HH production from VBS: an efficient test of the Higgs self-coupling at the LHC

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Based on [arXiv:1807.09736]
E. Arganda, C. Garcia-Garcia, M.J. Herrero
Introduction/Motivation

Aim

- Measure the Higgs self-coupling $\lambda$
- Check SM relation between $\lambda$ and $m_H$
- Test BSM alternatives of $\lambda$

Current status and sensitivity to $\lambda$ at the LHC

- Studies focus on gluon gluon fusion (dominant) $HH$ production
  

- Different ggF channels considered (th. and exp.): $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\bar{\tau}$...

- Current sensitivity: exp. global analysis constrains $\lambda \in [-5.0, 12.1]$ $\lambda_{SM}$ at 95% C.L.

  [ATLAS-CONF-2018-043]

Future prospects at linear colliders

- $e^+e^-$ linear colliders (ILC, CLIC) will allow for most precise $\lambda_{SM}$ measurements


- Still far (and/or unknown) in the future!!
Our proposal: VBS to test $\lambda$ BSM at the LHC

**ggF: $gg \rightarrow HH$**

$\sigma_{ggF}(14\,\text{TeV}, \kappa = \lambda/\lambda_{SM} = 1) \sim 32\,\text{fb}$
- 1-loop + top physics involved
- Largest cross section near $t\bar{t}$ threshold
- Sizable NLO corrections: big uncertainties
- Less specific kinematics

**VBS: $q_1q_2 \rightarrow HHq_3q_4$**

$\sigma_{VBS}(14\,\text{TeV}, \kappa = \lambda/\lambda_{SM} = 1) \sim 2\,\text{fb}$
- Tree level + no top physics involved
- Largest cross section near $HH$ threshold
- Small NLO corrections, more accurate
- Very characteristic kinematics

VBS smaller cross section than ggF , but with interesting features

$\sigma_{ggF}$ and $\sigma_{VBS}$ are compared in the plots.

More on comparing VBS and ggF

**ggF**: $gg \rightarrow HH$

\[ \sigma_{ggF}(14 \text{ TeV}, \kappa = \lambda/\lambda_{SM} = 1) \sim 32 \text{ fb} \]

\[
\begin{align*}
\text{here is } \lambda & \quad \text{only trilinear}
\end{align*}
\]

BUT: ggF and VBS different final state

**ggF**: $gg \rightarrow HHjj$

\[ \sigma_{ggF}^{HHjj}(14 \text{ TeV}, \kappa = \lambda/\lambda_{SM} = 1) \sim 5.5 \text{ fb} \]

- Contributes to our signal: **same final state** and it is also sensitive to $\lambda$
- But: our VBS selection cuts reduce cross section below pure VBS one
  - For instance for $M_{jj}>500 \text{ GeV} \rightarrow ggF<1/20 \text{ VBS}$
- Not taken into account in the present work

**VBS**: $q_1q_2 \rightarrow HHq_3q_4$

\[ \sigma_{VBS}(14 \text{ TeV}, \kappa = \lambda/\lambda_{SM} = 1) \sim 2 \text{ fb} \]

\[
\begin{align*}
\text{here is } \lambda & \quad + \text{ others non-VBS}
\end{align*}
\]

\[
\begin{align*}
W_L^+W_L^- & \rightarrow HH & \text{probes } \Phi^4 & \text{at high energy}
\end{align*}
\]

Defining our signal at the LHC: \( pp \rightarrow HHjj \)

**Signal:** prediction of \( q_1q_2 \rightarrow HHq_3q_4 \) for given \( \lambda \neq \lambda_{\text{SM}} \)

We consider \( \lambda \in [-10, 10] \lambda_{\text{SM}} \)

All our LHC estimates are computed using MadGraph5

Extra jets identify VBS configurations among all contributing diagrams

Two opposite-side forward/backward jets with large pseudorapidity gap required

\[ |\Delta \eta_{jj}| \equiv |\eta_{j_1} - \eta_{j_2}| \]

and with large invariant masses \( M_{jj} \)

Defining VBS selection cuts

Our benchmark is (for others see arXiv:1807.09736):

\[ |\Delta \eta_{jj}| > 4 \]

\[ M_{jj} > 500 \text{ GeV} \]

Basic detection cuts: \( p_{T_j} > 20 \text{ GeV}, \quad |\eta_j| < 5, \quad \Delta R_{jj} > 0.4, \quad |\eta_H| < 2.5 \)
Characterization of VBS: $\Delta\eta_{jj}$ and $M_{jj}$

How VBS-dominated is our signal?

VERY MUCH (for all $\lambda$) !!!

- Checked: 55-75% of $q_1 q_2 \rightarrow HHq_3 q_4$ events occur through VBS
Our signal after Higgs decays

- HH production observed through Higgs decay products
- Two decays considered: \( H \rightarrow b\bar{b} \) and \( H \rightarrow \gamma\gamma \)

\[
\begin{align*}
pp & \rightarrow HHjj \rightarrow b\bar{b}b\bar{b}jj \ (q_1q_2 \rightarrow b\bar{b}b\bar{b}q_3q_4) \\
& \quad \text{Highest rates due to large BR}(H \rightarrow b\bar{b}) \sim 60 \%
\end{align*}
\]

\[
\begin{align*}
pp & \rightarrow HHjj \rightarrow b\bar{b}\gamma\gamma jj \ (q_1q_2 \rightarrow b\bar{b}\gamma\gamma q_3q_4) \\
& \quad \text{Much cleaner channel. Small and controllable backgrounds}
\end{align*}
\]

\[
\begin{align*}
pp & \rightarrow HHjj \rightarrow b\bar{b}\gamma\gamma jj \ (q_1q_2 \rightarrow b\bar{b}\gamma\gamma q_3q_4) \\
& \quad \text{Lower statistics due to small BR}(H \rightarrow \gamma\gamma) \sim 0.2 \%
\end{align*}
\]
**pp → bbbbjj backgrounds**

### multijet QCD $pp \to bbbbjj$
- **Dominant** background by many orders of magnitude
- **Additional** selection cuts apart from VBS required

### $tt \to bW^+bW^- \to bbbbjj$
- CKM suppressed
- Radically **different kinematics** respect to VBS
- Under control (negligible after VBS cuts)

### $pp \to ZZjj \to bbbbjj$ & $pp \to ZHjj \to bbbbjj$
- Take place in part through VBS configurations
- **Additional** selection cuts apart from VBS required

*Estimated with MG5 Checked with AlpGen*
Signal versus QCD-bkg in $b\bar{b}b\bar{b}jj$ : VBS

Signal & QCD bkg populate different kinematical regions

**Multijet QCD characterized by**

Most of signal events in VBS kin. region

VBS cuts tried. Our benchmark choice is: $|\Delta\eta_{jj}| > 4, M_{jj} > 500$ GeV
Signal versus QCD-bkg in $b\bar{b}b\bar{b}jj$ : HH

Signal & QCD bkg populate different ($M_{bb1}, M_{bb2}$) regions

- b-quarks paired as HH candidates: pairing minimizing $|M_{bb1} - M_{bb2}|$

Multijet QCD background events lie mainly at low $[M_{bb1}, M_{bb2}]$

Signal events lie near $[M_{bb1}, M_{bb2}] \sim [M_H, M_H]$
HH candidate cuts in $b\bar{b}b\bar{b}jj$

b-quark pairs identified as HH decays

HH candidate cuts:

We follow recent cuts proposed by ATLAS [arXiv: 1804.06174] and CMS [CMS-PAS-HIG-16-026]

\[ p_{T_b} > 35 \text{ GeV} \]

\[ 0.2 < \Delta R_{bb^l} < \frac{653}{M_{4b} \text{ GeV}} + 0.475 ; \ 0.2 < \Delta R_{bb^s} < \frac{875}{M_{4b} \text{ GeV}} + 0.35 , M_{4b} < 1250 \text{ GeV} \]

Small angular separation between Higgs decay products

\[ \hat{\Delta}R_{bb} \equiv \begin{cases} 
0.2 < \Delta R_{bb^l} < 1 ; \ 0.2 < \Delta R_{bb^s} < 1 , M_{4b} > 1250 \text{ GeV} 
\end{cases} \]

\[ \hat{p}_{T_{bb}} \equiv p_{T_{bb^l}} > M_{4b}/2 - 103 \text{ GeV} ; \ p_{T_{bb^s}} > M_{4b}/3 - 73 \text{ GeV} \]

\[ \chi_{HH} \equiv \sqrt{\left( \frac{M_{bb^l} - m_H}{0.05 m_H} \right)^2 + \left( \frac{M_{bb^s} - m_H}{0.05 m_H} \right)^2} < 1 \]
Efficiency of the selection cuts in $b\bar{b}b\bar{b}jj$

In addition to the basic detection cuts:

$p_{T_{j,b}} > 20$ GeV; $|\eta_j| < 5$; $|\eta_b| < 2.5$; $\Delta R_{jj,jb} > 0.4$; $\Delta R_{bb} > 0.2$

Combined HH candidate and VBS cuts

<table>
<thead>
<tr>
<th>Cut</th>
<th>$\sigma_{QCD}$ [pb]</th>
<th>$\sigma_{ZHjj,ZZjj}$ [pb]</th>
<th>$\sigma_{\text{Signal};\kappa=1}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic detection cuts</td>
<td>602.72</td>
<td>0.028</td>
<td>5.1$\cdot$10$^{-4}$</td>
</tr>
<tr>
<td>$p_{T_b} &gt; 35$ GeV</td>
<td>98.31</td>
<td>0.01</td>
<td>3.0$\cdot$10$^{-4}$</td>
</tr>
<tr>
<td>$\hat{\Delta}R_{bb}$</td>
<td>33.80</td>
<td>6.3$\cdot$10$^{-3}$</td>
<td>1.1$\cdot$10$^{-4}$</td>
</tr>
<tr>
<td>$\hat{p}<em>{T</em>{bb}}$</td>
<td>29.77</td>
<td>5.8$\cdot$10$^{-3}$</td>
<td>9.0$\cdot$10$^{-5}$</td>
</tr>
<tr>
<td>$\chi_{HH} &lt; 1$, VBS cuts in</td>
<td>7.9$\cdot$10$^{-2}$</td>
<td>8.6$\cdot$10$^{-6}$</td>
<td>9.0$\cdot$10$^{-5}$</td>
</tr>
<tr>
<td></td>
<td>6.8$\cdot$10$^{-3}$</td>
<td>5.5$\cdot$10$^{-6}$</td>
<td>4.1$\cdot$10$^{-5}$</td>
</tr>
</tbody>
</table>

Cuts subsequently applied

- Signal mildly reduced; similar results for other $\kappa = \lambda/\lambda_{SM} \neq 1$
- Very reduced backgrounds!!!
**pp → b\bar{b}γγjj backgrounds and selection cuts**

**mixed QCDEW pp → b\bar{b}γγjj**
- Dominant background but easy to control
- Additional selection cuts apart from VBS required

**pp → ZHjj → b\bar{b}γγjj**
- Take place in part through VBS configurations
- Additional selection cuts apart from VBS required

**Selection cuts**

**VBS cuts + HH candidate**

\[
p_{T_j}/M_{γγ} > 1/3; \quad p_{T_γ}/M_{γγ} > 1/4; \quad \chi_{HH} = \sqrt{ \left( \frac{M_{bb} - m_H}{0.05 m_H} \right)^2 + \left( \frac{M_{γγ} - m_H}{0.05 m_H} \right)^2 } < 1
\]

**VERY REDUCED BACKGROUNDS!**

**Basic detection cuts:**
- \( p_{T,j,b} > 20 \text{ GeV} \)
- \( p_{T_γ} > 18 \text{ GeV} \)
- \( |η_j| < 5 \)
- \( |η_{b,γ}| < 2.5 \)
- \( ΔR_{jj,jb,γb,γj} > 0.4 \)
- \( ΔR_{bb} > 0.2, p_{T_γ} \)
Results for $pp \to b\bar{b}b\bar{b}jj : M4b$ distributions

Signal = $q_1q_2 \to HHq_3q_4 \to b\bar{b}b\bar{b}q_3q_4$ (sensitive to $\lambda$)
SM Background = multijet QCD + $ZHjj + ZZjj$ leading to $b\bar{b}b\bar{b}jj$

- Clear deviations for $\lambda \neq \lambda_{SM}$ respect the SM bkg and the $\lambda_{SM}$ prediction
- Largest sensitivity near HH production threshold. More sensitivity to negative $\lambda$

Some predictions ($\lambda = -10 \, \lambda_{SM}$) even above backgrounds!
Results for $pp \rightarrow b\bar{b}\gamma\gamma jj : M2b2\gamma$ distributions

- Similar results as in $pp \rightarrow b\bar{b}b\bar{b}jj$ varying $\lambda$ but with smaller rates
- Again clear deviations respect to the background and the $\lambda_{SM}$ prediction

- Very reduced and steeper backgrounds
- All tested values of $\lambda$ above background!
Results: Sensitivity to $\lambda$ in $b\bar{b}b\bar{b}jj$ and $b\bar{b}\gamma\gamma jj$

**Statistical significance**: $S_{\text{stat}}$
for different $\lambda$ values and different luminosities

**$b\bar{b}b\bar{b}jj$:**
High sensitivity, even for the lowest luminosity. High signal rates $N_S$!!!

**$b\bar{b}\gamma\gamma jj$:**
Modest sensitivity, lower signal rates $N_S$, but cleaner

\[ S_{\text{stat}} = -\frac{N_S}{\sqrt{N_B}} - 2 \left( (N_S + N_B) \log \left( \frac{N_B}{N_S + N_B} \right) + N_S \right) \]
Which $\lambda$ intervals can we probe through VBS?

- **$b\bar{b}b\bar{b}jj$**: very promising and competitive !!!

<table>
<thead>
<tr>
<th>$L$ [fb$^{-1}$]</th>
<th>50</th>
<th>300</th>
<th>1000</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa &gt; 0$</td>
<td>$\kappa &gt; 5.4$ (7.0)</td>
<td>$\kappa &gt; 4.3$ (4.8)</td>
<td>$\kappa &gt; 3.7$ (4.2)</td>
<td>$\kappa &gt; 3.2$ (3.7)</td>
</tr>
<tr>
<td>$\kappa &lt; 0$</td>
<td>$\kappa &lt; -2.4$ (-3.8)</td>
<td>$\kappa &lt; -1.0$ (-1.7)</td>
<td>$\kappa &lt; -0.3$ (-0.8)</td>
<td>$\kappa &lt; 0$ (-0.2)</td>
</tr>
</tbody>
</table>

Very broad intervals probed even for low luminosities!

**HL-LHC**: able to test small deviations and be sensitive to all $\lambda < 0$ values

- **$b\bar{b}\gamma\gamma jj$**: more modest, need HL

<table>
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<tr>
<th>$L$ [fb$^{-1}$]</th>
<th>50</th>
<th>300</th>
<th>1000</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa &gt; 0$</td>
<td>$\kappa &gt; 9.9$ (14.2)</td>
<td>$\kappa &gt; 6.4$ (8.4)</td>
<td>$\kappa &gt; 4.6$ (6.0)</td>
<td>$\kappa &gt; 3.8$ (4.7)</td>
</tr>
<tr>
<td>$\kappa &lt; 0$</td>
<td>$\kappa &lt; -6.7$ (-10.0)</td>
<td>$\kappa &lt; -2.7$ (-4.6)</td>
<td>$\kappa &lt; -1.1$ (-2.3)</td>
<td>$\kappa &lt; -0.2$ (-1.0)</td>
</tr>
</tbody>
</table>

*WARNING!*: Naive results. Hadronization and detector effects not taken into account
Conclusions

VBS is an efficient channel to test large BSM \( \lambda \) at the LHC !!!

- We find competitive sensitivities in VBS to \( \lambda \):
  - in two decay channels after VBS and HH candidate selection

  - \( pp \to \bar{b}bbjj \): large rates but large backgrounds

    High and promising sensitivities already for \( L = 50 \text{ fb}^{-1} \)

    HL-LHC could probe small deviations:

    \[ \lambda = (3 - 5)\lambda_{SM} \]

    Better if \( \lambda < 0 \)

  - \( pp \to bb\gamma\gamma jj \): small rates but very controlled backgrounds

    Modest but interesting sensitivities. Need to go to \( L \geq 300 \text{ fb}^{-1} \)

- Promising results !!! BUT PARTON LEVEL YET
  Deserve further study including hadronization and detector effects!!!

Starting a project in collaboration with exp. group to perform a realistic study including these effects
Back up slides
Definition of unitarity violation: absolute value of $J^{th}$ (angular momentum) partial wave of $VV \to HH$ becomes 1

$$|a_J| = \left| \frac{1}{64\pi} \int_{-1}^{1} d\cos \theta A(VV \to HH) P_J(\cos \theta) \right| > 1$$

We have checked that all our partial waves for $\lambda \in [-10,10] \lambda_{SM}$ are below 0.1

No unitarity violation in this channel

Other channels such as HH HH might violate unitarity for $\kappa \sim 7$ values at low energies

“Pollution” from ggF HHjj production?

- Initial cross section twice as big as pure VBS


- They also impose cuts on low $M_{HH}$ masses near threshold where most of VBS signal lies

- Checked: VBS cut on $M_{jj} > 500$ GeV leads to a strong reduction ggF < 1/20 VBS
Comment on tagging efficiencies effects

- Results modified taking into account b and γ tagging efficiencies

**Current values:**

<table>
<thead>
<tr>
<th></th>
<th>b-tagging eff. ~ 70%</th>
<th>γ-tagging eff. ~ 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of events reduction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bbbbjj</td>
<td>N_{eff}/N ~ 0.25</td>
<td>S_{eff}/S ~ 0.5</td>
</tr>
<tr>
<td>bbγγjj</td>
<td>N_{eff}/N ~ 0.5</td>
<td>S_{eff}/S ~ 0.7</td>
</tr>
</tbody>
</table>

- Examples of accessible values of λ for L = 1000 fb^{-1} without and with efficiencies

<table>
<thead>
<tr>
<th></th>
<th>κ &gt; 0</th>
<th>κ &gt; 0 (eff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbbjj</td>
<td>κ &gt; 3.7 (4.2)</td>
<td>κ &gt; 4.3(4.9)</td>
</tr>
<tr>
<td>bbγγjj</td>
<td>κ &gt; 4.6 (6.0)</td>
<td>κ &gt; 6.0 (8.0)</td>
</tr>
</tbody>
</table>

- These efficiencies might improve! Easy way to apply the new ones!
Features of sensitivity to $\lambda$ at different $\sqrt{s}$

Interplay between diagrams

- $\lambda > 0$: negative interference
- $\lambda < 0$: positive interference

Sensitivity to $\lambda > 0$ and to $\lambda < 0$ different!

Better sensitivity for $\lambda < 0$ for same $|\lambda|$.

Cancellations and analytical sensitivity to $\lambda$ depend on energy and $\lambda$ value.

Highest sensitivity outside the interval around minimum

Largest cross section and sensitivity near the HH threshold.
Study of VBS cuts in $pp \to b\bar{b}b\bar{b}jj$

- We analyze the fraction of events that satisfy different sets of VBS cuts
- Signal dominated by VBS topologies
- QCD background reduced in 1-1.5 orders of magnitude

<table>
<thead>
<tr>
<th>Set of VBS cuts</th>
<th>$A_{\text{QCD}}^{\text{VBS}}$</th>
<th>$A_{\text{Signal; } \kappa=1}^{\text{VBS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta \eta_{jj}</td>
<td>&gt; 4, M_{jj} &gt; 500 \text{ GeV}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta_{jj}</td>
<td>&gt; 4, M_{jj} &gt; 600 \text{ GeV}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta_{jj}</td>
<td>&gt; 4, M_{jj} &gt; 700 \text{ GeV}$</td>
</tr>
<tr>
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<td>&gt; 3, M_{jj} &gt; 500 \text{ GeV}$</td>
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<td>$</td>
<td>\Delta \eta_{jj}</td>
<td>&gt; 3, M_{jj} &gt; 700 \text{ GeV}$</td>
</tr>
</tbody>
</table>

- Different sets give similar results

We stick to:

- $|\Delta \eta_{jj}| > 4$
- $M_{jj} > 500 \text{ GeV}$

**Basic detection cuts:** $p_{T_{jj}} > 20 \text{ GeV}$; $|\eta_{j}| < 5$; $|\eta_{b}| < 2.5$; $\Delta R_{jj, jb} > 0.4$; $\Delta R_{bb} > 0.2$
Sensitivity to $\lambda$ in HHjj: MHH distributions

- $pp \to HHjj$ VBS-dominated
  - Direct translation form subprocess results

- **Visible deviations** respect to the SM!!!

- Different sensitivity to $\lambda > 0$ and to $\lambda < 0$ remains positive interference for $\lambda < 0$, negative for $\lambda > 0$

- Largest sensitivity still near HH production threshold
BSM distortions varying $\kappa = \lambda / \lambda_{SM}$

- We study $\lambda \in [-10, 10] \lambda_{SM}$

- Energy and angular behaviour change when varying $\lambda$

- $\lambda \neq \lambda_{SM}$ leads to sizable (exp. observable) deviations from the SM

- Largest deviations near HH production threshold
Sensitivity to $\lambda$ in $pp \rightarrow b\bar{b}b\bar{b}jj$

High sensitivity to BSM $\lambda$
even for the lowest luminosities!!!

**Statistical significance** for different $\lambda$ values and different luminosities

**Luminosity required** to observe a $\lambda$ value at 3$\sigma$ and 5$\sigma$

\[ S_{\text{stat}} = -2 \left( (N_S + N_B) \log \left( \frac{N_B}{N_S + N_B} \right) + N_S \right) \]
Sensitivity in $pp \to b\bar{b}\gamma\gamma jj$

Modest but interesting channel to probe the H self-coupling

Statistical significance for different $\lambda$ values and different luminosities

Luminosity required to observe a $\lambda$ value at $3\sigma$ and $5\sigma$

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Learning from SM subprocess VV→HH

Diagrams that contribute:

- \( \lambda \) present only in s-channel
- Cross section dominated by \( V_L V_L \rightarrow HH \)
- \( \lambda \) contribution subleading in SM
- Main c+t+u cancellations lead to \( \sigma \) flatness at high \( \sqrt{s} \)
- Negative interference between \( \lambda \) diagram and the rest. More relevant near HH threshold

\( \lambda \neq \lambda_{SM} \) leads to sizable (exp. observable) deviations from the SM !!!

See next how to look for these deviations at the LHC