Status of off-shell Higgs studies

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Why off-shell Higgs?

A probe of the Higgs width:

\[ \sigma_{\text{onshell}}^{gg \to H \to VV} \sim \frac{c_{ggH}^2 c_{VVH}^2}{m_H \Gamma_H} \]

\[ \sigma_{\text{offshell}}^{gg \to H \to VV} \sim \frac{c_{ggH}^2 c_{VVH}^2}{m_{ZZ}^2} \]

CMS, 2202.06923

\[ \Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV} \]

ATLAS, 2022-068

\[ \Gamma_H = 4.6^{+2.6}_{-2.5} \text{ MeV} \]

Caola and Melnikov arXiv:1307.4935
Off-shell Higgs

Why is this process interesting?
- Crucial for Higgs width determination
- Access to high energy regions due to large invariant masses:
  - Models with new heavy resonances
  - Sensitivity to SMEFT operators

Why is this process tough?
- Signal background interference
- Loop induced: hard to compute higher order corrections

Full top amplitudes only recently computed:

- Complex EFT structure
LHCHWG Off-Shell Task Force

LHCHWG-2022-001

May 16, 2022

LHC Higgs Working Group

PUBLIC NOTE

Off-shell Higgs Interpretations Task Force

Models and Effective Field Theories Subgroup Report

ArXiv:2203.02418

Some highlights from this report to follow

1 Introduction

2 What can off-shell Higgs measurements tell us about BSM physics?
   2.1 Going beyond a universal flat direction
   2.2 SMEFT effects in $gg \rightarrow ZZ$
   2.3 Brief review of models testable in off-shell production

3 Off-shell Higgs production in the SMEFT
   3.1 Studies with the SMEFTatNLO framework
   3.1.1 Relevant Operators
   3.1.2 Generation using SMEFTatNLO
   3.1.3 Results
   3.2 Studies with the JHUGen+MCFM framework
   3.2.1 Relevant Operators
   3.2.2 Differential Distributions and Expected Constraints

4 Summary of the Higgs basis parametrization of the SMEFT
   4.1 Pep talk
   4.2 Definition of the Higgs basis
   4.3 Lagrangian for mass eigenstates
   4.4 New variables
   4.5 Final Lagrangian
   4.6 Discussion

5 Short notes on the SMEFT
   5.1 Higgs basis with additional constraint
   5.2 Relation between Higgs and Warsaw bases

6 Effective Field Theory calculations and tools

7 Summary and conclusions

A Higgs basis parametrization of the SMEFT: Notation and conventions
Off-shell in Universal directions models

Golden rule:

\[ \sigma_{gg \to H \to VV}^{\text{on-shell}} \sim \frac{c_{gg}^2 H c_{VV}^2}{m_H \Gamma_H} \]

\[ \sigma_{gg \to H \to VV}^{\text{off-shell}} \sim \frac{c_{gg}^2 H c_{VV}^2}{m_{ZZ}^2} \]

Universal direction:

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

Flat direction from on-shell:

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

Off-shell measurement gives a bound on \( \kappa_{\text{univ}} \)

Realised in particular BSM scenarios with specific couplings

\[ \mathcal{L}_{\text{BSM}} \ni \frac{cH}{2f^2} (\partial_{\mu} H \mu^2) - \lambda_H \varphi H \varphi^2 \quad \text{e.g. Triplet scalars} \]
Thus, two conditions need to be met to obtain a universal flat direction: first, from operators, such as illustration, we consider a scalar extension of the SM containing the following interactions,

\[ g_{h_{\text{iii}}} = \kappa_{\text{univ}} g_{h_{\text{iii}}}^{\text{SM}} \quad \Gamma_h = \kappa_{\text{univ}}^4 \Gamma_h^{\text{SM}} \]

For the flat direction from on-shell:

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

Off-shell measurement gives a bound on \( \kappa_{\text{univ}} \)

Realised in particular BSM scenarios with specific couplings

\[ \mathcal{L}_{\text{BSM}} \ni \frac{c_H}{2f^2} (\partial_\mu |H|^2)^2 - \lambda_H \varphi |H|^2 \varphi^2 \quad \text{e.g. Triplet scalars} \]

Azatov, de Blas, Grojean, Salvioni

E.Vryonidou

LHCP2023, 25/05/23

arXiv:2203.02418
Beyond Universal directions

Relaxing universality assumption: $\tilde{\kappa}_{\text{univ}}, \kappa_b, \text{BR}_{\text{exo}}$

Hbb coupling

Use on-shell VH, ttH with Higgs to bb and off-shell

$\text{BR}_{\text{exo}} = 1 - \mu_{\text{on}} \frac{\tilde{\kappa}_{\text{univ}}^2(1 - \text{BR}_{\text{SM}}^{bb}) + \kappa_b^2 \text{BR}_{\text{SM}}^{bb}}{\tilde{\kappa}_{\text{univ}}^4}, \quad \kappa_b^2 = \frac{\mu_{Vh,bb}}{\mu_{\text{on}}} \tilde{\kappa}_{\text{univ}}^2, \quad \mu_{\text{off}} = a + b\tilde{\kappa}_{\text{univ}}^2 + c\tilde{\kappa}_{\text{univ}}^4$

Off-shell can help for large untagged widths

Azatov, de Blas, Grojean, Salvioni

E.Vryonidou

LHCP2023, 25/05/23

arXiv:2203.02418
Going more general: SMEFT

The signal

The background

The Higgs width
The Higgs propagator

\[ \mathcal{M} \propto \frac{c_i}{s - M_H^2 + i\Gamma_H(c_i)M_H} \]

\[ s \gg M_H^2 \]

\[ s \sim M_H^2 \]

\[ \mathcal{M} \propto \frac{c_i}{s - M_H^2} \cdot \sigma_H(c_i) \cdot \frac{\Gamma^4_{H}(c_i)}{\Gamma_{H}(c_i)} \]
Off-shell Higgs in SMEFT

Higgs basis: Top and Higgs interactions

\[ \Delta \mathcal{L} = \frac{h}{v} \left( c_{gg} \frac{g_s^2}{4} G^a_{\mu\nu} G^{\mu\nu \, a} - m_t [\delta y_u]_{33} \bar{t}_L t_R + \text{h.c.} + \delta c_z \frac{g_Z^2 v^2}{4} Z_\mu Z^\mu + c_{zz} \frac{g_Z^2}{4} Z_\mu Z^{\mu \nu} + c_z \Box g_L^2 Z_\mu \partial_\nu Z^{\mu \nu} \right. \]
\[ \left. + \tilde{c}_{gg} \frac{g_s^2}{4} G^a_{\mu\nu} G^{\mu\nu \, a} + \tilde{c}_{zz} \frac{g_Z^2}{4} Z_\mu \tilde{Z}^{\mu \nu} \right) - g_Z (\delta g^Z_{L u})_{33} Z_\mu \bar{t}_L \gamma^\mu t_L - g_Z (\delta g^Z_{R u})_{33} Z_\mu \bar{t}_R \gamma^\mu t_R \]
\[ - \frac{m_t}{4v^2} \left( 1 + \frac{h}{v} \right) \left( g_s \bar{t}_R \sigma^{\mu \nu} T^a [d_{G u}]_{33} t_L G^a_{\mu\nu} + g_Z \bar{t}_R \sigma^{\mu \nu} T^a [d_{Z u}]_{33} t_L Z^{\mu \nu} \right) + \text{h.c.}, \]

red: CP odd, blue: CP even

- Top Yukawa: \( \frac{\sigma_{gg\to h}}{\sigma_{gg\to h}^{\text{SM}}} \approx \left( 1 + 12\pi^2 c_{gg} + \text{Re} [\delta y_u]_{33} \right)^2 \) \text{Degeneracy}
- Higgs-gluon
- Higgs couplings to gauge bosons: Probed in VH, VBF, Higgs decays
- Top couplings to the Z: Probed in tZ, ttZ
- Top-gluon interactions: Probed in top pair production

Ellis et al arXiv:2012.02779

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The operators: Warsaw basis

**Higgs operators**

| $O_{\phi G}$ | cpG | $(\phi^\dagger \phi - \frac{v^2}{2}) G^\mu_\nu G^A_{\mu\nu}$ |
| $O_{\phi B}$ | cpBB | $(\phi^\dagger \phi - \frac{v^2}{2}) B^\mu_\nu B_{\mu\nu}$ |
| $O_\phi$ | cp | $(\phi^\dagger \phi - \frac{v^2}{2}) \phi$ |
| $O_{\phi D}$ | cpDC | $(\phi^\dagger D_\mu \phi)^\dagger (\phi^\dagger D_\mu \phi)$ |

| $O_{\phi W}$ | cpW | $(\phi^\dagger \phi - \frac{v^2}{2}) W^\mu_\nu W^I_{\mu\nu}$ |
| $O_{\phi WB}$ | cpWB | $(\phi^\dagger \phi - \frac{v^2}{2}) B^\mu_\nu W^I_{\mu\nu}$ |

| $O_{\phi d}$ | cdp | $\partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi)$ |

**Top operators**

| $O_{t\phi}$ | ctp | $(\phi^\dagger \phi - \frac{v^2}{2}) \bar{Q} t \phi + h.c.$ |
| $O_{tG}$ | ctG | $i g_s (\bar{Q} t^\mu T_A t) \phi G^A_{\mu\nu} + h.c.$ |
| $O_{tQ}^{(3)}$ | cpQ3 | $i (\phi^\dagger D_\mu \tau_i \phi) (\bar{Q} \gamma^\mu t Q)$ |
| $O_{tQ}^{(-)}$ | cpQM | $O^{(1)}_{tQ} - O^{(3)}_{tQ}$ |

| $O_{tw}$ | ctW | $i (\bar{Q} \tau^\mu \tau_i t) \bar{\phi} W^I_{\mu\nu} + h.c.$ |
| $O_{tI}$ | - | $i (\bar{Q} t^\mu t) \bar{\phi} B_{\mu\nu} + h.c.$ |
| $O_{tZ}$ | ctZ | $- \sin \theta_W O_{tI} + \cos \theta_W O_{tw}$ |
| $O_{tI}$ | - | $i (\bar{D}_\mu \phi) (\bar{t} \gamma^\mu t)$ |

See also: Englert, Soreq, Spannowsky arXiv:1410.5440
Azatov et al arXiv:1406.6338, 1608.00977
SMEFT analysis of off-shell production

Things to consider:
• The relevant operators modifying the signal:
  • Higgs couplings
• The operators entering the gg\rightarrow ZZ background
  • The constraints on the top-operators
• Well-constrained operators \rightarrow small impact
• Unconstrained operators \rightarrow to be taken into account
What should we expect?

Helicity amplitude computation:

<table>
<thead>
<tr>
<th>$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$</th>
<th>$O_{\varphi B}$</th>
<th>$O_{\varphi W}$</th>
<th>$O_{\varphi G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$++, +, +, +$</td>
<td>$\frac{m_t^2 s_w^2 g_2^2}{8\sqrt{2}\pi^2} \left[ \log\left( \frac{s}{m_t^2} \right) - i\pi \right]^2$</td>
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</tr>
<tr>
<td>$++, +, -$, $-$</td>
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<td>-</td>
</tr>
<tr>
<td>$++, 0, 0$</td>
<td>-</td>
<td>-</td>
<td>$s \frac{v^2 e^2}{2\sqrt{2} m_t^2 c_w^2 s_w^2}$</td>
</tr>
</tbody>
</table>

Logarithmic growth

<table>
<thead>
<tr>
<th>$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$</th>
<th>$O_{t\varphi}$</th>
<th>$O_{\varphi t}$</th>
<th>$O_{\varphi Q}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$++, 0, 0$</td>
<td>$\frac{m_t v^3 c_w^2 g_2^2}{128\pi^2 m_t^2 c_w^2 s_w^2} \left[ \log\left( \frac{s}{m_t^2} \right) - i\pi \right]^2$</td>
<td>$\frac{m_t^2 v^2 e^2 g_2^2}{32\sqrt{2}\pi^2 m_t^2 c_w^2 s_w^2} \left[ \log\left( \frac{s}{m_t^2} \right) - i\pi \right]^2$</td>
<td>$\frac{m_t^2 v^2 e^2 g_2^2}{32\sqrt{2}\pi^2 m_t^2 c_w^2 s_w^2} \left[ \log\left( \frac{s}{m_t^2} \right) - i\pi \right]^2$</td>
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Rossi, Thomas, EV soon
What should we expect?

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<td>$\frac{m_t^2 s_w^2 g_2^2}{8 \sqrt{2} \pi^2} \left[ \log\left( \frac{s}{m_t^2} \right) - i\pi \right]^2$</td>
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<td>$-$</td>
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<td>$\frac{m_t^2 s_w^2 g_2^2}{8 \sqrt{2} \pi^2} \left[ \log\left( \frac{s}{m_t^2} \right) - i\pi \right]^2$</td>
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<td>$-$</td>
</tr>
<tr>
<td>$+, +, 0, 0$</td>
<td>$-$</td>
<td>$-$</td>
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Logarithmic growth

Rossia, Thomas, EV soon
Higgs-gauge interactions

\[ \mathcal{O}_{\varphi G} \quad \text{cpG} \quad \left( \varphi^{\dagger} \varphi - \frac{v^2}{2} \right) G_{\mu \nu}^A G_{\mu \nu}^A \]

\[ \mathcal{O}_{\varphi W} \quad \text{cpW} \quad \left( \varphi^{\dagger} \varphi - \frac{v^2}{2} \right) W_{\mu \nu}^I W_{\mu \nu}^I \]

Figure 3.2: Differential distributions for Higgs operators, modifying Higgs couplings to the gauge bosons. For the interference, dashed lines denote a negative contribution.

Thomas, EV in arXiv:2203.02418
Top Yukawa

\[ \mathcal{O}_{t\varphi} \quad ctp \quad (\varphi^\dagger \varphi - \frac{v^2}{2}) \bar{Q} t \tilde{\varphi}. \]

Figure 3.6: Differential distributions for maximum allowed values of the coefficients extracted from global SMEFT fits [45]. Both SM-NP interference and NP terms are included.

Figure 3.5: Differential distributions for top Yukawa and top chromomagnetic dipole moment operators. For the interference, dashed lines denote a negative contribution.

Allowed from global fits

\[ \frac{d\sigma}{dm} \quad [\text{fb/GeV}] \]

\[ m_{ZZ} \quad [\text{GeV}] \]

\[ \text{MadGraph5.aMC@NLO} \]

Thomas, EV in arXiv:2203.02418
Top Yukawa

\[ \mathcal{O}_{t\varphi} = c_{tp} \left( \varphi^\dagger \varphi - \frac{v^2}{2} \right) \bar{Q} t \tilde{\varphi} \]

Figure 3.6: Differential distributions for maximum allowed values of the coefficients extracted from global SMEFT fits [45]. Both SM-NP interference and NP terms are included.

Figure 3.5: Differential distributions for top Yukawa and top chromomagnetic dipole moment operators. For the interference, dashed lines denote a negative contribution.

Allowed from global fits

Thomas, EV in arXiv:2203.02418
Top-Z couplings

$$O_{\varphi t} \quad \text{cpt} \quad i(\varphi^\dagger D_\mu \varphi)(\bar{t} \gamma^\mu t)$$

Poorly constrained from top data

Allowed from global fits

Thomas, EV in arXiv:2203.02418
Top-Z couplings

\[ \mathcal{O}_{\varphi t} \quad \text{cpt} \quad i(\varphi^{\dagger} D_{\mu} \varphi)(\bar{t} \gamma^\mu t) \]

Poorly constrained from top data

Allowed from global fits

Thomas, EV in arXiv:2203.02418
Going beyond gluon fusion

Also allowing CP odd Higgs couplings

Gritsan, Kang, Sarica in arXiv:2203.02418
Conclusions

• Off-shell Higgs production key in constraining the Higgs width
• Off-shell measurements can break degeneracies from on-shell production
• SMEFT analysis of off-shell Higgs production needs to take into account:
  • Operators modifying the signal
  • Operators modifying the loop-induced background
• Operators modifying the top-Z coupling play a special role, as they are loosely constrained and lead to energy growing amplitudes
• More systematic and realistic studies needed
Thank you for your attention