Supersymmetric Custodial Triplets

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Outline

The outline of this talk is

- Introduction
- GM model
- Supersymmetric Custodial Triplets model
- The Higgs sector
- Unitarity
- Higgs signal strengths @ LHC
- Custodial Symmetry Breaking
- Conclusion and outlook

Work done with (PhD students @ IFAE) Luis Cort and Mateo Garcia: arXiv:1308.4025

Introduction

- ATLAS & CMS have discovered a scalar boson with properties consistent with those of the SM Higgs and a mass ∼126 GeV.
- Whether or not it actually is the SM Higgs depends on possible (future) deviations from the SM predictions in Higgs strengths (e.g. $\gamma\gamma$ channel)
- In view of possible departures it is *interesting to explore* possible extensions of the Higgs sector
- A particularly appealing extension, which includes singly and doubly charged states, consists in adding triplets with $|Y| = 0, 1$
- Triplets have the general problem that their VEV contributes to the ρ parameter at the tree-level, strongly constraining the model as experimentally

$$\rho - 1 = \alpha T, \qquad -0.09 < T < 0.23 \quad @ \quad 95\% CL$$

- Problem solved by Georgi and Machacek (GM)

Georgi-Machacek model

- Georgi and Machacek [1]considered an extended SM Higgs sector
- The SM doublet ($Y = 1/2$)

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- A real $Y = 0$ triplet (ξ) and a complex $Y = 1$ triplet (χ)

$$\chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix} \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix} \quad \begin{matrix} \xi^- = -\xi^{+*} \\ \xi^0 = \xi^{0*} \end{matrix}$$

- They create a ρ parameter

$$\rho = 1 + \frac{v_\xi^2 - v_\chi^2}{v_\phi^2/2 + 2v_\chi^2}, \quad \langle\phi^0\rangle = v_\phi, \quad \langle\xi^0\rangle = v_\xi, \quad \langle\chi^0\rangle = v_\chi$$

[1] Georgi-Machacek, NPB **262** (1985) 463; Chanowitz-Golden, PLB **165** (1985) 105; Gunion-Vega-Wudka, PRD **42** (1990) 1673.

- They introduced

A global $SU(2)_L \otimes SU(2)_R$ invariance of the Higgs sector

- The Higgs transforms as a bi-doublet (Φ) and the triplet as a bi-triplet (χ)

$$\Phi^T = \begin{pmatrix} \tilde{\phi} \\ \phi \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix} \quad \begin{array}{c} \chi^- = -\chi^{+*} \\ \chi^{--} = \chi^{++*} \end{array}$$

- Transforming under $SU(2)_L \otimes SU(2)_R$ as

$$\Phi \to U_L \Phi U_R^\dagger \;, \quad \chi \to U_L \chi U_R^\dagger$$

- Broken to the custodial

$SU(2)_{L+R}$, ($\vec{\theta}_L = \vec{\theta}_R$) by the EW vacuum provided that

$$\langle \xi^0 \rangle = \langle \chi^0 \rangle$$

SCT: THE MODEL

- To supersymmetrize the GM model we need to double the number of Higgses (as in $SM \to MSSM$)

One doublet $\phi \Rightarrow$ Two doublets $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$

One real triplet $\xi \Rightarrow$ One complex triplet $\Sigma_0 = \begin{pmatrix} \phi^+ \\ \phi^0 \\ \phi^- \end{pmatrix}$

One triplet $\chi \Rightarrow$ Two triplets $\Sigma_1 = \begin{pmatrix} \psi^{++} \\ \psi^+ \\ \psi^0 \end{pmatrix} \oplus \Sigma_{-1} = \begin{pmatrix} \chi^{--} \\ \chi^- \\ \chi^0 \end{pmatrix}$

- The $SU(2)_L \otimes SU(2)_R$ bidoublets and bitriplets are organized as

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

where we are using the representation

$$\Sigma_{-1} = \begin{pmatrix} \frac{\chi^-}{\sqrt{2}} & \chi^0 \\ \chi^{--} & -\frac{\chi^-}{\sqrt{2}} \end{pmatrix}, \quad \Sigma_0 = \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}, \quad \Sigma_1 = \begin{pmatrix} \frac{\psi^+}{\sqrt{2}} & \psi^{++} \\ \psi^0 & -\frac{\psi^+}{\sqrt{2}} \end{pmatrix}$$

- The $SU(2)_L \otimes SU(2)_R$ invariant superpotential is

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

- The $SU(2)_L \otimes SU(2)_R$ invariant soft breaking potential

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

- The minimum equations are solved for the custodial point

$$v_1 = v_2 \equiv v_H, \quad v_\phi = v_\psi = v_\chi \equiv v_\Delta$$

- Electroweak breaking is guaranteed by the condition $\mathcal{H}$=Hessian matrix

$$\det \mathcal{H}|_0 < 0$$

or in the limit of $v_\Delta \to 0$ by

$$\lambda(2\mu - \mu_\Delta) - A_\lambda > 0$$

$$A_\lambda = A_{\lambda_3} = 0,\ \mu = \mu_\Delta = 250 \text{ GeV},\ m_3 = 500 \text{ GeV},\ B_\Delta = -m_3^2$$

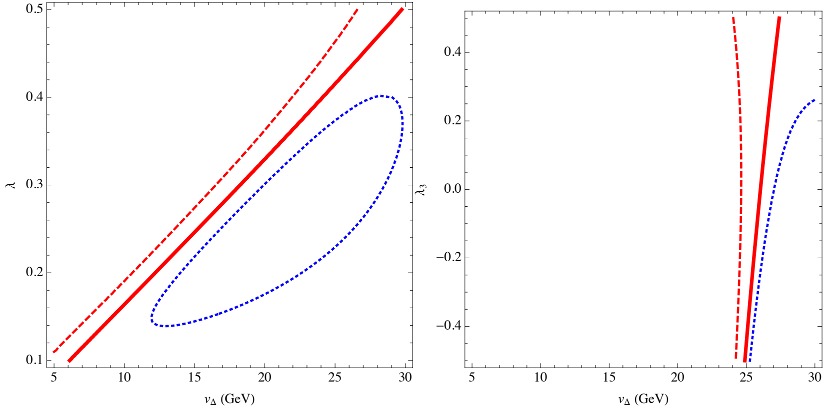


Figure: $\det \mathcal{H}|_0/v^{10}$ =-10 (dashed line), 0 (solid line) and 5 (dotted line). Left panel: $\lambda_3 = -0.35$. Right panel: $\lambda = 0.45$

- Using the $SU(2)_V$ invariance we can decompose supersymmetrically

$$H = h_1 \oplus h_3; \quad \Delta = \delta_1 \oplus \delta_3 \oplus \delta_5$$

$$h_1^0 = \frac{1}{\sqrt{2}}(H_1^0 + H_2^0); \quad h_3 = \left[h_3^+ = H_2^+,\ h_3^0 = \frac{1}{\sqrt{2}}(H_1^0 - H_2^0),\ h_3^- = H_1^-\right]$$

$$\delta_1^0 = \frac{\phi^0 + \chi^0 + \psi^0}{\sqrt{3}},\ \delta_3 \left[\delta_3^+ = \frac{\psi^+ - \phi^+}{\sqrt{2}}, \delta_3^0 = \frac{\chi^0 - \psi^0}{\sqrt{2}}, \delta_3^- = \frac{\phi^- - \chi^-}{\sqrt{2}}\right]$$
$$\delta_5 \left[\delta_5^{++} = \psi^{++},\ \delta_5^+ = \frac{\phi^+ + \psi^+}{\sqrt{2}},\ \delta_5^0 = \frac{-2\phi^0 + \psi^0 + \chi^0}{\sqrt{6}}\right.$$
$$\left.\delta_5^- = \frac{\phi^- + \chi^-}{\sqrt{2}},\ \delta_5^{--} = \chi^{--}\right]$$

- Explicitly: $X = (X_R + iX_I)/\sqrt{2},\ X = h_{1,3},\ \delta_{1,2,3}$

The Higgs sector

- There are a total of: 2 complex singlets (h_1, δ_1) 2 complex triplets (h_3, δ_3) and 1 complex fiveplet (δ_5)
- After electroweak breaking they break up into real $SU(2)_V$ multiplets

Singlets: 2 real scalars $\oplus$ 2 real pseudoscalars

- Scalars

$$\begin{pmatrix} h^0_{1R} \\ \delta^0_{1R} \end{pmatrix} \Rightarrow \begin{pmatrix} S_1 \\ S_2 \end{pmatrix} \otimes \alpha_S$$

- Pseudoscalars

$$\begin{pmatrix} h^0_{1I} \\ \delta^0_{1I} \end{pmatrix} \Rightarrow \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} \otimes \alpha_P$$

Goldstone triplet (massless)

$$G^0 = \cos\theta\, h^0_{3I} + \sin\theta\, \delta^0_{3I}; \qquad G^\mp = \cos\theta\, \frac{h_3^{\pm *} - h_3^\mp}{\sqrt{2}} + \sin\theta\, \frac{\delta_3^{\pm *} - \delta_3^\mp}{\sqrt{2}}$$

$$\sin\theta = \frac{2\sqrt{2}v_\Delta}{v}$$

3 massive triplets and 2 fiveplets

$$A=\left\{\begin{array}{c} A^0=-\sin\theta\, h^0_{3I}+\cos\theta\,\delta^0_{3I} \\ A^{\mp}=-\sin\theta\,\frac{h_3^{\pm *}-h_3^{\mp}}{\sqrt{2}}+\cos\theta\,\frac{\delta_3^{\pm *}-\delta_3^{\mp}}{\sqrt{2}}\end{array}\right.$$

$$T_H=\left(\begin{array}{c}\frac{1}{\sqrt{2}}(h_3^+ + h_3^{-*}) \\ h^0_{3R} \\ \frac{1}{\sqrt{2}}(h_3^- + h_3^{+*})\end{array}\right),\quad T_\Delta=\left(\begin{array}{c}\frac{1}{\sqrt{2}}(\delta_3^+ + \delta_3^{-*}) \\ \delta^0_{3R} \\ \frac{1}{\sqrt{2}}(\delta_3^- + \delta_3^{+*})\end{array}\right)$$

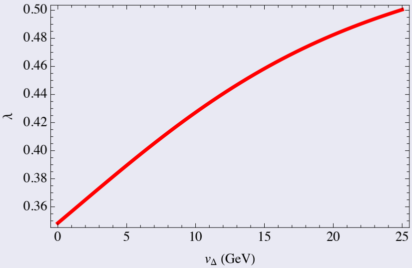
$$\left(\begin{array}{c} T_H \\ T_\Delta\end{array}\right)\Rightarrow\left(\begin{array}{c} T_1 \\ T_2\end{array}\right)\otimes\alpha_T$$

$$F_S=\left(\begin{array}{c}\frac{1}{\sqrt{2}}(\delta_5^{++}+\delta_5^{--*}) \\ \frac{1}{\sqrt{2}}(\delta_5^{+}+\delta_5^{-*}) \\ \delta^0_{5R} \\ \frac{1}{\sqrt{2}}(\delta_5^{-}+\delta_5^{+*}) \\ \frac{1}{\sqrt{2}}(\delta_5^{--}+\delta_5^{++*})\end{array}\right),\quad F_P=\left(\begin{array}{c}\frac{1}{\sqrt{2}}(\delta_5^{--*}-\delta_5^{++}) \\ \frac{1}{\sqrt{2}}(\delta_5^{-*}-\delta_5^{+}) \\ \delta^0_{5I} \\ \frac{1}{\sqrt{2}}(\delta_5^{+*}-\delta_5^{-}) \\ \frac{1}{\sqrt{2}}(\delta_5^{++*}-\delta_5^{--})\end{array}\right)$$

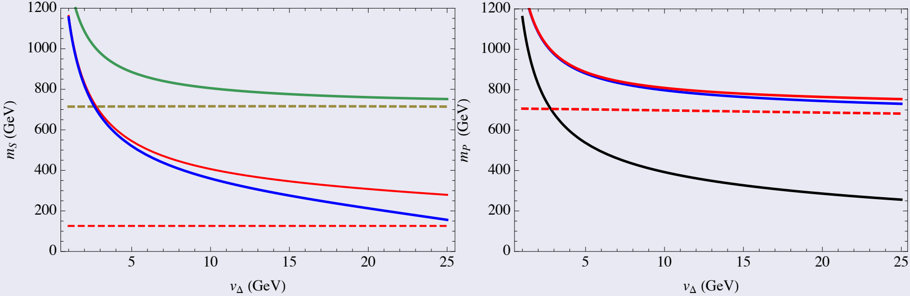
There are two decoupling limits in the Higgs sector

- The limit $m_\Delta \to \infty$ (i.e. $v_\Delta \to 0$)
  - Heavy states: S_2, P_2, T_2, A, F_S and F_P
  - Light states: G, S_1, P_1 and T_1
- The limit $m_H \to \infty$ (i.e. $m_3^2 \to \infty$)
  - Heavy states: P_1, T_1. P_1 plays the role of the massive MSSM pseudoscalar
  - Ligh states: S_1 which plays the role of the MSSM light SM-like Higgs

$\lambda = \lambda(v_\Delta)$ for: $A_\lambda = A_{\lambda_3} = 0, \mu = \mu_\Delta = 250\ \mathrm{GeV}, m_3 = 500\ \mathrm{GeV},\ B_\Delta = -m_3^2,\ \lambda_3 = -0.35$ and $m_{S_1} = 126$ GeV



Left panel: From bottom-up: S_1, F_S, S_2, T_1, T_2 Right panel: From bottom-up: A, P_1, F_P, P_2



In general because of the $SU(2)_V$ invariance all masses and mixing angles can be expressed analytically: mass matrices are at most 2×2 matrices

Unitarity

- It is interesting to check how the model unitarizes, e.g. $V_L V_L \to V_L V_L$
- Consider for instance the channel

$$W_L^+ W_L^+ \to W_L^+ W_L^+$$

- In the SM the Higgs h_{SM} contributes in the t and u channels so that in the limit where $s \to \infty$ the amplitude is proportional to $t + u$ with a coupling
$$(g_{hWW}^{SM})^2 = g^2 m_W^2$$
- Now there are neutral scalars $\mathcal{H}_i^0 = S_1, S_2, F_S^0$ which contribute to the t and u channels with an amplitude, in the limit $s \to \infty$, proportional to $t + u$.
- The doubly charged scalar F_S^{++} is exchanged in the s channel with an amplitude proportional to $-(t + u)$.

- The relevant couplings are

$$
\begin{aligned}
g_{F_S^{++}W^-W^-} = g_{F_S^{--}W^+W^+} &= -\sqrt{2} g m_W \sin\theta \\
g_{S_1 W^+W^-} &= g m_W \left(\cos\theta \cos\alpha_S - \sqrt{\tfrac{8}{3}} \sin\theta \sin\alpha_S \right) \\
g_{S_2 W^+W^-} &= g m_W \left(\cos\theta \sin\alpha_S + \sqrt{\tfrac{8}{3}} \sin\theta \cos\alpha_S \right) \\
g_{F_S^0 W^+W^-} &= -\tfrac{g m_W \sin\theta}{\sqrt{3}}
\end{aligned}
$$

- They enter the amplitude $A(W_L^+ W_L^+ \to W_L^+ W_L^+)$ asymptotically $(s \to \infty)$ proportional to

$$
\sum_{\mathcal{H}_i^0 = S_1, S_2, F_S^0} g^2_{\mathcal{H}_i^0 W^+W^-} - g^2_{F_S^{++}W^-W^-} = g^2 m_W^2 = (g_{hWW}^{SM})^2
$$

- At high energy the amplitude is unitarized as in the SM

Higgs signal strengths at LHC

- If we identify the recently discovered Higgs boson at LHC with S_1 the relevant couplings are

$r_{S_1 VV}$	$r_{S_1 ff}$	$r_{S_2 VV}$	$r_{S_2 ff}$
$c_S c_\theta - \sqrt{\frac{8}{3}} s_S s_\theta$	$\frac{c_S}{c_\theta}$	$s_S c_\theta + \sqrt{\frac{8}{3}} c_S s_\theta$	$\frac{s_S}{c_\theta}$

Table: *Notation:* $c_S = \cos\alpha_S$, $c_\theta = \cos\theta$, ...

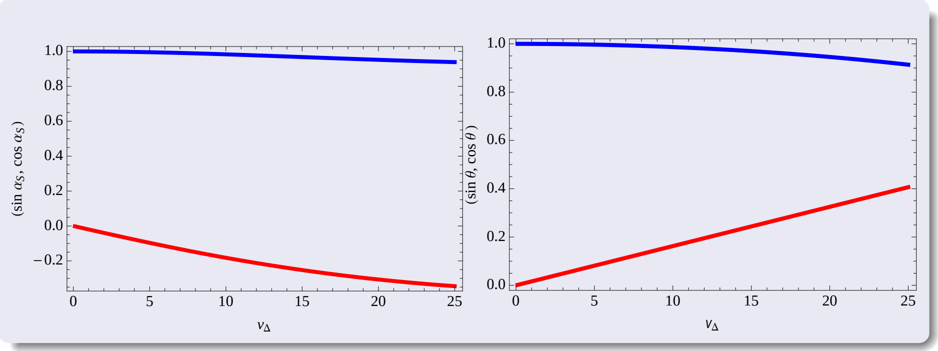
$r_{T_i^0 VV}$	$r_{T_1^0 uu}$	$r_{T_1^0 dd}$	$r_{T_2^0 uu}$	$r_{T_2^0 dd}$	$r_{F_S^0 WW}$	$r_{F_S^0 ZZ}$	$r_{F_S^0 ff}$
0	$-\frac{c_T}{c_\theta}$	$\frac{c_T}{c_\theta}$	$-\frac{s_T}{c_\theta}$	$\frac{s_T}{c_\theta}$	$\frac{s_\theta}{\sqrt{3}}$	$-\frac{2 s_\theta}{\sqrt{3}}$	0

Table: *Notation:* $s_T = \sin\alpha_T$, $s_\theta = \sin\theta$, ...

- Where

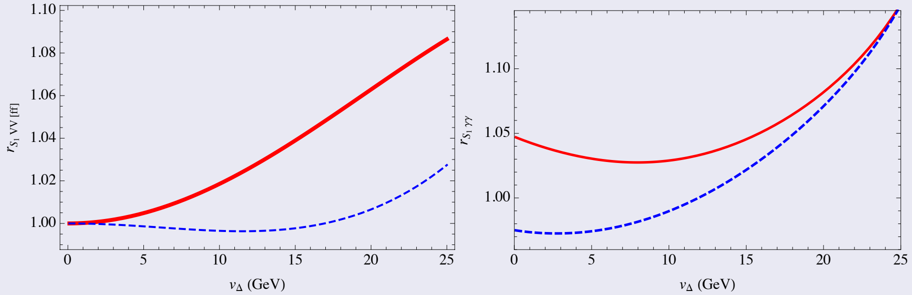
$$r_{\mathcal{H}XX} = g_{\mathcal{H}XX} / g_{hXX}^{\rm SM}$$

- The tree-level couplings of S_1 to WW, ZZ and ff (and its departure from the SM results) depend on α_S and θ
- For our typical set of values and $\lambda = \lambda(v_\Delta)$ fixing $m_{S_1} = 126$ GeV



- The larger v_Δ the larger the departure with respect to the SM values
- The loop couplings to $\gamma\gamma$ also depend on the masses of extra states (e.g. doubly charged scalars and fermions)

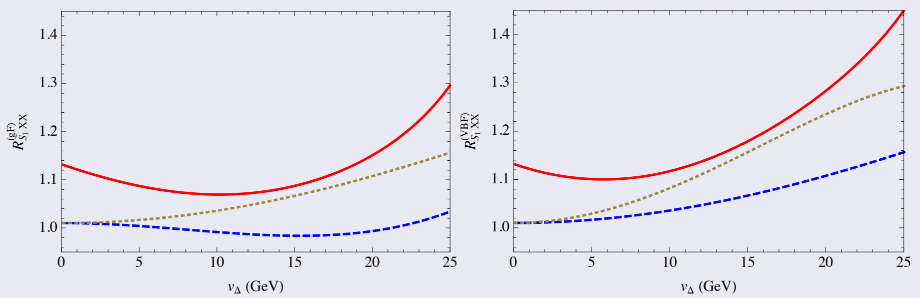
- The ratios to WW, ZZ, ff and $\gamma\gamma$ are given by



- Left panel: red (solid) is WW, ZZ and blue (dashed) is ff
- Right panel: red (solid) is $M_2 = 150$ GeV and blue (dashed) is $M_2 = 300$ GeV

- The Higgs signal strengths are defined as

$$\mathcal{R}_{S_1XX} = \frac{\sigma(pp \to S_1)BR(S_1 \to XX)}{[\sigma(pp \to h)BR(h \to XX)]_{SM}}$$



- Left panel: Gluon-fusion: Solid is $\gamma\gamma$, dashed is $bb, \tau\tau$, dotted is WW, ZZ
- Right panel: Vector boson fusion, same colour codes

Custodial symmetry breaking

- As the (top) Yukawa and hypercharge couplings explicitly violate the custodial symmetry, radiative corrections will spoil the custodial invariance of the vacuum
- If the custodial vacuum should be considered as a good approximation we should impose some conditions on the fundamental (UV) theory responsible for supersymmetry breaking

1. Soft supersymmetry breaking generated at some scale M respects the $SU(2)_L \otimes SU(2)_R$ symmetry in the Higgs sector. This means that supersymmetry breaking is generated by effective operators as

$$\int d^4\theta \frac{X^\dagger X}{M^2} Y^\dagger Y, \quad Y = H,\, \Delta,\, Q,\, L,\, E^c,\, U^c,\; D^c$$

where $\langle X \rangle = \theta^2 F$ is responsible for supersymmetry breaking

2. The breaking induced by RGE between the scales M and $m_{\widetilde{Q}}$ should be consistent with electroweak precision measurement, in particular with the T-parameter which measures the failure of custodial invariance. This translates into a *small enough* value of the variable $\log(M/m_{\widetilde{Q}})$ which is responsible for the RGE running

- In the theory with $SU(2)_L \otimes SU(2)_R$ the minimum equations at the VEV

$$v_1 = v_H,\ v_2 = v_H \tan\beta,\ v_\phi = v_\Delta(1+\delta\phi),\ v_\psi = v_\Delta(1+\delta\psi),\ v_\chi = v_\Delta(1+\delta\chi)$$

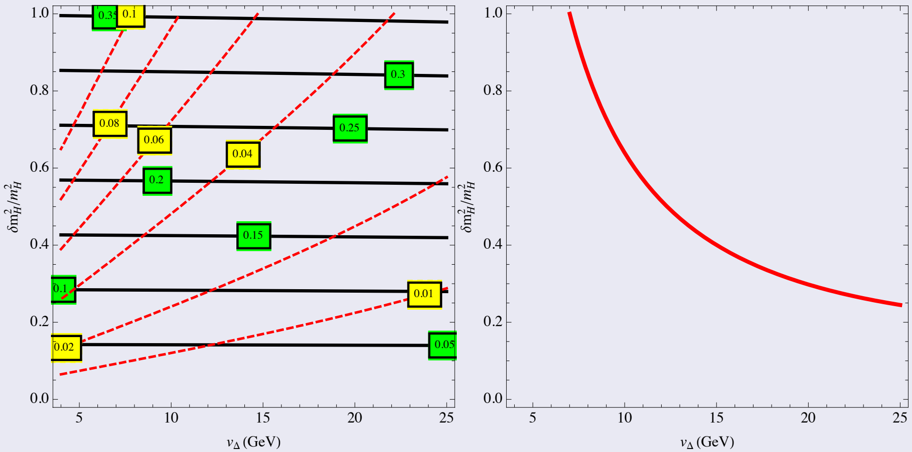
are identically satisfied at the custodial point

$$\tan\beta = 1, \delta\phi = \delta\psi = \delta\chi = 0$$

- Let us consider for simplicity only the leading effect of custodial breaking provided by the top Yukawa coupling

- In this case the soft breaking masses of the Higgs fields H_1 and H_2 are no longer equal so that $\delta m_H^2 \equiv m_{H_1}^2 - m_{H_2}^2 \neq 0$ is generated

Left: $tan\beta - 1$ (yellow), $\delta = 2\delta\phi - \delta\psi - \delta\chi$ (green). Right: Bound from T



- RGE running controlled by the one-loop β-function

$$8\pi^2\beta_{\delta m_H^2} = 3h_t^2(m_{H_2}^2 + m_Q^2 + m_{U^c}^2) + 6\chi_2^2(2m_{H_2}^2 + m_{\Sigma_{-1}}^2) - 6\chi_1^2(2m_{H_1}^2 + m_{\Sigma_1}^2)$$

- The second term is generated at two-loop as the departure from the tree-level relations $\chi_1 = \chi_2$ and $m_{\Sigma_{-1}}^2 = m_{\Sigma_1}^2$ only happens at one-loop
- In the one-loop approximation

$$\begin{aligned}\delta m_H^2/m_H^2 &\simeq 3h_t^2(m_{H_2}^2 + m_Q^2 + m_{U^c}^2)/m_H^2 \log(M/m_{\widetilde{Q}})/8\pi^2 \\ &\simeq (0.1 - 0.2)\, h_t^2(m_{H_2}^2 + m_Q^2 + m_{U^c}^2)/m_H^2\end{aligned}$$

for values $M \simeq 10 - 100$ TeV

- Its precise value should depend to a large extent on the particular mechanism of supersymmetry breaking

Conclusion and outlook

- We have presented a supersymmetric model with triplets and custodial symmetry at tree level
- It is a supersymmetrization of the GM model
- No quadratic divergences at loop order anywhere and in particular in the ρ parameter
- Rich phenomenology (to be explored) from singly and doubly scalars and fermions
- Landau pole at some intermediate scale $\Lambda \sim 10^3 - 10^5$ TeV
- Consistency for low supersymmetry breaking scale: $M \sim 10 - 100$ TeV
- It can provide, as type II seesaw, a renormalizable neutrino Majorana mass term from the $\Delta L = 2$ superpotential $W_\nu = h_\nu^{ij} L_i \Sigma_1 L_j$ which yields $\mathcal{M}_\nu^{ij} = h_\nu^{ij} v_\Delta$