Vhh Production at the HL-LHC

Karl Nordström†, Andreas Papaefstathiou

IRN Terascale@Strasbourg May, 2018

Brief outline

- Obligatory di-Higgs motivation
- Quick discussion about cross section scaling with trilinear coupling modifications in different channels
- Analysis strategy
- Results + Discussion

Di-Higgs motivation

It is a truth universally acknowledged, that a single Higgs in possession of a good mass, must be in want of a measurement of the scalar potential.

– Jane Austen on Higgs pheno post-discovery

In the Standard Model the scalar sector is remarkably simple:

$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\lambda}{2}} m_h h^3 \qquad (1)$$

After measurements of v (weak boson masses, for example) and m_h everything is fixed. However small modifications to the scalar sector break these tree-level relationships. For conciseness let's call the h^3 coefficient λ_3.

Di-Higgs motivation

Consider a real singlet scalar extension with a vev of the type sometimes considered in the simplified dark matter model literature:

$$S = (x + s), \quad V(H, S) \supset \lambda_{HS}(H^\dagger H)S^2 \supset \frac{\lambda_{HS} x^2}{2} h^2 \qquad (2)$$

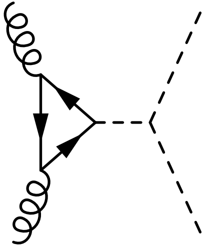
λ_3 is not affected, so the Standard Model relationship between m_h and λ_3 is broken.[1]

$\Rightarrow$ Since m_h is measured, a measurement of λ_3 can potentially offer a very clear window into extensions of the Standard Model which modify the scalar sector.

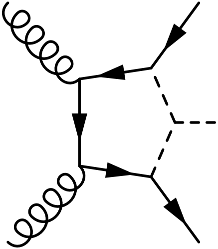
[1] Well, λ_{HS} also induces mass mixing between the CP-even scalars so the situation is a bit more complicated, but you get the idea...

Di-Higgs motivation

Two main production[2] avenues λ_3 can be measured through:



Direct di-Higgs production e.g. [Dolan, Englert, Spannowsky], [Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira]



Radiative corrections to single Higgs production [McCullough], [Degrassi, Giardino, Maltoni, Pagani]

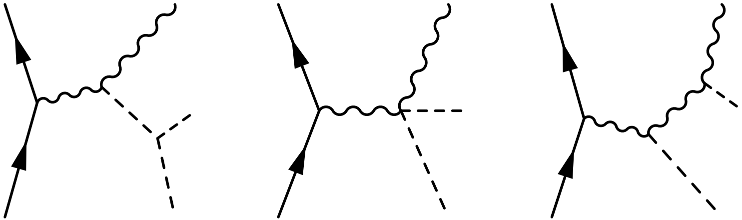
[2] Branching ratios to *WW* and *ZZ* are also quite sensitive, see [Degrassi, Giardino, Maltoni, Pagani].

Cross section scaling with λ_3

We can parameterise deviations from the Standard Model expectation of λ_3 using the κ framework, such that $\lambda_3 = \kappa \lambda_3^{\mathrm{SM}}$.

The interference between different diagrams in the leading production channels (gluon fusion, weak boson fusion) is such that $\kappa > 1$ reduces the cross section (until some value $\kappa \gg 1$ where the λ_3 contribution starts to dominate).

Cross section scaling with λ_3

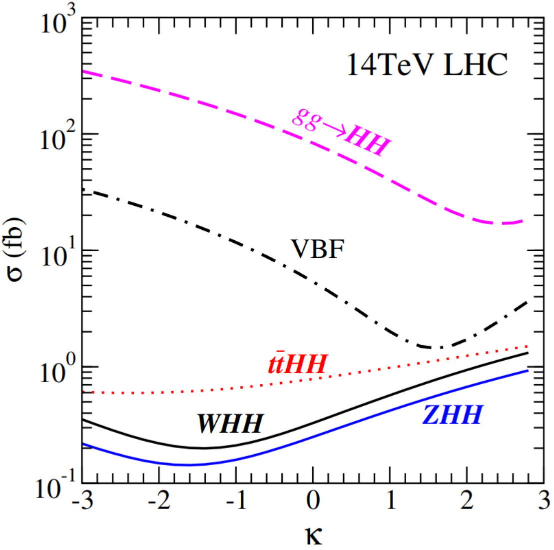


Amputating the quarks to focus on the $V^\mu \to V^\nu hh$ component close to threshold, we have (setting $m_h = m_V$ for simplicity):

$$M^{\mu\nu} = \frac{2g^{\mu\nu} m_h^2}{3v^2}(7 + 3\kappa) \tag{3}$$

$\Rightarrow$ Should expect maximal destructive interference for $\kappa \approx -2$!

Cross section scaling with λ_3



Taken from [Cao, Liu, Yan].

Some literature context

Total signal cross section has been calculated at NNLO QCD in e.g. [Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira][3].

Fully differential NNLO QCD distributions recently presented for *Whh* in [Li, Wang] and for *Zhh* in [Li, Li, Wang].

First HL-LHC parton level pheno analysis with background estimates in [Cao, Liu, Yan] shows quite promising results, however there are a number of questions about its validity (they use very aggressive 'jet' smearing and *b*-tagging assumptions, for example).

[3] Leading order *pp* calculation first done by [Barger, Han, Phillips] in 1988 in SSC context!

Event generation and analysis

We use the MadGraph5_aMC@NLO framework to generate our signal and background samples, at NLO QCD for ≤ 5 legs and leading order for > 5 legs. These are decayed using MadSpin, showered using Herwig 7, and analysed using Rivet[4].

We reweight samples using higher order K-factors where available and significant ([Czakon, Fiedler, Mitov] for $t\bar{t}$, [Bredenstein, Denner, Dittmaier, Pozzorini] for $\bar{t}t\bar{b}b$).

We focus on the $hh \to \bar{b}b\bar{b}b$ final state so our background samples are:

$Z\bar{b}b\bar{b}b$, $W\bar{b}b\bar{b}b$, $Z\bar{b}b\bar{c}c$, $W\bar{b}b\bar{c}c$, $Z\bar{t}t$, $W\bar{t}t$, $ZZ\bar{b}b$, $\bar{t}th$, $\bar{t}t\bar{b}b$, $\bar{t}t\bar{c}c$, $\bar{t}t$

[4]While the results I present here do not consider detector effects, we also make use of the recently added fast detector sim capability to assess how sensitive the results are to a more realistic detector.

Event generation and analysis

We separate the analysis into three different channels based on the V decay:

- $Z \to \nu\nu$, 0 leptons and missing transverse momentum
- $W \to l\nu$, 1 lepton and missing transverse momentum
- $Z \to ll$, 2 same flavour opposite charge leptons

We will use minimised goodness-of-reconstruction variables, e.g. for four b-jets i, i', j, j':

$$\chi_{hh} = \min \sqrt{\left(\frac{m_{ij} - m_h}{\sigma_{m_h}}\right)^2 + \left(\frac{m_{i'j'} - m_h}{\sigma_{m_h}}\right)^2} \tag{4}$$

quantifies how well the b-jets are able to reconstruct two dijet systems each with $m_{bb} \sim m_h$. σ_{m_h} is just a normalisation factor which we set to 12.5 GeV.

$Z \to \nu\nu$

1. Require no identified leptons with $p_T \geq 5$ GeV inside $|\eta| \leq 2.5$.
2. Require $|E_T^{\mathrm{miss}}| \geq 100$ GeV.
3. Require at least 4 jets with $p_T \geq 40$ GeV.
4. Require the 4 leading jets to be *b*-tagged with an efficiency of 77% when a *b*-meson can be ghost associated to the jet, falling to (100/6)% for *c*-mesons and (100/134)% for light jets, corresponding to a standard operating point for the ATLAS MV2c10 algorithm.
5. Require that these *b*-tagged jets have the kinematics of a *hh* pair decay, $\chi_{hh} \leq 1.6$.

$Z \to ll$

1. Require exactly two same flavor opposite charge electrons or muons inside $|\eta| \leq 2.5$ with $p_T \geq 25$ GeV.
2. Require these leptons to have an invariant mass compatible with originating from a Z boson decay, $|m_{ll} - m_Z| \leq 5$ GeV.
3. Require $|E_T^{\mathrm{miss}}| \leq 50$ GeV.
4. Require at least 4 jets with $p_T \geq 40$ GeV. Veto event if any of these overlap with a lepton.
5. Require the 4 leading jets to be b-tagged with an efficiency of 77% when a b-meson can be ghost associated to the jet, falling to (100/6)% for c-mesons and (100/134)% for light jets.
6. Require that these b-tagged jets have the kinematics of a hh pair decay, $\chi_{hh} \leq 1.6$.

$W \to l\nu$

1. Require exactly one electron or muon inside $|\eta| \leq 2.5$ with $p_T \geq 25$ GeV.
2. Require $|E_T^{\mathrm{miss}}| \geq 40$ GeV.
3. Require at least 4 jets with $p_T \geq 40$ GeV. Veto event if any of these overlap with a lepton.
4. Require the 4 leading jets to be *b*-tagged with an efficiency of 77% when a *b*-meson can be ghost associated to the jet, falling to (100/6)% for *c*-mesons and (100/134)% for light jets.
5. Require that these *b*-tagged jets have the kinematics of a *hh* pair decay, $\chi_{hh} \leq 1.6$.
6. Require that neither of the dijet systems have the kinematics of a *t* decay by trying all possible combinations with other jets and vetoing if $\chi_t \leq 3.2$.
7. Require $m_T \leq m_W$ for the *W* system and $H_T \geq 400$ GeV.

Cut ($Z \to ll$)	ZHH	$Zb\bar{b}b\bar{b}$	$Zb\bar{b}c\bar{c}$	$Zt\bar{t}$	$ZZb\bar{b}$	$t\bar{t}H$	$t\bar{t}b\bar{b}$	$t\bar{t}c\bar{c}$	$t\bar{t}$
2 same flavour leptons	5.9×10^{-6}	5.0×10^{-1}	1.1×10^{-1}	3.1×10^{-2}	4.3×10^{-3}	5.9×10^{-3}	4.4×10^{-2}	5.7×10^{-2}	1.9×10^{1}
$\lvert m_{ll} - m_Z \rvert < 5$ GeV	4.9×10^{-6}	4.2×10^{-1}	9.0×10^{-2}	2.3×10^{-2}	3.6×10^{-3}	3.7×10^{-4}	2.9×10^{-3}	3.1×10^{-3}	1.1
$\lvert E_T^{\text{miss}} \rvert < 50$ GeV	4.9×10^{-6}	4.2×10^{-1}	9.0×10^{-2}	1.9×10^{-2}	3.6×10^{-3}	9.5×10^{-5}	7.6×10^{-4}	7.3×10^{-4}	3.3×10^{-1}
≥ 4 jets with $p_T > 40$ GeV	1.4×10^{-6}	3.1×10^{-3}	3.1×10^{-3}	1.0×10^{-2}	1.0×10^{-4}	3.2×10^{-5}	1.6×10^{-4}	2.0×10^{-4}	1.8×10^{-2}
4 leading jets b-tagged	1.1×10^{-7}	4.5×10^{-5}	2.4×10^{-6}	4.1×10^{-6}	3.8×10^{-6}	2.0×10^{-6}	7.8×10^{-6}	3.5×10^{-7}	7.5×10^{-7}
$\chi_{HH} < 1.6$	5.4×10^{-8}	2.4×10^{-6}	2.0×10^{-7}	4.1×10^{-7}	3.6×10^{-7}	6.4×10^{-8}	5.1×10^{-7}	1.7×10^{-8}	$<7.5 \times 10^{-7}$
Events in 3 ab^{-1}	1.6×10^{-1}	7.3	6.0×10^{-1}	1.3	1.1	1.9×10^{-1}	1.5	5.3×10^{-2}	< 2.3

Cut ($Z \to \nu\nu$)	ZHH	$Zb\bar{b}b\bar{b}$	$Zb\bar{b}c\bar{c}$	$Zt\bar{t}$	$ZZb\bar{b}$	$t\bar{t}H$	$t\bar{t}b\bar{b}$	$t\bar{t}c\bar{c}$	$t\bar{t}$	$Wb\bar{b}b\bar{b}$
No identified leptons	1.8×10^{-5}	1.7×10^{-2}	3.9×10^{-1}	4.8×10^{-2}	1.5×10^{-2}	1.1×10^{-1}	5.8	9.6×10^{-1}	3.4×10^{2}	1.1×10^{-4}
$\lvert E_T^{\text{miss}} \rvert > 100$ GeV	9.1×10^{-6}	6.4×10^{-3}	6.7×10^{-2}	7.8×10^{-4}	2.7×10^{-3}	1.6×10^{-3}	7.6×10^{-2}	1.3×10^{-2}	5.0	8.6×10^{-5}
≥ 4 jets with $p_T > 40$ GeV	3.3×10^{-6}	1.6×10^{-3}	5.7×10^{-3}	4.7×10^{-4}	2.1×10^{-4}	1.2×10^{-3}	2.5×10^{-2}	7.2×10^{-3}	1.0	1.1×10^{-5}
4 leading jets b-tagged	2.5×10^{-7}	8.8×10^{-5}	3.6×10^{-6}	1.0×10^{-5}	8.4×10^{-6}	1.7×10^{-5}	1.9×10^{-4}	4.3×10^{-6}	2.7×10^{-4}	1.3×10^{-6}
$\chi_{HH} < 1.6$	1.3×10^{-7}	5.6×10^{-6}	1.7×10^{-7}	6.5×10^{-7}	5.7×10^{-7}	6.2×10^{-7}	3.9×10^{-5}	3.0×10^{-7}	2.3×10^{-5}	9.8×10^{-8}
Events in 3 ab^{-1}	3.9×10^{-1}	1.7×10^{1}	5.2×10^{-1}	1.9	1.7	1.8	1.2×10^{2}	8.9×10^{-1}	6.9×10^{1}	2.9×10^{-1}

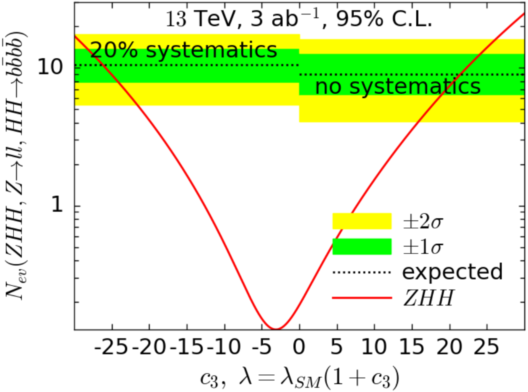
Results

- $Z \to ll$ has a lower cross section due to a lower branching fraction by a factor of ~ 3, but a much higher S/B after cuts.
- $Z \to \nu\nu$ struggles with $t\bar{t}$ backgrounds which completely overwhelm the signal.
- $W \to l\nu$ (not presented on last slide) is similar to $Z \to \nu\nu$ but even worse, even after additional cuts designed to reduce top backgrounds made possible by the higher signal cross section.

$\Rightarrow Z \to ll$ is most sensitive under any reasonable systematics assumption[5]. This channel was not even considered in [Cao, Liu, Yan]!

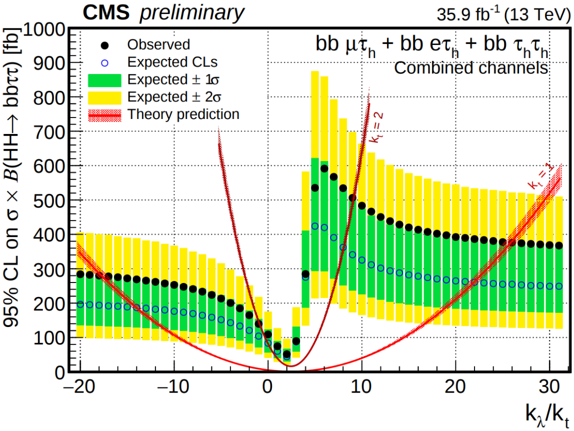
[5] And also by far the most stable to detector effects, I have the table in the appendix if someone really wants to see more numbers. . .

Results



Signal prediction includes kinematic dependence on λ_3 here. In the end the sensitivity is comparable to *already published measurements from 8 and 13 TeV even though we assume 3 ab*$^{-1}$.

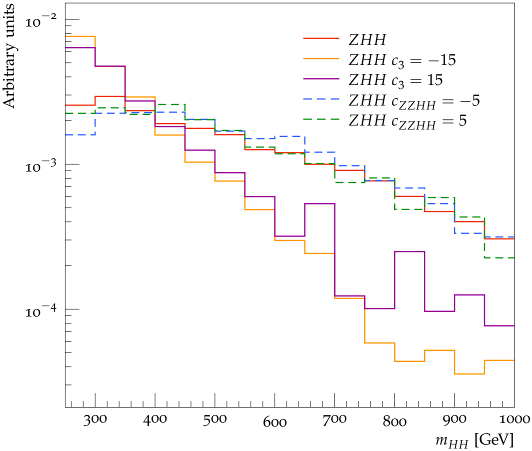
Results



Signal prediction is given as total cross section here, so the kinematic dependence on λ_3 is expressed by the varying limits.

Results

Boosted techniques are unlikely to save us, since the cross section already is tiny and the λ_3 component scales as v^4/m_{hh}^4 whereas the others scale as v^2/m_{hh}^2 at large m_{hh}:



Summary

- $Z \to ll$ is likely to be the most sensitive *Vhh* channel wrt λ_3 under any realistic systematics and detector scenario.
- This is because of large top backgrounds, which are difficult to sufficiently control due to the tiny signal cross section and soft kinematics without being able to reconstruct the leptonically decaying Z completely.
- Due to the small signal cross section the sensivity is very limited. A multivariate approach would be necessary to improve the results presented here, however such an analysis would have to deal with a large number of very complex backgrounds which will ultimately require experimental expertise for realistic estimates.

Cut ($Z \to ll$)	ZHH	$Zb\bar{b}b\bar{b}$	$Zb\bar{b}c\bar{c}$	$Zt\bar{t}$	$ZZb\bar{b}$	$t\bar{t}H$	$t\bar{t}b\bar{b}$	$t\bar{t}c\bar{c}$	$t\bar{t}$
2 same flavour leptons	2.6×10^{-6}	3.5×10^{-3}	7.4×10^{-2}	2.8×10^{-2}	2.7×10^{-3}	3.1×10^{-3}	2.5×10^{-2}	1.5×10^{-1}	5.8×10^{1}
$\lvert m_{ll} - m_Z \rvert < 5$ GeV	1.6×10^{-6}	1.9×10^{-3}	5.4×10^{-2}	1.1×10^{-2}	1.9×10^{-3}	2.0×10^{-4}	1.6×10^{-3}	6.3×10^{-3}	2.6
$\lvert E_T^{\text{miss}} \rvert < 50$ GeV	1.5×10^{-6}	1.8×10^{-3}	5.4×10^{-2}	7.9×10^{-3}	1.9×10^{-3}	5.1×10^{-5}	4.4×10^{-4}	3.0×10^{-3}	9.5×10^{-1}
≥ 4 jets with $p_T > 40$ GeV	4.0×10^{-7}	2.5×10^{-4}	1.3×10^{-3}	4.3×10^{-3}	3.2×10^{-5}	1.5×10^{-5}	8.5×10^{-5}	9.1×10^{-4}	8.0×10^{-2}
4 leading jets b-tagged	3.9×10^{-8}	2.0×10^{-5}	2.4×10^{-6}	3.1×10^{-6}	1.5×10^{-6}	7.9×10^{-7}	3.9×10^{-6}	5.6×10^{-7}	6.0×10^{-6}
$\chi_{HH} < 1.6$	2.2×10^{-8}	1.6×10^{-6}	2.4×10^{-7}	7.2×10^{-7}	2.2×10^{-7}	3.4×10^{-9}	1.6×10^{-7}	2.3×10^{-8}	$<6.0 \times 10^{-6}$
Events in 3 ab^{-1}	6.6×10^{-2}	4.7	7.1×10^{-1}	2.2	6.6×10^{-1}	1.0×10^{-2}	4.7×10^{-1}	7.0×10^{-2}	$< 1.8 \times 10^{1}$

Cut ($Z \to \nu\nu$)	ZHH	$Zb\bar{b}b\bar{b}$	$Zb\bar{b}c\bar{c}$	$Zt\bar{t}$	$ZZb\bar{b}$	$t\bar{t}H$	$t\bar{t}b\bar{b}$	$t\bar{t}c\bar{c}$	$t\bar{t}$	$Wb\bar{b}b\bar{b}$
No identified leptons	1.2×10^{-5}	1.3×10^{-2}	3.6×10^{-1}	4.2×10^{-2}	1.3×10^{-2}	9.2×10^{-2}	5.8	9.5×10^{-1}	5.2×10^{2}	2.1×10^{-4}
$\lvert E_T^{\text{miss}} \rvert > 100$ GeV	5.7×10^{-6}	4.2×10^{-3}	5.8×10^{-2}	4.0×10^{-3}	2.0×10^{-3}	8.0×10^{-3}	4.0×10^{-1}	7.2×10^{-2}	3.0×10^{1}	1.8×10^{-4}
≥ 4 jets with $p_T > 40$ GeV	1.9×10^{-6}	9.0×10^{-4}	4.2×10^{-3}	2.9×10^{-3}	1.3×10^{-4}	6.0×10^{-3}	1.7×10^{-1}	4.5×10^{-2}	9.7	2.0×10^{-5}
4 leading jets b-tagged	1.8×10^{-7}	6.9×10^{-5}	7.8×10^{-6}	4.7×10^{-5}	6.8×10^{-6}	8.8×10^{-5}	1.1×10^{-3}	6.2×10^{-5}	4.5×10^{-3}	2.8×10^{-6}
$\chi_{HH} < 1.6$	1.0×10^{-7}	4.0×10^{-6}	2.5×10^{-7}	4.2×10^{-6}	4.9×10^{-7}	1.3×10^{-5}	7.8×10^{-5}	4.2×10^{-6}	1.2×10^{-4}	2.8×10^{-7}
Events in 3 ab^{-1}	3.1×10^{-1}	1.2×10^{1}	7.4×10^{-1}	1.3×10^{1}	1.5	3.9×10^{1}	2.4×10^{2}	1.3×10^{1}	3.6×10^{2}	8.3×10^{-1}