Contribution of Scalar Singlet and Dimension 5 operator in Higgs Physics

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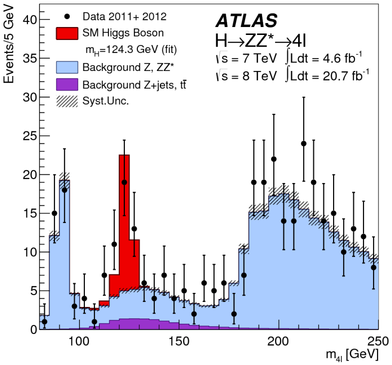
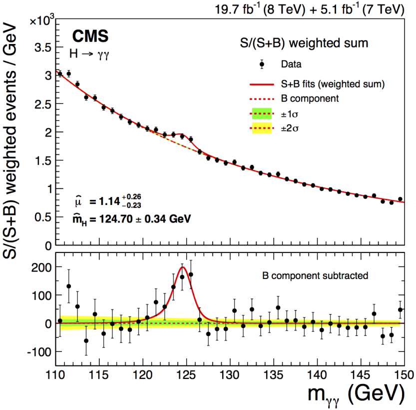
Higgs Boson



Higgs boson in 4l channel [www.atlasexperiment.org]



Higgs boson in diphoton channel [cms.web.cern.ch]

Significance and Motivation for BSM

- Its discovery verifies well established SM theory.
- Central piece of SM.
- Associated with Higgs mechanism that explain how particle get mass.

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BUT!

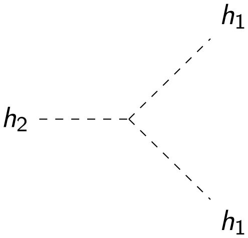
- Is SM Higgs the only scalar?
- No other scalar been seen yet.
- To search for new scalar, we need to go beyond SM.
- One of the simplest model is the singlet scalar extension of SM.

Singlet Extension of SM

• One of the simplest extension of SM is by adding real scalar singlet.

• After EWSB, singlet mixes with SM Higgs as a result, shape of potential as well as Higgs coupling to SM particles are changed.

• New decay signature is observed: $h_2 \rightarrow h_1 h_1$



Further Extension with Effective Lagrangian

Further extention of SM

Further potential shape and Higgs coupling are altered with the inclusion of effective Lagrangian.

• The effective Lagrangian approach is a model-independent way to describe new physics at some cut-off scale (Λ).

• Effective Lagrangian has higher dimension operator suppressed by some power of Λ.

$$\mathcal{L}^d = \Sigma_i \frac{c_i^d}{\Lambda^{d-4}} O_i^d \text{ for d} > 4 \quad (1)$$

Model

- The model contains SM and new physics Lagrangian.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}^s_{\leq 5} \quad (2)$$

- $\mathcal{L}^s_{\leq 5}$ is NP Lagrangian up to dim 5 built from (S) and SM fields.
- $\mathcal{L}^s_{\leq 5}$ can be split as scalar interaction up to dim 4 and effective interaction($\mathcal{L}^s_5$) of dim 5.

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Effective Lagrangian

[M. Bauer, A. Butter, J. Gonzalez-Fraile, T. Plehn, and M. Rauch,Phys. Rev., vol. D95, no. 5, p. 055011, 2017]

$$\begin{aligned}\mathcal{L}^{s}_{5} = &-\frac{a_3}{2\Lambda}S^3(\Phi^\dagger\Phi) - \frac{a_4}{2\Lambda}S(\Phi^\dagger\Phi)^2 - \frac{b_5}{5\Lambda}S^5 + g_s^2\frac{f^s_{GG}}{\Lambda}SG^a_{\mu\nu}G^{a\ \mu\nu} \\ &+ \frac{e^2}{cos^2\theta_w}\frac{f^s_{BB}}{\Lambda}SB_{\mu\nu}B^{\mu\nu} + \frac{e^2}{sin^2\theta_w}\frac{f^s_{WW}}{\Lambda}SW^a_{\mu\nu}W^{a\ \mu\nu} \\ &+ (-\frac{f^s_d}{\Lambda}S\bar{Q}_L\Phi d_R - \frac{f^s_u}{\Lambda}S\bar{Q}_L\tilde{\Phi}u_R - \frac{f^s_l}{\Lambda}S\bar{L}_L\Phi l_R + h.c)\end{aligned} \quad (3)$$

Potential Model

- The scalar potential contains Higgs doublet(Φ) and an additional singlet(S).

$$V(\Phi, S) = V_{\phi}(\Phi) + V_{\phi s}(\Phi, S) + V_s(S) \tag{4}$$

- In the absence of Z_2- symmetry,

$$\begin{aligned} V(\Phi, S) =& -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \\ & + \frac{a_1}{2}(\Phi^\dagger\Phi)S + \frac{a_2}{2}(\Phi^\dagger\Phi)S^2 + \frac{a_3}{2\Lambda}(\Phi^\dagger\Phi)S^3 + \frac{a_4}{2\Lambda}(\Phi^\dagger\Phi)^2 S \\ & + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4 + \frac{b_5}{5\Lambda}S^5 \end{aligned} \tag{5}$$

where $\Phi = \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$ and $S = s + x$

- v and x are the vacuum expectation value of doublet and singlet.

Potential Contd..

- $S \to S + \delta S$ means redefining parameters of scalar potential.
- We are free to choose x and we choose it to zero.
- The electroweak symmetry breaking is at (v,0).
- The scalar mixing is parametrized as

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix} \tag{6}$$

- The masses of h_1 and h_2 be m_{h_1} and m_{h_2}.
- We assume $m_{h_2} > m_{h_1}$.

Potential Model Parameters

• At the Lagrangan level, the free potential parameters are:
$\mu^2, \lambda, a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4, b_5$ and Λ
• After some algebra, some of the parameters can be rewritten in terms of physical masses and mixing angles.

$$\begin{aligned} a_1 =& \frac{m_{h_1}^2 - m_{h_2}^2}{v_{ew}}(\sin 2\theta - \frac{a_4 v_{ew}^2}{\Lambda}) \\ b_1 =& -(\frac{v_{ew}^2}{4}a_1 + \frac{a_4}{8\Lambda}v_{ew}^4) \\ b_2 + \frac{v_{ew}^2}{2}a_2 =& m_{h_1}^2 + m_{h_2}^2 - 2\mu^2 \\ \mu^2 =& \frac{m_{h_1}^2 \cos^2\theta + m_{h_2}^2 \sin^2\theta}{2} \text{ and } \lambda = \frac{\mu^2}{v_{ew}^2} \end{aligned} \tag{7}$$

• The free parameters are then: $m_{h_1} = 125\,\mathrm{GeV},\ m_{h_2},\ \theta,\ v_{ew} = 246\,\mathrm{GeV},\ x = 0,\ a_2,\ a_3,\ a_4,\ b_3,\ b_4,\ b_5$ and $\Lambda = 2\,\mathrm{TeV}$

Decay Width

- We start with scattering amplitude

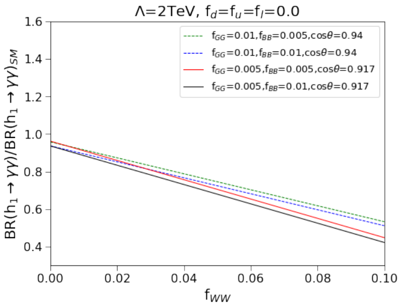
$$\mathcal{M} = \mathcal{M}_{SM} + \mathcal{M}_{dim=5} \tag{8}$$

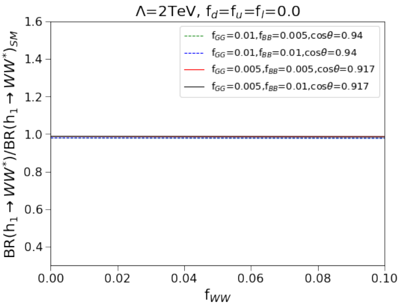
- The squared amplitude is

$$\underset{\sim \frac{1}{\Lambda^0}}{\mid \mathcal{M} \mid^2 = \mid \mathcal{M}_{SM} \mid^2} + \underset{\sim \frac{1}{\Lambda^2}}{\mid \mathcal{M}_{dim=5} \mid^2} + \underset{\sim \frac{1}{\Lambda^1}}{2Re(\mid \mathcal{M}_{SM} \mid\mid \mathcal{M}_{dim=5} \mid)} \tag{9}$$

- The decay width has contribution from all three terms.
- We take SM and interference term only and see how branching ratios (BR) of Higgs are affected.

Higgs to $\gamma\gamma$ and WW^*



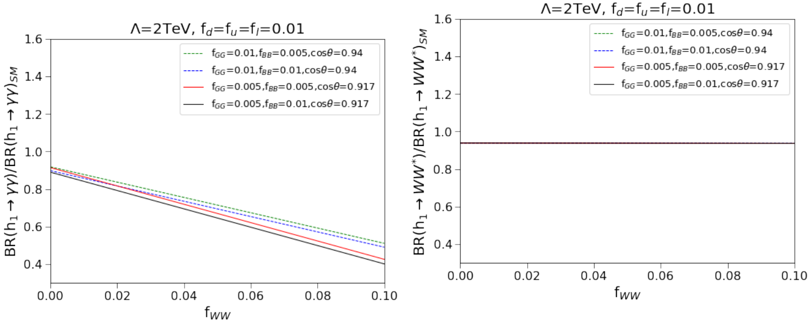


$\Rightarrow$ BR off by approx. 50% compared to SM

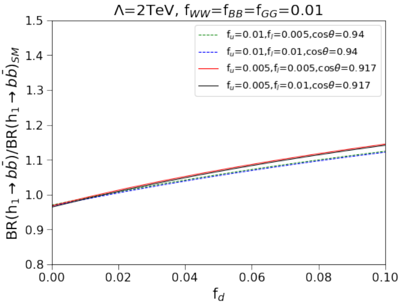
$\Rightarrow$ sensitive to f_{WW}

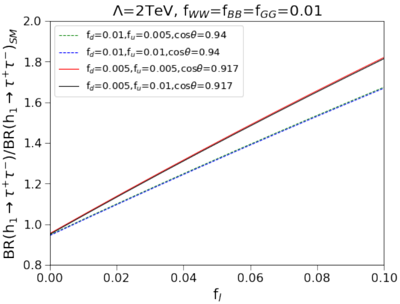
$\Rightarrow$ BR off by approx. 5% compared to SM

$\Rightarrow$ Less sensitive to f_{WW}



- BR shift downward due to increase in total width but the partial width remains same.





Higgs to $b\bar{b}$

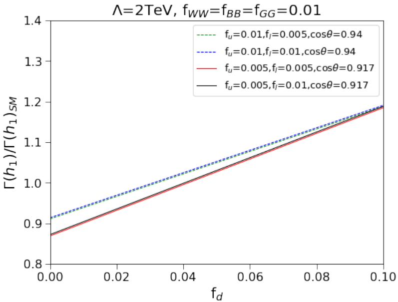
- BR increases by approximately 10-15% compared to SM.

Higgs to $\tau^+\tau^-$

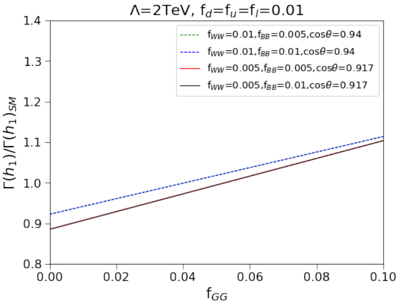
- BR increases by approximately 65-80% compared to SM.

- BR is more sensitive to effective fermionic coupling coefficient in $h_1 \to \tau^+\tau^-$ compared to $h_1 \to b\bar{b}$

Variation of Higgs total width with f_d and f_{GG} need to fix



Variation of Higgs total width with f_d



Variation of Higgs total width with f_{GG}

- With increase in f_d and f_{GG}, the total width also increases.

Constraints from Higgs Measurements

• One of the important constraint that is applied to this model comes from signal strength measurements.
• Should not exceed signal strength measurement bounds.

• The production signal strength for h_1 from gluon fusion is defined as:

$$\mu_{ggF} = \frac{\sigma(pp \to h_1)}{\sigma(pp \to h_1)_{SM}} = \frac{\Gamma(h_1 \to gg)}{\Gamma(h_1 \to gg)_{SM}} \tag{10}$$

where $\sigma(pp \to h_1)$ is the hadronic cross section.

and the signal strength to final state is:

$$\mu_{ii} = \frac{\sigma(pp \to h_1)}{\sigma(pp \to h_1)_{SM}} \times \frac{BR(h_1 \to \text{final state})}{BR(h_1 \to \text{final state})_{SM}} \tag{11}$$

Constraints from Higgs Measurements ($\sqrt{s}$=7 and 8 TeV) [ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002]

• The observed signal strength for Higgs production from gluon fusion is:

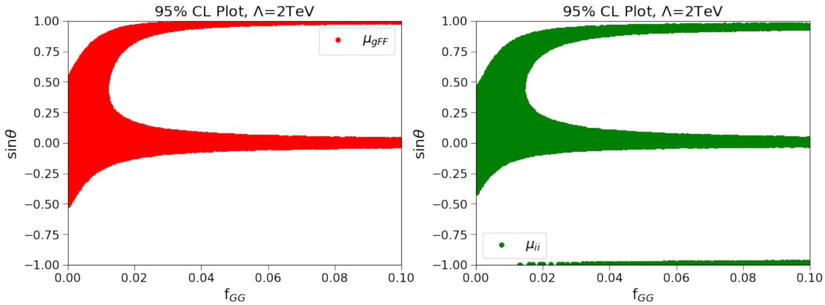
$$\mu_{ggF} = 1.03^{.16}_{-.14} \tag{12}$$

• The Higgs signal strength decaying to final states are:

$$\begin{aligned} \mu^{\gamma\gamma} &= 1.16^{.20}_{-.18} \\ \mu^{ZZ} &= 1.31^{.27}_{-.24} \\ \mu^{WW} &= 1.11^{.18}_{-.17} \\ \mu^{\tau\tau} &= 1.12^{.25}_{-.23} \\ \mu^{bb} &= 0.69^{.29}_{-.27} \end{aligned} \tag{13}$$

• The observed signal strengths will put bounds on mixing angle and effective coupling coefficients.

Limits on Mixing angle and f_{GG}

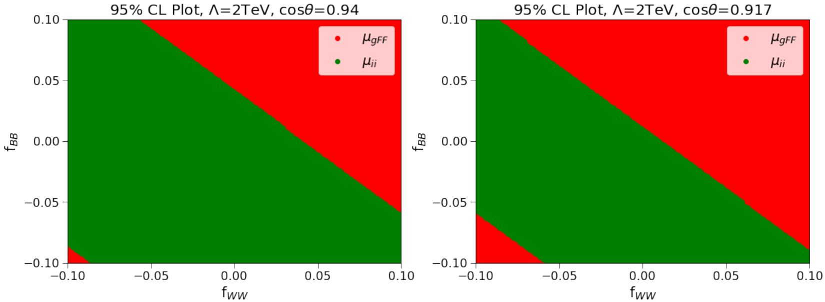


95% CL allowed region of $\sin\theta$ and f_{GG}

Red is allowed region by a fit to μ_{ggF} and green to μ^{ii}

[S. Dawson and I. M. Lewis, Phys. Rev., vol. D95, no. 1, p. 015004, 2017]

Limits on Effective Coupling Coefficient (f_{BB} and f_{WW})



95% CL allowed region of f_{BB} and f_{WW}

⇒Red is allowed region by a fit to μ_{ggF} and green to μ^{ii}.
⇒With decrease in $cos\theta$, the green region shrink.

Conclusion

• Adding real scalar singlet and dimension 5 operator into SM, we found Higgs physics deviated from SM sector.

• Using fit to observed signal strengths, we found the allowed regions of scalar mixing angle and effective coupling coefficients.

THANK YOU

Higgs to $Z\gamma$ and ZZ^*