A Supersymmetric Higgs Triplet Model with Custodial Symmetry

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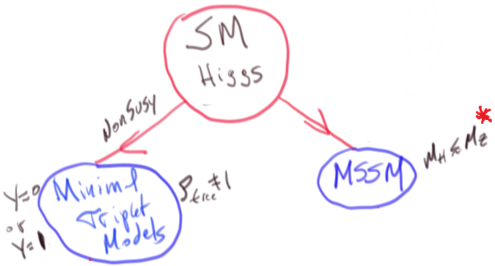
Overview

- Motivations
- Review the Georgi-Machacek (GM) Model
- Higgs Triplets in SUSY Models
- A Supersymmetric Model with Custodial Triplets

Two popular extension paths for the SM



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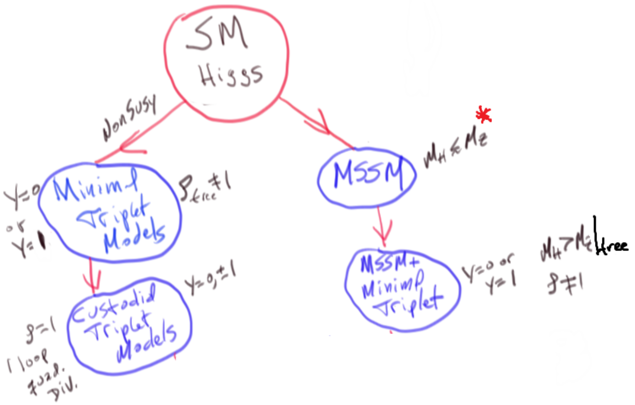

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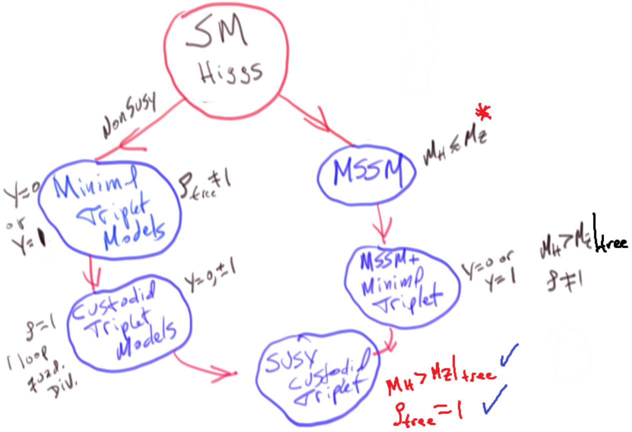

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- It seems a SUSY version of the GM model would solve both problems
- What does this model look like?
- Can the GM be recovered as some limit of this SUSY model?
- In other words, can the GM model be made natural?

Georgi-Machacek Model

- The field content: $\phi = \begin{pmatrix} h_1^+ \\ h_1^o \end{pmatrix} \quad \zeta = \begin{pmatrix} \phi_+ \\ \phi_o \\ \phi_- \end{pmatrix} \quad \chi = \begin{pmatrix} \psi_{++} \\ \psi_+ \\ \psi_o \end{pmatrix}$

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  If $\phi^c = i\sigma_2\phi^*$ and $\chi^c = C\chi^*$, where, $C = \begin{pmatrix} 0 & 0 & 1 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$

  Then, ϕ^c abd χ^c transform like ϕ and χ respectively, but have opposite hyper charges. This allows us to define 2×2 and 3×3 matrices: $\Phi = (\phi^c, \phi)$ and $\boldsymbol{\chi} = (\chi^c, \zeta, \chi)$ that transform consistently under $SU(2)_L \times SU(2)_R$, i.e. $\Phi \to U_L \Phi U_R^\dagger$ and $\boldsymbol{\chi} \to U_L \boldsymbol{\chi} U_R^\dagger$.

GM Model: The $SU(2)_L \otimes SU(2)_R$ invariant potential

- Explicitly the matrices have the form:

$$\Phi = \begin{pmatrix} {h_o}^* & h_+ \\ h_- & h_o \end{pmatrix} \qquad \chi = \begin{pmatrix} \psi_o^* & \phi_+ & \psi_{++} \\ \psi_- & \phi_o & \psi_+ \\ \psi_{--} & \phi_- & \psi_o \end{pmatrix}$$

where phase convention is: $h_-^* = -h_+$, $\psi_-^* = -\psi_+$, $\phi_+^* = -\phi_-$, $\psi_{++}^* = \psi_{--}$, and $\phi_0^* = \phi_0$. In this form it is easy to build a potential which is invariant under $SU(2)_L \times SU(2)_R$.

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$$\begin{aligned} V = &\lambda_1 \left(Tr(\Phi^\dagger \Phi) - v_H^2\right)^2 + \lambda_3 \left(Tr(\Phi^\dagger \Phi) - v_H^2 + Tr(\chi^\dagger \chi) - 3v_\Delta^2\right) \\ &+ \lambda_4 \left(Tr(\Phi^\dagger \Phi)\, Tr(\chi^\dagger \chi) - 2\,Tr(\Phi^\dagger \sigma^i \Phi \sigma^j)\, Tr(\chi^\dagger t^i \chi t^j)\right) \\ &+ \lambda_2 \left(Tr(\chi^\dagger \chi) - 3v_\Delta^2\right)^2 + \lambda_5 \left(3\,Tr(\chi^\dagger \chi)^2 - (Tr(\chi^\dagger \chi))^2\right) \\ &+ \lambda_6 \left(Tr(\Phi^\dagger \sigma_i \Phi \sigma_j)\,(U\chi U^\dagger)_{ij} - Tr(\chi^\dagger\, T_i\, \chi\, T_j)\right)\, (U\chi U^\dagger)_{ij} \end{aligned}$$

GM Model: Custodial Fields after SSB

The custodial symmetry preserves hermiticity and trace properties:

$$\chi = \left[\frac{1}{2}(\chi + \chi^{\dagger}) - \frac{1}{3}Tr\chi\right] + \frac{1}{2}(\chi - \chi^{\dagger}) + \frac{1}{3}Tr\chi$$

The first term represents the fiveplet, the second the triplet, and the third the singlet.

$$H_5^{++} = \psi_{++} \qquad H_5^{+} = \frac{(\psi_+ - \phi_+)}{\sqrt{2}} \qquad H_5^0 = \frac{(\sqrt{2}\psi_{or} - 2\phi_o)}{\sqrt{6}}$$

$$\zeta_+ = \frac{(\psi_+ + \phi_+)}{\sqrt{2}} \qquad \zeta_o = \psi_{oi} \qquad \zeta_- = \frac{(\psi_- + \phi_-)}{\sqrt{2}}$$

$$H_1^{o\prime} = \frac{\sqrt{2}\psi_{or} + \phi_o}{\sqrt{3}}$$

Similarly for the doublet fields the custodial components: $h^{\pm}$ and h_{oi} form a triplet, and $H_1^o = h_{or}$ the singlet.

GM Model: Custodial Fields

- Some definitions,

$$\langle h_{or} \rangle = v_H \qquad \langle \phi_o \rangle = v_\Delta \qquad \langle \psi_o \rangle = v_\Delta$$

$$v^2 = 2v_H^2 + 8v_\Delta^2 \qquad c_H = \frac{v_H}{v} \qquad s_H = \frac{2\sqrt{2}v_\Delta}{v}$$

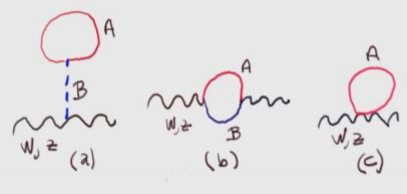
- The Goldstone Bosons and the Triplets. Note H_3^o is a pseudo-scalar.

$$G_3^\pm = c_H i h_\pm + s_H \zeta_\pm \qquad G_3^o = i(-c_H h_{oi} + s_H \psi_{oi})$$
$$H_3^\pm = s_H i h_\pm - c_H \zeta_\pm \qquad H_3^o = i(s_H h_{oi} + c_H \psi_{oi})$$

- The decoupling limit is obtained by taking $v_\Delta \to 0$ or $s_H \to 0$ in this limit the triplet field couplings to the gauge bosons drop out and m_{H_5} and m_{H_3} get very large. One scalar, the H_1^o remains and its mass is given by,

$$m^2_{H_1^o} = 8\lambda_1 v_H^2$$

GM Model: The hypercharge terms spoil $SU(2)_c$ Symmetry



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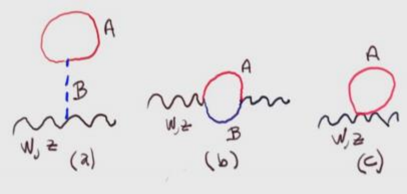

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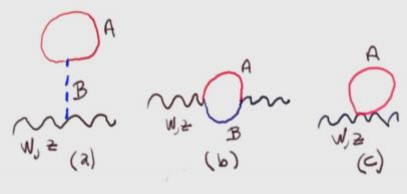

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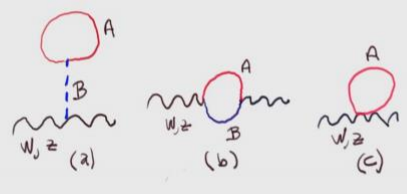
- Allowing for small custodial violation terms in the scalar sector leads to a relative shifts in the *vev*'s of the triplet fields by parametrized δ,

$$\langle\phi_o\rangle = \langle\psi_o\rangle(1+\delta) = v_\Delta(1+\delta)$$

- As a consequence the W-mass also shifts, but the Z-mass does not,

$$m_W^2 = \frac{1}{4}g^2v^2(1+s_H^2\delta) \Longrightarrow \boxed{\Delta\rho|_\delta = s_H^2\delta}$$

GM Model: Fine Tuning for ρ



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$$\Sigma = \begin{pmatrix} \xi^0/\sqrt{2} & -\xi_2^+ \\ \xi_1^- & -\xi^0/\sqrt{2} \end{pmatrix}$$

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- Delgado et.al. show the follwoing for the tree level mass of the SM-like Higgs,

$$m_{h,\text{tree}}^2 = m_Z^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2 \sin^2 2\beta$$

- The additional charge scalars serve to modified the $h \to \gamma\gamma$ decay rate.
- Must fine tune $v_\Delta < 4 GeV$ to comply with $\rho = 1$ at tree level

The SUSY Custodial Triplet Model

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$$W_0 = \frac{\mu}{2}\, Tr\left(\sigma_2 \Phi^T \sigma_2 \Phi\right) + 2 * \lambda\, Tr\left(\sigma_2 \Phi^T \sigma_2 \sigma_i \Phi \sigma_j\right) (U \boldsymbol{\chi} U^\dagger)_{ij}$$

$$+ \frac{\mu_\Delta}{2}\, Tr\left(C \boldsymbol{\chi}^T C \boldsymbol{\chi}\right) + \frac{\lambda_3}{6}\, Tr\left(C \boldsymbol{\chi}^T C\, T_i\, \boldsymbol{\chi}\, T_j\right) (U \boldsymbol{\chi} U^\dagger)_{ij}$$

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- After EWSB there remains a custodial $SU(2)$ symmetry in scalar potential and states can be classified into custodial multiplets
- Note that now we have two complex doublets, two complex $Y = \pm 1$ triplets, and one complex $Y = 0$ triplet, double the scalar spectrum

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$$\delta_1^0 = \frac{\phi^0 + \chi^0 + \psi^0}{\sqrt{3}}$$

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- Again these are chiral super fields (complex scalars + fermions)
- The physical scalar mass eigenstates will consist of a pseudo scalar triplet, two scalar triplets, a scalar fiveplet, a pseudo scalar fiveplet, two scalar singlets, and two pseudo scalar singlets
- Note this is double the scalar spectrum of the GM model!

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$$m_{S_1}^2 = 6\lambda^2 v_H^2 + \mathcal{O}(v_\Delta)$$

- Note $\tan\beta = 1$ at tree level in this model so no MSSM-type contribution
- λ is the parameter for the term in the super-potential quadratic in doublet and linear triplet fields:

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- Since we start with a $SU(2)_L \otimes SU(2)_R$ invariant W_o and soft breaking sector, $\rho = 1$ at tree level
- We expect this model is free of the quadratic divergences in the ρ parameter present in GM model (In the process of explicitly verifying this)

Breaking Custodial Symmetry at Loop Level

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- However, $SU(2)_L \times SU(2)_R$ broken by hyper-charge (and Yukawas)
- Leads to breaking of custodial symmetry and $\rho \neq 1$ at loop level!

The Neutral Fermion Mass Matrix

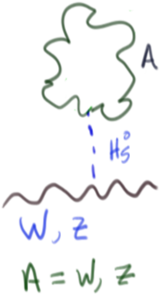
- We have an enlarged neutral-ino sector in $(\tilde{\gamma}, \tilde{h}_1^0, \tilde{\delta}_1^0, \tilde{Z}, \tilde{h}_3^0, \tilde{\delta}_3^0, \tilde{\delta}_5^0)$ basis

$$\begin{pmatrix} \frac{g^2\,M1+gY^2\,M2}{g^2+gY^2} & 0 & 0 & \frac{g\,gY\,(-M1+M2)}{g^2+gY^2} & 0 & 0 & 0 \\ 0 & 3\,v\Delta\,\lambda-\mu & \sqrt{6}\,vH\,\lambda & 0 & 0 & 0 & 0 \\ 0 & \sqrt{6}\,vH\,\lambda & -2\,v\Delta\,\lambda3+\mu\Delta & 0 & 0 & 0 & 0 \\ \frac{g\,gY\,(-M1+M2)}{g^2+gY^2} & 0 & 0 & \frac{gY^2\,M1+g^2\,M2}{g^2+gY^2} & \sqrt{g^2+gY^2}\,vH & 2\sqrt{g^2+gY^2}\,v\Delta & 0 \\ 0 & 0 & 0 & \sqrt{g^2+gY^2}\,vH & v\Delta\,\lambda+\mu & -2\,vH\,\lambda & 0 \\ 0 & 0 & 0 & 2\sqrt{g^2+gY^2}\,v\Delta & -2\,vH\,\lambda & v\Delta\,\lambda3-\mu\Delta & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & v\Delta\,\lambda3+\mu\Delta \end{pmatrix}$$

- Note custodial symmetry recovered in limit $g_Y \to 0$
- These give the cancellation of Λ^2 divergence in ρ in GM model
- Will contribute to RG running and (may) possess a DM candidate
- Currently studying the LHC pheno of these (and charged) fermions

Canceling Quadratic Divergence in ρ in GM Model

- The cancellation of quadratic divergences in ρ in GM model involve only two sets of diagrams



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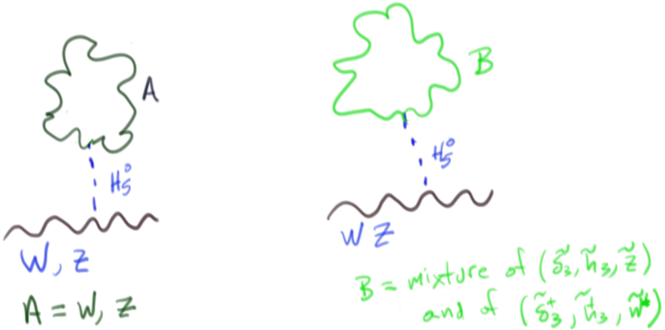

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- At the SUSY breaking scale the super potential and soft breaking sectors are $SU(2)_L \times SU(2)_R$ invariant

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- Of course M_{SUSY} must be high enough to evade LHC constraints

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- This leads to a correction to $\rho - 1$ or αT given by

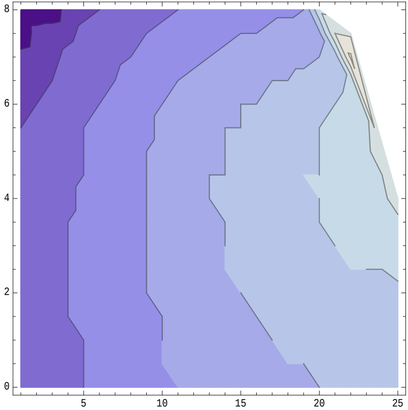
$$\alpha T = \frac{2v_\phi^2 - (v_\psi^2 + v_\chi^2)}{\frac{1}{2}(v_1^2 + v_2^2) + 2(v_\psi^2 + v_\chi^2)} = -4\frac{\cos 2\theta_0\, v_\Delta^2}{v_H^2 + 8\cos^2\theta_0 v_\Delta^2}$$

- We see corrections to ρ only will depend on parameter θ_0

The Custodial SUSY Triplet Model (CSHTM)

- We show contours of λ for $Log(M_{SUSY}/v_{EW})$ vs v_Δ

(PRELIMINARY!)



- We show $0.3 \lesssim \lambda \lesssim 0.6$ for $M_{SUSY} \lesssim 500\ TeV$ and $v_\Delta \lesssim 25\ GeV$
- These points satisfy $\rho \sim 1$, $m_H \sim 125\ GeV$ and $m_t \sim 174\ GeV$ at weak scale as well as condition of EWSB at weak scale!

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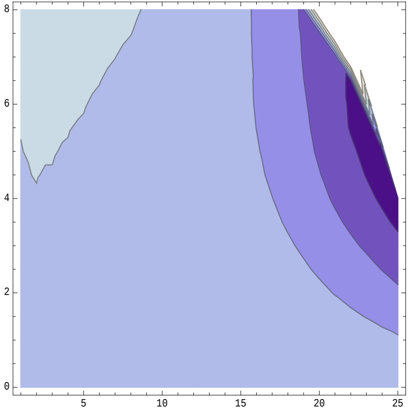
- We show contours of δT for $Log(M_{SUSY}/v_{EW})$ vs v_Δ

(PRELIMINARY!)



- We show $-0.06 \lesssim \delta T \lesssim 0$ for $M_{SUSY} \lesssim 500$ TeV and $v_\Delta \lesssim 25$ GeV
- These points satisfy $\rho \sim 1$, $m_H \sim 125$ GeV and $m_t \sim 174$ GeV at weak scale as well as condition of EWSB at weak scale!

Ongoing Work/Conclusions

- So far we are finding that triplet VEV of ~ 25 *GeV* and $M_{SUSY} \sim 500$ *TeV* satisfy m_h, ρ, m_t and EWSB constraints
- We have found the limit in which the GM model is recovered when $m_3^2, B_\Delta \to \infty$
- Soft breaking masses are taken to be $\sim$ *TeV* at SUSY breaking scale
- We are in the process of performing a more general parameter scan
- Note that scalar and fermion spectrum is in general not exactly custodial at weak scale
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- Thank you!