

Triplet Extension of the MSSM and its Higgs Physics

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Based on

A. Delgado, G.N., M. Quirós

arXiv:1207.6596 , arXiv:1303.0800

Outline

- 1 Introduction
 - The model
- 2 Higgs Phenomenology
 - Spectrum
 - Features of the decoupling limit
 - Features at small m_A
- 3 Conclusion

Motivation

- No clear discrepancies between data and SM predictions with $m_h \simeq 126 \text{ GeV}$
- If we do not give up with the (Planck/GUT - EW) hierarchy problem, **SUSY** is (one of) the favourite UV option
- In the **MinimalSSM** $m_h \simeq 126 \text{ GeV}$ requires “heavy” stop sector \Rightarrow **Little Hierarchy Problem**, i.e. some fine-tuning
- Non-minimalSSM models can alleviate this problem as they can enhance the tree-level Higgs mass via
 - D-terms: Extra gauge interactions
 - F-terms: Extra scalar sector (singlets and/or triplets)

If $\Gamma(h \rightarrow \gamma\gamma)$ is confirmed by future data...

... the extra **charged** fermions in the triplet superfield are (potentially) largely coupled to the Higgs and can make the job

The $Y=0$ Triplet Extension

(Espinosa&Quiros'92)

$$\Sigma = \begin{pmatrix} \xi^0/\sqrt{2} & -\xi_2^+ \\ \xi_1^- & -\xi^0/\sqrt{2} \end{pmatrix}, \quad \Delta W = \lambda H_1 \cdot \Sigma H_2 + \frac{1}{2} \mu_\Sigma \text{tr} \Sigma^2 + \mu H_1 \cdot H_2$$

- T parameter bound requires $\langle \xi^0 \rangle \lesssim 4 \text{ GeV}$ which imposes (unless of fine-tuning)

$$|A_\lambda|, |\mu|, |\mu_\Sigma| \lesssim \frac{m_\Sigma^2 + \lambda^2 v^2 / 2}{10^2 \lambda v}$$

- This hierarchy implies decoupling between ξ^0 and H_1, H_2

$$\text{Mass boost: } V(H_1, H_2) \simeq V_{MSSM} + \lambda^2 |H_1^0 H_2^0|^2$$

(other tripl. SUSY extens. in E.J.Chun&al,1209.1303; Z.Kang&al,1301.2204)

The relevant spectrum

- Heavy scalar triplet [$\gtrsim 1 \text{ TeV}$]
- Minimiz. conditions

$$m_3^2 = m_A^2 \sin \beta \cos \beta, \quad m_Z^2 = \frac{m_2^2 - m_1^2}{\cos 2\beta} - m_A^2 + \frac{\lambda^2}{2} v^2$$

- CP-odd/charged Higgses [no preferences]

$$m_A^2 = m_1^2 + m_2^2 + 2|\mu|^2 + \frac{\lambda^2}{2} v^2, \quad m_{H^\pm}^2 = m_A^2 + m_W^2 + \frac{\lambda^2}{2} v^2$$

- Charginos [$\mathcal{O}(100 \text{ GeV})$ if diphoton excess]

$$\left(\tilde{W}^-, \tilde{H}_1^-, \tilde{\xi}_1^- \right) \mathcal{M}_{ch}^\pm \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_2^+ \\ \tilde{\xi}_2^+ \end{pmatrix}, \quad \mathcal{M}_{ch}^\pm = \begin{pmatrix} M_2 & gv_2 & 0 \\ gv_1 & \mu & -\lambda v_2 \\ 0 & -\lambda v_1 & \mu_\Sigma \end{pmatrix}$$

The relevant spectrum

- CP-even Higgs masses (basis h_2, h_1)

$$\mathcal{M}_0^2 = \begin{pmatrix} m_A^2 \cos^2 \beta + m_Z^2 \sin^2 \beta & (\lambda^2 v^2 - m_A^2 - m_Z^2) \sin 2\beta/2 \\ (\lambda^2 v^2 - m_A^2 - m_Z^2) \sin 2\beta/2 & m_A^2 \sin^2 \beta + m_Z^2 \cos^2 \beta \end{pmatrix}$$

- After including radiative corrections $\Delta\mathcal{M}_t^2(h_t)$ and $\Delta\mathcal{M}_\Sigma^2(\lambda)$ (also in the min.condts) [$m_h = 126 \text{ GeV}$]

$$\begin{pmatrix} h_2 \\ h_1 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

Coupling ratios $r_{\mathcal{H}XX} = g_{\mathcal{H}XX}/g_{hXX}^{\text{SM}}$ ($\mathcal{H} = h, H$)

r_{hVV}^0	r_{HVV}^0	r_{htt}^0	r_{Htt}^0	r_{hdd}^0	r_{Hdd}^0
$\sin(\beta - \alpha)$	$\cos(\beta - \alpha)$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\cos \beta}$

Decoupling limit $m_A \rightarrow \infty$

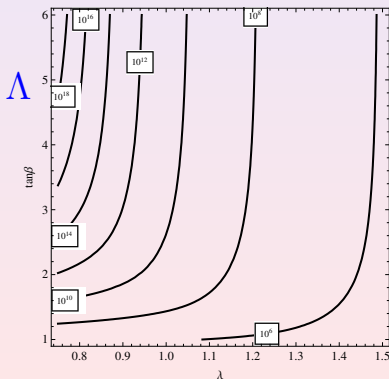
If $m_A \gg m_h \dots$

Decoupling limit $m_A \rightarrow \infty$

Tree-level Higgs mass

$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta / 2$$

Little hierarchy problem pushes towards small $\tan \beta$ and large λ , but perturbation theory may break down at the scale Λ



curves:
 $10^{18}, 10^{16}, 10^{14}, \dots, 10^6$

Decoupling limit $m_A \rightarrow \infty$ Signal strength $\mathcal{R}_{\gamma\gamma}$ $[= BR(h \rightarrow \gamma\gamma)/BR(h \rightarrow \gamma\gamma)_{SM}]$

$$\frac{\partial}{\partial \log v} \log \det \mathcal{M}_{ch}(v) = - \frac{v^2(\lambda^2 M_2 + g^2 \mu_\Sigma) \sin 2\beta}{M_2 \mu \mu_\Sigma - \frac{1}{2} \lambda^2 v^2 (\lambda^2 M_2 + g^2 \mu_\Sigma) \sin 2\beta}$$

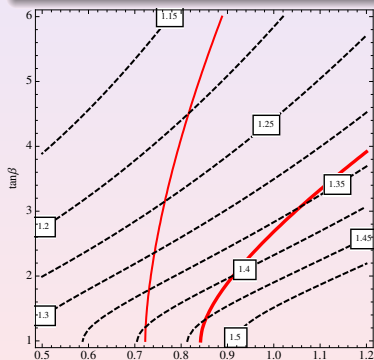
- ATLAS: 1.65 ± 0.30 ; CMS: $0.8 - 1.1 \pm 0.3$
- Loop-induced process which is sensitive to new charged particles
- New triplet charged fermion can enhance $R_{\gamma\gamma}$ ($\lesssim 1.1$ via MSSM charginos; e.g. Casas,Moreno,Rolbiecki,Zaldivar '13)
- As no (large) modifications in the Higgs production exist for $m_A \rightarrow \infty$, the diphoton enhancement is (easily implemented from the QED eff.pot. Ellis&al,79; Shifman&al,79; Carena&al,12)

$$R_{\gamma\gamma} = \left| 1 + \left(\frac{4}{3} \frac{\partial}{\partial \log v} \log \det \mathcal{M}_{ch}(v) \right) / \left(A_1(\tau_W) + \frac{4}{3} A_{1/2}(\tau_t) \right) \right|^2$$

Decoupling limit $m_A \rightarrow \infty$

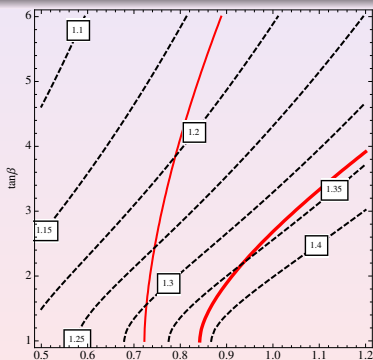
Signal strength $\mathcal{R}_{\gamma\gamma}$ $[= BR(h \rightarrow \gamma\gamma)/BR(h \rightarrow \gamma\gamma)_{SM}]$

$$\frac{\partial}{\partial \log v} \log \det \mathcal{M}_{ch}(v) = - \frac{v^2(\lambda^2 M_2 + g^2 \mu_\Sigma) \sin 2\beta}{M_2 \mu \mu_\Sigma - \frac{1}{2} \lambda^2 v^2 (\lambda^2 M_2 + g^2 \mu_\Sigma) \sin 2\beta}$$



$M_2 = 250 \text{ GeV}^\lambda$

$X_t = 4, \mathbf{0}; m_Q = 700 \text{ GeV}$
 $\mu = \mu_\Sigma \rightarrow m_{\chi_1^\pm} \sim 105 \text{ GeV}$



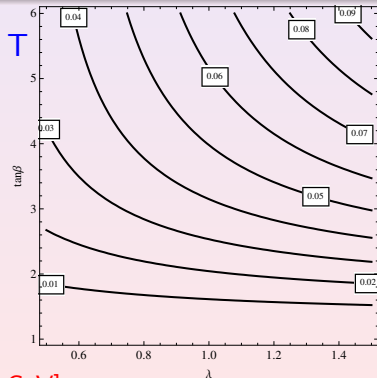
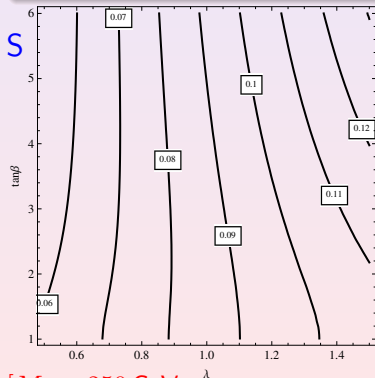
$M_2 = 750 \text{ GeV}$

Decoupling limit $m_A \rightarrow \infty$

S and T parameters (due to EWKinos)

$$\alpha S = \frac{s_W^2 \lambda^2}{10\pi^2} \frac{m_W^2}{\mu^2} \left[1 + \frac{19}{24} \sin 2\beta \right] + \mathcal{O}(g^4), \quad S = 0.04 \pm 0.09$$

$$\alpha T = \frac{3\lambda^2}{128\pi^2} \frac{m_W^2}{\mu^2} \cos^2 2\beta + \mathcal{O}(g^4), \quad T = 0.07 \pm 0.08$$



$[M_2 = 250 \text{ GeV}, \mu = \mu_\Sigma \rightarrow m_{\chi_1^\pm} \sim 105 \text{ GeV}]$

Small m_A

And now let us

DECREASE m_A

without upsetting the h Higgs
signatures

Small m_A

(similar idea in C.Wagner'talk)

- CP-even Higgs masses (basis h_2, h_1)

$$\mathcal{M}_0^2 = \begin{pmatrix} m_A^2 \cos^2 \beta + m_Z^2 \sin^2 \beta & (\lambda^2 v^2 - m_A^2 - m_Z^2) \sin 2\beta/2 \\ (\lambda^2 v^2 - m_A^2 - m_Z^2) \sin 2\beta/2 & m_A^2 \sin^2 \beta + m_Z^2 \cos^2 \beta \end{pmatrix}$$

$$\begin{pmatrix} h_2 \\ h_1 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

- Tree-level h couplings are SM-like if $\alpha = \beta - \pi/2$. With \mathcal{M}_0^2 :

$$\beta_c = \frac{\pi}{4}, \quad \lambda_c = \sqrt{2} \frac{m_h}{v}$$

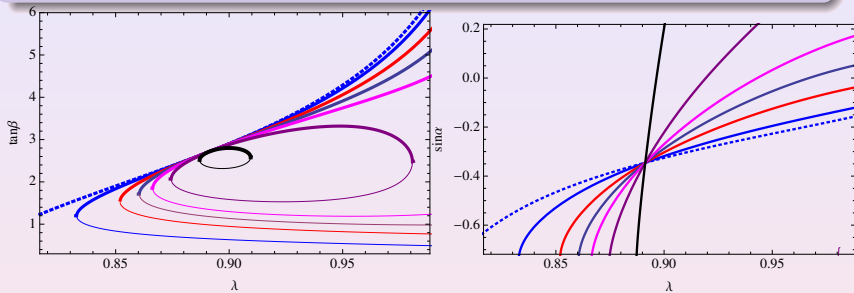
- More generically with \mathcal{M}^2 , fixing h mass yields (no $m_A^4!$):

$$A(\tan \beta, \lambda, m_h) m_A^2 + B(\tan \beta, \lambda, m_h) = 0$$

SM-LIKE POINT $(\lambda_c, \tan \beta_c)$ INDEPENDENT OF m_A

Small m_A

$\tan \beta(\lambda)$ and $\sin \alpha(\lambda)$ fixing $m_h = 126$ GeV



Radiative correction $\Delta \mathcal{M}_t^2(h_t)$ and $\Delta \mathcal{M}_\Sigma^2(\lambda)$ included
 ($m_Q = 700$ GeV, $A_t = 0$, $m_\Sigma = 5$ TeV).

Curves: $m_A = \infty, 200, 155, 145, 140, 135, 130$ GeV

- No attempt to reproduce data with $m_H = 126$ GeV (but worth to check!)

Small m_A Signal strengths $\mathcal{R}_{\mathcal{H}XX}$

$$\mathcal{R}_{\mathcal{H}XX} = \frac{\sigma(pp \rightarrow \mathcal{H}) BR(\mathcal{H} \rightarrow XX)}{[\sigma(pp \rightarrow h) BR(h \rightarrow XX)]_{SM}}$$

$$\mathcal{R}_{\mathcal{H}XX}^{(ggF)} = \mathcal{R}_{\mathcal{H}XX}^{(\mathcal{H}tt)} = \frac{r_{\mathcal{H}tt}^2 r_{\mathcal{H}XX}^2}{\mathcal{D}}, \quad \mathcal{R}_{\mathcal{H}XX}^{(VBF)} = \mathcal{R}_{\mathcal{H}XX}^{(V\mathcal{H})} = \frac{r_{\mathcal{H}WW}^2 r_{\mathcal{H}XX}^2}{\mathcal{D}}$$

$$\begin{aligned} \mathcal{D} = & BR(h \rightarrow b b)_{SM} r_{\mathcal{H}bb}^2 + BR(h \rightarrow gg, cc)_{SM} r_{\mathcal{H}tt}^2 \\ & + BR(h \rightarrow \tau\tau)_{SM} r_{\mathcal{H}\tau\tau}^2 + BR(h \rightarrow WW, ZZ)_{SM} r_{\mathcal{H}WW}^2 \end{aligned}$$

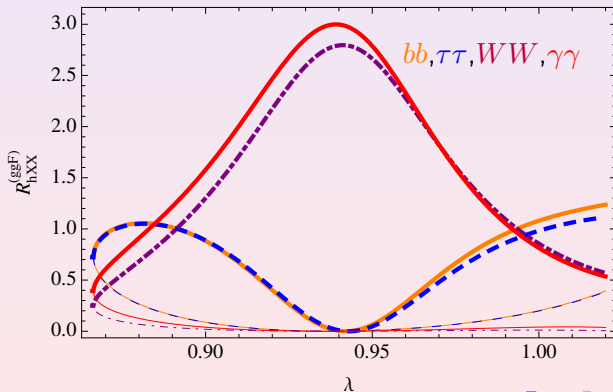
- No extra inv. width, i.e. $m_{\chi_0} \gtrsim m_{\mathcal{H}}/2$
- sbottom-gluino may correct r_{hbb} ($M_3 = 1 \text{ TeV}, m_{\tilde{b}} = 700 \text{ GeV}$)

Small m_A

$$m_A = 140 \text{ GeV}, \mu = \mu_\Sigma = 250 \text{ GeV}, m_{\chi^\pm} = 104 \text{ GeV}$$

Signal strengths \mathcal{R}_{hXX} from ggF and htt

$$\mathcal{R}_{\mathcal{H}XX} = \frac{\sigma(pp \rightarrow \mathcal{H})BR(\mathcal{H} \rightarrow XX)}{[\sigma(pp \rightarrow h)BR(h \rightarrow XX)]_{SM}}$$

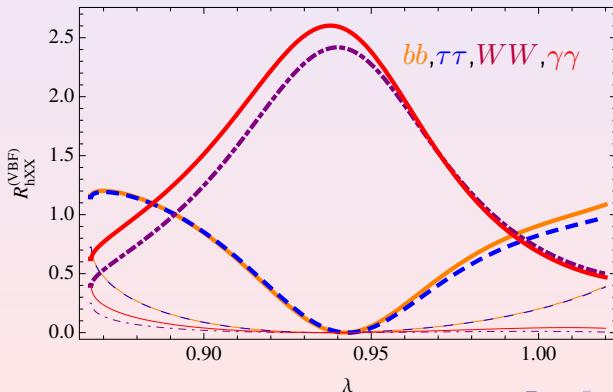


Small m_A

$$m_A = 140 \text{ GeV}, \mu = \mu_\Sigma = 250 \text{ GeV}, m_{\chi^\pm} = 104 \text{ GeV}$$

Signal strengths \mathcal{R}_{hXX} from VBF and Vh

$$\mathcal{R}_{\mathcal{H}XX} = \frac{\sigma(pp \rightarrow \mathcal{H})BR(\mathcal{H} \rightarrow XX)}{[\sigma(pp \rightarrow h)BR(h \rightarrow XX)]_{SM}}$$

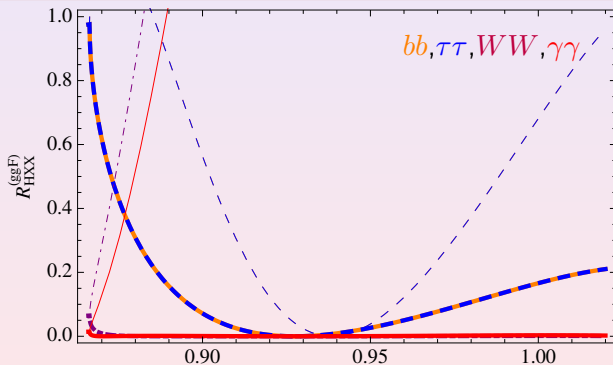


Small m_A

$$m_A = 140 \text{ GeV}, \mu = \mu_\Sigma = 250 \text{ GeV}, m_{\chi^\pm} = 104 \text{ GeV}$$

Signal strengths \mathcal{R}_{HXX} from ggF and htt

$$\mathcal{R}_{\mathcal{H}XX} = \frac{\sigma(pp \rightarrow \mathcal{H})BR(\mathcal{H} \rightarrow XX)}{[\sigma(pp \rightarrow h)BR(h \rightarrow XX)]_{SM}}$$



- Further reduction if $m_{\chi_0} \lesssim m_H/2$ ($m_H \sim 138 \text{ GeV}$)

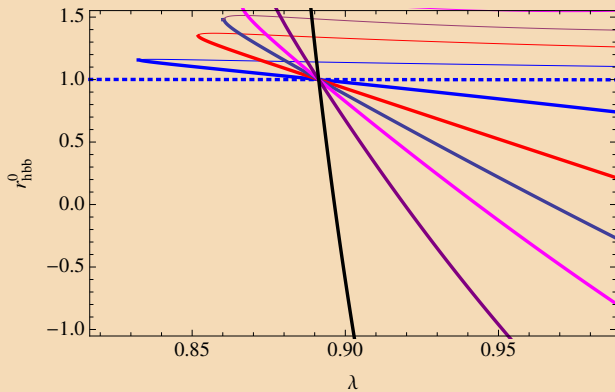
Conclusion

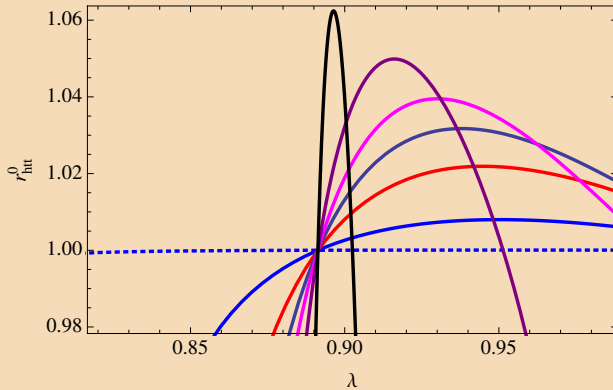
- Triplet extension alleviates the fine-tuning with respect to the MSSM
- At very small m_A there are 2 regions around $\lambda \approx 0.9$ and $\lambda \approx 1$ that mimic the signal strength of a SM Higgs. The exact values depend on m_Σ , m_Q and m_U .
- Some small deviations from a pure SM Higgs (e.g. $\gamma\gamma$, bb , $\tau\tau$) can also be encompassed without need of modifying other rates
- The argument to prove the existence of the SM-like point is quite generic and can be extended to other models (e.g. singlet exts.)

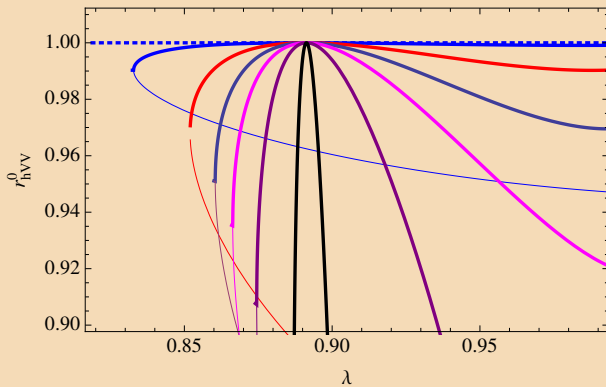
The extra Higgs sector may be at the EW scale but hidden
and only tiny deviations in \mathcal{R}_{hXX} may be present

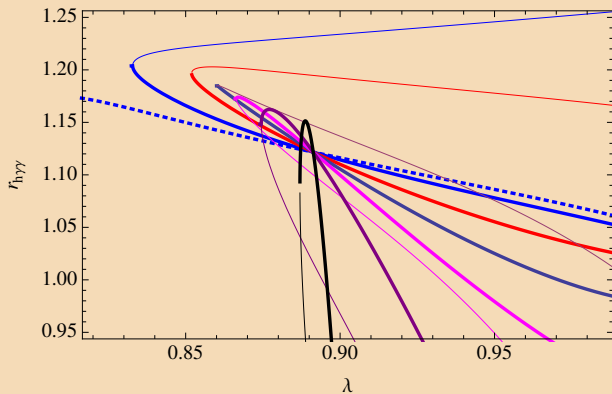
- Dedicated analyses on H^\pm and A are worthwhile (generalizations of L.Diaz Cruz and M.Battaglia's talks)

EXTRAS

Plot of r_{hdd}^0 

Plot of r_{Htt}^0 

Plot of r_{HVV}^0 

Plot of $r_{h\gamma\gamma}$ 

$m_{\chi_1^\pm} = 104$ GeV (solid line), $m_{\chi_1^\pm} = 150$ GeV with $\mu = \mu_\Sigma = 300$ GeV (dashed line) and $m_{\chi_1^\pm} = 200$ GeV with $\mu = \mu_\Sigma = 350$ GeV (dotted line)

