Double Higgs production at LHC in the Standard Model extended with an isosinglet

1503.01618

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June 24–July 1 2015,
Samara, Russia

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?

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. $\left.\frac{\partial V_1}{\partial \phi}\right|_{\phi=0,\ \chi=0} = 0,$
2. $\left.\frac{\partial V_1}{\partial \chi}\right|_{\phi=0,\ \chi=0} = 0,$
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:

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

Experimental data (signal strength):

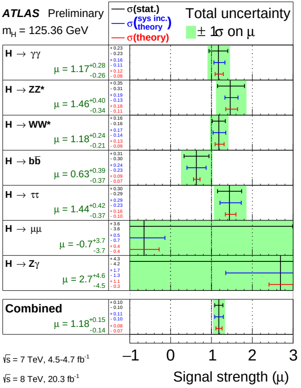
$$\mu_i \equiv \frac{\sigma_{pp\to h} \cdot \Gamma_{h\to f_i}/\Gamma_h}{(\sigma_{pp\to h} \cdot \Gamma_{h\to f_i}/\Gamma_h)_{\text{SM}}}$$

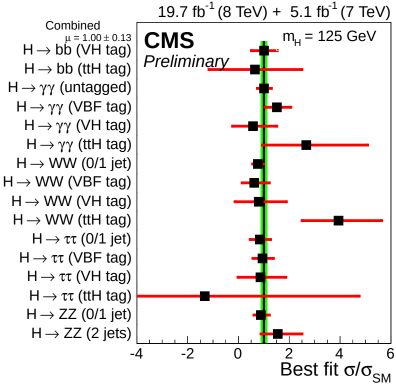
In the model with an isosinglet: $\mu_i = \cos^2\alpha$.

Experiment results:

ATLAS $\mu = 1.18^{+0.15}_{-0.14}[\pm 0.10\ (\text{stat.}) \pm 0.07\ (\text{syst.})^{+0.08}_{-0.07}\ (\text{theor.})]$

CMS $\mu = 1.00^{+0.14}_{-0.13}[\pm 0.09\ (\text{stat.}) \pm 0.07\ (\text{syst.})^{+0.08}_{-0.07}\ (\text{theor.})]$



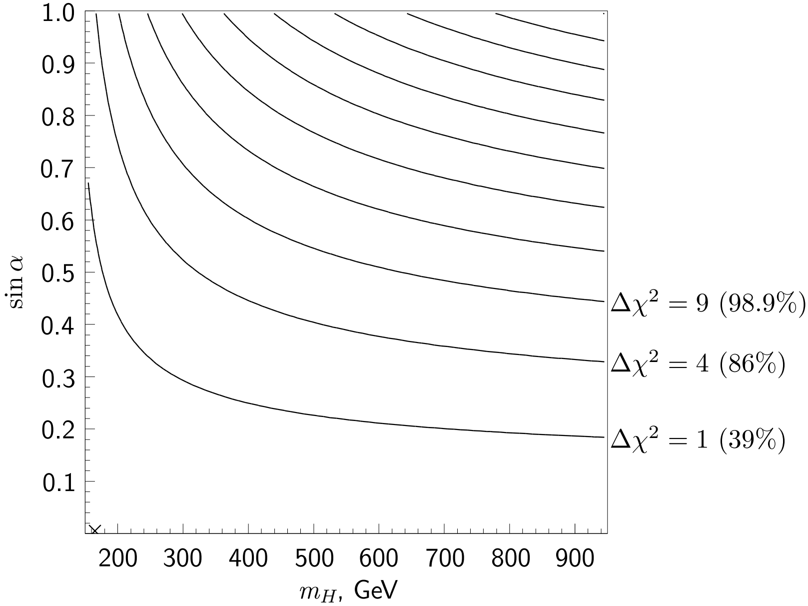


A fit of the Standard Model to electroweak precision observables with $m_h = 125.14$ GeV computed with the help of LEPTOP program.

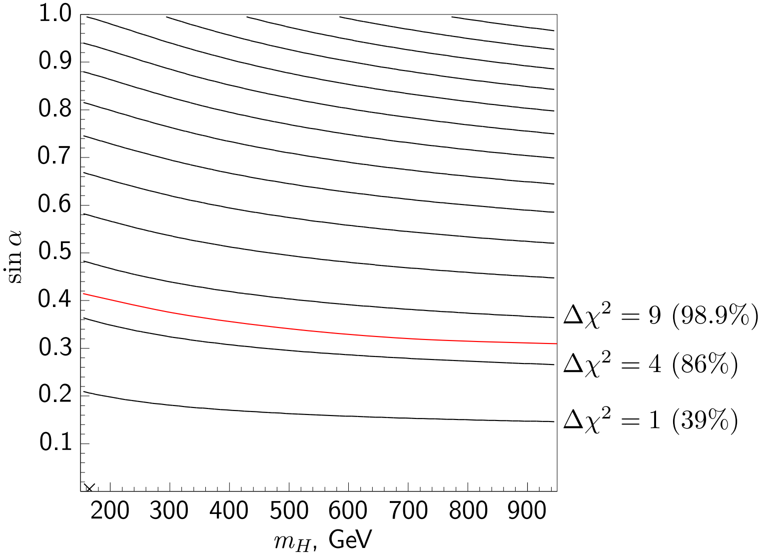
Observable	Experimental value	Standard Model	Pull
Γ_Z, GeV	$2.4952(23)$	$2.4966(14)$	-0.5895
σ_h, nb	$41.541(37)$	$41.475(14)$	1.7746
R_l	$20.771(25)$	$20.744(18)$	1.0831
A^l_{FB}	$0.0171(10)$	$0.0165(2)$	0.6572
A_τ	$0.1439(43)$	$0.1484(7)$	-1.0452
R_b	$0.2163(7)$	$0.2158(0)$	0.7699
R_c	$0.1721(30)$	$0.1722(0)$	-0.0277
A^b_{FB}	$0.0992(16)$	$0.1040(5)$	-3.0303
A^c_{FB}	$0.0707(35)$	$0.0744(4)$	-1.0565
s^2_l (Q_{FB})	$0.2324(12)$	$0.2313(1)$	0.8771
A_{LR}	$0.1514(22)$	$0.1484(7)$	1.3822
A_b	$0.923(20)$	$0.9349(1)$	-0.5941
A_c	$0.670(27)$	$0.6685(3)$	0.0567
M_W, GeV	$80.3846(146)$	$80.3725(67)$	0.8322
m_t, GeV	$173.24(95)$	$174.32(89)$	-1.1370
$1/\bar{\alpha}$	$128.954(48)$	$129.023(37)$	-1.4378

$\chi^2/n_{\text{d.o.f.}} = 19.6/13$ (was $18/12$ [arXiv:0904.4570]).

A fit of the Standard Model with an extra isosinglet to electroweak precision observables.

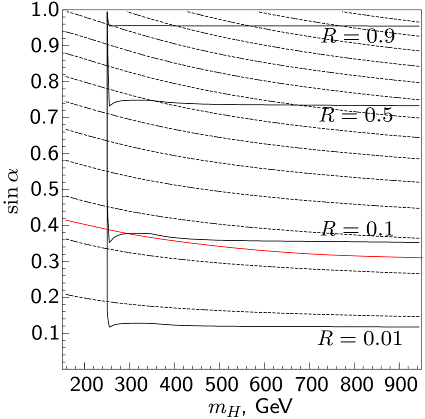


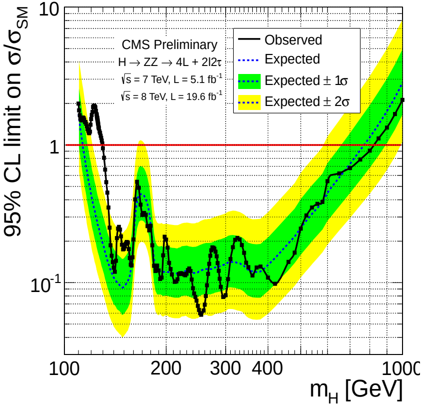
A fit of the Standard Model with an extra isosinglet to electroweak precision observables and μ measurements.



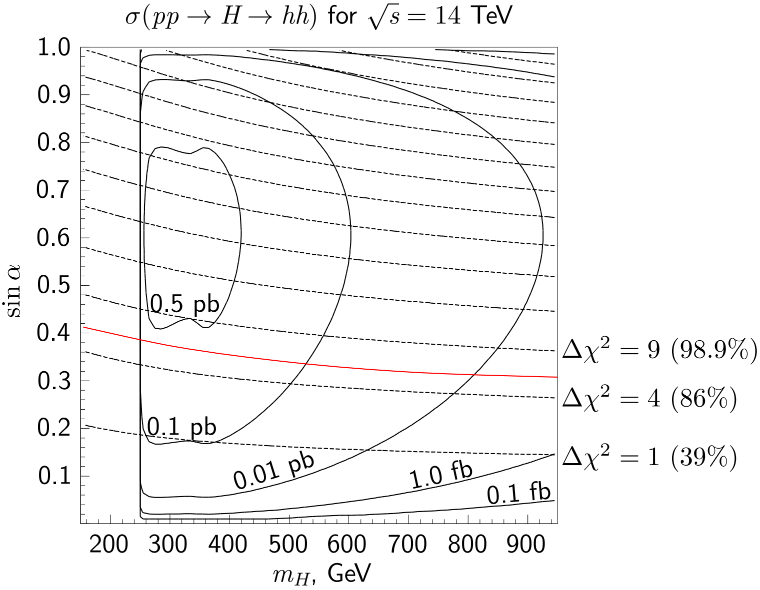
$\chi^2_{\text{min}}/n_{\text{d.o.f}} = 19.6/11$

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





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


$\sigma(pp \to H \to hh)$ 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
$\sin\alpha$
200
300
400
500
600
700
800
900
m_H, GeV
0.5 pb
0.1 pb
0.01 pb
1.0 fb
0.1 fb
$\Delta\chi^2 = 9$ (98.9%)
$\Delta\chi^2 = 4$ (86%)
$\Delta\chi^2 = 1$ (39%)

Conclusions

- $pp \to H \to hh$ cross section at $\sqrt{s} = 14$ TeV can reach 0.4 pb, ten times larger than the Standard Model value.
- $pp \to H \to ZZ$ is the golden mode for the heavy higgs boson discovery. Experimental data start to be sensitive to the isosinglet model for maximally allowed values of $\sin\alpha$.
- Keep an eye open for extra scalar particles!