Probing anomalous ZZH and γZH interactions at an e^+e^- linear collider with polarized beams

Pankaj Sharma

Based on : (a) Physical Review D **79**, 075007
(b) arxiv:1001.4931

Authors : Saurabh D. Rindani and Pankaj Sharma

International Linear Collider Workshop (ILCWS 2010)

Theoretical Physics Division
Physical Research Laboratory
Ahmedabad

Introduction

Standard Model

The Standard Model has been a crown jewel of fundamental particle physics for the past several decades.

Problems in the SM

- Insufficient CP violation present in the SM to explain the baryon asymmetry of the universe
- Origin of CP violation is unknown
- Experimentally observed neutrino masses
- No explanation for the patterns of masses among different generations of fermions
- Naturalness problem

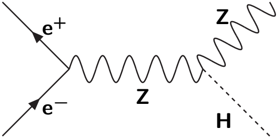
All these problems motivate us to look beyond the SM.

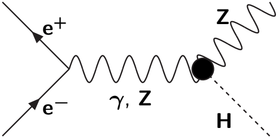
Introduction Contd.

- Mechanism of (EWSB) predicts the existence of a fundamental scalar known as the Higgs which has not been discovered yet
- One of the main aims for the current (Tevatron, LHC) and future (ILC, CLIC) colliders is to discover the Higgs
- Some models predict the existence of more than one Higgs
- So even if one discovers a Higgs at these colliders, it is not a confirmation for the SM Higgs
- A thorough study is needed to study its properties to be ascertained that it is indeed the SM Higgs
- This type of precision study can easily be done at $\mathbf{e^+e^-}$ linear colliders.
- Any deviation in the SM values of the Higgs couplings at these colliders would be a signal of new physics
- As Higgs couplings are proportional to mass, we study the interaction of the Higgs with heavier particles like top quark and the electroweak bosons i.e., $\mathbf{W^\pm}$ and $\mathbf{Z}$

Introduction Contd.

- We consider in a general model-independent way the production of a Higgs **H** through the process $e^+e^- \longrightarrow HZ$ mediated by s-channel virtual γ and **Z**
- Other important mechanisms $e^+e^- \longrightarrow e^+e^-H$ and $e^+e^- \longrightarrow \nu\bar{\nu}H$ proceeding via vector-boson fusion
- In SM, this process gets contribution from s-channel exchange of **Z** at tree level and from γ-exchange only at the loop level as there is no γ**ZH** couplings at the tree level
- At the lowest order, the **ZZH** vertex in this diagram would be simply a point-like coupling





Beam polarizations

Availability of beam polarization

- Both longitudinal and transverse polarization are expected to be available at linear collider,
- Expected electron polarization is about **80%** and positron polarization is about **60%**,

Role of longitudinal polarization

- Reduces background,
- Increases sensitivity

Role of transverse polarization

- provides very useful variable i.e., azimuthal angle,
- which, in turns, provides additional asymmetries and correlations,
- probes couplings which are not accessible with longitudinal polarized beams.

Structure of the anomalous VZH couplings

- We have studied the most general set of anomalous $\mathbf{VZH}$ $(\mathbf{V} = \gamma, \mathbf{Z})$ couplings, in order to put limits on them, at a linear collider in the process $\mathbf{e^+e^- \longrightarrow ZH}$,
- Demanding Lorentz invariance, the general structure of the vertex $\mathbf{V^*_\mu(k_1) \longrightarrow Z^*_\nu(k_2)H}$, where $(\mathbf{V} = \mathbf{Z}, \gamma)$, can be expressed as (Hagiwara & Stong)

$$\Gamma_{\mu\nu} = g_V \left[a_V g_{\mu\nu} + \frac{b_V}{M_Z^2}(k_{1\nu} k_{2\mu} - g_{\mu\nu} k_1.k_2) + \frac{\tilde{b}_V}{M_Z^2} \epsilon_{\mu\nu\alpha\beta} k_1^\alpha k_2^\beta \right],$$

- Our emphasis has been on simultaneous independent determination of couplings, to the extent possible, making use of a combination of observables and/or polarizations,
- We have also tried to consider rather simple observables, conceptually, as well as from an experimental point of view,
- We find that longitudinal polarization is particularly useful in achieving our purpose of determining a different combination of couplings compared to the unpolarized case,
- The total cross section with transverse polarization generally provides combinations of the same couplings as in unpolarized case.

Angular distributions for longitudinally polarized beams

The anomalous $\mathbf{ZZH}$ and $\boldsymbol{\gamma}\mathbf{ZH}$ contributions to the process for longitudinally polarized beams are

$$\frac{d\sigma^{L}_{Z,\gamma}}{d\Omega} \propto \left(1 - P_L \overline{P}_L\right) \left[A^{Z,\gamma}_{L} + B^{Z,\gamma}_{L} \sin^2\theta + C^{Z,\gamma}_{L} \cos\theta\right]$$

From above equation, we can infer following points:

- Here, coefficients A^Z_L, A^γ_L, $B^{Z,\gamma}_L$ and $C^{Z,\gamma}_L$ contain anomalous couplings $\mathrm{Re}\Delta a_Z$, $\mathrm{Re}a_\gamma$, $\mathrm{Re}b_{Z,\gamma}$ and $\mathrm{Im}\tilde{b}_{Z,\gamma}$ respectively
- Imaginary parts of $\Delta a_{\gamma,Z}$, $b_{\gamma,Z}$, and real parts of $\tilde{b}_{\gamma,Z}$ do not contribute to the angular distributions at this order, and hence remain undetermined
- The differential cross section with longitudinally polarized beams, apart from an overall factor $(1 - P_L\overline{P}_L)$, depends on the "effective polarization" $P^{\mathrm{eff}}_L = \frac{P_L - \overline{P}_L}{1 - P_L\overline{P}_L}$,
- Since P^{eff}_L is about 0.946 for $P_L = 0.8$, $\overline{P}_L = -0.6$, and 0.385 for $P_L = 0.8$, $\overline{P}_L = 0.6$, a high degree of effective polarization can be achieved for e^- and e^+ beams opposite in sign to each other
- With longitudinal polarization turned on, with a reasonably large value of P^{eff}_L, the coefficients C^Z_L with $(g_V^2 + g_A^2)P^{\mathrm{eff}}_L$, A^γ_L and B^γ_L both with $(g_V - g_A P^{\mathrm{eff}}_L)$ would become significant. In that case, the sensitivity to $\mathrm{Re}a_\gamma$, $\mathrm{Re}b_\gamma$ and $\mathrm{Im}\tilde{b}_Z$ would be significant

Forward backward asymmtery $\mathbf{A_{FB}}$

- The terms proportional to $\cos\theta$ i.e., $C_L^{Z,\gamma}$ can be determined using a simple forward-backward asymmetry:

$$A^L_{FB}(\theta_0) = \frac{1}{\sigma(\theta_0)}\left[\int_{\theta_0}^{\pi/2}\frac{d\sigma}{d\theta}d\theta - \int_{\pi/2}^{\pi-\theta_0}\frac{d\sigma}{d\theta}d\theta\right],$$

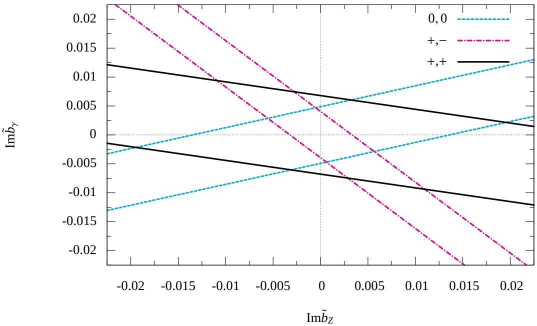
- It separates out a definite combination of couplings $\mathrm{Im}\tilde{b}_Z, \mathrm{Im}\tilde{b}_\gamma$ for unpolarized and different combination for longitudinally polarized beams
- With $\sqrt{s} = 500$ GeV, and $\int \mathcal{L}dt = 500\ \mathrm{fb}^{-1}$, individual 95% CL limits on $\mathrm{Im}\tilde{b}_\gamma$, $\mathrm{Im}\tilde{b}_Z$ using A_{FB}

	$\lvert\mathrm{Im}\tilde{b}_\gamma\rvert$	$\lvert\mathrm{Im}\tilde{b}_Z\rvert$
Unpolarized	0.00392	0.0108
$P_L = 0.8,\ \overline{P}_L = +0.6$	0.00543	0.0229
$P_L = 0.8,\ \overline{P}_L = -0.6$	0.00320	0.00262

- Sensitivity to $\mathrm{Im}\tilde{b}_Z$ is enhanced by about a factor of **5** using opposite beam polarization because of the P_L^{eff}

Simultaneous limits on couplings from asymmtery $\mathbf{A_{FB}}$

As an illustration, we show a plot how we determine simultaneous limits using $\mathbf{A_{FB}}$



- Simultaneous limits (S.L.) are obtained by looking at the extremeties of the enclosed region.

The best simultaneous limits are obtained by considering the region enclosed by the lines corresponding to $\mathbf{P_L = \overline{P}_L = 0}$ and $\mathbf{(P_L, \overline{P}_L) = (0.8, -0.6)}$. These limits are

$$|\mathrm{Im}\tilde{b}_\gamma| \leq 4.69 \cdot 10^{-3}; |\mathrm{Im}\tilde{b}_Z| \leq 5.61 \cdot 10^{-3}.$$

Angular distribution for transversely polarized beams

The anomalous **ZZH** and γ**ZH**contribution to the process for transversely polarized beams is

$$\frac{d\sigma^{T}_{Z,\gamma}}{d\Omega} \propto \left[\frac{d\sigma^{SM}}{d\Omega} + P_T \overline{P}_T \left\{ D^{Z,\gamma}_T \sin^2\theta \cos 2\phi + E^{\gamma}_T \sin^2\theta \sin 2\phi \right\} \right]$$

Here, $\mathbf{D_T}$ contains anomalous couplings $\mathbf{Re\Delta a_Z}$ and $\mathbf{Rea_\gamma}$ while $\mathbf{E_T}$ contains only $\mathbf{Ima_\gamma}$. From above equation, we can infer following points:

- To study any effects of transverse polarization, and of the azimuthal distribution of the **Z**, both electron and positron beams have to be polarized
- If the azimuthal angle ϕ of **Z** is integrated over, there is no difference between the transversely polarized and unpolarized cross sections. Thus the usefulness of transverse polarization comes from the study of nontrivial ϕ dependence
- The $\mathbf{\cos 2\phi}$ (the $\mathbf{D_T}$) term determines a combination only of the couplings $\mathbf{Re\Delta a_Z}$ and $\mathbf{Rea_\gamma}$
- A glaring advantage of using transverse polarization would be to determine $\mathbf{Ima_\gamma}$ from the $\mathbf{\sin 2\phi}$ term. $\mathbf{E_T}$ receives contribution only from $\mathbf{E^{\gamma}_T}$, which determines $\mathbf{Ima_\gamma}$ independently of any other coupling
- The couplings $\mathbf{Re\tilde{b}_Z}$, $\mathbf{Re\tilde{b}_\gamma}$, $\mathbf{Imb_Z}$, $\mathbf{Imb_\gamma}$ and $\mathbf{Im\Delta a_Z}$ remain undetermined with either longitudinal or transverse polarization

Azimuthal asymmtery ($\mathbf{A_T}$)

- We can define an azimuthal asymmetry which can be used to separate out coefficient of $\sin^2\theta \sin 2\phi$ which is $\mathbf{E_T^\gamma}$ since $\mathbf{E_T^Z}$ and $\mathbf{E_T^{SM}}$ are vanishing:

$$\mathbf{A^T(\theta_0)} = \frac{1}{\sigma_T^{SM}(\theta_0)}\Big[\int_{\theta_0}^{\pi-\theta_0} d\theta\Big(\int_0^{\pi/2} d\phi - \int_{\pi/2}^{\pi} d\phi + \int_{\pi}^{3\pi/2} d\phi - \int_{3\pi/2}^{2\pi} d\phi\Big)\frac{d\sigma_T}{d\theta d\phi}\Big], \quad (1)$$

- This is the most important result that a measurement of $\mathbf{A^T(\theta_0)}$ directly gives us a measurement of $\mathbf{Im\ a_\gamma}$, which cannot be measured without the use of transverse polarization,
- Using $\mathbf{A_T}$, $\mathbf{95\%}$ CL simultaneous limit on the coupling $\mathbf{Im a_\gamma}$ is $\mathbf{4.01 \times 10^{-2}}$ for $\mathbf{m_H = 120}$ GeV,
- In principle, any odd function of $\sin 2\phi$ can probe $\mathbf{E_T}$ i.e., $\mathbf{Im a_\gamma}$,
- For example, sign($\sin 2\phi$) $\equiv \mathbf{A_T}$, $\sin 2\phi$ and $\sin^3 2\phi$

Azimuthal asymmetry, $\mathbf{A'_T}$

- We can define another azimuthal asymmetry which can be used to separate out coefficient of $\sin^2\theta\cos 2\phi$ which is $\mathbf{D_T}$:

$$\mathbf{A'^T}(\theta_0) = \frac{1}{\sigma_T^{SM}(\theta_0)}\Big[\int_{\theta_0}^{\pi-\theta_0} d\theta\Big(\int_{-\pi/4}^{\pi/4} d\phi - \int_{\pi/4}^{3\pi/4} d\phi + \int_{5\pi/4}^{3\pi/4} d\phi - \int_{5\pi/4}^{7\pi/4} d\phi\Big)\frac{d\sigma_T}{d\theta d\phi}\Big],$$

- $\mathbf{D_T}$ contains anomalous couplings $\mathbf{Re\Delta a_Z}$ and $\mathbf{Re a_\gamma}$,
- So, measurement of $\mathbf{A'_T}$ would probe a combination of $\mathbf{Re\Delta a_Z}$ and $\mathbf{Re a_\gamma}$,
- The individual limits using $\mathbf{A'^T}$ on $\mathbf{Re a_\gamma}$ and $\mathbf{Re\Delta a_Z}$, each taken nonzero by turns, are

$$|\mathbf{Re a_\gamma}| \leq 0.334, \; |\mathbf{Re\Delta a_Z}| \leq 0.0270$$

Story So far ...

- Without including decay, we find that we could put limits on anomalous couplings $\mathbf{Re\Delta a_Z}$, $\mathbf{Rea_\gamma}$, $\mathbf{Reb_Z}$, $\mathbf{Reb_\gamma}$, $\mathbf{Im\tilde{b}_Z}$ and $\mathbf{Im\tilde{b}_\gamma}$,
- We do not have any access on anomalous couplings $\mathbf{Im\Delta a_Z}$, $\mathbf{Imb_Z}$, $\mathbf{Imb_\gamma}$, $\mathbf{Re\tilde{b}_Z}$ and $\mathbf{Re\tilde{b}_\gamma}$ so far,
- $\mathbf{Ima_\gamma}$ is only accessible through transverse polarization,
- We find that longitudinal polarization helps in enhancing the sensitivity,
- To probe other couplings which are not accessible so far, we need to construct other observables which can only be possible if we have other momenta available,

The process $\mathbf{e^+(p_1)e^-(p_2) \rightarrow HZ(q)}$ with $\mathbf{Z(q) \rightarrow l^-(p_3)l^+(p_4)}$

- Next, we include the decay of the **Z** into charged lepton pair,
- We get contributions from couplings which are earlier inaccessible without the decay of **Z** like $\mathbf{Imb_Z}$, $\mathbf{Imb_\gamma}$, $\mathbf{Re\tilde{b}_Z}$ and $\mathbf{Re\tilde{b}_\gamma}$,
- Lots of correlations can be constructed with the available momenta of leptons and spins of the intial electron and positron,
- Here, we construct various observables based on the **CP** and **T** transformations properties, to separate the couplings having same **CP** and **T** properties,
- We suggest measurement of correlations with different combinations of polarization,
- Since these would give different combinations of couplings, their measurements may be used to put simultaneous limits on couplings, without assuming any coupling to be zero.

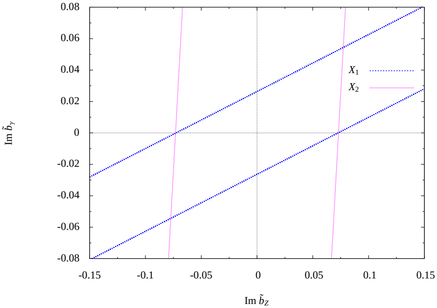
Observables sensitive to longitudinal polarization with **CP** and **T** properties

Symbol	Observable	CP	T	Couplings
X_1	$(p_1 - p_2).q$	$-$	$+$	$\mathrm{Im}\tilde{b}_Z,\ \mathrm{Im}\tilde{b}_\gamma$
X_2	$P.(p_3 - p_4)$	$-$	$+$	$\mathrm{Im}\tilde{b}_Z,\ \mathrm{Im}\tilde{b}_\gamma$
X_3	$(\overrightarrow{p_3} \times \overrightarrow{p_4})_z$	$-$	$-$	$\mathrm{Re}\tilde{b}_Z,\ \mathrm{Re}\tilde{b}_\gamma$
X_4	$(p_1 - p_2).(p_3 - p_4)(\overrightarrow{p}_{l-} \times \overrightarrow{p}_{l+})_z$	$-$	$-$	$\mathrm{Re}\tilde{b}_Z,\ \mathrm{Re}\tilde{b}_\gamma$
X_5	$(p_1 - p_2).q(\overrightarrow{p_3} \times \overrightarrow{p_4})_z$	$+$	$-$	$\mathrm{Im}b_Z,\ \mathrm{Im}b_\gamma$
X_6	$P.(p_3 - p_4)(\overrightarrow{p_3} \times \overrightarrow{p_4})_z$	$+$	$-$	$\mathrm{Im}b_Z,\ \mathrm{Im}b_\gamma$
X_7	$[(p_1 - p_2).q]^2$	$+$	$+$	$\mathrm{Re}b_Z,\ \mathrm{Re}b_\gamma$
X_8	$[(p_1 - p_2).(p_3 - p_4)]^2$	$+$	$+$	$\mathrm{Re}b_Z,\ \mathrm{Re}b_\gamma$

- For X_7 and X_8, which are **CP** and **T** even should get contribution from all **CP** even couplings,
- Numerator in the expectation value does get contribution from all **CP** even couplings, but the denominator at the linear order cancels the contribution of $\mathrm{Re}\Delta a_Z$ and $\mathrm{Re}a_\gamma$ exactly leaving behind the contribution of $\mathrm{Re}b_Z$ and $\mathrm{Re}b_\gamma$,

Sensitivities with Unpolarized beams

- $\mathbf{X_1}$ and $\mathbf{X_2}$ probe different combinations of $\mathbf{Im\tilde{b}_Z}$ and $\mathbf{Im\tilde{b}_\gamma}$. We show, as an illustration, a plot in the space of the couplings $\mathbf{Im\tilde{b}_Z}$ and $\mathbf{Im\tilde{b}_\gamma}$.



The simultaneous limits obtained by considering the extremities of closed region are

$$|\mathbf{Im\tilde{b}_Z}| \leq \mathbf{7.73 \times 10^{-2}},\ |\mathbf{Im\tilde{b}_\gamma}| \leq \mathbf{5.44 \times 10^{-2}}.$$

- Similarly, using $\mathbf{X_3}$ and $\mathbf{X_4}$, we get **95** % CL simultaneous limits as :

$$|\mathbf{Re\tilde{b}_Z}| \leq \mathbf{6.08 \times 10^{-2}}, |\mathbf{Re\tilde{b}_\gamma}| \leq \mathbf{1.12 \times 10^{-1}}.$$

- And, using $\mathbf{X_5}$ and $\mathbf{X_6}$, we get **95%** CL simultaneous limits as :

$$|\mathbf{Imb_Z}| \leq \mathbf{1.25 \times 10^{-1}},\ |\mathbf{Imb_\gamma}| \leq \mathbf{9.39 \times 10^{-2}}$$

Sensitivity with longitudianlly polarized beams

- For each observable getting contribution from two couplings, longitudinal polarization helps to enhance the contribution of one of the couplings to the correlation with respect to other, as shown in the table

Observable	Couplings	Enhancement factor
X_1	$\mathrm{Im}\tilde{b}_Z$	$(g_V^2 + g_A^2)P_L^{eff}/(2g_Vg_A) \approx -4.3$
X_2	$\mathrm{Im}\tilde{b}_\gamma$	$g_AP_L^{eff}/g_V \approx 8.3$
X_3	$\mathrm{Re}\tilde{b}_Z$	$(g_V^2 + g_A^2)P_L^{eff}/(2g_Vg_A) \approx -4.3$
X_4	$\mathrm{Re}\tilde{b}_\gamma$	$g_AP_L^{eff}/g_V \approx 8.3$
X_5	$\mathrm{Im}b_\gamma$	$g_AP_L^{eff}/g_V \approx 8.3$
X_6	$\mathrm{Im}b_Z$	$(g_V^2 + g_A^2)P_L^{eff}/(2g_Vg_A) \approx -4.3$
X_7	$\mathrm{Re}b_\gamma$	$g_AP_L^{eff}/g_V \approx 8.3$
X_8	$\mathrm{Re}b_\gamma$	$g_AP_L^{eff}/g_V \approx 8.3$

Individual limits to the anomalous couplings using longitudinally polarized beams

	Coupling	$P_L = 0$, $\overline{P}_L = 0$	$P_L = 0.8$, $\overline{P}_L = 0.6$	$P_L = 0.8$, $\overline{P}_L = -0.6$
X_1	$\mathrm{Im}\tilde{b}_Z$	4.11×10^{-2}	8.69×10^{-2}	9.94×10^{-3}
	$\mathrm{Im}\tilde{b}_\gamma$	1.49×10^{-2}	2.06×10^{-2}	1.22×10^{-2}
X_2	$\mathrm{Im}\tilde{b}_Z$	4.12×10^{-2}	5.99×10^{-2}	3.84×10^{-2}
	$\mathrm{Im}\tilde{b}_\gamma$	5.23×10^{-1}	3.12×10^{-1}	5.52×10^{-2}
X_3	$\mathrm{Re}\tilde{b}_Z$	1.41×10^{-1}	2.97×10^{-1}	3.40×10^{-2}
	$\mathrm{Re}\tilde{b}_\gamma$	5.09×10^{-2}	7.05×10^{-2}	4.15×10^{-2}
X_4	$\mathrm{Re}\tilde{b}_Z$	2.95×10^{-2}	4.29×10^{-2}	2.75×10^{-2}
	$\mathrm{Re}\tilde{b}_\gamma$	3.81×10^{-1}	2.24×10^{-1}	3.95×10^{-2}
X_5	$\mathrm{Im}b_Z$	7.12×10^{-2}	1.04×10^{-1}	6.64×10^{-2}
	$\mathrm{Im}b_\gamma$	9.10×10^{-1}	5.42×10^{-1}	9.53×10^{-2}
X_6	$\mathrm{Im}b_Z$	7.12×10^{-2}	1.50×10^{-1}	1.72×10^{-2}
	$\mathrm{Im}b_\gamma$	2.58×10^{-2}	3.57×10^{-2}	2.10×10^{-2}
X_7	$\mathrm{Re}b_Z$	1.75×10^{-2}	2.54×10^{-2}	1.63×10^{-2}
	$\mathrm{Re}b_\gamma$	2.23×10^{-1}	1.34×10^{-1}	2.35×10^{-2}
X_8	$\mathrm{Re}b_Z$	1.53×10^{-2}	2.22×10^{-2}	1.42×10^{-2}
	$\mathrm{Re}b_\gamma$	1.94×10^{-1}	1.16×10^{-1}	2.04×10^{-2}

Observables sensitive to transverse polarization with **CP** and **T** properties

Symbol	Observable	**CP**	**T**	Couplings
$\mathbf{Y}_1$	$(q_x q_y)$	$+$	$-$	$\mathrm{Im}a_\gamma$
$\mathbf{Y}_2$	$(q_x^2 - q_y^2)$	$+$	$+$	$\mathrm{Re}b_Z$, $\mathrm{Re}a_\gamma$, $\mathrm{Re}b_\gamma$
$\mathbf{Y}_3$	$(p_3 - p_4)_x (p_3 - p_4)_y$	$+$	$-$	$\mathrm{Im}a_\gamma$, $\mathrm{Im}b_\gamma$
$\mathbf{Y}_4$	$q_x q_y (p_3 - p_4)_z$	$-$	$-$	$\mathrm{Re}\tilde{b}_Z$, $\mathrm{Re}\tilde{b}_\gamma$
$\mathbf{Y}_5$	$(p_3 - p_4)_x (p_3 - p_4)_y q_z$	$+$	$-$	$\mathrm{Im}b_Z$, $\mathrm{Im}b_\gamma$
$\mathbf{Y}_6$	$[(p_3)_x^2 - (p_4)_x^2] - [(p_3)_y^2 - (p_4)_y^2]$	$-$	$+$	$\mathrm{Im}\tilde{b}_Z$, $\mathrm{Im}\tilde{b}_\gamma$

Table: Observables to constrain anomalous couplings, their CP and T properties and the couplings they probe. Here, $\mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2$ and $\mathbf{q} = \mathbf{p}_3 + \mathbf{p}_4$

.

Observables $\mathbf{Y}_1$-$\mathbf{Y}_6$ are sensitive to transverse polarization and their correlations are zero with longitudinally polarized beams.

Sensitivity with transversely polarized beams

- As seen earlier, using transversely polarized beams, we can constrain $\mathbf{Im a_\gamma}$ independently from all other couplings using observable $\mathbf{Y_1}$,
- We find that correlation of each observable is dominated by a single coupling in each case,
- So, if we assume all couplings contributing to a correlation to be of the same order, then each observable puts almost independent limit on dominant anomalous coupling,
- In evaluating the correlation of $\mathbf{Y_2}$, the numerator gets contributions from $\mathbf{Re\Delta a_Z}$ and $\mathbf{Re a_\gamma}$, but the denominator at linear order in anomalous couplings cancel the contribution of $\mathbf{Re\Delta a_Z}$ completely while introducing the contributions from $\mathbf{Re b_Z}$ and $\mathbf{Re b_\gamma}$ to the correaltion,

Individual limits with transversely polarized beams

	Observable	Coupling	Limits for polarizations $P_T = 0.8$, $\overline{P}_T = \pm 0.6$
Y_1	$(q_x q_y)$	$\mathrm{Im}a_\gamma$	1.98×10^{-1}
Y_2	$(q_x^2 - q_y^2)$	$\mathrm{Re}a_\gamma$	8.15×10^{-1}
		$\mathrm{Re}b_Z$	2.65×10^{-2}
		$\mathrm{Re}b_\gamma$	3.41×10^{-1}
Y_3	$(p_3 - p_4)_x (p_3 - p_4)_y$	$\mathrm{Im}a_\gamma$	9.62
		$\mathrm{Im}b_\gamma$	4.72×10^{-2}
Y_4	$q_x q_y (p_{l^-} - p_{l^+})_z$	$\mathrm{Im}b_Z$	1.58×10^{-1}
		$\mathrm{Im}b_\gamma$	1.96
Y_5	$(p_3 - p_4)_x (p_3 - p_4)_y q_z$	$\mathrm{Re}\tilde{b}_Z$	5.56×10^{-2}
		$\mathrm{Re}\tilde{b}_\gamma$	6.89×10^{-1}
Y_6	$[(p_3)_x^2 - (p_4)_x^2] - [(p_3)_y^2 - (p_4)_y^2]$	$\mathrm{Im}\tilde{b}_Z$	1.10×10^{-1}
		$\mathrm{Im}\tilde{b}_\gamma$	1.36

Table: The **95** % C.L. limits on the anomalous **ZZH** and **γZH** couplings, chosen nonzero one at a time from observables with transversely polarized beams for $\sqrt{s} = 500$ GeV and $\int \mathcal{L}\, dt = 500$ fb^{-1}.

Kinematical cuts

In practice, any measurement will need kinematical cuts for the identification of the decay leptons. We have examined the effect on our results of the following kinematical cuts :

1. $\mathbf{E_f \geq 10}$ GeV for each outgoing charged lepton,
2. $\mathbf{5^\circ \leq \theta_0 \leq 175^\circ}$ for each outgoing charged lepton to remain away from the beam pipe,
3. $\mathbf{\Delta R_{ll} \geq 0.2}$ for the pair of charged lepton, where $\mathbf{(\Delta R)^2 \equiv (\Delta\phi)^2 + (\Delta\eta)^2}$, $\mathbf{\Delta\phi}$ and $\mathbf{\Delta\eta}$ being the separation in azimuthal angle and rapidity, respectively
4. In addition to this, we imposed a cut on the invariant mass of the $\mathbf{f\bar{f}}$ so as to confirm onshellness of the $\mathbf{Z}$ - boson, which is

$$\mathbf{R1 \equiv |m_{f\bar{f}} - M_Z| \leq 5\Gamma_Z}$$

This cut also reduce the contamination from $\gamma\gamma\mathbf{H}$ couplings.

Sensitivities at different centre of mass energies

1. Observables $\mathbf{X_1}$, $\mathbf{X_2}$, $\mathbf{X_7}$ and $\mathbf{Y_6}$ become less sensitive to couplings $\mathbf{Im\tilde{b}_Z}$ and $\mathbf{Im\tilde{b}_\gamma}$ as center of mass energy increases.
2. Observables $\mathbf{X_3}$, $\mathbf{X_4}$, $\mathbf{X_5}$, $\mathbf{X_6}$, $\mathbf{X_8}$ and $\mathbf{Y_4}$ become more sensitive at higher energies.
3. Observables $\mathbf{Y_1}$, $\mathbf{Y_2}$ and $\mathbf{Y_5}$ which are sensitive only to transverse polarization become less sensitive at higher energies.
4. Observable $\mathbf{Y_3}$ behave very differently relative to all other observables. While limits on $\mathbf{Ima_\gamma}$ improves about an order, limits on $\mathbf{Imb_\gamma}$ get worse with the increase in center of mass energy.

Summary and Conclusion

- We have studied the most general set of anomalous **VZH** couplings using different beam polarizations, in order to put limits on them, at a linear collider in the process $\mathbf{e^+e^- \longrightarrow ZH}$
- Longitudinal polarization helps to enhance the contribution of couplings and thereby improving the sensitivity
- The main advantage of transverse polarization is that it helps to determine $\mathbf{Im a_\gamma}$ independent of all other couplings through the $\sin^2\theta \sin 2\phi$ term
- Also, transverse polarization helps to probe a combination of $\mathbf{Re\Delta a_Z}$ and $\mathbf{Re a_\gamma}$ independently of $\mathbf{Re b_Z}$ and $\mathbf{Re b_\gamma}$
- Opposite sign polarization enhance the sensitivity compared to unpolarized beams. Like-sign polarizations make the limits worse
- Anomalous couplings $\mathbf{Im\Delta a_Z}$, $\mathbf{Im b_Z}$, $\mathbf{Im b_\gamma}$, $\mathbf{Re\tilde{b}_Z}$ and $\mathbf{Re\tilde{b}_\gamma}$ are absent in the absence of **Z** decay and can only be determined by including $\mathbf{Z - decay}$
- Though SM couplings have been used in this analysis, trivial modifications can be done to incorporate the extensions of SM like MSSM, two-Higgs doublet model