Boosting Higgs CP properties via VH Production at the Large Hadron Collider

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We consider ZH and WH production at the Large Hadron Collider, where the Higgs decays to a $b\bar{b}$ pair. We use jet substructure techniques to reconstruct the Higgs boson and construct angular observables involving leptonic decay products of the vector bosons. These efficiently discriminate between the tensor structure of the HVV vertex expected in the Standard Model and that arising from possible new physics, as quantified by higher dimensional operators. This can then be used to examine the CP nature of the Higgs as well as CP mixing effects in the HZZ and HWW vertices separately.

The recently discovered Higgs-like particle \cite{1} at the Large Hadron Collider (LHC) will dominate global particle physics effort for many years to come. Whether or not this is the Standard Model (SM) Higgs boson necessitates precise study of its couplings to other SM particles in all production and decay channels. In this letter we focus on the determination of the tensor structure and hence the CP properties of the vertex responsible for the production of a Higgs boson associated with a $V = W, Z$ boson as well as CP violating effects in the same. We show that this process allows one to disentangle CP even and CP odd new physics from the SM contribution (and from each other). Furthermore, one may probe the HWW and HZZ vertices separately. The $VH$ channel, though subdominant, has been shown to be viable due to the use of modern jet substructure techniques \cite{2}. We show that, interestingly, the very kinematic cuts that are required to make the detection of the $VH$ channel viable at the LHC using this technique, automatically add to its discriminatory power.

Corrections to the Standard Model $HVV$ vertex can be written by supplementing the SM Lagrangian with higher dimensional operators that can originate from Beyond the SM (BSM) physics:

$$ g_W^2 \frac{c_1}{2\Lambda_1^2} \Phi^{\dagger} F_{\mu\nu} F^{\mu\nu}, \quad g_W^2 \frac{c_2}{2\Lambda_2^2} \Phi^{\dagger} \tilde{F}_{\mu\nu} F^{\mu\nu}, \quad (1) $$

with $g_W$ and $F_{\mu\nu}$ the electroweak coupling constant and SU(2) field strength tensor, $\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}$, $\Phi$ the (SU(2) doublet) Higgs field and $c_i$ (complex) constants. These operators (CP even/odd respectively) arise from integrating out higher energy dynamics, are suppressed by mass scales $\Lambda_i^2$, and modify the $HWW$ vertex to

$$ ig_W M_W \left[ g_{\mu\nu} + \frac{4c_1}{\Lambda_1^2} (p^\mu q^\nu - g_{\mu\nu} p \cdot q) + \frac{8c_2}{\Lambda_2^2} \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right] $$

where $M_W$ is the $W$ boson mass and $p$ and $q$ the $W$ boson momenta.

The nature of the $HZZ$ interaction in the four lepton channel was investigated in \cite{3,4} and has now been probed with current LHC data, disfavouring a pure pseudoscalar hypothesis at $\sim 2-3\sigma$ \cite{5,6}. Similar constraints on the $HWW$ vertex using the $H \rightarrow WW$ decay are hard to achieve since the kinematical cuts necessary to eliminate backgrounds hamper the analysis. Although the tensor structure of the $HVV$ vertex can be investigated using kinematic and angular correlations \cite{7,8} in Vector Boson Fusion (VBF), one cannot separately study the $Z$ and $W$ contributions in this channel. Furthermore, non-SM HVV vertices have a reduced acceptance to VBF-like kinematic cuts. Electron-positron colliders with polarized beams can offer precision information on the $HZZ$ vertex (e.g. CP structure), via angular distributions of leptonic decay products of the vector bosons \cite{9,10}. However, the determination of the $HWW$ vertex \cite{11}, possible only by studying $e^+ e^- \rightarrow \nu \bar{\nu} H$, has an irreducible background from $ZH$ production followed by $Z \rightarrow \nu \bar{\nu}$. Thus an unambiguous separate determination of the $HWW$ and $HZZ$ vertices through VBF is possible only at the proposed LHeC \cite{12}. In order to elucidate the nature of the HVV couplings at the LHC, one is unavoidably led to VH production.

At the LHC, where until recently even the detection of the Higgs in the $VH$ channel was considered difficult, studies of the nature of the $HVV$ vertex were not contemplated. Here we show that modern jet substructure techniques \cite{2}, which probe the kinematical region where the Higgs is highly boosted and decays to a $b\bar{b}$ pair, increase the sensitivity to BSM couplings. We furthermore demonstrate that angular correlations of decay leptons produced in the $VH$ process, are able to distinguish between the different contributions in eq. (1). We simulate all processes using \textsc{MadGraph5} \cite{13} interfaced with \textsc{Pythia6} \cite{14} and use the \textsc{FastJet} package \cite{15} to cluster the jets. The effective Lagrangian was implemented in \textsc{FeynRules} \cite{16}.

**EVENT SELECTION**

It is important to apply selection criteria to distinguish between the signal and background processes. For $ZH$ production we require:
TABLE I. Cross-sections (fb) evaluated at leading order for the 14 TeV LHC after applying all cuts. V + jets corresponds to the Z + jets background for the ZH process and W + jets for the WH process. For the last two columns the SM contribution was set to zero and the values of $\Lambda_1$ and $\Lambda_2$ were set to reproduce the SM total cross-section before applying cuts. These results do not require $W$ reconstruction.

| Channel | $V H_{SM}$ | V+jets | $t\bar{t}$ | Single top | $V H^T_{BSM}$ | $V H^B_{BSM}$ |
|---------|-----------|--------|--------|-----------|-------------|-------------|
| ZH      | 0.153     | 0.416  | 0      | 0         | 0.61        | 0.93        |
| WH      | 0.455     | 0.33   | 0.16   | 0.06      | 1.86        | 2.74        |

1. A fat jet (radius $R = 1.2$, $p_T > 200$ GeV). After applying the filtering procedure of [2], we require no more than three subjets with $p_T > 20$ GeV, $|\eta| < 2.5$, and radius $R_{sub} = \min(0.3, R_{bb})$, where $R_{bb}$ is the separation of the two hardest subjets, both of which must be $b$-tagged.

2. Exactly 2 leptons (transverse momentum $p_T > 20$ GeV, pseudo-rapidity $|\eta| < 2.5$) of same flavour and opposite charge, with invariant mass within 10 GeV of the $Z$ mass $M_Z$. These should be isolated: the sum of all particle transverse momenta in a cone of radius $R = 0.3$ about each lepton should not exceed 10% of that of the lepton.

3. Demand that the reconstructed $Z$ has a $p_T > 150$ GeV, with azimuthal angle satisfying $\Delta \phi(Z, H) > 1.2$.

After cuts, the only significant surviving background process is $Z +$ jets. Cross-sections at Leading Order (LO) before and after the cuts are shown in Table I. The $H \rightarrow b\bar{b}$ branching ratios were taken from Ref. [13]. Since the $K$ factors for the background and the signal are not too different [2] our results are not expected to be significantly different at Next to Leading Order (NLO). In principle our analysis is sensitive to the $b$-tagging efficiency and light quark jet rejection rate [2] (here set to $c_b = 0.6$ and $r_j = 100$ respectively). However, we checked that this has no impact on the angular observables.

For WH production we require:

1. The Higgs reconstructed as above.

2. Exactly 1 hard lepton ($p_T > 30$ GeV, $|\eta| < 2.5$), isolated as above.

3. Missing transverse momentum $\not{p}_T > 30$ GeV.

4. The reconstructed $W$ has $p_T > 150$ GeV and azimuthal angle satisfying $\Delta \phi(H, W) > 1.2$.

5. No additional jet activity with $p_T^{jet} > 30$ GeV, $|\eta| < 3$ (to suppress single and top pair production backgrounds).

Again, major backgrounds are detailed in Table I.

Reconstructing the neutrino momentum

One must reconstruct the neutrino in $WH$ production to determine our angular observables. We identify the neutrino transverse momentum $\vec{p}_T^\nu$ with the missing transverse momentum $\not{p}_T$, and demand the squared sum of the neutrino and lepton momenta be equal to the squared $W$ boson mass $((\vec{p}_\nu + \vec{p}_l)^2 = M_W^2)$, solving the resulting quadratic equation. Comparing with the “true” Monte-Carlo generated neutrino momentum, we find that choosing a given solution out of the two possible ones, reconstructs the true neutrino momentum 50% of the time, with $\pm 5\%$ giving imaginary solutions. One can also compare the boosts of the Higgs $\beta_z^H$ and reconstructed $W$ $\beta_z^W$ in the $z$ direction. The solution with the minimum value for $|\beta_z^W - \beta_z^H|$ gives the true neutrino momentum in 65% of cases.

We present results for angular observables for the three cases listed below and show that the differences are small:

- Choose the solution by demanding the difference in boost of $W$ and $H$ is minimized (BT).
- Use the “Monte-Carlo Truth” (MCT), where the neutrino momentum is reconstructed from the $p_T$ of the “true” neutrino rather than the $\not{p}_T$.
- Use both solutions of the quadratic equation (BN).

Sensitivity to new operators

The BSM operators of eq. (1) push the $p_T$, invariant mass ($\sqrt{s_{HV}}$) and rapidity separation ($\Delta y_{HV}$) distributions of the $VH$ system to larger values [20-22], leading...
to larger Higgs boosts and a reduced separation between the leptons ($R_{ll}$), and $b$ jets $R_{bb}$. Consequently, the above selection cuts enhance BSM effects. In Table I one sees the acceptance of these operators to the selection cuts is very good: $\sim 4$ ($\sim 6$) times the SM acceptance for the CP even (odd) operator.

In Fig. 11 we consider the SM Lagrangian supplemented by either the CP odd or even operator applied to the $WH$ channel. We show the ratio of the SM+BSM and SM cross-sections both for the total cross-section ($R_{tot}^X = \sigma_{tot}^{SM+BSM}/\sigma_{tot}^{SM}$) and the cross-section after applying selection cuts ($R_{jetsub}^X = \sigma_{jetsub}^{SM+BSM}/\sigma_{jetsub}^{SM}$). As expected, the BSM contribution is larger for smaller values of the new physics scales $\Lambda_i$. We also see that $R_{jetsub}$ increases at a faster rate than $R_{tot}$ with decreasing values of $\Lambda_i$. While the rates alone cannot provide information about the $HVV$ interactions, the variation of the rates with the $p_T$ cuts used can provide information on the presence of BSM physics. This behaviour would also be observable in both $pp \rightarrow ZH \rightarrow llbb$ and $pp \rightarrow ZH \rightarrow \nu\bar{\nu}bb$.

**ANGULAR OBSERVABLES**

To fully distinguish CP even and odd BSM contributions, one must construct CP-odd observables, which is difficult in principle [23]. For ZH production, Ref. [24] considered two such observables, although these are sensitive to radiation and hadronisation corrections; Ref. [25] defined observables which are insensitive to the CP structure of BSM contributions. Ref. [26] examined $WH$ production with the decay $H \rightarrow WW$, though the effect of the BSM CP even term was not considered. Recently an analysis of Tevatron data used the transverse mass to distinguish between a CP odd, spin-2 and SM state [27], although this does not distinguish between the CP even and CP odd terms and has shown to be an insensitive observable at the LHC [21]. The suggestion in Ref. [2] to distinguish the CP nature from threshold behaviour is incompatible with jet substructure methods, which require the Higgs be highly boosted. However, the Lorentz structure of the BSM vertices will be reflected in the angular distribution of the gauge boson’s decay products. The momenta of the $V$ and Higgs bosons are reconstructed from the leptons and jets as follows:

\[ p_V = p_{l_1} + p_{l_2}, \quad p_H = p_{b_1} + p_{b_2} + p_j, \]

where $\{p_{b_i}\}$ are the momenta of the $b$ jets, $p_j$ is the momentum of the light quark jet if it is reconstructed and $p_{l_1}$ and $p_{l_2}$ are the momenta of the lepton and the anti-lepton respectively (for $WH$, $p_{l_1}$ corresponds to the lepton momentum and $p_{l_2}$ to the neutrino). With these momenta,

| Asymmetries | $ZH_{SM}$ | $ZH_{BSM}$ | $ZH_{BSM}$ | $Z+jets$ |
|-------------|-----------|------------|------------|----------|
| $A(\cos \theta^*)$ | 0.35 | -0.05 | -0.02 | 0.07 |
| $A(\cos \delta^+)$ | -0.207 | -0.262 | 0.088 | -0.188 |
| $A(\cos \delta^-)$ | -0.209 | -0.435 | -0.103 | -0.321 |

**TABLE II.** Asymmetries for the angles defined eq. (4) in ZH production for the SM and BSM vertices at 14 TeV LHC after application of all cuts.

| Asymmetries | $WH_{SM}$ | $WH_{BSM}$ | $WH_{BSM}$ | $W+jets$ |
|-------------|------------|------------|------------|----------|
| $A(\cos \theta^*)$ | $0.396^{+0.143}_{-0.131}$ | $0.073^{+0.082}_{-0.080}$ | $0.100^{+0.096}_{-0.095}$ | $0.149^{+0.152}_{-0.142}$ |
| $A(\cos \delta^+)$ | $-0.150^{+0.187}_{-0.162}$ | $-0.284^{+0.344}_{-0.299}$ | $0.142^{+0.191}_{-0.144}$ | $-0.138^{+0.194}_{-0.188}$ |
| $A(\cos \delta^-)$ | $-0.058^{+0.104}_{-0.058}$ | $-0.353^{+0.363}_{-0.367}$ | $0.042^{+0.003}_{-0.038}$ | $-0.118^{+0.172}_{-0.182}$ |

**TABLE III.** Asymmetries for WH production. The numbers are written as $BT_{BN}^{MCT}$, where $BN$, MCT and $BT$ are the three reconstructions of the neutrino momentum.

we may define

\[ \cos \theta^* = \frac{\langle \vec{p}_V \cdot \vec{p}_H \rangle}{\langle |\vec{p}_V||\vec{p}_H| \rangle}, \quad \cos \delta^+ = \frac{\langle \vec{p}_V \cdot (\vec{p}_V \times \vec{p}_H) \rangle}{\langle |\vec{p}_V||\vec{p}_V \times \vec{p}_H| \rangle}, \]

\[ \cos \delta^- = \frac{\langle (\vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)}) \cdot \vec{p}_V \rangle}{\langle |\vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)}||\vec{p}_V| \rangle}. \]

Here $\vec{p}_X^{(Y)}$ corresponds to the three momentum of the particle $X$ in the rest frame of the particle $Y$. If $Y$ is not specified then the momentum is defined in the lab frame. Momenta labels are as follows: $H$ corresponds to the Higgs boson, $H^-$ stands for the four momentum obtained when the sign of the spatial component of the Higgs momentum is inverted ($\vec{p}_H \rightarrow -\vec{p}_H$) and $V = W^\pm, Z$.

Fig. 2 shows distributions of these angles in $WH$ production for pure SM, pure BSM and for the dominant $W + jets$ background. The $\cos \theta^*$ distribution is the same for the backgrounds and both BSM operators. The angle $\cos \theta^*$ was first defined in [12] and distinguishes the SM from BSM operators, whereas $\cos \delta^+$ distinguishes the BSM CP even contribution. Finally, $\cos \delta^-$ distinguishes the CP odd and CP even (SM or BSM) contributions. Results for $ZH$ production (not shown) are qualitatively similar. Also, the distributions for $\cos \theta^*$ and $\cos \delta^+$ are the same if $\vec{p}_{l_1}$ is replaced by $\vec{p}_{l_2}$ in eq. (4), so one could use both leptons to improve the statistics.

Motivated by Fig. 2 we define the asymmetry parameters

\[ A(X) = \frac{\sigma(|X| < 0.5) - \sigma(|X| > 0.5)}{\sigma(|X| < 0.5) + \sigma(|X| > 0.5)} \]

where $X \in \{\cos \theta^*, \cos \delta^+, \cos \delta^-\}$. The SM, pure BSM and the dominant background are shown for $ZH$ and
with $\Lambda_i$ tries are robust against this systematic uncertainty. Thus differences in asymmetry are not significant if the parameter $\Lambda_i$ is varied through the parameters $\Lambda_i$. The horizontal lines indicate the asymmetry in SM. Their mutual interference gives CP conserving (CPC) or CP violating (CPV) processes if the CP even or odd operators are present respectively. Our results include the dominant $Wjj$ background. As expected, the asymmetries approach the SM value with increasing $\Lambda_i$. For $\cos \theta^*$ the CP even and odd operators both reduce the asymmetry, whereas for $\cos \delta^\pm$ their effects are of opposite sign. One can thus effectively discriminate the BSM contributions to the vertex. Similar results are obtained for $ZH$ production. Fig. 3 includes an estimate of the statistical uncertainty. Bounds on the value of $\Lambda_i > 400 \text{ GeV}$ can be easily placed and for the CPV scenario this may be extended up to $\Lambda_2 > 600 \text{ GeV}$ for $300 \text{ fb}^{-1}$ of LHC data. Obviously the suggested reach of $3000 \text{ fb}^{-1}$ of data for LHC will reduce the uncertainties and therefore higher values of scales $\Lambda_i$ can be probed with more data. One may also combine kinematic and asymmetry information in a multivariate analysis.

**CONCLUSIONS**

We examine $ZH$ and $WH$ production at the LHC, where the Higgs decays to a $bb$ pair. Combining jet substructure techniques with vector boson polarisation (via angular distributions of decay products), we give observables that can distinguish between new operators coupling the Higgs to vector bosons. Importantly (given that the newly discovered boson cannot be purely CP-odd), our analysis applies when both BSM and SM operators are present, and mutually interfere. We show that in $VH$ production, sensitivity to BSM physics is enhanced through an increased acceptance of BSM couplings to the selection cuts, and the $HWW$ and $HZZ$ couplings can be studied independently of each other. Further investigation, including possible detector effects, is ongoing.

**FIG. 2.** Distributions of the angles defined in eq. 4 for $WH$ production in the SM (solid red lines), pure BSM CP even (dot-dashed blue lines), pure BSM CP odd (dashed green lines) and for the dominant $W + jets$ background (dotted black lines). (a) $\cos \theta^*$, (b) $\cos \delta^+$ (c) $\cos \delta^-$, constructed with the $BT$ algorithm.

**FIG. 3.** The value of the asymmetries defined in eq. 5 for $WH$ production defined in eq. 4 for $WH$ production in the SM (solid red lines), pure BSM CP even (dot-dashed blue lines), pure BSM CP odd (dashed green lines) and for the dominant $W + jets$ background (dotted black lines). (a) $\cos \theta^*$, (b) $\cos \delta^+$ (c) $\cos \delta^-$, constructed with the $BT$ algorithm.

$WH$ production in Tables I and II respectively. We see that $A(\cos \theta^*)$ discriminates SM from pure BSM contributions for both $WH$ and $ZH$ production. The other angles discriminate the BSM CP odd and even vertices. In $WH$ production, reconstruction ambiguities of the $W$ shift the absolute value of the asymmetries by roughly the same amount, cf. Table III. Thus differences in asymmetries are robust against this systematic uncertainty.

In Fig. 3 we show the variation of these asymmetries with $\Lambda_i$ in $WH$ production, including the new operators with the SM. Their mutual interference gives CP conserving (CPC) or CP violating (CPV) processes if the CP even or odd operators are present respectively. Our results include the dominant $Wjj$ background. As expected, the asymmetries approach the SM value with increasing $\Lambda_i$. For $\cos \theta^*$ the CP even and odd operators both reduce the asymmetry, whereas for $\cos \delta^\pm$ their effects are of opposite sign. One can thus effectively discriminate the BSM contributions to the vertex. Similar results are obtained for $ZH$ production. Fig. 3 includes an estimate of the statistical uncertainty. Bounds on the value of $\Lambda_i > 400 \text{ GeV}$ can be easily placed and for the CPV scenario this may be extended up to $\Lambda_2 > 600 \text{ GeV}$ for $300 \text{ fb}^{-1}$ of LHC data. Obviously the suggested reach of $3000 \text{ fb}^{-1}$ of data for LHC will reduce the uncertainties and therefore higher values of scales $\Lambda_i$ can be probed with more data. One may also combine kinematic and asymmetry information in a multivariate analysis.
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