Implications of LHC data on 125 GeV Higgs-like boson for the SM and its various extensions

Pyungwon Ko (KIAS)

Based on arXiv:1307.3948, JHEP (2013) with Suyong Choi and Sunghoon Jung
What can we learn about BSM from Higgs properties?

- Higgs signal strength \( \sim \) SM like
- ATLAS diphoton rate may require new charged particles at EW scale
- Important to measure Higgs couplings to the SM particles as precisely as possible
- Most works EFT approach assuming New Physics scale is high enough
• However this needs not be true

• There could be an additional singlet scalar “S” at EW scale that mixes with the SM Higgs boson (especially motivated by hidden sector DM with Higgs portal or singlet portal)

• Then we cannot integrate out “S”

• We include “S” explicitly
Assumptions

• Impose the full SM gauge symmetry, not just its unbroken subgroup

• Assume there is an additional SM singlet scalar, extra vector-like fermions, hDM etc

• “S” could be a remnant of the spontaneous breaking of extra gauge symmetry such as dark gauge symmetry or $U(1)_{B-L}$

• Our assumptions encompass a large class of BSMs
(3,2,1) or SU(3)c × U(1)em?

• Well below the EW sym breaking scale, it may be fine to impose SU(3)c × U(1)em.

• At EW scale, better to impose (3,2,1) which gives better description in general after all.

• Majorana neutrino mass is a good example.

• For example, in the Higgs + dilaton (radion) system, and you get different results.

• Singlet mixing with SM Higgs.
Issue here is whether we use

\[ L_{\text{int}} \simeq -\frac{\phi}{f_\phi} T_\mu^\mu = -\frac{\phi}{f_\phi} \left[ m_H^2 H^\dagger H - 2m_W^2 W^+ W^- - m_Z^2 Z_\mu Z^\mu + \sum_f m_f \bar{f} f + \sum_G \frac{\beta_G}{g_G} G_{\mu\nu} G^{\mu\nu} \right], \]

(1)

OR

\[ T_\mu^\mu (\text{SM}) = 2\mu_H^2 H^\dagger H + \sum_G \frac{\beta_G}{g_G} G_{\mu\nu} G^{\mu\nu}. \]

arXiv:1401.5586 with D.W.Jung
In the usual earlier approach, one has

\[ \mathcal{L}(f, \bar{f}, \phi) = -\frac{mf}{f^2} \bar{f} f h e^{-\Phi/f} \phi. \]

In the new approach, one has

\[ \mathcal{L}(f, \bar{f}, H_{i=1,2}) = -\frac{mf}{v} \bar{f} f h = -\frac{mf}{v} \bar{f} f (H_1 c_\alpha + H_2 s_\alpha), \]

These two lead to very different predictions for Higgs phenomenology at the LHC, especially for H to diphoton, and gg fusion for H productions (see the paper for the details)
• Orthogonal ways to modify the same observable.
• Our framework is suitable to get insight on singlet mixing, singlet couplings as well as Higgs couplings.
SM Higgs

\[-L_{h,\text{int}} = \sum_f b_f \frac{m_f}{v} h f \bar{f} - \left\{ 2b_W \frac{h}{v} + b'_W \left( \frac{h}{v} \right)^2 \right\} m_W^2 W_\mu^+ W^{-\mu} - \left\{ b_Z \frac{h}{v} + \frac{1}{2} b'_Z \left( \frac{h}{v} \right)^2 \right\} m_Z^2 Z_\mu Z^\mu + \frac{\alpha}{8\pi} r_{\gamma}^\gamma \left\{ b_\gamma h \frac{v}{v} + \frac{1}{2} b'_\gamma \left( \frac{h}{v} \right)^2 \right\} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\gamma}^g \left\{ b_g h \frac{v}{v} + \frac{1}{2} b'_g \left( \frac{h}{v} \right)^2 \right\} G_{\mu\nu}^a G^{a\mu\nu} + \alpha^2 \frac{2}{\pi} \left\{ 2b_{dW} \frac{h}{v} + b_{dW'} \left( \frac{h}{v} \right)^2 \right\} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{2}{\pi} \left\{ 2b_{dZ} \frac{h}{v} + b_{dZ'} \left( \frac{h}{v} \right)^2 \right\} Z_{\mu\nu} Z^{\mu\nu} + \frac{\alpha}{\pi} \left\{ 2b_Z \frac{h}{v} + b_{Z\gamma'} \left( \frac{h}{v} \right)^2 \right\} F_{\mu\nu} Z^{\mu\nu} \right\] (2.1)

Singlet Scalar S

\[-L_{s,\text{int}} = \sum_f c_f \frac{m_f}{v} s \bar{f} f - \left\{ 2c_W s \frac{v}{v} + c'_W \left( \frac{s}{v} \right)^2 \right\} m_W^2 W_\mu^+ W^{-\mu} - \left\{ c_Z s \frac{v}{v} + \frac{1}{2} c'_Z \left( \frac{s}{v} \right)^2 \right\} m_Z^2 Z_\mu Z^\mu + \frac{\alpha}{8\pi} r_{\gamma}^\gamma \left\{ c_\gamma s \frac{v}{v} + \frac{1}{2} c'_\gamma \left( \frac{s}{v} \right)^2 \right\} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\gamma}^g \left\{ c_g s \frac{v}{v} + \frac{1}{2} c'_g \left( \frac{s}{v} \right)^2 \right\} G_{\mu\nu}^a G^{a\mu\nu} + \alpha^2 \frac{2}{\pi} \left\{ 2c_{dW} s \frac{v}{v} + c_{dW'} \left( \frac{s}{v} \right)^2 \right\} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{2}{\pi} \left\{ 2c_{dZ} s \frac{v}{v} + c_{dZ'} \left( \frac{s}{v} \right)^2 \right\} Z_{\mu\nu} Z^{\mu\nu} + \frac{\alpha}{\pi} \left\{ 2c_Z s \frac{v}{v} + c_{Z\gamma'} \left( \frac{s}{v} \right)^2 \right\} F_{\mu\nu} Z^{\mu\nu} - L_{\text{nonSM}} \right\] (2.10)

(2.11)
Typical Sizes of b,c’s

\[ b_i \sim “1” + \frac{g^2 m^2}{(4\pi)^2 M^2}, \quad \text{or} \quad “1” + \frac{g^2 m^2}{M^2} \]

Most of dim-6 operators lead to the definite relation, \( b_i = b_i' \), since they involve \( H^\dagger H \) which yields \((v + h)^2\). But this is not the case for \( b_f \) and \( b_f' \). For example, the following operators \((q_L \equiv (t_L, b_L))\), which are invariant under the full SM gauge group \( SU(3)_C \times SU(2)_L \times U(1)_Y \),

\[ \bar{q}_L D_\mu b_R D^{\mu} H, \quad \bar{q}_L D_\mu t_R D^{\mu} \tilde{H}, \]

\[ c_i \sim “0” + \frac{g^2 m^2}{(4\pi)^2 M^2}, \quad “0” + \frac{g^2 m^2}{M^2}, \]

All the c_i’s from nonrenormalizable operators
• 125GeV Higgs (mass-eigenstate) is

\[ H = h \cos \alpha - s \sin \alpha \]

h: SU(2) doublet interaction eigenstate
s: SU(2) singlet interaction eigenstate
alpha: mixing angle (alpha=0 means SM-like)

• h and s effective couplings are parameterized by \{b_i\}, \{c_i\}. Some terms are shown below.

\[
-L_{h,\text{int}} = \sum_{f} b_{f} \frac{m_{f}}{v} h\bar{f}f - \left(2b_{W} \frac{h}{v} + b'_{W} \left(\frac{h}{v}\right)^{2}\right) m_{W}^{2} W_{\mu}^{+} W_{-\mu} - \left(b_{Z} \frac{h}{v} + \frac{1}{2} b'_{Z} \left(\frac{h}{v}\right)^{2}\right) m_{Z}^{2} Z_{\mu} Z_{\mu}^{\mu} + \frac{\alpha}{8\pi} r_{s_{\text{sm}}}^{\gamma} \left(b_{\gamma} \frac{h}{v} + \frac{1}{2} b'_{\gamma} \left(\frac{h}{v}\right)^{2}\right) F_{\mu\nu} F^{\mu\nu} + \frac{\alpha_{s}}{16\pi} r_{s_{\text{sm}}}^{g} \left(b_{g} \frac{h}{v} + \frac{1}{2} b'_{g} \left(\frac{h}{v}\right)^{2}\right) G_{\mu\nu}^{a} G^{a\mu\nu}
\]

NB: b_i=1, c_i=0 mean SM-like
• Models are ubiquitous, and singlet scalar is versatile:

• If Hidden fermion is DM, s is needed for correct thermal relic density.

$$\mathcal{L}_{\text{hidden}} = \mathcal{L}_S + \mathcal{L}_\psi - \lambda S\overline{\psi}\psi,$$

$$\mathcal{L}_{\text{portal}} = -\mu_{HS}SH^\dagger H - \frac{\lambda_{HS}}{2}S^2H^\dagger H,$$

• If an extra vector exists, “s” may result from spontaneous gauge symmetry breaking. Gauge symmetry may needed for various reasons: just another force, or ensuring DM stability, etc...
• Singlet-Higgs mixing is just gauge invariant, renormalizable.

\[ \mathcal{L}_{\text{portal}} = -\mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H, \]

• S and Mixing eventually modify Higgs properties!

• Many interesting examples are built to enhance Higgs-to-diphoton rate.

\[ l_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix} \sim (1, 2, -1/2), \ e_4^c \sim (1, 1, 1), \]

\[ \tilde{l}_4 = \begin{pmatrix} \tilde{\nu}_4 \\ \tilde{e}_4 \end{pmatrix} \sim (1, 2, 1/2), \ \tilde{e}_4^c \sim (1, 1, -1), \]

\[ -\mathcal{L} = M_{l_4}\tilde{l}_4 + M_{e_4}\tilde{e}_4^c + M_{e_4^c}\tilde{e}_4 \]

\[ + y_e H l_4 e_4^c + \tilde{y}_e \tilde{l}_4 H^\dagger \tilde{e}_4^c - \]

\[ + \frac{x_l}{\sqrt{2}} S l_4 \tilde{l}_4 + \frac{x_e}{\sqrt{2}} S e_4 \tilde{e}_4^c \]

\[ \mathcal{M}'_e = \begin{pmatrix} M_l + x_l w/\sqrt{2} & \tilde{y}_e v/\sqrt{2} \\ y_e v/\sqrt{2} & M_e + x_e w/\sqrt{2} \end{pmatrix} \quad \mathcal{L} \supset \frac{\alpha}{16\pi v} b_{EM} \left( \frac{\partial}{\partial \log v} \log \det \mathcal{M} \mathcal{M}^\dagger \right) h F_{\mu\nu} F^{\mu\nu} \]
• Production times BR is measured: signal strength. So hard to extract info on individual couplings.

\[
R \left( \sigma(i \rightarrow h) \frac{\Gamma(h \rightarrow j)}{\Gamma_{tot}} \right) = \frac{\kappa_i^2 \kappa_j^2}{\kappa_H^2}
\]

\[
\kappa_i^2 = \frac{\Gamma(h \rightarrow i)}{\Gamma(h \rightarrow i)_{SM}} \quad \kappa_H^2 = \frac{\Gamma_{tot}}{\Gamma_{tot}^{SM}}
\]

• Unknown width leaves overall normalization undetermined.

\[
\frac{\kappa_i^2 \kappa_j^2}{\kappa_H^2} \equiv \hat{\kappa}_i^2 \hat{\kappa}_j^2,
\]

• If nonSM decay width exists, generally no unique solution of global fit is found. But statistically useful info can still be obtained, and built-in restrictions may further provide info.
• Higgs is produced via several channel. They are properly weighted-summed by couplings and density.

\[
R(\sigma(pp \rightarrow h)) = \kappa_g^2 A_g + \kappa_W^2 A_W + \kappa_Z^2 A_Z
\]

\[
A_g = \frac{\sigma(ggF)}{\sigma(ggF) + \sigma(VBF))} \approx 0.925,
\]

\[
R(\sigma(pp \rightarrow V h)) = \kappa_W^2 A_W' + \kappa_Z^2 A_Z'
\]

How to parameterize modifications to loop-induced gg fusion will be discussed later.
• How is decay width ratio, kappa, parameterized in terms of \{\alpha, b_i, c_i\}?

• Tree-level decay to WW, ZZ, ff:

\[
\kappa_i^2 = \frac{\Gamma(h \to i)}{\Gamma(h \to i)_{SM}} = (b_i c_\alpha - c_i s_\alpha)^2
\]

• Loop induced decay to gg, gamma gamma:

\[
\kappa_g^2 = (b_g c_\alpha - c_g s_\alpha)^2 = (c_\alpha (b_t c_t + \Delta b_g) - c_g s_\alpha)^2
\]

\[
\kappa_\gamma^2 = (b_\gamma c_\alpha - c_\gamma s_\alpha)^2 = (c_\alpha (b_W B_W + b_t B_t + \Delta b_\gamma) - c_\gamma s_\alpha)^2
\]

Scalar mixing modification of W, top coupling modification of diphoton coupling inherit from singlet

• NB: b, Delta b, c are norm. to SM coupling.

\[
B_W = \frac{A_1(\tau_W)}{A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)} \approx 1.283,
\]
• Moriond 2013 data used (to be updated after ICHEP)

• Best fit values of each channel is used. The minimum of each channel occurs at slightly different mh.

<table>
<thead>
<tr>
<th>channel</th>
<th>luminosity ($fb^{-1}$)</th>
<th>$\mu$</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>24.7</td>
<td>$0.78^{+0.28}_{-0.26}$</td>
<td>[15]</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>24.7</td>
<td>$0.91^{+0.30}_{-0.24}$</td>
<td>[16]</td>
</tr>
<tr>
<td>$WW$</td>
<td>24.7</td>
<td>$0.76^{+0.21}_{-0.21}$</td>
<td>[17]</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>24.3</td>
<td>$1.1^{+0.4}_{-0.4}$</td>
<td>[18]</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>17</td>
<td>$1.3^{+0.7}_{-0.6}$</td>
<td>[19]</td>
</tr>
<tr>
<td>ATLAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>25</td>
<td>$1.65^{+0.35}_{-0.30}$</td>
<td>[20]</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>25</td>
<td>$1.7^{+0.50}_{-0.40}$</td>
<td>[21]</td>
</tr>
<tr>
<td>$WW$</td>
<td>25</td>
<td>$1.01^{+0.31}_{-0.31}$</td>
<td>[22]</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>18</td>
<td>$0.7^{+0.7}_{-0.7}$</td>
<td>[23]</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>18</td>
<td>$-0.4^{+1.06}_{-1.06}$</td>
<td>[24]</td>
</tr>
</tbody>
</table>
• Preliminaries without singlet mixing: New effects are now multiplicatively rescaling SM Higgs effective Lagrangian by \( \{b_i\} \). (ex: composite Higgs analysis)

<table>
<thead>
<tr>
<th></th>
<th>both</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>( \chi^2/\nu = \frac{12.01}{10} = 1.20 )</td>
<td>( \frac{2.33}{5} = 0.466 )</td>
<td>( \frac{9.69}{5} = 1.94 )</td>
</tr>
<tr>
<td>( (\Delta b_\gamma) )</td>
<td>( (0.090) )</td>
<td>( (-0.117) )</td>
<td>( (0.28) )</td>
</tr>
<tr>
<td></td>
<td>( \frac{11.19}{9} = 1.24 )</td>
<td>( \frac{1.71}{4} = 0.428 )</td>
<td>( \frac{4.99}{4} = 1.25 )</td>
</tr>
<tr>
<td>( (\Delta b_g, \Delta b_\gamma) )</td>
<td>( (-0.018, 0.107) )</td>
<td>( (-0.078, -0.048) )</td>
<td>( (0.11, 0.17) )</td>
</tr>
<tr>
<td></td>
<td>( \frac{11.13}{8} = 1.39 )</td>
<td>( \frac{0.859}{3} = 0.286 )</td>
<td>( \frac{4.14}{3} = 1.38 )</td>
</tr>
<tr>
<td>( (b_V, b_f) )</td>
<td>( (1.031, 0.962) )</td>
<td>( (0.898, 1.021) )</td>
<td>( (1.345, 0.808) )</td>
</tr>
<tr>
<td></td>
<td>( \frac{11.74}{8} = 1.47 )</td>
<td>( \frac{0.808}{3} = 0.27 )</td>
<td>( \frac{4.52}{3} = 1.51 )</td>
</tr>
</tbody>
</table>

• CMS and ATLAS indicate different directions. They are about 2sigma away each other (even most other below).
Table 4. Comparison of our fit results with results available in other literature. Only results based on up-to-date data after Moriond 2013 are compared. We sometimes re-interpret other’s results in accordance with our notation. If only best-fit figure is available, we cite relevant figure and reference. Cases that are not shown here do not have equivalent results in literature.

Table 5. Best-fit results using $b_i$ only from both CMS and ATLAS data as well as individual. Errors are shown in text.
• All signal strengths are *universally modified* if just scalar mixing ($\alpha$) and/or non-SM width ($\kappa_{H}$).

\[
\{ \alpha, BR_{\text{nonSM}} \}: \text{In this case,} \\
\kappa_{\text{univ}} = c_{\alpha}, \quad \kappa_{H} = \frac{c_{\alpha}^{2}}{1 - BR_{\text{nonSM}}}. \\
\]

• Data is parameterized by one while theory has two.

\[
\mu_{i} = \kappa_{\text{univ}}^{2} \frac{\kappa_{\text{univ}}^{2}}{\kappa_{H}^{2}} = \hat{\kappa}_{\text{univ}}^{2} \hat{\kappa}_{\text{univ}}^{2}. \\
\]

• Overall, enhancement is slightly preferred although not significant

\[
\hat{\kappa}_{\text{univ}}^{2} = 1.012^{+0.0517}_{-0.0549}, \\
\]

\[
BR_{\text{nonSM}} \leq 18.8\% \text{ at } 95\% \text{C.L. if } c_{\alpha} = 1 \text{ fixed} \\
c_{\alpha} \geq 0.904 \text{ at } 95\% \text{C.L. if } BR_{\text{nonSM}} = 0 \text{ fixed} \\
\]
• Models with extra leptons or $W'$ which couple to singlet scalar: \{alpha, c_{\gamma}\}

$$\kappa_\gamma^2 = (c_\alpha - c_{\gamma} s_\alpha)^2, \quad \kappa_g^2 = \kappa_{\text{mix}}^2 = c_\alpha^2, \quad \kappa_H^2 \approx c_\alpha^2$$

$$c_\alpha = 0.98_{-0.056}, \quad c_{\gamma} = -0.55^{+0.50}_{-0.45},$$

• Constraints on singlet parameter space

$$c_{\gamma} = \frac{v}{\sqrt{2} A_{\gamma}^{SM}} \frac{x A_{1/2}(m_{H_1}^2/4m_L^2)}{m_L}.$$  

$x$: singlet coupling to extra lepton $L$
• Interestingly, by having nonSM width in global fit,\
  \{ \alpha, c_{\gamma\gamma}, BR(\text{nonSM}) \},\
we can generically set upper bound on it.

• Built-in restriction in this framework, \cos \alpha < 1;\
the upper bound on \cos \alpha and best-fit range of\nkappa_H give the upper bound on \text{BR(\text{nonSM})}.

\[ \kappa_H^2 = \frac{c_{\alpha}^2}{1 - BR_{\text{nonSM}}} \]

• \text{BR(\text{nonSM})} < 0.15(1 \text{sigma}), 0.24(95\% \text{CL}).\n(For most other cases, \text{BR(\text{nonSM})} < 10-25\%(1 \text{sigma})).
## General Cases

<table>
<thead>
<tr>
<th>Models</th>
<th>Best-fit results</th>
<th>$\chi^2/\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td></td>
<td>12.01/10 = 1.20</td>
</tr>
<tr>
<td>universal modification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\kappa^2_{\text{univ}})$</td>
<td>(1.012)</td>
<td>11.96/9 = 1.33</td>
</tr>
<tr>
<td>$\langle \text{BR}_{\text{nonSM}} \rangle$</td>
<td>$\leq 18.8%$ at 95%CL</td>
<td></td>
</tr>
<tr>
<td>$(\cos \alpha)$</td>
<td>$\geq 0.904$ at 95%CL</td>
<td></td>
</tr>
<tr>
<td>VL lepton, $W'$, $S'$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(c_{\alpha}, c_{\gamma})$</td>
<td>(0.98, -0.55)</td>
<td>11.1/8 = 1.39</td>
</tr>
<tr>
<td>VL quark</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(c_{\alpha}, g, c_{\gamma})$</td>
<td>(0.947, -0.128, -0.313)</td>
<td>11.1/7 = 1.58</td>
</tr>
<tr>
<td>$(c_{\alpha}, c_{\gamma}, \text{BR}_{\text{nonSM}})$</td>
<td>$\text{BR}_{\text{nonSM}} \leq 24%$ at 95%CL</td>
<td>11.1/8 = 1.39</td>
</tr>
<tr>
<td>$(c_{\alpha}, g, c_{\gamma}, \text{BR}_{\text{nonSM}})$</td>
<td>$\text{BR}_{\text{nonSM}} \leq 39%$ at 95%CL</td>
<td>11.1/7 = 1.58</td>
</tr>
<tr>
<td>singlet mixed-in $\hat{\kappa}$</td>
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<td></td>
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<tr>
<td>$(\hat{\kappa}<em>g^2, \hat{\kappa}</em>{\gamma}^2, \hat{\kappa}_{\text{mix}}^2)$</td>
<td>(1.03, 1.15, 0.942)</td>
<td>11.1/7 = 1.58</td>
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<tr>
<td>singlet mixed-in theory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\hat{c}<em>g, \hat{c}</em>\gamma, \hat{c}_\alpha)$</td>
<td>(-0.176, -0.432, 0.971)</td>
<td>11.1/7 = 1.58</td>
</tr>
</tbody>
</table>

**Table 7.** Summary of best-fit results with scalar mixing. If $\text{BR}_{\text{nonSM}}$ is included in fit, no unique solution is found, and its upper bound at 95%CL is presented. Only central values of best-fit are shown, and errors can be found in text.
Results

• Although it is premature to say definitely due to large uncertainties, the SM gives the best fit in terms of the $\chi^2$/d.o.f.

• Even if we include more parameters with new physics, it does not improve the overall fit very much (small decrease in total $\chi^2$)

• Mixing with an extra singlet scalar is slightly disfavored now, but the CMS data alone favors such a scenario
Important to seek for

- The 2nd singlet-like scalar boson (which might couple to the DM) is very generic in any DM models with hidden sector (with local dark gauge symmetries) where DM is stabilized by local dark gauge symmetry.

- Can solve some puzzles in CDM models with DM self-interaction from light mediator (2nd scalar or dark gauge boson).

- Additional singlet S improves EW Vac stability, and Higgs inflation with larger “r”
Signal Strengths

\[ \mu \equiv \frac{\sigma \cdot \text{Br}}{\sigma_{SM} \cdot \text{Br}_{SM}} \]

\[
\begin{array}{|c|c|c|}
\hline
\text{Decay Mode} & \text{ATLAS} & \text{CMS} \\
\hline
H \rightarrow bb & -0.4 \pm 1.0 & 1.15 \pm 0.62 \\
H \rightarrow \tau\tau & 0.8 \pm 0.7 & 1.10 \pm 0.41 \\
H \rightarrow \gamma\gamma & 1.6 \pm 0.3 & 0.77 \pm 0.27 \\
H \rightarrow WW^* & 1.0 \pm 0.3 & 0.68 \pm 0.20 \\
H \rightarrow ZZ^* & 1.5 \pm 0.4 & 0.92 \pm 0.28 \\
\text{Combined} & 1.30 \pm 0.20 & 0.80 \pm 0.14 \\
\hline
\end{array}
\]

\[ \langle \mu \rangle = 0.96 \pm 0.12 \]

Getting smaller
Low energy phenomenology

- Universal suppression of collider SM signals

- If “$m_h > 2 m_\phi$”, non-SM Higgs decay!

- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

\[
\lambda_{PH} \Rightarrow \lambda_H = \left[ 1 + \left( \frac{m_\phi^2}{m_h^2} - 1 \right) \sin^2 \alpha \right] \lambda_{H,SM}^{SM}
\]

- If “$m_\phi > m_h$”, vacuum instability can be cured.

[See 1112.1847, Seungwon Baek, P. Ko & WIPark]

[G. Degrassi et al., 1205.6497]

[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]
Higgs-portal Higgs inflation

\[ m_t = 173.2 \text{ GeV} \]
\[ M_h = 125.5 \text{ GeV} \]

\[ m_\Phi = 500 \text{ GeV} \]
\[ \alpha = \begin{cases} 
0.074223 \\
0.074222 \\
0.074221 
\end{cases} \]

\[ \alpha = 0.07 \]
\[ m_\Phi = \begin{cases} 
528.28 \text{ GeV} \\
528.27 \text{ GeV} \\
528.26 \text{ GeV} 
\end{cases} \]

\[ \xi = \begin{cases} 
10 \\
15 \\
30 
\end{cases} \]

* Inflection point control \((\alpha, m_\Phi) \& \lambda_{\Phi H}\)

Result of numerical analysis

<table>
<thead>
<tr>
<th>(k_\ast \times \text{Mpc})</th>
<th>(N_\epsilon)</th>
<th>(h_\ast/M_{\text{Pl}})</th>
<th>(\epsilon_\ast)</th>
<th>(\eta_\ast)</th>
<th>(10^9 P_S)</th>
<th>(n_s)</th>
<th>(r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002</td>
<td>59</td>
<td>0.83</td>
<td>0.00448</td>
<td>-0.02465</td>
<td>2.2639</td>
<td>0.9238</td>
<td>0.0717</td>
</tr>
<tr>
<td>0.05</td>
<td>56</td>
<td>0.72</td>
<td>0.00525</td>
<td>-0.00190</td>
<td>2.1777</td>
<td>0.9647</td>
<td>0.0840</td>
</tr>
</tbody>
</table>

- Result depends very sensitively on \(\alpha, m_\Phi\) and \(\lambda_{\Phi H}\) -

H.P.H.I allows Higgs inflation matching to BICEP2 result without resorting to \(m_t\) and \(M_h\).