Probing anomalous **VZH** couplings at ILC with polarized beams

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Work is done in collaboration with : Prof. Saurabh D. Rindani

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- Phys. Rev. D **79** (2009), arXiv:0901.2821[hep-ph]

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EWSB and Higgs

- EWSB predicts a fundamental scalar known as the Higgs
- In SM, there is one CP even neutral Higgs
- The aim of current (LHC) and future (ILC, CLIC) colliders is to discover the Higgs
- Some models like MSSM, 2HDM etc. predict existence of more than one Higgs
- Even if one discovers a Higgs, it is not a confirmation for SM Higgs

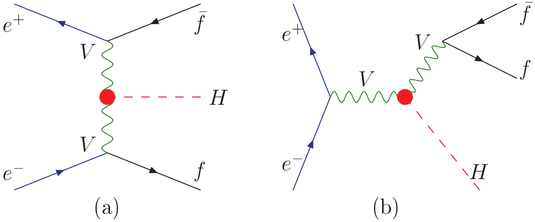
EWSB and Higgs

- For this, a thorough study is needed to study its properties
- Which is easier at $\mathbf{e^+e^-}$ linear colliders than hadron colliders.
- Any deviation in SM values of the Higgs couplings would be a signal of new physics
- Higgs couplings are proportional to mass of particle which it couples,
- Interesting to study Higgs interactions with heavier particles like top quark and the electroweak bosons

Higgs production at $\mathbf{e^+e^-}$ collider

Higgs @ ILC

$\mathbf{e^+e^-}$	$\longrightarrow$	$\mathbf{e^+e^-Z^*Z^*}$	$\longrightarrow$	$\mathbf{e^+e^-H}$	(**Z**-fusion)
	$\longrightarrow$	$\boldsymbol{\nu_e\bar{\nu}_e}\mathbf{W^*W^*}$	$\longrightarrow$	$\boldsymbol{\nu_e\bar{\nu}_e}\mathbf{H}$	(**W**-fusion)
	$\longrightarrow$	$\mathbf{ZH}$	$\longrightarrow$	$\mathbf{f\bar{f}H}$	(Bjorken)



(a) Gauge Boson Fusion (b) Bjorken

The process $\mathbf{e^+e^-} \longrightarrow \boldsymbol{\nu_e\bar{\nu}_e}\mathbf{H}$ has the highest rate for an intermediate mass Higgs boson.

Beam polarizations

- Full potential of ILC can only be utilized with polarization of beams,
- Earlier, **SLAC** used polarized $\mathbf{e^-}$ beams for **SLD** experiment,
- **80%** of $\mathbf{e^-}$ polarization has been achieved at **SLAC**,
- For **ILC**, **90%** $\mathbf{e^-}$ polarization is expected,
- For $\mathbf{e^+}$ beam, **30%** polarization already achieved,
- For **ILC** expectation is **60%** polarization for $\mathbf{e^+}$ beam,
- Both $\mathbf{e^-}$ and $\mathbf{e^+}$ beam polarizations are important for studying new physics (will be discussed later),

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- Both $\mathbf{e^-}$ and $\mathbf{e^+}$ beam polarizations are important for studying new physics (will be discussed later),

With unpolarized beams, cross section for $\mathbf{e^+e^-}$ annihilation process can be written as :

$$\sigma = \sigma_{\mathbf{LL}} + \sigma_{\mathbf{RR}} + \sigma_{\mathbf{RL}} + \sigma_{\mathbf{LR}}$$

Effective polarization, P_L^{eff}

With longitudinal polarization, cross section for e^+e^- annihilation process can be written as :

$$\begin{aligned}\sigma &= \frac{1+P_L}{2}\frac{1-\overline{P}_L}{2}\sigma_{RL} + \frac{1-P_L}{2}\frac{1+\overline{P}_L}{2}\sigma_{LR}\\ &= (1-P_L\overline{P}_L)[\sigma_0 + \frac{P_L-\overline{P}_L}{1-P_L\overline{P}_L}\frac{\sigma_{RL}-\sigma_{LR}}{4}]\\ &= (1-P_L\overline{P}_L)[\sigma_0 + P_L^{eff}\frac{\sigma_{RL}-\sigma_{LR}}{4}]\end{aligned}$$

where $P_L^{eff} = \frac{P_L-\overline{P}_L}{1-P_L\overline{P}_L}$ is "effective polarization".

		P_L^{eff}	$\mathcal{L}_{eff}/\mathcal{L}$
$P_L = 0$,	$\overline{P}_L = 0$	0%	0.50
$P_L = 80\%$,	$\overline{P}_L = 0$	80%	0.50
$P_L = -80\%$,	$\overline{P}_L = 60\%$	-95%	0.74
$P_L = 80\%$,	$\overline{P}_L = 60\%$	39%	0.26

Role of beam polarization

Role of longitudinal polarization

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Role of longitudinal polarization

- Increases signal,

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- Reduces background,

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Role of transverse polarization

- breaks rotational invariance of initial state,

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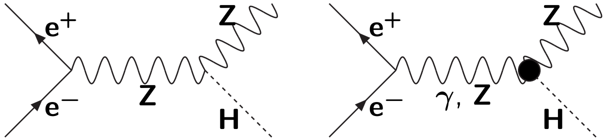
- Hence, provides additional asymmetries and correlations,
- No need for measurement of polarizations of final state particles,
- probes couplings which are not accessible otherwise.

The process $e^+e^- \to HZ$

- We consider production of a Higgs through the process $e^+e^- \to HZ$ mediated by **s**-channel virtual γ and **Z**
- In SM, only contribution from s-channel exchange of **Z** at tree level
- No γ**ZH** couplings at tree level in SM, γ-exchange only at the loop level
- At the lowest order, the **ZZH** vertex in this diagram would be simply a point-like coupling



Structure of the anomalous VZH couplings

- Demanding Lorentz invariance, the general structure of the vertex $\mathbf{V}^*_\mu(\mathbf{k_1}) \longrightarrow \mathbf{Z}^*_\nu(\mathbf{k_2})\mathbf{H}$, where $(\mathbf{V} = \mathbf{Z}, \gamma)$, can be expressed as (Hagiwara & Stong)[1]

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

- $\mathbf{a_V}$ and $\mathbf{b_V}$ are **CP** - even, and $\tilde{\mathbf{b}}_\mathbf{V}$ is **CP** - odd,
- We have studied these anomalous **VZH** $(\mathbf{V} = \gamma, \mathbf{Z})$ couplings at a linear collider in process $\mathbf{e^+e^- \longrightarrow ZH}$,
- Couplings are taken to be complex, so six parameters to be determined in each case,

[1] Z.Phys.C62 : 99 − 108, 1994

Review of earlier works done on **VZH** couplings

Recent works on **VVH** couplings at linear collider are of Biswal[2] et al., Hagiwara[3] et al. and Han[4] et al.

- Biswal et al. studied **ZZH** and **WWH** couplings at linear collider with polarized beams,
- They did not include γ**ZH** couplings in their analysis,
- Hagiwara et al. did include γ**ZH** couplings in their analysis,
- But, they use complicated techniques of b-tagging and measurement of final state τ polarization,
- Han et al. only considered **CP** odd **ZZH** couplings in their analysis

[2] **Phys.Rev.D79 : 035012, Phys.Lett.B680 : 81 − 87**
[3] **Eur.Phys.J.C14 : 457 − 468, 2000**
[4] **Phys.Rev.D63 : 096007, 2001**

Our Procedure

- Obtain analytical expressions for angular distributions using both longitudinally and transversely polarized beams,
- Construct rather simpler observables like asymmetry and correlations,
- Observables are simple conceptually as well as experiment point of view,
- Observables have definite **CP** and **T** transformation properties,
- We make use of a combination of observables and/or polarizations,
- *Main emphasis on simultaneous independent determination of couplings*,

Angular distributions for unpolarized beams

Unpolarized beams

$$\frac{d\sigma_{Z,\gamma}}{d\Omega} \propto \left[A^{Z,\gamma}(1+\sin^2\theta) + B^{Z,\gamma} + C^{Z,\gamma}\cos\theta\right]$$

	Z	γ	Couplings
A	$(g_V^2 + g_A^2)$	g_V	$\mathrm{Re}\Delta a_Z, \mathrm{Re}a_\gamma$
B	$(g_V^2 + g_A^2)$	g_V	$\mathrm{Re}b_Z, \mathrm{Re}b_\gamma$
C	$-2g_V g_A$	g_A	$\mathrm{Im}\tilde{b}_Z, \mathrm{Im}\tilde{b}_\gamma$

- $\mathrm{Im}\Delta a_Z, \mathrm{Im}a_\gamma, \mathrm{Im}b_Z, \mathrm{Im}b_\gamma, \mathrm{Re}\tilde{b}_Z, \mathrm{Re}\tilde{b}_\gamma$ are absent,
- $g_V = -0.12$, $g_A = -1$,

Angular distributions for longitudinally polarized beams

Longitudinally Polarized beams

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

	Z	γ	Couplings
A	$(g_V^2 + g_A^2) - 2g_V g_A P_L^{eff}$	$g_V - g_A P_L^{eff}$	$\mathrm{Re}\Delta a_Z, \mathrm{Re}a_\gamma$
B	$(g_V^2 + g_A^2) - 2g_V g_A P_L^{eff}$	$g_V - g_A P_L^{eff}$	$\mathrm{Re}b_Z, \mathrm{Re}b_\gamma$
C	$(g_V^2 + g_A^2) P_L^{eff} - 2g_V g_A$	$g_A - g_V P_L^{eff}$	$\mathrm{Im}\tilde{b}_Z, \mathrm{Im}\tilde{b}_\gamma$

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- $\mathrm{Im}\Delta a_Z, \mathrm{Im}a_\gamma, \mathrm{Im}b_Z, \mathrm{Im}b_\gamma, \mathrm{Re}\tilde{b}_Z, \mathrm{Re}\tilde{b}_\gamma$ are absent,
- $g_V = -0.12$, $g_A = -1$,
- Non-trivial dependence on P_L^{eff}
- With P_L^{eff}, sensitivities to $\mathrm{Re}a_\gamma$, $\mathrm{Re}b_\gamma$ and $\mathrm{Im}\tilde{b}_Z$ become significant.

Forward backward asymmetry $\mathsf{A_{FB}}$

- The terms proportional to $\cos\theta$ i.e., $\mathbf{Im\tilde{b}_Z, Im\tilde{b}_\gamma}$ can be determined using a simple forward-backward asymmetry:

$$\mathsf{A}^{\mathsf{L}}_{\mathbf{FB}} = \frac{\sigma(\cos\theta \geq 0) - \sigma(\cos\theta \leq 0)}{\sigma(\cos\theta \geq 0) + \sigma(\cos\theta \leq 0)},$$
$$\propto [\qquad\qquad - 2g_V g_A]\mathrm{Im}\tilde{b}_Z$$
$$+ [g_A \qquad\qquad]\mathrm{Im}\tilde{b}_\gamma$$

- 95% CL individual limits on $\mathbf{Im\tilde{b}_\gamma}$, $\mathbf{Im\tilde{b}_Z}$ using $\mathsf{A_{FB}}$

	$\lvert\mathrm{Im}\tilde{b}_\gamma\rvert$	$\lvert\mathrm{Im}\tilde{b}_Z\rvert$
Unpolarized	0.00392	0.0108

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$\mathbf{P_L = 0.8,\ \overline{P}_L = +0.6}$	0.00543	0.0229
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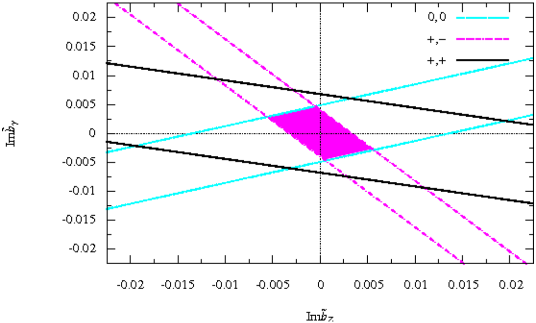
- Sensitivity to $\mathbf{Im\tilde{b}_Z}$ is enhanced by about a factor of **5** using opposite beam polarization because of the $\mathbf{P_L^{eff}}$

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

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



- (S.L.) are extremeties of enclosed region.

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

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

Angular distribution for transversely polarized beams

With Transversely polarized beams

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

- $\mathbf{D_T}$ contains $\mathbf{Re\Delta a_Z}$ and $\mathbf{Re a_\gamma}$ while $\mathbf{E_T}$ contains only $\mathbf{Im a_\gamma}$,
- Usefulness of TP comes from nontrivial ϕ dependence,
- Both electron and positron beams have to be polarized,
- $\mathbf{Im a_\gamma}$ is now accessible,
- *Most important result* : Independent determination of $\mathbf{Im a_\gamma}$ from the $\mathbf{\sin 2\phi}$ term,
- $\mathbf{Re\tilde{b}_Z}$, $\mathbf{Re\tilde{b}_\gamma}$, $\mathbf{Im b_Z}$, $\mathbf{Im b_\gamma}$ and $\mathbf{Im\Delta a_Z}$ remain undetermined

Azimuthal asymmetry (A_T)

- $\mathbf{A_T}$ separate out coefficient of $\sin 2\phi$ i.e., $\mathrm{Im} a_\gamma$

$$\mathbf{A}^{\mathrm{T}}(\theta_0) \;=\; \frac{\sigma(\pi/2 > \phi > 0) - \sigma(\pi > \phi > \pi/2)}{\sigma(\pi/2 > \phi > 0) + \sigma(\pi > \phi > \pi/2)},$$

Most important result

Measurement of $\mathbf{A}^{\mathrm{T}}(\theta_0)$ directly probes $\mathrm{Im}\ \mathbf{a}_\gamma$, which is inaccessible without the use of transverse polarization,

- Using $\mathbf{A_T}$, **95%** CL simultaneous limit on the coupling $\mathrm{Im} a_\gamma$ is 4.01×10^{-2} for $m_H = 120$ GeV,
- In principle, any odd function of $\sin 2\phi$ can probe $\mathrm{Im} a_\gamma$,
- For example, sign($\sin 2\phi$) $\equiv \mathbf{A_T}$, $\sin 2\phi$ and $\sin^3 2\phi$

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- With observables, constructed from **Z** boson momenta only, couplings $\mathbf{Im\Delta a_Z}$, $\mathbf{Imb_Z}$, $\mathbf{Imb_\gamma}$, $\mathbf{Re\tilde{b}_Z}$, $\mathbf{Re\tilde{b}_\gamma}$ can not be probed,

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- To probe those couplings, we utilize momenta of leptons coming from **Z**-decay, to construct **T** odd observables.

Observables chosen for the analysis

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	$[(p_1 - p_2).(p_3 - p_4)]^2$	$+$	$+$	$\mathrm{Re}b_Z,\ \mathrm{Re}b_\gamma$

THANK YOU FOR YOUR ATTENTION