Beyond the Standard Model EFT: The Singlet Extended Standard Model

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Outline

- Introduction and Motivation
- Model
- Result and Conclusion
• 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.
Higgs Boson

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Several models 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: $h_2 \to h_1 h_1$ 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.

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

• Start with potential:

\[ V(\Phi, S) = V_\phi(\Phi) + V_{\phi S}(\Phi, S) + V_s(S) \] (1)

• In the absence of \(Z_2\)-symmetry,

\[ V(\Phi, S) = -\mu^2(\Phi^\dagger \Phi) + \lambda(\Phi^\dagger \Phi)^2 \]
\[ + \frac{a_1}{2} (\Phi^\dagger \Phi) S + \frac{a_2}{2} (\Phi^\dagger \Phi) S^2 + \frac{a_3}{2\Lambda} (\Phi^\dagger \Phi) S^3 + \frac{a_4}{2\Lambda} (\Phi^\dagger \Phi)^2 S \]
\[ + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 + \frac{b_5}{5\Lambda} S^5 \] (2)

where \(\Phi = \begin{pmatrix} 0 \\ h + v \sqrt{2} \end{pmatrix} \)

• The scalar mixing is parametrized as

\[ \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix} \] (3)
The free parameters are then: $m_{h_1} = 125.09 \text{ GeV}$, $m_{h_2}$, $\theta$, $v_{ew} = 246 \text{ GeV}$, $\langle S \rangle = 0$, $a_2$, $a_3$, $a_4$, $b_3$, $b_4$, $b_5$ and $\Lambda = 3 \text{ TeV}$.

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

$$\lambda_{111} = \frac{3 m_1^2}{v} \cos^3 \theta + 2 b_3 \sin^3 \theta + 3 a_2 v \cos \theta \sin^2 \theta + \frac{3 a_3 v^2}{2 \Lambda} \sin^3 \theta$$

$$+ \frac{3 a_4 v^2}{\Lambda} \cos^2 \theta \sin \theta \tag{4}$$

$$\lambda_{211} = -\frac{m_2^2 + 2 m_1^2}{v} \cos^2 \theta \sin \theta + 2 b_3 \cos \theta \sin^2 \theta$$

$$+ a_2 v \sin \theta \left(2 \cos^2 \theta - \sin^2 \theta\right) + \frac{3 a_3 v^2}{2 \Lambda} \cos \theta \sin^2 \theta$$

$$+ \frac{a_4 v^2}{\Lambda} \cos \theta \left(\cos^2 \theta - 2 \sin^2 \theta\right). \tag{5}$$
Power Counting

SMEFT:
Amplitude:

\[ A_{\text{SMEFT}} \sim A_{\text{ren}} + \frac{1}{\Lambda^2} A_{6,\text{SMEFT}} + \frac{1}{\Lambda^4} A_{8,\text{SMEFT}} + \mathcal{O}(\Lambda^{-6}) \]

Squared Amplitude:

\[ |A_{\text{SMEFT}}|^2 \sim |A_{\text{ren}}|^2 + \frac{1}{\Lambda^2} A_{\text{ren}} A_{6,\text{SMEFT}} + \frac{1}{\Lambda^4} |A_{6,\text{SMEFT}}|^2 \]
\[ + \frac{1}{\Lambda^4} A_{\text{ren}} A_{8,\text{SMEFT}} + \mathcal{O}(\Lambda^{-6}) \]

With Singlet:
Amplitude:

\[ A_{h_1} \sim \cos \theta (A_{\text{ren}} + \frac{A_{6,\text{SMEFT}}}{\Lambda^2}) + \sin \theta \left( \frac{A_{5,\text{S}}}{\Lambda} + \frac{A_{6,\text{S}}}{\Lambda^2} \right) + \mathcal{O}(\Lambda^{-3}) \]
Squared Amplitude:

\[ |A_{h_1}|^2 \sim \cos^2 \theta |A_{\text{ren}}|^2 + \sin \theta \cos \theta \frac{A_{\text{ren}}A_{5,S}}{\Lambda} \]

\[ + \frac{1}{\Lambda^2} \left( \sin^2 \theta |A_{5,S}|^2 + \sin \theta \cos \theta A_{\text{ren}}A_{6,S} + \cos^2 \theta A_{\text{ren}}A_{6, \text{SMEFT}} \right) \]

\[ + \mathcal{O}(\Lambda^{-3}). \]

At large mixing angle:

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

For \( h_2 \):

\[ A_{h_2} \sim \sin \theta A_{\text{ren}} + \sin \theta \frac{A_{6, \text{SMEFT}}}{\Lambda^2} + \cos \theta \left( \frac{A_{5,S}}{\Lambda} + \frac{A_{6,S}}{\Lambda^2} \right) + \mathcal{O}(\Lambda^{-3}) \]

– For Higgs precision measurements, we compare \( \mathcal{O}(\Lambda^{-1}) \) to \( \mathcal{O}(\Lambda^{-2}) \).
- $h_1 \to WW$ 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 $f_\tau$
• All loop level processes depend relatively strongly on $f_t$. 

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• One of the important constraints 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:

\[ \mu^f = \frac{\sigma(pp \rightarrow h_1)}{\sigma(pp \rightarrow h_1)_{SM}} \times \frac{BR(h_1 \rightarrow \text{final state})}{BR(h_1 \rightarrow \text{final state})_{SM}} \]  

(6)

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

\[ \chi_{i, h_1}^{f, 2} = \left( \frac{\mu_i^f - \hat{\mu}_i^f}{\delta\mu_i^f} \right)^2, \]  

(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 resonance searches

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

\[
\chi_{i,h_2}^f = \left( \frac{\sigma_i^f - \hat{\sigma}_i^f}{\delta\sigma_i^f} \right)^2,
\]

Calculated: $\sigma_i^f = \sigma_i^{f,SM} + \sigma(i \rightarrow h_2)\text{BR}(h_2 \rightarrow f)$

Uncertainty: $\delta\sigma_i^f \approx \hat{\sigma}_i^{f,Exp}/1.96$,

Observed: $\hat{\sigma}_i^f \approx \sigma_i^{f,SM} + \hat{\sigma}_i^{f,Obs} - \hat{\sigma}_i^{f,Exp}$,

\[
\chi_{i,h_2}^f = \left( \frac{\sigma(i \rightarrow h_2)\text{BR}(h_2 \rightarrow f) + \hat{\sigma}_i^{f,Exp} - \hat{\sigma}_i^{f,Obs}}{\hat{\sigma}_i^{f,Exp}/1.96} \right)^2.
\]

All scalar searches: $\chi_{h_2}^2 = \sum_{i,f} \chi_{i,h_2}^{f,2}$

Higgs+scalar: $\chi_{\text{Tot}}^2 = \chi_{h_1}^2 + \chi_{h_2}^2$
Results: Heavy resonance searches

$m_\phi = 200$ GeV
$|f| < 4\pi, \Lambda = 3$ TeV

$m_\phi = 400$ GeV
$|f| < 4\pi, \Lambda = 3$ TeV

$m_\phi = 600$ GeV
$|f| < 4\pi, \Lambda = 3$ TeV

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Results: Heavy resonance searches

$m_2 = 400$ GeV
$|f| < 4\pi, \Lambda = 3$ TeV

$m_2 = 600$ GeV
$|f| < 4\pi, \Lambda = 3$ TeV
• 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 $\chi^2$ analysis to combine heavy resonance searches with precision measurements.
THANK YOU