Triplet Extended MSSM: Fine Tuning vs Perturbativity & Experiment

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P.Bandyopadhyay, SD, K.Huitu, A.Sabanci; arXiv:1407.xxxx

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Motivations

- Triplet contributes @ tree level to $m_H \Rightarrow$ less fine-tuning
- Possible enhancement of $H \rightarrow \gamma\gamma$
- Spontaneous CP violation $\Rightarrow$ right amount of baryon asymmetry
Triplet Extension of MSSM

Triplet of $SU(2)_L$ (adjoint, $Y = 0$) defined by

$$T = \begin{pmatrix} \frac{1}{\sqrt{2}} T^0 & T^+ \\ T^- & -\frac{1}{\sqrt{2}} T^0 \end{pmatrix}.$$

The renormalizable superpotential of TESSM includes only two extra terms as compared to MSSM:

$$W_{\text{TESSM}} = \mu_T \text{Tr}(TT) + \mu_D H_d H_u + \lambda H_d T H_u + y_u U H_u Q - y_d D H_d Q - y_e E H_d L,$$

Soft terms:

$$V_S = \left[ \mu_T B_T \text{Tr}(TT) + \mu_D B_D H_d H_u + \lambda A_T H_d T H_u + y_t A_t \tilde{t}_R^* H_u \tilde{Q}_L + h.c. \right]$$

$$+ m_T^2 \text{Tr}(T^\dagger T) + m_u^2 |H_u|^2 + m_d^2 |H_d|^2 + \ldots,$$
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Soft terms:

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Real vevs for the scalar neutral components:

\[ \langle T^0 \rangle = \frac{v_T}{\sqrt{2}} \, , \quad \langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}} \, , \quad \langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}} \, , \]

give non-zero tree level contribution to the EW $T$ parameter

\[ \alpha T = \frac{\delta m_W^2}{m_W^2} = \frac{4v_T^2}{v^2} \, , \quad \alpha T \leq 0.2 \quad \Rightarrow \quad v_T \lesssim 5 \text{ GeV} \, . \]

In the limit of large $|B_D|$ (favoured by stability):

\[ m_{h_1^0}^2 \leq m_Z^2 \left(c_{2\beta} + \frac{\lambda^2}{g_1^2 + g_2^2 s_{2\beta}} \right) \, , \quad t_\beta = \frac{v_u}{v_d} \, , \]

Large values of $\lambda$ reduce quantum corrections $\Rightarrow$ less fine tuning (FT).
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1L contribution to scalar masses obtained from Coleman-Weinberg $V$

\[ V_{\text{CW}} = \frac{1}{64\pi^2} \text{STr} \left[ M^4 \left( \log \frac{M^2}{\mu_r^2} - \frac{3}{2} \right) \right], \]

with $M^2 =$ mass matrices with fields not replaced by vevs.

Neutral scalar mass matrix 1L contribution, $\Delta M_{h^0}^2$, given by

\[ (\Delta M_{h^0}^2)_{ij} = \left. \frac{\partial^2 V_{\text{CW}}(a)}{\partial a_i \partial a_j} \right|_{\text{vev}} - \left. \frac{\delta_{ij}}{\langle a_i \rangle} \frac{\partial V_{\text{CW}}(a)}{\partial a_i} \right|_{\text{vev}}, \quad a_i = \left| H_u^0, H_d^0, T^0 \right| / \sqrt{2} \]

Derivatives evaluated numerically at each data point in parameter space.

Espinosa, Quiros '92; Setzer, Spinner '06; Diaz-Cruz et al. '07; SD, Hsieh '08; Delgado et al. '12,'13; Arina et al. '14

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To evaluate the phenomenological viability of TESSM we scan randomly the parameter space in the region defined by:

$$1 \leq t_\beta \leq 10 \ , \ |\lambda| \leq 2 \ , \ |\mu_D, \mu_T| \leq 2 \text{ TeV} \ , \ |M_1, M_2| \leq 1 \text{ TeV} \ ,$$

$$|A_t, A_T, B_D, B_T| \leq 2 \text{ TeV} \ , \ 500 \text{ GeV} \leq m_Q, m_{\tilde{t}}, m_{\tilde{b}} \leq 2 \text{ TeV}$$

and stop after collecting 13347 points satisfying exp constraints

$$m_{h_1^0} = 125.5 \pm 0.1 \text{ GeV} \ ; \ m_{A_{1,2}}, m_{\chi_{1,2,3,4,5}} \geq 65 \text{ GeV} \ ;$$

$$m_{h_{2,3}, m_{h_{1,2,3}}, m_{\chi_{1,2,3}} \geq 100 \text{ GeV} \ ; \ m_{\tilde{t}_{1,2}}, m_{\tilde{b}_{1,2}} \geq 650 \text{ GeV} \ .$$

$$m_{h_1^0}$$ matched to 125.5 GeV by tuning $\lambda$. 
Perturbativity

We calculate the 2 loop beta functions for $y_t, y_b, y_\tau, \lambda, g_3, g_2, g_1$ (new result) and require those to be less than $2\pi^*$ at the GUT scale ($2 \times 10^{16}$ GeV): 7732 satisfy perturbativity constraint. Then we calculate FT in $m_{u}^{2*}$ by using its full 1L beta $\beta_{m_{u}^{2}}$ (new result):

$$\text{FT} \equiv \frac{\partial \log v_{\text{EW}}^{2}}{\partial \log m_{u}^{2} (\Lambda)}, \quad m_{u}^{2} (\Lambda) = m_{u}^{2} (M_{Z}) + \frac{\beta_{m_{u}^{2}}}{16\pi^{2}} \log \left( \frac{\Lambda}{M_{Z}} \right).$$

Red = non-perturbative, yellow = perturbative @ 2L, blue = perturbative; $\lambda$ too small to reduce FT, but

- no GUT for TESSM
- Spontaneous SUSY breaking might change $\beta$

We choose $\Lambda_{UV} = 10^{4}$ TeV.

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At $\Lambda_{UV} = 10^4$ TeV 11244 perturbative viable points

$tan \beta$ and $\lambda$ strongly correlated: $tan \beta \sim 1$ with small FT viable only for large $\lambda$
Small $|A_t|$ with small FT accessible only for large $|\lambda|$ (not in MSSM)
Higgs linear coupling terms accounting for the TESSM contributions:

\[ \mathcal{L}_{\text{eff}} = a_W \frac{2m_W^2}{v_W} hW^+ W^- \mu + a_Z \frac{m_Z^2}{v_W} hZ \mu Z^\mu - \sum_{\psi = t, b, \tau} a_{\psi} \frac{m_{\psi}}{v_W} h\bar{\psi} \psi \]

\[ -a_{\Sigma} \frac{2m_{\Sigma}^2}{v_W} h\Sigma^* \Sigma - a_S \frac{2m_S^2}{v_W} hS^+ S^- , \]

where \( \Sigma \) and \( S \) are, respectively, coloured and charged scalars, with

\[ a_S \equiv -3 \sum_{i}^3 \left( F_{h_i^\pm} + F_{\chi_i^\pm} \right) - \sum_{j}^2 \left( 4F_{\tilde{t}_j} + F_{\tilde{b}_j} \right) , a_{\Sigma} \equiv -3 \sum_{j}^2 \left( F_{\tilde{t}_j} + F_{\tilde{b}_j} \right) , \]

\( F_i \) being decay amplitudes to diphoton/digluon. We impose also lower bound on \( m_{h_2}^0 \): 10957 out of 11244 perturbative data points satisfy it.
Higgs Physics at LHC

Higgs linear coupling terms accounting for the TESSM contributions:

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\]

\[
- a_\Sigma \frac{2m_\Sigma^2}{v_w} h \Sigma^* \Sigma - a_S \frac{2m_S^2}{v_w} h S^+ S^-,
\]

where \( \Sigma \) and \( S \) are, respectively, coloured and charged scalars, with

\[
a_S \equiv -3 \sum_{i} 3 \left( F_{h_i}^+ + F_{\chi_i}^+ \right) - \sum_{j} 2 \left( 4F_{\tilde{t}_j} + F_{\tilde{b}_j} \right),
\]

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We find both enhanced and suppressed Higgs to diphoton decay rates relative to SM: apparently different from results in literature.

\( h \rightarrow \gamma \gamma \)
Comparison with previous results

Scanning similar* region of parameter space ($\lambda, \mu_D, \mu_T, M_2 > 0$ with light chargino) we get equivalent results, so TESSM does not naturally enhance the Higgs to diphoton decay.

* SD, Hsieh '08; Delgado et al. '12,'13; Arina et al. '14
Even for low values of $\tan\beta$, $\text{Br}(B_s \rightarrow X_s\gamma)$ possibly large: we calculate it at NLO.
Goodness of Fit

We minimize the quantity

$$\chi^2 = \sum_i \left( \frac{O_i^{\text{exp}} - O_i^{\text{th}}}{\sigma_i^{\text{exp}}} \right)^2,$$

including $ZZ$, $WW$, $\tau\tau$, $b\bar{b}$, $\gamma\gamma$ (all topologies) signal strengths, and $b \to s\gamma$, for a total of 49 observables. In the limit of small deviations from the optimal values, for $a_W = a_Z = 1$, $a_\psi = a_f$, neglecting $b \to s\gamma$:

$$\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}} = \delta^T \rho^{-1} \delta, \quad \delta^T = \left( \frac{a_f - \hat{a}_f}{\sigma_f}, \frac{a_S - \hat{a}_S}{\sigma_S}, \frac{a_\Sigma - \hat{a}_\Sigma}{\sigma_\Sigma} \right),$$

with

$$\hat{a}_f = 1.13, \quad \sigma_f = 0.17,$$
$$\hat{a}_S = 0.80, \quad \sigma_S = 2.79,$$
$$\hat{a}_\Sigma = 0.25, \quad \sigma_\Sigma = 0.43,$$

and

$$\rho = \begin{pmatrix} 1 & -0.55 & -0.67 \\ -0.55 & 1 & 0.70 \\ -0.67 & 0.70 & 1 \end{pmatrix}.$$
Values of $a_u$ ($a_d$) for viable data points shown in gray (black).
Viable regions

Viable data points in black: no point matches optimal $a_\Sigma$ value.

In general TESSM under constrained by Higgs physics, but that might change at LHC2.
Large values of $\lambda$ disfavored as compared to MSSM-like data points, because of $\text{Br}(B_s \to X_s\gamma)$. If large enhancement/suppression of $h \to \gamma\gamma$ (ATLAS/CMS) confirmed at LHC2, though, TESSM better suited than MSSM to explain (=fit) it.
Conclusions

- TESSM can have much smaller fine-tuning than MSSM
- Large enhancement/suppression of $H \rightarrow \gamma\gamma$ both possible
- Large values of $\lambda$ disfavored as compared to MSSM-like data points, because of $\text{Br}(B_s \rightarrow X_s\gamma)$.

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THANK YOU!
$\Gamma_{h\rightarrow \gamma\gamma} = \frac{\alpha_e^2 m_h^3}{256\pi^3 v^2} \left| \sum_i N_i e_i^2 a_i F_i \right|^2$, $i = W, t, b, \tau, c, S$.

with $N_i$ number of colors, $e_i$ electric charge, and $F_i$ partial amplitudes. In the limit of heavy $S^\pm$, one finds

$$F_S = -\frac{1}{3}, \ a_S \equiv -3 \left[ \sum_i^3 \left( F_{h_i^\pm} + F_{\chi_i^\pm} \right) + \sum_j^2 \left( \frac{4}{3} F_{\tilde{t}_j} + \frac{1}{3} F_{\tilde{b}_j} \right) \right].$$
Higgs to diphoton

\[ \Gamma_{h \rightarrow \gamma\gamma} = \frac{\alpha^2 e m_h^3}{256 \pi^3 v^2_w} \left| \sum_i N_i e_i^2 a_i F_i \right|^2, \ i = W, t, b, \tau, c, S, \]

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\Gamma_{h\rightarrow gg} = \frac{\alpha_s^2 m_h^3}{128\pi^3 v_w^2} \left| \sum_i a_i F_i \right|^2, \quad i = t, b, c, \Sigma,
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where

\[
a_\Sigma \equiv -3 \sum_j^{2} \left( F_{t_j} \bar{F}_{t_j} + F_{b_j} \bar{F}_{b_j} \right)
\]

Applying the formulas above to the heavy Higgs, we impose the constraint:

\[
a'_g \frac{(770 \text{ GeV})^2}{m_{h_2}^2} < 0.8, \quad a'_g = \frac{\Gamma_{h_2\rightarrow gg}}{\Gamma_{h\rightarrow gg}^{SM}}
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10957 out of 11244 perturbative data points satisfy it.
Higgs to 2 gluons & mH constraint

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