HH resonant production in VBF

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Outline

Introduction

- Significant deviations from the SM expectation have remained mostly elusive at the LHC searches.
- The coupling of the Higgs with the gauge bosons and the third generation fermions have been measured with an improved precision.
- Our understanding of the fundamental nature of the electroweak symmetry breaking (EWSB) is still lacking.
- Probing the multi-Higgs production processes can shed more light on the nature of EWSB.
- However, the experimental investigations of multi-Higgs states suffer from low statistics.

Non-resonant di-Higgs searches

Gluon-fusion (GF) mode in SM

- Contributes to $\gtrsim 90\%$ of the total NR *hh* cross-section at the LHC.
- Destructive interference between the triangle and the box diagram leads to a small cross-section, ~ 33 fb at $\sqrt{s} = 13$ TeV.

VBF mode in SM

- Very small cross-section at 13 TeV LHC: ~ 1.73 fb.
- Sensitive to both λ as well as c_{2v}.

The small cross-section makes it extremely challenging to probe di-Higgs production at the current LHC.

However, phenomenologically rich final states can emerge:

hh $\rightarrow$ 4b (33 %), 2b2W (25 %), 2b2τ (7 %), 2b2γ (10^{-3})

Limits from non-resonant *hh* searches

- ATLAS: 13.3 fb^{-1}: 4b: $\sim$ 29 times
- ATLAS: 36.1 fb^{-1}: $2b2\tau$: $\sim$ 13 times
- CMS: 35.9 fb^{-1}: $2b2\gamma$: $\sim$ 30 times
- CMS: 35.9 fb^{-1}: $2b2\gamma$: $\sim$ 19 times

- An enhancement in the *hh* cross-section could make the channel noticeable.

Various new physics scenarios can lead to such an enhancement.

Non-resonant enhancement:

- Deviations from λ_{SM} $\rightarrow$ can modify the GF as well as the WBF *hh* production rates.
- Deviations in c_{2v} $\rightarrow$ can significantly increase the WBF *hh* cross-section. [1]

Resonant enhancement:

- BSM theories consisting of new particles which can decay to *hh* $\rightarrow$ enhance the detectability of both GF and WBF *hh* modes.
- Heavy Higgs states in well-motivated BSM scenarios: MSSM, NMSSM, singlet-extensions, etc.

[1] Eur.Phys.J. C **77** 481 (2017)

Status of (non-) resonant di-Higgs searches

$\sqrt{s} = 13$ TeV, $\mathcal{L} \sim 36$ fb^{-1}

Channel	CMS (NR) (×SM)	CMS (R) [fb, (GeV)]	ATLAS (NR) (×SM)	ATLAS (R) [fb, (GeV)]
$b\bar{b}b\bar{b}$	75	1500 – 45 (260 – 1200)	13	2000 – 2 (260 – 3000)
$b\bar{b}\gamma\gamma$	24	240 – 290 (250 – 900)	19.2	1100 – 120 (260 – 1000)
$b\bar{b}\tau^+\tau^-$	30	3110 – 70 (250 – 900)	12.7	1780 – 100 (260 – 1000)
$\gamma\gamma WW^*$ ($\gamma\gamma\ell\nu jj$)			200	40000 – 6100 (260 – 500)
$b\bar{b}\ell\nu\ell\nu$	79	20500 – 800 (300 – 900)	300	6000 – 170 (500 – 3000)
WW^*WW^*			160	9300 – 2800 (260 – 500)

Mass range, Upper limit, NR: non-resonant, R: resonant.

Resonant hh production via WBF mode at the HL-LHC

- Resonant production in WBF has been relatively less studied from a phenomenological perspective than their GF counterparts.
- Scenarios with nonalignment remains a viable sector where WBF can play an extremely relevant role.
- For example, WBF production becomes more pertinent in scenarios with singlet-like Higgs states at $\sim O\,(\mathrm{TeV})$ where the GF and WBF productions become comparable.
- In such cases, it is expected that both the WBF and GF signals would play an important role in the discovery of new physics.

A typical example $\rightarrow$ NMSSM with a dominantly singlet-like heavy Higgs.
[Phys. Rev. D **99**, 095035]

- Searches in the $H \rightarrow t\bar{t}$ mode might impart a smaller sensitivity due to the accidental destructive interference with the QCD continuum $t\bar{t}$ production $\longrightarrow$ in such a case, $H \rightarrow hh$ could be the only phenomenologically robust search mode.

The model

The SM Higgs doublet (Φ_{SM}) is extended with an additional singlet (Φ_s) under the SM gauge group.

$$V = \mu_s^2|\Phi_s|^2 + \lambda_s|\Phi_s|^4 + \mu_h^2|\Phi_h|^2 + \lambda_h|\Phi_h|^4 + \eta|\Phi_s|^2|\Phi_h|^2$$

With Φ_i defined as $(v_i + H_i)/\sqrt{2}$, the Higgs mass eigenstates can be expressed as:

$$\begin{aligned} h &= \quad \cos\theta\, H_{SM} + \sin\theta\, H_S \\ H &= -\sin\theta\, H_{SM} + \cos\theta\, H_S\,. \end{aligned} \tag{1}$$

h is is identified with the SM 125 GeV Higgs boson.

- Compared to SM, the signal strength of h gets modified by $\cos^2\theta$.
- For $m_H \leq 2m_h$, $\sigma(pp \to H) = \sin^2\theta\ \sigma(pp \to h)_{m_h=m_H}$.
- We consider the case where $m_H > 2m_h$.

The WBF channel

We focus on WBF Higgs pair production via: $pp \to Hjj \to (hh \to 4b)jj$.

- This final state benefits from the improved signal yield due to the large $h \to b\bar{b}$ branching ratio.
- This final state also suffers from a large multijet background.
- However, the characteristic WBF topology helps in efficiently discriminating the signal from the background.
- The VBF topology features two forward *jets* well separated by rapidity.
- These forward *jets* also feature a large invariant mass.
- Reduced hadronic activity in the central region.
- The lighter Higgs bosons can acquires a considerable boost.

The WBF channel

- WBF signal generation: $pp \to Hjj \to (H \to hh \to 4b)\ jj$, with VBFNLO.
- The dominant backgrounds are: $4b + 2j$, $2b + 4j$ and $t\bar{t}b\bar{b}$.
- Backgrounds are generated at LO with MadGraph5_aMC@NLO; Showering and hadronization simulated with Pythia-8.
- *Jets* defined with anti-k_t algorithm: $\mathrm{R} = 0.4$, $p_{T_j} > 30$ GeV, $|\eta_j| < 4.5$. using FastJet.
- *b*-tagging efficiency is assumed to be 70%.

The entire analysis can be sub-divided into three categories:

1. Basic selection.
2. Identification of WBF topology.
3. Higgs boson reconstruction.

The WBF channel

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1. Basic selection.

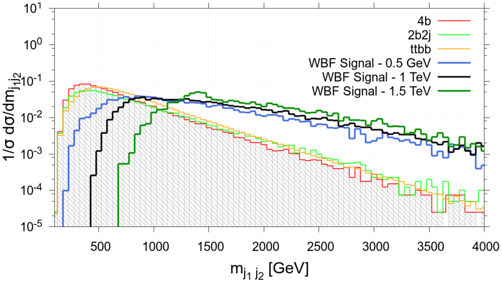
- $N_j \geq 6$, $N_{b-jets} = 4$.
- Veto leptons with $p_t > 12$ GeV and $|\eta| < 2.5$.
- Invariant mass of the 4 *b-jets*, $m_{4b} > 350$ GeV.

The WBF topology

The WBF topology is identified through:

- Two light-flavored highest rapidity *jets* falling in different hemispheres: $\eta_{j_1}\eta_{j_2} < 0$.
- Large rapidity separation: $|\eta_{j_1} - \eta_{j_2}| > 4.2$.

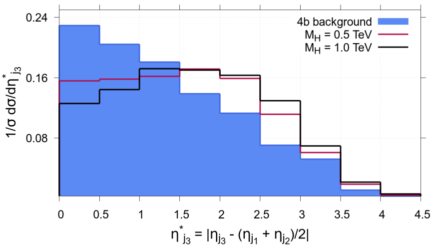
The WBF signal is also characterized by a large $m_{j_1 j_2}$:



- We also demand: $m_{j_1 j_2} > 1\ \mathrm{TeV}$.

The WBF topology

- The WBF signal displays suppressed *jet* emissions in the central region.
- However, the bulk of the QCD background is centred around the central region.
- Furthermore, the more massive the resonance, the further forward the tagging *jets*.



Therefore, we also impose:

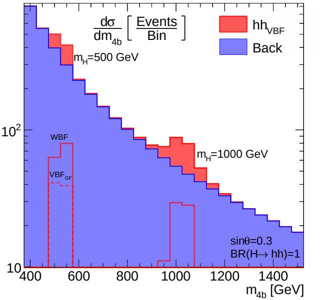
$$\left|\eta_{j3} - \frac{\eta_{j1} + \eta_{j2}}{2}\right| > 2.5$$

Higgs reconstruction

Higgs boson reconstruction

1. The *b-jet* pairs with invariant mass closest to 125 GeV is identified with h_1 (the other pair with h_2).
2. The signal region is defined to be within the circular region:

$$\sqrt{\left(\frac{m_{h1} - 125\ \mathrm{GeV}}{20\ \mathrm{GeV}}\right)^2 + \left(\frac{m_{h2} - 125\ \mathrm{GeV}}{20\ \mathrm{GeV}}\right)^2} < 1 \qquad (2)$$



- The stacked m_{4b} distribution is shown.
- The solid red line represents the individual WBF component.
- The dashed red line represents the VBF GF component.
- The reconstructed Higgs boson's four-momentum has been scaled with $m_h/m_{1(2)}$.

Cut-flow table

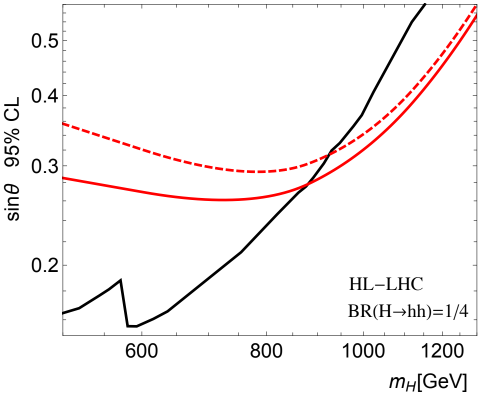
- Although, dominant contribution to the signal arises from the WBF component, the VBF GF signal also contributes non-negligibly.
- Larger $m_H \to$ relatively larger contribution from WBF.

Cross-section (in fb) at $\sqrt{s} = 13$ TeV

	Basic selections	VBF topology	Double Higgs reconstruction
WBF $m_H = 500$ GeV	2.6×10^{-1}	1.3×10^{-1}	5.0×10^{-2}
GF $m_H = 500$ GeV	2.2×10^{-1}	7.1×10^{-2}	2.8×10^{-2}
WBF $m_H = 1$ TeV	9.4×10^{-2}	5.4×10^{-2}	3.2×10^{-2}
GF $m_H = 1$ TeV	2.2×10^{-2}	8.3×10^{-3}	4.7×10^{-3}
$4b$	250	47	1.2
$2b2j$	4.9×10^{-1}	1.0×10^{-1}	-
$t\bar{t}b\bar{b}$	90	3.7	3.0×10^{-3}

The 95% C.L. sensitivity to $\sin\theta$ as a function of m_H, for $\sqrt{s} = 13$ TeV LHC at $\mathcal{L} = 3000\ \mathrm{fb}^{-1}$.

- Red-dashed: WBF signal only
- Red-solid: WBF + GF signals.
- **Black**: GF signal only, derived from the CMS $pp \to H \to hh \to 4b$ study [JHEP08 (2018) 152] through scaling with the integrated luminosity.



- The sensitivity of the gluon fusion mode and the WBF search becomes comparable at ~ 900 GeV.
- The WBF HH search displays stronger sensitivity in the high $m_H \gtrsim 900$ GeV regime.

1 Introduction

2 The VBF topology

3 Implications on a singlet-extension scenario

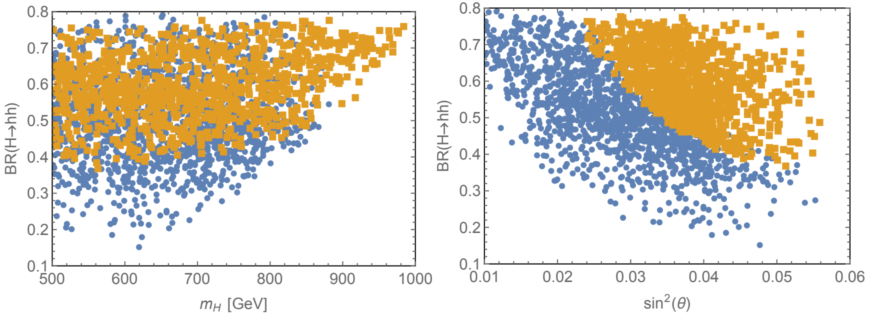
4 Conclusion

Implications on the singlet-extension scenario

The VBF and GF limits are interpreted on the singlet-extension model discussed earlier.

Blue points: projected reach from GF signal.

Orange color: projected reach of $pp \to hhjj$ signal.



- The VBF provides significant sensitivity at higher masses where the GF projection becomes insensitive.
- We also observe regions in $Br(H \to hh)$ where the VBF provides new sensitivity that cannot be accesses by the GF projection.

Conclusions

- Given that the weak boson fusion production cross-section becomes comparable to the GF cross-section for SM-like production around 1 TeV, the WBF channel is a phenomenologically important channel even at small mixing angles.
- The weak boson fusion provides a unique opportunity to probe new physics scenarios through its distinct phenomenological features.
- In scenarios with isospin singlet-mixing, the $H \to hh$ modes might provide phenomenologically robust signals compared to the more obvious decays into top quarks or massive weak bosons.
- The VBF GF channel remains phenomenologically important and should be rightfully included along with the WBF channel in the signal component.

Thank you.