Constraining the Higgs boson self-coupling via single-Higgs and double-Higgs production and decay measurements

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on behalf of the ATLAS Collaboration

Higgs Couplings 2019 - 30 September-4 October 2019
Oxford UK
Theoretical model: double-Higgs production

The amplitude of the process can be expressed as:

$$\mathcal{A}(\kappa_t, \kappa_\lambda) = \kappa_t^2 \mathcal{A}_1 + \kappa_t \kappa_\lambda \mathcal{A}_2$$

- The $\mathcal{A}_1$ amplitude is proportional to the square of the Higgs boson coupling to the top-quark, and the $\mathcal{A}_2$ amplitude to the product of the coupling to the top-quark and the Higgs boson self-coupling.
- In the SM, the interference between these two amplitudes is destructive and yields an overall cross section of $\sigma_{ggF}^{SM}(pp \rightarrow HH) = 33.5$ fb at $\sqrt{s} = 13$ TeV.
- Assuming the matrix element contribution can be factorised, the total $\sigma_{ggF}^{SM}(pp \rightarrow HH)$ cross section is:

$$\sigma_{ggF}(pp \rightarrow HH) \sim \kappa_t^4 \left( |\mathcal{A}_1|^2 + 2\frac{\kappa_\lambda}{\kappa_t} \Re \mathcal{A}_1^* \mathcal{A}_2 + \left( \frac{\kappa_\lambda}{\kappa_t} \right)^2 |\mathcal{A}_2|^2 \right)$$

- Both acceptance and shape variations are taken into account.
Double-Higgs production: latest results

arXiv:1906.02025

- The branching fractions of the Higgs boson have been assumed to be equal to the SM predictions;
- all couplings except the Higgs boson self-coupling have been set to their SM values;
- exclusion limits are set after a $\kappa_\lambda$-scan on the cross section and a comparison with the theoretical $\sigma_{ggF}(pp\to HH)$ cross section as a function of $\kappa_\lambda$.

Further details in Alessandra Betti’s talk

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Single Higgs processes are sensitive to $\lambda_3$ via loop corrections. NLO EW $\kappa_\lambda$-dependent corrections can be divided into two categories:

- a universal part, **quadratically dependent on** $\lambda_3$, which originates from the diagram in the wave function renormalisation constant of the external Higgs field.
- a process-dependent part ($C_1$) **linearly proportional to** $\lambda_3$ which is different for each process and **kinematics**.

NLO EW $\kappa_\lambda$-dependent corrections affect:

- inclusive cross-sections ($t\bar{t}H, ggF, ZH, WH, VBF$);
- **kinematics** properties of the event (differential distributions);
- Higgs boson decay BRs.

**Examples of process-dependent part**

- **corrections to $t\bar{t}H$**

- **corrections to $VH$**

**Range of validity** detailed in theory papers

$$|\kappa_\lambda| \lesssim 20$$
Theoretical model

- The production cross sections $\sigma_i$ and the branching fractions $BR_f$ normalised to their SM values, i.e. $\mu_i$ and $\mu_f$, are parameterised as functions of $\kappa_i$:

$$\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda) = \frac{\sigma_i(\kappa_\lambda)}{BR_{SM,f}} \times \frac{BR_f(\kappa_\lambda)}{\sigma_{SM,i}}$$

- $\kappa_i$ and $\kappa_f$ represent multiplicative modifiers to other Higgs boson couplings for initial and final states, parameterised as in the LO $\kappa$-framework;

$$K_E^i = \frac{\sigma_{SM,i}^{NLO}}{\sigma_{LO,i}}$$

accounts for the complete NLO EW correction of the production cross section for the process in the SM hypothesis (i.e. $\kappa_\lambda=1$).

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JHEP 1612, 080 (2016)
The results are obtained using ATLAS data corresponding to a luminosity of up to 80 fb\(^{-1}\).

Two different inputs, (containing production and decay modes) have been considered:

- one is used for inclusive estimations;
- the second one is profiled in bins of truth-level observables, \(p_T^H\) (Simplified Template Cross Sections STXS bins); it can be used for differential estimations; the analysis VBF H->bb has been excluded from the input (low impact + no STXS bins).

### Constructed from Figures in arXiv: 1610.07922
Single-Higgs production: results of fit to $\kappa_\lambda$

- A likelihood fit is performed to constrain the value of $\kappa_\lambda$.
- All other couplings are set to their SM values.

$$\kappa_\lambda = 4.0^{+4.3}_{-4.1} = 4.0^{+3.7}_{-3.6} \text{ (stat.)} +1.6_{-1.5} \text{ (exp.)} +1.3_{-0.9} \text{ (sig. th.)} +0.8_{-0.9} \text{ (bkg. th.)}$$

$-3.2 < \kappa_\lambda < 11.9 \text{ (obs) at 95% CL}$

$-6.2 < \kappa_\lambda < 14.4 \text{ (exp) at 95% CL}$
Single-Higgs production: fit to $\kappa_\lambda$ and either $\kappa_F$ or $\kappa_V$

- A simultaneous fit is performed to $\kappa_\lambda$ and $\kappa_F$, or to $\kappa_\lambda$ and $\kappa_V$; the remaining coupling modifier that is not included in the fit is kept fixed to the SM prediction.
- Including additional degrees of freedom to the fit reduces the constraining power of the measurement.
- An even less constrained fit, performed by fitting simultaneously $\kappa_\lambda, \kappa_F$ and $\kappa_V$ results in nearly no sensitivity to $\kappa_\lambda$. 

![Contour plots](image)

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 36.1 - 79.8 fb$^{-1}$

$m_H = 125.09$ GeV, $\kappa_V = 1$

- **SM**
- **Best Fit**
- **68% CL**
- **95% CL**

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Data and input measurements: H+HH combination

ATLAS-CONF-2019-049

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated luminosity (fb⁻¹)</th>
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<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>79.8</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$ (including $t\bar{t}H$, $H \rightarrow ZZ^* \rightarrow 4\ell$)</td>
<td>79.8</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow e\nu\mu\nu$</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>36.1</td>
</tr>
<tr>
<td>$VH, H \rightarrow b\bar{b}$</td>
<td>79.8</td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow b\bar{b}$ and $t\bar{t}H$ multilepton</td>
<td>36.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}b\bar{b}$</td>
<td>27.5</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\tau^+\tau^-$</td>
<td>36.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>36.1</td>
</tr>
</tbody>
</table>

- The results are obtained using ATLAS data corresponding to a luminosity of up to 80 fb⁻¹.
- The $t\bar{t}H \rightarrow \gamma\gamma$ categories included in the single-Higgs analysis exploited to constrain $\kappa_\lambda$ have been removed from this combination because there are categories where up to 50% of the selected $t\bar{t}H \rightarrow \gamma\gamma$ events are selected by the $HH \rightarrow b\bar{b}\gamma\gamma$ analysis too.
A likelihood fit is performed to constrain the value of $\kappa_\lambda$; all other couplings are set to their SM values.

$$\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.3^{+2.9}_{-3.5} \text{ (stat.)} +1.2_{-1.2} \text{ (exp.)} +0.7_{-0.5} \text{ (sig. th.)} +0.6_{-1.0} \text{ (bkg. th.)} \text{(obs.)}$$

- $-2.3 < \kappa_\lambda < 10.3 \text{ (obs) at 95\% CL}$
- $-5.1 < \kappa_\lambda < 11.2 \text{ (exp) at 95\% CL}$

The total uncertainty is dominated by the statistical component.

- The double-Higgs boson production measurements are more sensitive than the single-Higgs boson measurement for $\kappa_\lambda >> 1$ and show similar sensitivity for negative $\kappa_\lambda$.
- The combination significantly improves the constraining power on $\kappa_\lambda$. 

Eleonora Rossi

02/10/2019
In order to exploit the sensitivity of the double-Higgs production mechanism and the strong dependence of the double-Higgs cross section $\sigma_{ggF}(pp \to HH)$ on $\kappa_t$, a likelihood fit is performed to constrain at the same time $\kappa_\lambda$ and $\kappa_t$; all other couplings are set to their SM values.

While in single-Higgs analyses a significant loss in sensitivity is present when fitting both $\kappa_\lambda$ and $\kappa_t$, the constraining power of the measurement remains almost the same in the H+HH combined result.

New

ATLAS-CONF-2019-049
H+$\phi$ combination: generic model

- The constraining power of the single Higgs-boson production measurement allows to perform a fit in a most generic model, fitting simultaneously $\kappa_{\lambda} - \kappa_W - \kappa_Z - \kappa_{\text{lepton}} - \kappa_{b} - \kappa_{t}$.
- The combination of single- and double-Higgs analyses allows to put sizable constraints even in this more generic model.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_{W}^{+1\sigma}$</th>
<th>$\kappa_{Z}^{+1\sigma}$</th>
<th>$\kappa_{t}^{+1\sigma}$</th>
<th>$\kappa_{b}^{+1\sigma}$</th>
<th>$\kappa_{l}^{+1\sigma}$</th>
<th>$\kappa_{\lambda}^{+1\sigma}$</th>
<th>$\kappa_{\lambda} [95% \text{ CL}]$</th>
</tr>
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<tbody>
<tr>
<td>$\kappa_{\lambda}$-only</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>$4.6^{+3.2}_{-3.8}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.00{+0.08}_{-0.08}$</td>
<td>$1.00{+0.08}_{-0.08}$</td>
<td>$1.00{+0.08}_{-0.08}$</td>
<td>$1.00{+0.08}_{-0.08}$</td>
<td>$1.00{+0.08}_{-0.08}$</td>
<td>$[-2.3, 10.3]$</td>
</tr>
<tr>
<td>Generic</td>
<td>$1.00{+0.08}_{-0.08}$</td>
<td>$1.10^{+0.09}_{-0.09}$</td>
<td>$1.00{+0.12}_{-0.11}$</td>
<td>$1.00{+0.12}_{-0.11}$</td>
<td>$1.03{+0.20}_{-0.18}$</td>
<td>$1.06^{+0.16}_{-0.16}$</td>
<td>$5.5^{+3.5}_{-5.2}$</td>
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<tr>
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<td></td>
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<td></td>
<td></td>
<td>$[-3.7, 11.5]$</td>
</tr>
</tbody>
</table>

New
Summary

- In the simplified assumption that all deviations from the SM expectation have to be interpreted as modifications of the trilinear coupling of the Higgs boson, the best fit value of $\kappa_\lambda$ from the combination of single and double-Higgs analyses is $\kappa_\lambda = 4.6^{+3.2}_{-3.8}$, excluding at the 95% C.L. values outside the interval $-2.3 < \kappa_\lambda < 10.3$.

- The H+HH combination result constitutes a significant improvement on the constraints on $\kappa_\lambda$ obtained from single-Higgs and double-Higgs analyses alone.

- Moreover, the H+HH combination allows to decouple the self-coupling and top-Yukawa coupling as well as other couplings.

Fig. 81: Results of the two-dimensional likelihood scan in $\Delta H$-vs-$\mu_H$, where $\mu_H$ allows all Higgs boson production modes to scale relative to the SM prediction. The 68% and 95% confidence level contours are shown by the solid and dashed lines respectively. The SM expectation is shown by the black cross.

Fig. 82: Analysis of the Higgs self-coupling $\Delta \lambda$ using single- and double-Higgs processes for the HL-LHC at 13 TeV and 3 ab$^{-1}$. The widths of the lines correspond to the differences between the scenarios S1 and S2.

Left: Comparison of the constraints obtained using inclusive single-Higgs processes (orange), with the ones using differential observables (blue). Dashed is an exclusive fit while solid is the result of a global fit.

Right: Comparison of the constraints from differential single Higgs (blue), with those from differential double-Higgs data (dashed red) and its combination (pink).

As input for the uncertainties we consider the S1 and S2 scenarios, corresponding to the projected HL-LHC prospects, Yellow Report results.

arXiv:1902.00134v2
\[ L = - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} + \phi_i \partial_i \phi^2 - V(\phi) \]
Theoretical model: kinematic dependent coefficients $C_1^i$

- The parameterisation of the variation of the production cross-section as a function of $\kappa_A$ can be adapted to describe the cross-section in each single STXS region.
- This requires re-deriving the value of the kinematic dependent coefficients $C_1^i$ in each region defined in the measurement.
- For each VBF, ZH, WH region of the STXS stage-1 framework, the $C_1^i$ coefficients have been computed.

### Constructed from Figures in arXiv: 1610.07922

#### ATL-PHYS-PUB-2019-009

<table>
<thead>
<tr>
<th>STXS region</th>
<th>VBF $C_1^i \times 100$</th>
<th>WH $C_1^i \times 100$</th>
<th>ZH $C_1^i \times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $+ V(had)H$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF-cuts + $p_T^{VH} &lt; 200 \text{ GeV}, \leq 2j$</td>
<td>0.63</td>
<td>0.91</td>
<td>1.07</td>
</tr>
<tr>
<td>VBF-cuts + $p_T^{VH} &lt; 200 \text{ GeV}, \geq 3j$</td>
<td>0.61</td>
<td>0.85</td>
<td>1.04</td>
</tr>
<tr>
<td>$VH$-cuts + $p_T^{VH} &lt; 200 \text{ GeV}$</td>
<td>0.64</td>
<td>0.89</td>
<td>1.10</td>
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<tr>
<td>no VBF/$VH$-cuts, $p_T^{VH} &lt; 200 \text{ GeV}$</td>
<td>0.65</td>
<td>1.13</td>
<td>1.28</td>
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<tr>
<td>$p_T^{VH} &gt; 200 \text{ GeV}$</td>
<td>0.39</td>
<td>0.23</td>
<td>0.28</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>STXS region</th>
<th>VBF $C_1^i \times 100$</th>
<th>WH $C_1^i \times 100$</th>
<th>ZH $C_1^i \times 100$</th>
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</thead>
<tbody>
<tr>
<td>$qq \rightarrow H\ell\nu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^V &lt; 150 \text{ GeV}$</td>
<td>1.15</td>
<td>0.18</td>
<td>0.31</td>
</tr>
<tr>
<td>$150 &lt; p_T^V &lt; 250 \text{ GeV}, 0j$</td>
<td>0.33</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$p_T^V &gt; 250 \text{ GeV}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$qq \rightarrow H\ell\ell$</td>
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<td></td>
</tr>
<tr>
<td>$p_T^V &lt; 150 \text{ GeV}$</td>
<td>1.33</td>
<td>0.20</td>
<td>0.39</td>
</tr>
<tr>
<td>$150 &lt; p_T^V &lt; 250 \text{ GeV}, 0j$</td>
<td>0.39</td>
<td>0</td>
<td>0</td>
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<tr>
<td>$p_T^V &gt; 250 \text{ GeV}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>$qq \rightarrow H\nu\nu$</td>
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<tr>
<td>$p_T^V &lt; 150 \text{ GeV}$</td>
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</tr>
<tr>
<td>$150 &lt; p_T^V &lt; 250 \text{ GeV}, 0j$</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>$p_T^V &gt; 250 \text{ GeV}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Single-Higgs production: results of fit to $\kappa_\lambda$

- The impact on the $\kappa_\lambda$ determination of using an inclusive cross-section measurement, rather than the differential cross-section information contained in the STXS bins, has been studied.
- $VBF$, $VH$ and $ZH$ production modes are considered as single inclusive bins.
- Compared to the use of differential information, the inclusive fit does not currently lead to a significant loss in sensitivity to $\kappa_\lambda$.

<table>
<thead>
<tr>
<th>POIs</th>
<th>Granularity</th>
<th>$\kappa_F^{+1\sigma}_{-1\sigma}$</th>
<th>$\kappa_V^{+1\sigma}_{-1\sigma}$</th>
<th>$\kappa_\lambda^{+1\sigma}_{-1\sigma}$</th>
<th>$\kappa_\lambda$ [95% C.L.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_\lambda$</td>
<td>STXS</td>
<td>1</td>
<td>1</td>
<td>$4.0^{+4.3}_{-4.1}$</td>
<td>$[-3.2, 11.9]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1.0^{+8.8}_{-4.4}$</td>
<td>$[-6.2, 14.4]$</td>
</tr>
<tr>
<td>$\kappa_\lambda$</td>
<td>inclusive</td>
<td>1</td>
<td>1</td>
<td>$4.6^{+4.3}_{-4.2}$</td>
<td>$[-2.9, 12.5]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1.0^{+9.5}_{-4.3}$</td>
<td>$[-6.1, 15.0]$</td>
</tr>
</tbody>
</table>
The global likelihood shape depends on combining the contributions from the different production and decay modes, that have different sensitivities and in most cases also significantly different likelihood shapes.

The dominant contributions to the $\kappa_\lambda$ sensitivity derive from the HH channels, from the di-boson decay channels $\gamma\gamma$, $ZZ$, $WW$ and from the $ggF$ and $ttH$ production modes.
HL-LHC projection

- HH analyses currently are very limited by statistics also in its systematic uncertainties (e.g. bkg systematics), therefore at HL they can gain (obviously) a lot in sensitivity.

- The gain for single Higgs is not so enhanced by the increasing of luminosity since at a certain point it becomes limited by systematic uncertainties, that in the HL projection are not so much reduced.

- Differential information has a great impact on the measurement.

**HL-LHC prospects, Yellow Report results**  
**arXiv:1902.00134v2**