Azimuthal Angle Probe of Anomalous HWW Couplings at a High Energy ep Collider

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A high energy ep collider, such as the proposed LHeC, possesses the unique facility of permitting direct measurement of the HWW coupling without contamination from the HZZ coupling. At such a machine, the fusion of two W bosons through the HWW vertex would give rise to typical charged current events accompanied by a Higgs boson. We demonstrate that azimuthal angle correlations between the observable charged current final states could then be a sensitive probe of the nature of the HWW vertex and hence of the CP properties of the Higgs boson.

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The Higgs boson has long been sought as the cornerstone to the entire mechanism of electroweak symmetry breaking [1] in the Standard Model (SM) [2]. The hunt has been long and frustrating, but since the announcement of the latest search results by the experimental collaborations [3], we now know that a new boson has been found with a mass of around 126 GeV and that this boson resembles the Higgs boson of the SM. By the end of the current year we may have enough data to identify this particle as a Higgs boson H^0 with couplings proportional to mass-which in turn will provide very convincing evidence that the electroweak symmetry is indeed spontaneously broken through a scalar doublet Φ acquiring a nonzero vacuum expectation value. However, mere identification as a Higgs boson is not enough, for it will leave open a host of other questions, such as whether this scalar is elementary or composite, CP conserving or CP violating, and so on. Of course, the minimal SM has only one physical scalar H^0, with $J^{PC} = 0^{++}$, but this, like so much else in the SM, is essentially an *ad hoc* assumption made with a view towards economy of fields and interactions, rather than the product of any deeper understanding of the underlying physics. It will, therefore, be necessary to test the spin and CP properties of the new boson experimentally, before we can truly identify it with the Higgs boson of the SM.

The all-important question of how the symmetry breaking is transmitted from the scalar sector to the gauge sector is answered in the SM by having gauge boson-scalar couplings arising from the assignment of nontrivial gauge quantum numbers to the scalar fields in the theory. As a result, the couplings of the H^0 to the heavy electroweak gauge bosons $W^\pm$ and Z^0 are precisely formulated in the SM, and come out as [2]

$$\mathcal{L}_{\text{int}} = -gM_W\left(W_\mu W^\mu + \frac{1}{2\cos\theta_W} Z_\mu Z^\mu\right)H. \tag{1}$$

Since g, M_W, and θ_W are all accurately measured, this vertex is fully determined in the SM. However, if we wish to confirm that the SM mechanism for breaking electroweak symmetry is the correct one, we would require an independent measurement of these vertices. This is easier said than done, though, because (a) one will require the production of a substantial number of Higgs bosons through these electroweak vertices, which will require the accumulation of considerable statistics before a precision result can be claimed, and more importantly because (b) these vertices are sensitive to the presence of new physics beyond the SM, with corrections occurring mostly at the one-loop level. If we parametrize the $H(k) - W_\mu^+(p) - W_\nu^-(q)$ vertex in the general form

$$i\Gamma^{\mu\nu}(p,q)\epsilon_\mu(p)\epsilon_\nu^*(q), \tag{2}$$

any deviations from the simple SM formula $\Gamma^{\mu\nu}_{(\text{SM})}(p,q) = -gM_W g^{\mu\nu}$ in Eq. (1)-at a level incompatible with SM radiative corrections-would immediately indicate the presence of new physics beyond the SM (BSM). Following Ref. [4], we can parametrize these deviations using two dimension-5 operators

$$\Gamma^{\text{BSM}}_{\mu\nu}(p,q) = \frac{g}{M_W}[\lambda(p\cdot q g_{\mu\nu} - p_\nu q_\mu) + i\lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma], \tag{3}$$

where λ and λ' are, respectively, the effective coupling strengths for the anomalous CP-conserving and the CP-violating operators. One can make [4] a similar parametrization for the $H(k) - Z_\mu(p) - Z_\nu(q)$ vertex, with another pair of unknown couplings $\tilde{\lambda}$ and $\tilde{\lambda}'$ and the replacement $M_W \to M_Z$. We can even have a $H\gamma\gamma$ vertex with yet another pair of unknown couplings [5]. This last will vanish in the SM at tree level, but it certainly appears at the one-loop level, where it is well known to provide one of the cleanest channels [3] to search for the H^0.

The above parametrization of anomalous HWW and similar couplings illustrates the important point that the CP properties of the Higgs boson are rather difficult to measure directly, but will be known if we can determine the couplings λ and λ' to any degree of certainty. A survey of the literature throws up several suggestions [6–8] on how this can be done at colliders, mostly using angular correlations between the final states. An additional complication arises, however, as all the observables studied so far in the context of hadronic colliders [6,7,9], as well as the electron positron colliders [8,9], are dependent on more than one of these couplings. Thus, even if a deviation from the SM prediction is observed, it will be difficult to disentangle the responsible vertex in such studies [7,8,10]. As pointed out in Refs. [11,12], a study of $e^+e^- \to t\bar{t}H^0$ production offers the possibility of a clear and unambiguous determination of the CP properties of the H^0; however, at the LHC this process may be accessible only in the high energy and luminosity phase. However, it is interesting to note that the production of a Higgs boson in the WW fusion process in the charged current (CC) reactions $e + p \to \nu H^0 X$ [13,14] or $\nu + p \to e H^0 X$ [15] arises only from a single Feynman diagram involving the HWW vertex as shown in Fig. 1 for $e + p \to \nu_e + X + H(b\bar{b})$. These modified charged current processes not only provide the best way to observe the $H \to b\bar{b}$ decay, but also render the measurement of the HWW vertex free from possible contamination by contributions from HZZ or $H\gamma\gamma$ vertices. Moreover, the ep collision has an additional advantage over the LHC in that the initial states would be asymmetric. Thus, we can disentangle backward scattering from forward scattering and study these separately, which is not possible at the LHC. In this Letter, therefore, we focus on the measurement of the HWW vertex in such CC events at the high-energy high-luminosity ep collider envisaged in the LHeC proposal [13], where a high energy ($\sim$ 50–150 GeV) beam of electrons would be made to collide with the multi-TeV beams from the LHC. Such a machine will have a center-of-mass energy as high as 1–1.5 TeV and can therefore produce H^0 events copiously [13,14].

A glance at Fig. 1 will show that the final state has missing transverse energy (MET) and three jets J_1, J_2, and J_3, of which two (say J_2 and J_3) can be tagged as b jets. At the parton level, the squared and spin-summed-averaged matrix element for the process

$$e^-(k_1) + q(k_2) \to \nu_e(p_1) + q'(p_2) + H(p_3)$$

can now be worked out to be

$$\begin{aligned}\overline{|\mathcal{M}|^2} = {}& \left(\frac{4\pi^3\alpha^3}{\sin^6\theta_W}\right)\frac{1}{M_W^2(\hat{t}_1 - M_W^2)^2(\hat{u}_2 - M_W^2)^2} \times [4M_W^4\hat{s}\hat{s}_1 + \lambda^2\{\hat{t}_1\hat{u}_2(\hat{s}^2 + \hat{s}_1^2 + \hat{t}_1\hat{u}_2 - 2\hat{t}_2\hat{u}_1) + (\hat{s}\hat{s}_1 - \hat{t}_2\hat{u}_1)^2\} \\ & + 2\lambda M_W^2(\hat{s} + \hat{s}_1)(\hat{s}\hat{s}_1 + \hat{t}_1\hat{u}_2 - \hat{t}_2\hat{u}_1) + \lambda'^2\{\hat{t}_1\hat{u}_2(\hat{s}^2 + \hat{s}_1^2 - \hat{t}_1\hat{u}_2 + 2\hat{t}_2\hat{u}_1) - (\hat{s}\hat{s}_1 - \hat{t}_2\hat{u}_1)^2\} \\ & - 2\lambda' M_W^2(\hat{s} - \hat{s}_1)(\hat{s}\hat{s}_1 + \hat{t}_1\hat{u}_2 - \hat{t}_2\hat{u}_1) + 2\lambda\lambda'\hat{t}_1\hat{u}_2(\hat{s}_1^2 - \hat{s}^2)], \end{aligned} \tag{4}$$

where the invariant variables are defined by $\hat{s} = (k_1 + k_2)^2$, $\hat{t}_1 = (k_1 - p_1)^2$, $\hat{u}_1 = (k_1 - p_2)^2$, $\hat{s}_1 = (p_1 + p_2)^2$, $\hat{t}_2 = (k_2 - p_1)^2$, and $\hat{u}_2 = (k_2 - p_2)^2$. The first term inside the square brackets is the SM contribution and is, of course, just the beta decay matrix element. The other terms include direct and interference BSM contributions of both CP-conserving and CP-violating types and even a crossed term between the two types of BSM contributions.

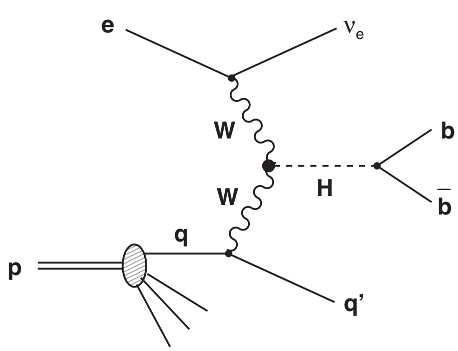

FIG. 1. Higgs boson production at an ep collider through WW fusion and the HWW vertex.

The expression in Eq. (4), though exact, is not very transparent. It can be shown In Ref. [4], however, that in the limit when there is practically no energy transfer to the W bosons and the final states are very forward, the CP-conserving (CP-violating) coupling λ (λ') contributes to the matrix element for this process a term of the form

$$\mathcal{M}_\lambda \propto +\lambda\vec{p}_{T1}.\vec{p}_{T2}, \qquad \mathcal{M}'_\lambda \propto -\lambda'\vec{p}_{T1}.\vec{p}_{T2}, \tag{5}$$

where $\vec{p}_{T1}$ is the vector of the missing transverse energy. These terms $\mathcal{M}_\lambda$ and $\mathcal{M}'_\lambda$ both go through a zero when the azimuthal angle $\Delta\varphi_{\text{MET-}J}$ between the non-b jet J_1 (arising from the parton q') and the missing transverse energy is $\pi/2$ or $3\pi/2$. When $\mathcal{M}_\lambda$ and $\mathcal{M}'_\lambda$ are added to the relatively flat (in $\Delta\varphi_{\text{MET-}J}$) SM background, one predicts a curve with a peak (dip) around $\Delta\varphi_{\text{MET-}J} \approx 0(\pi)$ for the λ operator and the opposite behavior for the λ' operator, when the signs of λ, λ' are positive and vice versa when they are negative. The exact behavior is illustrated in Fig. 2, which was generated for the case of a 140 GeV electron colliding with a 6.5 TeV proton and setting the Higgs boson mass to 125 GeV. Since the approximations which reduce Eq. (4) to Eq. (5) are somewhat too drastic, these curves show the expected qualitative behavior but the peaks (dips) are somewhat displaced from the values quoted above.

In generating these 'theoretical' distributions, no kinematic cuts were applied. The choices of λ, $\lambda' = 0, \pm 1$ in Fig. 2 are completely *ad hoc*-in a specific BSM model the actual value can vary considerably-but they serve the purposes of illustration well. Of course, the precise value of λ (or λ') is crucial to any actual study-in the limit $\lambda \to 0$ (or $\lambda' \to 0$) we would naturally get distributions which are practically indistinguishable from the SM prediction. In our subsequent analysis, we shall see how we can constrain the values of λ, λ' in a model-independent way. We find it convenient to study the cases of CP-conserving anomalous couplings and CP-violating anomalous couplings separately, for the CP-conserving λ term will be generated even in the SM at the one-loop level, whereas the CP-violating λ' will arise at this order only if there is new BSM physics. Thus, in Fig. 2, we consider $\lambda \neq 0$ when $\lambda' = 0$ and vice versa.

In this, and the subsequent numerical analysis, we are careful to use the exact formulae in Eq. (4), convoluted with parton density functions (PDFs) from the CTEQ6L set [16] as well as the MSTW-2008 set [17]. PDF errors were estimated by running over all the available CTEQ6L and MSTW LO data sets. We found that Hessian errors and differences in fitting techniques between the CTEQ and MSTW PDFs do lead to fairly significant overall changes in the overall cross section, but when it comes to the normalized distributions in azimuthal angle of Fig. 2, the differences turn out to be so small that they can practically be absorbed in the thickness of the lines shown in Fig. 2. We do not, therefore, include PDF uncertainties in our error analysis. It is also worth noting that if we vary the Higgs boson mass between 120–130 GeV, the production cross section changes somewhat, but again this hardly affects the normalized distributions shown in Fig. 2.

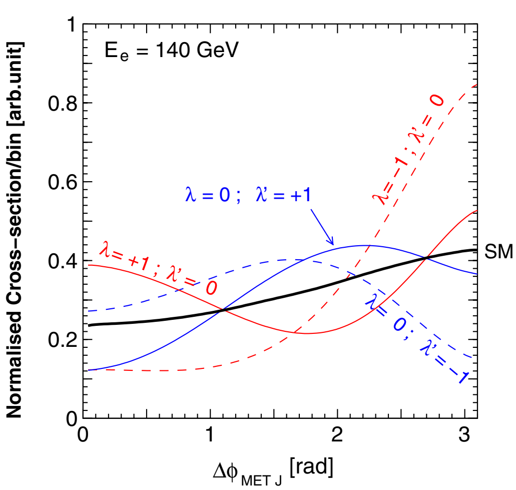

FIG. 2 (color online). Azimuthal angle distributions in the SM and with anomalous HWW couplings.

In order to go beyond the simple-minded parton-level study, however, it is necessary to apply kinematic cuts and simulate the fragmentation of the partons to jets, before a realistic estimate of the sensitivity of this process to λ and λ' can be estimated. These effects tend to distort the characteristic curves shown in Fig. 2-but not enough to disrupt their qualitative differences. Instead of making a detailed simulation of the fragmentation processes, however, we have smeared the partonic energies with the hadronic energy relative resolution $\sigma_E/E = \sqrt{\alpha^2/E + \beta^2}$, where $\alpha = 0.6\ \mathrm{GeV}^{1/2}$ and $\beta = 0.03$. This leads to a resolution of about 7% on the invariant mass of the Higgs boson if we do not smear the angular distribution of the jets. Once this is done, we make a detailed simulation based on the exact kinematic criteria and efficiencies adopted in Ref. [14], which studies the same process from the point of view of determining $Hb\bar{b}$ coupling for a SM Higgs boson. These criteria may be summarized as follows: (1) It is required that $MET > 25$ GeV. (2) Two b partons with $p_T^b > 30$ GeV and $|\eta_b| < 2.5$ must be present. The invariant mass of these b partons must lie within 10 GeV of the Higgs boson mass. (3) Of the remaining partons, the leading one must have $p_T > 30$ GeV and $1 < \eta < 5$. This will be called the forward tagging parton. (4) We require $\Delta\varphi_{\mathrm{MET}-J} > 0.2$ rad for all the jets (J). (5) A veto on leptons ($\ell = e, \mu, \tau$) with $p_T^\ell > 10$ GeV and $|\eta_\ell| < 2.5$ is required. (6) The invariant mass of the Higgs boson candidate and the forward tagging jet must be greater than 250 GeV. (7) We require a b-tagging efficiency $\varepsilon_b = 0.6$ for $|\eta_b| < 2.5$. The mistagging factors for c and light quark jets are taken as 0.1 and 0.01, respectively.

Taking all these criteria, the azimuthal distribution has been simulated in 10 bins, each of width $\pi/5$, and the signal for each value of λ (λ') and the SM backgrounds have been calculated in each bin using the same formulae used to create Fig. 2. Assuming statistical errors dependent on the integrated luminosity, L, we then determine the sensitivity, for a given L, of the experiment to λ, λ' by making a log-likelihood analysis. The background estimation has been taken from the studies described in Ref. [18]. It may be noted that these criteria are optimized for a Higgs boson mass of 120 GeV, as in Ref. [14], and could change marginally for the favored range set by the experimental collaborations [3]. However, such changes hardly matter for the present analysis.

Our results are exhibited in Fig. 3, where we present 95% exclusion plots for the anomalous couplings as a function of L. The left panel shows the exclusion plot for λ, while the right shows the exclusion plot for λ'. It is clear from this figure that by the time the LHeC has collected 10 fb^{-1} of data, we will be able to discover anomalous couplings down to the level of 0.3 or lower, or else to exclude such couplings and establish to that extent that the HWW vertex indeed resembles the SM vertex. We note that the process in question is somewhat more sensitive to

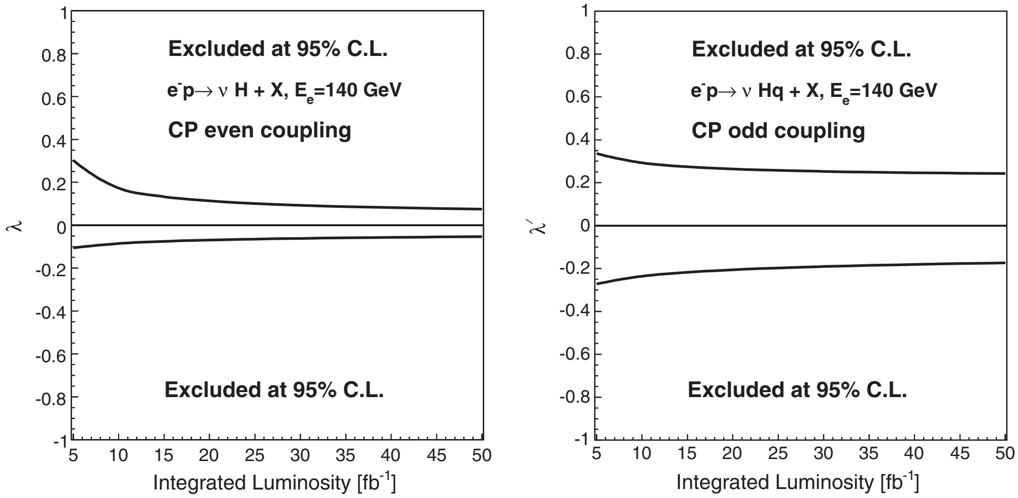

FIG. 3. Exclusion plots obtainable by a study of the azimuthal angle distributions at the LHeC for the CP-even coupling λ and the CP-odd coupling λ'.

the CP-even coupling, as evidenced by the narrower inaccessible region indicated on the left panel.

It is interesting to ask what happens if the energy of the electron beam is different from 140 GeV, as assumed in the previous discussion. The azimuthal angle distributions shown in Fig. 2 hardly change as the electron beam energy E_e is changed through 50–200 GeV. The acceptance of the CC Higgs boson signal has been evaluated in Ref. [14]. If E_e is decreased while keeping the energy of the proton beam constant, the acceptance decreases minimally so long as E_e is above 100 GeV, but begins to decrease significantly for E_e less than 100 GeV. The acceptance of the Higgs boson signal for $E_e = 50$ GeV is, in fact, diminished by 25% with respect to that of $E_e = 100$ GeV. Most of this acceptance loss stems from the requirement of two b jets. Part of the acceptance can be recovered by allowing the tracking and calorimeter coverage to increase in the forward direction.

In summary, the LHeC is the only machine where one can measure the HWW coupling directly without making any prior assumptions about new BSM physics. We have shown that the azimuthal angle $\Delta\varphi_{\text{MET-}J}$ in CC events accompanied by a H boson at the LHeC is a powerful and unambiguous probe of anomalous HWW couplings, both of the CP-conserving and the CP-violating type, and is robust against uncertainties in the exact Higgs boson mass and the PDF errors. We conclude that an integrated luminosity of around 10 fb^{-1} would suffice to probe reasonably small values of these couplings.

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