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Determining the Structure of Higgs Couplings at the LHC

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Abstract

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.

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 [1,2], including general MSSM parameterizations [1,3], and even invisible Higgs decays [4]. This capability has been greatly enhanced recently by the addition of the weak boson fusion (WBF) production channel to the search strategies [3,5,6].

Observation of a resonance in some expected decay channel is, however, only the beginning of Higgs physics. Continuing efforts will include the search for more than one Higgs boson, as predicted e.g. by two-Higgs doublet models, of which the MSSM [7,8] is a subset. At least as important is the detailed study of the properties of the Higgs-like resonance, not only at a future Linear Collider [9] 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. While charge and color identification is straightforward and a technique has been proposed for the gauge and Yukawa coupling determinations [10], the LHC has considerable difficulty in practice to determine the Higgs CP transformation properties for intermediate Higgs masses [11], and no technique has yet been proposed to identify the tensor structure of the Higgs-weak boson vertex in the intermediate mass range.

In this letter we propose a technique which achieves this last goal 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 a Higgs-like scalar which is independent of the Higgs decay channel observed.

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

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

lead to anomalous couplings between the Higgs-type scalar and two charged gauge bosons [12]. 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:

$$\mathcal{L}_5 = \frac{1}{\Lambda_{\mathrm{e},5}} \; H \; W^+_{\mu\nu} W^{-\,\mu\nu} + \frac{1}{\Lambda_{\mathrm{o},5}} \; H \; \widetilde{W}^+_{\mu\nu} W^{-\,\mu\nu} \tag{2}$$

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 like $\Phi^\dagger\Phi \;\; B_{\mu\nu}B^{\mu\nu}$, the WWH and ZZH couplings are related by the same $\cos^2\theta_W$ factor as in the SM.

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 order 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 D5 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 $\alpha_W/\pi \sim 10^{-2}$ and hence not observable at the LHC, as we will see later. Another source would be a Higgs-like top-pion that is a general feature of topcolor models [13] and which couples to weak bosons like $\Pi \widetilde{W}^+_{\mu\nu} W^{-\,\mu\nu}$ 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.

One particularly nice feature appears once we require U(1) and SU(2) gauge invariance of the higher dimensional operators: the set of D6 operators in Eq. (1) would give rise to a direct $\gamma\gamma H$ coupling. This might dramatically enhance the Higgs branching fraction to photons, thus speeding up observation in the WBF production mode [5]. In addition, the azimuthal asymmetry, to be defined below, would make it possible to identify the nature of the additional coupling unambiguously [14].

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

$$pp \to qq'H \to qq'\tau\tau, \;\; qq'WW, \;\; qq'\gamma\gamma \tag{3}$$

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.

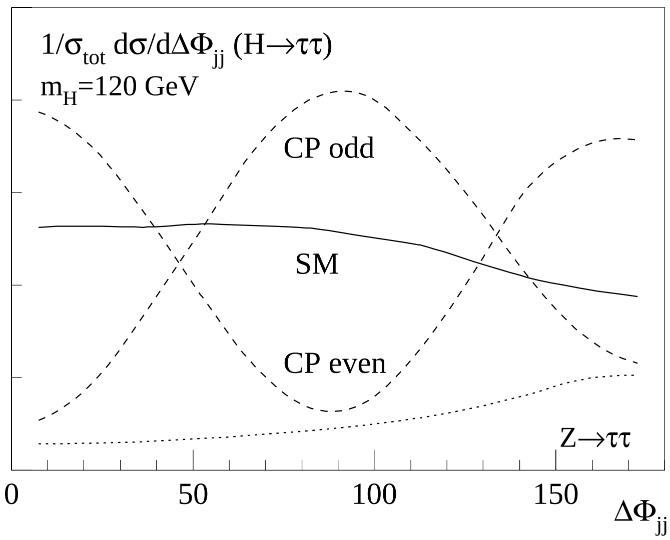

Figure 1. Azimuthal angle distribution between the two tagging jets for the signal and dominant $\tau\tau$ backgrounds, $M_H = 120$ GeV. Cross sections for the D5 operators are normalized to the SM value, after cuts as in Eq.(4) and Ref. [3]. The expected SM background is added to all three Higgs curves.

To illustrate this we consider leptonic final states in $H \to \tau\tau$ decays as in Ref. [3]. We emphasize the $H \to \tau\tau$ 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 $(m_A\text{-}\tan\beta)$ plane after combining the leptonic and semileptonic decay channels of the tau pair [3]. The basic set of cuts on the outgoing partons consists of

$$\begin{aligned} p_{T_j} \geq 20 \text{ GeV} \qquad \triangle R_{jj} \geq 0.6 \qquad |\eta_j| \leq 4.5 \\ |\eta_{j_1} - \eta_{j_2}| \geq 4.2 \qquad \eta_{j_1} \cdot \eta_{j_2} < 0 \end{aligned} \tag{4}$$

in addition to the separation and acceptance cuts for the decay leptons, which we don't 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 [15].) In the parton level analysis we are left with a cross section of $\sigma \sim 0.5$ fb for a 120 GeV SM Higgs boson, leading to a Gaussian significance $\sigma_{\text{Gauss}} = 6.8$ and $S/B = 2.8/1$ [3]. 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 $H \to WW$ and $t\bar{t}+$ jets, are of minor importance and can safely be neglected in the following qualitative analysis.

1. 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 scales of order $\Lambda_5 \sim 500$ GeV ($\Lambda_6 \sim 230$ GeV). A particularly interesting kinematic variable is the azimuthal angle $\Delta\phi_{\text{jj}}$ between the two tagging jets. For forward scattering, which is dominant due to the W-propagator factors, the remaining SM matrix element squared for $qq \to qqH$ is proportional to $\hat{s}\ m_{jj}^2$, where m_{jj} is the invariant mass of the two

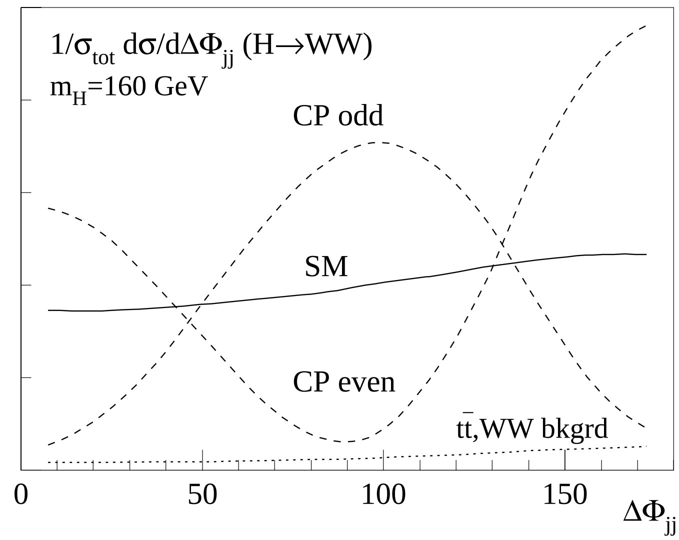

Figure 2. As in Fig. 1, for $H \to WW \to l\bar{\nu}\bar{l}\nu$ at $M_H = 160$ GeV, with acceptance cuts as in Eq.(4) and Ref. [6]. The dominant backgrounds are $t\bar{t}$+jets and electroweak WW production.

tagging jets. This leads to an essentially flat azimuthal angle distribution between the two jets, as shown in Figs. 1 and 2. In the $H \to \tau\tau$ 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 $Z \to \tau\tau$, 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 $|p_z^{(\rm tag)}| \gg |p_{x,y}^{(\rm tag)}|$ and small energy loss of the two scattered quarks, we can approximate the matrix element by

$$\begin{aligned} \mathcal{M}_{\rm e,5} &\propto \frac{1}{\Lambda_{\rm e,5}} J_1^\mu J_2^\nu \;\left[g_{\mu\nu}(q_1 \cdot q_2) - q_{1\nu} q_{2\mu} \right] \\ &\sim \frac{1}{\Lambda_{\rm e,5}} \left[J_1^0 J_2^0 - J_1^3 J_2^3 \right] \mathbf{p}_{\rm T}^{(\rm tag1)} \cdot \mathbf{p}_{\rm T}^{(\rm tag2)} \end{aligned} \qquad (5)$$

where q_i, J_i are the momenta and currents of the intermediate weak gauge bosons. For $\Delta\phi_{\rm jj} = \pi/2$ 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. *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. Utilizing this observable does not involve any reconstruction or manipulation beyond what is necessary to extract the WBF signal in the first place.

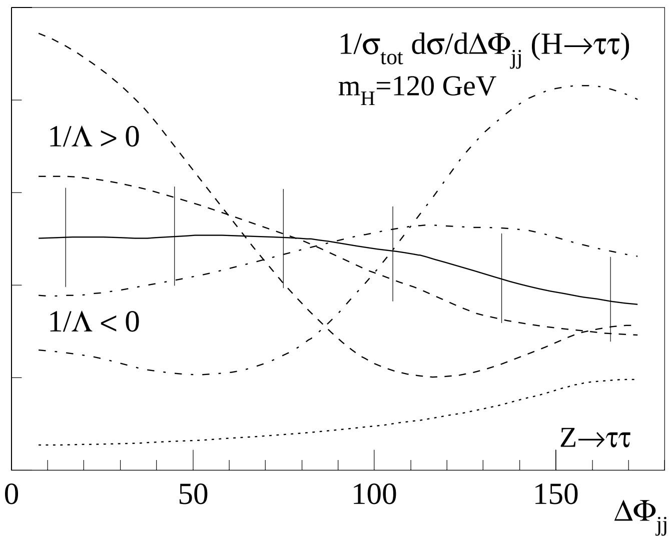

Figure 3. Azimuthal jet angle distribution for the SM and interference with a CP even D5 coupling. The two curves for each sign of the operator correspond to values $\sigma/\sigma_{\rm SM} = 0.04, 1.0$. Error bars for the signal and the dominant backgrounds correspond to an integrated luminosity of 100 fb^{-1} per experiment, distributed over 6 bins, and are statistical only.

2. 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 non-zero 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 cancel in any hadronic differential cross sections. 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 $\phi_{\rm jj}$ distribution. All additional terms in the squared amplitude $|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM} + \mathcal{M}_{\rm e,5}|^2$ have an approximate zero at $\Delta\phi_{\rm jj} = \pi/2$, 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 $\pi/2$. Fig. 3 shows that, dependent on the sign of the D5 operator, the maximum of the distribution is shifted to large or small angles $\Delta\phi_{\rm jj}$. Results are shown for two different values of the scale Λ_5 which are chosen such that the D5 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, $\sigma_{\rm SM}$. 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

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

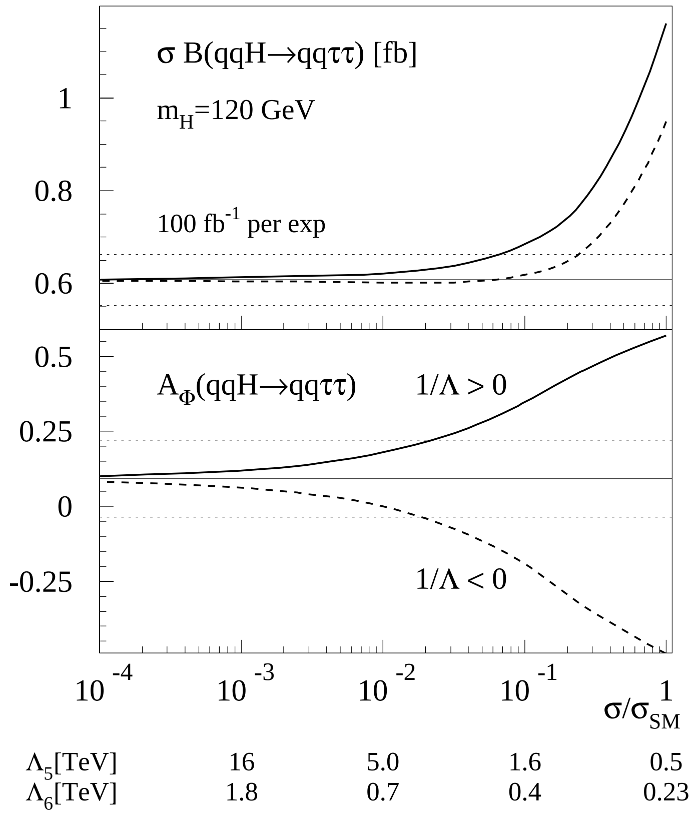

Figure 4. Comparison between a total cross section (counting) experiment and the azimuthal angle asymmetry, Eq.(6), to determine an interference with a CP even D5 coupling. The horizontal lines represent one sigma statistical deviations from the SM value. The secondary axes show the corresponding values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

One major source of systematic uncertainty will be the gluon fusion induced $H + 2$ jets background, which in the large top mass limit is proportional to the CP even D5 operator $HG_{\mu\nu}G^{\mu\nu}$. At the amplitude level, 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 WBF. This gluon fusion contribution can exceed $\mathcal{O}(10\%)$ of the signal after cuts [17] and is expected to have large higher order QCD corrections [16]. The measurement of the absolute rate of WBF 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 to distinguish this noninterfering gluon fusion background from an interfering D5 HWW coupling: the asymmetry is dominated by the interference terms. As mentioned before there is a loop induced WWH coupling, but it is expected to contribute with size $\sigma \sim (\alpha/\pi)^2 \ \sigma_{SM}$, beyond the reach of even a linear collider precision experiment [9].

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 experiment, a total cross section measurement at the LHC is sensitive (at the 1-σ level, and considering statistical errors only) to $\Lambda_{e,5} < 2.5$ TeV ($1/\Lambda > 0$) or 0.8 TeV ($1/\Lambda < 0$). In contrast, A_ϕ is a much more sensitive observable, and equally sensitive to positive and negative Λ. For both signs of the D5 coupling the reach in the leptonic $\tau\tau$ channel is ~ 4.5 TeV, significantly better than the counting experiment. A rough estimate shows that the possible reach for a 120 GeV Higgs boson will reach $\Lambda_5 \sim 10$ TeV, after adding the statistics of both $\tau\tau$ [3], the WW [6], and the $\gamma\gamma$ [5] WBF channels. This would lead to a reach similar to the linear collider analysis [9].

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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