Di-Higgs production at HL/HE-LHC

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Workshop on the Physics of HL-LHC and Perspectives at HE-LHC
Motivation

Is the mechanism responsible for EWSB and fermion mass generation in the SM minimal?

What we know:

- One complex scalar doublet acquires a vev, breaks EW symmetry and gives W/Z and third generation fermions (most) of their masses

What we don’t know:

- Do the first and second generation fermions also get their masses from the same doublet?
- Is this Higgs vev the only source of EWSB?

HL(HE)-LHC are crucial steps towards answering these questions!
Perturbative unitarity: a lamppost

\[ g_{hVV} \equiv c_V g_{hVV}^{SM}, \quad g_{hhVV} \equiv c_{2V} g_{hhVV}^{SM} \]

VBS

\[ \propto \frac{\hat{s}}{v^2} \left( 1 - c_V^2 \right) \]

\[ \sqrt{\hat{s}} \gg m_W \]

di-Higgs

\[ \propto \frac{\hat{s}}{v^2} \left( c_{2V} - c_V^2 \right) \]

Deviations = new physics at some scale
Double Higgs production

GGF

VBF

\[ \sim c_3 \]

\[ \sim c^2_V \]

\[ \sim c_{2V} \]
HH production at pp colliders

- VBF cross-section at the LHC is small $\sim 2$ [fb] w/o $BR$s
- But, it is a unique probe of the EWSB mechanism

Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro: 1401.7340

![Graph showing HH production at pp colliders at NLO in QCD](image-url)
Is EWSB (non-)linearly realised?

\[ \mathcal{L} \supset \frac{1}{2} (\partial_\mu h)^2 - V(h) \]
\[ + \frac{v^2}{4} \text{Tr} (D_\mu \Sigma^\dagger D^\mu \Sigma) \left[ 1 + 2c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2} + \ldots \right] \]
\[ - m_i \bar{\psi}_{Li} \Sigma \left( 1 + c_\psi \frac{h}{v} + \ldots \right) \psi_{Ri} + \text{h.c.} , \]

\[ V(h) = \frac{1}{2} m_h^2 h^2 + c_3 \frac{1}{6} \left( \frac{3m_h^2}{v} \right) h^3 + c_4 \frac{1}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 + \ldots \]

- In the minimal SM, linear realization
  \[ \rightarrow c_V = c_{2V} = c_3 = 1 \text{ and all } \ldots \text{ terms vanish} \]
- Measuring \( c_{2V} \neq 1 \rightarrow \text{non-linearity!} \]
In minimal SO(5)/SO(4) models, the couplings $c_V$ and $c_{2V}$ are given by

$$c_V = \sqrt{1 - \xi}, \quad c_{2V} = 1 - 2\xi$$

where $\xi = v^2/f^2$

And, looking at the longitudinal vector boson scattering we see that

$$\mathcal{A}(V_LV_L \rightarrow hh) \simeq \frac{\hat{s}}{v^2} (c_{2V} - c_V^2)$$

Choose a benchmark with $c_{2V} = 0.8$ (to roughly correspond to $\xi = 0.1$ which is at the boundary of exclusion by ATLAS)

ATLAS: [1509.00672]
Sensitivity to $\delta_{c3}$ and $\delta_{c2V}$

- To illustrate, consider total $\sigma$ before and after cuts with $\frac{\sigma}{\sigma_{SM}} = 1 + a\delta + b\delta^2$

- Sensitivity to $\delta_{c2V}(\delta_{c3})$ is enhanced (suppressed) by the cuts

$\delta_i \equiv c_i - 1$

Dashed: before cuts
Solid: after cuts

(fb contino rojo [1611.03860])
## Kinematic cuts & b-tagging

### Final cuts:

<table>
<thead>
<tr>
<th>Cut</th>
<th>14 TeV</th>
<th>100 TeV</th>
<th>27 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>acceptance cuts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_{T_j}$ (GeV) ≥</td>
<td>25</td>
<td>40</td>
<td>?</td>
</tr>
<tr>
<td>$p_{T_b}$ (GeV) ≥</td>
<td>25</td>
<td>35</td>
<td>?</td>
</tr>
<tr>
<td>$</td>
<td>\eta_j</td>
<td>≤$</td>
<td>4.5</td>
</tr>
<tr>
<td>$</td>
<td>\eta_b</td>
<td>≤$</td>
<td>2.5</td>
</tr>
<tr>
<td>vbf cuts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta y_{jj}</td>
<td>≥$</td>
<td>5.0</td>
</tr>
<tr>
<td>$m_{jj}$ (GeV) ≥</td>
<td>700</td>
<td>1000</td>
<td>?</td>
</tr>
<tr>
<td>central jet veto</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_{T_{j3}}$ (GeV) ≤</td>
<td>45</td>
<td>65</td>
<td>?</td>
</tr>
<tr>
<td>$m_{hh}$ (GeV) ≥</td>
<td>500</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

### B-tagging parameters:

$$\varepsilon(b\text{-tag}) = 0.75, \quad \varepsilon(c\text{-mistag}) = 0.1, \quad \varepsilon(q, g\text{-mistag}) = 0.01$$
• At 14 TeV, $|\eta_j^{\text{max}}| < 4.5$ retains 95% of the cross-section
• At 27 TeV, $|\eta_j^{\text{max}}| < 4.5$ retains 80% of the cross-section
- Key feature: $m_{hh}$ tail is harder when $c_V^2 \neq c_{2V}$

- Signal events will have boosted Higgs pairs → handle to reduce background
Higgs reconstruction

- 4 small-\( R \) b-tagged jets
- Consider hardest 6
- \( h_1 \leftrightarrow \) b-jet pair with \( \min\{|m_{bb} - 125|\} \)
- \( h_2 \leftrightarrow \) b-jet pair with \( \min\{|m_{bb} - m_{h_1}|\} \)
- 2 large-\( R \) jet \( \supset \) 2 b-quarks each
- \( h_1 \leftrightarrow \) large-\( R \) jet with \( \min\{|m_j - 125|\} \)
- \( h_2 \leftrightarrow \) large-\( R \) with \( \min\{|m_{j_2} - m_{j_1}|\} \)
The $hh$ invariant mass distribution

14 TeV

- SM
- $c_{2V} = 0.8$
- Bkgd fit

100 TeV

- SM
- $c_{2V} = 0.8$
- Bkgd fit

$\sigma/dm_{hh}$ [fb/bin]

$m_{hh}$ [TeV]
Results: probability intervals on $\delta_{c_{2V}}$

FB, Contino, Rojo [1611.03860] \(\delta_{c_{2V}} \equiv c_{2V} - 1\)

Results for HE-LHC (27 TeV) will be available shortly

<table>
<thead>
<tr>
<th></th>
<th>68% probability interval on $\delta_{c_{2V}}$</th>
<th>95% probability upper limit on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1 \times \sigma_{\text{bkg}}$ $3 \times \sigma_{\text{bkg}}$</td>
<td>$1 \times \sigma_{\text{bkg}}$ $3 \times \sigma_{\text{bkg}}$</td>
</tr>
<tr>
<td>LHC$_{14}$</td>
<td>$[-0.37, 0.45]$ $[-0.43, 0.48]$</td>
<td>LHC$_{14}$ 109  210</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>$[-0.15, 0.19]$ $[-0.18, 0.20]$</td>
<td>HL-LHC 49  108</td>
</tr>
<tr>
<td>FCC$_{100}$</td>
<td>$[0, 0.01]$ $[-0.01, 0.01]$</td>
<td>FCC$_{100}$ 12  23</td>
</tr>
</tbody>
</table>

Results for HE-LHC (27 TeV) will be available shortly
Validity of the EFT description

- If NP is characterized by coupling $g_*$ and scale $\Lambda$
- One expects $\delta_{c2V} \approx g^2_* v^2 / \Lambda^2$
- Saturating the strong coupling limit then gives $\delta_{c2V} \approx 16\pi^2 v^2 / \Lambda^2$

This procedure was outlined in [Contino, Falkowski, Goertz, Grojean, Riva: 1604.06444]

FB, Contino, Rojo [1611.03860]
Summary

- Double Higgs production in VBF will constrain deviations, if present, in $hhVV$ couplings

- Boosted kinematics gives a crucial handle to tame backgrounds

- 20% precision achievable at the HL-LHC and projections for HE-LHC will be available shortly

This is a crucial probe of the EWSB sector of the SM
Thank you!
Taming the background

Only includes events where rapidity of 3\textsuperscript{rd} jet falls between VBF jets
Scale invariant tagging

![Scale invariant tagging](image-url)
Populating the tail in our analysis

- Sensitivity is driven by the tail. Therefore, good modelling is imperative.
  - Solution: generate weighted events and fit the background.
  - For signal, can also put a generation cut on $m_{hh}$ but this does not work for background.

\[ d\sigma/db_j/\left(\sum_i d\sigma/db_i\right) \sim 10^{-6} \]
\[ \Rightarrow \text{need 1M events to get 1 event in this bin.} \]
\[ \Rightarrow \text{Accounting for efficiency of all cuts and requiring 100 events here means need to generate } 10^{12} \text{ events!} \]