SUSY Custodial Higgs Triplets

& BREAKING OF UNIVERSALITY

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IFT CSIC/UAM

Physics Challenges in the face of LHC-14

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Introduction

- ATLAS & CMS have discovered a scalar boson with properties consistent with those of the SM Higgs and a mass $\sim$125 GeV.
- Whether it actually is the SM Higgs depends on possible (future) deviations from the SM predictions in Higgs strengths (e.g. in the $\gamma\gamma$, or any other, channel)
- In view of possible SM departures in EWSB it is *interesting to explore* simple 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 (as generic non-doublet representations) the general problem that their VEVs contribute to the ρ parameter at the tree-level, strongly constraining the model, as experimentally we know

$$\rho - 1 = \Delta\rho, \qquad -4 \times 10^{-4} < \Delta\rho < 10^{-3} \quad @ \quad 95\% CL$$

- Problem considered by Georgi and Machacek (GM) in 1985!!!

Outline

- Overview of GM (non-supersymmetric ancestor) model
- Supersymmetric Custodial Triplet model
  - The Higgs sector
  - Unitarity
- Custodial Symmetry Breaking
  - Higgs mass
  - T parameter and custodial breaking
  - Higgs BR's and universality breaking
- Conclusion and outlook

Based on work done with L Cort, M Garcia (IFAE), arXiv:1308.4025; M Garcia (IFAE), S Gori (Perimeter), R Vega-Morales (Orsay), R Vega (SMU, Dallas), T-T Yu (Stoney Brook), arXiv:1409.5737

Georgi-Machacek (GM) 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 generically produce at tree level a ρ parameter

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

- Phenomenology widely studied

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

- They introduced

A global $SO(4) \simeq SU(2)_L \otimes SU(2)_R$ invariance of the Higgs sector

- The Higgs transforms as a bi-doublet (Φ) and the triplets as a bi-triplet (χ), with the identification $Y \equiv T_{R3}$

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

- 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

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

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

SUSY Custodial Triplet Model (SCTM)

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

One doublet $\phi \Rightarrow$ Two doublets $H_{1,-1/2} = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, H_{2,+1/2} = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$

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 $(\mathbf{2}, \overline{\mathbf{2}})$ and bitriplets $(\mathbf{3}, \overline{\mathbf{3}})$ are organized as $\overline{T}_{3R} \equiv Y$

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

where we are using the representation

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

- 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

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

- The EoM 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, not necessary (in preparation)

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

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

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

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

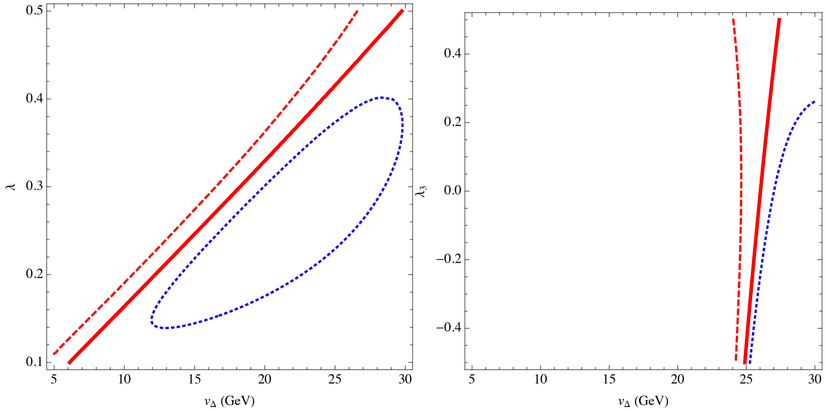


Figure: $\det \mathcal{H}|_0 / v^{10}$ =-10 (dashed line), 0 (solid line) and +5 (dotted line). Left panel: $\lambda_3 = -0.35$. Right panel: $\lambda = 0.45$

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

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

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

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

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

$$\left. \delta_5^- = \frac{\phi^- + \chi^-}{\sqrt{2}},\ \delta_5^{--} = \chi^{--} \right]$$

- Explicitly after EWSB: $X^0 = (X_R^0 + iX_I^0)/\sqrt{2}$, $X = h^0_{1,3},\ \delta^0_{1,3,5}$

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

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

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

$$\begin{pmatrix} T_H \\ T_\Delta \end{pmatrix} \Rightarrow \begin{pmatrix} T_1 \\ T_2 \end{pmatrix} \otimes \alpha_T$$

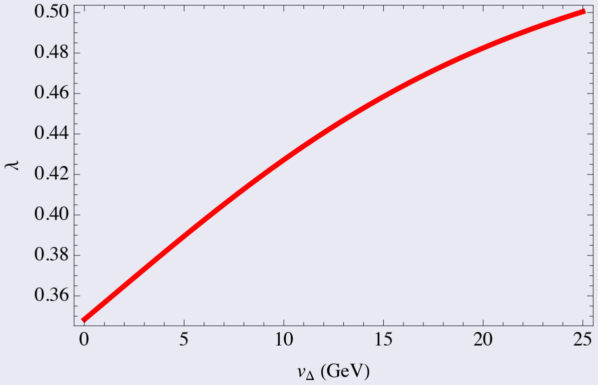
$$F_S = \begin{pmatrix} \frac{1}{\sqrt{2}}(\delta_5^{++} + \delta_5^{--*}) \\ \frac{1}{\sqrt{2}}(\delta_5^{+} + \delta_5^{-*}) \\ \delta^0_{5R} \\ \frac{1}{\sqrt{2}}(\delta_5^{-} + \delta_5^{+*}) \\ \frac{1}{\sqrt{2}}(\delta_5^{--} + \delta_5^{++*}) \end{pmatrix}, \quad F_P = \begin{pmatrix} \frac{1}{\sqrt{2}}(\delta_5^{--*}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

There are two decoupling limits in the Higgs sector

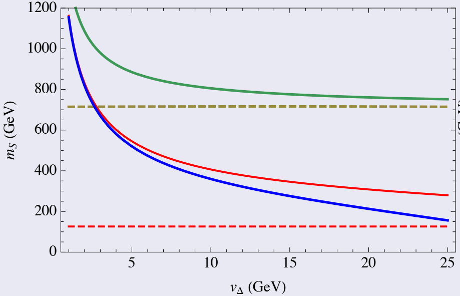
- The limit $m_\Delta \to \infty$ (i.e. $v_\Delta \to 0$)
  - 6 Heavy states: S_2, P_2, T_2, A, F_S and F_P
  - 4 Light states: G, S_1, P_1 and T_1
- The limit $m_H \to \infty$ (i.e. $m_3^2 \to \infty$)
  - Heavy states: P_1, T_1. P_1 plays the role of the MSSM pseudoscalar
  - Ligh state: S_1 which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

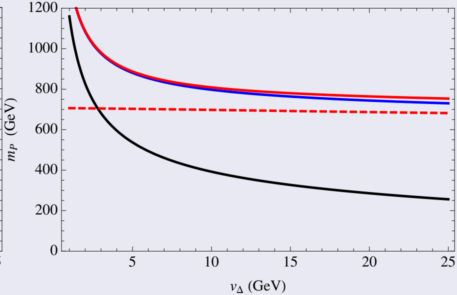
- The parameter λ gives a tree-level mass to the Higgs S_1 so that the LHC value can be reached with light stops and little mixing

$\lambda = \lambda(v_\Delta)$ 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 $m_{S_1} = 125$ GeV



From bottom-up: S_1, F_S, S_2, T_1, T_2 | **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

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

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

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

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

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
- As RGE running will break custodial symmetry, at which scale is the theory custodial invariant?
- A sensible assumption is

1. Soft supersymmetry breaking generated at some scale M (messenger scale) 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 the spurion responsible for supersymmetry breaking

2. The breaking induced by RGE between the scales M and $m_{SUSY} \sim 1$ TeV should be consistent with electroweak precision measurement, in particular with the T-parameter which measures the failure of custodial invariance. This should translate into a *region* in the plane defined by the variables $[\log(M/m_{\widetilde{Q}}), v_\Delta]$ which are responsible for RGE running

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

$$\tan\beta = \frac{v_2}{v_1}, \quad v_1 = \sqrt{2}\cos\beta v_H, \quad v_2 = \sqrt{2}\sin\beta v_H$$

$$\tan\theta_1 = \frac{v_\chi}{v_\psi}, \quad \tan\theta_0 = \frac{\sqrt{2}v_\phi}{\sqrt{v_\psi^2 + v_\chi^2}}$$

$$v_\psi = 2\cos\theta_1\cos\theta_0 v_\Delta, \quad v_\chi = 2\sin\theta_1\cos\theta_0 v_\Delta, \quad v_\phi = \sqrt{2}\sin\theta_0 v_\Delta$$

are identically satisfied at the custodial point

$$\tan\beta = \tan\theta_0 = \tan\theta_1 = 1$$

- However, the RGE running $M \to m_{SUSY}$ induces custodial breaking, and the parameters in the potential for the neutral components depart, at $Q = m_{SUSY}$, from their custodial values
- We write the most general non-custodial potential (neutral components)

$$
\begin{aligned}
W^0 &= \lambda_a H_d \Psi H_d + \lambda_b H_u \mathcal{X} H_u + \lambda_c H_d \Phi H_u + \lambda_3 \Psi \Phi \mathcal{X} \\
&- \mu H_d H_u + \frac{\mu_a}{2}\Phi^2 + \mu_b \Psi \mathcal{X} \\
V_D &= \frac{g^2 + g'^2}{8}(|H_d|^2 - |H_u|^2 + 2|\mathcal{X}|^2 - 2|\Psi|^2)^2 \\
V_{soft} &= m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_{\Sigma_1}|\Psi|^2 + m^2_{\Sigma_{-1}}|\mathcal{X}|^2 + m^2_{\Sigma_0}|\Phi|^2 \\
&+ \{A_a H_d \Psi H_d + A_b H_u \mathcal{X} H_u + A_c H_d \Phi H_u + A_3 \Psi \Phi \mathcal{X} \\
&- m_3^2 H_d H_u + B_a \Phi^2/2 + B_b \Psi \mathcal{X} + h.c.\}
\end{aligned}
$$

with Custodial values @ M (boundary condition)

$$\lambda_a = \lambda_b = \lambda_c \equiv \lambda$$
$$\mu_a = \mu_b \equiv \mu_\Delta$$
$$m_{H_u} = m_{H_d} \equiv m_H$$
$$m_{\Sigma_0} = m_{\Sigma_1} = m_{\Sigma_{-1}} \equiv m_\Delta$$
$$A_a = A_b = A_c \equiv A_\lambda$$
$$B_a = B_b \equiv B_\Delta$$

- This departure will trigger departure of the VEV's with respect to their custodial values, i.e.

$$\tan\beta \neq 1, \quad \tan\theta_0 \neq 1, \quad \tan\theta_1 \neq 1$$

after solving the EoM of the non-custodial theory

- With the corresponding generation of the T parameter as

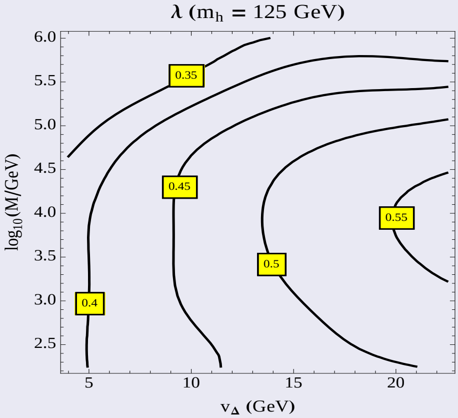
$$\alpha T = \frac{2v_\phi^2 - (v_\psi^2 + v_\chi^2)}{\frac{1}{2}(v_1^2 + v_2^2) + 2(v_\psi^2 + v_\chi^2)} = -4\frac{\cos 2\theta_0 \, v_\Delta^2}{v_H^2 + 8\cos^2\theta_0 v_\Delta^2}$$

- The RGE running will generate, mainly through its h_t dependence (but also through its g' dependence) a non-custodial value of $\tan\beta$ which in turn will trigger non-custodial values for the angles $\tan\theta_0$ and $\tan\theta_1$
- As we can see the T parameter is only sensitive to the non-custodial value of $\tan\theta_0$

A) Higgs mass

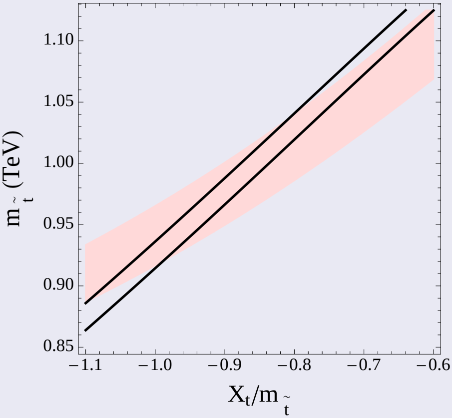
- We have to first fix λ for $m_{\mathcal{H}} \sim 125$ GeV:

$\lambda_3 = -0.35,\ m_{H,\Delta} = 1$ TeV, $M_a = 1.2$ TeV, $m_0/2 = \mu = \mu_\Delta = 250$ GeV



- We improve over the MSSM ($m_{\tilde{t}} \gtrsim 6$ TeV) for the Higgs mass with light stops and little mixing (as e.g. in gauge mediated models)

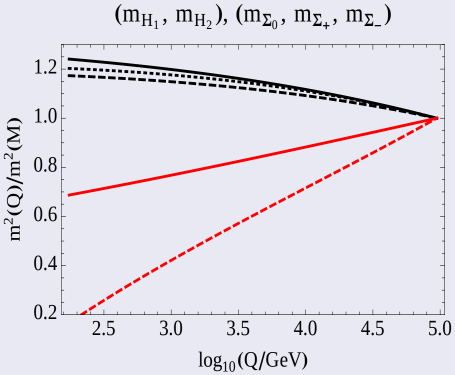
$\lambda = 0.45$, $\mathcal{M}$=65 TeV, $M_a = 1.2$ TeV, $v_\Delta = 10$ GeV, $m_0 \in [0.5, 1]$ TeV, $A_0 \in [-250, 500]$ GeV [pink band allowed by T (see later)]



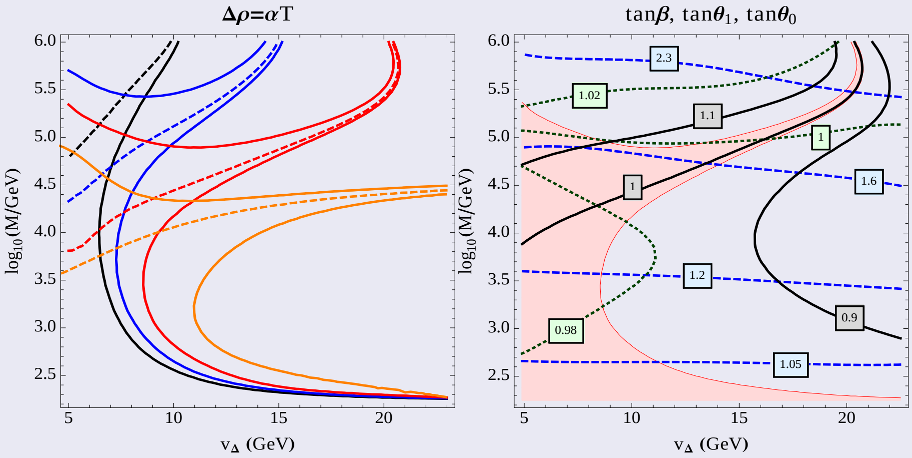
B) T-parameter & custodial breaking

- The more the couplings run (the larger M), the more loop corrections contribute to the custodial breaking ($m^2_{H_{u,d}}$, $m^2_{\Sigma_{0\pm}}$)

$M_a = 1.2$ TeV, $\mathcal{M} = 10^5$ GeV, $v_\Delta = 20$ GeV



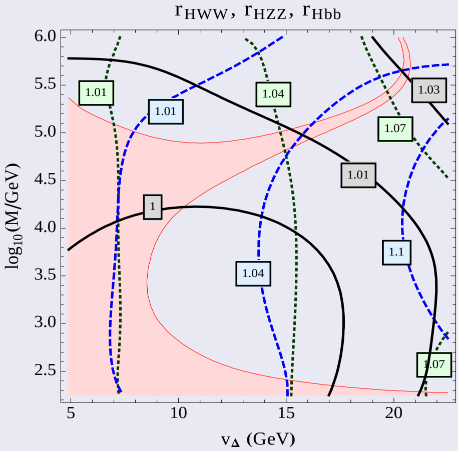
T [M_a=1 (black), 1.1 (blue), 1.2 (red), 1.3 (orange) TeV] tan β (blue), tan θ_0 (black), tan θ_1 (green) [M_a=1.2 TeV]

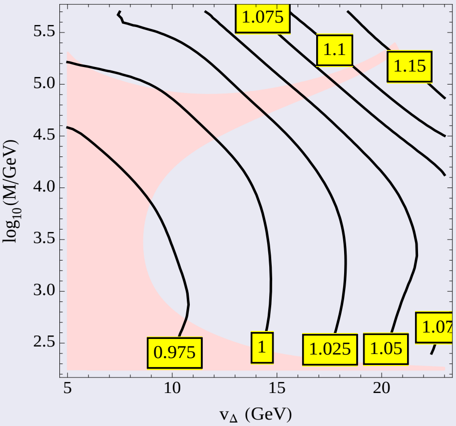


c) Higgs BR's & universality breaking

Defining the ratios [M_a=1.2 TeV]: $r_{\mathcal{H}XX} \equiv g_{\mathcal{H}XX}/g^{SM}_{hXX}$

$r_{\mathcal{H}WW}$ (green), $r_{\mathcal{H}ZZ}$ (blue), $r_{\mathcal{H}bb}$ (black) — $r_{\mathcal{H}\gamma\gamma}$

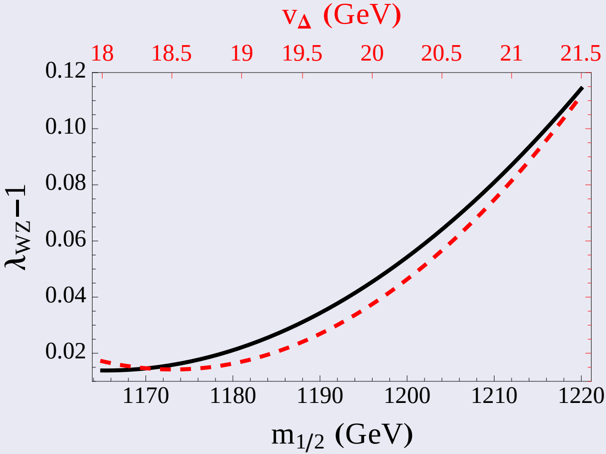




Smoking gun: A spin-off of the breaking of custodial invariance is that $\mathcal{H}$ couples to WW and ZZ differently to the SM (breaking of universality)

$$\lambda_{WZ} \equiv r_{\mathcal{H}WW}/r_{\mathcal{H}ZZ} \neq 1 \Rightarrow CSV$$

ATLAS: $\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$ CMS: $\lambda_{WZ} = 0.94^{+0.22}_{-0.18}$



Conclusion and outlook

- We have presented a supersymmetric model with triplets and custodial symmetry at tree level (super GM model)
- Higgs mass easily reproduced without the need of heavy stops or large stop mixing
- No quadratic sensitivity to the UV physics
- Consistent with strong first order phase transition (in preparation)
- Rich phenomenology (to be explored) from singly and doubly scalars and fermions
- Consistency for low supersymmetry breaking scale: $M \lesssim 10^8$ GeV
- 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 $\mathcal{M}_\nu^{ij} = h_\nu^{ij} v_\Delta$