Supersymmetric Custodial Triplets

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Why do we extend the Higgs sector?

- Motivation

How do we extend the Higgs sector?

- The Model

What happens if we do so?

- The spectrum
- Couplings (not enough time!)
- Higgs rates (not enough time!)
- Breaking the custodial symmetry (not enough time!)

What is important about all this?

- Summary

Motivation

The main question

Is a Higgs at $m_H \sim 125$ GeV too heavy for supersymmetry?

Higgs Mass

$$m_h^2 = m_Z^2 \cos 2\beta^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + \frac{X_t^2}{m_S^2}\left(1 - \frac{X_t^2}{12m_S^2}\right)\right]$$

A way of thinking about naturalness:

Radiative effects must not exceed tree-level effects in size.

How could we alleviate this so that the Higgs gets his mass more naturally?

- Enhance the logarithm by making m_S large
- Enhance the threshold correction by living close to maximal mixing
- Enhance the loop level contribution to the Higgs mass with additional matter
- Enhance the tree level contribution to the Higgs mass

Enhance the tree level contribution to the Higgs mass?

The Higgs mass is directly related to the value of the quartic couplings $\rightarrow$ Enhance the quartic couplings either throught D-terms (extending the gauge structure of the theory) or F-terms (extending the Higgs sector).

Besides,

- Precision measurements of the Higgs are key if we want to unveil the true nature of the particle, in particular the Higgs couplings to other SM particles are pretty sensitive to some NP scenarios.
- By adding new Higgs degrees of freedom we can modify the couplings to SM particles.
- These new d.o.f. will also have the possibility of propagating through loops that give rise to Higgs decay modes (e.g. $h \to \gamma\gamma$).
- Also, by the extending the Higgs sector one can generate neutrino masses. (e.g. a type-II seesaw model can be accommodated when adding $SU(2)_L$ triplets to the theory.)

So,

$m_h = 125\ \mathrm{GeV}$ + possible departures of Higgs strengths with respect to the SM ones + neutrino masses

It seems that extending the Higgs structure of the theory is a possibility worth being pursued.

But!

One thing that has to be kept in mind when adding new scalar d.o.f. to the theory is that they will probably acquire a vev, in that case potentially dangerous contributions to the masses of the W and the Z could arise, spoiling the value of the ρ parameter.

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 + loops$$

Two possibilities,

Either we make the vev's really small by hand (adding large soft terms) or we protect the ρ parameter with a symmetry.

The custodial symmetry!

A global $SU(2)_L \otimes SU(2)_R$ spontaneously broken to $SU(2)_V$. Well known from the usual SM case, keeps $\rho = 1$ at tree level and protects it from dangerous loop level contributions.

The Model

Add triplets to the MSSM and write with them custodial invariants?

Georgi and Machacek already did this in the non supersymmetric case!
Doubly Charged Higgs Bosons, Nucl. Phys. B 262 (1985)

The MSSM Higgs sector H_1 and H_2 with respective hypercharges $Y = (-1/2,\, 1/2)$, is complemented with $SU(2)_L$ triplets, Σ_{-1}, Σ_0 and Σ_1 with hypercharges $Y = (-1,\, 0,\, 1)$.

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}, \quad \Sigma_{-1} = \Sigma_{-1}^i \sigma_i = \begin{pmatrix} \frac{\chi^-}{\sqrt{2}} & \chi^0 \\ \chi^{--} & -\frac{\chi^-}{\sqrt{2}} \end{pmatrix},$$

$$\Sigma_0 = \Sigma_0^i \sigma_i = \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}, \quad \Sigma_1 = \Sigma_1^i \sigma_i = \begin{pmatrix} \frac{\psi^+}{\sqrt{2}} & \psi^{++} \\ \psi^0 & -\frac{\psi^+}{\sqrt{2}} \end{pmatrix}.$$

How do we construct $SU(2)_L \otimes SU(2)_R$ invariants?

The two doublets and the three triplets are organized under $SU(2)_L \otimes SU(2)_R$ as $\bar{H} = (\mathbf{2}, \bar{\mathbf{2}})$, and $\bar{\Delta} = (\mathbf{3}, \bar{\mathbf{3}})$

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

under $SU(2)_L \otimes SU(2)_R$ transformations,

$$\bar{H} \to \bar{U}_R \otimes U_L \bar{H}, \quad \bar{\Delta} \to \bar{U}_R \otimes U_L \, \bar{\Delta} \, U_L^\dagger \otimes \bar{U}_R^\dagger$$

in the vacuum the condition for the custodial symmetry to be fulfilled is,

$$\langle \bar{H} \rangle = \bar{U}_R \otimes U_L \langle \bar{H} \rangle, \quad \langle \bar{\Delta} \rangle = \bar{U}_R \otimes U_L \, \langle \bar{\Delta} \rangle \, U_L^\dagger \otimes \bar{U}_R^\dagger$$

this will be true if $v_\chi = v_\phi = v_\psi \equiv v_\Delta$ and $v_{H_1} = v_{H_2} \equiv v_H \to$ Custodially preserving direction.

Custodial invariants: The superpotential and soft terms

$$W_0 = \lambda \bar{H} \cdot \bar{\Delta} \bar{H} + \frac{\lambda_3}{3} \mathrm{tr} \bar{\Delta}^3 + \frac{\mu}{2} \bar{H} \cdot \bar{H} + \frac{\mu_\Delta}{2} \mathrm{tr} \bar{\Delta}^2$$

$$\begin{aligned} V_{\rm soft} &= m_H^2 |\bar{H}|^2 + m_\Delta^2 \mathrm{tr} |\bar{\Delta}|^2 + \frac{1}{2} m_3^2 \bar{H} \cdot \bar{H} \\ &+ \left\{ \frac{1}{2} B_\Delta \mathrm{tr} \bar{\Delta}^2 + A_\lambda \bar{H} \cdot \bar{\Delta} \bar{H} + \frac{1}{3} A_{\lambda_3} \mathrm{tr} \bar{\Delta}^3 + h.c. \right\} \end{aligned}$$

The custodial symmetry is not exact!

$U(1)_Y$ and Yukawa couplings will explicitly break the custodial symmetry, therefore the RGE running will split the coefficients written in the expressions above in non custodially invariant coefficients.

- We expect the superpotential to be custodially symmetric at the EW scale $\rightarrow$ Bottom-up splitting.
- Since we write the soft terms at the SUSY breaking scale, we expect them to be custodially invariant at that scale $\rightarrow$ Top-down splitting.

The spectrum: Higgs sector

A good thing about this model is his calculabilty

The model has a very simple structure as a consequence of the underliying $SU(2)_V$ symmetry: scalars are classified into singlets, triplets and fiveplets with degenerate masses.

The change of basis to $SU(2)_V$ reps,

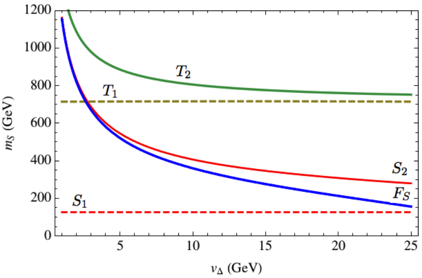
$$\bar{H} = (\mathbf{2}, \bar{\mathbf{2}}) = \mathbf{h_1} \oplus \mathbf{h_3}$$
$$\bar{\Delta} = (\mathbf{3}, \bar{\mathbf{3}}) = \delta_{\mathbf{1}} \oplus \delta_{\mathbf{3}} \oplus \delta_{\mathbf{5}}$$

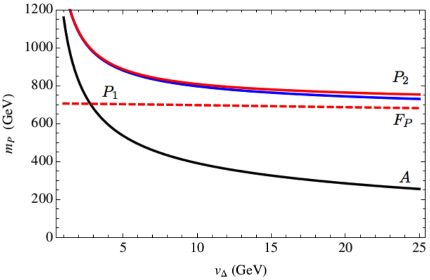
makes the structure of the mass eigenstates much simpler.

In fact, the EW breaking conditions coming from the derivatives of the scalar potential simplify from 5 to 2 when choosing the custodially preserving direction. Thus, only mixing between same $SU(2)_V$ representations will appear in mass eigenstates.

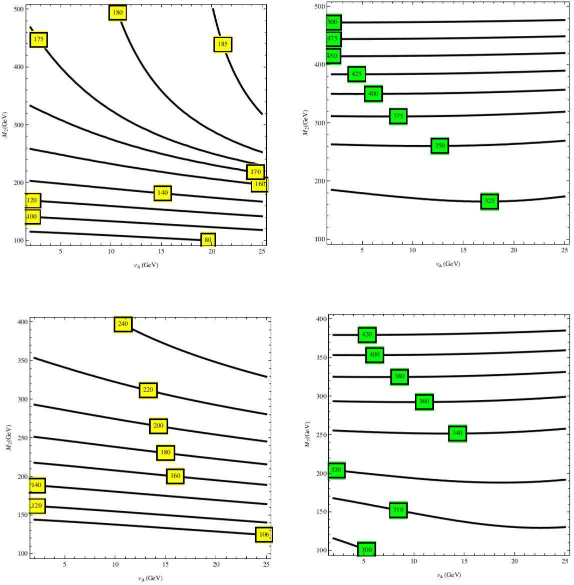
At the end of the day the mass eigenstates are classified into $SU(2)_V$ multiplets degenerate in mass,

- $SU(2)_V$ singlets: The scalars S_1 (the "Higgs-like" state) and S_2 and the pseudoscalars P_1 and P_2.
- $SU(2)_V$ triplets: The scalars T_1 and T_2 and the pseudoscalars G (the goldstone triplet) and A.
- $SU(2)_V$ quintuplets: The scalars F_S and the pseudoscalar F_P, these two contain doubly charged states).





The spectrum: Neutralinos and Charginos



Summary

- This model is a supersymmetrization of the (non-supersymmetric) model proposed long ago by Georgi and Machacek in,
  Doubly Charged Higgs Bosons, Nucl. Phys. B 262 (1985)
- The bosonic sector of the model has a very simple structure as a consequence of the underliying $SU(2)_V$ symmetry.
- The model shows to different decoupling regimes: *i)* $m_\Delta \to \infty$ ($v_\Delta \to 0$), in this case the triplet scalars become infinitely heavy and are decoupled from the doublet scalars (MSSM picture with $\tan\beta = 1$). Unlike other Higgs sector extensions, this limit is not compulsory since the custodial symmetry takes care of dangerous deviations of the ρ parameter. *ii)* $m_3^2 \to \infty$, this regime is similar to the MSSM one where the only surviving light state is the SM-like Higgs.

- Deviations in couplings and Higgs rates can be accommodated within the large parameter space.
- The model contains (bosonic and fermionic) doubly charged states which should yield typical signatures at the LHC.
- Due to the breaking of the custodial symmetry in the RGE running and the fact that as the adimensional couplings of the superpotential develop Landau poles sooner than in the non-extended cases, a low scale ($10 - 100$ TeV) supersymmetry breaking is expected.
- Finally, a loop analysis of the model is necessary in order to constrain regions in the large available parameter space.

THANK YOU FOR YOUR ATTENTION!