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

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Work done with Sudip Jana
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 $\approx 507$ 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

<table>
<thead>
<tr>
<th>Run1</th>
<th>Run2 13 fb$^{-1}$</th>
<th>Run2 36 fb$^{-1}$</th>
</tr>
</thead>
</table>

\[ \mu_{ttH} = \frac{\sigma_{ttH}}{\sigma_{SM}} \]

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run1 comb.</td>
<td>2.3$^{+0.7}_{-0.6}$</td>
<td>4.4$^\sigma$ (2.0$^\sigma$ exp)</td>
</tr>
<tr>
<td>$bb$</td>
<td>2.1$^{+1.0}_{-0.9}$</td>
<td>-0.2$\pm$ 0.8</td>
</tr>
<tr>
<td>multileptons</td>
<td>2.5$^{+1.3}_{-1.1}$</td>
<td>1.5$\pm$ 0.5</td>
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<tr>
<td>$\tau_h+X$</td>
<td>0.7$^{+0.6}_{-0.5}$</td>
<td>3.3$^\sigma$ (2.5$^\sigma$ exp)</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.5$^{+0.6}_{-0.6}$</td>
<td>2.2$^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$&lt;7.5 @ 95%\text{CL}$</td>
<td>3.3$^\sigma$ (1.5$^\sigma$ exp)</td>
</tr>
</tbody>
</table>

K.S. Babu (OSU)  
Enhanced $t\bar{t}h$ and $hh$ production in 2HDM  
Paolo Meridiani, EPS Conference on High Energy Physics, July 2017
Di-Higgs production in SM

- Probes trilinear Higgs coupling and tests EW symmetry breaking mechanism

- Cross section \( \simeq 33.5 \text{ fb} \) 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
<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>$&lt;29$ (38)</td>
<td>$&lt;342$ (308)</td>
</tr>
<tr>
<td>$b\bar{b}W\bar{W}$</td>
<td></td>
<td>$&lt;79$ (89)</td>
</tr>
<tr>
<td>$b\bar{b}\tau\bar{\tau}$</td>
<td></td>
<td>$&lt;28$ (25)</td>
</tr>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>$&lt;117$ (161)</td>
<td>$&lt;19$ (17)</td>
</tr>
<tr>
<td>$W\bar{W}\gamma\gamma$</td>
<td>$&lt;747$ (386)</td>
<td></td>
</tr>
</tbody>
</table>

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

Paolo Meridiani, EPS Conference on High Energy Physics, July 2017
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:
  \[
  \begin{align*}
  \mu_{\gamma\gamma} &= 1.075^{+0.15}_{-0.14} \\
  \mu_{ZZ^*} &= 1.165^{+0.165}_{-0.155} \\
  \mu_{WW^*} &= 1.09^{+0.18}_{-0.16} \\
  \mu_{\tau\tau} &= 1.06^{+0.25}_{-0.24} \\
  \mu_{b\bar{b}} &= 0.90^{+0.28}_{-0.26}
  \end{align*}
  \]
- Here $\mu_f^i = \mu_i \mu_f$, 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

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Production Mode</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>$ggF$</td>
<td>1.05$^{+0.19}_{-0.19}$</td>
<td>0.80$^{+0.19}_{-0.18}$</td>
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<td>$VBF$</td>
<td>0.6$^{+0.6}_{-0.5}$</td>
<td>2.1$^{+0.6}_{-0.6}$</td>
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<tr>
<td></td>
<td>$Wh$</td>
<td>3.1$^{+1.50}_{-1.30}$</td>
<td>0.7$^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td></td>
<td>$Zh$</td>
<td>0.0$^{+0.9}_{-0.0}$</td>
<td>0.7$^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td>$ZZ^*$</td>
<td>$ggF$</td>
<td>1.20$^{+0.22}_{-0.21}$</td>
<td>1.11$^{+0.23}_{-0.27}$</td>
</tr>
<tr>
<td></td>
<td>$VBF$</td>
<td>0.05$^{+1.03}_{-0.05}$</td>
<td>4.0$^{+2.1}_{-1.8}$</td>
</tr>
<tr>
<td></td>
<td>$Wh$</td>
<td>0.0$^{+2.66}_{-0.00}$</td>
<td>&lt; 3.8</td>
</tr>
<tr>
<td></td>
<td>$Zh$</td>
<td>0.0$^{+2.66}_{-0.00}$</td>
<td>&lt; 3.8</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>$ggF$</td>
<td>0.9$^{+0.40}_{-0.30}$</td>
<td>1.02$^{+0.29}_{-0.26}$</td>
</tr>
<tr>
<td></td>
<td>$VBF$</td>
<td>1.4$^{+0.8}_{-0.8}$</td>
<td>1.7$^{+1.1}_{-0.9}$</td>
</tr>
<tr>
<td></td>
<td>$Vh$</td>
<td>2.1$^{+2.3}_{-2.2}$</td>
<td>3.2$^{+4.4}_{-4.2}$</td>
</tr>
<tr>
<td></td>
<td>$ggF + VBF + Vh$</td>
<td>1.05$^{+0.26}_{-0.26}$</td>
<td>-</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>$Vh$</td>
<td>1.0$^{+0.5}_{-0.5}$</td>
<td>0.9$^{+0.28}_{-0.26}$</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>$ggF$</td>
<td>1.05$^{+0.49}_{-0.46}$</td>
<td>2.0$^{+0.8}_{-0.8}$</td>
</tr>
<tr>
<td></td>
<td>$VBF + Vh$</td>
<td>1.07$^{+0.45}_{-0.43}$</td>
<td>1.24$^{+0.58}_{-0.54}$</td>
</tr>
<tr>
<td></td>
<td>$ggF + VBF + Vh$</td>
<td>1.06$^{+0.25}_{-0.24}$</td>
<td>1.43$^{+0.43}_{-0.37}$</td>
</tr>
</tbody>
</table>
The Two Higgs Doublet Model (2HDM)

- Renormalizable standard model with two Higgs doublets $\Phi_1$ and $\Phi_2$
- Both $\Phi_1$ and $\Phi_2$ 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 $\Phi_1$ and $\Phi_2$ so that only one combination $H_1$ has nonzero VEV: $\langle H_1^0 \rangle = v$, $\langle H_2^0 \rangle = 0$
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:

\[ H_1 = \left( \frac{1}{\sqrt{2}} \left( G^+ \sqrt{2} \left( \nu + \varphi^0_1 + iG^0_0 \right) \right) \right), \quad H_2 = \left( \frac{1}{\sqrt{2}} \left( \varphi^0_2 + iA \right) \right) \]

Scalar potential:

\[ V = M_{11}^2 H_1^\dagger H_1 + M_{22}^2 H_2^\dagger H_2 - [M_{12}^2 H_1^\dagger H_2 + h.c.] \]
\[ + \frac{1}{2} \Lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2} \Lambda_2 (H_2^\dagger H_2)^2 + \Lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \Lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \]
\[ + \left\{ \frac{1}{2} \Lambda_5 (H_1^\dagger H_2)^2 + \left[ \Lambda_6 (H_1^\dagger H_1) + \Lambda_7 (H_2^\dagger H_2) \right] H_1^\dagger H_2 + \text{h.c.} \right\} \]
Higgs Boson Masses

- Minimization conditions:
  \[ M_{11}^2 = -\frac{1}{2} \Lambda_1 v^2, \quad M_{12}^2 = \frac{1}{2} \Lambda_6 v^2 \]

- Mass squared matrix:
  \[
  M^2 = \begin{pmatrix}
  \Lambda_1 v^2 & \text{Re}(\Lambda_6) v^2 & \text{Re}(\Lambda_6) v^2 & -\text{Im}(\Lambda_6) v^2 \\
  \text{Re}(\Lambda_6) v^2 & M_{22}^2 + \frac{1}{2} v^2 (\Lambda_3 + \Lambda_4 + \text{Re}(\Lambda_5)) & -\frac{1}{2} \text{Im}(\Lambda_5) v^2 & -\frac{1}{2} \text{Im}(\Lambda_5) v^2 \\
  -\text{Im}(\Lambda_6) v^2 & -\frac{1}{2} \text{Im}(\Lambda_5) v^2 & M_{22}^2 + \frac{1}{2} v^2 (\Lambda_3 + \Lambda_4 - \text{Re}(\Lambda_5)) & -\frac{1}{2} \text{Im}(\Lambda_5) v^2 \\
  -\text{Im}(\Lambda_6) v^2 & -\frac{1}{2} \text{Im}(\Lambda_5) v^2 & -\frac{1}{2} \text{Im}(\Lambda_5) v^2 & M_{22}^2 + \frac{1}{2} v^2 (\Lambda_3 + \Lambda_4 - \text{Re}(\Lambda_5))
  \end{pmatrix}
  \]

- 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:

\[ \left\{ \tilde{Y}_t, \ \tilde{Y}_b, \ \tilde{Y}_\tau, \ M_H, \ \sin \alpha \right\} \]
Flavor Violation in 2HDM

$B_s - \bar{B}_s$ mixing, $B_d - \bar{B}_d$ mixing, $K - \bar{K}$ mixing constraints satisfied with 
$Y_{ij} \sim \tilde{Y}_{ij} \sim c_{ij} m_i / \nu, \ i < j$

CKM mixings correctly reproduced with $c_{12} \sim 4, c_{13} \sim 3, c_{23} \sim 2$
Mixing modifies SM Higgs partial decay widths:

\[
\begin{align*}
\Gamma_{h \to \gamma \gamma} &= \kappa_{\gamma \gamma}^2 \Gamma_{h \to \gamma \gamma}^{\text{SM}}, \\
\Gamma_{h \to WW^*} &= \Gamma_{h \to WW^*}^{\text{SM}} \cos^2 \alpha, \\
\Gamma_{h \to ZZ^*} &= \Gamma_{h \to ZZ^*}^{\text{SM}} \cos^2 \alpha, \\
\Gamma_{h \to b \bar{b}} &= \kappa_b^2 \Gamma_{h \to b \bar{b}}^{\text{SM}}, \\
\Gamma_{h \to \tau^+ \tau^-} &= \kappa_{\tau}^2 \Gamma_{h \to \tau^+ \tau^-}^{\text{SM}}, \\
\Gamma_{h \to c \bar{c}} &= \Gamma_{h \to c \bar{c}}^{\text{SM}}, \\
\Gamma_{h \to Z \gamma} &= \kappa_{Z \gamma}^2 \Gamma_{h \to Z \gamma}^{\text{SM}},
\end{align*}
\]
Scaling factors

\[ \kappa_{W,Z} = \cos \alpha, \]

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

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

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

\[ \kappa_{\gamma\gamma} = \frac{\frac{4}{3} \kappa_t F_{1/2}(m_h) + F_1(m_h) \cos \alpha + \frac{v \lambda_{HH^+} - F_0(m_h)}{2m_{H^+}^2}}{\frac{4}{3} F_{1/2}(m_h) + F_1(m_h)}, \]

\[ \kappa_{Z\gamma} = \frac{\frac{2}{\cos \theta_W} \left( 1 - \frac{8}{3} \sin^2 \theta_W \right) \kappa_t F_{1/2}(m_h) + F_1(m_h) \cos \alpha + \frac{v \lambda_{HH^+} - \lambda_{ZH^+} - F_0(m_h)}{2m_{H^+}^2}}{\frac{2}{\cos \theta_W} \left( 1 - \frac{8}{3} \sin^2 \theta_W \right) F_{1/2}(m_h) + F_1(m_h)}. \]
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 $H \rightarrow hh$, enhances di-Higgs production

Signal strength relative to the SM expectation $\mu_{hh}$ defined as follows:

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

where

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

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

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

BR(\(H \rightarrow hh\))
BR(\(H \rightarrow WW\))
BR(\(H \rightarrow ZZ\))
BR(\(H \rightarrow t\bar{t}\))
BR(\(H \rightarrow b\bar{b}\))
BR(\(H \rightarrow \tau\bar{\tau}\))
BR(\(H \rightarrow gg\))
BR(\(H \rightarrow \gamma\gamma\))
Contourplot of $\mu_{hh}$

**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 $\mu_{hh}$

**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**

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

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

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 sufficient conditions for the potential to be bounded from below.

- For this specific choice, we get Higgs masses to be: \( \{125 \text{ GeV}, 751 \text{ GeV}, 706 \text{ GeV}\}. \) 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