Azimuthal Angle Probe of Anomalous $HWW$ Couplings at the LHeC

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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 (CC) events accompanied by a Higgs boson. We demonstrate that azimuthal angle correlations between the observable CC 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 for 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 around 126 GeV and that this boson resembles the Higgs boson of the SM. By the symmetry-breaking [1] in the Standard Model (SM) [2].

The above parametrisation 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 $\lambda$ and $\lambda'$ to any degree of certainty. A survey of the literature throws up several suggestions [7–9] 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 [6–8] as well as the electron positron colliders [6, 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 through these electroweak vertices, which would require accumulation of considerable statistics before a precision result can be claimed, and more importantly, (b) because these vertices are sensitive to the presence of new physics beyond the SM, with corrections occurring mostly at the one-loop level. If we parametrise the $H(k) - W^+_\mu(p) - W^-_\nu(q)$ vertex in the general form

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

any deviations from the simple SM formula $\Gamma^{\mu\nu}_{\text{SM}}(p, q) = -g M_W g^{\mu\nu}$ in Eqn. (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 parametrise these deviations using two dimension-5 operators

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

where $\lambda$ and $\lambda'$ are, respectively, effective coupling strengths for the anomalous $CP$-conserving and the $CP$-violating operators. One can make [4] a similar parametrisation for the $H(k) - Z_\mu(p) - Z_\nu(q)$ vertex, with another pair of unknown couplings $\lambda$ and $\lambda'$ and the replacement $M_W \rightarrow M_Z$. 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 $H^0$. 

Since $g$, $M_W$ and $\theta_W$ 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 to produce a substantial number of Higgs bosons
in such studies [8–10]. As pointed out in Refs. [11, 12] a study of e⁺e⁻ → ttH⁰ production offers the possibility of a clear and unambiguous determination of the CP properties of the H⁰; 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 reactions e⁺ + p → νX [13, 14] or ν → eH⁰X [15] arise only from a single Feynman diagram involving the HWW vertex as shown in the Figure 1 for e⁺ + p → νe + X + H(bb). These modified charged current (CC) processes not only provide the best way to observe the H → bb decay, but also render the measurement of the HWW vertex free from possible contamination by contributions from HZZ or Hγγ 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 (~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 centre-of-mass energy as high as 1 – 1.5 TeV and can therefore produce H⁰ events copiously [13, 14]. A glance at Figure 1 will show that the final state has missing transverse energy (MET) and three jets J₁, J₂ and J₃, of which two (say J₂ and J₃) can be tagged as b-jets. At the parton level, the squared and spin-summed-averaged matrix element for the process

\[ e^- (k_1) + q (k_2) \rightarrow \nu \bar{e} (p_1) + q' (p_2) + H (p_3) \]

can now be worked out to be

\[
|M|^2 = \left( \frac{4\pi^3 \alpha^3}{\sin^6 \theta_W} \right) \frac{1}{M_H^2 (t_1 - M_W^2)^2 (\hat{u}_2 - M_W^2)^2} \times \left[ 4M_W^4 \hat{s} \hat{s} (\hat{s}_1 \hat{s}_1 + \hat{t}_1 \hat{u}_2 - \hat{t}_2 \hat{u}_1) \right. \\
+ \lambda^2 \{ \hat{t}_1 \hat{u}_2 (\hat{s}^2 + \hat{s}_1^2 + \hat{t}_1 \hat{u}_2 - 2\hat{t}_2 \hat{u}_1) + (\hat{s}_1 \hat{t}_1 - \hat{t}_2 \hat{u}_1)^2 \} \\
+ 2\lambda' \hat{t}_1 \hat{u}_2 (\hat{s}^2 + \hat{s}_1^2 - \hat{t}_1 \hat{u}_2 + 2\hat{t}_2 \hat{u}_1) - (\hat{s}_1 \hat{t}_1 - \hat{t}_2 \hat{u}_1)^2 \} \\
\left. - 2\lambda' \hat{t}_1 \hat{u}_2 (\hat{s}_1^2 - \hat{s}^2) \right]
\]

(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.

The expression in Eqn. (4), though exact, is not very transparent. It can be shown [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 \( \lambda \) (\( \lambda' \)) contributes to the matrix element for this process a term of the form

\[ M_\lambda \propto +\lambda \bar{p}_{T1}.\bar{p}_{T2} \]

\[ M'_{\lambda} \propto -\lambda' \bar{p}_{T1}.\bar{p}_{T2} \]

(5)

where \( \bar{p}_{T1} \) is the vector of the missing transverse energy. These terms \( M_\lambda \) and \( M'_{\lambda} \) both go through a zero when the azimuthal angle \( \Delta \varphi_{\text{MET}-1} \) 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 \( M_\lambda \) and \( M'_{\lambda} \) are added to the relatively flat (in \( \Delta \varphi_{\text{MET}-1} \)) SM background, one predicts a curve with a peak (dip) around \( \Delta \varphi_{\text{MET}-1} \approx 0(\pi) \) for the \( \lambda \) operator and the opposite behaviour for the \( \lambda' \) operator, when the signs of \( \lambda, \lambda' \) are positive and vice versa when they are negative. The exact behaviour is illustrated in Figure 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 Eqn. (4) to Eqn. (5) are somewhat too drastic, these curves show the expected qualitative behaviour 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 \( \lambda, \lambda' = 0, \pm 1 \) in Figure 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 \( \lambda \) (or \( \lambda' \)) is crucial to any actual study
FIG. 2: Azimuthal angle distributions in the SM and with anomalous $HWW$ couplings.

- 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 $\lambda, \lambda'$ is 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 $\lambda$ term will be generated even in the SM at one-loop level, whereas the $CP$-violating $\lambda'$ will arise at this order only if there is new BSM physics. Thus, in Figure 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 Eqn. (4), convoluted with parton density functions 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 CTEQ and MSTW PDFs do lead to fairly significant overall changes in the overall cross-section, but when it comes to the normalised distribution in azimuthal angle of Figure 2, the differences turn out to be so small that they can practically be absorbed in the thickness of the lines shown on Figure 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 normalised distributions shown in Figure 2.

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 $\lambda$ and $\lambda'$ can be estimated. These effects tend to distort the characteristic curves shown in Figure 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 $\alpha = 0.6$ 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 have made 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 $Hbb$ coupling for a SM Higgs boson. These criteria may be summarised as follows:

1. It is required that $MET > 25$ GeV.
2. Presence of two $b$-partons with $p_T^b > 30$ GeV and $|\eta_b| < 2.5$. 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 $\Delta \phi_{MET-J} > 0.2$ 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. $b$-tagging efficiency: $\varepsilon_b = 0.6$ for $|\eta_b| < 2.5$. The mis-tagging factor for $c$ and light quark jets is 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 $\lambda (\lambda')$ and SM backgrounds have been calculated in each bin using the same formulae used to create Figure 2. Assuming statistical errors dependent on the integrated luminosity, $L$, we then determine the sensitivity, for a given $L$, of the experiment to $\lambda, \lambda'$ 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 optimised for a Higgs mass of 120 GeV, as in in Ref. [14], and could change marginally for the favoured range set by the experimental collaborations [3]. However, such changes hardly matter for the present analysis.

Our results are exhibited in Figure 3, where we present 95% exclusion plots for the anomalous couplings as a function of $L$. The left panel shows the exclusion plot for $\lambda$, while the right shows the exclusion plot for $\lambda'$. 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 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 Figure 2 hardly change as the electron beam energy $E_e$ is changed through 50 GeV to 200 GeV. The acceptance of the CC Higgs boson signal has been evaluated in [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 for tracking and calorimeter coverage to increase in the forward direction.

In summary, the LHeC is the only machine where one can measure the $HWW$ couplings 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 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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[1] F. Englert and R. Brout, Phys. Rev. Lett. 13, 321 (1964); P.W. Higgs, Phys. Rev. Lett. 13, 508 (1964); G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble, Phys. Rev. Lett. 13, 585 (1964).
[2] S.L. Glashow, Nucl. Phys. 22, 579 (1961); S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam (1968) in N. Svartholm, ed. Eighth Nobel Symposium: Stockholm [Almqvist and Wiksell, pp. 367].
[3] G. Aad et al (ATLAS Collaboration), Phys. Lett. B716, 1 (2012); S. Chatrchyan et al (CMS Collaboration), Phys. Lett. B716, 30 (2012); TEVPH Working Group (for the CDF, D0 Collaborations), FERMILAB preprint FERMILAB-CONF-12-318-E, arXiv:1207.0449 [hep-ex] (2012).
[4] T. Plehn, D.L. Rainwater and D. Zeppenfeld, Phys. Rev. Lett. 88, 051801 (2002).
[5] D.L. Rainwater, hep-ph/9908378 (1999); K. Cranmer, et al, ATLAS Physics Note ATL-PHYS-2003-036, hep-ph/0401088 (2004).
[6] R.M. Godbole et al, hep-ph/0404024 (2004); S. Kraml et al., CPNSH report, hep-ph/0608079 (2006).
[7] M. Duhrssen, et al, Phys. Rev. D70, 113009 (2004); V. del Duca et al, JHEP 0610, 016 (2006); R.M. Godbole, D.J. Miller and M.M. Mühlleitner, JHEP 0712, 031 (2007); J.R. Andersen, K. Arnold and D. Zeppenfeld, JHEP 1006, 091 (2010); A. de Rujula et al, Phys. Rev. D82, 013003 (2010); N. Desai, D.K. Ghosh and B. Mukhopadhyaya, Phys. Rev. D83, 113004 (2011);
[8] F. Campanario, M. Kubocz and D. Zeppenfeld, Phys. Rev. D84, 095025 (2011); C. Englert, M. Spannowsky and M. Takeuchi, JHEP 1206, 108 (2012); S. Bolognesi et al, arXiv:1208.4018 [hep-ph]; I. Low, J. Lykken and G. Shaughnessy, arXiv:1207.1093 [hep-ph].
[9] V. Hankele, G. Klumke, D. Zeppenfeld and T. Figy, Phys. Rev. D74, 095001 (2006).
[10] See, for example, S.S. Biswal, D. Choudhury, R.M. Godbole and Mamta, Phys. Rev. D79, 035012 (2009); S. Dutta, K. Hagiwara and Y. Matsumoto, Phys. Rev. D78, 115016 (2008).
[11] C. Ruwiedel, N. Vermes and M. Schumacher, Eur. Phys. J. C51, 385 (2007).
[12] J.F. Gunion, B. Grzadkowski and X.-G. He, Phys. Rev. Lett. 77, 5172 (1996).
[13] P.S. Bhupal Dev et al, Phys. Rev. Lett. 100, 051801 (2008).
[14] J.L. Abelleira-Fernandez et al (LHeC Study Group), J. Phys. G39, 075001 (2012).
[15] T. Han and B. Mellado, Phys. Rev. D82, 016009 (2010).
[16] R. M. Godbole, Phys. Rev. D18, 95 (1978).
[17] CTEQ Collaboration (J. Pumplin et al), JHEP 0207, 012 (2002) and references therein.
[18] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, Eur. Phys. J. C70, 51 (2010) and references therein.
[19] U. Klein (2011), talk at DIS 2011, URL: http://www.ep.ph.bham.ac.uk/exp/LHeC/talks/DIS11.Klein2.pdf.