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W boson polarization as a measure of gauge-Higgs anomalous couplings at the LHC

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Abstract

We show how the W boson polarization in the process of associated $W^{\pm}H$ production at the Large Hadron Collider (LHC) can be used to constrain anomalous WWH couplings. We first calculate the spin density matrix for the W to linear order in the anomalous couplings, which are assumed to be small. We then evaluate angular asymmetries in the decay distributions of leptons produced in the decay of the W and show how they can be used to measure the individual elements of the polarization tensor. We estimate the limits that can be placed on the anomalous WWH couplings at a future run of the LHC.

1. Introduction

After the discovery of the Higgs boson with a mass of around 125 GeV, several measurements at the Large Hadron Collider (LHC) indicate that its couplings are consistent with those predicted by the standard model (SM). However, a complete confirmation that the Higgs boson H discovered at the LHC is indeed the Higgs boson of the SM will require precise determination of all the couplings of H, including Higgs self-couplings. A simplistic analysis, usually adopted in the interpretation of Higgs data, attempts to measure the ratio κ of the coupling to that in the standard model. In this procedure, the so-called κ framework, the forms of the interactions assumed

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are the same as in the SM at tree level. An attempt to introduce more general tensor forms of couplings is not permitted by the present accuracy of the experiments. However, in future experiments at higher luminosities, it is hoped that such general forms of couplings will be constrained. This could include measurement of differential cross sections, which would be highly data intensive. Alternatively, one could measure partial cross sections, or angular or energy asymmetries of final state particles.

An interesting additional variable which we consider in this work is the polarization of the $W^{\pm}$ produced in association with the Higgs. Measurement of polarization of a heavy particle requires the observation of decay distributions of the particle. Again one can construct appropriate asymmetries from the kinematical distributions of the decay particles. In particular, charged lepton distributions in the decay of the W would enable the measurement of W polarization parameters, which in turn would constrain the strengths of the tensor structures of the WWH interactions.

W polarization has been discussed recently in the context of polarized top decays and diboson resonances at the LHC [1], and earlier in the context of various single, pair and associated W production processes [2]. For details of the formalism in the context of LEP experiments, see [3]. Z polarization has been studied in the context of new physics at e^+e^- colliders [4,5].

W helicity fractions, which measure the degree of longitudinal or transverse polarizations, have been measured in top decay $t \to bW$ at the LHC from the polar-angle distributions, integrated over the azimuthal angle [6]. These correspond to the diagonal elements of the W production spin-density matrix. In what follows, we also consider measurement of the off-diagonal density-matrix elements [7–11] through angular asymmetries of the leptons produced in W decay.

The asymmetries we consider are defined in the rest frame of the decaying W. Measurement of these asymmetries would therefore involve transforming laboratory-frame kinematic variables to the W rest frame. This in turn needs the knowledge of the W four-momentum. This is a potential problem because the W decays into a neutrino, which is not detected. While the transverse momentum of the neutrino can be reconstructed with good accuracy using momentum conservation, the longitudinal momentum cannot be measured directly. The usual procedure [6] is to constrain the invariant mass of the W decay products to be equal to the W mass. Moreover, the construction of the polarization asymmetries, which are related to the elements of the W density matrix requires the W to be on-shell [10,11]. Since the on-shell constraint gives rise to a quadratic equation, there is a two-fold ambiguity in the determination of the neutrino longitudinal momentum. Various procedures have been considered to choose one of the two solutions allowed. One procedure followed in a recent study of WH production by ATLAS is to take the smaller of the two solutions [12]. Another suggestion [13] is to compare the longitudinal boosts β_z^W and β_z^H of the reconstructed W and the H, and choose the solution which gives the lower value for $|\beta_z^W - \beta_z^H|$, which was found in simulations to give the true neutrino momentum in 65% of the cases.

W and Z polarization in associated Higgs production has been studied recently in [14], with which our work has considerable overlap. While [14] contains expressions for W spin density matrices which we obtained independently, their analysis deals with hadronic decay of the vector bosons, whereas we concentrate on leptonic decay of the W. While the hadronic branching ratios are larger, it is not possible to determine the charge of the jets. On the other hand, though the branching ratio of W into leptons is smaller, greater precision is possible, as well as charge discrimination is available.

The WWH vertex for a process $W^{+*} \to W^+H$ may be written in a model-independent way as

$$\Gamma_{\mu\nu} = g m_W \left[a_W g_{\mu\nu} + \frac{b_W}{m_W^2}(q_\mu k_\nu - g_{\mu\nu} q \cdot k) + \frac{\tilde{b}_W}{m_W^2} \epsilon_{\mu\nu\alpha\beta} q^\alpha k^\beta \right], \tag{1}$$

where q is the incoming W^* momentum and k is the outgoing W momentum, and ν, μ are their respective polarization indices. g is the weak coupling constant, and $a_W = 1$ in the SM at tree level. b_W and $\tilde{b}_W$ which are vanishing in the SM at tree level, are anomalous couplings, taken to be complex form factors. An analogous vertex for the process $W^{-*} \to W^-H$ may also be written. While the first two terms would arise from terms in an effective Lagrangian and are invariant under CP, the $\tilde{b}_W$ term would correspond to a CP-violating term in the Lagrangian. The anomalous couplings could arise at one or more loops in the SM, or in extensions of the SM, with heavy particles (the top quark, W, Z and H in the SM, or other additional particles in SM extensions) occurring in the loops, and coupling to the Higgs boson. However, we will not be concerned here with predictions of any specific model.

2. Helicity amplitudes and density matrix

We consider the process $pp \to W^\pm HX$ at the LHC, which at the partonic level proceeds via the process $q\bar{q}' \to W^* \to W^\pm H$, where q and q' are quarks. After calculating the helicity amplitudes for the process in the presence of anomalous WWH couplings, we evaluate the production density matrix elements for the spin of the W at the partonic level and consequently for a hadronic initial state, to linear order in the anomalous couplings. We further examine how each of these polarization tensor elements may be measured from various angular asymmetries of charged leptons produced in the decay of the W, and also estimate the sensitivity of these measurements for an assumed integrated luminosity of the experiment.

To calculate the helicity amplitudes for the production process in the quark–antiquark c.m. (centre-of-mass) frame,

$$u(p_1) + \bar{d}(p_2) \to W^+(k) + H, \tag{2}$$

where u and d are respectively up-type and down-type quarks of any generation, we make use of the following representation for the polarization vectors of the W:

$$\epsilon^\mu(k, \pm) \equiv \left(0, \mp\frac{\cos\theta}{\sqrt{2}}, -\frac{i}{\sqrt{2}}, \pm\frac{\sin\theta}{\sqrt{2}}\right), \tag{3}$$

$$\epsilon^\mu(k, 0) \equiv \left(\frac{|\vec{k}|}{m_W}, \frac{E_W \sin\theta}{m_W}, 0, \frac{E_W \cos\theta}{m_W}\right) \tag{4}$$

where E_W is the energy of the W and $\vec{k}_W$ its momentum, with polar angle θ with respect to the direction of the u quark taken as the z axis.

The nonzero helicity amplitudes in the limit of massless quarks are given by

$$M(-,+,-) = -g^2 V_{qq'} m_W \frac{\sqrt{\hat{s}}}{2} \left[a_W - (b_W + i\beta_W \tilde{b}_W) \frac{\sqrt{\hat{s}} E_W}{m_W^2} \right] \frac{(1+\cos\theta)}{(\hat{s} - m_W^2)} \tag{5}$$

$$M(-,+,0) = -g^2 V_{qq'} \sqrt{\frac{\hat{s}}{2}} E_W \left[a_W - b_W \frac{\sqrt{\hat{s}}}{E_W} \right] \frac{\sin\theta}{(\hat{s} - m_W^2)} \tag{6}$$

$$M(-,+,+) = -g^2 V_{qq'} m_W \frac{\sqrt{\hat{s}}}{2}\left[a_W - (b_W - i\beta_W \tilde{b}_W)\frac{\sqrt{\hat{s}}E_W}{m_W^2}\right]\frac{(1-\cos\theta)}{(\hat{s}-m_W^2)} \tag{7}$$

where $\sqrt{\hat{s}}$ is the total energy in the parton c.m. frame, $\beta_W = |\vec{k}_W|/E_W$, and $V_{qq'}$ is the appropriate element of the Cabibbo–Kobayashi–Maskawa matrix, and the first two entries in M correspond to helicities $-1/2$ and $+1/2$ of the quark and anti-quark, respectively, and the third entry is the W helicity.

The helicity amplitudes for the W^- production process

$$d(p_1) + \bar{u}(p_2) \to W^-(k) + H \tag{8}$$

are also given by eqns. (5)–(7), with the first two entries in M denoting the helicities of the d and $\bar{u}$, and θ representing the angle between W^- and d. Here it is assumed that the same couplings a_W, b_W and $\tilde{b}_W$ occur in the process $W^{-*} \to W^- H$ as in $W^{+*} \to W^+ H$, as in an effective field theory approach [14].

In terms of the helicity amplitudes, the spin-density matrix for W production is defined as

$$\rho(i,j) = \overline{\sum_{h_q,h_{\bar{q}}}} M(h_q, h_{\bar{q}}, i) M(h_q, h_{\bar{q}}, j)^*, \tag{9}$$

the sum and average being over initial helicities h_q, $h_{\bar{q}}$ of the quark and anti-quark, respectively, and also over initial colour states, not shown explicitly. The diagonal elements for $i = j$ would correspond to production probabilities with definite W polarization labelled by $i = j$ as applicable, for example, in the study of helicity fractions. However, in the description of W production followed by decay, where measurement is made on the decay products, the full density matrix description, which includes off-diagonal elements, is needed. This is because a full description requires multiplying the helicity amplitudes for production with the helicity amplitudes for decay in a coherent fashion (see, for example, [15]).

The density matrix elements derived from the helicity amplitudes (5)–(7), to linear order in the couplings b_W and $\tilde{b}_W$, setting $a_W = 1$ are as follows.

$$\rho(\pm,\pm) = \frac{g^4}{12}\frac{m_W^2 \hat{s}}{4(\hat{s}-m_W^2)^2}|V_{qq'}|^2(1 \mp \cos\theta)^2\left[1 - 2(\mathrm{Re}b_W - \beta_W \mathrm{Im}\tilde{b}_W)\frac{\sqrt{\hat{s}}E_W}{m_W^2}\right] \tag{10}$$

$$\rho(0,0) = \frac{g^4}{12}\frac{E_W^2 \hat{s}}{2(\hat{s}-m_W^2)^2}|V_{qq'}|^2 \sin^2\theta\left[1 - 2\mathrm{Re}b_W \frac{\sqrt{\hat{s}}}{E_W}\right] \tag{11}$$

$$\rho(\mp,0) = \frac{g^4}{12}\frac{\hat{s} m_W E_W}{2\sqrt{2}(\hat{s}-m_W^2)^2}|V_{qq'}|^2 \sin\theta(1 \pm \cos\theta) \tag{12}$$

$$\times\left[1 - \mathrm{Re}b_W \sqrt{\hat{s}}\frac{(E_W^2 + m_W^2)}{E_W m_W^2} - i\mathrm{Im}b_W \sqrt{\hat{s}}\frac{\beta_W^2 E_W}{m_W^2} \mp i\beta_W \tilde{b}_W \frac{\sqrt{\hat{s}}E_W}{m_W^2}\right] \tag{13}$$

$$\rho(\mp,\pm) = \frac{g^4}{12}\frac{m_W^2 \hat{s}}{4(\hat{s}-m_W^2)^2}|V_{qq'}|^2 \sin^2\theta\left[1 - 2(\mathrm{Re}b_W \pm i\beta_W \mathrm{Re}\tilde{b}_W)\frac{\sqrt{\hat{s}}E_W}{m_W^2}\right] \tag{14}$$

We have used the analytical manipulation software FORM [16] to check these expressions.

Defining an integral of this density matrix over an appropriate kinematic range as $\sigma(i,j)$, the latter can be parametrized in terms of the linear polarization $\vec{P}$ and the tensor polarization T as follows [15].

$$\sigma(i,j) \equiv \sigma \begin{pmatrix} \frac{1}{3}+\frac{P_z}{2}+\frac{T_{zz}}{\sqrt{6}} & \frac{P_x-iP_y}{2\sqrt{2}}+\frac{T_{xz}-iT_{yz}}{\sqrt{3}} & \frac{T_{xx}-T_{yy}-2iT_{xy}}{\sqrt{6}} \\ \frac{P_x+iP_y}{2\sqrt{2}}+\frac{T_{xz}+iT_{yz}}{\sqrt{3}} & \frac{1}{3}-\frac{T_{zz}}{\sqrt{6}} & \frac{P_x-iP_y}{2\sqrt{2}}-\frac{T_{xz}-iT_{yz}}{\sqrt{3}} \\ \frac{T_{xx}-T_{yy}+2iT_{xy}}{\sqrt{6}} & \frac{P_x+iP_y}{2\sqrt{2}}-\frac{T_{xz}+iT_{yz}}{\sqrt{3}} & \frac{1}{3}-\frac{P_z}{2}+\frac{T_{zz}}{\sqrt{6}} \end{pmatrix} \tag{15}$$

where $\sigma(i,j)$ is the integral of $\rho(i,j)$, and σ is the production cross section,

$$\sigma = \sigma(+,+)+\sigma(-,-)+\sigma(0,0). \tag{16}$$

The vector and tensor polarizations then can be obtained by inverting eqn. (15):

$$P_x = \frac{1}{(\sqrt{2}\sigma)}[\sigma(+,0)+\sigma(0,+)+\sigma(-,0)+\sigma(0,-)] \tag{17}$$

$$P_y = \frac{i}{(\sqrt{2}\sigma)}[\sigma(+,0)-\sigma(0,+)-\sigma(-,0)+\sigma(0,-)] \tag{18}$$

$$P_z = \frac{1}{\sigma}[\sigma(+,+)-\sigma(-,-)] \tag{19}$$

$$T_{xy} = \frac{i\sqrt{6}}{(4\sigma)}[\sigma(+,-)-\sigma(-,+)] \tag{20}$$

$$T_{xz} = \frac{\sqrt{3}}{(4\sigma)}[\sigma(+,0)+\sigma(0,+)-\sigma(-,0)-\sigma(0,-)] \tag{21}$$

$$T_{yz} = \frac{i\sqrt{3}}{(4\sigma)}[\sigma(+,0)-\sigma(0,+)+\sigma(-,0)-\sigma(0,-)] \tag{22}$$

$$T_{xx}-T_{yy} = \frac{\sqrt{6}}{(2\sigma)}[\sigma(+,-)+\sigma(-,+)] \tag{23}$$

$$T_{zz} = \frac{\sqrt{6}}{(6\sigma)}[\sigma(+,+)+\sigma(-,-)-2\sigma(0,0)]. \tag{24}$$

3. Leptonic asymmetries

Obtaining spin information of the W requires measurements to be made on the decay products of the W. Using leptonic decays is more convenient than using hadronic decays because charge identification is difficult, if not impossible, for that latter case. Expressions may be obtained for the decay-lepton distribution in the W production process by combining the relevant production-level density matrix elements with appropriate decay density matrix elements and integrating over the appropriate phase space. As mentioned before, a full measurement of the lepton distribution would require a very large number of events. It is more economical to use integrated angular asymmetries, which utilize all relevant events. We therefore adopt this approach and define different angular asymmetries of the charged lepton.

Following [5], we define angular asymmetries of the lepton arising from W decay, evaluated in the rest frame of the W, which isolate various elements of the polarization tensor:

$$A_x = \frac{\sigma(\cos\phi^* > 0)-\sigma(\cos\phi^* < 0)}{\sigma(\cos\phi^* > 0)+\sigma(\cos\phi^* < 0)}, \tag{25}$$

$$A_y = \frac{\sigma(\sin\phi^* > 0)-\sigma(\sin\phi^* < 0)}{\sigma(\sin\phi^* > 0)+\sigma(\sin\phi^* < 0)}, \tag{26}$$

$$A_z = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}, \tag{27}$$

$$A_{xy} = \frac{\sigma(\sin 2\phi^* > 0) - \sigma(\sin 2\phi^* < 0)}{\sigma(\sin 2\phi^* > 0) + \sigma(\sin 2\phi^* < 0)}, \tag{28}$$

$$A_{xz} = \frac{\sigma(\cos\theta^* \cos\phi^* < 0) - \sigma(\cos\theta^* \cos\phi^* > 0)}{\sigma(\cos\theta^* \cos\phi^* > 0) + \sigma(\cos\theta^* \cos\phi^* < 0)}, \tag{29}$$

$$A_{yz} = \frac{\sigma(\cos\theta^* \sin\phi^* > 0) - \sigma(\cos\theta^* \sin\phi^* < 0)}{\sigma(\cos\theta^* \sin\phi^* > 0) + \sigma(\cos\theta^* \sin\phi^* < 0)}, \tag{30}$$

$$A_{x^2-y^2} = \frac{\sigma(\cos 2\phi^* > 0) - \sigma(\cos 2\phi^* < 0)}{\sigma(\cos 2\phi^* > 0) + \sigma(\cos 2\phi^* < 0)}, \tag{31}$$

$$A_{zz} = \frac{\sigma(\sin 3\theta^* > 0) - \sigma(\sin 3\theta^* < 0)}{\sigma(\sin 3\theta^* > 0) + \sigma(\sin 3\theta^* < 0)}. \tag{32}$$

The direction of the quark momentum is defined as the z axis, and the x axis chosen so that the W lies in the xz plane. Using these axes, the angles θ^* and ϕ^* are the polar and azimuthal angles of the decay lepton, defined in the rest frame of the W, with respect to the boost direction of the W.

It may be observed that since the sign of the triple vector product of the beam direction, the W momentum direction and the lepton momentum direction determines the sign of $\sin\phi^*$, the asymmetries A_y, A_{xy}, A_{yz} which are linear in $\sin\phi^*$ are measures of this triple vector product. These asymmetries are therefore odd under naive time reversal operation $\mathrm{T_N}$, which is simply reversal of all momentum and spin directions. Hence these asymmetries would be either proportional to the T-odd parameter $\tilde{b}_W$, or proportional to the T-even coupling b_W, but to satisfy unitarity and the CPT theorem, proportional only to its imaginary part. This will be seen in the numerical expressions or asymmetries which follow later on.

The above results assume that the quark and antiquark directions can be identified unambiguously. This is not true in the case of the LHC, where the quark could arise from either proton, and the choice of the z axis is not unique. Taking into account the two possibilities when the quark (and antiquark) arise from the two oppositely directed proton beams, we find that the density matrix elements $\sigma(\pm, 0)$ and $\sigma(0, \pm)$ vanish, as also the polarizations P_x, P_y, P_{xz}, P_{yz} and the corresponding asymmetries A_x, A_y, A_{xz}, A_{yz}.

In what follows we will take the z axis to be defined by the direction of the reconstructed momentum of the combination WH. In this case, the density matrix elements, polarizations and asymmetries which were vanishing when the z was chosen to be the beam direction now turn out to be nonzero.

4. Numerical results

To start with, we have evaluated the production spin density matrix elements after integrating over the parton distribution functions as well as the final-state phase space. We do not restrict ourselves to any particular decay mode of the Higgs, but assume that full identification is possible. In practice, one would have to apply kinematic cuts for lepton identification, elimination of backgrounds, etc., as also take into account the Higgs detection efficiency, which will require a more refined analysis.

We use the MMHT2014 parton distributions [17] with factorization scale chosen as the square root of the partonic c.m. energy. For the two cases of W^+ and W^- production, though the par-

Table 1
Production spin density matrix elements for the W^+ (in units of fb) for the SM and the coefficients of various couplings in each matrix element.

	SM	Re b_W	Im b_W	Re $\tilde{b}_W$	Im $\tilde{b}_W$
$\sigma(\pm,\pm)$	165.8	−1757	0	0	$\mp$1273
$\sigma(0,0)$	388.7	−1757	0	0	0
$\sigma(\pm,\mp)$	82.91	−878.6	0	$\pm i$636.8	0
$\sigma(\pm,0)$	95.96	−872.8	$-i$431.7	$\pm i$518.9	$\mp$518.9
$\sigma(0,\pm)$	95.96	−872.8	i431.7	$\mp i$518.9	$\mp$518.9

Table 2
Production spin density matrix elements for the W^- (in units of fb) for the SM and the coefficients of various couplings in each matrix element.

	SM	Re b_W	Im b_W	Re $\tilde{b}_W$	Im $\tilde{b}_W$
$\sigma(\pm,\pm)$	110.2	−1140	0	0	$\mp$817.1
$\sigma(0,0)$	251.5	−1140	0	0	0
$\sigma(\pm,\mp)$	55.10	−570.0	0	$\pm i$408.5	0
$\sigma(\pm,0)$	49.86	−439.6	$-i$209.9	$\pm i$255.0	$\mp$255.0
$\sigma(0,\pm)$	49.86	−439.6	i209.9	$\mp i$255.0	$\mp$255.0

tonic level cross sections and density matrices have the same expressions, the parton densities corresponding to the initial states are different. Hence the numerical results are different.

As mentioned before, we choose as z axis the direction of the combined momenta of W and H.

The results for the density matrices for W^+ production and W^- production are shown respectively in Table 1 and Table 2.

The total cross section for W^+ production has the expression

$$\sigma = (720.2 - 5271\,\mathrm{Re}\,b_W)\ \mathrm{fb}, \tag{33}$$

and that for W^- production the expression

$$\sigma = (471.8 - 3420\,\mathrm{Re}\,b_W)\ \mathrm{fb}. \tag{34}$$

The total cross section for W^+ production could put a limit on Re b_W of 2.28×10^{-4} with an integrated luminosity $L = 500\ \mathrm{fb}^{-1}$, and of 1.61×10^{-4} with $L = 1000\ \mathrm{fb}^{-1}$. The corresponding limits using cross section for W^- production are 2.84×10^{-4} and 2.01×10^{-4}. Measurement of the cross section using only electron and muon decay modes of the W^+ assuming branching ratios of 10.71% and 10.63% respectively, we can therefore set a limit of 4.93×10^{-4} on the coupling Re b_W for $L = 500\ \mathrm{fb}^{-1}$, and 3.49×10^{-4} for $L = 1000\ \mathrm{fb}^{-1}$. The corresponding numbers for W^- are respectively 6.15×10^{-4} and 4.35×10^{-4}.

The leptonic asymmetries corresponding to the different polarizations in W^+ production and decay, in an obvious notation, are given by

$$A_x = -0.282 + 0.502\,\mathrm{Re}\,b_W \tag{35}$$

$$A_y = 1.52\,\mathrm{Re}\,\tilde{b}_W \tag{36}$$

$$A_z = 2.60\,\mathrm{Im}\,\tilde{b}_W \tag{37}$$

$$A_{xy} = -0.563\,\mathrm{Re}\,\tilde{b}_W \tag{38}$$
$$A_{xz} = 0.649\,\mathrm{Im}\,\tilde{b}_W \tag{39}$$
$$A_{yz} = 0.540\,\mathrm{Im}\,b_W \tag{40}$$
$$A_{x^2-y^2} = 0.0733 - 0.240\,\mathrm{Re}\,b_W \tag{41}$$
$$A_{zz} = -0.116 - 0.849\,\mathrm{Re}\,b_W \tag{42}$$

The corresponding asymmetries in W^- production and decay are

$$A_x = -0.224 + 0.351\,\mathrm{Re}\,b_W \tag{43}$$
$$A_y = 1.15\,\mathrm{Re}\,\tilde{b}_W \tag{44}$$
$$A_z = 2.65\,\mathrm{Im}\,\tilde{b}_W \tag{45}$$
$$A_{xy} = -0.551\,\mathrm{Re}\,\tilde{b}_W \tag{46}$$
$$A_{xz} = 0.487\,\mathrm{Im}\,\tilde{b}_W \tag{47}$$
$$A_{yz} = 0.401\,\mathrm{Im}\,b_W \tag{48}$$
$$A_{x^2-y^2} = 0.0744 - 0.230\,\mathrm{Re}\,b_W \tag{49}$$
$$A_{zz} = -0.112 - 0.814\,\mathrm{Re}\,b_W \tag{50}$$

As remarked earlier, the reconstruction of the W rest frame in which the above asymmetries are defined usually requires constraining the $\ell\nu$ invariant mass to be equal to the W mass. We have checked that if we do not use this restriction and allow an off-shell W to produce the $\ell\nu$ pair, the asymmetries do not change by more than a few per cent in most cases. Thus, the usual algorithms for constructing the W rest frame would work with good accuracy.

In order to evaluate the 1-σ limit C_{limit} on a coupling C which can be obtained from the asymmetries, assuming one coupling to be nonzero at a time, and an integrated luminosity L, we use the expression

$$C_{\mathrm{limit}} = \frac{\sqrt{1 - A_{\mathrm{SM}}^2}}{|A - A_{\mathrm{SM}}|}\frac{1}{\sqrt{\sigma_{\mathrm{SM}} L}}, \tag{51}$$

where A is the asymmetry for unit value of the coupling C. For W^+ production, for integrated luminosities of 500 fb^{-1} and 1000 fb^{-1}, we obtain the limits shown in Table 3. The corresponding limits from W^- production and decay are shown in Table 4.

The cross sections give the best limits on Re b_W. The results on the limits from leptonic asymmetries show that the asymmetries which are the most sensitive ones are A_{zz} for Re b_W, A_{yz} (the only one) for Im b_W, A_y for Re $\tilde{b}_W$ and A_z for Im $\tilde{b}_W$. The limits from W^+H production are better than those from W^-H production in all cases. However, it would be advantageous to combine results from both final states to improve the results.

5. Conclusions

It is important to obtain complete information about the Higgs boson discovered at the LHC, including the tensor form of the couplings. A proposal to measure form and magnitude of the coupling of the Higgs boson to a pair of W bosons through the polarization data of the W is investigated here. The polarization density matrix elements of the W can be measured through certain angular asymmetries of the charged lepton produced in W decay, and we have studied the

Table 3
1-σ limits which could be obtained from various leptonic asymmetries in W^+ production and decay, with integrated luminosities of 500 and 1000 fb^{-1}.

Asymmetry	Coupling	Limit (in 10^{-3}) ($L = 500$ fb^{-1})	Limit (in 10^{-3}) ($L = 1000$ fb^{-1})
A_x	Re b_W	6.9	4.9
A_y	Re $\tilde{b}_W$	2.4	1.7
A_z	Im $\tilde{b}_W$	1.4	0.96
A_{xy}	Re $\tilde{b}_W$	6.4	4.5
A_{xz}	Im $\tilde{b}_W$	5.6	3.9
A_{yz}	Im b_W	6.7	4.7
$A_{x^2-y^2}$	Re b_W	15	11
A_{zz}	Re b_W	4.2	3.0

Table 4
1-σ limits which could be obtained from various leptonic asymmetries in W^- production and decay, with integrated luminosities of 500 and 1000 fb^{-1}.

Asymmetry	Coupling	Limit (in 10^{-3}) ($L = 500$ fb^{-1})	Limit (in 10^{-3}) ($L = 1000$ fb^{-1})
A_x	Re b_W	12	8.7
A_y	Re $\tilde{b}_W$	3.9	2.7
A_z	Im $\tilde{b}_W$	1.7	1.2
A_{xy}	Re $\tilde{b}_W$	8.1	5.7
A_{xz}	Im $\tilde{b}_W$	9.2	6.5
A_{yz}	Im b_W	11	7.9
$A_{x^2-y^2}$	Re b_W	19	14
A_{zz}	Re b_W	5.4	3.9

sensitivity of these asymmetries to the anomalous couplings b_W and $\tilde{b}_W$ defined in eqn. (1). Our results for W^+ and W^- are shown in Tables 3 and 4.

We see that a high degree of accuracy could be obtained in the measurement of the WWH anomalous couplings from the measurement of the W polarization parameters through suitable angular asymmetries of leptons assuming an integrated luminosity of 500 fb^{-1}. There is considerable improvement, as expected, if the luminosity is increased to 1000 fb^{-1}. The 1-σ limits in most cases are of the order of a few times 10^{-3}.

As mentioned earlier, the angular asymmetries we discuss are defined in the rest frame of the W. The reconstruction of the W rest frame in the presence of the undetected neutrino has its drawbacks, and would entail some loss in efficiency. We have also not taken into account acceptance and isolation cuts on leptons. We also assume 100% efficiency for the detection of the Higgs. To get some idea of the effect of cuts, we did evaluate the angular asymmetries and the sensitivities in the presence of generic LHC acceptance cuts on the transverse momentum and the rapidity of the leptons. We found that the asymmetries do not change much. A full-scale analysis using an event generator coupled with all appropriate cuts relevant to the decay channels of the Higgs would be able to refine the actual sensitivities that we have obtained. It would also be profitable to combine the results from W^+ and W^- production processes, which would improve the accuracy.

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