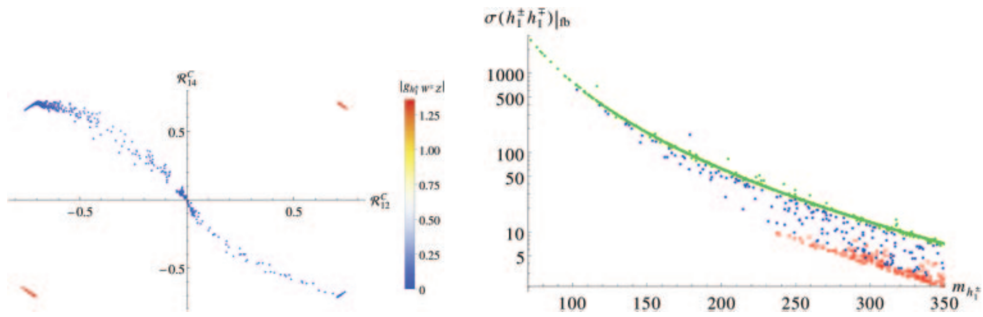
This symmetry is spontaneously broken by the vev of the doublets, triplet and the singlet fields and should contain a physical massless pseudoscalar, $a_1$, the Nambu-Goldstone boson of the symmetry. The soft breaking parameters will then lift the mass of $a_1$, turning it into a pseudo-Goldstone mode whose mass will depend on the $A_i$. We have considered the possibility, depicted in fig. 1, that a Higgs boson decays into a light pseudoscalar pair, with fermionic final states.

The fermionic final states are $2b+2\tau$, $3\tau$, $2b+2\mu$ and $2\tau+2\mu$, derived from the decays of such pseudoscalars. Depending on the specific channel, such light pseudoscalars can be probed with early LHC data ($\sim$25 fb$^{-1}$) at 13 and 14 TeV. The $2\tau + 2\mu$ decay mode of such states, though much cleaner compared to other channels, need higher luminosity ($\sim$2000 fb$^{-1}$) in order to be significant [3].

Apart from the presence of a light pseudoscalar in the spectrum, the charged Higgs sector of the TNMSSM presents distinctive features. This is due to the presence of the triplet, which enlarges the number of physical charged Higgses.

In general the interaction eigenstates are obtained via a mixing of the two Higgs doublets, the triplet and the singlet scalar. However, the singlet does not contribute to the charged Higgs bosons, which are mixed states generated only by the $SU(2)$ doublets and triplets. The rotations from gauge eigenstates to the interaction eigenstates are

$$h_i = \mathcal{R}^S_{ij} H_j, \quad a_i = \mathcal{R}^P_{ij} A_j, \quad h^\pm_i = \mathcal{R}^C_{ij} H^\pm_j, \tag{3}$$




(a) (b)

Fig. 2. – Relation between the coupling $g_{h_1^\pm W^\mp Z}$ and the rotation angels of the triplet (a) and pair production of light charged Higgs bosons at the LHC (b).

where $h_i = (h_1, h_2, h_3, h_4)$, $H_i = (H^0_{u,r}, H^0_{d,r}, S_r, T^0_r)$, $a_i = (a_0, a_1, a_2, a_3)$, $A_i = (H^0_{u,i}, H^0_{d,i}, S_i, T^0_i)$, $h_i^\pm = (h_0^\pm, h_1^\pm, h_2^\pm, h_3^\pm)$ and $H_i^+ = (H_u^+, T_2^+, H_d^{-*}, T_1^{-*})$. The phenomenology of the charged sector of theories with triplets is interesting for the presence of the $h^\mp Z W^\pm$ vertex at the tree level [4,5]. In the TNMSSM the coupling is given by

$$(4) \qquad g_{h_i^\pm W^\mp Z} = -\frac{i}{2}\left(g_L\, g_Y \left(v_u \sin\beta\, \mathcal{R}^C_{i1} - v_d \cos\beta\, \mathcal{R}^C_{i3}\right) + \sqrt{2}\, g_L^2 v_T \left(\mathcal{R}^C_{i2} + \mathcal{R}^C_{i4}\right)\right).$$

In fig. 2(a) we show the value of the coupling $g_{h_1^\pm W^\mp Z}$ as a function of the rotation angles $\mathcal{R}^C_{12}$ and $\mathcal{R}^C_{14}$, characterising the triplet. We can see that the $g_{h_1^\pm W^\mp Z}$ coupling is enhanced when $|\mathcal{R}^C_{12}| \sim |\mathcal{R}^C_{14}|$. This corresponds to the limit $\lambda_T \sim 0$ [4]. We have considered the pair production of such a light charged Higgs at the LHC, again looking for multileptonic final states. In fig. 2(b) we show the cross-section for the pair production of charged Higgs bosons, marking in green, red and blue the triplet-like, the doublet-like and the mixed states, respectively. Each of the triplet-like charged Higgs decays mostly in $a_1 W^\pm$ of $ZW^\pm$, because the decay into fermion is suppressed [4]. An interesting case is the $h_1^\pm h_1^\mp \to Z\, W^\pm Z\, W^\mp$ with $\geq 5\ell + \not{E}_T$ final state. This channel has more than $14\sigma$ of signal significance at an integrated luminosity of $1000\,\text{fb}^{-1}$. The integrated luminosity for $5\sigma$ of signal significance is $120\,\text{fb}^{-1}$. However, other decay channels have an integrated luminosity for $5\sigma$ of signal significance which is $\sim 1000\,\text{fb}^{-1}$ [4].

## 3. – Conclusions

The extension of the Higgs sector with higher representation of $SU(2)_w$ is interesting from both the theoretical and the phenomenological point of view. It can introduce new decay channels for the neutral Higgses ($h_i \to a_j\, a_k$) as well as new decay channels and production processes for the charged Higgses, as the charged vector boson fusion. The phenomenological studies done on the TNMSSM have shown the testability of such model, and similar, with early data at the LHC and at future colliders.

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