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

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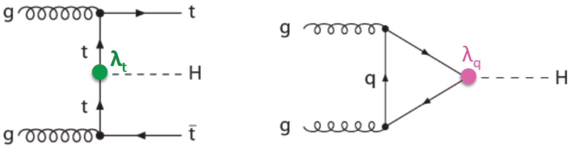
Introduction

- 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

	ATLAS Run 2		CMS Run 2		
bb	2.1	$^{+1.0}_{-0.9}$	−0.2	$^{+0.8}_{-0.8}$	*PAS HIG 16-038*
multilep	2.5	$^{+1.3}_{-1.1}$	1.5	$^{+0.5}_{-0.5}$	*PAS HIG 17-004 (35.9 fb^{-1})*
γγ	−0.3	$^{+1.2}_{-1.0}$	1.9	$^{+1.5}_{-1.2}$	*PAS HIG 16-020*
4ℓ			0.0*	$^{+1.2*}_{-0.0*}$	*PAS HIG 16-041 (35.9 fb^{-1})*
comb.	1.8	$^{+0.7}_{-0.7}$			

ATLAS-CONF-2016-068

(*) $-2\Delta\ln L = 1$ interval with $\mu \geq 0$ constraint

Run1 comb. 2.3 $^{+1.2}_{-1.0}$

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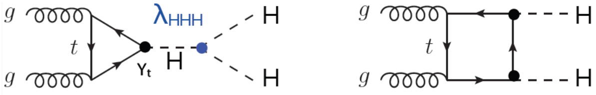
Giovanni Petrucciani, Recontres de Moriond, EW Interactions & Unified Theories, March 2017

Di-Higgs production in SM



- Probes trilinear Higgs coupling and tests EW symmetry breaking mechanism
- Cross section $\simeq$ 34 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 29 times the SM cross section

Di-Higgs production measurements

Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM} ATLAS	CMS
bbbb	29 (38)	342 (308)
bbWW	-	410 (227)
$bb\tau\tau$	-	28 (25)
$bb\gamma\gamma$	117 (161)	91 (90)
$WW\gamma\gamma$	747 (386)	-

2.3-3.2 fb^{-1}	13.3 fb^{-1}	35.9 fb^{-1}

Luca Cadamuro, Recontres de Moriond, EW Interactions & Unified Theories, March 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:

$$\begin{aligned}
\mu_{\gamma\gamma} &= 0.95^{+0.20}_{-0.20} \\
\mu_{ZZ^\star} &= 1.05^{+0.19}_{-0.17} \\
\mu_{WW^\star} &= 1.09^{+0.18}_{-0.16} \\
\mu_{\tau\tau} &= 1.11^{+0.24}_{-0.22} \\
\mu_{b\bar{b}} &= 0.70^{+0.29}_{-0.27}
\end{aligned}$$

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

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

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:

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

- 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:

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

- 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:

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

2HDM: Parameters

- Neutral Higgs boson mixing angle:

$$\begin{aligned} h &= \varphi_1^0 \cos\alpha + \varphi_2^0 \sin\alpha, \\ H &= \varphi_2^0 \cos\alpha - \varphi_1^0 \sin\alpha, \end{aligned}$$

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

- 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:

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

Decay widths of h

Mixing modifies SM Higgs partial decay widths:

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

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

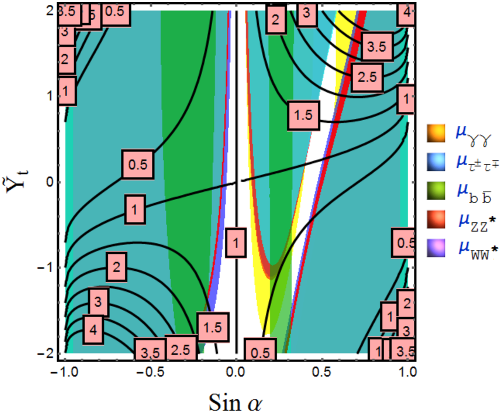


Figure: Contour plot of $\mu^{t\bar{t}h}$. Here $\tilde{Y}_b = -0.09$ is kept fixed. White region is allowed.

Constraints on Model Parameters

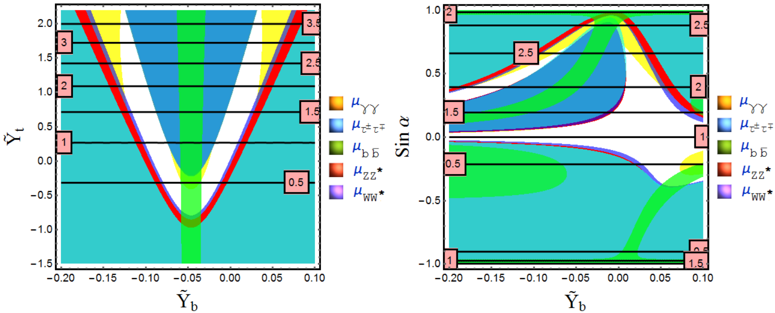


Figure: $\sin\alpha = 0.5$ (left); $\tilde{Y}_t = 1.25$ (right)

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

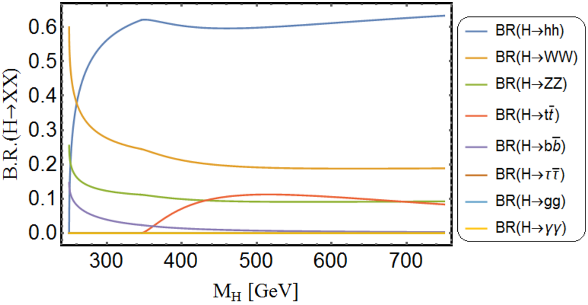


Figure: Branching ratio to different decay modes of H as a function of mass M_H.

Contourplot of μ_{hh}

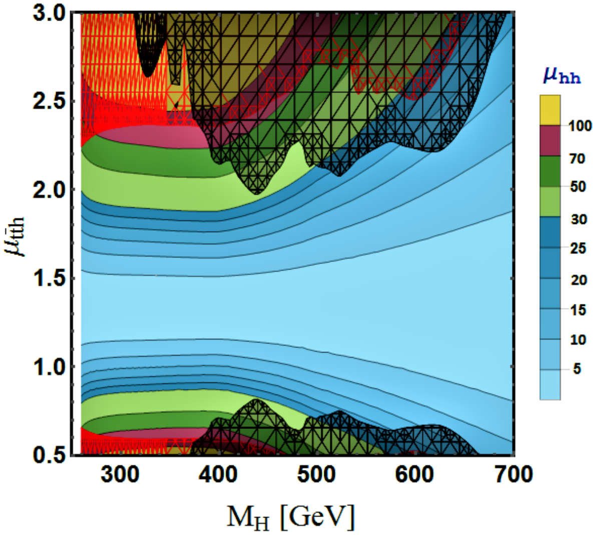


Figure: Black meshed zone excluded from current di-Higgs limit, red meshed zone excluded from resonant ZZ and W^+W^- production constraints. $\sin\alpha = 0.5$, $\tilde{Y}_b = -0.09$, $\tilde{Y}_\tau = 10^{-3}$.

Sample Points

Benchmark Points	$\tilde{\mathbf{Y}}_{\mathbf{t}}$	$\tilde{\mathbf{Y}}_{\mathbf{b}}$	$\tilde{\mathbf{Y}}_{\tau}$	$\sin\alpha$	$M_H[GeV]$	$\mu_{t\bar{t}h}$	μ_{hh}
BP1	1.1	−0.1	10^{-3}	0.5	500	2.01	24
BP2	1.5	−0.09	10^{-3}	0.56	700	2.81	14
BP3	−1.0	0.01	10^{-3}	−0.2	600	1.4	19

T and S parameters

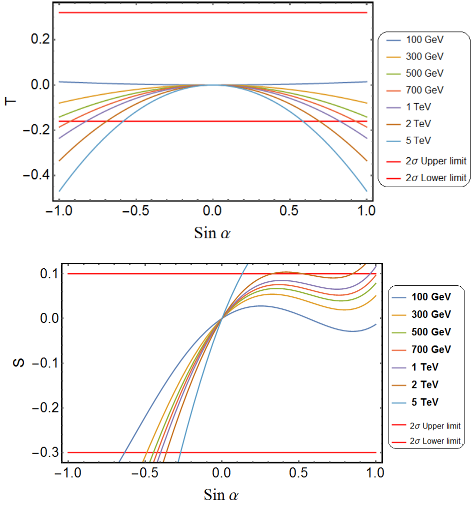


Figure: T and S parameters as a function of $\sin\alpha$ for different heavy Higgs masses.

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