What can off-shell Higgs tell us?

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Off-shell interpretations task force
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What can off-shell Higgs production tell us?

**off-shell**

- **width**
  - exact flat direction
  - approximate flat direction?

  - difficult

- **top/Higgs couplings**
  - $K_t$ vs $K_g$
  - top EW couplings

  - still need $\kappa_V > 1$?
  - need to relax $V_h(h\rightarrow bb)$
  - which deviation of on-shell rate will give more freedom?

- UV models ($\kappa_V > 1$, tuning)

  - weaker than $tth$ 
    - $\sim (40\% \text{ vs. } 10\% \text{ @HL-LHC})$

  - weaker than $ttZ$ 
    - $\sim (30\% \text{ vs. } 10\%)$

  - top CPV?
Flat direction in on-shell Higgs measurements

\[ \sigma(XX \to h) \text{BR}(h \to YY) \propto g_{hXX}^2 \frac{g_{hYY}^2}{\Gamma_h} \]

\[ g_{hii} = \kappa_{\text{univ}} g_{hii}^{\text{SM}} \]

\[ \Gamma_h = \kappa_{\text{univ}}^4 \Gamma_h^{\text{SM}} \]

all on-shell rates unchanged

\[ \Gamma_h = \kappa_{\text{univ}}^2 \Gamma_h^{\text{SM}} + \Gamma_h^{\text{exo}} \rightarrow \text{BR}_{\text{exo}} = \frac{\kappa_{\text{univ}}^2 - 1}{\kappa_{\text{univ}}^2} \]

untagged BR gives most leeway,
invisible BR already strongly constrained

\[ \text{BR}(\text{Higgs} \to \text{invisible}) < 13\% \ (95\% \ CL) \]

[ATLAS-CONF-2020-008]

thanks to Jorge de Blas for providing the likelihood from [1905.03764]
Flat direction vs off-shell Higgs

\[ \sigma(XX \rightarrow h) \text{BR}(h \rightarrow YY) \propto g_{hXX}^2 \frac{g_{hYY}^2}{\Gamma_h} \]

\[ g_{hii} = \kappa_{\text{univ}} g_{hii}^{\text{SM}} \]

\[ \Gamma_h = \kappa_{\text{univ}}^4 \Gamma_h^{\text{SM}} \]

\[ \Gamma_h = \kappa_{\text{univ}}^2 \Gamma_h^{\text{SM}} + \Gamma_h^{\text{exo}} \rightarrow \text{BR}_{\text{exo}} = \frac{\kappa_{\text{univ}}^2 - 1}{\kappa_{\text{univ}}^2} \]

Going to off-shell region:

\[ \frac{d\sigma_{gg \rightarrow h^* \rightarrow ZZ}}{ds} \propto \frac{g_{hgg}^2 g_{hZZ}^2}{(s - m_h^2)^2 + \Gamma_h^2 m_h^2} \sim \frac{g_{hgg}^2 g_{hZZ}^2}{s^2} \]

which grows as \( \kappa_{\text{univ}}^4 \)

upper bound on off-shell cross section translates to upper bound on width

[Caola and Melnikov 1307.4935]
Universal flat direction

How to realize a universal flat direction? Toy setup:

\[ \mathcal{L}_{BSM} = \frac{c_H}{f^2} (\partial_\mu |H|^2)^2 + \lambda_H |H|^2 \phi^2 \]

\[ \frac{g_{hii}}{g_{SM}^{hii}} = 1 - c_H \frac{v^2}{f^2} \quad \text{for example} \quad \Gamma(h \rightarrow \phi\phi) \sim \frac{\lambda_H^2 v^2}{8\pi m_h} \]

Requires:

- \( c_H < 0 \), possible but somewhat exotic. For example [Georgi and Machacek 1985]
  - E.g., pNGB of non-compact coset, or models with larger scalar reps.
- \( \phi \) decays to hadrons, for example color octet or singlet \( \rightarrow gg \)
- A “conspiracy” relating \( c_H \) and \( \lambda_H \phi \)
Relaxing coupling universality?

Flat direction is lifted very rapidly when we depart from universal rescaling of Higgs couplings.
Beyond the Higgs width: (SM)EFT

- $gg \rightarrow ZZ$ [Higgs-mediated + continuum] is sensitive to Higgs/top operators.

In Higgs basis:

9 CP-even coefficients

\[ \{c_{gg}, (\delta y_u)_{33}, \delta c_z, c_{zz}, c_z\Box, (\delta g_L^Z)_{33}, (\delta g_R^Z)_{33}, \text{Re} (d_{Zu})_{33}, \text{Re} (d_{Gu})_{33}\} \]

5 CP-odd coefficients

\[ \{\tilde{c}_{gg}, (\phi_u)_{33}, \tilde{c}_{zz}, \text{Im}(d_{Zu})_{33}, \text{Im}(d_{Gu})_{33}\} \]

\[
\mathcal{L} = \frac{h}{v} \left[ \tilde{c}_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a - m_t (\delta y_u)_{33} e^{i(\phi_u)_{33}} \bar{t}_R t_L + \text{h.c.} + \delta c_z \frac{g_2 v^2}{4} Z_{\mu} Z^{\mu} + c_{zz} \frac{g_2}{4} Z_{\mu\nu} Z^{\mu\nu} + c_z \Box g_2 Z_{\mu} \partial_\nu Z^{\mu\nu} + \tilde{c}_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{zz} \frac{g_2^2}{4} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] 
\]

\[
+ g_Z (\delta g_L^Z)_{33} Z_{\mu} \bar{t}_L \gamma^\mu t_L + g_Z (\delta g_R^Z)_{33} Z_{\mu} \bar{t}_R \gamma^\mu t_R - \frac{m_t}{4 v^2} \left[ g_s \bar{t}_L \sigma^{\mu\nu} T^a (d_{Gu})_{33} t_R G^{\mu\nu\alpha} + g_Z \bar{t}_L \sigma^{\mu\nu} T^a (d_{Zu})_{33} t_R Z^{\mu\nu} \right] + \text{h.c.}
\]
Beyond the Higgs width: (SM)EFT

- $gg \rightarrow ZZ$ [Higgs-mediated + continuum] is sensitive to Higgs/top operators.
  In Higgs basis:
  
  $$\{ c_{gg}, (\delta y_u)_{33}, \delta c_z, c_{zz}, c_{z\Box}, (\delta g^{Zu}_{L})_{33}, (\delta g^{Zu}_{R})_{33}, \text{Re} (d_{Zu})_{33}, \text{Re} (d_{Gu})_{33} \}$$

  \[
  \frac{\sigma_{gg\rightarrow h}}{\sigma_{gg\rightarrow h}^{SM}} \sim [1 + c_{gg} - (\delta y_u)_{33}]^2
  \]

  blind direction in on-shell gluon fusion production

[Azatov, Grojean, Paul, Salvioni 1608.00977]
Beyond the Higgs width: (SM)EFT

- $gg \rightarrow ZZ$ [Higgs-mediated + continuum] is sensitive to Higgs/top operators.

In Higgs basis:

$$\{c_{gg}, (\delta y_u)_{33}, \delta c_z, c_{zz}, c_{z\square}, (\delta g^Z_{LU})_{33}, (\delta g^Z_{RU})_{33}, \text{Re} (d_{Zu})_{33}, \text{Re} (d_{Gu})_{33}\}$$

probed by $t\bar{t}Z$, $tZ$

probed by $t\bar{t}$

9 CP-even coefficients

68% CL bounds on $\frac{\Lambda}{\sqrt{C_i}}$ [TeV]

- $C_{\phi Q} : [-0.50, 0.37]$
- $C_{\phi t} : [-0.24, 0.55]$
- $C_{tZ} : [-0.66, 0.66]$
- $C_{tG} : [1.2, 1.8]$

**current bound on** $C_{tG} \leftrightarrow \text{Re} (d_{Gu})_{33}$ **is significantly stronger than for others**

[Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang 1910.03606]
Beyond the Higgs width: (SM)EFT

• $gg \to ZZ$ [Higgs-mediated + continuum] is sensitive to Higgs/top operators. In Higgs basis:

\[
\{ c_{gg}, (\delta y_u)_{33}, \delta c_z, c_{zz}, c_z^\Box, (\delta g_L^{Z u})_{33}, (\delta g_R^{Z u})_{33}, \text{Re} (d_{Z u})_{33}, \text{Re} (d_{G u})_{33}\}
\]

9 CP-even coefficients

• $gg \to ZZ$ is mostly sensitive to axial vector coupling $\propto (\delta g_L^{Z u})_{33} - (\delta g_R^{Z u})_{33}$

[Azatov, Grojean, Paul, Salvioni 1608.00977]

• Angular distributions can be exploited to isolate LL pol. mode, which is enhanced for BSM couplings

[Cao, Yan, Yuan, Zhang 2004.02031]