Light Yukawa couplings in HH production

LHC-HH Subgroup Meeting

Lina Alasfar
Humboldt-Universität zu Berlin

In collaboration with
Roberto Corral Lopez (Universidad de Granada)
and Ramona Gröber (Università di Padova)


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What can be known about the Higgs?

Known, $124.97 \pm 0.24$ GeV

ATLAS, 1806.00242

Higgs

- Spin
- Mass
- CP
- Width
What can be known about the Higgs?

Higgs

\( \Gamma / \Gamma^{SM} < 3.5 \), model-dependent

ATLAS 1808.001191
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Even CP is favoured, ATLAS 1506.05669
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What can be known about the Higgs?

Higgs couplings:
We define the scaling factor $a$ coupling $\kappa$ as $\kappa = \frac{g_h}{g_{h_{SM}}}$

- To electroweak bosons Known, $\kappa_{W/Z/\gamma} \sim 0.6 - 1.2$
- To 3rd family quarks Known, most recent CMS-TOP-17-004 $\kappa_t < 1.67$, @ 95% CL)
- To $\tau$ Known, CMS-HUG-16-043
- The coupling $g_{h\mu\mu}$ has a recent bound ATLAS-CONF-2019-028.
- To 1st and 2nd generation quarks.
- Self couplings
What can be known about the Higgs?

Higgs couplings:
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Current bounds are not very constraining
The current bounds on the light Yukawa couplings (2nd and 1st generation quarks), are (model-dependent, global fit):

$$|\kappa_d| < 1270, \quad |\kappa_u| < 1150;$$

$$|\kappa_s| < 53, \quad |\kappa_c| < 5.$$ 

Obtained by allowing the couplings to be scaled one at a time F. Yu,'16

The current bounds are very weak :(
New Higgs fermion coupling from linear SMEFT

We have the Lagrangian:

\[
\mathcal{L} \supset - \mathcal{Y}_u \bar{Q}_L \Phi u_R - \mathcal{Y}_d \bar{Q}_L \tilde{\Phi} d_R + h.c.
\]

\[
+ \frac{\Phi^+ \Phi}{\Lambda^2} \left( c_u \bar{Q}_L \Phi u_R + c_d \bar{Q}_L \tilde{\Phi} d_R + h.c \right)
\]

**SMEFT Yukawa**

\[
g_{hff} = g_{hff}^{SM} - \frac{\xi}{\sqrt{2}} c_f = \kappa_f g_{hff}^{SM}.
\]

**Linear \( hff \) coupling**

\[
g_{hff} = -3 g_{hff}^{SM} \frac{(1 - \kappa_f)}{v}
\]

We identify:

\[
g_{hff}^{SM} = \frac{m_f}{v}, \quad \xi = \frac{v^2}{\Lambda^2},
\]

and the scaling:

\[
\kappa_f = \left( 1 - \frac{c_f}{\sqrt{2}} \frac{\xi}{m_f} \frac{v}{m_f} \right).
\]
The channel $q\bar{q} \rightarrow hh$ (inclusive cross section)

$pp \rightarrow hh (q\bar{q}A) \sqrt{s} = 14$ TeV

$\kappa_c$
$\kappa_s/5$
$\kappa_u/100$
$\kappa_d/100$

$ggF$ (NNLO) + Crossed

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The channel $q\bar{q} \rightarrow hh$ (differential cross section)

$pp \rightarrow hh \sqrt{s} = 14$ TeV

The distribution shape is different for $qqA$!
The channel \( q\bar{q} \rightarrow hh \) (differential cross section)

\[ pp \rightarrow hh \quad \sqrt{s} = 14 \text{ TeV} \]

The distribution shape is different for \( qqA \)!
The channel $q\bar{q} \rightarrow hh$ (partial widths)

The branching ratios (BR) are changed significantly with $\kappa_f$ scaling. The BR’s were calculated via a modified version of HDECAY A. Djouadi et al. ‘98
Analysis strategy

The expected number of Higgs pairs that are produced at the LHC and decaying into $b\bar{b}(c\bar{c})\gamma\gamma$ with particular $b(c)$-tagging working point is given by

- $3\text{ pb}^{-1}$ (High Luminosity-LHC) end of run II.

$$\mathcal{N} = \int \mathcal{L} dt \cdot \sigma_{pp \to hh} \cdot 2\mathcal{B}_h \to \gamma\gamma \mathcal{B}_h \to b\bar{b} \varepsilon_{\text{Sel}}$$

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- $\varepsilon = \varepsilon_{\text{Acc}} \cdot \varepsilon_{\text{Rec}} \cdot \varepsilon_{\text{Meth}} \cdot \varepsilon_{\text{Trig}} \cdot \varepsilon_{\text{Strip}} \approx 0.052 - 0.045$
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- We get $N \approx 13(\text{SM}) - 50(1\text{st gen}) - 9(2\text{nd gen})$ events Run II of HL-LHC
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Use combination of $b$- and $c$- tagging to probe $hh \rightarrow c\bar{c}\gamma\gamma$, as we shall see later on.
Analysis strategy

We define the signal strength

\[ \mu = \frac{N_s}{N_{s}^{SM} + N_{b}^{SM}} \]

We use toy experiments to generate Asimov data, for the HL-LHC sensitivity estimation, we find that

\[ \hat{\mu} = 1.2 \pm 0.9 (\text{@} 95\% CL) \]

Here, we have assumed that the null hypothesis is the SM HH with SM background.

The backgrounds are taken from A. Azatov et al. '15.
Preforming a Liklihood fit on the 1nd generation scaling, we obtain the bounds

HL-LHC: \( \sqrt{s} = 14 \text{ TeV}, \, L = 3 \text{ ab}^{-1} \)

- \( \kappa_u \in [-1771, 1750] \)
- \( \kappa_d \in [-853, 856] \)

Profiling @ 95% CL
Results for non-linear EFT

We could consider scenarios where HH production is particularly sensitive to, mainly speaking the non-linear EFT emerging from the chiral Lagrangian (0 th mode)

\[-\mathcal{L} = \bar{q}_L \frac{m_q}{\nu} \left( \nu + c_q h + \frac{c_{qq}}{\nu} h^2 + \ldots \right) q_R + h.c.\]

Resulting in the couplings:

Yukawa coupling

\[g_{h\bar{q}_i q_i} = c_q g^{\text{SM}}_{h\bar{q}_i q_i},\]

hhq̅ coupling

\[g_{hh\bar{q}_i q_i} = c_{qq} g^{\text{SM}}_{h\bar{q}_i q_i} \nu^{-1}.\]

Here, the Yukawa couplings are independent / uncorrelated from the hhq̅ coupling.
We could consider scenarios where HH production is particularly sensitive to, mainly speaking the non-linear EFT emerging from the chiral Lagrangian (0 th mode)

\[ -\mathcal{L} = \bar{q}_L \frac{m_q}{v} \left( v + c_q h + \frac{c_{qq}}{v} h^2 + \ldots \right) q_R + h.c. \]

Resulting in the couplings:

**Yukawa coupling**

\[ g_{h\bar{q}_i q_i} = c_q g_{h\bar{q}_i q_i}^{SM} , \]

**hhq\bar{q}** coupling

\[ g_{hh\bar{q}_i q_i} = c_{qq} g_{h\bar{q}_i q_i}^{SM} v^{-1} . \]

Here, the Yukawa couplings are independent / uncorrelated from the **hhq\bar{q}** coupling.

**No other accessible processes are sensitive to** \( c_{qq} \) **other than HH !**
Results for non-linear EFT

$\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$, $pp \rightarrow hh \rightarrow bb\gamma\gamma$ ($q = u$)

$\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$, $pp \rightarrow hh \rightarrow bb\gamma\gamma$ ($q = d$)

$\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$, $pp \rightarrow hh \rightarrow bb\gamma\gamma$ ($q = c$)

$\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$, $pp \rightarrow hh \rightarrow bb\gamma\gamma$ ($q = s$)

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Applying the technique developed by D. Kim et al. & G. Perez et al. (’15 ’16), it is possible to probe the final state $hh \rightarrow \bar{c}c\gamma\gamma$ without full $c-$ tagging. The signal strength is given by

$$\hat{\mu} = \mu_b \epsilon_f + 0.05 \cdot (\epsilon_{c/b}^{b\text{-tag}})^2 \epsilon_f \cdot \mu_c,$$

The ratio of a flavour $f$-tagging efficiencies is defined as

$$\left( \epsilon_{c/b}^{f_1\text{-tag}} \right)^2 = \frac{\epsilon_{f_1 \rightarrow f_2,1} \epsilon_{f_1 \rightarrow f_2,2}}{\epsilon_{f_1} \epsilon_{f_1}}.$$

<table>
<thead>
<tr>
<th>$c$-tagging</th>
<th>$\epsilon_c$</th>
<th>$\epsilon_{c \rightarrow b}$</th>
<th>$\mu_c$(up) 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$-tag I</td>
<td>19%</td>
<td>13%</td>
<td>10.1</td>
</tr>
<tr>
<td>$c$-tag II</td>
<td>30%</td>
<td>20%</td>
<td>8.2</td>
</tr>
<tr>
<td>$c$-tag III</td>
<td>50%</td>
<td>20%</td>
<td>3.8</td>
</tr>
</tbody>
</table>

HL-LHC: $\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$, $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$
Results from $hh \rightarrow \bar{c}c\gamma\gamma$

HL-LHC: $\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$

Profiling @ 95% CL

- $\kappa_c \in [-9.2, 9.0]$
- $\kappa_s \in [-117, 120]$

HL-LHC: $\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$

Profiling @ 95% CL

- $\kappa_c \in [-8.0, 8.2]$
- $\kappa_s \in [-102, 101]$

HL-LHC: $\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$

Profiling @ 95% CL

- $\kappa_c \in [-4.8, 4.6]$
- $\kappa_s \in [-102, 103]$
HH production offer promising sensitivity bounds on light-quark Yukawa couplings, comparable to other processes e.g. exotic Higgs decays $h \rightarrow M \gamma$ etc... G. T. Bodwin et al. '13.

Combining $c-$ and $b-$ tagging working points for the process $hh \rightarrow jj\gamma\gamma$ would offer a better probe for the 2nd gen. (mainly $c$) Yukawa couplings.

The HH production (also HH$j$) is the only accessible process at the LHC that could probe the coupling $g_{hh\bar{q}q}$, particularly the non-linearity between this coupling and Yukawa.

This work could be extended by analysis of final states $hh \rightarrow \bar{b}b\bar{b}b$, $hh \rightarrow \bar{b}b\bar{c}c$, $hh \rightarrow \bar{c}c\bar{c}c$, and so on.. applying $c-$ tagging working points.
Backup Slides
Gluon gluon fusion (ggF), is the dominant channel for the SM double Higgs production at the LHC.
The SM backgrounds

\[ \sqrt{s} = 14 \text{ TeV}, \ L = 3 \text{ ab}^{-1}, \ pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma \]

![Graph showing events distribution](image)

- \(b\bar{b}h + Zh\)
- \(\gamma\gamma jj\)
- \(t\bar{t}h\)
- \(\gamma\gamma b\bar{b}\)
- \(hh\ (SM-NNLO)\)

The $p_T$ distributions are not very sensitive to small changes in $\kappa_c$, unlike the $hj$. F. Bishara et al. '16
Next-to-leading order (NLO) QCD corrections to the s-channel $q\bar{q} \rightarrow hh$ have been calculated using the same corrections for $b\bar{b} \rightarrow h$ D. Dicus et al., C. Balazs et al., M. Spira and T. Plehn et al.
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\[
\sigma(q\bar{q} \rightarrow h) = \sigma_{LO} + \Delta\sigma_{q\bar{q}} + \Delta\sigma_{qg}
\]

\[
\Delta\sigma_{q\bar{q}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_H}^{1} d\tau \sum_q \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \sigma_0 \int_{\tau}^{1} dz \omega_{q\bar{q}}(z)
\]

\[
\Delta\sigma_{qg} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_H}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{bg}}{d\tau} \sigma_0 \int_{\tau}^{1} dz \omega_{qg}(z)
\]

with $z = \tau_H / \tau$, $\tau_H = \left(2 m_h \right)^2 / s$. 

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ROOT was used to carry out the analysis of generated events, along with FASTJET, the Mass-drop tagger M. Dasgupta et al. 13' for identifying b-jets was applied, and cuts as in A. Azatov et al. 15'.

- Select within LHC reconstruction requirements:

\[ p_T(\gamma/j) > 25 \text{ GeV}, \quad |\eta(\gamma/j)| < 2.5; \]

- Veto events with hard leptons:

\[ p_T(\ell) > 20 \text{ GeV}, \quad |\eta(\ell)| < 2.5; \]

- Select only hardest b-tagged jets, and photons

\[ p_T> (b/\gamma) > 50 \text{ GeV}, \quad p_T< (b/\gamma) > 30 \text{ GeV}; \]
• Ensure well-separated b jets and photons:

\[ \Delta R(b, b) < 2, \quad \Delta R(\gamma, \gamma) < 2, \quad \Delta R(b, \gamma) > 1.5 \]

Where \( \Delta R \) is the jet-radius, and it is given by:

\[ \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]

• Higgs mass window:

\[ 105 < m_{b\bar{b}} < 145 \text{ GeV}, \quad 123 < m_{\gamma\gamma} < 130 \text{ GeV} \]
Analysis of $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$

Mass drop tagger, $\Delta R(bb) < 2$

$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$

$pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ (SM)
References


