

Determining the Structure of Higgs Couplings at the CERN Large Hadron Collider

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Higgs boson production via weak boson fusion at the CERN Large Hadron Collider has the capability to determine the dominant CP nature of a Higgs boson, via the tensor structure of its coupling to weak bosons. This information is contained in the azimuthal angle distribution of the two outgoing forward tagging jets. The technique is independent of both the Higgs boson mass and the observed decay channel.

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The CERN Large Hadron Collider (LHC) is generally regarded as a tool that can guarantee direct observation of a Higgs boson, the remnant of the mechanism believed responsible for electroweak symmetry breaking and fermion mass generation, and the last unobserved element of the standard model (SM) of elementary particle physics. Furthermore, the LHC promises complete coverage of Higgs decay scenarios [1], including general minimal supersymmetry standard model (MSSM) parametrizations [1,2], and even invisible Higgs decays [3]. This capability has been greatly enhanced recently by the addition of the weak boson fusion (WBF) production channel to the search strategies [2,4,5]. While being extremely useful at the LHC, WBF has too low a rate and is too similar to background processes at the Fermilab Tevatron [6].

Observation of a resonance in some expected decay channel is, however, only the beginning of Higgs physics. At least as important is the detailed study of the properties of this resonance, not only at a future linear collider [7] but also at the LHC: determination of all the quantum numbers and couplings of the state. These include the gauge, Yukawa and self-couplings as well as the charge, color, spin, and CP quantum numbers. Charge and color identification is straightforward and a technique has been proposed for the gauge and Yukawa coupling determinations [8]. The measurement of CP transformation properties of couplings is more difficult. Investigations of the $t\bar{t}H$ vertex become severely limited by statistics at the Higgs boson masses of present interest [9], and past proposals for the CP study of couplings to weak bosons rely on $H \rightarrow VV$ decays above threshold [10].

In this Letter we propose a technique which identifies the tensor structure of the Higgs weak boson vertex in the intermediate mass range, via a study of WBF events. WBF Higgs production, while not the largest cross section at the LHC, is useful because of its characteristic kinematical structure, involving two forward tagging jets and central Higgs decay products, which allows one to isolate the signal in a low background environment. The angular distribution of the two tagging jets carries unambiguous information on the CP properties of the Higgs couplings to weak bosons which is independent of the Higgs decay channel observed.

As a theoretical framework we consider two possible ways to couple a spin zero field to two gauge bosons via higher-dimensional operators. In a gauge invariant dimension six (D6) Lagrangian, the terms

$$\mathcal{L}_6 = \frac{g^2}{2\Lambda_{e,6}^2} (\Phi^\dagger \Phi) V_{\mu\nu} V^{\mu\nu} + \frac{g^2}{2\Lambda_{o,6}^2} (\Phi^\dagger \Phi) \tilde{V}_{\mu\nu} V^{\mu\nu} \quad (1)$$

lead to anomalous couplings between the Higgs-type scalar and two charged gauge bosons [11]. The scales Λ_e and Λ_o set the coupling strength of CP -even and CP -odd scalars, respectively. The Feynman rules can be read off the dimension five (D5) operators that result when Φ is given a physical field expansion:

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}} HW_{\mu\nu}^+ W^{-\mu\nu} + \frac{1}{\Lambda_{o,5}} H\tilde{W}_{\mu\nu}^+ W^{-\mu\nu} \quad (2)$$

and similarly for the Z boson. The two scales are related via $1/\Lambda_5 = g^2 v/\Lambda_6^2$. Since we assume $SU(2)$ invariance and do not consider additional D6 operators such as $\Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu}$, the WWH and ZZH couplings are related by the same $\cos^2\theta_W$ factor as in the SM. The two operators in Eqs. (1) and (2), together with the SM HVV coupling, give the most general tensor structure of the HVV coupling which can contribute to $qq \rightarrow qqH$ for massless quarks.

In principle, one would have to introduce a form factor to ensure the unitarity of scattering amplitudes involving these operators. However, we have checked that at the LHC the typical p_T of the tagging jets, for WBF processes generated by the D5 operators, remains comparable to the SM case and is well below the scale Λ , which we assume to be of the order of a few hundred GeV or above. Thus, form-factor effects would remain small in a more complete treatment and they would not distort the angular distributions to be discussed below.

The analog of the CP -even operators is present in Higgs production through gluon fusion, as $HG_{\mu\nu}G^{\mu\nu}$, and gives an excellent approximation for the ggH coupling induced by heavy quark (and squark) loops. In the low energy limit the D5 operators also appear in the one-loop WWH coupling, but their size is suppressed by a factor $\alpha_W/\pi \sim 10^{-2}$ which is not observable at the LHC.

Another source would be a Higgs-like top pion that is a general feature of top color models [12] and which couples to weak bosons such as $\Pi \tilde{W}_{\mu\nu}^+ W^{-\mu\nu}$ with a coefficient that is considerably larger than in the SM and is expected to lead to observable rates of production in the WBF channel.

For a true Higgs boson the WWH and ZZH couplings originate from the kinetic energy term of the symmetry breaking field, $(D_\mu \Phi)^\dagger (D^\mu \Phi)$, which mediates couplings proportional to the metric tensor. This tensor structure is not gauge invariant by itself and identifies the Higgs field as the remnant of spontaneous symmetry breaking. It is thus crucial to distinguish it from the effective couplings derived from Eq. (1). Since the partons in the WBF processes,

$$pp \rightarrow qq'H \rightarrow qq'\tau\tau, \quad qq'WW, \quad qq'\gamma\gamma, \quad (3)$$

are approximately massless, the production cross section is proportional to the Higgs weak boson coupling squared. Replacing the $g^{\mu\nu}$ coupling with a higher-dimensional coupling changes the kinematical structure of the final state scattered quarks.

To illustrate this we consider leptonic final states in $H \rightarrow \tau\tau$ decays as in Ref. [2]. We emphasize the $H \rightarrow \tau\tau$ decay channel because it is resilient to modifications of the Higgs sector as encountered in the MSSM: a luminosity of 40 fb^{-1} guarantees coverage of the entire $(m_A - \tan\beta)$ plane after combining the leptonic and semileptonic decay channels of the tau pair [2]. The basic set of cuts on the outgoing partons consists of

$$\begin{aligned} p_{T_j} &\geq 20 \text{ GeV} & \Delta R_{jj} &\geq 0.6 & |\eta_j| &\leq 4.5 \\ |\eta_{j_1} - \eta_{j_2}| &\geq 4.2 & \eta_{j_1} \cdot \eta_{j_2} &< 0, \end{aligned} \quad (4)$$

in addition to the separation and acceptance cuts for the decay leptons, which we do not discuss here. (Further cuts on the invariant mass of the tagging jets and the tau pair decay kinematics are necessary to extract the signal. These details and the final step of reconstructing the tau pair invariant mass are currently under study by various CMS and ATLAS groups, with very encouraging results [13].) In the parton level analysis we are left with a cross section of $\sigma \sim 0.5 \text{ fb}$ for a 120 GeV SM Higgs boson, leading to $S/B = 2.7/1$ and a Gaussian significance $\sigma_{\text{Gauss}} = 6.8$ for 60 fb^{-1} of data [2]. The two largest backgrounds are QCD and electroweak $\tau\tau jj$ production, which together are $\lesssim 30\%$ of the signal cross section after cuts. The other backgrounds, including $H \rightarrow WW$ and $t\bar{t} + \text{jets}$, are of minor importance and can safely be neglected in the following qualitative analysis.

Let us first assume that a Higgs-like scalar signal is found at the LHC in this channel at the expected SM rate. We must experimentally distinguish a SM $g^{\mu\nu}$ -type coupling from the tensor structures implied by the D5 operators of Eq. (2). A SM rate induced by one of the D5 operators requires a scale $\Lambda_5 \approx 480 \text{ GeV}$ ($\Lambda_6 \approx 220 \text{ GeV}$). A particularly interesting kinematic variable

is the azimuthal angle $\Delta\phi_{jj}$ between the two tagging jets. For forward scattering, which is dominant due to the W -propagator factors, the remaining SM matrix element squared for $qq \rightarrow qqH$ is proportional to $\hat{s}m_{jj}^2$, where m_{jj} is the invariant mass of the two tagging jets. This leads to an essentially flat azimuthal angle distribution between the two jets, as shown in Figs. 1 and 2. In the $H \rightarrow \tau\tau$ case, a slight bias toward small angles is introduced by selection cuts, which require a substantial transverse momentum for the Higgs boson. The major backgrounds, Zjj production with $Z \rightarrow \tau\tau$, possess mostly back-to-back tagging jets.

For the CP -odd D5 operator, the shape of the distribution follows from the presence of the Levi-Civita tensor in the coupling: it gives a nonzero result only if there are four independent momenta in the process (here, the four external parton momenta). For planar events, i.e., for tagging jets which are back-to-back or collinear in the transverse plane, the matrix element vanishes.

The CP -even operator given in Eq. (2) develops a special feature for forward tagging jets. In the limit of $|p_z^{(\text{tag})}| \gg |p_{x,y}^{(\text{tag})}|$ and small energy loss of the two scattered quarks, we can approximate the matrix element by

$$\begin{aligned} \mathcal{M}_{e,5} &\propto \frac{1}{\Lambda_{e,5}} J_1^\mu J_2^\nu [g_{\mu\nu}(q_1 \cdot q_2) - q_{1\nu}q_{2\mu}] \\ &\sim \frac{1}{\Lambda_{e,5}} [J_1^0 J_2^0 - J_1^3 J_2^3] \mathbf{p}_T^{(\text{tag}1)} \cdot \mathbf{p}_T^{(\text{tag}2)}, \end{aligned} \quad (5)$$

where q_i, J_i are the momenta and currents of the intermediate weak gauge bosons. For $\Delta\phi_{jj} = \pi/2$ the last term vanishes, leading to an approximate zero in the distribution. From the three curves shown in Fig. 1 we conclude that the azimuthal angle distribution is a gold-plated observable for determining the dominant CP nature and the tensor structure of the Higgs coupling. With 100 fb^{-1}

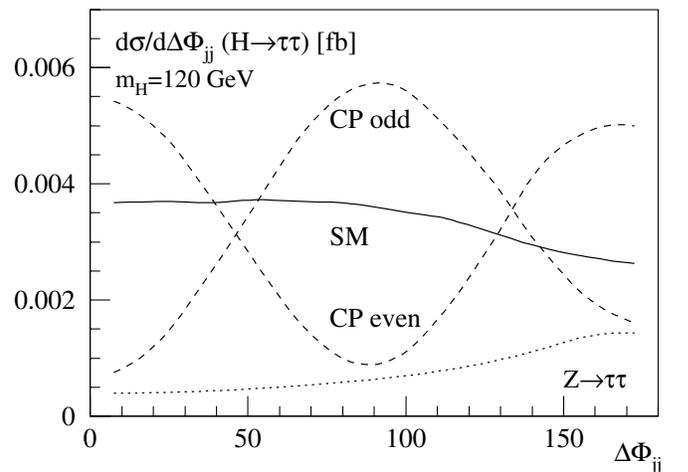


FIG. 1. Azimuthal angle distribution between the two tagging jets for the signal and dominant $\tau\tau$ backgrounds, $m_H = 120 \text{ GeV}$. Cross sections for the D5 operators correspond to $\Lambda_5 = 480 \text{ GeV}$, which reproduces the SM cross section, after cuts, as shown in Eq. (4) and Ref. [2]. The expected SM background is added to all three Higgs curves.

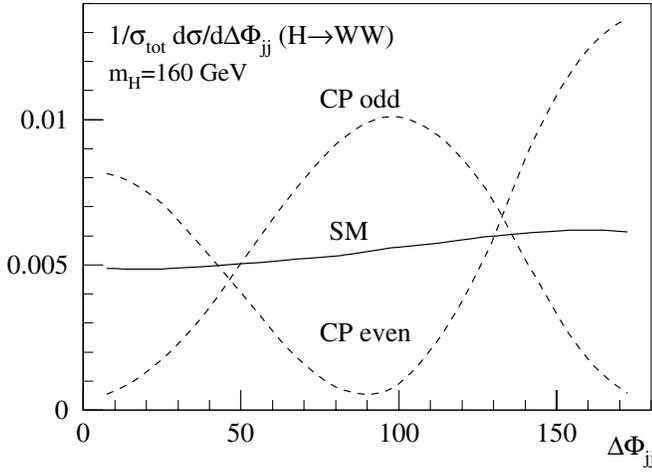


FIG. 2. Normalized distributions of the azimuthal angle between the two tagging jets, for the $H \rightarrow WW \rightarrow e\mu\cancel{p}_T$ signal at $m_H = 160$ GeV. Curves are for the SM and for single D5 operators as given in Eq. (2), after cuts as in Eq. (4) and Ref. [5].

of data per experiment, the SM case can be distinguished from the CP -even (CP -odd) D5 couplings with a statistical power of ~ 5 (4.5) sigma, from the $H \rightarrow \tau\tau$ channels [2] alone. *This observable is furthermore independent of the particular decay channel and Higgs mass range.* We have explicitly checked the case of a 160 GeV Higgs boson decaying to W pairs and find exactly the same features (shown in Fig. 2). Note, however, that in this case decay distributions will depend on the structure of the HWW vertex also.

Let us now examine the following scenario: a Higgs candidate is found at the LHC with a predominantly standard model $g^{\mu\nu}$ coupling. How sensitive will experiments be to any additional D5 contribution?

For the CP -odd D5 coupling we do not observe any interference term between the standard model and the D5 matrix element. Although there is a nonzero contribution at the matrix element level, any hadron collider observable is averaged over charge conjugate processes since we cannot distinguish quark from antiquark jets. As a result, interference effects largely cancel. Using the azimuthal angle distribution will only marginally enhance the sensitivity to a small contribution of the CP -odd Higgs coupling beyond what a measurement of the Higgs production cross section could give.

In the case of a contribution from a CP -even D5 operator, interference effects are important for the distortion of the ϕ_{jj} distribution. All additional terms in the squared amplitude $|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}} + \mathcal{M}_{e,5}|^2$ have an approximate zero at $\Delta\phi_{jj} = \pi/2$, according to Eq. (5). Moreover, the dominant piece of the anomalous amplitude changes sign at this approximate zero which results in a sign change of the interference term at $\pi/2$. Figure 3 shows that, dependent on the sign of the D5 operator, the maximum of the distribution is shifted to large or small angles $\Delta\phi_{jj}$. Results are shown for two different values of the scale Λ_5 which are chosen such that the D5

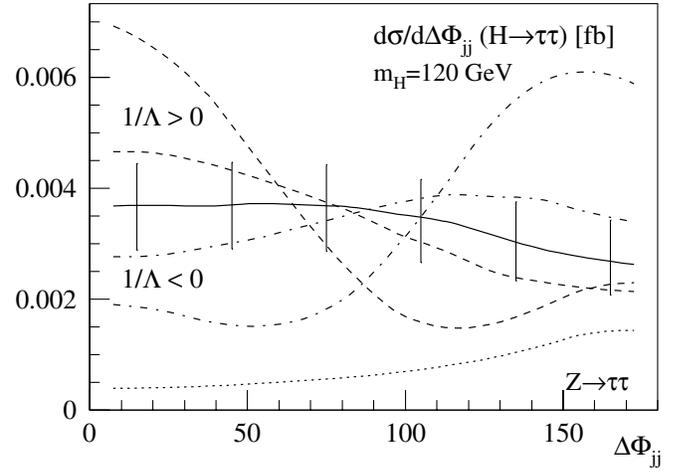


FIG. 3. Azimuthal jet angle distribution for the SM and interference with a CP -even D5 coupling. The two curves for each sign of the operator correspond to values $\sigma/\sigma_{\text{SM}} = 0.04, 1.0$. Error bars for the signal and the dominant backgrounds correspond to an integrated luminosity of 100 fb^{-1} per experiment, distributed over six bins, and are statistical only.

operator alone, without a SM contribution, would produce a Higgs production cross section, σ , which equals 0.04 (1.0) of the SM cross section, σ_{SM} . While changes in cross sections of a few percent are most likely beyond the reach of any LHC counting experiment, we see that in the differential cross section the effect of D5 operators is quite significant [14].

To quantify this effect and at the same time minimize systematic errors we define the asymmetry

$$A_\phi = \frac{\sigma(\Delta\phi_{jj} < \pi/2) - \sigma(\Delta\phi_{jj} > \pi/2)}{\sigma(\Delta\phi_{jj} < \pi/2) + \sigma(\Delta\phi_{jj} > \pi/2)}. \quad (6)$$

One major source of systematic uncertainty will be the gluon fusion-induced $H + 2$ jet background, which in the large top mass limit is proportional to the CP -even D5 operator $HG_{\mu\nu}G^{\mu\nu}$. This operator induces the same azimuthal angle dependence of the two jets as the CP -even operator of Eq. (2). However, since it contributes to $H + 2$ jets via t -channel gluon (color octet) exchange, it cannot interfere with WWF. This gluon fusion contribution can exceed $\mathcal{O}(10\%)$ of the signal after cuts [15] and is expected to have large higher order QCD corrections [16]. The measurement of the absolute rate of WWF events would therefore be systematics limited, due to the unknown K factor for the gluon fusion contamination. Assuming that this K factor does not vary with $\Delta\phi_{jj}$, a full shape analysis of the azimuthal angle distribution allows one to distinguish this noninterfering gluon fusion background from an interfering D5 HWW coupling: the asymmetry is dominated by the interference terms.

In Fig. 4 we compare the sensitivity to D5 couplings expected from the total cross section and the azimuthal asymmetry, respectively. In the integrated cross section, interference effects between the SM $g^{\mu\nu}$ coupling and the CP -even D5 coupling largely cancel. With 100 fb^{-1} per

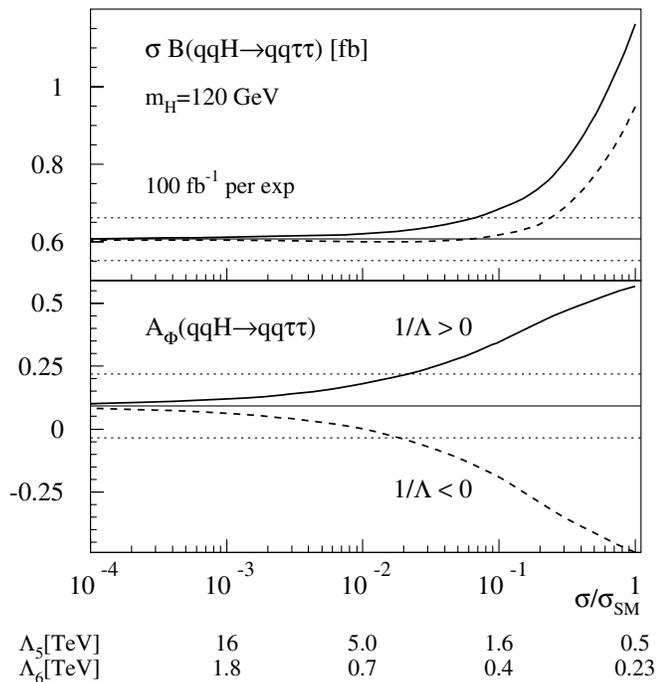


FIG. 4. Comparison of the sensitivity of a total cross section (counting) experiment and the azimuthal angle asymmetry, Eq. (6), to the presence of a CP -even D5 coupling. The horizontal lines represent one-sigma statistical deviations from the SM value. The secondary axes show the corresponding values of Λ_5 and Λ_6 , as defined in Eqs. (1) and (2).

experiment, a total cross section measurement at the LHC is sensitive to (at the $1\text{-}\sigma$ level, and considering statistical errors only) $\Lambda_{e,6} < 510$ GeV ($1/\Lambda > 0$) or 290 GeV ($1/\Lambda < 0$). In contrast, A_ϕ is a much more sensitive observable, and equally sensitive to positive and negative Λ . For both signs of the D6 coupling the reach in the leptonic $\tau\tau$ channel is ~ 690 GeV, significantly better than the counting experiment. A rough estimate shows that, for a 120 GeV Higgs boson, the LHC will be sensitive to $\Lambda_6 \sim 1$ TeV, after adding the statistics of the $\tau\tau$ [2], the WW [5], and the $\gamma\gamma$ [4] WBF channels. This reach could be improved by increasing the LHC integrated luminosity beyond 100 fb^{-1} , or at a high luminosity linear collider [7].

In summary, the weak boson fusion production process is not only a competitive discovery channel for an intermediate mass Higgs boson, it also offers the opportunity to unveil the structure of the Higgs field's coupling to gauge bosons. Using information obtained with generic weak boson fusion cuts for the intermediate-mass Higgs search, one can unambiguously determine the CP nature of a Higgs-like scalar: the azimuthal angle distribution between the tagging jets clearly distinguishes the standard model $g^{\mu\nu}$ coupling from a typical loop-induced CP -even or CP -odd coupling. In a search for dimension five operators which interfere with the SM HWW coupling, an asymmetry analysis of this azimuthal angle distribution improves the reach far beyond what is possible in a counting experiment, including the determination of the sign of the additional coupling.

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