Probing the spin-parity of the Higgs boson via jet kinematics in vector boson fusion

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Abstract

Determining the spin and the parity quantum numbers of the recently discovered Higgs–like boson at the LHC is a matter of great importance. In this paper, we consider the possibility of using the kinematics of the tagging jets in Higgs production via the vector boson fusion (VBF) process to test the tensor structure of the Higgs–vector boson (HVV) interaction and to determine the spin and CP properties of the observed resonance. We show that an anomalous HVV vertex, in particular its explicit momentum dependence, drastically affects the rapidity between the two scattered quarks and their transverse momenta and, hence, the acceptance of the kinematical cuts that allow to select the VBF topology. The sensitivity of these observables to different spin-parity assignments, including the dependence on the LHC center of mass energy, are evaluated. In addition, we show that in associated Higgs production with a vector boson some kinematical variables, such as the invariant mass of the system and the transverse momenta of the two bosons and their separation in rapidity, are also sensitive to the spin–parity assignments of the Higgs–like boson.

1. Introduction

The mechanism for electroweak symmetry breaking\cite{ref1} is minimally realized in the Standard Model (SM) of particle physics\cite{ref2} by introducing a doublet of complex scalar fields that develops a non-zero vacuum expectation value; this leads to the existence of only one physical scalar boson $H$, with the spin, parity and charge conjugation assignments of a $J^{PC}=0^{++}$ state.
Accumulated data by the ATLAS and CMS collaborations seem to indicate that the newly observed bosonic particle with a mass around 125 GeV [3] has production and decay rates that are compatible with those expected for the SM Higgs particle. However, it will be necessary that experiments test the spin and CP properties of the new boson before we can truly identify the observed particle with the Higgs boson of the minimal SM. In particular, more data will be required in order to verify that the Higgs sector is not extended in order to contain CP-violating interactions that could make the observed Higgs particle a mixture of CP-even and CP-odd states. In addition, while it is clear from the observation of the $\gamma\gamma$ decay channel that the observed bosonic state cannot have spin equal to one [4], it is not yet entirely excluded that it has a spin equal to two or more.

It is well known that the structure of the Higgs to vector boson ($HVV$) coupling is a possible tool to probe the Higgs $J^{PC}$ quantum numbers [1] at the LHC, ILC and the LHeC. Distributions in various kinematic variables, the virtuality of the off-shell gauge boson, and angular correlations of the decay products in the decay channel $H \rightarrow VV \rightarrow 4f$ with $V = W, Z$ in particular, allow to discriminate between CP-even and CP-odd states as well as spin-zero from higher spin particles [5, 6, 7, 8, 9, 10]. It is also known that the azimuthal angle distribution of the two outgoing forward tagging jets in Higgs production in the vector boson fusion (VBF) process effectively discriminates between the CP quantum numbers of a scalar resonance [11, 12] as well as the spin [10].

In the present paper, we consider Higgs production in the vector boson fusion mechanism, $pp \rightarrow Hjj$, in the presence of an anomalous Higgs–vector boson vertex that parametrises different spin and CP assignments of the produced state. The anomalous $HVV$ coupling is introduced by allowing for an effective Lagrangian with higher dimensional operators, that include four momentum terms which are absent in the SM. We show that the kinematics of the forward tagging jets in this process is highly sensitive to the structure of the anomalous $HVV$ coupling and that it can effectively discriminate between different assignments for the spin (spin-0 versus spin-2) and the parity (CP–even versus CP–odd) of the produced particle.

$^1$Strictly speaking a 0$^{--}$ CP–odd state will not have a tree–level coupling to massive gauge bosons; the coupling is generated through loop corrections and should be thus small. We will nevertheless, for the sake of comparison, follow the current trend and allow for couplings to VV states that are of the same order as those of the SM 0$^{++}$ CP–even state.
We find, in particular, that the correlation between the separation in rapidity and the transverse momenta of the scattered quarks in the VBF process, in addition to the already discussed distribution of the azimuthal jet separation, can be significantly altered compared to the SM expectation. These kinematical variables define new corners of the phase-space that have not been explored by the experiments at the LHC to probe anomalous HVV couplings and check the $J^{PC}$ assignments of the newly observed particle. Some of these observables significantly depend on the center of mass energy and strong constraints on anomalous couplings can be obtained by performing measurements at the LHC with energies of $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV. Finally, we also consider associated Higgs production with a massive gauge boson (VH), $qq \rightarrow VH$ with $V = W^{\pm}$ and $Z$, and show that the invariant mass of the $VH$ system as well as the transverse momenta and rapidities of the $H$ and $V$ bosons are also sensitive to anomalous HVV couplings.

An analysis that is, in some aspects, similar to ours has been recently reported in Ref. [13] and we will discuss the main differences between this study and the one presented here at the end of the paper.

For the rest of this article, the next section describes the physical set-up and sections 3 and 4 our phenomenological analyses in the VBF and VH processes; section 5 summarizes the main findings.

2. The physical set-up

In the SM, the couplings of the Higgs boson to the massive electroweak gauge bosons are precisely formulated and come out as $g_{HVV} \propto g_{M V} V_{\mu} V_{\mu}$ with $g$ the SU(2) coupling constant. However, this is not the most general form of the Higgs–gauge boson vertex. Parametrising the coupling of a scalar state to two vector bosons in the form $i \Gamma_{\mu \nu}(p, q) \epsilon_{\mu}(p) \epsilon^{\ast}_{\nu}(q)$, one can write down the most general form of the $HVV$ vertex as $\Gamma_{\mu \nu}(p, q) = \Gamma_{\mu \nu}^{\text{SM}} + \Gamma_{\mu \nu}^{\text{BSM}}(p, q)$, with the SM and the beyond SM components given by

$$
\Gamma_{\mu \nu}^{\text{SM}} = - g_{M V} g_{\mu \nu} \tag{1}
$$

$$
\Gamma_{\mu \nu}^{\text{BSM}}(p, q) = \frac{g}{M_{V}} [\lambda (p \cdot q g_{\mu \nu} - p_{\nu}q_{\mu}) + \lambda' \epsilon_{\mu \nu \rho \sigma} p^{\rho} q^{\sigma}] \tag{2}
$$

where $\lambda$ and $\lambda'$ are effective coupling strengths for, respectively, higher dimension CP–even and CP–odd operators and we will assume that they are the same for $W$ and $Z$ bosons. These operators may be generated within the SM at higher orders of perturbation theory, although the resulting couplings
are likely to be very small. In general, \( \lambda \) and \( \lambda' \) can be treated as momentum dependent form factors that may also be complex valued. However, we take the approach that beyond the SM (BSM) vertices can be generated from an effective Lagrangian, which treats \( \lambda \) and \( \lambda' \) as coupling constants [11]. The most striking difference between the SM and BSM vertices of eqs. (1) and (2) is that the latter has an explicit dependence on the momentum of the gauge bosons. It is this feature that is the source of the differences that the BSM vertices generate in the kinematic distributions of tagging jets in the VBF and VH processes, compared to the SM case.

In the case of a spin-2 resonance coupling to \( VV \) states, we will follow Ref. [14] and adopt the following effective Lagrangian

\[
L_{\text{eff}} = \frac{1}{\Lambda} T_{\alpha\beta} (f_1 g_{\mu\nu} B^{\mu\alpha} B^{\nu\beta} + f_2 g_{\mu\nu} W^{\mu\alpha} W^{\nu\beta})
\]

where \( T_{\alpha\beta} \) is the spin-2 field and \( B_{\mu\nu}, W_{\mu\nu} \) are the U(1) and SU(2) field strengths, respectively, and \( \Lambda \) corresponds to a cut-off scale which should be set at a value of the order of the TeV scale. The two operators in the equation above do not account for all possible terms of the most general spin-2–VV vertex and one could, for instance, include operators such as \( \partial_\mu \partial_\nu T_{\alpha\beta} (\tilde{B}^{\mu\alpha} B^{\nu\beta} + \tilde{W}^{\mu\alpha} W^{\nu\beta}) \) but which are of higher dimension. We restrict ourselves to the terms proportional to \( f_1 \) and \( f_2 \) of eq. (3), setting the cut-off scale to \( \Lambda = 3 \) TeV in our numerical illustration.

The purpose of our analysis is to identify observables and model independent tendencies in the kinematics of partons due to the anomalous \( HVV \) couplings above in electroweak processes in which the Higgs–like boson is produced in association with two jets, i.e. in vector boson fusion and in associated Higgs production with vector bosons. For a given choice of the spin and parity assignments, we identify regions of the phase–space that would be populated differently by the Higgs–like boson with anomalous couplings compared to the expectation in the SM.

In our analysis, the vertices for the Lagrangians in the SM and in BSM with spin-0 and spin-2 bosons are calculated in FEYNRULES [15] and passed to the program Madgraph [16], which is used for the generation of the matrix elements for Higgs production in VBF and VH. To obtain the cross sections and distributions at the hadronic level, the CTEQ6L1 parton distribution functions are used [17]. For completeness, associated SM Higgs production with two high \( p_T \) jets in the gluon–gluon fusion process (ggF) is also considered; the cross sections and kinematical distributions are obtained using the
MCFM [18] program that incorporates the QCD process $pp \rightarrow H + 2j + X$ at next-to-leading order (NLO). The factorization and normalization scales are set on an event-by-event basis to the transverse energy of the Higgs boson. For the selection cuts, partons are required to have transverse momentum $p_T > 20$ GeV, rapidity $|y| < 4.5$ and be separated by $\Delta R > 0.7$.

3. Spin and parity determination in VBF

The differences in the tensor structure of the different terms in the $HVV$ vertex would significantly impact the kinematic distributions of the tagging jets produced in VBF. For example, in Ref. [11] the difference in azimuthal angle between the scattered quarks ($\Delta \phi_{jj}$) was found to be an effective discriminant for the various terms in eq. (2) for a scalar boson. As we will show below, the momentum dependence of the BSM vertex has further strong implications for a number of hadronic observables. These include the transverse momenta of the tagging partons $p_T^{j_1}, p_T^{j_2}$ and the rapidity difference ($\Delta y_{jj}$) between them. The obvious advantage of looking at such observables is that they do not require a full reconstruction of the Higgs–like boson from its decay products and one can use all the search channels at our disposal at the LHC, including the $H \rightarrow \gamma\gamma$ and $H \rightarrow \tau^+\tau^-$ modes.

In this section we describe the effect on the rapidity and transverse momentum distributions of the jets due to each of the operators of eqs. (2–3), without considering any interference between them. In doing so it is important to understand that the distributions are independent of the strength or sign of the couplings ($\lambda, \lambda', f_1, f_2$) which only affect the value of the total cross-section. The strength of these couplings play an important role when one considers the simultaneous presence of these operators in the $HVV$ vertex and we will discuss this at the end of this section.

Figure 1 displays the difference in rapidity between tagging partons ($\Delta y_{jj}$) for each of the higher dimensional operators.

We see that the rapidity differences for each of the operators are shifted to smaller values. While the BSM $0^+$ and $0^-$ cases display a behavior in this observable that is almost identical, for a spin-2 particle the peak in the $\Delta y_{jj}$ distribution is shifted to even smaller values.

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2 Tagging partons are defined as the scattered quarks in the process $pp \rightarrow Hjj$; at NLO, these are defined as the leading partons in transverse momentum.
Figure 1: Normalized distribution of the difference in rapidity between the scattered quarks in the VBF process for each of the SM (black-solid-line) and BSM operators individually; the spin2 (green-dashed) CP even (red-dotted-dashed) and the CP odd (blue-dotted).

The dramatic behavior of this observable makes it a strong candidate to distinguish between the SM and the BSM vertex structures.

We also observe that the transverse momenta of the tagging partons become significantly larger for pure BSM $0^+$ and $0^-$ states. This feature is more pronounced for a spin-2 state. However, the $M_{jj}$ distributions are not altered and we will thus not display them.

The above mentioned features of the $\Delta y_{jj}$ and $p_T$ distributions are due to the presence of momentum dependent structures in the vertices of eqs. (2,3). The factors involving four momenta in the BSM vertices mean that the momentum flow through the vertex allows for a greater push being given to the jets resulting in a shift of the $p_T$ distribution to larger values. This effect has been observed in Refs. [19, 14] for both the scalar and the spin-2 case.

An analytic calculation of the matrix element reveals that for both the SM and BSM cases, the vector boson propagator can be approximated to $1/((\hat{s} p_T_{j1} p_T_{j2} e^{-\Delta y_{jj}})^2$ for large values of the incoming parton momenta. The effect of this term is to push $p_T$ to smaller values and, at the same time, push $\Delta y_{jj}$ to larger values. For the SM, the remainder of the terms in the square of the matrix element are proportional to $\hat{s} p_T_{j1} p_T_{j2} \text{Cosh}(\Delta y_{jj})$, which further reinforces the occurrence of large rapidity differences.

For $\Gamma^{\text{BSM}}_{\mu\nu}$ of eq. (2), the additional terms have a dependence of the form $(\hat{s} p_T_{j1} p_T_{j2})^2$. This leads to much larger and flatter $p_T$ distributions as
compared to the SM. Although the rapidity dependence for these additional terms is complicated, it can be shown to have an opposite behavior to the propagator terms, unlike the SM case, pushing the rapidity difference to smaller values. Thus, the correlations between $\Delta y_{jj}$ and $p_{Tj1}$, $p_{Tj2}$ and/or $M_{jj}$ critically depends on the tensor structure of the HVV vertex.

This is further illustrated in Fig. 2, where we use the observable $\sqrt{p_{Tj1} \cdot p_{Tj2}}$ in view of the above considerations. This figure also suggests a new region of the phase-space for the exploration of physics beyond the SM in the Higgs sector by using hadronic observables. BSM vertices tend to populate a region of the phase-space where the production of the SM Higgs boson is signifi-

Figure 2: Two-dimensional distributions of the difference in rapidity and the square root of the product of the transverse momenta of the tagging partons. The upper plots correspond to the SM with electroweak (left) and ggF+2j (right) production while the lower plots to an admixture with a BSM $0^+$ state with $\lambda = 1$ (left) and a pure $2^+$ state (right). Points with the same cross-section are indicated with color contours. The level of cross-sections is indicated by the color code in the bar on the right of each of the plots. Thus area with the largest and lowest cross-sections is indicated with dark red and dark blue respectively.
Table 1: Acceptance, expected cross-sections (in fb) and the ratio of BSM Higgs boson cross-section to that in the SM populating the BSM electroweak region ($\Delta y_{jj} < 4$ and $\sqrt{p_{T1} \cdot p_{T2}} > 100$ GeV). Pure BSM states are considered. The cross-sections are given for the $H \to \gamma\gamma$ decay and 8 TeV center of mass energy (see text).

- The QCD region in which the production of $ggF+2j$ is dominant. Here, the partons tend to be close in rapidity and display moderate $p_T$ with $<\sqrt{p_{T1} \cdot p_{T2}} >\approx 50$ GeV. In this corner of the phase-space, associated Higgs production with a vector boson with $V \to jj$ contributes as a sub-leading process for which $<\sqrt{p_{T1} \cdot p_{T2}} >\approx 45$ GeV.

- The SM VBF region which is populated by the SM Higgs boson produced via the VBF process. This corresponds to intermediate $p_T$ tagging partons with $<\sqrt{p_{T1} \cdot p_{T2}} >\approx 55$ GeV with a large separation in rapidity of $<\Delta y_{jj} >\approx 4.5$. Production of additional central partons is depleted, which is a typical signature of electroweak processes.

- The BSM electroweak region which populates a corner of the phase-space defined by $3\sqrt{p_{T1} \cdot p_{T2}} > 100$ GeV and $\Delta y_{jj} < 4$. The VBF and VH production channels can be separated by requiring that the invariant mass of the leading partons be away from the weak boson invariant mass. A distinct BSM VBF region is defined where electroweak-like gluon radiation is expected to occur. This feature is important to further differentiate and suppress QCD Higgs boson production.

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3The separation in rapidity in the BSM electroweak region tends to be somewhat larger compared to that displayed by $ggF+2j$ production. For instance, $<\Delta y_{jj} >\approx 2.1$ for a pure BSM $0^+$ state compared to $<\Delta y_{jj} >\approx 1.7$ for $ggF+2j$. 
Table I displays the acceptance of the SM Higgs boson and other BSM pure states in the BSM electroweak region. The latter is defined as $\Delta y_{jj} < 4$ and $\sqrt{p_{Tj1} \cdot p_{Tj2}} > 100 \text{ GeV}$, where tagging partons are required to have $p_T > 25 \text{ GeV}$ and $|y| < 5$.

The table shows the acceptance of each process, separating the VBF and VH mechanisms. The BSM cross-sections are assumed to be the same as the one for electroweak SM $H j j$ production which is normalized to the NNLO–QCD value $[20]$; all cross sections are given for the $H \rightarrow \gamma \gamma$ decay.

The SM Higgs boson production displays acceptances$^4$ of less than 10%. In this process, additional gluons are radiated more copiously than in the electroweak processes. The fraction of the events in the BSM electroweak region that survive a veto on additional gluons with $p_T > 25 \text{ GeV}$ and $|y| < 5$ is $50^{+30}_{-25}\%$. The last row gives the ratio of the BSM contribution to that of the SM, where only electroweak processes are taken into account. In order to give a rough estimate of the signal significance for different scenarios with the $H \rightarrow \gamma \gamma$ decay, the non-resonant production of two photons and two partons is modeled with Madgraph $[16]$. The cross-sections of pure BSM signals, of background and the corresponding signal significance are scanned as a function of the lower bound on $\sqrt{p_{Tj1} \cdot p_{Tj2}}$.

It is found that for pure BSM scalar states maximal significance is obtained with $\sqrt{p_{Tj1} \cdot p_{Tj2}} \gtrsim 100 \text{ GeV}$ and for a pure spin-2 state is obtained for $\sqrt{p_{Tj1} \cdot p_{Tj2}} \gtrsim 300 \text{ GeV}$. Assuming 8 TeV center of mass energy and 25 fb$^{-1}$ of integrated luminosity, a significance of approximately 1.4 $\sigma$ and 5 $\sigma$ can be achieved for the pure BSM scalar and spin-2 cases considered here, respectively. This sensitivity is achieved with signal-to-background ratios of 0.08 and 1.5 for the pure BSM scalar and spin-2 states, respectively. This is defined in the di-photon invariant mass window $120 < M_{\gamma \gamma} < 130 \text{ GeV}$.

It is important to note that the experiments at the LHC currently do not explore the BSM electroweak region. This region is vetoed by requiring a large separation in rapidity of the tagging partons, in order to isolate the SM VBF process.

Another discriminating feature is the relative increase of the cross-section with the energy of the collisions. This feature can be studied when the LHC begins its higher energy run. Figure 3 shows how the ratio of the cross-

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$^4$The acceptance of the ggF process is reported with respect to the generator cuts given in section 2.
sections at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV for the higher dimension operators differ from the SM case as the lower cutoff on the value of the di-parton invariant mass ($M_{jj}$) is changed (x-axis of the plot).

The advantage of using these ratios, besides that they are free from many systematics [21], is that they are independent of the values of the couplings $\lambda, \lambda', f_1$ and $f_2$. This ratio is greater than unity and rises with the $M_{jj}$ cut for all the SM and BSM cases under consideration. For the spin-0 case this ratio is larger for the BSM operators as compared to SM. This occurs in spite of the total cross-section (without the application of any cuts) rising at the same rate (an increase by a factor of 2.3 from 8 TeV to 13 TeV) with $\sqrt{s}$ for $\Gamma_{\mu\nu}^{SM}$ as well as each of the terms in $\Gamma_{\mu\nu}^{BSM}$.

This result is a mere consequence of the difference in the energy dependence of the acceptance for different spin-parity combinations.

As noted above for spin-2, the increase is much larger ($\approx 7$) and in fact the ratios of cross-sections grow much more rapidly for large values of the $M_{jj}$ cut. This raises a concern about possible violation of unitarity for large $M_{jj}$ values. However, there are several ways in which the spin-2 model can be unitarised. If the unitarisation prescription were to cut off the phase space concerned with large transverse momentum of the jets, then the $\Delta y_{jj}$ distributions

![Figure 3: Left: ratio of the cross-sections of the VBF process at $\sqrt{s} = 13$ TeV to that obtained at $\sqrt{s} = 8$ TeV as a function of the lower bound on the invariant mass of the scattered quarks $M_{jj}$; results are shown for SM (black solid line) and compared to those of the pure BSM $0^+$ (red-dotted-dashed) $0^-$ (blue-dotted) and spin 2 (green-dashed) states. Right: the distributions of the rapidity difference of the scattered quarks for three different values of the upper bound on $M_{jj}$. In all plots a bound $M_{jj} > 200$ GeV has been set.](image)
would shift to larger values simply due to the kinematic structure of the VBF mechanism. However, in a reasonable model, the unitarisation may also be implemented such that large values of $M_{jj}$ are cut off. In this case, the peak in the $\Delta y_{jj}$ distributions at small values will remain as shown in the right panel of Fig. 3.

So far, our discussion was independent of the strength of the couplings in the $HVV$ vertex. While this coupling strength is fixed in the SM, it is not the case for the BSM couplings and clearly this will affect the actual values of the cross-sections. Setting $\lambda = 0.4$, $\lambda' = 0.47$ and $f_1 = 0.37 = f_2$ ensures that $\sigma_{SM} \approx \sigma_{BSM}$. An additional complication is worth noting. The acceptance for these operators are not the same in the same regions of phase space and caution is needed when correlating the number of observed events to a total cross-section. For example, applying an $M_{jj}$ cut removes more events from the additional operators than from SM. One must be more careful with the total rate when looking at admixtures of these operators, which is possible only for the spin-0 case. The value of $\sigma_{BSM}$ may increase or decrease depending on the sign, magnitude and on whether the couplings are real or complex.

A cleaner discrimination between the SM and BSM may be possible when the information on rates is supplemented with that on the kinematic distributions. To this end let us now consider effect on these, of the simultaneous

Figure 4: Normalized distributions of the difference in rapidity between the scattered quarks in VBF production: the SM Higgs case (solid lines) is compared with the case of BSM admixtures with a $0^+$ term (left) and a $0^-$ term (right) as discussed in the text.
presence of both SM and BSM operators. Of course, this can happen only for spin-0. In Fig. 4, the left panel compares the expectation from the SM (solid line) with an admixture with a BSM $0^+$ scalar with $\lambda = 1$ (dashed line) and $\lambda = i$ (dotted line). The right panel shows the same for the $0^-$ scalar with $\lambda' = 0.1 \cdot i$ and $\lambda' = 0.1$. Only the strength of the coupling, and not the choice of BSM operators, affect this distribution. Hence, the plot on the right would look the same if a $0^-$ operator instead of the $0^+$ one were used along with SM. $\Delta y_{jj}$ can therefore effectively be used to differentiate a SM from a momentum dependent $HVV$ vertex, for larger values of these couplings. The plot on the left illustrates the fact that for not so small values of $\lambda, \lambda'$, it is no longer possible to disentangle the SM Higgs boson from admixtures with BSM states using rapidity distributions. However, the angular correlation $\Delta \phi_{jj}$ still shows small deviations from the SM case for $\lambda' = 0.1$. One should note that the difference in the $\Delta \phi_{jj}$ distributions can be enhanced by looking at events with large $p_Tj > 80$ GeV. A similar observation is valid for comparable values of $\lambda$.

An important and interesting observation when considering admixtures of the BSM operators with SM is that for a certain choice of the parameters, $SM = 1$ and $\lambda = \lambda' = 1$, the $\Delta \phi_{jj}$ distribution becomes indistinguishable from the SM case. Although this is a special case and the cross-section is much larger here, it accentuates the importance of the $\Delta y_{jj}$ distribution and makes it necessary to complement them with $\Delta \phi_{jj}$ distributions.

### 4. Kinematics in the VH mechanism

Recently, the invariant mass of the di-boson system in associated Higgs production with a vector boson has been suggested as a useful observable to distinguish the case of a SM Higgs boson from pure BSM $0^-$ and $2^+$ states Ref. [22]. We briefly survey the effect of admixtures of the SM operator with the BSM CP–even and CP–odd operator in the case of the VH production mechanism.

Figure 5 shows the invariant mass of the di-boson system, as well as the transverse momentum and the separation in rapidity between the Higgs and vector bosons. It compares the prediction for the SM Higgs boson and different admixtures with the CP even operator. With the enhancement of the boson transverse momentum, the overlap with the BSM electroweak region increases, as illustrated in Tab. [1].
Figure 5: Invariant mass of the Higgs and the weak boson (left), the transverse momentum of the boson (center) and the separation in rapidity between the bosons (right). The solid line corresponds to the SM Higgs boson. The blue dashed, green dotted-dashed and red dotted lines correspond to admixtures of the SM Higgs boson with a scalar CP-even state with $\lambda = 1, 0.5$ and $0.1$, respectively.

We see that along with the invariant mass of the system, the rapidity difference and the transverse momentum of the bosons are also useful observables to identify the nature of the $HVV$ interactions. Both the BSM CP-even and CP-odd operators behave identically and tend to push all three distributions to larger values. With diminishing value of the BSM couplings these distributions tend to become more like the SM distributions, making it harder to determine the BSM couplings at the LHC. However unlike the rapidity difference shown in Fig. 4 for VBF, these observables are more sensitive to the vertex structure.

5. Conclusions

Probing the spin and CP structure of the recently discovered boson at the LHC is of prime importance. In this paper, the sensitivity to physics beyond the SM via anomalous Higgs couplings to weak bosons is considered, where contributions from admixtures of BSM spin-0 and spin-2 states to the $HVV$ coupling are tested. A phenomenological survey is performed by exploring various observables in the electroweak production of the Higgs boson with two high $p_T$ jets. It is found that the kinematics of the tagging jets in the vector boson fusion mechanism is strongly modified in the presence of momentum dependent anomalous $HVV$ couplings. In particular, compared to the SM, the correlation between the separation in rapidity and the transverse momenta of the scattered quarks varies significantly in the presence of new
physics. The separation in rapidity is reduced while the transverse momenta becomes significantly larger. In addition, there is some complementarity between the behavior of the azimuthal and rapidity separation between the scattered quarks. This defines a new corner of the phase-space that has not been explored by the ATLAS and CMS experiments to test the spin and CP structure of the Higgs to vector boson coupling.

When this analysis was in the completion stage, Ref. [13] appeared on the archives, wherein the use of the rapidity separation $\Delta y_{jj}$ to distinguish between various CP and spin states is also advocated. In our paper, we have in addition investigated the effect of anomalous couplings on the correlations between $\sqrt{p_{Tj1}p_{Tj2}}$ and $\Delta y_{jj}$, thereby uncovering new regions of phase-space for exploiting the VBF production process. Besides showing that the acceptance of the VBF process to the $M_{jj}$ cut is different for different spin and parity assignments, we have evaluated how the acceptance (and hence the various kinematical variables) varies with the center of mass energy of the proton-proton collision and explored the use of relative rates between 13 TeV and 8 TeV LHC to sharpen up the differences. Finally, in addition to the VBF process, we have also considered associated Higgs production with vector bosons and shown that some kinematical variables such as the invariant mass of the $VH$ system are sensitive to anomalous couplings too.

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