All about the Triplet

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• Introduction

• Increasing the Higgs mass w/o fine-tuning

• The Georgi-Machacek model, solving the T-parameter: susy breaking and dark matter.

• Conclusions
Introduction

• The run I of the LHC has discovered the last building block of the SM: The Higgs

• Its properties are compatible with the ones of the SM: minimal realization of the Higgs potential

• But an extended Higgs sector is not yet excluded and can have different and interesting signatures.
• One way of deviating from the minimal model is to include extra Higgses:
  • More doublets
  • singlets
  • Triplets
  • ……
• These extra fields could appear in a UV completion of the model and could remain light by the same mechanism as the SM Higgs

• Pseudo-goldstone boson

• Supersymmetry
• In this talk I am going to explore different aspects of an extended Higgs sector with triplets in a supersymmetric model.

• In general there are two possible triplets that could mix with the Higgs, Y=0 and Y=1.

• The kind of couplings are:

\[ W = \lambda_0 H_u T_0 H_d + \lambda_{+1} H_d T_{+1} H_d + \lambda_{-1} H_u T_{-1} H_u \]
• In principle the triplet will get a vev once EWSB occurs and can lead to a dangerous contribution to the T-parameter

• I will either make sure that the vev of the triplet component is small or implement a symmetry to avoid contributions to the T-parameter.
Increasing the Higgs mass w/o fine tuning

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• One of the properties of adding an extended Higgs sector in supersymmetry is that one can deviate from the usual formula:

\[ m_h^2 \leq m_z^2 \]

• Unfortunately one has to pay a price in fine tuning, in order to maximize the new contribution one has to decoupled non-supersymmetrically the new states.
One way to avoid the fine-tuning is to double the fields, to couple one to the Higgs and decouple the other one:

\[ W = \mu H_u \cdot H_d + \mu_\Sigma \text{Tr}(\Sigma_1 \cdot \Sigma_2) + W_{H-\Sigma} + W_{\text{Yukawa}} \]

This trick was previously exploited for the case of singlets arXiv:1308.0792

We will use triplets for a different dependence on \( \tan \beta \).
• In the case of \( Y=0 \) the effect is similar than the singlet.

• On the other hand for the case of \( Y=1 \) the two fields are already needed to cancel anomalies

• I will couple one of the two triplets to the Higgses and the other one will be inert:

\[
W_{H-\Sigma} = \lambda H_u \cdot \Sigma_1 H_u
\]
• We can write the potential in the following way:

\[
\Sigma_1 = \begin{pmatrix} T^- / \sqrt{2} & -T^0 \\ T^- & -T^- / \sqrt{2} \end{pmatrix}
\]

\[
\Sigma_2 = \begin{pmatrix} \chi^+ / \sqrt{2} & -\chi^{++} \\ \chi^0 & -\chi^+ / \sqrt{2} \end{pmatrix}
\]

\[
V_{\text{neutral}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_{\chi}^2 |\chi^0|^2 + m_T^2 |T^0|^2 \\
+ |2\lambda H_u^0 T^0 + \mu H_d^0|^2 + |\mu H_u^0|^2 + |\mu_S T^0|^2 + |\mu_S \chi^0 + \lambda H_u^0 H_u^0|^2 \\
+ \frac{g^2 + g'^2}{8} \left( H_u^0 H_u^0 - H_u^0 H_u^0 + 2T^0 T^0 - 2\chi^0 \chi^0 \right)^2 \\
+ \left( -\lambda A \lambda H_u^0 H_u^0 T^0 - \mu B \mu H_d^0 H_d^0 - \mu_S B_S T^0 \chi^0 + \text{h.c.} \right)
\]
Upon integration of the triplets and going to the decoupling limit one gets the following mass for the Higgs (SM-like):

\[
m_h^2 = m_Z^2 \cos^2(2\beta) + \text{(stop loops)} + 4v^2 \lambda^2 \sin^4(\beta) \left( \frac{m_\chi^2}{\mu^2_\Sigma + m_\chi^2} \right) \\
- \frac{v^2 \lambda^2 \sin^2(2\beta)}{\mu^2_\Sigma + m_T^2} |2\mu^* - A_\lambda \tan(\beta)|^2.
\]
• Problems:

• Fine-tuning:

\[ \Delta = \frac{2}{m_h^2} \max \left( m_{H_u}^2, m_{H_d}^2, \frac{dm_{H_u}^2}{d \log (u)} L, \frac{dm_{H_d}^2}{d \log (u)} L, \delta m_{H_u}^2, \mu B_{\mu, \text{eff}} \right) \]

• T-parameter:

\[
\langle T^0 \rangle_{Y=-1} \approx -\frac{v^2 \lambda \sin(2\beta) (2\mu^* - A_\lambda \tan(\beta))}{2 \mu_\Sigma^2 + m_T^2} \quad \text{and} \quad \langle \chi^0 \rangle_{Y=1} \approx v^2 \frac{-\lambda \mu_\Sigma \sin^2(\beta)}{\mu_\Sigma^2 + m_\chi^2}
\]
$m_T = 800 \text{ TeV} \quad \lambda = 0.25$
• This model also changes the different decays channels since there are more states.

• Specially having more charginos can lead to distinct patterns of decays of stops

• The main drawback are the bounds that come from the T-parameter
The (SUSY)-Georgi-Machacek model: SUSY breaking and DM

- The GM model was proposed to ensure a custodial structure with triplets.

- It was supersymmetrized in arXiv:1308.4025

\[
\bar{H} = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}, \quad \bar{\Delta} = \begin{pmatrix} -\Sigma_1/\sqrt{2} & -\Sigma_{-1} \\ -\Sigma_1 & \Sigma_0/\sqrt{2} \end{pmatrix}
\]

\[
W_0 = \lambda \bar{H} \cdot \bar{\Delta} \bar{H} + \frac{\lambda_3}{3} \text{tr} \bar{\Delta}^3 + \frac{\mu}{2} \bar{H} \cdot \bar{H} + \frac{\mu}{2} \text{tr} \bar{\Delta}^2 + h_t \bar{Q}_L \cdot H_2 t_R + h_b \bar{Q}_L \cdot H_1 b_R
\]
• RGE evolution, yukawa and U(1) break the custodial limit and generate a non-zero $\rho$ so in general:

$$W = -\lambda_a H_1 \cdot \Sigma_1 H_1 + \lambda_b H_2 \cdot \Sigma_{-1} H_2 + \sqrt{2} \lambda_c H_1 \cdot \Sigma_0 H_2 + \sqrt{2} \lambda_3 \text{tr} \Sigma_1 \Sigma_0 \Sigma_{-1}$$
$$- \mu H_1 \cdot H_2 + \frac{\mu \Delta_a}{2} \text{tr} \Sigma_0^2 + \mu \Delta_b \text{tr} \Sigma_1 \Sigma_{-1} + h_t \overline{Q}_L \cdot H_2 t_R + h_b \overline{Q}_L \cdot H_1 b_R$$

$$V_{\text{SOFT}} = m_{H_1}^2 H_1^\dagger H_1 + m_{H_2}^2 H_2^\dagger H_2 + m_{\Sigma_0}^2 \Sigma_0^\dagger \Sigma_0 + m_{\Sigma_1}^2 \Sigma_1^\dagger \Sigma_1 + m_{\Sigma_{-1}}^2 \Sigma_{-1}^\dagger \Sigma_{-1} - m_3^2 H_1 \cdot H_2$$
$$+ \left\{ \frac{B_{\Delta_a}}{2} \text{tr} \Sigma_0^2 + B_{\Delta_b} \text{tr} \Sigma_1 \Sigma_{-1} - A_{\lambda_a} H_1 \cdot \Sigma_1 H_1 + A_{\lambda_b} H_2 \cdot \Sigma_{-2} H_2$$
$$+ \sqrt{2} A_{\lambda_c} H_1 \cdot \Sigma_0 H_2 + \sqrt{2} A_{\lambda_3} \text{tr} \Sigma_1 \Sigma_0 \Sigma_{-1} + a_t \overline{Q}_L \cdot H_2 \tilde{t}_R + a_b \overline{Q}_L \cdot H_1 \tilde{b}_R + h.c. \right\}$$
• I am going to embed this model into a predictive scenario of SUSY breaking like GMSB to see the deviation from the custodial limit:

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\[ W = \left( \tilde{\lambda}^{ij}_8 X + M^{ij}_8 \right) \Phi_{8i} \Phi_{8j} + \left( \tilde{\lambda}^{ij}_3 X + M^{ij}_3 \right) \Phi_{3i} \Phi_{3j} + \left( \tilde{\lambda}^{ij}_1 X + M^{ij}_1 \right) \Phi_{1i} \Phi_{1j} \]

\[ M_3 = \frac{\alpha_3(M)}{4\pi} 3 n_8 g(\Lambda_8 / M) \Lambda_8, \]
\[ M_2 = \frac{\alpha_2(M)}{4\pi} 2 n_3 g(\Lambda_3 / M) \Lambda_3, \]
\[ M_1 = \frac{\alpha_1(M)}{4\pi} \frac{6}{5} n_1 g(\Lambda_1 / M) \Lambda_1, \]

\[ m_f^2 = 2[C_3^f \left( \frac{\alpha_3(M)}{4\pi} \right)^2 3 n_8 f(\Lambda_8 / M) \Lambda_8^2 + C_2^f \left( \frac{\alpha_2(M)}{4\pi} \right)^2 2 n_3 f(\Lambda_3 / M) \Lambda_3^2 + C_1^f \left( \frac{\alpha_1(M)}{4\pi} \right)^2 \frac{1}{2} \left( \frac{6}{5} \right)^2 n_1 f(\Lambda_1 / M) \Lambda_1^2]. \]
• The spectrum is generated at a high scale $M$
• Run down to the EW scale
• EWSB it is imposed
• $m_h=125$ GeV
• All experimental constrains (direct & indirect) are satisfied
\[ n_1 = 1, \ n_3 = 2, \ n_8 = 6 \quad \text{and} \quad \tilde{\lambda}_1 = 0.9, \ \tilde{\lambda}_3 = 0.5, \ \tilde{\lambda}_8 = 0.1. \]
5.2 Sleptons

ATLAS and CMS searches place strong bounds on slepton masses [30, 31]. These will change depending on whether \( \tilde{\tau}_R \) is the NLSP or not. If \( \tilde{\tau}_R \) is the NLSP, LHC searches give \( m_{\tilde{\tau}_R} \leq 250 \text{ GeV} \) and \( m_{\tilde{\tau}_L} \leq 300 \text{ GeV} \). Bounds are relaxed if we have a neutralino NLSP to which the \( \tilde{\tau}_R \) decays. In this case, from the exclusion regions in the \((m_{\tilde{\chi}_0^1}, m_{\tilde{\tau}_R})\) plane from decays \( \tilde{\tau}_R \rightarrow \tilde{\chi}_0^1 \), it turns out that for \( m_{\tilde{\chi}_0^1} \leq 100 \text{ GeV} \), there is no LHC constraint on \( m_{\tilde{\tau}_R} \), so that only the LEP bound \( m_{\tilde{\tau}_R} \leq 100 \text{ GeV} \) survives. The latter case applies to our benchmark scenario #1 where \( m_{\tilde{\chi}_0^1} > 100 \text{ GeV} \). In the benchmark scenario #2 we explore the former case and we can see from the mass spectrum that \( m_{\tilde{\tau}_R} \) and \( m_{\tilde{\tau}_L} \) are above their experimental lower bounds.

5.3 Higgs scalars

There are a total of five neutral \( CP \)-even, 4 \( CP \)-odd, 5 singly charged, and two doubly charged massive Higgs scalar fields in this model. With the help of a smooth limit to the MSSM scalar sector, when \( v \rightarrow 0 \), we can identify the MSSM-like states as those which remain light in that limit [18]. Due to the small mixing angles between doublets and triplets, the MSSM-like scalars

\[ \tan \beta = 1.38 \]
• There are deviations on Higgs properties and exotic decays like:

\[ H^\pm \rightarrow W^\pm Z \]

<table>
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<tr>
<th>Scenario #1</th>
<th>WW</th>
<th>ZZ</th>
<th>bb</th>
<th>tt</th>
<th>γγ</th>
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<td>( r_{hXX} )</td>
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<td>1.04</td>
<td>1.01</td>
<td>1.01</td>
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<tr>
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<td>( \mu_{hXX}^{(WF)}, \mu_{hXX}^{(Wh)} )</td>
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<td>1.14</td>
<td>1.08</td>
<td>1.07</td>
<td>1.58</td>
</tr>
<tr>
<td>( \mu_{hXX}^{(ZF)}, \mu_{hXX}^{(Zh)} )</td>
<td>1.14</td>
<td>1.11</td>
<td>1.06</td>
<td>1.05</td>
<td>1.54</td>
</tr>
</tbody>
</table>
How about DM?

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- Having extra fermionic states can have an impact in the composition and properties of the LSP
- I am going to present different cases where the relic abundance is obtained
- NB: I am deviating from GMSB. i.e. the gravitino is not the LSP!!!!!! (thanks to E. Pontón)
The composition of the LSP in terms of the gauge eigenstates is shown in Fig. 3 for the

\[ M = \begin{pmatrix}
    M_1 & 0 & -\frac{g'}{\sqrt{2}} c_\beta v_H & \frac{g'}{\sqrt{2}} s_\beta v_H & 0 & -g' v_\Delta & g' v_\Delta \\
    0 & M_2 & \sqrt{2} g_2 c_\beta v_H & -\frac{g_2}{\sqrt{2}} s_\beta v_H & 0 & g_2 v_\Delta & -g_2 v_\Delta \\
    -\frac{g'}{\sqrt{2}} c_\beta v_H & \frac{g'}{\sqrt{2}} g_2 c_\beta v_H & -\sqrt{2} \lambda v_\Delta & -\frac{\sqrt{2}}{\sqrt{2}} \lambda v_\Delta - \mu & -\lambda s_\beta v_H & 0 & -2 \lambda c_\beta v_H \\
    \sqrt{2} g' s_\beta v_H & -\frac{g'}{\sqrt{2}} g_2 s_\beta v_H & -\sqrt{2} \lambda v_\Delta - \mu & -\sqrt{2} \lambda v_\Delta & -\lambda c_\beta v_H & -2 \lambda s_\beta v_H & 0 \\
    0 & 0 & -\lambda s_\beta v_H & \lambda c_\beta v_H & \mu & -\frac{1}{\sqrt{2}} \lambda s_\beta v_H & -\frac{1}{\sqrt{2}} \lambda c_\beta v_H \\
    -\lambda v_\Delta & g_2 v_\Delta & 0 & -2 \lambda s_\beta v_H & -\frac{1}{\sqrt{2}} \lambda s_\beta v_H & 0 & \mu \Delta - \frac{1}{\sqrt{2}} \lambda v_\Delta \\
    -g_2 v_\Delta & -2 \lambda c_\beta v_H & 0 & -\frac{1}{\sqrt{2}} \lambda s_\beta v_H & \mu \Delta - \frac{1}{\sqrt{2}} \lambda s_\beta v_H & 0 & 0
\end{pmatrix} \]

Neutralino Mass-Matrix
Composition of the LSP

\[ \mu = 250 \text{ GeV}; \mu = 250 \text{ GeV}; \nu = 10 \text{ GeV} \]

\[ \mu = 250 \text{ GeV}; \mu = 200 \text{ GeV}; \nu = 10 \text{ GeV} \]

\[ \mu = 250 \text{ GeV}; \mu = 400 \text{ GeV}; \nu = 10 \text{ GeV} \]

\[ M_2 = 1 \text{ TeV} \]
Relic Abundance
Spin independent xsec

The spin-independent cross section is mediated by the doublet scalars. There is not much suppression for masses in this range for the LSP, the values of which can be excluded by LUX. The points are achieved through a triplet funnel, and to get lower spin-independent cross section.

The larger value of maximum value of $v_\Delta$ is what drives the nuclear cross sections so large. The cross sections are lower when the $v_\Delta$ for masses in this range for the LSP, the values of which can be excluded by LUX. The points are achieved through a triplet funnel, and to get lower spin-independent cross section.

Figure 6. Spin-independent dark matter nucleon cross sections. Each point meets the correct relic abundance with the annihilation mode marked. Points with smaller Higgsino components have a lower spin-independent cross section.

The spin-independent cross section is maximized at each point respectively. The shaded blue region is excluded by LUX. The larger value of maximum value of $v_\Delta$ is what drives the nuclear cross sections so large. The cross sections are lower when the $v_\Delta$ for masses in this range for the LSP, the values of which can be excluded by LUX. The points are achieved through a triplet funnel, and to get lower spin-independent cross section.

$\nu_\Delta = 10 \text{ GeV}; \tan \beta = 1$

$\nu_\Delta = \text{max}; \tan \beta = 1$

$\nu_\Delta = 10 \text{ GeV}; \tan \beta = 2$

$\nu_\Delta = \text{max}; \tan \beta = 2$
Spin dependent xsec
Indirect detection

Indirect detection limits. The points with low values have at least a moderate Higgsino component compared to the model points giving the correct relic abundance with the current best direct detection limits. The lines mark the limits assuming the annihilation occurs 100% of the time in the early universe over a large range of values for the Higgsino mass parameter.

The annihilation cross section times velocity of dark matter in the galaxy in the current universe marked. Each point meets the correct relic abundance with the annihilation mode in the early universe marked. The lines mark the limits assuming the annihilation occurs 100% of the time in the early universe.
Conclusions

• One of the multiple possibilities for physics beyond the SM is an extended Higgs sector

• Extra scalars appear naturally in UV theories attempting to explain the Hierarchy problem

• In this talk I have supposed that supersymmetry is the explanation of the EW scale and moreover that there are triplets coupled to the usual Higgses.
• I have studied the reduction of fine tuning in the case where there is only a triplet of $Y=1$.

• Indeed one can find regions of the parameter space where there is sensibly much less tuning and the phenomenology of stops can be greatly changed.

• The main drawback is that one has to be careful about contributions to the $T$-parameter.
• One way to automatically have the T-parameter under control is the GM model.

• I have introduced the SCTM and study how can it be embedded into GMSB

• It naturally leads to a low messenger scale

• But one can successfully have a complete model with low tan β
• Finally I have analyzed the implications that having an extended sector of neutralinos on DM.

• New regions appear that can have very interesting implications for direct and indirect detection.

• The SCTM has very exotic decays for the Higgs sectors that I am currently studying.