SM-like Higgs in non-decoupled SUSY

BSM After the First run of LHC
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- In the MSSM the couplings of the Higgs h to gauge bosons and fermions go to the Standard Model ones only in the decoupling limit
- In other words only when the heavy scalar H and pseudoscalar A are superheavy
- FAQ: is this general in supersymmetric theories?
- Is it possible that the Higgs couplings "mimic" those of the Standard Model even in the presence of other light scalars?

Outline

The outline of this talk is

Outline

Work done with: A. Delgado and G. Nardini: arXiv:1207.6596 [hep-ph], arXiv:1303.0800 [hep-ph]

INTRODUCTION

- The ATLAS & CMS collaborations are finding no clear discrepancies between data and the SM predictions with $m_h \simeq 126$ GeV
- Moreover although the MSSM solves the Grand Hierarchy Problem it requires some fine-tuning in the EW sector to reproduce the Higgs mass $\Rightarrow$ Little Hierarchy Problem (LHP) from heavy stop sector
- Non-minimal supersymmetric scenarios are generically motivated to circumvent the LHP
- The usual solution consists in providing an extra tree-level contribution to the Higgs mass by
  1. D-terms: i.e. extending the gauge interactions and/or
  2. F-terms: i.e. extending the scalar sector (singlets and/or triplets)
- Extensions with triplets have extra charged fermions which can eventually increase the decay rate $h \to \gamma\gamma$ if some excess is confirmed by future data
- We will consider for simplicity a $Y = 0$ triplet [1]

[1] A. Delgado, G. Nardini, MQ, arXiv:1207.6596 & 1303.0800 [hep-ph]

The model

The model is the MSSM + a $Y = 0$ triplet

The most general superpotential

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

There is no cubic term as

$$\mathrm{tr}\,\Sigma^3 = 0$$

- The full potential for neutral scalars is

$$
\begin{aligned}
V &= m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 + m_4^2|\xi^0|^2 \\
&+ \left|\mu H_2^0 - \lambda H_2^0\xi^0/\sqrt{2}\right|^2 + \left|\mu H_1^0 - \lambda H_1^0\xi^0/\sqrt{2}\right|^2 \\
&+ \left|\mu_\Sigma \xi^0 - \lambda H_1^0 H_2^0/\sqrt{2}\right|^2 + \frac{g^2+g'^2}{8}\left(|H_2^0|^2 - |H_1^0|^2\right)^2 \\
&+ \left(B_\Sigma \mu_\Sigma \xi^0 \xi^0 - A_\lambda \lambda H_1^0 H_2^0 \xi^0/\sqrt{2} - m_3^2 H_1^0 H_2^0 + \mathrm{h.c.}\right)
\end{aligned}
$$

- The minimum equation along the field ξ^0 fixes a relation as

$$\xi^0 m_\Sigma^2 = f(\mu, \mu_\Sigma, \dots)$$

so in the limit where $\xi^0 \to 0$, $m_\Sigma \to \infty$ and the Higgs doublet-Triplet sectors decouple

- The experimental bound on the T parameter requires $\langle\xi^0\rangle \sim$ few GeV
- Unless of fine-tuning this imposes the hierarchy

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

which we will assume

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

$$V \simeq V_{MSSM} + \lambda^2 |H_1^0 H_2^0|^2$$

- Before going on, a parenthesis on electroweak oservables and perturbativity

Electroweak observables

- An important question is how the zero-hypercharge supersymmetric triplet modifies the electroweak observables: in particular the T parameter is particularly sensitive to the presence of the triplet
- The triplet contributes to the T parameter at tree-level as the ρ-parameter and T are related by $\rho - 1 = \alpha T$
- Electroweak breaking produces at tree-level a tadpole in its neutral component ξ^0 and the experimental constraint on this contribution then requires $\langle \xi^0 \rangle \lesssim 4$ GeV at 95% CL.
- Moreover at one-loop the fermion triplet contributes to the electroweak observables through its coupling to the Higgs sector and, for $\mu = \mu_\Sigma$, the oblique S and T parameters to $\mathcal{O}(g^4)$

$$\alpha S = \frac{s_W^2 \lambda^2}{10\pi^2} \frac{m_W^2}{\mu^2} \left[1 + \frac{19}{24} \sin 2\beta \right], \quad \alpha T = \frac{3\lambda^2}{128\pi^2} \frac{m_W^2}{\mu^2} \cos^2 2\beta$$

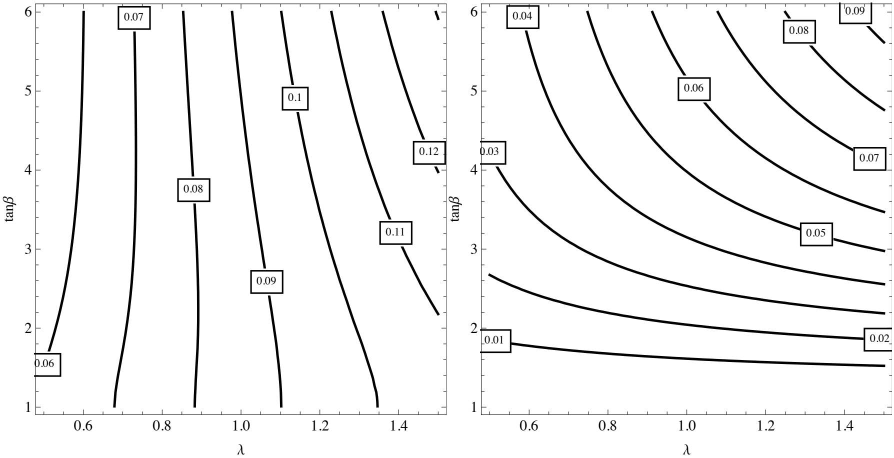


Figure: *Contour plots of S (left panel) and T (right panel) parameters in the plane* $(\lambda, \tan\beta)$ *for* $\mu = \mu_\Sigma \simeq 200$ *GeV from triplet fermions.*

$$S = 0.04 \pm 0.09, \quad T = 0.07 \pm 0.08 \qquad (88\% \text{ correlation}) .$$

The contribution from the Higgs sector is tiny

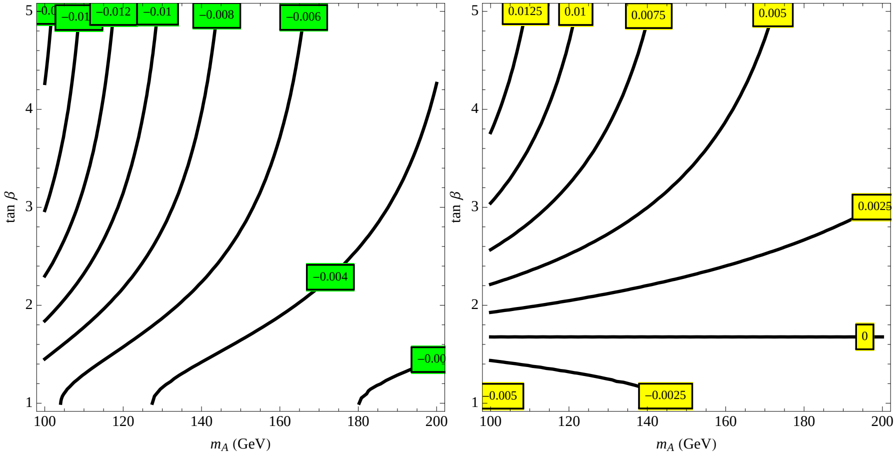


Figure: *Contour plots of S (left panel) and T (right panel) parameters in the plane* $(m_A, \tan\beta)$.

Perturbativity

- An issue which has to be considered is perturbativity of couplings
- The evolution with the scale of the couplings λ and h_t are given by the RGE

$$
\begin{aligned}
8\pi^2 \dot{\lambda} &= \left(-\frac{7}{2}g^2 - \frac{1}{2}g'^2 + 2\lambda^2 + \frac{3}{2}h_t^2\right)\lambda \\
8\pi^2 \dot{h}_t &= \left(-\frac{3}{2}g^2 - \frac{13}{18}g'^2 - \frac{8}{3}g_3^2 + \frac{3}{4}\lambda^2 + 3h_t^2\right)h_t \\
16\pi^2 \dot{g} &= 3g^2\ , \quad 16\pi^2\dot{g}' = 11g'^2 16\pi^2 \dot{g}_3 = -3g_3^3
\end{aligned}
$$

- We can see that for large enough initial values of $\lambda \equiv \lambda(m_t)$, the running coupling $\lambda(\mathcal{Q})$ is driven to larger values at high scales and eventually it reaches non-perturbative values
- This means that the theory becomes non-perturbative, unless it is UV completed at some scale smaller than Λ

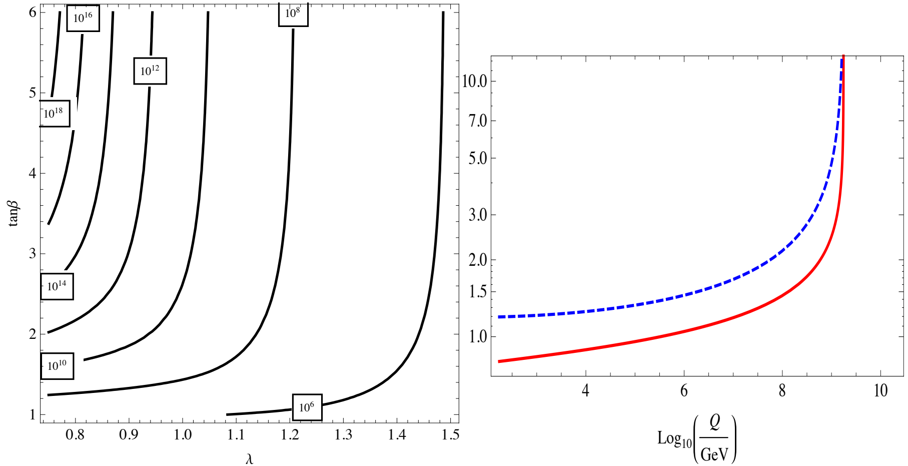


Figure: *Left panel: Contour lines for constant values of the cutoff Λ (in GeV) in the plane $(\lambda, \tan\beta)$. Right panel: Plot of $\lambda(t)$ [solid (red) line] and $h_t(t)$ [dashed (blue) line] for $\tan\beta = 1.5$ and $\lambda = 0.8$.*

The SM-like point

- The pseudo scalar (A) and charged Higgs ($H^\pm$) masses are

$$m_X^2 = \left(m_X^2\right)_{MSSM} + \frac{\lambda^2}{2}v^2, \quad X = A, H^\pm$$

- The CP-even neutral scalars (h, H) are

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

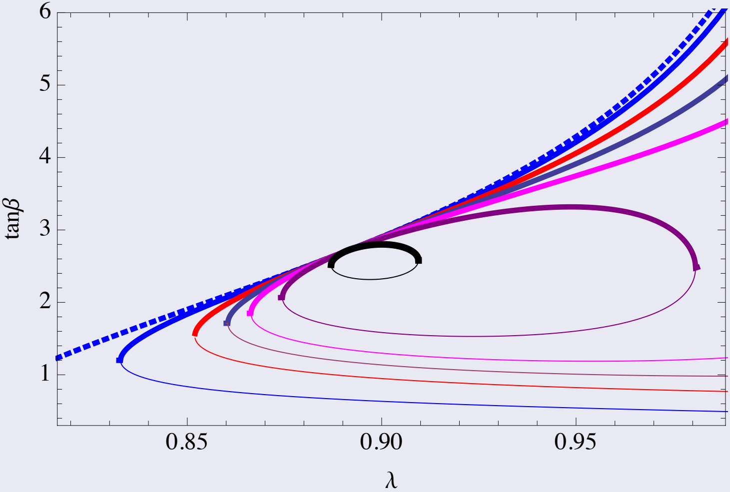
- The equation fixing m_h (e.g. to 126 GeV) is (no m_A^4 term!)

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

- This fixes for $m_h = 126$ GeV

$$\beta = \beta(\lambda; m_A)$$

Plot $\beta = \beta(\lambda; m_A)$: m_A =130, 135, 140, 145, 155, 200 GeV and decoupling; $(\tan\beta_c, \lambda_c) \simeq (2.7, 0.9)$



- The squared-mass matrix for scalars is

$$\mathcal{M}^2 = \begin{pmatrix} m_A^2 \cos^2\beta + m_{11}^2 \sin^2\beta & (-m_A^2 + m_{12}^2)\sin\beta\cos\beta \\ (-m_A^2 + m_{12}^2)\sin\beta\cos\beta & m_A^2 \sin^2\beta + m_{22}^2 \cos^2\beta \end{pmatrix} ,$$

- Where we have used the redefinitions

$$m_{12}^2 = \lambda^2 v^2 - m_Z^2 + \Delta_{\tilde{t}}\mathcal{M}_{12}^2 + \Delta_\Sigma \mathcal{M}_{12}^2 \ , \quad (1)$$

$$m_{11}^2 = m_Z^2 + \Delta_{\tilde{t}}\mathcal{M}_{11}^2 + \Delta_\Sigma \mathcal{M}_{11}^2 \ , \quad (2)$$

$$m_{22}^2 = m_Z^2 + \Delta_\Sigma \mathcal{M}_{22}^2 \ . \quad (3)$$

- And $\Delta_{\tilde{t},\Sigma}$ are radiative corrections from the couplings h_t, λ
- From $\mathcal{M}^2$ the masses and couplings are obtained

- For any value of m_A there is a SM-like point

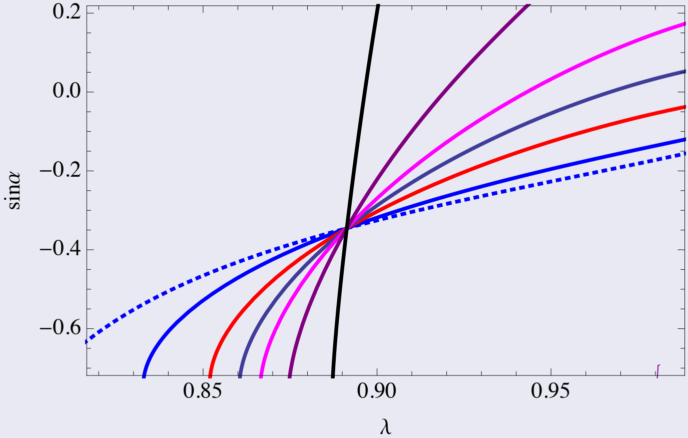
$$A(\tan\beta_c, \lambda_c, m_h) = B(\tan\beta_c, \lambda_c, m_h) = 0$$

$$\begin{cases} A = m_h^4 + \cos^2\beta \left(m_h^2(m_{11}^2 - m_{22}^2) + \sin^2\beta \left(m_{11}^2 m_{22}^2 - m_{12}^4 \right) \right) - m_h^2 \\ B = -m_h^2 + m_{11}^2 \sin^4\beta + (m_{22}^2 - 2m_{12}^2)\cos^4\beta + 2m_{12}^2\cos^2\beta \end{cases}$$

- From where

$$\begin{aligned} m_{12,c}^2 &= m_h^2 + \sqrt{(m_h^2 - m_{11}^2)(m_h^2 - m_{22}^2)}\,, \\ \cos^2\beta_c &= \left(1 + \sqrt{\frac{m_h^2 - m_{22}^2}{m_h^2 - m_{11}^2}} \right)^{-1} \end{aligned}$$

Plot of $\sin\alpha$ along $\beta(\lambda; m_A)$: $\alpha_c = \beta_c - \pi/2$ (as in decoupling limit!)



The Higgs couplings

- The angle α determines the Higgs couplings

$$r_{\mathcal{H}XX} = \frac{g_{\mathcal{H}XX}}{g^{\rm SM}_{hXX}} \quad \text{with} \quad \mathcal{H} = h, H$$

$V = (W, Z)$, $d = (b, \tau)$: tree level couplings

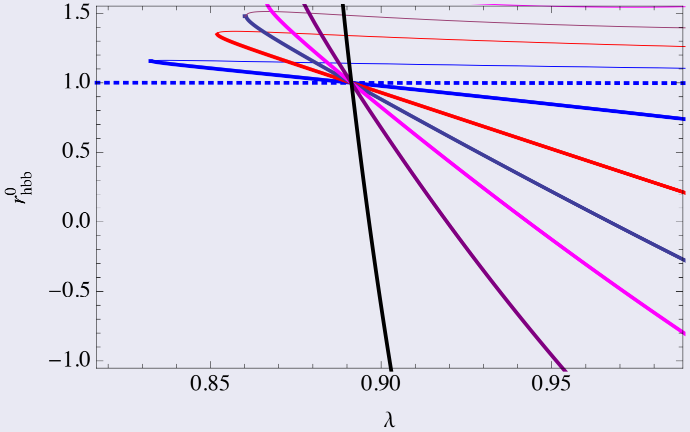
r^0_{hVV}	r^0_{HVV}	r^0_{htt}	r^0_{Htt}	r^0_{hdd}	r^0_{Hdd}
$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\dfrac{\cos\alpha}{\sin\beta}$	$\dfrac{\sin\alpha}{\sin\beta}$	$-\dfrac{\sin\alpha}{\cos\beta}$	$\dfrac{\cos\alpha}{\cos\beta}$

- At the SM-like point one reaches the SM values

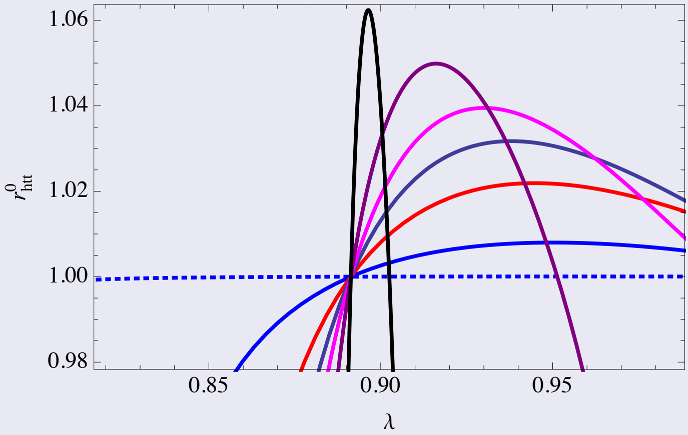
$\alpha_c = \beta_c - \pi/2$

$$r^0_{hVV}\Big|_c = r^0_{htt}\Big|_c = r^0_{hdd}\Big|_c = 1$$

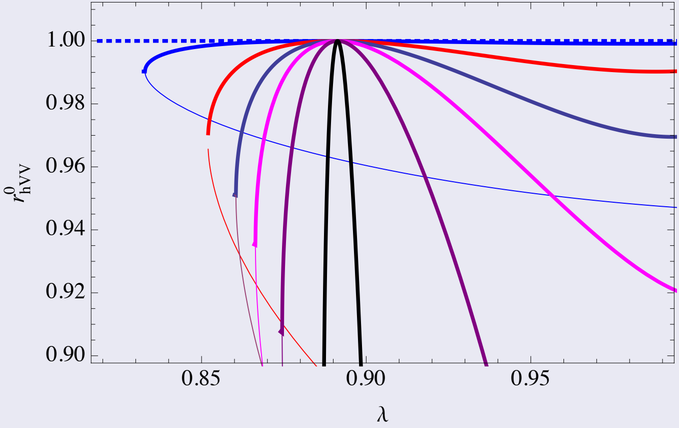
Plot of r_{hdd}



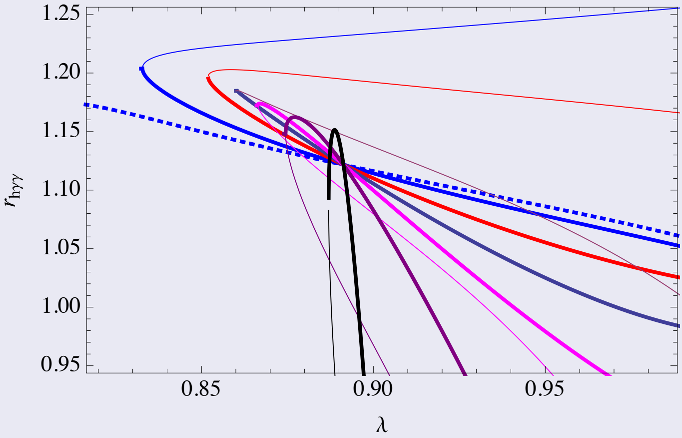
Plot of r_{htt}



Plot of r_{hVV}



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



Higgs production rates at LHC

- From the values of $r_{\mathcal{H}XX}$ determined in the previous section one can compute the predicted signal strength $\mathcal{R}_{\mathcal{H}XX}$ of the decay channel $\mathcal{H} \to XX$

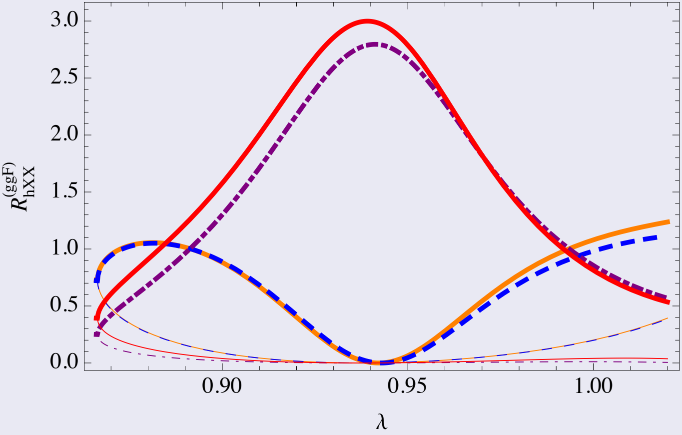
$$\mathcal{R}_{\mathcal{H}XX} = \frac{\sigma(pp \to \mathcal{H}) BR(\mathcal{H} \to XX)}{[\sigma(pp \to h) BR(h \to XX)]_{SM}}$$

- For the different production mechanisms

$$\begin{aligned}
\mathcal{R}^{(ggF)}_{\mathcal{H}XX} &= \mathcal{R}^{(\mathcal{H}tt)}_{\mathcal{H}XX} = \frac{r^2_{\mathcal{H}tt}\; r^2_{\mathcal{H}XX}}{\mathcal{D}}\,, \quad \mathcal{R}^{(VBF)}_{\mathcal{H}XX} = \mathcal{R}^{(V\mathcal{H})}_{\mathcal{H}XX} = \frac{r^2_{\mathcal{H}WW}\; r^2_{\mathcal{H}XX}}{\mathcal{D}} \\
\mathcal{D} &= BR(h \to b\, b)_{SM}\; r^2_{\mathcal{H}bb} + BR(h \to gg, cc)_{SM}\; r^2_{\mathcal{H}tt} \\
&+ BR(h \to \tau\tau)_{SM}\; r^2_{\mathcal{H}\tau\tau} + BR(h \to WW, ZZ)_{SM}\; r^2_{\mathcal{H}WW}
\end{aligned}$$

The plot of $\mathcal{R}_{hXX}$ shows the SM-like point, with some excess due to extra charginos: $m_{\chi_1^\pm} = 104$ GeV. Here is the Higgs production by gluon-fusion

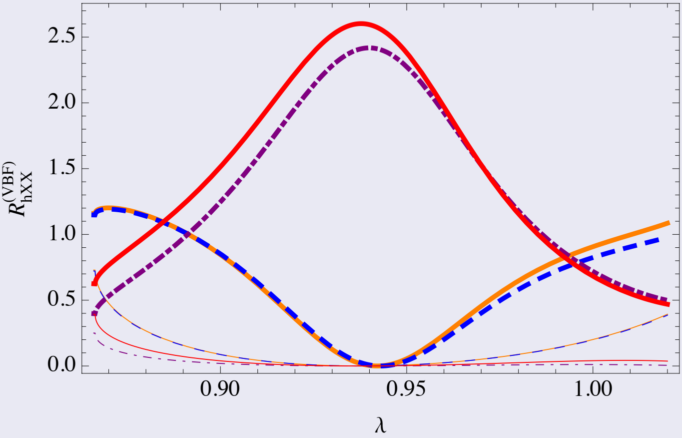
Plot of $\mathcal{R}_{hXX}^{(ggF)}$: $m_A = 140$ GeV



$\gamma\gamma$, bb, $\tau\tau$, WW, ZZ

The Higgs production by vector boson fusion

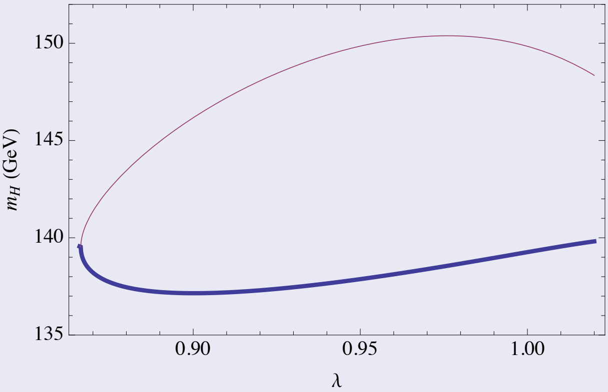
Plot of $\mathcal{R}_{hXX}^{(VBF)}$: $m_A = 140$ GeV



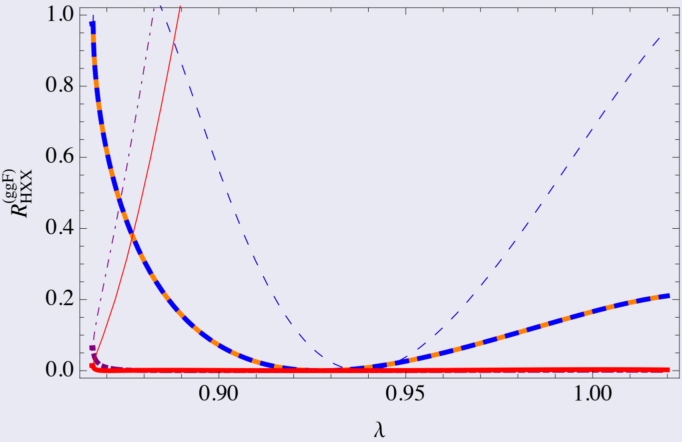
$\gamma\gamma$, bb, $\tau\tau$, WW, ZZ

The heavy Higgs is suppressed. For the $H \to bb$ and $H \to \tau\tau$ channels the rates are $\sim 10\%$ the SM rates

Plot of the next-to-lightest Higgs mass m_H as a function of λ for $m_A = 140\,\text{GeV}$



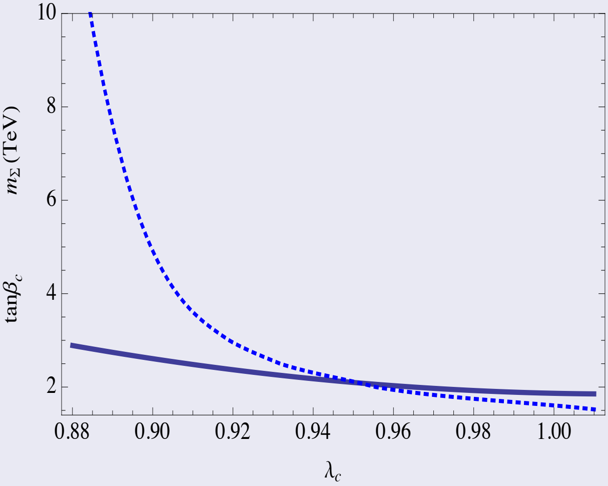
Plot of $\mathcal{R}^{(ggF)}_{HXX}$: $m_A = 140$ GeV



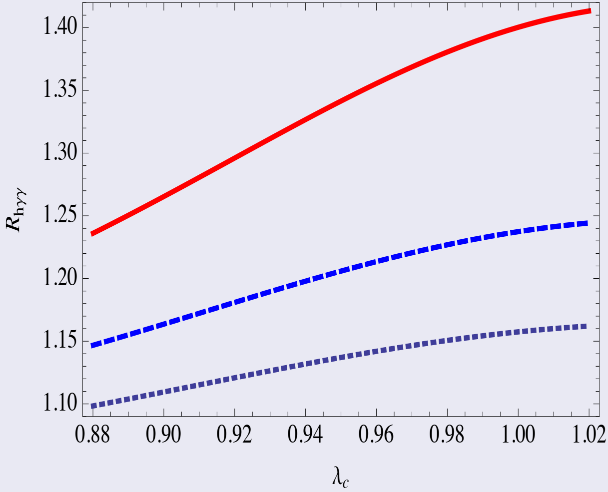
$\gamma\gamma$, bb, $\tau\tau$, WW, ZZ

The range of SM-like

Values of $(\tan\beta_c, \lambda_c)$ (solid) for m_Σ (dotted) in the range $1.5\ \mathrm{TeV} \leq m_\Sigma \leq 10\ \mathrm{TeV}$



$\mathcal{R}_{h\gamma\gamma}$ as a function of λ_c for $m_{\chi_1^\pm} = 104$ GeV (red), $m_{\chi_1^\pm} = 150$ GeV (blue) and $m_{\chi_1^\pm} = 200$ GeV (purple)



Conclusion

- In our model we can mimic the signal strength of a SM Higgs
- Some small deviations from a pure SM Higgs (e.g. $\gamma\gamma$, bb, $\tau\tau$) can also be encompassed if necessary
- When different channels will be measured with more accuracy one can make a *global fit* to all data and select regions at different C.L's
- Unfortunately still we will have to wait a few years until this happens

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