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Probing anomalous Higgs couplings at an $e\gamma$ collider using unpolarised beams

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Abstract. We examine the sensitivity of $e\gamma$ colliders (based on e^+e^- linear colliders of c.m. energy 500 GeV) to the anomalous couplings of the Higgs to W-boson via the process $e^-\gamma \longrightarrow \nu WH$. This has the advantage over e^+e^- collider in being able to dissociate WWH vertex from ZZH. We are able to construct several dynamical variables which may be used to constrain the various couplings in the WWH vertex.

Keywords. Higgs; anomalous couplings; photon collider.

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1. Introduction

The dominant neutral Higgs production modes at a linear collider proceed via its coupling with a pair of gauge bosons ($VV,\ V = W, Z$), and hence these are expected to be sensitive to the VVH couplings (see refs [1,2]). It is possible to obtain $\gamma\gamma$ and $e\gamma$ colliders with real photons from the high energy ee colliders using the Compton back-scattering of laser light [4]. Thus, one may now consider a process such as $e^- + \gamma \longrightarrow \nu_e + W^- + H$ to probe WWH vertex.

Demanding only Lorentz and gauge invariance, the most general coupling structure involving the Higgs boson and a pair of gauge bosons may be expressed as

$$\Gamma^V_{\mu\nu} = g_V \left[a_V g_{\mu\nu} + \frac{b_V}{m_V^2}(k_{2\mu}k_{1\nu} - g_{\mu\nu} k_1 \cdot k_2) + \frac{\beta_V}{m_V^2}\epsilon_{\mu\nu\alpha\beta} k_1^\alpha k_2^\beta \right], \qquad (1)$$

where k_1^μ and k_2^ν are the momenta of two W's (or Z's) with $g_W^{\rm SM} = e\cot\theta_W M_Z$ and $g_Z^{\rm SM} = 2eM_Z/\sin 2\theta_W$. In the context of the SM, at the tree level, $a_W^{\rm SM} = a_Z^{\rm SM} = 1$, while the other couplings vanish identically. The general structure of these anomalous couplings can be obtained from dimension-6 operators in an effective theory [3].

Table 1. Transformation properties of the terms in the Lagrangian corresponding to the various couplings given by eq. (1).

Trans.	a_W	$\mathcal{R}(b_W)$	$\mathcal{R}(\beta_W)$	$\mathcal{I}(b_W)$	$\mathcal{I}(\beta_W)$
C	+	+	+	+	+
P	+	+	−	+	−
$\hat{T}$	+	+	−	−	+

2. The process and cross-sections

To the lowest order, Higgs production at an $e\gamma$ collider – the process $e^- + \gamma \to \nu_e + W^- + H$ – receives contributions from three Feynman diagrams. Retaining contributions only up to the lowest non-trivial order in the anomalous couplings, the cross-section may be written as

$$\sigma = (1 + 2\Delta a_W)\sigma_0 + \mathcal{R}(b_W)\sigma_1 + \mathcal{R}(\beta_W)\sigma_2 + \mathcal{I}(b_W)\sigma_3 + \mathcal{I}(\beta_W)\sigma_4, \quad (2)$$

where we have assumed that $a_W \equiv 1 + \Delta a_W$ is close to its SM value. Being odd under $\hat{T}$ (table 1), some of the terms in eq. (1) would not contribute, at the linear order, to the total rate.

To be quantitative, we shall choose to work with a Higgs boson of mass 120 GeV and a parent e^+e^- machine operating at a center of mass energy of 500 GeV. The final state comprises of four jets and missing momentum. Of the jets, two must be b-like and these must reconstruct to m_H and the other two must reconstruct to m_W. To be detectable, we consider the events characterized by the following acceptance cuts:

$$\begin{array}{rcll} p_T^{\text{miss}} & \geq & 20\,\text{GeV}, & \\ -3.0 \leq \eta_j & \leq & 3.0, & \text{for rapidity of each jet,} \\ p_T & \geq & 10\,\text{GeV}, & \text{for each jet,} \\ \Delta R_{j_1 j_2} & \geq & 0.7, & \text{for each pair of jets,} \end{array} \quad (3)$$

where $(\Delta R_{j_1 j_2})^2 \equiv (\Delta\phi)^2 + (\Delta\eta)^2$ with $\Delta\phi$ and $\Delta\eta$ denoting the separation between the two jets in azimuthal angle and rapidity respectively.

A statistical measure of agreement with the SM expectations is given by $(\delta\sigma)^2 = \sigma_{\text{SM}}/(\mathcal{L} + \epsilon^2\sigma_{\text{SM}}^2)$. Here σ_{SM} is the SM value of the cross-section, $\mathcal{L}$ is the integrated luminosity of the machine and ϵ is the fractional systematic error. We shall, henceforth, consider $\epsilon = 0.01$.

3. $\hat{T}$ even couplings $\Delta a_W, \mathcal{R}(b_W)$ and $\mathcal{I}(\beta_W)$

The relative contribution of the couplings can be enhanced or reduced by using different cuts on kinematic observables. A partial list of such cuts and the corresponding cross-sections are displayed in table 2. The set of cuts $\mathcal{C}_{3,4}$ eliminate the

Table 2. Various cuts and the corresponding rates, in femtobarns, for unpolarised scattering with $\sqrt{s_{ee}} = 500$ GeV.

	Cut	σ_0	σ_1	σ_4
$\mathcal{C}_0$	Acceptance cuts	4.15	−16.10	−1.96
$\mathcal{C}_1$	$p_{\mathrm{T}}(W) \geq 80$ GeV and $\lvert\sin\phi_{HW}\rvert \geq 0.4$	0.25	−2.58	−0.73
$\mathcal{C}_2$	$p_{\mathrm{T}}(W) \geq 80$ GeV and $p_{\mathrm{T}}^{\mathrm{miss}} \geq 60$ GeV	0.19	−2.37	−0.74
$\mathcal{C}_3$	$p_{\mathrm{T}}(W) \leq 80$ GeV and $\lvert\sin\phi_{HW}\rvert \leq 0.4$	1.11	−2.55	0.18
$\mathcal{C}_4$	$p_{\mathrm{T}}(W) \leq 80$ GeV and $\lvert\cos\theta_H\rvert \leq 0.8$	1.89	−5.56	0.044
$\mathcal{C}_5$	$p_{\mathrm{T}}(W) \geq 80$ GeV and $\lvert\sin\phi_{HW}\rvert \leq 0.4$	0.50	−3.49	−0.62

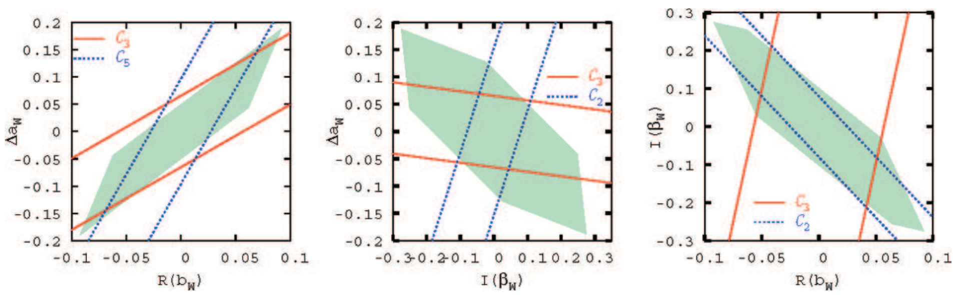

Figure 1. The pairs of oblique lines denote the region allowed by the corresponding cut, at the 3σ level, when the third anomalous coupling is identically zero. Intersection of strips, thus, gives the area allowed by both the observables. The shaded regions constitute the projections of the parameter space that leads to observables indistinguishable from the SM expectations for each of the cuts of table 2 when all three couplings are allowed to be non-zero. In each case, an integrated luminosity of 500 fb^{-1} has been used.

bulk of the $\mathcal{I}(\beta_W)$ contribution, while the cuts $\mathcal{C}_{1,2}$ serve to enhance the effect of $\mathcal{I}(\beta_W)$. If we make the simplifying assumption that only one anomalous coupling may be non-zero, the corresponding individual limits are easy to obtain. In figure 1, we display the regions allowed at 3σ level in the three different planes corresponding to each of the three pairs of anomalous couplings. The individual and simultaneous limits of these couplings are listed in table 3.

Table 3. Achievable upper limits (3σ) on $\hat{T}$ even couplings. Individual limits are obtained under the assumption that only one of the couplings is non-zero. The simultaneous limits are based on the shaded regions of figure 1.

Coupling	Individual limit	Observable used	Simultaneous limit
$\lvert\Delta a_W\rvert$	0.050	σ with $\mathcal{C}_4$	0.19
$\lvert\mathcal{R}(b_W)\rvert$	0.035	σ with $\mathcal{C}_4$	0.09
$\lvert\mathcal{I}(\beta_W)\rvert$	0.078	σ with $\mathcal{C}_2$	0.27

4. $\hat{T}$ odd couplings $\mathcal{I}(b_W)$ and $\mathcal{R}(\beta_W)$

On restricting the W-boson to lie above the plane of production of the Higgs (defined in conjunction with the beam axis), i.e. ($\sin\phi_{HW} \geq 0$), we have, for the corresponding partial cross-section,

$$\begin{aligned}\sigma(\sin\phi_{HW} \geq 0) = 2.07(1 + 2\Delta a_W) - 8.04\mathcal{R}(b_W) - 0.982\mathcal{I}(\beta_W)\\ +1.50\mathcal{I}(b_W) - 3.11\mathcal{R}(\beta_W).\end{aligned} \tag{4}$$

For events in the other hemisphere ($\sin\phi_{HW} \leq 0$), $\sigma_{0,1,4}$ remain the same, while $\sigma_{2,3}$ reverse sign. This, then, prompts the use of a $\hat{T}$-odd asymmetry of the form

$$\mathcal{A} \equiv \frac{\sigma_{\sin\phi_{HW}\geq 0} - \sigma_{\sin\phi_{HW}\leq 0}}{\sigma_{\sin\phi_{HW}\geq 0} + \sigma_{\sin\phi_{HW}\leq 0}}. \tag{5}$$

The employment of further kinematic cuts do not alter the relative contributions of $\mathcal{I}(b_W)$ and $\mathcal{R}(\beta_W)$ in any significant way. Thus the best bounds on these two couplings are obtained from eq. (5). Neglecting the anomalous contributions in the denominator (which is in consonance with our approximation of retaining terms which are at best linear in the anomalous couplings) and assuming that only one of these couplings is non-zero, the corresponding 3σ bounds are

$$|\mathcal{I}(b_W)| \leq 0.092 \quad \text{and} \quad |\mathcal{R}(\beta_W)| \leq 0.045 \tag{6}$$

for an integrated luminosity of 500 fb^{-1}.

5. Use of the $e^+\gamma$ initial state

We now consider the action of the composite discrete symmetry $P\hat{T}$. This is best achieved by comparing the results obtained until now using the $e^-\gamma$ colliders with those expected from the conjugate process, namely $e^+\gamma \longrightarrow \bar{\nu}W^+H$. The total cross-section for the conjugate process is related to that obtained earlier in a simple fashion:

$$\begin{aligned}\sigma_{e^+\gamma} = [\sigma_0(1 + 2\Delta a_W) + \sigma_1\mathcal{R}(b_W) + \sigma_2\mathcal{R}(\beta_W)]_{e^-\gamma}\\ - [\sigma_3\mathcal{I}(b_W) + \sigma_4\mathcal{I}(\beta_W)]_{e^-\gamma}\,.\end{aligned} \tag{7}$$

Table 4. Limits on anomalous couplings at 3σ level using unpolarised beams with an integrated luminosity of 250 fb^{-1} for each of the $e^-\gamma$ and $e^+\gamma$ modes.

Coupling	$3\delta\mathcal{A}$ bound	Observable used
$\lvert\mathcal{I}(\beta_W)\rvert$	0.092	$\mathcal{A}_1$ with $\mathcal{C}_1$
$\lvert\mathcal{I}(b_W)\rvert$	0.096	$\mathcal{A}_3$ with acceptance cuts
$\lvert\mathcal{R}(\beta_W)\rvert$	0.046	$\mathcal{A}_2$ with acceptance cuts

This leads us to construct the asymmetries

$$\mathcal{A}_1 \equiv \frac{\sigma_{e^+\gamma} - \sigma_{e^-\gamma}}{\sigma_{e^+\gamma} + \sigma_{e^-\gamma}},$$
$$\mathcal{A}_2 = \frac{(\sigma_{++} - \sigma_{+-}) - (\sigma_{-+} - \sigma_{--})}{(\sigma_{++} + \sigma_{+-}) + (\sigma_{-+} + \sigma_{--})},$$
$$\mathcal{A}_3 = \frac{(\sigma_{++} - \sigma_{--}) - (\sigma_{+-} - \sigma_{-+})}{(\sigma_{++} + \sigma_{--}) + (\sigma_{+-} + \sigma_{-+})}, \tag{8}$$

where

$$\sigma_{++} = \sigma_{e^+\gamma,\, \sin\phi_{HW}>0}, \quad \sigma_{+-} = \sigma_{e^+\gamma,\, \sin\phi_{HW}<0},$$
$$\sigma_{-+} = \sigma_{e^-\gamma,\, \sin\phi_{HW}>0}, \quad \sigma_{--} = \sigma_{e^-\gamma,\, \sin\phi_{HW}<0}. \tag{9}$$

Again retaining only terms linear in the anomalous couplings, $\mathcal{A}_1$ contains only the $\mathcal{I}(\beta_W)$ term (if no cut is imposed on $\sin\phi_{HW}$). Similarly, $\mathcal{A}_2$ and $\mathcal{A}_3$ are functions of only $\mathcal{I}(b_W)$ and $\mathcal{R}(\beta_W)$ respectively. This allows us to obtain a direct bound on each one of these couplings alone, something that we were hitherto unable to do (table 4).

6. Conclusions

Since the WWH couplings are not contaminated by the ZZH couplings in the process studied, $e\gamma$ colliders can be used to constrain the anomalous WWH couplings independent of the ZZH couplings. Thus $e\gamma$ colliders are better equipped than e^+e^- colliders to study these couplings.

Comparing our results to those of ref. [1], we find that we obtain better individual limits for all couplings, bar Δa_W. Furthermore, in ref. [1], the authors were unable to construct observables that depend on only one of the couplings. Hence their limits on WWH couplings are not independent of each other. However, using the process $e^-\gamma \longrightarrow \nu W^- H$ in conjunction with the conjugate process $e^+\gamma \longrightarrow \bar{\nu} W^+ H$, and using the $P\hat{T}$ properties of various contributions to the total rate, we are able to construct observables that are functions of only one of the couplings. Thus we are able to derive constraints on each of the couplings $\mathcal{I}(\beta_W)$, $\mathcal{I}(b_W)$ and $\mathcal{R}(\beta_W)$ independent of the value of any other coupling. Δa_W and $\mathcal{R}(b_W)$, however, cannot be constrained independent of each other.

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