Double Higgs boson production in the Standard Model with extra scalar particles

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Motivation

- A scalar with mass 125 GeV has been discovered in 2012.
- In order to confirm that this is the Standard Model Higgs boson, its couplings have to be measured.
- Triple coupling: $g_{hhh} \sim \frac{m_h^2}{v}$. It can be measured in the $pp \to hh$ process.
- Standard Model prediction for the $pp \to hh$ cross section is 40 fb for $\sqrt{s} = 14$ TeV. That can only be measured at HL-LHC.
- What if there are other scalar particles?

Isosinglet

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Scalar sector:

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + \phi + i\eta) \end{pmatrix}, \quad X = v_X + \chi$$

Potential:

$$V_1(\Phi, X) = -\frac{1}{2} m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda}{2} (\Phi^\dagger \Phi)^2 + \frac{1}{2} m_X^2 X^2 + \mu \Phi^\dagger \Phi X$$

Mixing:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ \chi \end{pmatrix}.$$

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1. $\frac{\partial V_1}{\partial \phi}\Big|_{\phi=0,\ \chi=0} = 0,$
2. $\frac{\partial V_1}{\partial \chi}\Big|_{\phi=0,\ \chi=0} = 0,$
3. $v_\Phi = 246$ GeV from the Fermi coupling in muon decay.
4. h is associated with the SM-like higgs, so $m_h = 125$ GeV.

Remaining model parameters: $\sin\alpha$ and m_H.

H decay widths:

$$\Gamma(H \to W^+ W^-) = \frac{m_H^3 \sin^2\alpha}{16\pi v_\Phi^2}\left[1 - 4\frac{m_W^2}{m_H^2} + 12\frac{m_W^4}{m_H^4}\right]\sqrt{1 - \left(\frac{2m_W}{m_H}\right)^2}$$

$$\Gamma(H \to ZZ) = \frac{m_H^3 \sin^2\alpha}{128\pi v_\Phi^2}\left[1 - 4\frac{m_Z^2}{m_H^2} + 12\frac{m_Z^4}{m_H^4}\right]\sqrt{1 - \left(\frac{2m_Z}{m_H}\right)^2}$$

$$\Gamma(H \to t\bar{t}) = \frac{3m_t^2 m_H \sin^2\alpha}{8\pi v_\Phi^2}\left[1 - \left(\frac{2m_t}{m_H}\right)^2\right]^{\frac{3}{2}}$$

$$\Gamma(H \to hh) = \frac{(2m_h^2 + m_H^2)^2}{32\pi v_\Phi^2 m_H}\sin^2\alpha\cos^4\alpha\sqrt{1 - \left(\frac{2m_h}{m_H}\right)^2}$$

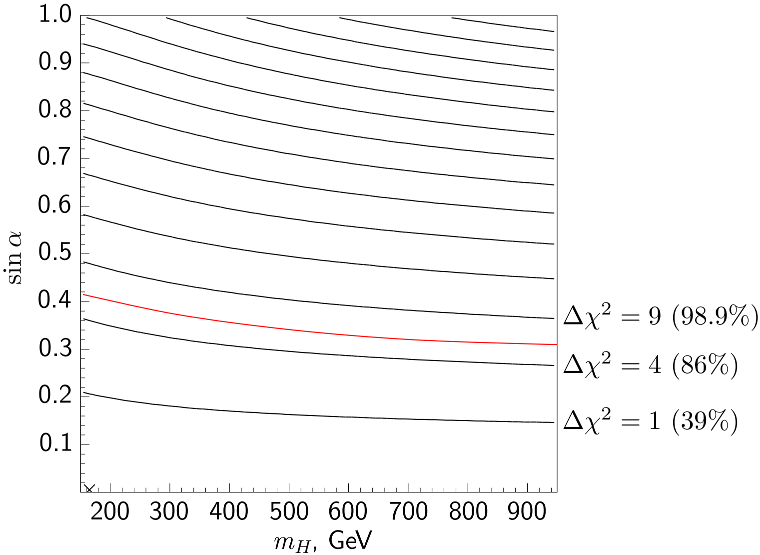
h double production cross section:

$$\sigma(pp \to H \to hh) = \sigma(pp \to h)_{\mathsf{SM}} \cdot \sin^2\alpha \cdot \mathrm{Br}(H \to hh)$$

$$\mu_i = \frac{\sigma(pp \to h) \cdot \mathrm{Br}(h \to f_i)}{(\sigma(pp \to h) \cdot \mathrm{Br}(h \to f_i))_{\mathsf{SM}}} = \cos^2\alpha$$

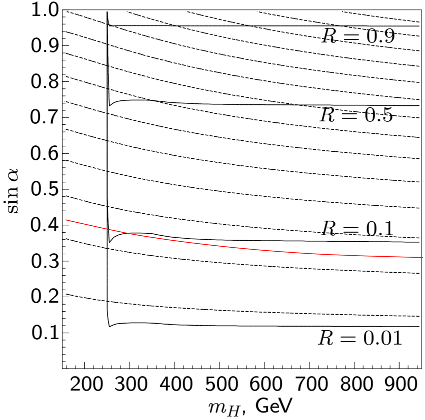
ATLAS: $\mu = 1.30^{+0.18}_{-0.17}$, CMS: $\mu = 1.00^{+0.14}_{-0.13}$.

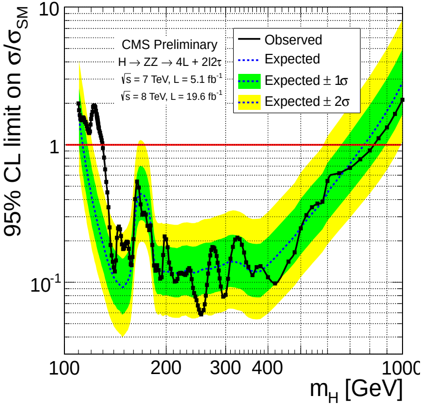
Bounds from electroweak precision observables and μ measurements:



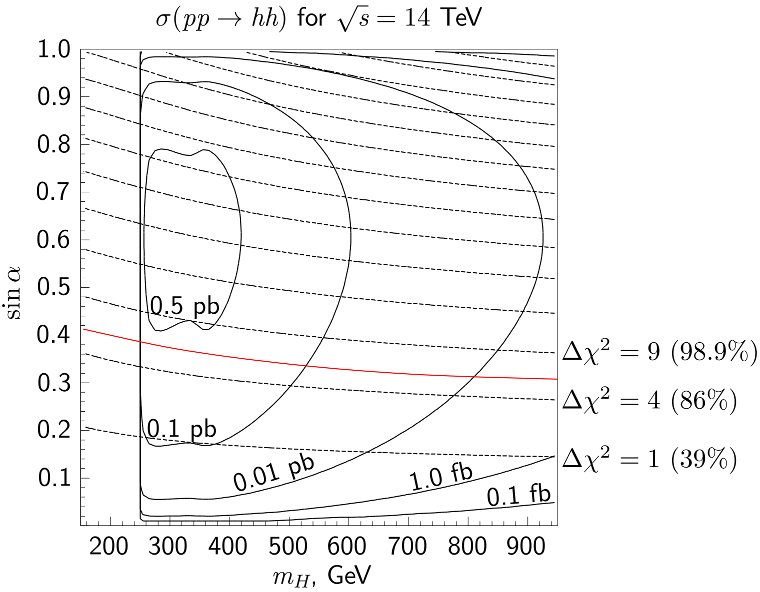
$\chi^2_{\text{min}}/n_{\text{d.o.f}} = 19.6/11$

$$R \equiv \frac{\sigma(pp\to H)\,\mathrm{Br}(H\to ZZ)}{(\sigma(pp\to h)\,\mathrm{Br}(h\to ZZ))_{\mathrm{SM}}} = \frac{\sin^4\alpha}{\sin^2\alpha + \frac{\Gamma(H\to hh)}{\Gamma_{\mathrm{SM}}}}$$





Experiment: $R < 0.1$ for 200 GeV$M m_H < 400$ GeV
(CMS PAS HIG-13-002).


$\sigma(pp \to hh)$ for $\sqrt{s} = 14$ TeV
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$\sin\alpha$
0.5 pb
0.1 pb
0.01 pb
1.0 fb
0.1 fb
200
300
400
500
600
700
800
900
m_H, GeV
$\Delta\chi^2 = 9$ (98.9%)
$\Delta\chi^2 = 4$ (86%)
$\Delta\chi^2 = 1$ (39%)

Isotriplet

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Scalar sector:

$$\Phi = \begin{bmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + \phi + i\eta) \end{bmatrix}, \quad \Delta = \frac{\vec{\Delta}\vec{\sigma}}{\sqrt{2}} = \begin{bmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \frac{1}{\sqrt{2}}(v_\Delta + \delta + i\rho) & -\delta^+/\sqrt{2} \end{bmatrix}$$

Potential:

$$V(\Phi, \Delta) = -\frac{1}{2} m_\Phi^2 (\Phi^\dagger \Phi) + \frac{\lambda}{2} (\Phi^\dagger \Phi)^2 \\ + m_\Delta^2 \, \mathrm{tr}[\Delta^\dagger \Delta] + \frac{\mu}{\sqrt{2}} (\Phi^T i\sigma^2 \Delta^\dagger \Phi + \text{h.c.})$$

Mixing:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ \delta \end{pmatrix}.$$

$m_h = 125$ GeV.

Custodial symmetry breaking:

$$\left.\begin{aligned} m_W^2 &= \frac{g^2}{4}(v_\Phi^2 + 2v_\Delta^2) \\ m_Z^2 &= \frac{\bar{g}^2}{4}(v_\Phi^2 + 4v_\Delta^2) \end{aligned}\right\} \Rightarrow \frac{m_W}{m_Z} \approx \left(\frac{m_W}{m_Z}\right)_{\text{SM}} \left(1 - \frac{v_\Delta^2}{v_\Phi^2}\right)$$

$$\left(\frac{m_W}{m_Z \cos\theta_W}\right)_{\text{SM}} = 1.00040 \pm 0.00024 \Rightarrow v_\Delta < 5 \text{ GeV (at } 3\sigma \text{ level)}$$

In the following we assume $v_\Delta = 5$ GeV.

$$v_\Phi^2 + 2v_\Delta^2 = \frac{1}{\sqrt{2}G_F} = (246 \text{ GeV})^2 \Rightarrow v_\Phi \approx 246 \text{ GeV}.$$

With $v_\Delta \ll v_\Phi$ we get $\sin\alpha \approx \frac{2v_\Delta}{v_\Phi} \ll 1$.
Remaining model parameters: m_H. We will consider the case of $m_H = 300$ GeV.

$$\Gamma(H \to ZZ) = \frac{v_\Delta^2}{v^4} \frac{m_H^3}{8\pi} \left[\frac{1 - 2\left(\frac{m_h}{m_H}\right)^2}{1 - \left(\frac{m_h}{m_H}\right)^2} \right]^2 \left(1 - 4\frac{m_Z^2}{m_H^2} + 12\frac{m_Z^4}{m_H^4}\right) \sqrt{1 - \left(\frac{2m_Z}{m_H}\right)^2}$$

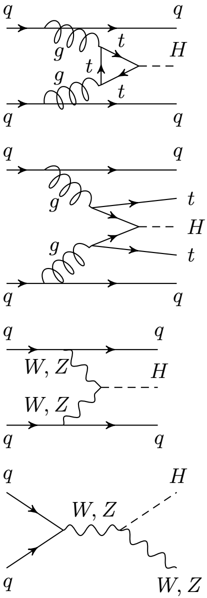
$$\Gamma(H \to WW) = \frac{v_\Delta^2}{v^4} \frac{m_H^3}{4\pi} \left[\frac{\left(\frac{m_h}{m_H}\right)^2}{1 - \left(\frac{m_h}{m_H}\right)^2} \right]^2 \left(1 - 4\frac{m_W^2}{m_H^2} + 12\frac{m_W^4}{m_H^4}\right) \sqrt{1 - \left(\frac{2m_W}{m_H}\right)^2}$$

$$\Gamma(H \to t\bar{t}) = \frac{v_\Delta^2}{v^4} \frac{3m_t^2 m_H}{2\pi} \left[\frac{1}{1 - \left(\frac{m_h}{m_H}\right)^2} \right]^2 \left(1 - \left(\frac{2m_t}{m_H}\right)^2\right)^{\frac{3}{2}}$$

$$\Gamma(H \to hh) = \frac{v_\Delta^2}{v^4} \frac{m_H^3}{8\pi} \left[\frac{1 + 2\left(\frac{m_h}{m_H}\right)^2}{1 - \left(\frac{m_h}{m_H}\right)^2} \right]^2 \sqrt{1 - \left(\frac{2m_h}{m_H}\right)^2}$$

$H \to WW$ decay is suppressed, $H \to ZZ$ is the “golden mode”.
$\mathrm{Br}(H \to hh) \approx 0.8$ for $m_H = 300$ GeV.

Heavy higgs production at the LHC:



$$\sigma(gg \to H) = \left[\frac{2v_\Delta}{v_\Phi} \frac{1}{1 - \left(\frac{m_h}{m_H}\right)^2} \right]^2 \sigma(gg \to h)_{\mathsf{SM}}$$

$$= 2.4 \cdot 10^{-3} \cdot \sigma(gg \to h)_{\mathsf{SM}}$$

$$\sigma(ZZ \to H) = \left[\frac{2v_\Delta}{v_\Phi} \frac{1 - 2\left(\frac{m_h}{m_H}\right)^2}{1 - \left(\frac{m_h}{m_H}\right)^2} \right]^2 \sigma(ZZ \to h)_{\mathsf{SM}}$$

$$= 1.0 \cdot 10^{-3} \cdot \sigma(ZZ \to h)_{\mathsf{SM}}$$

$$\sigma(WW \to H) = \left[\frac{2v_\Delta}{v_\Phi} \frac{\left(\frac{m_h}{m_H}\right)^2}{1 - \left(\frac{m_h}{m_H}\right)^2} \right]^2 \sigma(WW \to h)_{\mathsf{SM}}$$

$$= 7.3 \cdot 10^{-5} \cdot \sigma(WW \to h)_{\mathsf{SM}}$$

Higgs boson double production cross section at the LHC for $\sqrt{s} = 14$ TeV

	the SM h		H
Mass, GeV	125	300	300
$\sigma(gg \to h, H)$,[1] pb	50(5)	11(1)	$25(2)\cdot 10^{-3}$
$\sigma(gg \to t\bar{t} + h, H)$,[1] pb	0.61(6)	0.051(5)	$12(1)\cdot 10^{-6}$
$\sigma(W^+W^- \to h, H)$,[2] pb	3.272(4)	1.053(1)	$76.8(1)\cdot 10^{-6}$
$\sigma(ZZ \to h, H)$,[2] pb	1.087(1)	0.365(1)	$365(1)\cdot 10^{-6}$
$\sigma(W^* \to Wh, WH)$,[2] pb	0.150(6)	0.068(3)	$5.0(2)\cdot 10^{-6}$
$\sigma(Z \to Zh, ZH)$,[2] pb	0.88(5)	0.042(2)	$42(2)\cdot 10^{-6}$

$$\sigma(pp \to hh) = 40 \text{ fb (SM)} + 25 \text{ fb } (H \text{ production}) \cdot 0.8 \text{ (branching)}$$
$$= 60 \text{ fb}$$

[1]For the SM higgs values are from *Handbook of LHC Higgs cross sections*, CERN-2011-002

[2]Obtained with the help of the program HAWK at LO + QCD without electroweak corrections

$$\Phi = \begin{bmatrix} \phi^{0*} & \phi^+ \\ -\phi^- & \phi^0 \end{bmatrix}, \quad \Delta = \begin{bmatrix} \delta^{0*} & \xi^+ & \delta^{++} \\ -\delta^- & \xi^0 & \delta^+ \\ \delta^{--} & -\xi^- & \delta^0 \end{bmatrix}.$$

$$\phi^0 = \frac{1}{\sqrt{2}}(v_\Phi + \phi + i\chi), \quad \delta^0 = \frac{1}{\sqrt{2}}(v_\Delta + \delta + i\eta),$$

$$\xi^0 = v_\xi + \xi.$$

$$m_W^2 = \frac{g^2}{4}(v_\Phi^2 + 2v_\Delta^2 + 2v_\xi^2)$$

$$m_Z^2 = \frac{\bar{g}^2}{4}(v_\Phi^2 + 4v_\Delta^2)$$

$$(v_\Phi^2 + 2v_\Delta^2 + 2v_\xi^2) = \frac{1}{\sqrt{2}G_F} = (246\ \text{GeV})^2$$

When $v_\xi = v_\Delta$ the bound on v_Δ from the gauge bosons mass ratio is relieved. LHC measurements allowes v_Δ up to 50 GeV. In this case H production cross section can be as high as 2 pb depending on model parameters.

Thank you for your attention