Beyond the Standard Model EFT: The Singlet Extended Standard Model

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Outline

- Introduction and Motivation
- Model
- Result and Conclusion

Higgs Boson

- Discovered in 2012 at the LHC: great success for particle physics and SM
- Its discovery verifies well established SM theory.
- Central piece of SM.
- Associated with Higgs mechanism that explain how particles get mass.

Higgs Boson

• Discovered in 2012 at the LHC: great success for particle physics and SM
• Its discovery verifies well established SM theory.
• Central piece of SM.
• Associated with Higgs mechanism that explain how particles get mass.

BUT!
• Is SM Higgs the only scalar or a part of extended scalar sector?
• No other scalar been seen yet.
• To search for new scalar, we need to go beyond SM.
• There are several models that predict extended Higgs sector.

• Several model with extended Higgs sector:
→ Singlet Model
→2HDM
→ MSSM
→ 2 Higgs doublets + 1 Singlet
→ Higgs triplet model

Singlet Model:
• One of the simplest extension of SM is by adding real scalar singlet.
• After EWSB, singlet mixes with SM Higgs.
• New decay channel is observed: $h_2 \rightarrow h_1 h_1$ if kinematically allowed.

Further Extension with Effective Field Theory (EFT)

EFT :

- Further potential shape and Higgs coupling are altered by adding effective Lagrangian.
- New interactions between Higgs boson and fermions/bosons.
- Phenomenology can significantly change.

$$
\begin{aligned}
\mathcal{L}_{EFT} \supset & \frac{g_s^2}{16\pi^2}\frac{f_{GG}}{\Lambda} S\, G^A_{\mu\nu} G^{A,\mu\nu} + \frac{g^2}{16\pi^2}\frac{f_{WW}}{\Lambda} S\, W^a_{\mu\nu} W^{a,\mu\nu} \\
& + \frac{g'^2}{16\pi^2}\frac{f_{BB}}{\Lambda} S\, B_{\mu\nu} B^{\mu\nu} - \left(\frac{f_\mu}{\Lambda}\frac{m_\mu}{v} S\, \overline{L}_2 \Phi\, \mu_R + \frac{f_\tau}{\Lambda}\frac{m_\tau}{v} S\, \overline{L}_3 \Phi\, \tau_R + \mathrm{h.c.} \right) \\
& + \left(\frac{f_b}{\Lambda}\frac{m_b}{v} S\, \overline{Q}_3 \Phi\, b_R + \frac{f_t}{\Lambda}\frac{m_t}{v} S\, \overline{Q}_3 \widetilde{\Phi}\, t_R + \mathrm{h.c.} \right) \\
& - \frac{a_3}{2\Lambda} S^3 (\Phi^\dagger \Phi) - \frac{a_4}{2\Lambda} S (\Phi^\dagger \Phi)^2 - \frac{b_5}{5\Lambda} S^5
\end{aligned}
$$

,

Potential Model

- Start with potential:

$$V(\Phi, S) = V_\phi(\Phi) + V_{\phi s}(\Phi, S) + V_s(S) \quad (1)$$

- In the absence of Z_2- symmetry,

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

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

- The scalar mixing is parametrized as

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix} \quad (3)$$

Potential Model Contd

• The free parameters are then: $m_{h_1} = 125.09\,\mathrm{GeV}$, m_{h_2}, θ, $v_{ew} = 246\,\mathrm{GeV}$, $\langle S \rangle = 0$, a_2, a_3, a_4, b_3, b_4, b_5 and $\Lambda = 3\,\mathrm{TeV}$

• The scalar potential gives rise to important trilinear scalar couplings after EWSB:

$$V(h_1, h_2) \supset \frac{1}{3!}\lambda_{111} h_1^3 + \frac{1}{2}\lambda_{211} h_1^2 h_2,$$

where

$$\begin{aligned}\lambda_{111} &= \frac{3\,m_1^2}{v}\cos^3\theta + 2\,b_3\sin^3\theta + 3\,a_2 v\cos\theta\sin^2\theta + \frac{3\,a_3 v^2}{2\,\Lambda}\sin^3\theta \\ &\quad + \frac{3\,a_4 v^2}{\Lambda}\cos^2\theta\sin\theta \qquad (4)\end{aligned}$$

$$\begin{aligned}\lambda_{211} &= -\frac{m_2^2 + 2\,m_1^2}{v}\cos^2\theta\sin\theta + 2\,b_3\cos\theta\sin^2\theta \\ &\quad + a_2 v\sin\theta\left(2\cos^2\theta - \sin^2\theta\right) + \frac{3\,a_3 v^2}{2\,\Lambda}\cos\theta\sin^2\theta \\ &\quad + \frac{a_4 v^2}{\Lambda}\cos\theta\left(\cos^2\theta - 2\sin^2\theta\right). \qquad (5)\end{aligned}$$

Power Counting

SMEFT:

Amplitude:

$$\mathcal{A}_{\rm SMEFT} \sim \mathcal{A}_{\rm ren} + \frac{1}{\Lambda^2}\mathcal{A}_{6,\rm SMEFT} + \frac{1}{\Lambda^4}\mathcal{A}_{8,\rm SMEFT} + \mathcal{O}(\Lambda^{-6})$$

Squared Amplitude:

$$|\mathcal{A}_{\rm SMEFT}|^2 \sim |\mathcal{A}_{\rm ren}|^2 + \frac{1}{\Lambda^2}\mathcal{A}_{\rm ren}\mathcal{A}_{6,\rm SMEFT} + \frac{1}{\Lambda^4}|\mathcal{A}_{6,\rm SMEFT}|^2 + \frac{1}{\Lambda^4}\mathcal{A}_{\rm ren}\mathcal{A}_{8,\rm SMEFT} + \mathcal{O}(\Lambda^{-6})$$

With Singlet:

Amplitude:

$$\mathcal{A}_{h_1} \sim \cos\theta(\mathcal{A}_{\rm ren} + \frac{\mathcal{A}_{6,\rm SMEFT}}{\Lambda^2}) + \sin\theta\left(\frac{\mathcal{A}_{5,S}}{\Lambda} + \frac{\mathcal{A}_{6,S}}{\Lambda^2}\right) + \mathcal{O}(\Lambda^{-3})$$

Power Counting (contd)

Squared Amplitude:

$$|\mathcal{A}_{h_1}|^2 \sim \cos^2\theta |\mathcal{A}_{\rm ren}|^2 + \sin\theta\ \cos\theta\ \frac{\mathcal{A}_{\rm ren}\mathcal{A}_{5,S}}{\Lambda} + \frac{1}{\Lambda^2}\left(\sin^2\theta|\mathcal{A}_{5,S}|^2 + \sin\theta\cos\theta\mathcal{A}_{\rm ren}\mathcal{A}_{6,S} + \cos^2\theta\mathcal{A}_{\rm ren}\mathcal{A}_{6,\rm SMEFT}\right) + \mathcal{O}(\Lambda^{-3}).$$

At large mixing angle:

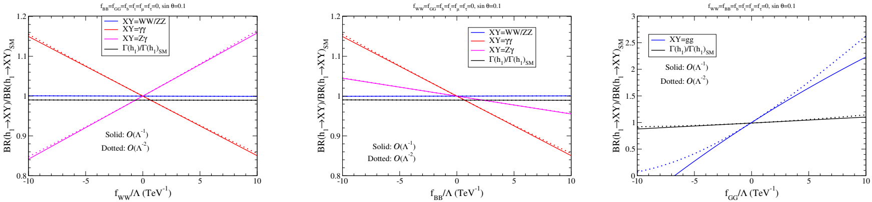
$$|\mathcal{A}_{h_1}|^2 \xrightarrow[|\sin\theta|\to 1]{} \frac{|\mathcal{A}_{5,S}|^2}{\Lambda^2} + \frac{\mathcal{A}_{6,S}\mathcal{A}_{5,S}}{\Lambda^3} + \mathcal{O}(\Lambda^{-4}).$$

For h_2 :

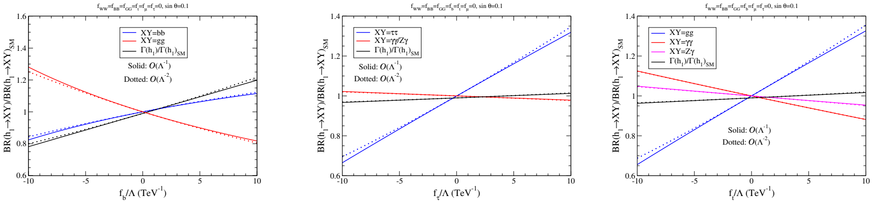
$$\mathcal{A}_{h_2} \sim \sin\theta\mathcal{A}_{\rm ren} + \sin\theta\ \frac{\mathcal{A}_{6,\rm SMEFT}}{\Lambda^2} + \cos\theta\left(\frac{\mathcal{A}_{5,S}}{\Lambda} + \frac{\mathcal{A}_{6,S}}{\Lambda^2}\right) + \mathcal{O}(\Lambda^{-3})$$

– For Higgs precision measurements, we compare $\mathcal{O}(\Lambda^{-1})$ to $\mathcal{O}(\Lambda^{-2})$.

Result: Higgs Branching Ratios Plot



- $h_1 \to WW$ and $h_1 \to ZZ$ branching ratios depend very little on f_{WW} and f_{BB} while the $h_1 \to \gamma\gamma$ and $h_1 \to Z\gamma$ depend strongly
- This is because $h_1 \to WW$, $h_1 \to ZZ$ are tree level in SM while $h_1 \to \gamma\gamma$, $h_1 \to Z\gamma$ are loop suppressed .
- $h_1 \to gg$ depends on f_{GG}.
- The total width has little dependence on f_{BB} and f_{WW} while more dependence on f_{GG}.
- This is because $h_1 \to \gamma\gamma$ and $h_1 \to Z\gamma$ has little contribution in SM compared to $h_1 \to gg$ which has larger contribution.



- BR into fermionic final states depend strongly on fermion wilson coefficient.
- The $h_1 \rightarrow bb$ BR varies less than $h_1 \rightarrow \tau\tau$ because total width of h_1 depends strongly on f_b than on f_τ
- All loop level processes depend relatively strongly on f_t.

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.

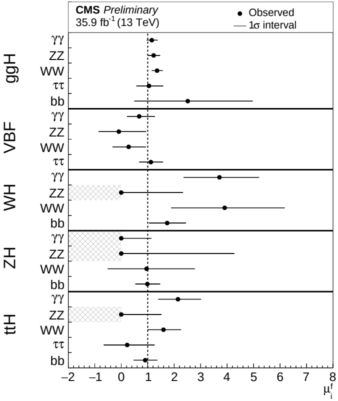
- The signal strength to final state is defined as:

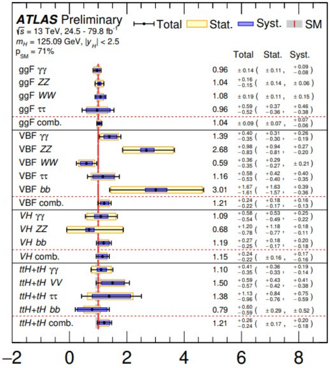
$$\mu^f = \frac{\sigma(pp \to h_1)}{\sigma(pp \to h_1)_{SM}} \times \frac{BR(h_1 \to \text{final state})}{BR(h_1 \to \text{final state})_{SM}} \tag{6}$$

- Production cross section comes from ggF, VBF, VH, ttH and tH.

$$\chi^{f,2}_{i,h_1} = \left(\frac{\mu_i^f - \hat{\mu}_i^f}{\delta \mu_i^f} \right)^2 , \tag{7}$$

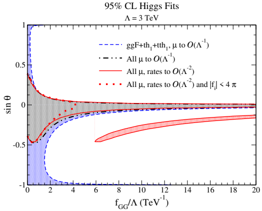
Constraints from Higgs Measurements ($\sqrt{s}$=13 TeV) [ATLAS-CONF-2019-005, CMS-PAS-HIG-17-031]

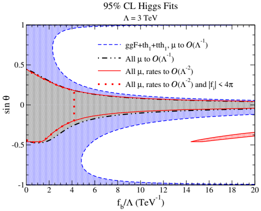


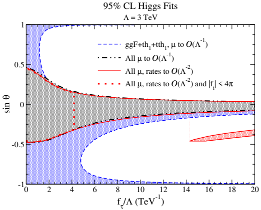


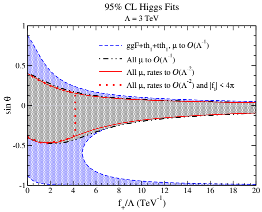
- Put bound on mixing angle and effective parameters.

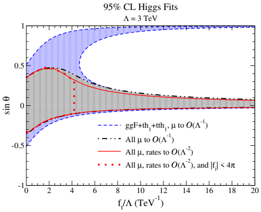
Limits on mixing angle and effective parameters











$$\sigma_{VBF/ZH/WH} \approx \cos^2\theta \sigma_{(VBF/ZH/WH)SM}$$

- Heavy scalar are regularly searched at LHC.
- Like h_1, we compute decay width and then do the chi-square fit.

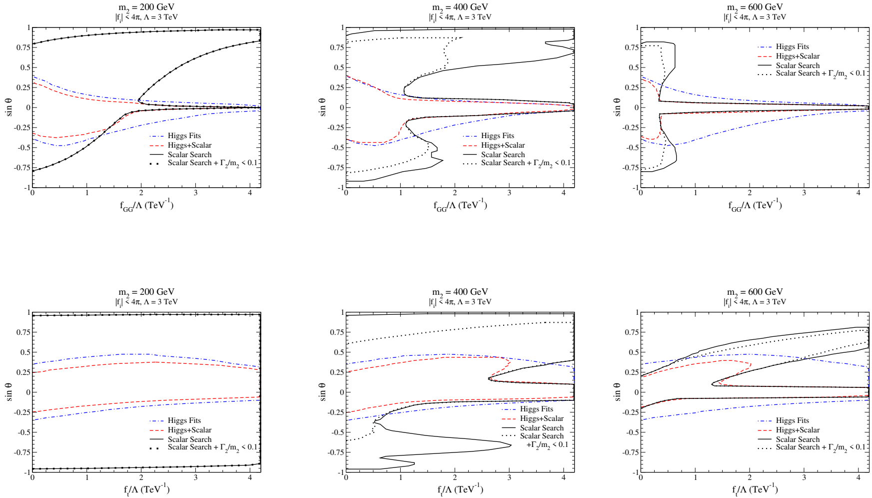
$$\chi^{f,2}_{i,h_2} = \left(\frac{\sigma^f_i - \hat{\sigma}^f_i}{\delta\sigma^f_i} \right)^2 , \qquad (8)$$

Calculated: $\sigma^f_i = \sigma^f_{i,SM} + \sigma(i \to h_2)\mathrm{BR}(h_2 \to f)$
Uncertainty: $\delta\sigma^f_i \approx \hat{\sigma}^f_{i,Exp}/1.96$,
Observed: $\hat{\sigma}^f_i \approx \sigma^f_{i,SM} + \hat{\sigma}^f_{i,Obs} - \hat{\sigma}^f_{i,Exp}$,

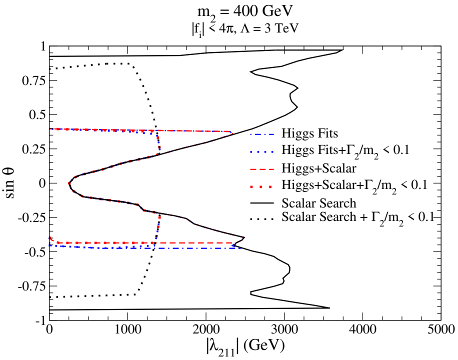
$$\chi^{f,2}_{i,h_2} = \left(\frac{\sigma(i \to h_2)\mathrm{BR}(h_2 \to f) + \hat{\sigma}^f_{i,Exp} - \hat{\sigma}^f_{i,Obs}}{\hat{\sigma}^f_{i,Exp}/1.96} \right)^2 . \qquad (9)$$

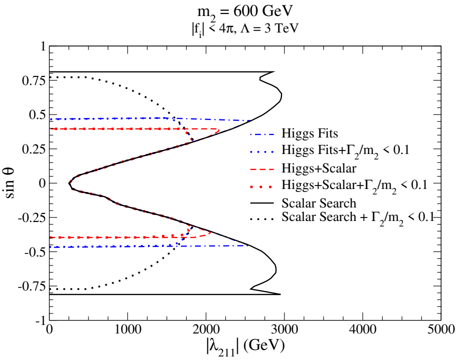
All scalar searches: $\chi^2_{h_2} = \sum_{i,f} \chi^{f,2}_{i,h_2}$ Higgs+scalar: $\chi^2_{\mathrm{Tot}} = \chi^2_{h_1} + \chi^2_{h_2}$

Results: Heavy resonance searches



Results: Heavy resonance searches





Conclusion

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

• 95 % CL fit :. Higgs measurement data and scalar searches data exclude large part of parameter space.

• We propose a new χ^2 analysis to combine heavy resonance searches with precision measurements.

THANK YOU