HIGGS + 2 JETS AS A PROBE FOR CP PROPERTIES

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Abstract
Azimuthal angle correlations of the jets in Hjj events at the LHC provide a probe of the CP nature of Higgs couplings to gauge bosons. In weak boson fusion the HWW and HZZ couplings are tested. Gluon fusion processes probe the tensor structure of the effective Hgg vertex and thus the CP nature of the dominant quark couplings.

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At the LHC, one would like to experimentally determine the CP nature of any previously discovered (pseudo)scalar resonance. Such measurements require a complex event structure in order to provide the distributions and correlations which can distinguish between CP-even and CP-odd couplings. This can either be done by considering decays, e.g. $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ and the correlations of the decay leptons [1, 2], or one can study correlations arising in the production process. Here the azimuthal angle correlations between the two additional jets in $Hjj$ events have emerged as a promising tool [3]. In the following we consider the prospects for using $\Phi jj$ events at the LHC, where $\Phi$ stands for either a CP even boson, H, or a CP odd state, A. Two production processes are considered. The first is vector boson fusion (VBF), i.e. the electroweak process $qQ \rightarrow qQ\Phi$ (and crossing related ones) where $\Phi$ is radiated off a $t$-channel electroweak boson. The second is gluon fusion where $\Phi$ is produced in QCD dijet events, via the insertion of a heavy quark loop which mediates $gg \rightarrow \Phi + 0, 1, 2$ gluons.

The CP properties of a scalar field are defined by its couplings and here we consider interactions with fermions as well as gauge bosons. Within renormalizable models the former are given by the Yukawa couplings

$$\mathcal{L}_Y = y_f \bar{\psi} H \psi + \bar{y}_f \bar{\psi} A \gamma_5 \psi,$$

where $H$ (and $A$) denote (pseudo)scalar fields which couple to fermions $\psi = t, b, \tau$ etc. In our numerical analysis we consider couplings of SM strength, $y_f = y_f = m_f / v = y_{SM}$. Via these Yukawa couplings, quark loops induce effective couplings of the (pseudo)scalar to gluons which, for (pseudo)scalar masses well below quark pair production threshold, can be described by the effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{y_f}{y_{SM}} \cdot \frac{\alpha_s}{12\pi v} \cdot H C_{\mu\nu}^a G^a_{\mu\nu} + \frac{\bar{y}_f}{y_{SM}} \cdot \frac{\alpha_s}{16\pi v} \cdot A C_{\rho\sigma}^a G^a_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma}.$$  \hspace{1cm} (2)

Similar to the $\Phi gg$ coupling, Higgs couplings to $W$ and $Z$ bosons will also receive contributions from heavy particle loops which can be parameterized by the effective Lagrangian

$$\mathcal{L}_5 = \frac{f_o}{\Lambda_5} H \bar{W}_\mu W^\mu + \frac{f_o}{\Lambda_5} A \bar{W}_\mu W^\mu \frac{1}{2} \varepsilon^{\mu\nu\rho\sigma}.$$  \hspace{1cm} (3)

For most models, one expects a coupling strength of order $f_i / \Lambda_5 \sim \alpha/(4\pi v)$ for these dimension 5 couplings and, hence, cross section contributions to vector boson fusion processes which are suppressed by factors $\alpha / \pi$ (for interference effects with SM contributions) or $(\alpha / \pi)^2$ compared to those mediated by the tree level $HVV$ ($V = W, Z$) couplings of the SM. However, together with the tree level couplings, the effective Lagrangian of Eq. (3) has the virtue that it parameterizes the most general $\Phi VV$ coupling which can contribute in the vector boson fusion process $qQ \rightarrow qQ\Phi$ and, thus, is a convenient tool for phenomenological discussions and for quantifying, to what extent certain couplings can be excluded experimentally. Neglecting terms which vanish upon contraction with the conserved quark currents, the most general tensor structure for the fusion vertex $V^\mu(q_1) V^\nu(q_2) \rightarrow \Phi$ is given by

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) [q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] + a_3(q_1, q_2) \varepsilon^{\mu\nu\alpha\beta} q_{1\alpha} q_{2\beta}.$$  \hspace{1cm} (4)

Here the $a_i(q_1, q_2)$ are scalar form factors, which, in the low energy limit, are given by the effective Lagrangian of Eq. (3). One obtains, e.g. for the $W^+ W^- \Phi$ coupling, $a_2 = -2f_o / \Lambda_5$ and $a_3 = 2f_o / \Lambda_5$, while $a_1 = 2m_W^2 / v$ is the SM vertex.

The CP-even and CP-odd couplings of Eqs. (2,3) lead to characteristic azimuthal angle correlations of the two jets in $\Phi jj$ production processes. Normalized distributions of the azimuthal angle between the two jets, $\Delta \phi_{jj}$, are shown in Fig. 1 for vector boson fusion (left panel) and for gluon fusion processes (right panel) leading to $\Phi jj$ events: A CP-odd coupling suppresses the cross section for planar events because the epsilon tensor contracted with the four linearly dependent momentum vectors of the incoming and outgoing partons disappears. For a CP-even coupling the dip, instead, appears at 90 degrees [3, 5]. Unfortunately, when both CP-even and CP-odd couplings are present simultaneously,
the two $\Delta \phi_{jj}$ distributions simply add, i.e. one does not observe interference effects. The dip-structure which is present for pure couplings is, thus, washed out.

This behavior is demonstrated in Fig. 2. For CP-even and CP-odd couplings of the same strength, i.e. $f_e = f_o$, the azimuthal angle distribution is very similar to the SM case. However, in order to test the presence of anomalous couplings in such cases, other jet distributions can be used, e.g. transverse momentum distributions. The $\Delta \phi_{jj}$ distribution is quite insensitive to variations of form factors, NLO corrections and the like [6]. On the other hand, $p_T$ distributions depend strongly on form factor effects. We study these effects for a particular parameterization of the momentum dependence:

\[ a_2(q_1, q_2) = a_3(q_1, q_2) \sim M^2 C_0 (q_1, q_2, M), \quad (5) \]

where $C_0$ is the familiar Passarino-Veltman scalar three-point function [7]. This ansatz is motivated by the fact that the $C_0$ function naturally appears in the calculation of one-loop triangle diagrams, where the mass scale $M$ is given by the mass of the heavy particle in the loop. As can be seen in the right panel of Fig. 2 even for a mass scale $M$ of the order of 50 GeV the anomalous couplings produce a harder $p_T$ distribution of the tagging jets than is expected for SM couplings. Thus it is possible to experimentally distinguish EW vector boson fusion as predicted in the SM from loop induced $WW\Phi$ or $ZZ\Phi$ couplings by the shape analysis of distributions alone.

Let us now consider the gluon fusion processes where, for $\Phi tt$ couplings of SM strength, one does expect observable event rates from the loop induced effective $\Phi gg$ couplings [5]. In order to assess the visibility of the CP-even vs. CP-odd signatures of the azimuthal jet correlations at the LHC, we consider Higgs + 2 jet production with the Higgs decaying into a pair of $W$-bosons which further decay leptonically, $\Phi \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu\bar{\nu}$. We only consider electrons and muons ($\ell = e^{\pm}, \mu^{\pm}$) in the final state. The Higgs-mass is set to $m_\Phi = 160$ GeV. From previous studies on Higgs production in vector boson fusion [4] the main backgrounds are known to be top-pair production i.e. $pp \rightarrow t\bar{t}, t\ell j, t\ell jj$ [8]. The three cases distinguish the number of $b$ quarks which emerge as tagging jets. The $t\bar{t}$ case corresponds to both bottom-quarks from the top-decays being identified as forward tagging jets, for $t\ell j$ production only one tagging jet arises from a $b$ quark, while the $t\ell jj$ cross section corresponds to both tagging jets

Fig. 1: Left: Normalized distributions of the azimuthal angle between the two tagging jets, for the $\Phi \rightarrow WW \rightarrow e\mu p_T$ signal in vector boson fusion at $m_\Phi = 160$ GeV, from Ref. [3]. Curves are for the SM and for single D5 operators as given in Eq. (3), after cuts as in Ref. [4]. Right: The same for Higgs production in gluon fusion at $m_\Phi = 120$ GeV. Curves are for CP-even and CP-odd $\Phi tt$ coupling.
arising from massless partons. Further backgrounds arise from QCD induced $W^+W^- + 2$ jet production and electroweak $W^+W^-jj$ production. These backgrounds are calculated as in Refs. [9] and [10], respectively. In the EW $W^+W^-jj$ background, Higgs production in VBF is included, i.e. the VBF Higgs signal is considered as a background to the observation of $Φjj$ production in gluon fusion. We do not consider backgrounds from $Zjj$, $Z→ττ$ and from $b¯¯bjj$ production because they have been shown to be small in the analyses of Refs. [4, 11].

Table 1: Signal rates and background cross sections for $m_Φ = 160$ GeV. Results are given for the inclusive cuts of Eq. (6), the additional selection cuts of Eq. (7) and b-quark identification as discussed in the text, and with the additional $Δη_{jj}$ cut of Eq. (10) which improves the sensitivity to the CP nature of the $Φtt$ coupling. The events columns give the expected number of events for $L_{int} = 30$ fb$^{-1}$.

| process                     | inclusive cuts $σ$ [fb] | selection cuts $σ$ [fb] | selection cuts + Eq. (10) $σ$ [fb] | events / 30 fb$^{-1}$ | events / 30 fb$^{-1}$ |
|-----------------------------|-------------------------|-------------------------|-----------------------------------|------------------------|------------------------|
| GF $pp→Φ+jj$               | 121.2                   | 39.2                    | 1176                              | 13.1                   | 393                    |
| VBF $pp→W^+W^- + jj$       | 75.2                    | 20.8                    | 624                               | 17.4                   | 521                    |
| $pp→tt$                    | 6832                    | 29.6                    | 888                               | 2.0                    | 60                     |
| $pp→tt+j$                  | 9712                    | 56.4                    | 1692                              | 15.6                   | 468                    |
| $pp→tt+jj$                 | 1200                    | 8.8                     | 264                               | 3.2                    | 97                     |
| QCD $pp→W^+W^- + jj$       | 364                     | 15.2                    | 456                               | 3.9                    | 116                    |

The inclusive cuts in Eq. (6) reflect the requirement that the two tagging jets and two charged leptons are observed inside the detector, and are well-separated from each other.

\[ p_{Tj} > 30 \text{ GeV}, \quad |η_j| < 4.5, \quad |η_{j1} - η_{j2}| > 1.0 \]

\[ p_{Tℓ} > 10 \text{ GeV}, \quad |η_ℓ| < 2.5, \quad ΔR_{jℓ} > 0.7 \]  

Fig. 2: Normalized distributions of the tagging jets in EW vector boson fusion with anomalous couplings and for a Higgs mass of $m_Φ = 120$ GeV. Typical VBF cuts of $p_{Tj} > 30$ GeV, $|η_j| < 4.5$, $|η_{j1} - η_{j2}| > 4.0$, $m_{jj} > 600$ GeV are applied. Left: Azimuthal angle distribution between the two tagging jets, for different strengths of the operators of Eq. (3). Right: Transverse momentum distribution of the hardest tagging jet for $f_e = f_o = 1$ and a form factor as in Eq. (5). The “no formfactor” curve corresponds to the limit $M → ∞$, i.e. a constant $a_i$. 

The events columns give the expected number of events for $L_{int} = 30$ fb$^{-1}$.
The resulting cross sections for these cuts are shown in Table I. The signal cross section of 121 fb (which includes the branching ratios into leptons) is quite sizeable. The QCD $W W jj$ cross section is about 3 times higher whereas the VBF process reaches 2/3 of the signal rate. The worst source of background arises from the $t \bar{t}$ processes, with a total cross section of more than 17 pb.

In order to improve the signal to background ratio the following selection cuts are applied:

\[
p_{T\ell} > 30 \text{ GeV}, \quad m_{\ell\ell} < 75 \text{ GeV}, \quad \Delta R_{\ell\ell} < 1.1
\]

\[
m_{WW}^{T} < 170 \text{ GeV}, \quad m_{\ell\ell} < 0.5 \cdot m_{WW}^{T}.
\]

Here, the transverse mass of the dilepton-$p_{T}$ system is defined as [4]

\[
m_{WW}^{T} = \sqrt{(E_{T} + E_{T,\ell\ell})^2 - (p_{T,\ell\ell} + p_{T})^2}
\]

in terms of the invariant mass of the two charged lepton and the transverse energies

\[
E_{T,\ell\ell} = (p_{T,\ell\ell}^2 + m_{\ell\ell}^2)^{1/2}, \quad E_{T} = (p_{T}^2 + m_{\ell\ell}^2)^{1/2}.
\]

In addition to these cuts we make use of a b-veto to reduce the large top-background. We reject all events where at least one jet is identified as a b-jet. Using numbers from Ref. [12], we assume b-tagging efficiencies in the range of 60% – 75% (depending on b-rapidity and transverse momentum) and an overall mistagging probability of 10% for light partons.

With the selection cuts and the b-veto the backgrounds can be strongly suppressed. Table I shows the resulting cross sections and the expected number of events for an integrated luminosity of $L_{\text{int}} = 30 \text{ fb}^{-1}$. The signal rate is reduced by a factor of 3 but the backgrounds now have cross sections of the same order as the signal. The largest background still comes from the $t \bar{t}$ processes, especially $t \bar{t} + 1 j$. For 30 fb$^{-1}$ we get about 1000 signal events on top of 4000 background events. This corresponds to a purely statistical significance of the gluon fusion signal of $S/\sqrt{B} \approx 18$ and a sufficient number of events to analyze the azimuthal jet correlations.
Fig. 3 shows the expected $\triangle \phi_{jj}$ distribution for 30 fb$^{-1}$. Plotted are signal events on top of the various backgrounds. An additional cut on the rapidity gap between the jets

$$|\eta_{j1} - \eta_{j2}| > 3.0$$

has been applied. It enhances the shape of the distribution that is sensitive to the nature of the $\Phi_{tt}$ coupling. Clearly visible, the distribution for the CP-even coupling has a slight minimum at $\triangle \phi_{jj} = 90^\circ$ whereas for the CP-odd case there is a pronounced maximum. In order to quantify this, we define the fit-function

$$f(\triangle \phi) = C \cdot (1 + A \cdot \cos 2\triangle \phi + B \cdot \cos \triangle \phi)$$

with free parameters $A$, $B$, $C$. The fit is shown as black curves in Fig. 3. The parameter $A$ is now a measure for the $\triangle \phi_{jj}$ asymmetry, i.e. whether there is a CP-even or CP-odd $\Phi_{tt}$ coupling. The fitted values are $A = 0.064 \pm 0.035$ for the CP-even and $A = -0.157 \pm 0.034$ for the CP-odd case, while $A_B = -0.039 \pm 0.040$ for the sum of all backgrounds. Defining a significance $s$ as

$$s = \frac{(A_{S+B} - A_B)}{\Delta A_{S+B}},$$

we get $s = 3.0$ and $s = -3.4$ for the CP-even and CP-odd case, respectively. Thus, a distinction of a CP-odd and CP-even $\Phi_{tt}$ coupling is possible at a 6$\sigma$ level for the considered process and a Higgs mass of 160 GeV. This implies that, at least for favorable values of the Higgs boson mass, (i) an effective separation of VBF and gluon fusion sources of $\Phi_{jj}$ events is possible and (ii) the CP nature of the $\Phi_{tt}$ coupling of Eq. (1) can be determined at the LHC.

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