Constraining the Higgs boson self-coupling in a combined measurement of single and double Higgs boson channels at the ATLAS experiment

Eleonora Rossi (eleonora.rossi@cern.ch)
on behalf of the ATLAS Collaboration

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University of Pittsburgh
Physics motivation

- Measuring the Higgs-boson self-couplings is a crucial validation of the Brout-Englert-Higgs (BEH) mechanism.

- The self-couplings determine the shape of the potential which is connected to the phase transition of the early universe from the unbroken to the broken electroweak symmetry.

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
+ \sum \overline{\psi} i \gamma_\mu \gamma_5 \psi + h.c. \\
+ \sum \overline{\psi} \gamma_\mu (m_\psi + \lambda \phi) \psi + h.c. \\
+ \frac{1}{2} \nabla_\mu \phi \nabla^\mu \phi - V(\phi)
\]

\[
V_H = \mu^2 \phi^4 + \frac{1}{2} \lambda (\phi^4)^2
\]

- The Higgs-potential low energy expansion around its minimum includes triple and quartic terms:

\[
V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 \nu H^3 + \lambda_4 H^4
\]

- In the SM, the Higgs field is fully determined by only two parameters, \( \nu = (\sqrt{2} G_\mu)^{-1/2} \sim 246 \text{ GeV} \), and \( \lambda \).

- New physics effects can be parameterised via a single parameter \( \kappa_\lambda \), i.e. the rescaling of the SM trilinear coupling, \( \lambda_3^{SM} \):

\[
\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}
\]
Physics motivation

- Measuring the Higgs-boson self-couplings is a crucial validation of the Brout-Englert-Higgs (BEH) mechanism.
- The self-couplings determine the shape of the potential which is connected to the phase transition of the early universe from the unbroken to the broken electroweak symmetry.

\[ V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 \nu H^3 + \lambda_4 H^4 \]

\( \lambda_3 \) can be probed at the LHC using:
- production of Higgs boson pairs;
- Next-to-Leading Order (NLO) electroweak (EW) corrections to single-Higgs processes.

\[ \kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}} \]
Higgs pair production

- Rare process of the Standard Model:
  - main production mode (90%) ggF: \( \sigma_{pp \to HH}^{ggF} = 31.05 \, \text{fb}^{(+2.2\%)}_{(-5.0\%)} \) (scale) \( \pm 3.0\% \) (PDF + \( \alpha_S \)) \( \pm 2.6\% \) (m_{top} unc)
  - the interference between box and triangle diagrams is destructive
    \[ \mathcal{A}(\kappa_t, \kappa_\lambda) = \kappa_t^2 \mathcal{A}_1 + \kappa_t \kappa_\lambda \mathcal{A}_2 \]
  - sensitive to the trilinear Higgs self-coupling at leading order in EW.

- \( \sigma_{ggF}(pp \to HH) \) in terms of \( \kappa_\lambda \) and \( \kappa_t \):
  \( \sigma_{ggF}(pp \to HH) \sim \kappa_t^4 \left[ |\mathcal{A}_1|^2 + 2 \frac{\kappa_\lambda}{\kappa_t} \Re \mathcal{A}_1^* \mathcal{A}_2 + \left( \frac{\kappa_\lambda}{\kappa_t} \right)^2 |\mathcal{A}_2|^2 \right] \)
  - the \( \kappa_t^4 \) factor affects only the total cross section; kinematic distributions and signal acceptances depend only on \( \kappa_\lambda/\kappa_t \).

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05/05/2020
Single-Higgs production

Theoretical framework described in:
- **JHEP 1612, 080 (2016)** G. Degrassi, P.P. Giardino, F. Maltoni, D. Pagani

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 Higgs-boson self-energy diagram;
- a process-dependent part, **linearly proportional to $\lambda_3$**.

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 branching fractions.

**Examples of process-dependent part:**
- corrections to $t\bar{t}H$
- corrections to $VH$

Universal part
corrections to $VV$

$|\kappa_\lambda| \lesssim 20$

Florence, Italy 05/05/2020

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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 Higgs-boson self-energy diagram;
- a process-dependent part, **linearly proportional to** $\lambda_3$.
Latest ATLAS experimental results

Double-Higgs production


$-5.0 < \kappa_\lambda < 12.0$ (obs) at 95% CL  
$-5.8 < \kappa_\lambda < 12.0$ (exp) at 95% CL

Single-Higgs production

ATLAS Preliminary  
$\sqrt{s} = 13$ TeV, $36.1 - 79.8$ fb$^{-1}$  
$m_H = 125.09$ GeV

$-3.2 < \kappa_\lambda < 11.9$ (obs) at 95% CL  
$-6.2 < \kappa_\lambda < 14.4$ (exp) at 95% CL

Table 2: Allowed $\lambda$ intervals at 95% CL for the $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}$ final states and their combination. The column “Obs.” lists the observed results, “Exp.” the expected results obtained including all statistical and systematic uncertainties in the fit, and “Exp. stat.” the expected results obtained including only the statistical uncertainties.
Single-Higgs inputs containing production and decay modes exploit:

- a luminosity of up to 80 fb\(^{-1}\);
- inclusive cross sections, branching fractions, and also differential information for VBF and VH production modes (using STXS truth bin definitions);

- the \( t\bar{t}H \rightarrow \gamma \gamma \) categories included in \( H \rightarrow \gamma \gamma \) analysis have been removed from the combination because they largely overlap with events selected by \( HH \rightarrow b\bar{b} \gamma \gamma \).

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated luminosity (fb(^{-1}))</th>
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<tbody>
<tr>
<td>( H \rightarrow \gamma \gamma )</td>
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<tr>
<td>( VH, H \rightarrow bb )</td>
<td>79.8</td>
</tr>
<tr>
<td>( t\bar{t}H, H \rightarrow bb ) &amp; ( t\bar{t}H ) multilepton</td>
<td>36.1</td>
</tr>
<tr>
<td>( HH \rightarrow b\bar{b}bb )</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>
Double-Higgs inputs exploit:

- a luminosity of up to 36.1 fb\(^{-1}\);
- the three most sensitive double-Higgs channels, used to produce latest double-Higgs results.
- variations of the inclusive cross section and branching fractions, and variations in the kinematic distributions.

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<td>(HH \rightarrow b\bar{b}\gamma\gamma)</td>
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</tr>
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</table>

**ATLAS-CONF-2019-049**

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**Phys. Lett. B 800 (2020) 135103**

\(HH \rightarrow b\bar{b}\tau^+\tau^-\) Relative large BR, cleaner final state

\(HH \rightarrow b\bar{b}\gamma\gamma\) small BR, clean signal extraction

\(HH \rightarrow b\bar{b}\bar{b}\bar{b}\) Highest BR, large multi-jet background
The global likelihood shape depends on combining the contributions from the different production and decay modes.

The decomposition of each production and decay contribution is based on the Asimov dataset.

The dominant contributions to the $\kappa_\lambda$ sensitivity derive from the $HH$ channels, from the diboson decay channels $\gamma\gamma$, $ZZ^*$, $WW^*$ and from the $ggF$ and $ttH$ production modes.
A likelihood fit is performed to constrain the value of $\kappa_\lambda$ in the theoretical allowed range $-20 < \kappa_\lambda < 20$; 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 double-Higgs boson production measurements are more sensitive than the single-Higgs boson measurement for $\kappa_\lambda \gg 1$ and show similar sensitivity for negative $\kappa_\lambda$.

The combination significantly improves the constraining power on $\kappa_\lambda$.

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H+HH combination: results of fit to $\kappa_{\lambda}$ and $\kappa_{t}$

- 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.
- Double–Higgs analyses alone cannot constrain $\kappa_{\lambda}$ and $\kappa_{t}$ simultaneously.
- The combination with single-Higgs measurements allows the determination of $\kappa_{t}$ to a sufficient precision to restore most of the ability of the double-Higgs analyses to constrain $\kappa_{\lambda}$.
The constraining power of the single Higgs-boson production measurement allows to perform a fit in a more generic model, fitting simultaneously $\kappa_{\lambda}$, $\kappa_{W}$, $\kappa_{Z}$, $\kappa_{lepton}$, $\kappa_{b}$, $\kappa_{t}$.

The combination of single- and double-Higgs analyses allows to put sizeable constraints even in this 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>$\kappa_{t}$-1$\sigma$</th>
<th>$\kappa_{b}$-1$\sigma$</th>
<th>$\kappa_{t}$ [95% CL]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{t}$-only</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>[−2.3, 10.3] obs.</td>
</tr>
<tr>
<td>Generic</td>
<td>1.03+0.08−0.08</td>
<td>1.10+0.09−0.09</td>
<td>1.00+0.12−0.11</td>
<td>1.03+0.20−0.18</td>
<td>1.06+0.16−0.15</td>
<td>5.5+3.5−5.2</td>
<td>[−3.7, 11.5] obs.</td>
</tr>
<tr>
<td></td>
<td>1.00+0.08−0.08</td>
<td>1.00+0.08−0.08</td>
<td>1.00+0.12−0.12</td>
<td>1.00+0.21−0.19</td>
<td>1.00+0.16−0.15</td>
<td>1.0+7.6−4.5</td>
<td>[−6.2, 11.6] exp.</td>
</tr>
</tbody>
</table>

-2 ln $\Lambda$ vs $\kappa_{t}$ for $\sqrt{s} = 13$ TeV, 27.5 - 79.8 fb$^{-1}$

**ATLAS**

**Preliminary**

ATLAS-CONF-2019-049

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05/05/2020
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% CL 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.

• Further improvements are expected with the increasing luminosity, as well as with the implementation of the differential information in analyses like $t\bar{t}H$.

• The ATLAS experiment has set the most stringent constraints on $\kappa_\lambda$ from experimental data.
$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \phi_i \phi_j \phi_k + \text{a.c.} + m_\phi^2 - V(\phi)$
The maximal self-coupling deviation from its SM value in different BSM theories.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta g_{hhh}/g_{hhh}^{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>$-18%$</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>tens of $%$</td>
</tr>
<tr>
<td>Minimal Supersymmetry</td>
<td>$-2%^a - 15%^b$</td>
</tr>
<tr>
<td>NMSSM</td>
<td>$-25%$</td>
</tr>
</tbody>
</table>

- Mixed-in Singlet Model: a theory with an extra singlet where the singlet mixes with the SM Higgs through a renormalisable operator.
- Composite Higgs Model: composite Higgs models are speculative extensions of the Standard Model (SM) where the Higgs boson is a bound state of new strong interactions.
- Minimal Supersymmetry Model: the Minimal Supersymmetric Standard Model (MSSM) exhibits an extended Higgs sector with two Higgs boson doublets, $H_d$ and $H_u$, which couple to down- and up-type quarks, respectively.
- NMSSM Model: extension of the MSSM adding a mass term $\mu$ in a way similar to the generation of quark and lepton masses in the SM.
**Latest experimental results**


- $-5.0 < \kappa_\lambda < 12.0$ (obs) at 95% CL
- $-5.8 < \kappa_\lambda < 12.0$ (exp) at 95% CL


- $-11.8 < \kappa_\lambda < 18.8$ (obs) at 95% CL
- $-7.1 < \kappa_\lambda < 13.6$ (exp) at 95% CL

**ATLAS: ATL-PHYS-PUB-2019-009**

- $-3.2 < \kappa_\lambda < 11.9$ (obs) at 95% CL
- $-6.2 < \kappa_\lambda < 14.4$ (exp) at 95% CL

**CMS: CMS-PAS-HIG-19-005**

- $-3.5 < \kappa_\lambda < 14.5$ (obs) at 95% CL
- $-5.1 < \kappa_\lambda < 13.7$ (exp) at 95% CL
Double-Higgs production: latest results

- The dependences on \( \kappa_\lambda \) of the Higgs boson branching fractions and of the single-Higgs background have been neglected;
- all couplings except the Higgs-boson self-coupling have been set to their SM values;
- exclusion limits have been 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 \( \kappa_\lambda \).

\[ \kappa_\lambda = \frac{\lambda_{\text{HHH}}}{\lambda_{\text{SM}}} \]

ATLAS Internal

\( \sqrt{s} = 13 \text{ TeV} \)

27.5 - 36.1 fb\(^{-1} \)

- Obs.
- Exp. (Exp. stat.)
- -5.0 - 12.0
- -5.8 - 12.0
- (-5.3 - 11.5)

\[
\begin{align*}
\text{HH} & \to b\bar{b}r^+r^- \\
\text{HH} & \to b\bar{b}\gamma \gamma \\
\text{HH} & \to b\bar{b}W^+W^- \\
\text{HH} & \to W^+W^+W^-
\end{align*}
\]

Obs. | Exp. | Exp. stat.
--- | --- | ---
12.5 | 15 | 12
12.9 | 21 | 18
20.3 | 26 | 26
160 | 120 | 77
230 | 170 | 160
305 | 305 | 240

95% CL upper limit on \( \sigma_{ggF}(pp \to HH) \) normalised to \( \sigma_{ggF}^{\text{SM}} \)

- Observed
- Expected ± 1\( \sigma \)
- Expected ± 2\( \sigma \)

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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 $\kappa_i$:

$$\mu_i(\kappa_i, \kappa_f) = \frac{\sigma_{BSM}^{i}}{\sigma_{SM}^{i}} = Z_{H}^{BSM}(\kappa_i) \left[ \left( \frac{(\kappa_i - 1)C_i^f}{K_{EW}^f} \right) \right]$$

$$\mu_f(\kappa_i, \kappa_f) = \frac{\sigma_{BSM}^{i}}{\sigma_{SM}^{i}} \times \frac{BR_f(\kappa_f)}{BR_{SM,f}} = \frac{\sigma_i(\kappa_i)}{\sigma_{SM,i}} \times \frac{BR_f(\kappa_f)}{BR_{SM,f}}$$

- $\kappa_i$ and $\kappa_f$ represent multiplicative modifiers to other Higgs boson couplings for initial and final states, parameterised as in the LO $\kappa$-framework;
- $K_{EW}^f = \sigma_{NLO}^{SM,i} / \sigma_{LO}^{SM,i}$ accounts for the complete NLO EW correction of the production cross section for the process in the SM hypothesis (i.e. $\kappa_i=1$).

**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 $VBF \ H \to b \bar{b}$ has been excluded from the input (low impact + no STXS bins).

![Diagram of Single-Higgs production: data and input measurements]

**Analysis**

- $H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)  
  $p_T^{jj} [0, 200]$  
  Integrated luminosity (fb$^{-1}$): 79.8

- $H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)  
  $p_T^{Hj} [0, 25]$  
  $p_T^{Hj} [25, \infty]$  
  $\geq 2$-jet VBF cuts  
  $\geq 2$-jet VH cuts  
  $\geq 3$-jet  
  $\geq 3$-jet VH cuts  
  Rest  
  Integrated luminosity (fb$^{-1}$): 36.1

- $H \to \tau\tau$  
  Integrated luminosity (fb$^{-1}$): 36.1

- $VH, H \to b\bar{b}$  
  Integrated luminosity (fb$^{-1}$): 79.8

- $t\bar{t}H, H \to b\bar{b}$ and $t\bar{t}H$ multilepton  
  Integrated luminosity (fb$^{-1}$): 36.1

**Table 1**

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<tr>
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**Section 2: Data and input measurements**

The note describes a global fit of cross-sections ($\sigma$) and decay rates ($\Gamma$) varies according to the production mode and the decay channel. Moreover, these functions depend on the values of the trilinear Higgs self-coupling ($\lambda$).

**Table 2: Integrated luminosity of the dataset used for each analysis**

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**Section 3: Theory framework**

The note is organized as follows: Section 1 reviews the dataset and input measurements, Section 2 presents the results of the fit, and Section 3 summarizes briefly the theoretical framework.

**Section 4: References**

The results shown in this note are based on data collected by the ATLAS experiment to each truth-level region defined within the simplified template cross-section framework ($\sigma$). It can be used for differential estimations; the analysis is particularly important for the integrated luminosity ($\sigma$) ranging from 36.1 fb$^{-1}$ to 79.1 fb$^{-1}$.

**References**

[20] eleonora.rossi@cern.ch
Single-Higgs production: kinematic dependent coefficients

- The parameterisation of the variation of the production cross-section as a function of $\kappa_\lambda$ can be adapted to describe the cross-section in each single STXS region.
- This requires re-deriving the values of the kinematic dependent coefficients $C^i_1$ in each region defined in the measurement.

**Constructived from Figures in arXiv: 1610.07922**

<table>
<thead>
<tr>
<th>STXS region</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^i_1 \times 100$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF + $V$(had)$H$</td>
<td>0.63</td>
<td>0.91</td>
<td>1.07</td>
</tr>
<tr>
<td>VBF-cuts + $p_T^{3j} &lt; 200$ GeV, $\leq 2j$</td>
<td>0.61</td>
<td>0.85</td>
<td>1.04</td>
</tr>
<tr>
<td>VBF-cuts + $p_T^{3j} &lt; 200$ GeV, $\geq 3j$</td>
<td>0.64</td>
<td>0.89</td>
<td>1.10</td>
</tr>
<tr>
<td>VH-cuts + $p_T^{3j} &lt; 200$ GeV</td>
<td>0.65</td>
<td>1.13</td>
<td>1.28</td>
</tr>
<tr>
<td>no VBF/VH-cuts, $p_T^{3j} &lt; 200$ GeV</td>
<td>0.39</td>
<td>0.23</td>
<td>0.28</td>
</tr>
</tbody>
</table>

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<tr>
<td>$qq \rightarrow H\ell\nu$</td>
<td>$p_T^V &lt; 150$ GeV</td>
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<td>1.08</td>
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<td>$150 &lt; p_T^V &lt; 250$ GeV, $0j$</td>
<td>0.18</td>
<td>0.33</td>
<td>0</td>
</tr>
<tr>
<td>$150 &lt; p_T^V &lt; 250$ GeV, $\geq 1j$</td>
<td>1.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^V &gt; 250$ GeV</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
</tr>
</tbody>
</table>

$\kappa_\lambda = \frac{\text{Secondary Vertex} \cdot \text{Higgs Production}}{\text{Higgs Production}}$
Single-Higgs production: results of fit to $\kappa_{\lambda}$

- Exploiting NLO electroweak corrections to single-Higgs processes, it is possible to extract constraints on $\kappa_{\lambda}$ through a global likelihood fit in the range $|\kappa_{\lambda}| < 20$.

- 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; thus VBF, $WH$ and $ZH$ production modes have been 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 $\kappa_{\lambda}$.

Results exploiting differential information

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

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

$-6.2 < \kappa_{\lambda} < 14.4$ (exp) at 95% CL

ATLAS Preliminary

$\bar{s} = 13$ TeV, 36.1 - 79.8 fb$^{-1}$
$m_{t}\bar{t} = 125.09$ GeV

- Stat. only
In order to target BSM models where new physics could affect only the Yukawa type terms of the SM ($\kappa_V = 1$) or only the couplings to vector bosons ($\kappa_F = 1$), in addition to the Higgs-boson self-coupling $\kappa_\lambda$, a simultaneous fit is performed to $\kappa_\lambda$ and $\kappa_F$, and to $\kappa_\lambda$ and $\kappa_V$; the remaining coupling modifier is kept fixed to the SM prediction.

- The sensitivity is not much degraded when simultaneously fitting $\kappa_\lambda$ and $\kappa_F$ while it is degraded by 50% in the case $\kappa_\lambda$ and $\kappa_V$.
- An even less constrained fit, performed by fitting simultaneously $\kappa_\lambda$, $\kappa_F$ and $\kappa_V$ results in nearly no sensitivity to $\kappa_\lambda$.
HL-LHC projection

- HH analyses currently are very limited by statistics also in its systematic uncertainties (eg. bkg systematics), therefore at HL-LHC 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-LHC projection are not so much reduced.

- Differential information has a great impact on the measurement.

HL-LHC prospects, Yellow Report results

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