Enhanced $t\bar{t}h$ and hh Production Rates in the Two Higgs Doublet Model

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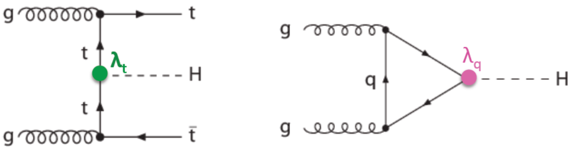
Introduction

- The Two Higgs Doublet Model (2HDM) is a simple and testable extension of SM
- It offers rich phenomenology at the LHC
- Properties of the 125 GeV SM-like Higgs may be significantly modified
- In particular, $t\bar{t}h$ production and hh production can shift significantly compared to SM, consistent with known Higgs properties
- Correlated enhancement in these rates is the main result of this talk

$t\bar{t}h$ production in SM



- Probes Yukawa coupling of the top quark directly
- Cross section ≈ 507 fb in SM, $1/96$ of single Higgs production
- CMS and ATLAS have preliminary evidence for seeing $t\bar{t}h$ process

$t\bar{t}h$ measurements

Run1 (yellow)

Run2: 13 fb^{-1} (green) | 36 fb^{-1} (red)

$\mu_{ttH} = \sigma_{ttH}/\sigma_{SM}$

	ATLAS	CMS	
Run1 comb.	$2.3^{+0.7}_{-0.6}$		← **4.4σ (2.0σ exp)**
bb	$2.1^{+1.0}_{-0.9}$	-0.2 ± 0.8	
multileptons	$2.5^{+1.3}_{-1.1}$	1.5 ± 0.5	← **3.3σ (2.5σ exp)**
τ_h+X		$0.7^{+0.6}_{-0.5}$	
γγ	$0.5^{+0.6}_{-0.6}$	$2.2^{+0.9}_{-0.8}$	← **3.3σ (1.5σ exp)**
ZZ	<7.5 @ 95%CL	$0.0^{(*)+1.2}_{-0.0}$	

(*): 68% CL interval with μ≥0

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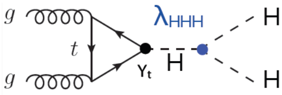
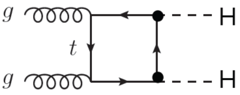
Di-Higgs production in SM





- Probes trilinear Higgs coupling and tests EW symmetry breaking mechanism
- Cross section $\simeq$ 33.5 fb in SM – the two diagrams interfere destructively
- If new resonances are present, they can decay into two Higgs and enhance di-Higgs production
- Current upper limit on di-Higgs production rate is about 19 times the SM cross section

Di-Higgs production measurements

σ/σ_{SM} 95% CL (exp)

	ATLAS	CMS
bbbb	<29 (38)	<342 (308)
bbWW		<79 (89)
$bb\tau\tau$		<28 (25)
$bb\gamma\gamma$	<117 (161)	<19 (17) NEW
$WW\gamma\gamma$	<747 (386)	

Run2			
	3 fb^{-1}	13 fb^{-1}	36 fb^{-1}

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Knowledge about 125 GeV Higgs

- Any deviation in $t\bar{t}h$ and hh production should be consistent with known information about 125 GeV Higgs
- Signal strengths normalized to SM values:

$$\mu_{\gamma\gamma} = 1.075^{+0.15}_{-0.14}$$

$$\mu_{ZZ^\star} = 1.165^{+0.165}_{-0.155}$$

$$\mu_{WW^\star} = 1.09^{+0.18}_{-0.16}$$

$$\mu_{\tau\tau} = 1.06^{+0.25}_{-0.24}$$

$$\mu_{b\bar{b}} = 0.90^{+0.28}_{-0.26}$$

- Here $\mu^i_f = \mu_i \mu^f$, where

$$\mu^i = \frac{\sigma^i}{(\sigma^i)_{SM}} \quad \text{and} \quad \mu_f = \frac{BR_f}{(BR_f)_{SM}}$$

Signal Strength Constraints on Higgs Observables at LHC

Decay channel	Production Mode	CMS	ATLAS
$\gamma\gamma$	ggF	$1.05^{+0.19}_{-0.19}$	$0.80^{+0.19}_{-0.18}$
	VBF	$0.6^{+0.6}_{-0.5}$	$2.1^{+0.6}_{-0.6}$
	Wh	$3.1^{+1.50}_{-1.30}$	$0.7^{+0.9}_{-0.8}$
	Zh	$0.0^{+0.9}_{-0.0}$	$0.7^{+0.9}_{-0.8}$
$ZZ^\star$	ggF	$1.20^{+0.22}_{-0.21}$	$1.11^{+0.23}_{-0.27}$
	VBF	$0.05^{+1.03}_{-0.05}$	$4.0^{+2.1}_{-1.8}$
	Wh	$0.0^{+2.66}_{-0.00}$	< 3.8
	Zh	$0.0^{+2.66}_{-0.00}$	< 3.8
W^+W^-	ggF	$0.9^{+0.40}_{-0.30}$	$1.02^{+0.29}_{-0.26}$
	VBF	$1.4^{+0.8}_{-0.8}$	$1.7^{+1.1}_{-0.9}$
	Vh	$2.1^{+2.3}_{-2.2}$	$3.2^{+4.4}_{-4.2}$
	$ggF + VBF + Vh$	$1.05^{+0.26}_{-0.26}$	-
$b\bar{b}$	Vh	$1.0^{+0.5}_{-0.5}$	$0.9^{+0.28}_{-0.26}$
$\tau^+\tau^-$	ggF	$1.05^{+0.49}_{-0.46}$	$2.0^{+0.8}_{-0.8}$
	$VBF + Vh$	$1.07^{+0.45}_{-0.43}$	$1.24^{+0.58}_{-0.54}$
	$ggF + VBF + Vh$	$1.06^{+0.25}_{-0.24}$	$1.43^{+0.43}_{-0.37}$

The Two Higgs Doublet Model (2HDM)

- Renormalizable standard model with two Higgs doublets Φ_1 and Φ_2
- Both Φ_1 and Φ_2 couple to fermions
- Flavor changing Higgs interactions are naturally suppressed as Yukawa couplings are proportional to fermion masses Cheng, Sher (1987)
- “Type III” or ”most general” designations not necessary
- $\langle \Phi_1^0 \rangle = v_1$, $\langle \Phi_2^0 \rangle = v_2 e^{i\xi}$
- Rotate Φ_1 and Φ_2 so that only one combination H_1 has nonzero VEV: $\langle H_1^0 \rangle = v$, $\langle H_2^0 \rangle = 0$

2HDM

- Rotated doublet fields:

$$H_1 = \Phi_1 \cos\beta + e^{-i\xi}\,\Phi_2 \sin\beta$$
$$H_2 = -e^{i\xi}\,\Phi_1 \sin\beta + \Phi_2 \cos\beta$$

- Can be written as:

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + \varphi_1^0 + iG^0\right) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(\varphi_2^0 + iA\right) \end{pmatrix}$$

- Scalar potential:

$$\mathcal{V} = M_{11}^2 H_1^\dagger H_1 + M_{22}^2 H_2^\dagger H_2 - [M_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.}]$$
$$+ \tfrac{1}{2}\Lambda_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2}\Lambda_2 (H_2^\dagger H_2)^2 + \Lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \Lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \left\{ \tfrac{1}{2}\Lambda_5 (H_1^\dagger H_2)^2 + \left[\Lambda_6 \,(H_1^\dagger H_1) + \Lambda_7 (H_2^\dagger H_2)\right] H_1^\dagger H_2 + \mathrm{h.c.} \right\}$$

Higgs Boson Masses

- Minimization conditions:

$$M_{11}^2 = -\tfrac{1}{2}\Lambda_1 v^2\,, \qquad\qquad M_{12}^2 = \tfrac{1}{2}\Lambda_6 v^2$$

- Mass squared matrix:

$$\mathcal{M}^2 = \begin{pmatrix} \Lambda_1 v^2 & \mathrm{Re}(\Lambda_6) v^2 & -\mathrm{Im}(\Lambda_6) v^2 \\ \mathrm{Re}(\Lambda_6) v^2 & M_{22}^2 + \frac{1}{2} v^2 (\Lambda_3 + \Lambda_4 + \mathrm{Re}(\Lambda_5)) & -\frac{1}{2}\mathrm{Im}(\Lambda_5) v^2 \\ -\mathrm{Im}(\Lambda_6) v^2 & -\frac{1}{2}\mathrm{Im}(\Lambda_5) v^2 & M_{22}^2 + \frac{1}{2} v^2 (\Lambda_3 + \Lambda_4 - \mathrm{Re}(\Lambda_5)) \end{pmatrix}$$

- Assume CP invariance (for simplicity of presentation). CP-even Higgs masses:

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + v^2(\Lambda_1 + \Lambda_5) \mp \sqrt{[m_A^2 + (\Lambda_5 - \Lambda_1) v^2]^2 + 4\Lambda_6^2 v^4} \right]$$

- CP-odd and charged Higgs masses:

$$m_A^2 = m_{H^\pm}^2 - \frac{1}{2} v^2 (\Lambda_5 - \Lambda_4)$$
$$m_{H^\pm}^2 = M_{22}^2 + \frac{1}{2} v^2 \Lambda_3$$

2HDM: Parameters

- Neutral Higgs boson mixing angle:

$$h = \varphi_1^0 \cos\alpha + \varphi_2^0 \sin\alpha,$$
$$H = \varphi_2^0 \cos\alpha - \varphi_1^0 \sin\alpha,$$

$$\sin[2\alpha] = \frac{2\Lambda_6 v^2}{m_H^2 - m_h^2}\,.$$

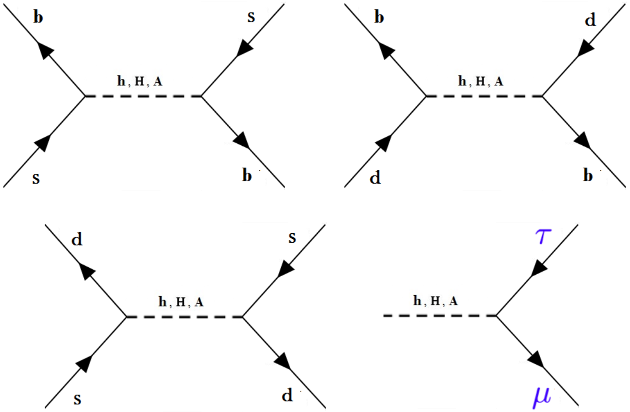
- Yukawa couplings:

$$\mathcal{L}_y = Y_d \bar{Q}_L d_R H_1 + \tilde{Y}_d \bar{Q}_L d_R H_2 + Y_u \bar{Q}_L u_R \tilde{H}_1 + \tilde{Y}_u \bar{Q}_L u_R \tilde{H}_2$$
$$+ Y_l \bar{\psi}_L H_1 \psi_R + \tilde{Y}_l \bar{\psi}_L H_2 \psi_R + h.c.,$$

- Relevant parameters for collider physics are:

$$\left\{ \tilde{Y}_t, \quad \tilde{Y}_b, \quad \tilde{Y}_\tau, \quad M_H, \quad \sin\alpha \right\}$$

Flavor Violation in 2HDM



$B_s - \overline{B_s}$ mixing, $B_d - \overline{B_d}$ mixing, $K - \overline{K}$ mixing constraints satisfied with $Y_{ij} \sim \tilde{Y}_{ij} \sim c_{ij} m_i / v, i < j$

CKM mixings correctly reproduced with $c_{12} \sim 4, c_{13} \sim 3, c_{23} \sim 2$

Decay widths of h

Mixing modifies SM Higgs partial decay widths:

$$\begin{aligned}
\Gamma_{h\to\gamma\gamma} &= \kappa_{\gamma\gamma}^2 \Gamma_{h\to\gamma\gamma}^{\mathrm{SM}}, \\
\Gamma_{h\to WW^*} &= \Gamma_{h\to WW^*}^{\mathrm{SM}} \cos^2\alpha, \\
\Gamma_{h\to ZZ^*} &= \Gamma_{h\to ZZ^*}^{\mathrm{SM}} \cos^2\alpha, \\
\Gamma_{h\to b\bar{b}} &= \kappa_b^2 \Gamma_{h\to bb}^{\mathrm{SM}}, \\
\Gamma_{h\to\tau^+\tau^-} &= \kappa_\tau^2 \Gamma_{h\to\tau\tau}^{\mathrm{SM}}, \\
\Gamma_{h\to c\bar{c}} &= \Gamma_{h\to cc}^{\mathrm{SM}}, \\
\Gamma_{h\to Z\gamma} &= \kappa_{Z\gamma}^2 \Gamma_{h\to Z\gamma}^{\mathrm{SM}},
\end{aligned}$$

Scaling factors

$$\kappa_{W,Z} = \cos\alpha,$$

$$\kappa_t = \left[\cos\alpha + \frac{\tilde{Y}_t v}{\sqrt{2}m_t}\sin\alpha\right],$$

$$\kappa_b = \left[\cos\alpha + \frac{\tilde{Y}_b v}{\sqrt{2}m_b}\sin\alpha\right],$$

$$\kappa_\tau = \left[\cos\alpha + \frac{\tilde{Y}_\tau v}{\sqrt{2}m_\tau}\sin\alpha\right],$$

$$\kappa_{\gamma\gamma} = \left|\frac{\frac{4}{3}\kappa_t F_{1/2}(m_h) + F_1(m_h)\cos\alpha + \frac{v\lambda_{hH^+H^-}F_0(m_h)}{2m_{H^+}^2}}{\frac{4}{3}F_{1/2}(m_h) + F_1(m_h)}\right|,$$

$$\kappa_{Z\gamma} = \left|\frac{\frac{2}{\cos\theta_W}\left(1-\frac{8}{3}\sin^2\theta_W\right)\kappa_t F_{1/2}(m_h) + F_1(m_h)\cos\alpha + \frac{v\lambda_{hH^+H^-}\lambda_{ZH^+H^-}F_0(m_h)}{2m_{H^+}^2}}{\frac{2}{\cos\theta_W}\left(1-\frac{8}{3}\sin^2\theta_W\right)F_{1/2}(m_h) + F_1(m_h)}\right|$$

Constraints on Model Parameters

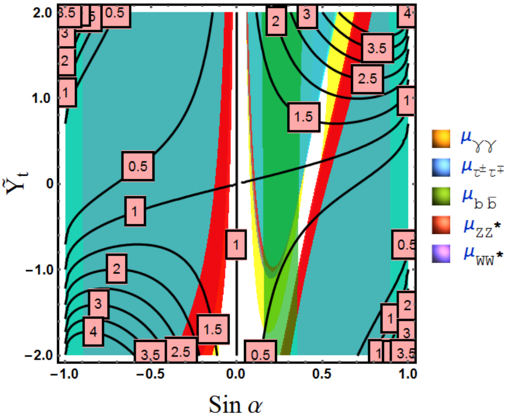


Figure: Contour plot of $\mu^{t\bar{t}h}$. Here $\tilde{Y}_b = -0.09$ is kept fixed. White region is allowed.

Constraints on Model Parameters

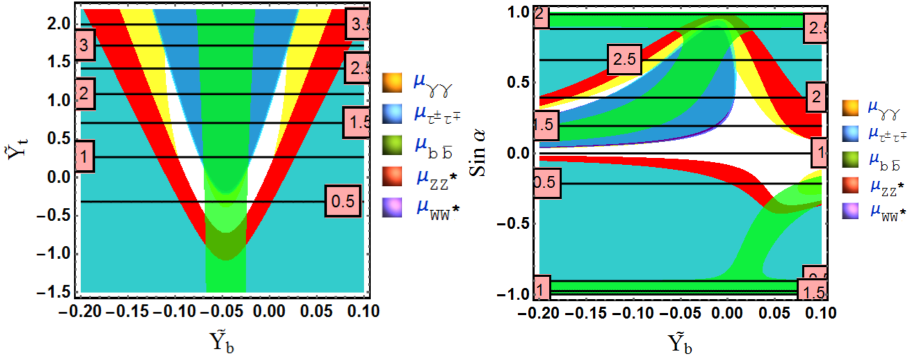


Figure: $\sin\alpha = 0.5$ (left); $\tilde{Y}_t = 1.25$ (right)

Di-Higgs production

Resonant H production, followed by $H \to hh$, enhances di-Higgs production

Signal strength relative to the SM expectation μ_{hh} defined as follows:

$$\mu_{hh} = \frac{\sigma(pp \to hh)_{2HDM}}{\sigma(pp \to hh)_{SM}} = \frac{\left[\sigma^{Res}(pp \to hh) + \sigma^{Non-Res}(pp \to hh)\right]_{2HDM}}{\sigma(pp \to hh)_{SM}},$$

where

$$\sigma^{Res}(pp \to hh) = \sigma(pp \to H) \times Br(H \to hh)$$

$$\sigma(pp \to H) = \sigma(pp \to h(M_H)) \times \left(-\sin\alpha + \frac{v\tilde{y}_t}{\sqrt{2}m_t}\cos\alpha\right)^2$$

Branching ratio of H

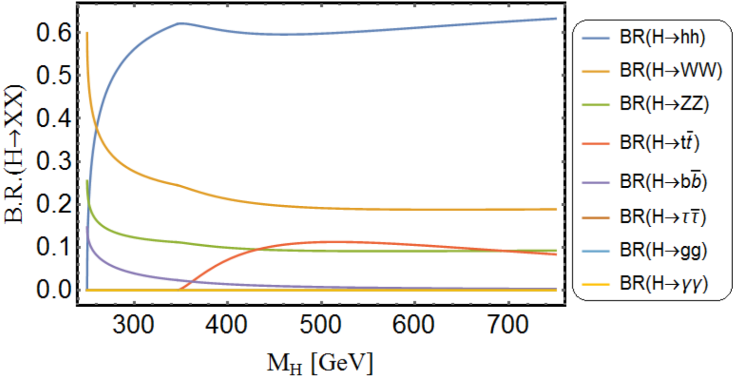


Figure: Branching ratio to different decay modes of H as a function of mass M_H.

Contourplot of μ_{hh}

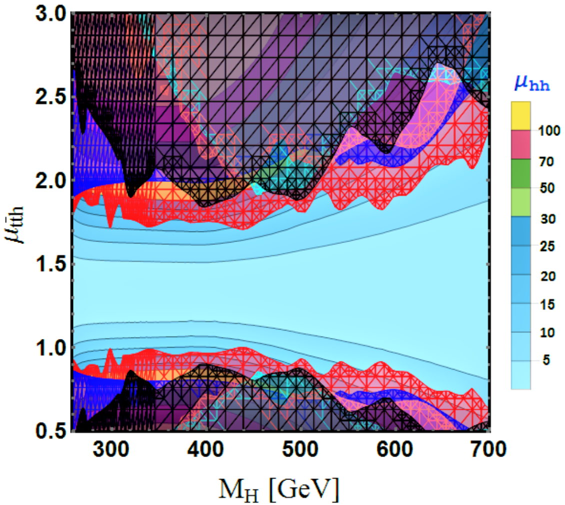


Figure: Black, pink and cyan colored meshed zones are excluded parameter space from current di-Higgs limit looking at different final states $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ respectively; red and blue meshed zone is the excluded parameter space from the resonant ZZ and W^+W^- production constraints. $\sin\alpha = 0.5$, $\tilde{Y}_b = -0.09$, $\tilde{Y}_\tau = 10^{-3}$.

Contourplot of μ_{hh}

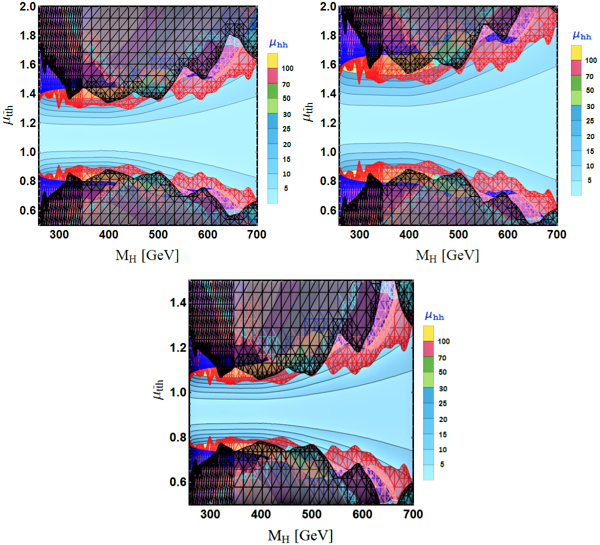


Figure: ($\sin\alpha = 0.3$, $\tilde{Y}_b = -0.09$, $\tilde{Y}_\tau = 10^{-3}$) for top left; ($\sin\alpha = 0.4$, $\tilde{Y}_b = 0.02$, $\tilde{Y}_\tau = 10^{-3}$) for top right and ($\sin\alpha = -0.2$, $\tilde{Y}_b = 0.04$, $\tilde{Y}_\tau = 10^{-3}$) for bottom one.

Sample Points

Benchmark Points	$\tilde{Y}_t$	$\tilde{Y}_b$	$\tilde{Y}_\tau$	sin	$M_H[GeV]$	Scaling Factors	$\mu_{t\bar{t}h}$	μ_{hh}
BP1	$+1.01$	-0.10	10^{-3}	$+0.50$	500	$\kappa_W = 0.866$ $\kappa_Z = 0.866$ $\kappa_t = 1.374$ $\kappa_b = -1.001$ $\kappa_\tau = 0.915$ $\kappa_{\gamma\gamma} = 0.723$ $\kappa_{Z\gamma} = 0.778$	1.89	15
BP2	$+1.2$	-0.09	10^{-3}	$+0.51$	700	$\kappa_W = 0.860$ $\kappa_Z = 0.860$ $\kappa_t = 1.475$ $\kappa_b = -0.854$ $\kappa_\tau = 0.910$ $\kappa_{\gamma\gamma} = 0.690$ $\kappa_{Z\gamma} = 0.740$	2.2	9
BP3	-1.0	$+0.01$	10^{-3}	-0.10	600	$\kappa_W = 0.995$ $\kappa_Z = 0.995$ $\kappa_t = 1.096$ $\kappa_b = 0.958$ $\kappa_\tau = 0.985$ $\kappa_{\gamma\gamma} = 0.966$ $\kappa_{Z\gamma} = 0.976$	1.2	10
BP4	1.25	$+0.05$	10^{-3}	-0.20	680	$\kappa_W = 0.980$ $\kappa_Z = 0.980$ $\kappa_t = 0.728$ $\kappa_b = 0.61$ $\kappa_\tau = 0.960$ $\kappa_{\gamma\gamma} = 1.05$ $\kappa_{Z\gamma} = 1.08$	0.53	11

T and S parameters

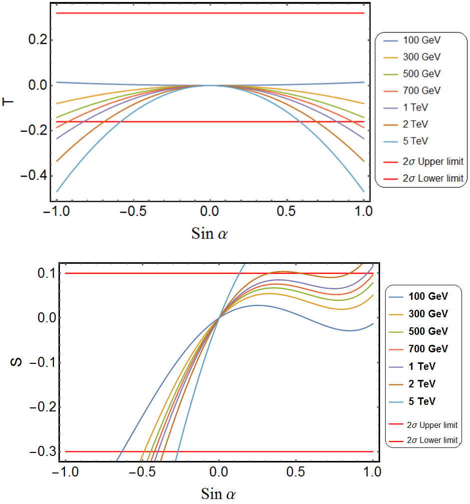


Figure: T and S parameters as a function of $\sin\alpha$ for different heavy Higgs masses.

Boundedness of Higgs Potential

- To ensure that the scalar potential is bounded from below, we evaluate the eigenvalues and eigenvectors of the following matrix:

$$\begin{bmatrix} \frac{1}{4}(\Lambda_1+\Lambda_2+2\Lambda_3) & -\frac{1}{2}(\Lambda_6+\Lambda_7) & 0 & -\frac{1}{4}(\Lambda_1-\Lambda_2) \\ \frac{1}{2}(\Lambda_6+\Lambda_7) & -\frac{1}{2}(\Lambda_4+\Lambda_5) & 0 & -\frac{1}{2}(\Lambda_6-\Lambda_7) \\ 0 & 0 & -\frac{1}{2}(\Lambda_4-\Lambda_5) & 0 \\ \frac{1}{4}(\Lambda_1-\Lambda_2) & -\frac{1}{2}(\Lambda_6-\Lambda_7) & 0 & -\frac{1}{4}(\Lambda_1+\Lambda_2+2\Lambda_3) \end{bmatrix}$$

  We choose all the quartic couplings to be real.
- One set of values of the quartic couplings:
  $\Lambda_1 = 1.4, \Lambda_2 = 0.01, \Lambda_3 = 1, \Lambda_4 = 0.1, \Lambda_5 = 0.001, \Lambda_6 = 3, \Lambda_7 = -1.2$.
- All the eigenvalues of the matrix are real, and the largest eigenvalue is positive: $\{2.0527, -1.75315, 0.649943, -0.0495\}$.
  This satisfies necessary and suffcient conditions for the potential to be bounded from below.
- For this specific choice, we get HIggs masses to be: {125 GeV, 751 GeV, 706 GeV.} The mixing parameter $\sin\alpha = 0.458$.

Conclusions

- 2HDM provides a framework to check EWSB dynamics
- Correlated enhancements is $t\bar{t}h$ and hh production possible
- Additional Higgs bosons below a TeV will be confirmation of the scenario