PROCEEDINGS OF SCIENCE

Constraining anomalous ZH couplings using Z polarization parameters

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We study the anomalous ZZH vertex contributing to the Higgsstrahlung process at the LHC and future e^+e^- colliders using the polarization of the Z as a probe. We calculate the eight independent polarization parameters of the Z boson by using the spin density matrix formalism. We estimate 1σ limits on the anomalous ZZH couplings using the angular asymmetries of leptons from Z decay which are simply related to the eight polarization parameters. We discuss the results for a) two possible c.m.energies ($\sqrt{s} =$) 250 GeV and 500 GeV for the e^+e^- colliders, with the possibility of polarized e^+e^- beams, b) LHC at $\sqrt{s} = 14$ TeV.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

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PoS(ICHEP2020)277

1. Introduction

After the discovery of a Higgs-like boson (H), the focus is on the precise measurement of the Higgs boson to the electroweak (EW) gauge bosons and the SM fermions, as it is required to unravel the exact mechanism of the EW symmetry breaking. These measurements of the couplings and other properties of the Higgs boson would need as many observables as possible apart from simple event counts. Among these, there has been a growing interest in the polarization parameters of the spin-1 Z boson. In this work we propose studying new possible physics in the associated production of Z with the Higgs due to a modified ZZH vertex, at the LHC and future e^+e^- colliders, using the spin observables of the produced Z boson. We adopt the formalism that connects the spin polarization parameters to the angular asymmetries constructed from the distribution of the leptons from Z decay [1, 2, 3]. These polarization observables, along with the total cross section can give insight into the production mechanism and also provide information about the nature of the tensorial structure as well as the strength of anomalous couplings in the ZZH interaction. We consider the processes $e^-e^+ \to ZH$ and $pp \to ZHX$, where the vertex $Z_\mu(k_1) \to Z_\nu(k_2)H$ has the Lorentz structure

$$\Gamma^V_{\mu\nu} = \frac{g}{\cos\theta_W} m_Z \left[a_Z g_{\mu\nu} + \frac{b_Z}{m_Z^2}\left(k_{1\nu}k_{2\mu} - g_{\mu\nu}k_1.k_2\right) + \frac{\tilde{b}_Z}{m_Z^2}\varepsilon_{\mu\nu\alpha\beta}k_1^\alpha k_2^\beta\right] \tag{1.1}$$

where g is the $SU(2)_L$ coupling and θ_W is the weak mixing angle.

The form factors a_Z, b_Z and $\tilde{b}_Z$ are in general complex. The first two couplings correspond to CP invariant terms in the interaction, while the third term is odd under CP. The coupling a_Z is unity in the SM at tree level, whereas the other two couplings b_Z, $\tilde{b}_Z$ vanish at tree level, denoting the deviation from the tree-level SM value. These couplings are the anomalous couplings which could arise from loop corrections in the SM or in any extension of SM with some new particles. We estimate 1σ limits on these anomalous couplings using the polarization asymmetries of the Z. The HVV vertex has been studied extensively both at the LHC and at e^+e^- colliders. Experimental bounds on the anomalous couplings are obtained by the CMS and ATLAS collaboration [4, 5, 6]. The upper bound (68% confidence level (CL))on the ZZH couplings, assuming them to be real, in our notation translate to $|\text{Re } b_Z| < 0.058$ and $|\text{Re } \tilde{b}_Z| < 0.078$ and are obtained from measurements of ratios of the cross section contributions arising from the different ZZH couplings. These constraints are still weak enough to allow for new contributions to the SM ZZH vertex.

2. Polarization parameters of Z boson and Lepton asymmetries

The production density matrix for Z expressed in terms of the helicity amplitudes M is given by

$$\rho(i,j) = \overline{\sum}_{\lambda,\lambda'} M(\lambda,\lambda',i)M^*(\lambda,\lambda',j) \tag{2.1}$$

the average being over the helicities λ, λ' of the incoming particles and the indices i, j represent the Z helicity indices and can take values $\pm, 0$. The usual helicity fractions are given by the diagonal elements of Eqn.(2.1). But to attain maximum possible spin information it is necessary to study the full density matrix which also includes the off-diagonal elements. The full density matrix Eqn.(2.1) on integrating over the phase space, would lead to the eight independent vector and tensor polarization components, known as the *polarization parameters* of the Z[7]. These eight independent vector and tensor polarization observables can be constructed using appropriate linear combinations of the integrated density matrix elements $\sigma(i,j)$ defined in Ref. [8]

$$P_x = \frac{\{\sigma(+,0)+\sigma(0,+)\}+\{\sigma(0,-)+\sigma(-,0)\}}{\sqrt{2}\sigma} \tag{2.2}$$

$$P_y = \frac{-i\{[\sigma(0,+)-\sigma(+,0)]+[\sigma(-,0)-\sigma(0,-)]\}}{\sqrt{2}\sigma} \tag{2.3}$$

$$P_z = \frac{[\sigma(+,+)]-[\sigma(-,-)]}{\sigma} \tag{2.4}$$

$$T_{xy} = \frac{-i\sqrt{6}[\sigma(-,+)-\sigma(+,-)]}{4\sigma} \tag{2.5}$$

$$T_{xz} = \frac{\sqrt{3}\{[\sigma(+,0)+\sigma(0,+)]-[\sigma(0,-)+\sigma(-,0)]\}}{4\sigma} \tag{2.6}$$

$$T_{yz} = \frac{-i\sqrt{3}\{[\sigma(0,+)-\sigma(+,0)]-[\sigma(-,0)-\sigma(0,-)]\}}{4\sigma} \tag{2.7}$$

$$T_{xx}-T_{yy} = \frac{\sqrt{6}[\sigma(-,+)+\sigma(+,-)]}{2\sigma} \tag{2.8}$$

$$\begin{aligned} T_{zz} &= \frac{\sqrt{6}}{2}\left\{\frac{[\sigma(+,+)]+[\sigma(-,-)]}{\sigma}-\frac{2}{3}\right\} \\ &= \frac{\sqrt{6}}{2}\left[\frac{1}{3}-\frac{\sigma(0,0)}{\sigma}\right] \end{aligned} \tag{2.9}$$

where P_x, P_y and P_z correspond to the 3 vector polarizations and T'_{ij}'s are the 5 tensor polarizations, with the constraint that the tensor is traceless. The trace of $\sigma(i,j)$ gives the total production cross section σ given by

$$\sigma = \sigma(0,0)+\sigma(+,+)+\sigma(-,-)$$

Lepton asymmetries

In an experiment, the kinematic distributions of the Z decay products provide its spin information. All the spin observables mentioned above can be connected to various angular asymmetries constructed in the rest frame of the Z [2, 8]

$$A_x = \frac{3\alpha P_x}{4} \equiv \frac{\sigma(\cos\phi^*>0)-\sigma(\cos\phi^*<0)}{\sigma(\cos\phi^*>0)+\sigma(\cos\phi^*<0)} \qquad A_y = \frac{3\alpha P_y}{4} \equiv \frac{\sigma(\sin\phi^*>0)-\sigma(\sin\phi^*<0)}{\sigma(\sin\phi^*>0)+\sigma(\sin\phi^*<0)}$$

$$A_z = \frac{3\alpha P_z}{4} \equiv \frac{\sigma(\cos\theta^*>0)-\sigma(\cos\theta^*<0)}{\sigma(\cos\theta^*>0)+\sigma(\cos\theta^*<0)} \qquad A_{xy} = \frac{2}{\pi}\sqrt{\frac{2}{3}}T_{xy} \equiv \frac{\sigma(\sin 2\phi^*>0)-\sigma(\sin 2\phi^*<0)}{\sigma(\sin 2\phi^*>0)+\sigma(\sin 2\phi^*<0)}$$

$$A_{xz} = \frac{-2}{\pi}\sqrt{\frac{2}{3}}T_{xz} \equiv \frac{\sigma(\cos\theta^*\cos\phi^*<0)-\sigma(\cos\theta^*\cos\phi^*>0)}{\sigma(\cos\theta^*\cos\phi^*>0)+\sigma(\cos\theta^*\cos\phi^*<0)} \qquad A_{yz} = \frac{2}{\pi}\sqrt{\frac{2}{3}}T_{yz} \equiv \frac{\sigma(\cos\theta^*\sin\phi^*>0)-\sigma(\cos\theta^*\sin\phi^*<0)}{\sigma(\cos\theta^*\sin\phi^*>0)+\sigma(\cos\theta^*\sin\phi^*<0)}$$

$$A_{x^2-y^2} = \frac{1}{\pi}\sqrt{\frac{2}{3}}(T_{xx}-T_{yy}) \equiv \frac{\sigma(\cos 2\phi^*>0)-\sigma(\cos 2\phi^*<0)}{\sigma(\cos 2\phi^*>0)+\sigma(\cos 2\phi^*<0)} \qquad A_{zz} = \frac{3}{8}\sqrt{\frac{3}{2}}T_{zz} \equiv \frac{\sigma(\sin 3\theta^*>0)-\sigma(\sin 3\theta^*<0)}{\sigma((\sin 3\theta^*>0)+\sigma((\sin 3\theta^*<0)}$$

where $\alpha = \frac{R_\ell^2-L_\ell^2}{R_\ell^2+L_\ell^2}$ is the Z boson polarization analyser, given in terms of its left and right handed couplings to charged leptons ℓ, L_ℓ and R_ℓ respectively. The angles θ^* and ϕ^* are polar and azimuthal angles of the charged leptons defined in the rest frame of the Z.

3. Results and Discussion

Sensitivity of the observables at e^+e^- collider

We compute the helicity amplitudes for the process

$$e^-(p_1) + e^+(p_2) \to Z^\alpha(p) + H(k) \tag{3.1}$$

in the massless limit of the initial particles, with the ZZH vertex given in Eqn.(1.1).

In table 1, we present numerical values for the sensitivities of the 8 angular asymmetries to the various anomalous couplings for the collider parameters,*viz.*,c.m. energy $\sqrt{s} = 250$GeV, with integrated luminosity $\int \mathscr{L} dt = 2\ ab^{-1}$ and c.m. energy 500 GeV with integrated luminosity $\int \mathscr{L} dt = 500$ fb^{-1}[9]. Limits are estimated considering one coupling to be non-zero at a time and for unpolarized and oppositely polarized initial beams neglecting systematic errors.

Observable	Coupling	Limit ($\times 10^{-3}$) for $P_L = 0$, $\bar{P}_L = 0$	Limit ($\times 10^{-3}$) for $P_L = -0.8$, $\bar{P}_L = 0.3$
σ	Re b_z	1.36	1.15
A_x	Re b_z	3480	478
A_y	Re $\tilde{b}_z$	303	41.7
A_z	Im $\tilde{b}_z$	32.3	27.2
A_{xy}	Re $\tilde{b}_z$	22.7	19.2
A_{yz}	Im b_z	189	26.1
A_{xz}	Im $\tilde{b}_z$	107	14.7
$A_{x^2-y^2}$	Re b_z	94.5	80.2
A_{zz}	Re b_z	26.8	22.8

Observable	Coupling	Limit ($\times 10^{-3}$) for $P_L = 0$, $\bar{P}_L = 0$	Limit ($\times 10^{-3}$) for $P_L = -0.8$, $\bar{P}_L = 0.3$
σ	Re b_z	3.32	2.8
A_x	Re b_z	394	54.2
A_y	Re $\tilde{b}_z$	204	28.2
A_z	Im $\tilde{b}_z$	47.9	40.4
A_{xy}	Re $\tilde{b}_z$	33.7	28.5
A_{yz}	Im b_z	77.7	10.7
A_{xz}	Im $\tilde{b}_z$	72.0	9.93
$A_{x^2-y^2}$	Re b_z	46.7	39.4
A_{zz}	Re b_z	12.8	10.8

Table 1: 1σ limit obtained from various leptonic asymmetries for unpolarized and polarized beams at $\sqrt{s} = 250$ GeV(Left) and $\sqrt{s} = 500$ GeV(Right).

It is observed that out of the four observables which are sensitive to the coupling Re b_z, the total cross section provides the best limit on the coupling which becomes more stringent for the combination $(P_L = -0.8, \bar{P}_L = 0.3)$ at $\sqrt{s} = 500$ GeV. However to probe the couplings which do not appear in the total cross section, one will require the other angular asymmetries.

The best bound of 9.93×10^{-3} is obtained on Im $\tilde{b}_z$, comes from A_{xz} whereas the best limit of 19.2×10^{-3} on Re $\tilde{b}_z$ can be obtained from the observable A_{xy} for a reduced beam energy of 250 GeV. Likewise on the coupling Im b_z, a best bound of 10.7×10^{-3} can be achieved from the observable A_{yz}, which gets improved as one increases the c.m. energy to 500 GeV.

From the tables it is apparent that the use of opposite sign beam polarization puts stronger constraints on the anomalous couplings, in some cases upto an order of magnitude better.

Thus we find that most of the 1σ limits on the anomalous couplings, derived from the polarization observables are of the order of a few times 10^{-3}. Also one important feature that we observe is that the oppositely polarized beams provides much tighter bounds on the couplings than the same sign polarized and unpolarized beams, which further gets improved as one increases the c.m. energy. We further find that a systematic uncertainty of 1% in the measurement of the asymmetries leads to a change in the limits by 5-10% for the case of c.m energy of 500 GeV. In the case of 250 GeV c.m. energy, the limits on couplings worsens by a factor lying between 1.5 and 3, still remain in the same ball park as the limits estimated without systematic uncertainty.

Similarly, for the total cross section a 1% uncertainty in its measurement leads to a change in the the limits by 5-7% at 500 GeV , for unpolarized and polarized beams respectively, whereas for the case of 250 GeV the (corresponding) limits worsen by a factor between 1.6 to 1.8.

Sensitivity of the observables at the LHC

At the LHC, we compute the helicity amplitudes for the process $pp \to ZHX$, which at the partonic level proceeds via

$$q(p_1) + \bar{q}(p_2) \to Z^{\alpha}(p) + H(k) \tag{3.2}$$

through Z mediated s-channel. q represents both up type and down type quarks of any generation, in the massless limit of the initial particles, with the ZZH vertex given in Eqn.(1.1). It is observed that the asymmetries A_x, A_y, A_{xz}, A_{yz} involving the density matrix elements $\sigma(\pm,0)$ and $\sigma(0,\pm)$ vanish due to the symmetric nature of the LHC, where the choice of z-axis is not unique. We redefine the positive z-axis to be the direction of the reconstructed momentum of the ZH combination so as to make the asymmetries non-zero.

In Figure 1, we present the one parameter sensitivity *i.e* $\mathscr{S} = 1$(or $\Delta\chi^2 = 1$) for the cross section and the 8 asymmetries, considered upto quadratic order in the anomalous couplings.

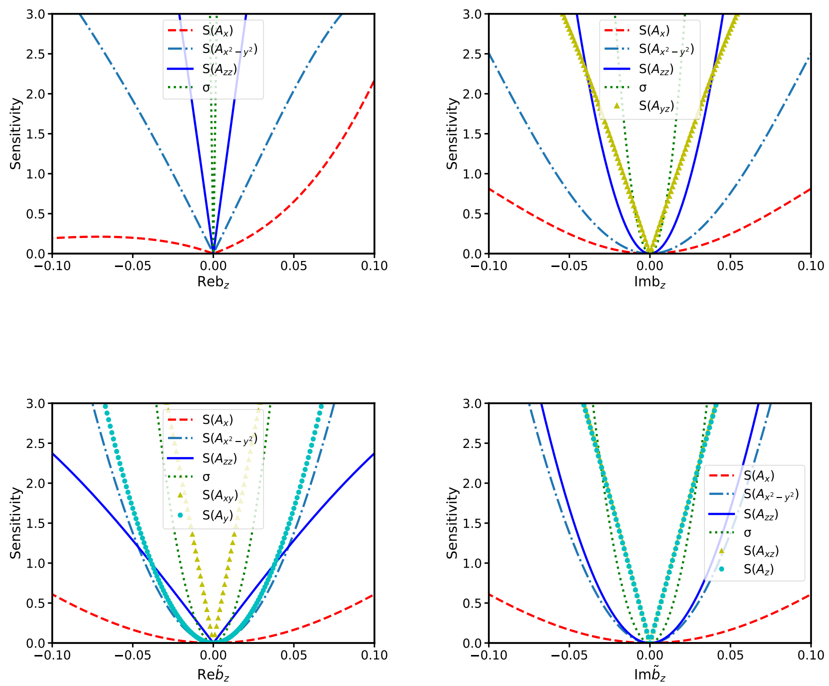

Figure 1: Sensitivities of cross section and asymmetries to anomalous couplings, including quadratic order at $\sqrt{s} = 14$TeV. Plots are obtained by varying one coupling at a time.

Observable	Coupling	Limit ($\times 10^{-3}$)
σ	$\|\text{Re } b_Z\|$	0.70
σ	$\|\text{Im } b_Z\|$	15.9
A_{xy}	$\|\text{Re } \tilde{b}_Z\|$	9.54
A_{xz}, A_z	$\|\text{Im } \tilde{b}_Z\|$	13.3

Table 2: The best 1σ limit on couplings and the corresponding observables at $\sqrt{s} = 14$ TeV, obtained from Figure 1.

It is observed that in the SM, along with the total cross section only three asymmetries, *viz.*, A_x, $A_{x^2-y^2}$ and A_{zz} are non-zero, which are sensitive to the real part of the anomalous couplings (upto linear order) or absolute square of the couplings to satisfy the CPT theorem, as can be seen from Figure 1. We see that on the coupling Re b_Z the tightest limit can be achieved from total cross section whereas on Im b_Z, both cross section and A_{yz} place comparable limits. The best limit on Re $\tilde{b}_Z$ can be obtained from the observable A_{xy}. In case of the coupling Im $\tilde{b}_Z$, the observables A_x and A_{xz} are found to be almost equally sensitive to it. In Table 2, we list the tightest 1σ level limit on the couplings, obtained from Figure 1. The limits obtained on the real parts of the couplings are found to be of the order of a few times 10^{-3} and an order of magnitude higher for the imaginary parts. Thus the 1σ limits obtained on the CP conserving couplings Re b_Z and Im b_Z for the $\sqrt{s} = 14$ TeV LHC with integrated luminosity $\int \mathscr{L} dt = 1000$ fb^{-1} are 0.7×10^{-3} and 15.9×10^{-3} respectively. Similarly the CP violating couplings, Re $\tilde{b}_Z$ and Im $\tilde{b}_Z$ get a best bound of 9.54×10^{-3} and 13.3×10^{-3} respectively. These limits are estimated by varying one coupling at a time. With two non-zero couplings, we observe a slight weakening of bounds on all the anomalous couplings as can be expected[10].

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