Di-Higgs resonance searches in weak boson fusion

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based on:
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Introduction

- The couplings of the observed 125 GeV resonance with the gauge bosons and the third generation fermions have been measured with considerable precision.
- Measurements of the Yukawa coupling with the second generation fermions is also improving in precision.
- However, our understanding of the fundamental nature of the electroweak symmetry breaking (EWSB) is still lacking.
- The main deterrent in the reconstruction of the full Higgs potential and deciphering the EWSB mechanism has been the elusive Higgs self-coupling.
- In the SM, double Higgs production is a direct probe for λ.
- However, the experimental investigations in the di-Higgs channels suffer from low statistics.

Resonant di-Higgs searches

- An enhancement in cross-section could make the di-Higgs channel relevant at the LHC.

Various new physics scenarios can lead to such an enhancement.

Non-resonant enhancement:

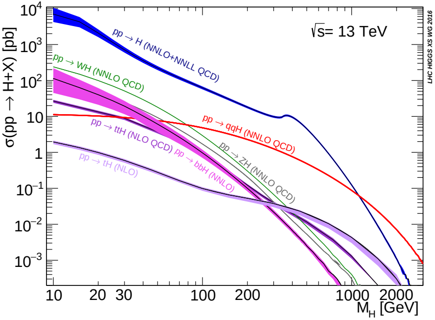
- Deviations from $\lambda_{SM} \rightarrow$ can modify the GF as well as the WBF hh production rates.
- Deviations in Higgs coupling with gauge bosons $\rightarrow$ can alter the WBF hh cross-section[1].

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] [Bishara, Contino, Rojo (EPJC **77** 481 (2017))]

Resonant di-Higgs production in WBF mode



Source: LHC Higgs XS Working Group Report (arXiv: 1610.07922)

- SM-like Higgs production cross-section in GF and VBF channels become comparable at $\sim \mathcal{O}(\mathrm{TeV})$.
- Discovery potential of resonant di-Higgs searches in the $m_H > \mathcal{O}\ (1)\ \mathrm{TeV}$ region can be improved through a combination of GF and VBF searches.

- In singlet-extension scenario where searches in the $H \to t\bar{t}$ might suffer from smaller sensitivity due to interference with $t\bar{t}$ continuum, the $H \to hh$ search mode could be possibly the only phenomenologically relevant and robust search channel.

Goal of our study

- Study the WBF production of exotic Higgs boson in the $pp \to Hjj$ channel at $\sqrt{s}$=13 TeV LHC.
- The gluon fusion samples may also contain forward jets and mimic the WBF final states. We investigate its potential contributions to the WBF signal, and estimate its role in improving the sensitivity of WBF channel at the LHC.
- Study the interplay of VBF (WBF + GF resembling WBF) and GF production channels and its relevance in improving the discovery potential of resonant di-Higgs searches at the LHC.
- We translate the projections to the parameter space of a singlet-extension model.

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 $\left(v_i + H_i\right)/\sqrt{2}$, 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 identified with the SM 125 GeV Higgs boson.

- Compared to SM, the signal strength of h gets modified by $\cos^2\theta$.
- The heavy Higgs production cross-section will be rescaled with $\sin^2\theta$ compared to its SM counterpart.
- 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.

Signal and background generation

- Signal generation: $pp \to Hjj \to (H \to hh \to 4b)\ jj$, with `VBFNLO`.
- Dominant backgrounds: $4b$, $2b2j$ and $t\bar{t}b\bar{b}$.
- Backgrounds generated at LO with MadGraph5_aMC@NLO; Showering and hadronization simulated with `Pythia-8`.
- b-tagging efficiency is assumed to be 70%.

The WBF channel

The analysis strategy can be sub-divided into three major categories:

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

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1. **Basic selection.**
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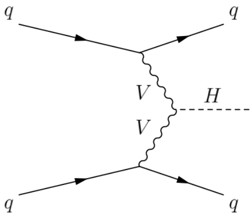
Basic Selection

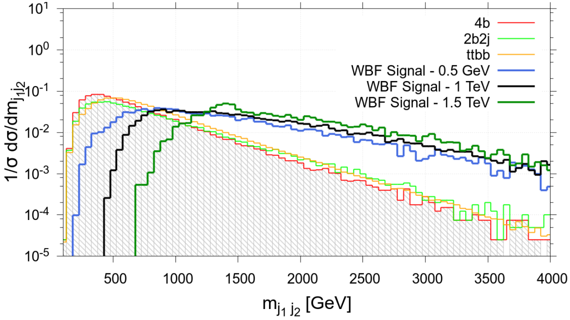
- $N_j \geq 6$; No. of *b*-tagged *jets*: 4.
- Veto on leptons with $p_t > 12$ GeV and $|\eta| < 2.5$.
- Invariant mass of the 4 *b-jets*, $m_{4b} > 350$ GeV.

The WBF topology

The WBF topology is characterized by:

- Two light-flavored large rapidity *jets* in different hemispheres: $\eta_{j_1}\eta_{j_2} < 0$.
- Large rapidity separation between j_1 and j_2: $|\eta_{j_1} - \eta_{j_2}| > 4.2$.
- Large invariant mass, $m_{j_1 j_2} > 1\ \mathrm{TeV}$.



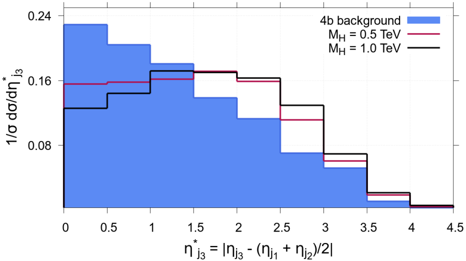


The WBF topology

The WBF topology is characterized by:

- $\eta_{j_1}\eta_{j_2} < 0$
- $|\eta_{j_1} - \eta_{j_2}| > 4.2$
- $m_{j_1 j_2} > 1$ TeV

- The WBF signal displays a reduced hadronic activity in the central region between the two VBF *jets*.
- On the other hand, the bulk of the QCD background is centred around the central region.



- In $VV \to hh$ scattering around the H pole, $\mathcal{A}_{LL}/\mathcal{A}_{TT} \sim m_H^2/m_V^2$ for $m_H >> m_V \to$ More massive the signal resonant Higgs is, the further forward the VBF-tagging *jets* are.

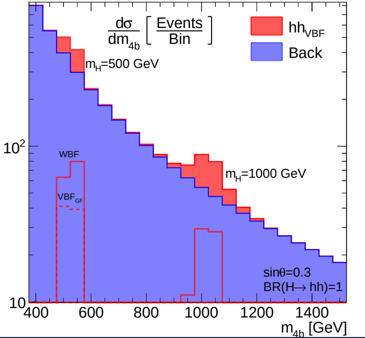
[Dawson (Nucl. Phys. B249 (1985) 42-60); Goncalves, Plehn, Thompson (PRD 95 (2017) 095011)]

- Events with a third *jet* in the central region are vetoed: $\left|\eta_{j3} - \frac{\eta_{j1}+\eta_{j2}}{2}\right| > 2.5$

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:

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



- The solid red line represents the individual WBF component.
- The dashed red line represents the GF component in VBF.
- The reconstructed Higgs boson's four-momentum has been scaled with $m_h/m_{h_1(h_2)}$. [CMS Collaboration (JHEP 08 (2018) 152)]

Cut-flow

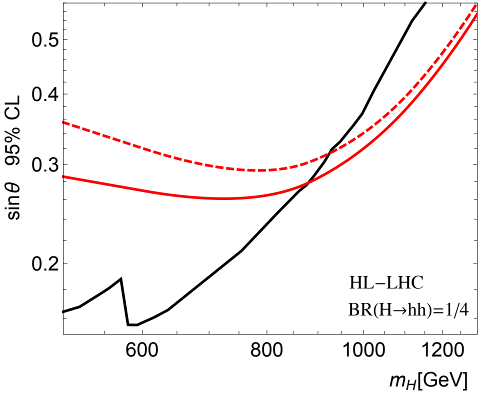
- Dominant contribution to the VBF signal arises from the WBF component.
- The GF component also contributes non-negligibly in VBF.
- Larger $m_H \to$ relatively larger contribution from WBF.

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

	Basic selections	WBF 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 $\sin\theta$, for $\sqrt{s} = 13\ \mathrm{GeV}$ LHC at $\mathcal{L} = 3000\ \mathrm{fb}^{-1}$.

- Red-dashed: WBF signal.
- Red-solid: VBF (WBF + WBF-like GF) signals.
- **Black**: GF signal only → derived from the CMS $pp \to H \to hh \to 4b$ study [JHEP08 (2018) 152].



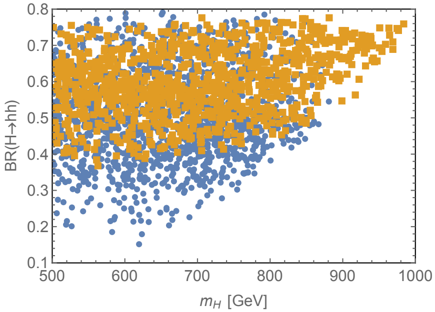
- The increase in the ratio of σ_{VBF}/σ_{GF} for large m_H leads to comparable sensitivities at $m_H \sim 900\ \mathrm{GeV}$.
- In the low mass region, $500\ \mathrm{GeV} < m_H < 900\ \mathrm{GeV}$, the GF component in VBF contributes non-negligibly in the overall VBF channel.
- In the $m_H \gtrsim 900\ \mathrm{GeV}$ regime, the VBF search displays stronger sensitivity.
- Combination between the GF and VBF analyses could help in further constraining the low mass scenario.

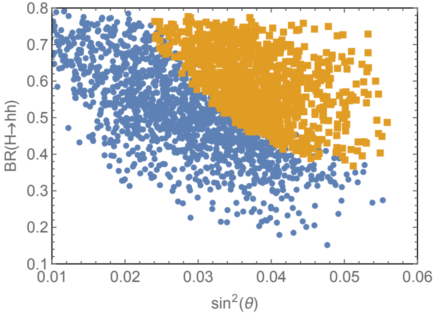
Implications on the singlet-extension scenario

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 VBF signal.





- The VBF channel provides new sensitivity in the high mass region where the GF projection becomes insensitive.

Conclusions

- Given that the WBF cross-section becomes comparable to the GF cross-section for SM-like production around 1 TeV, the WBF channel becomes a phenomenologically relevant channel even at small mixing angles.
- The GF component in the VBF channel remains sizeable and should be rightfully included in the collider analysis of WBF signal to enable a consistent theoretical interpretation.
- The VBF signal provides additional sensitivity over the GF searches in the large m_H ($m_H > 1\ \mathrm{TeV}$) regime.

THANK YOU