Study of anomalous VVH interactions at a Linear Collider

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VVH interaction

- VVH interaction is generated from the kinetic term of the Higgs field after symmetry breaking.
- The strength and structure of VVH interaction depends upon the quantum number of the Higgs field, such as CP, weak isospin, hypercharge etc.
- At an e^+e^- collider (like ILC), the VVH vertex can be studied through Gauge Boson Fusion and Bjorken process.

Anomalous Higgs interactions

Most general VVH coupling structure:

$$\Gamma_{\mu\nu} = g_V \left[a_V \; g_{\mu\nu} + \frac{b_V}{M_V^2} \; (k^1_\nu k^2_\mu - g_{\mu\nu} k^1.k^2) + \frac{\tilde{b}_V}{M_V^2} \; \epsilon_{\mu\nu\alpha\beta} k^{1\alpha} k^{2\beta} \right]$$

where,

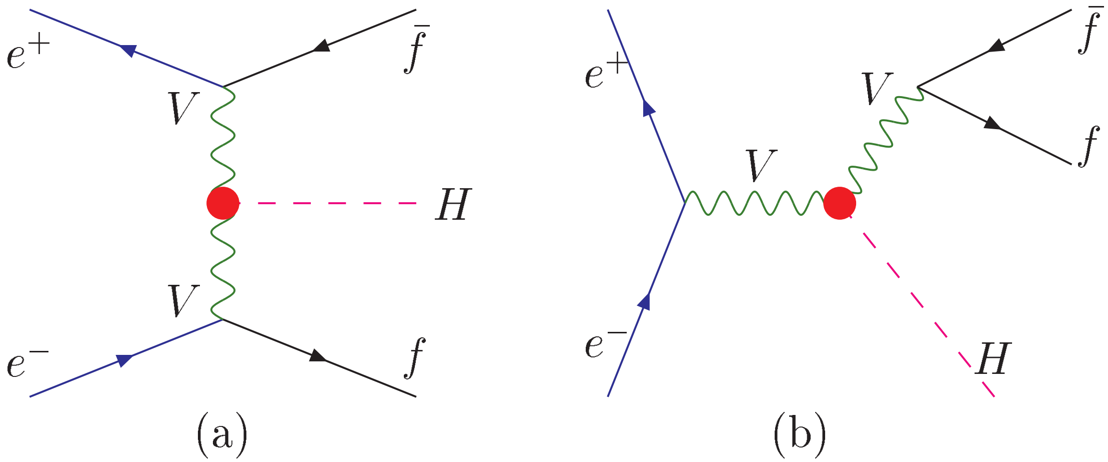
$$g_W^{SM} = e \cos\theta_w M_Z, \;\; g_Z^{SM} = 2 e m_Z / \sin 2\theta_w,$$

$a_W^{SM} = 1 = a_Z^{SM}$, $b_V^{SM} = 0 = \tilde{b}_V^{SM}$, and $a_V \; = \; 1 \; + \; \Delta a_V$.

b_V and $\tilde{b}_V$ can be complex. We treat them to be small parameters, i.e. , quadratic terms are dropped.

Higgs production at e^+e^- collider

$$
\begin{array}{lllllll}
e^+e^- & \rightarrow & e^+e^-Z^*Z^* & \rightarrow & e^+e^-H(b\bar{b}) & (Z\text{-fusion}) \\
 & \rightarrow & \nu_e\bar{\nu}_eW^*W^* & \rightarrow & \nu_e\bar{\nu}_eH(b\bar{b}) & (W\text{-fusion}) \\
 & \rightarrow & ZH & \rightarrow & f\bar{f}H(b\bar{b}) & (\text{Bjorken})
\end{array}
$$



$M_H = 120$ GeV, $Br(H \rightarrow b\bar{b}) \approx 0.68$

b-quark detection efficiency $= 0.7$

$\sqrt{s}$ = 500 GeV, $\mathcal{L}$ = 500 fb^{-1}

Some comments

- The process $e^+e^- \to \nu_e\bar{\nu}_e H$ has the highest rate for an intermediate mass Higgs boson.
- All non-standard couplings ($ZZH + WWH$) are involved.
- Final state has two neutrinos (missing). Only a few observables can be constructed.
- Interference of SM part of W fusion diagram with non-standard part of Bjorken diagram is large even away from Z pole and can not be separated by cutting out Z pole.
- Need to fix/constrain b_Z and $\tilde{b}_Z$ using Bjorken process before going to study WWH vertex using the process $e^+e^- \to \nu_e\bar{\nu}_e H$.

Observations with Unpolarized states

- Strong and robust limits on $\Re(b_z),\ \Re(\tilde{b}_Z)$ and $\Im(\tilde{b}_Z)$.
- Contamination from ZZH coupling to the determination of the WWH vertex is quite large.
- Relatively poor sensitivity to $\tilde{T}$-odd ($\Im(b_Z),\ \Re(\tilde{b}_Z)$) couplings.
- No direct probe for WWH couplings. However, quite strong limits are obtained for $\Re(b_W)$ and $\Im(\tilde{b}_W)$.

Biswal, Choudhury, Godbole and Singh, Phys. Rev. D 73, 035001 (2006).

Possible improvements ?

In this work we investigate:

- Use of Initial Beam Polarization.
- Measurement of final state τ Polarization.
- Going to higher c.m. energy.

An advance summary of our results:

- Use of Beam Polarization improves sensitivity to $\Im(\tilde{b}_Z)$, $\Im(b_W)$ and $\Re(\tilde{b}_W)$.
- Measurement of final state τ polarization helps to get stronger limit on $\Im(b_Z)$.
- At higher $\sqrt{s}$:
  - Observables constructed excluding Z-pole contributions become better probes and hence may probe WWH couplings better.
  - Increase in energy helps improve the probing of $\Re(\tilde{b}_Z)$ even after inclusion of both ISR and Beamstrahlung effects.

Kinematical cuts

- Plan: construct observables with definite $CP/\tilde{T}$ transformation properties using beam/final sate polarizations and other kinematic variables to probe the anomalous couplings.
- Need to devise kinemetical cuts to remove usual backgrounds.

Variable		Limit	Description
θ_0	$5^\circ \leq$	$\theta_0 \leq 175^\circ$	Beam pipe cut, for l^-, l^+, b and $\bar{b}$
E_b, $E_{\bar{b}}$, E_{l^-}, E_{l^+}	$\geq$	10 Gev	For jets/leptons
$p_T^{\rm miss}$	$\geq$	15 GeV	For neutrinos
$\Delta R_{b\bar{b}}$	$\geq$	0.7	Hadronic jet resolution
$\Delta R_{q_1 q_2}$	$\geq$	0.7	Hadronic jet resolution
$\Delta R_{l^- l^+}$	$\geq$	0.2	Leptonic jet resolution
$\Delta R_{l^+ b}$, $\Delta R_{l^+ \bar{b}}$, $\Delta R_{l^- b}$, $\Delta R_{l^- \bar{b}}$	$\geq$	0.4	Lepton-hadron resolution

Additionally we use two different cuts on $m_{f\bar{f}}$,

$$R1 \equiv \left| m_{f\bar{f}} - M_Z \right| \leq 5\,\Gamma_Z \qquad \text{select Z-pole ,}$$

$$R2 \equiv \left| m_{f\bar{f}} - M_Z \right| \geq 5\,\Gamma_Z \qquad \text{de-select Z-pole.}$$

Effect of Beam Polarization

$$\begin{aligned}\sigma(P_{e^-}, P_{e^+}) &= \frac{1}{4}[(1+P_{e^-})(1+P_{e^+})\sigma_{RR} \\ &+(1+P_{e^-})(1-P_{e^+})\sigma_{RL} \\ &+(1-P_{e^-})(1+P_{e^+})\sigma_{LR} \\ &+(1-P_{e^-})(1-P_{e^+})\sigma_{LL}]\end{aligned}$$

σ_{RL} : e^- and e^+ beams are completely right and left polarized respectively, i.e. , $P_{e^-} = +1$, $P_{e^+} = -1$.

$$\sigma^{-,+} = \sigma(P_{e^-} = -0.8, P_{e^+} = 0.6)$$

Asymmetries

$$\vec{P}_e = \vec{p}_{e^-} - \vec{p}_{e^+}, \qquad \vec{P}_f^- = \vec{p}_f - \vec{p}_{\bar{f}}, \qquad \vec{P}_f^+ = \vec{p}_f + \vec{p}_{\bar{f}} = -\vec{p}_H$$

	Combination	Asymmetry	Probe of
$\mathcal{C}_1$	$\vec{P}_e \cdot \vec{P}_f^+$ (CP - , $\tilde{T}$ +)	$A_{FB}(C_H) = \frac{\sigma(C_H>0)-\sigma(C_H<0)}{\sigma(C_H>0)+\sigma(C_H<0)}$	$\Im(\tilde{b}_V)$
$\mathcal{C}_2$	$[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-$ (CP - , $\tilde{T}$ -)	$A_{UD}(\phi) = \frac{\sigma(\sin\phi>0)-\sigma(\sin\phi<0)}{\sigma(\sin\phi>0)+\sigma(\sin\phi<0)}$	$\Re(\tilde{b}_V)$
$\mathcal{C}_3$	$\left[[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-\right]\left[\vec{P}_e \cdot \vec{P}_f^+\right]$ (CP - , $\tilde{T}$ -)	$A_{comb} = \frac{(FU)+(BD)-(FD)-(BU)}{(FU)+(BD)+(FD)+(BU)}$	$\Im(b_V)$

$F(B)$: H is in forward (backward) hemisphere w.r.t. the direction of initial e^-.
$U(D)$: Final state f is above (below) the H-production plane.

• We constructed 25 combinations in total. For each combination, asymmetry can be constructed as:

$$A^i = \frac{\sigma(\mathcal{C}_i > 0) - \sigma(\mathcal{C}_i < 0)}{\sigma(\mathcal{C}_i > 0) + \sigma(\mathcal{C}_i < 0)}.$$

A^i's constructed out of partially integrated cross-sections and hence can be directly proportional to CP(or $\tilde{T}$)-odd coupling.

Sensitivity Limits

Statistical fluctuation in the cross-section and that in an asymmetry:

$$\Delta\sigma = \sqrt{\sigma_{SM}/\mathcal{L} + \epsilon^2 \sigma_{SM}^2} \ ,$$

$$(\Delta A)^2 = \frac{1 - A_{SM}^2}{\sigma_{SM}\mathcal{L}} + \frac{\epsilon^2}{2}(1 - A_{SM}^2)^2.$$

where σ_{SM} and A_{SM} are the SM value of cross-section and asymmetry respectively, luminosity $\mathcal{L}$ = 500 fb^{-1} and systematic error ϵ = 0.01.

• Limits of sensitivity are obtained by demanding that the contribution from anomalous VVH couplings to the observable be less than the statistical fluctuation in these quantities at 3 σ level.

Effect of Beam Polarization: ZZH case

Limits of sensitivity

Unpolarized Beam	Polarized Beam	Observable used
$\|\Re(\tilde{b}_z)\| \leq 0.41$	$\|\Re(\tilde{b}_z)\| \leq 0.070$	$A_{UD}^{-,+}(R1;\mu)$
$\|\Im(\tilde{b}_z)\| \leq 0.042$	$\|\Im(\tilde{b}_z)\| \leq 0.0079$	$A_{FB}^{-,+}(R1;\mu,q)$

For polarized beams the luminosity of 500 fb^{-1} is divided equally among different polarizations.

Biswal, Choudhury, Godbole and Singh, Phys. Rev. D 73, 035001 (2006). This was for unpolarized initial and final states.

Han et al have also observed the improvement for $\Im(\tilde{b}_z)$. T. Han and J. Jiang, Phys. Rev. D **63**, 096007 (2001).

Effect of Beam Polarization: ZZH case

- Unpolarized beam with R1-Cut:

$$A_{FB} \propto (\ell_e^2 - r_e^2)$$
$$A_{UD}(\phi_f) \propto (\ell_e^2 - r_e^2)(r_f^2 - \ell_f^2)$$

  l_e : left handed coupling of the electron to the Z-boson.
  $\ell_e^2 > r_e^2 \Rightarrow$ observables constructed using $|M(-,+)|^2$ are more sensitive.

- Beam polarization gives improvement on limits of both the CP odd couplings ($\Re(\tilde{b}_z)$, $\Im(\tilde{b}_z)$) for R1-Cut.

- Limit on $\Im(\tilde{b}_z)$ improves upto a factor of 5-6.

- Sensitivity to $\Re(\tilde{b}_Z)$ is comparable to that obtained with unpolarized beams with R2-cut.

Use of τ Polarization: ZZH case

- τ polarization can be measured using the decay π energy distribution*.

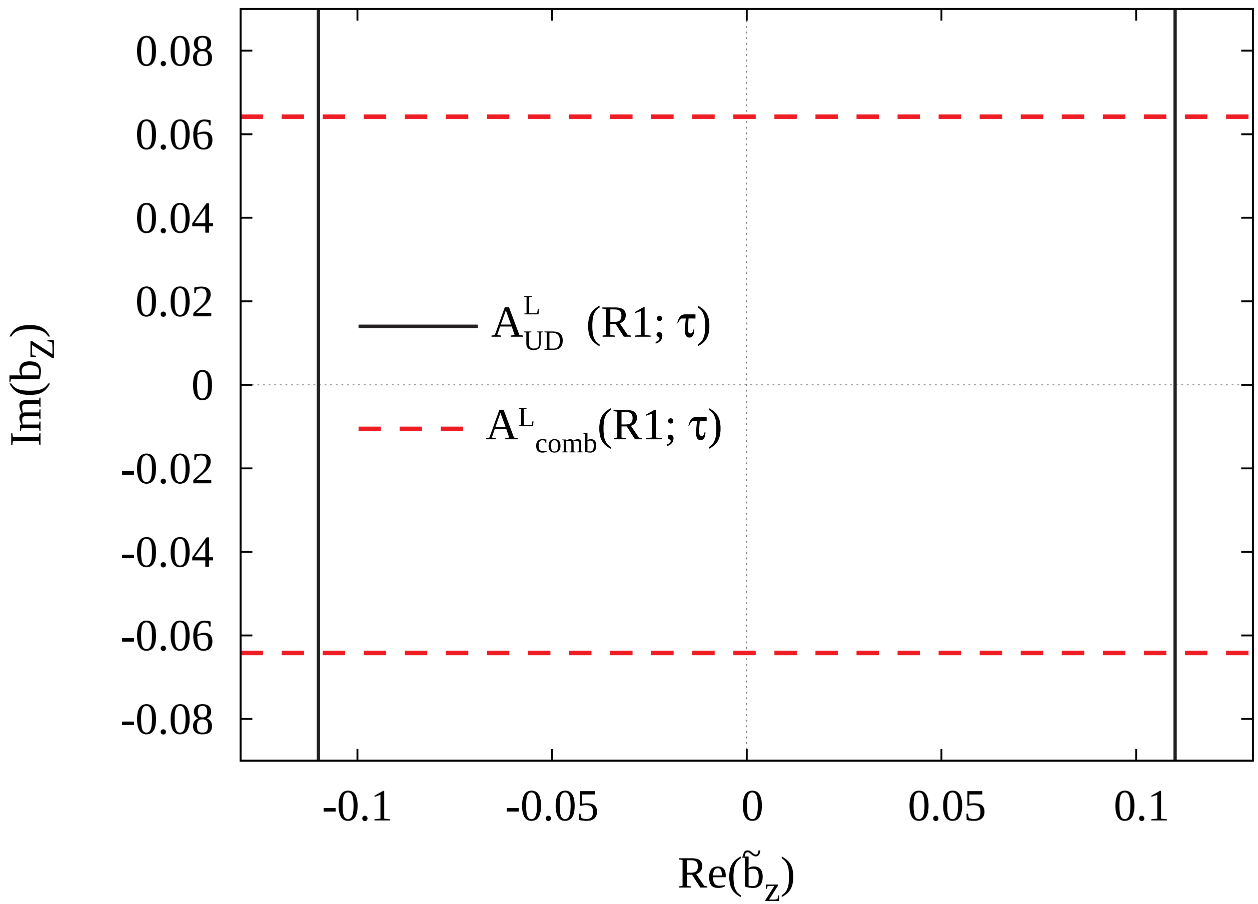
- Observables are constructed for τ's of definite helicity state.

- Analysis has been made assuming 100%, 40% and 25% efficiency of detecting final state τ's with a definite helicity state.

  L: τ^- is in -ve helicity state, λ_τ = - 1.

  * B. K. Bullock, K. Hagiwara and A. D. Martin, Nucl. Phys. B **395** 499 (1993).
  * K. Hagiwara, S. Ishihara, J. Kamoshita and B. A. Kniehl, Eur. Phys. J. C **14**, 457 (2000).
  * R. Godbole, M. Guchait and D.P. ROy, Phys. Lett. B **618**, 193 (2005).

Sensitivity of Asymmetries at 3 σ level



$$A^L_{comb} = \frac{(FU) + (BD) - (FD) - (BU)}{(FU) + (BD) + (FD) + (BU)}$$

Use of τ Polarization: ZZH case

Polarized final state τ ($\lambda_\tau = -1$)			Unpolarized state τ
100% eff.	40% eff.	25% eff.	
$\lvert\Im(b_z)\rvert \leq 0.064$	$\lvert\Im(b_z)\rvert \leq 0.10$	$\lvert\Im(b_z)\rvert \leq 0.13$	$\lvert\Im(b_z)\rvert \leq 0.23$
$\lvert\Re(\tilde{b}_z)\rvert \leq 0.11$	$\lvert\Re(\tilde{b}_z)\rvert \leq 0.18$	$\lvert\Re(\tilde{b}_z)\rvert \leq 0.23$	$\lvert\Re(\tilde{b}_z)\rvert \leq 0.41$

Combination: $\mathcal{C}'_3 = \left[[\vec{P}_e \times \vec{P}_f^{+}] \cdot \vec{P}_f^{-} \right] \left[\vec{P}_e \cdot \vec{P}_f^{+} \right]$

$$A'_3 = \frac{(FU) + (BD) - (FD) - (BU)}{(FU) + (BD) + (FD) + (BU)} = A_{comb}$$

$\Im(b_z)$: ${A^L}_{comb}$; $\Re(\tilde{b}_z)$: ${A^L}_{UD}$.

Use of τ Polarization: ZZH case

- Unpolarized initial states with R1-Cut:
$$A^{com} \propto (\ell_e^2 + r_e^2)(r_f^2 - \ell_f^2)$$
$$A_{UD}(\phi_f) \propto (\ell_e^2 - r_e^2)(r_f^2 - \ell_f^2)$$
$\ell_f^2 > r_f^2 \Rightarrow$ observables for final state τ in -ve helicity are more sensitive.
- Improvement on limits of both the $\tilde{T}$-odd couplings ($\Im(b_z)$ and $\Re(\tilde{b}_Z)$) with R1-Cut.
- Limit on $\Im(b_z)$ improves upto a factor of 2 assuming the efficiency of isolating events with τ's of -ve helicity state to be 25%.
- Sensitivity to $\Re(\tilde{b}_Z)$ is comparable to that obtained with unpolarized states with R2-cut.

Effect of Beam Polarization: WWH case

- Only two observables are available. i.e. Total Rate and FB-asymmetry w.r.t. polar angle of Higgs boson.
- No direct probe for $\tilde{T}$-odd couplings ($\Im(b_W),\ \Re(\tilde{b}_W)$).
- The RL amplitude gets contribution only from s-channel diagram. Beam polarization may help to decrease the contamination coming from ZZH couplings.

Effect of Beam Polarization: WWH case

Individual Limits at 3 σ Level

Coupling		Unpolarized	Polarized Beam	Observable
$\lvert\Im(b_W)\rvert$	$\leq$	0.62	0.31	$\sigma_{R1}(-,\ +)$
$\lvert\Re(\tilde{b}_W)\rvert$	$\leq$	1.6	0.76	$A^{FB}_{R1}(-,\ +)$

Simultaneous Limits at 3 σ Level

Coupling		Polarized Beam	Unpolarized
$\lvert\Im(b_W)\rvert$	$\leq$	0.71	1.6
$\lvert\Re(\tilde{b}_W)\rvert$	$\leq$	1.7	3.2

- Beam polarization improves the sensitivity to $\tilde{T}$-odd couplings upto a factor of 2.
- Little reduction in contamination from ZZH couplings.

Going to higher $\sqrt{s}$?

- Sensitivity to $\Re(\tilde{b}_Z)$, $\Re(b_W)$ and $\Re(\tilde{b}_W)$ is expected to increase at higher center of mass energy due to t-channel enhancement. However, using total rate and A_{FB}, we find

Coupling		E = 500 GeV	E = 1 TeV
$\Re(\tilde{b}_Z)$	$\leq$	0.064	0.031
$\Re(b_W)$	$\leq$	0.098	0.081
$\Re(\tilde{b}_W)$	$\leq$	0.39	0.41

Note that No ISR/Beamstrahlung effect have been included here.

- Improvement in sensitivity to $\Re(\tilde{b}_Z)$ upto a factor 2.
- Little improvement in sensitivity to WWH anomalous couplings.
- No reduction in contamination of WWH from ZZH couplings.

Effects of ISR and Beamstrahlung

- At $\sqrt{s}$ = 500 GeV :
  - Observables with R1 Cut (selecting Z-pole) yield the best limits.
  - with ISR: 5 - 10 % enhancement in both SM as well as anomalous contribution to rates (because of decrease in effective $\sqrt{s}$).
  - However, no effect on sensitivity.
- At high $\sqrt{s}$:
  - Observables with R2 Cut (de-selecting Z-pole) start playing role in probing VVH couplings.
  - Both ISR and Beamstrahlung effects need to be included.
  - These effects result in 10 - 15 % decrease in rates (due to the logarithmic enhancement in t-channel rates).
  - Negligible change in sensitivity.
  - Example: At $\sqrt{s}$ = 1 TeV, Up-down asymmetry with R2 Cut (de-select Z-pole),

$$|\Re(\tilde{b}_Z)| \leq 0.027, \quad \text{No ISR \& No Beamst}$$

$$|\Re(\tilde{b}_Z)| \leq 0.031, \quad \text{With ISR \& Beamst}$$

Summary

- Initial state beam polarization improves the sensitivity to $\Im(\tilde{b}_z)$ upto a factor of 5-6 *.

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Summary

- Initial state beam polarization improves the sensitivity to $\Im(\tilde{b}_z)$ upto a factor of 5-6 *.
- For W boson fusion process, due to ν's in the final state, direct probe of $\tilde{T}$ odd couplings is not possible. However, use of initial beam polarization improves the sensitivity to both the $\tilde{T}$-odd WWH couplings ($\Im(b_w)$ and $\Re(\tilde{b}_w)$) upto a factor of 2.

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- Use of final state τ polarization measurement improves the limit of $\Im(b_Z)$.

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Summary

- At higher $\sqrt{s}$
  - The sensitivity to $\Re(\tilde{b}_z)$ improves by a factor 2.
  - Little improvement on limits of WWH couplings.
  - No appreciable reduction in contamination from ZZH couplings.

*D. Choudhury and Mamta, Phys. Rev. D **74**, 115019 (2006)

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- WWH couplings can be probed better from the process $e\,\gamma \longrightarrow \nu\,W\,H$ at photon colider because of absence of any contamination from the ZZH couplings.*

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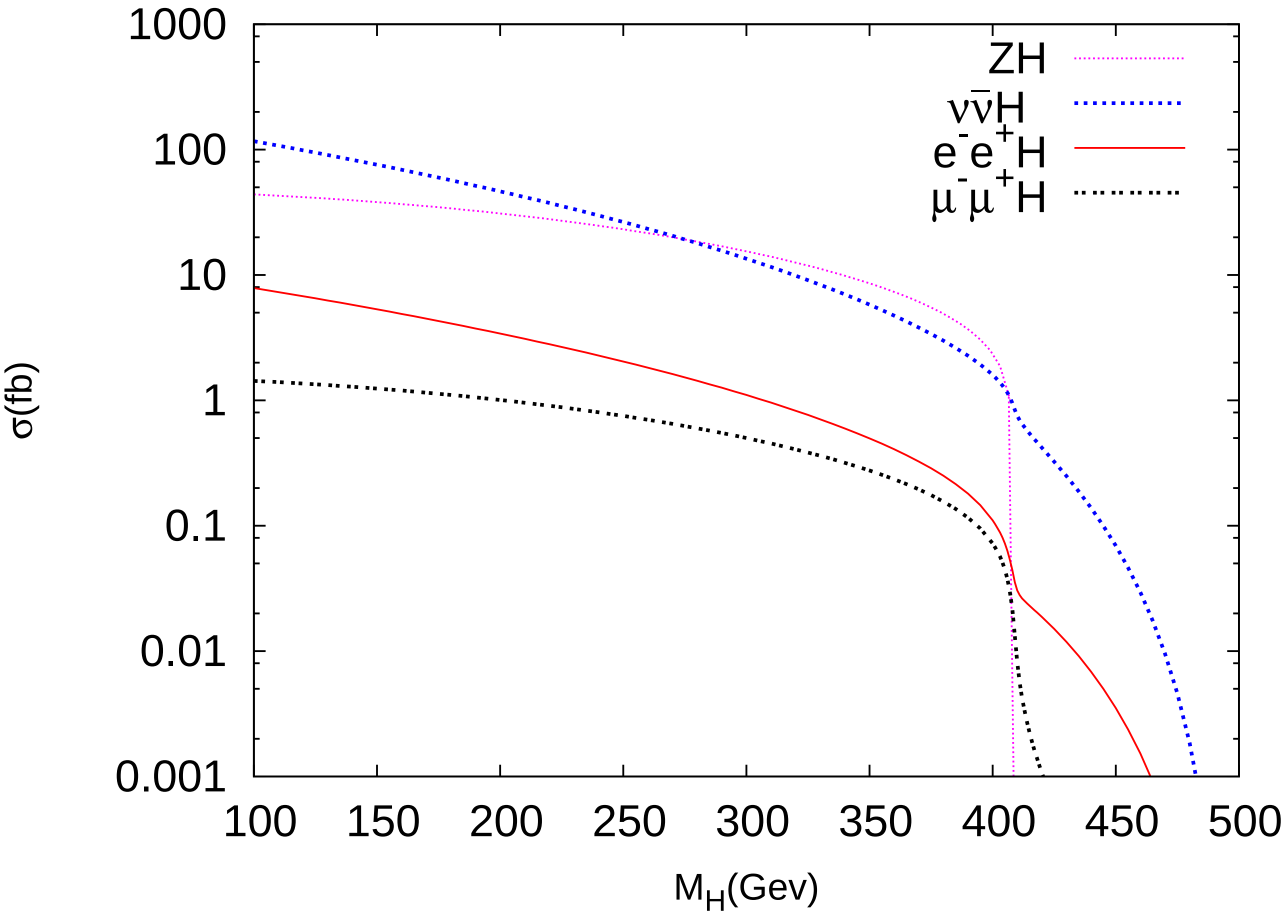
- WWH couplings can be probed better from the process $e\,\gamma \longrightarrow \nu\,W\,H$ at photon colider because of absence of any contamination from the ZZH couplings.*
- The effects of ISR and Beamstrahlung on the sensitivity are negligible.
- Use of Transverse polarization of e^+/e^- beams to probe the $\tilde{T}$-odd couplings needs to be explored.

*D. Choudhury and Mamta, Phys. Rev. D **74**, 115019 (2006)

Thank you !

Higgs Production Rates

At e^+e^- collider, at $\sqrt{s} = 500$ GeV;



$\sigma(\nu_e \bar{\nu}_e H) > \sigma(ZH)$ for $M_H < 250$ GeV.

Forward-backward asymmetry

Variable to constrain $\Im(\tilde{b}_Z)$.

Correlator: $\mathcal{C}_1 = \vec{P}_e \cdot \vec{P}_f^+$, $\quad CP$ odd and $\tilde{T}$ even

$$A_{FB}(\cos\theta_H) = \frac{\sigma(\cos\theta_H > 0) - \sigma(\cos\theta_H < 0)}{\sigma(\cos\theta_H > 0) + \sigma(\cos\theta_H < 0)}.$$

$F(B)$: H is in forward (backward) hemisphere w.r.t. the direction of initial e^-.

Forward-backward asymmetry

$$A^{1^{-,+}} = A_{FB}^{-,+}(\cos\theta_H) = \begin{cases} \dfrac{2.15\ \Re(\tilde{b}_Z) - 7.21\ \Im(\tilde{b}_Z)}{1.72} & (e^+e^-) \\ \dfrac{-7.13\ \Im(\tilde{b}_Z)}{1.69} & (\mu^+\mu^-) \\ \dfrac{-109\ \Im(\tilde{b}_Z)}{26.2} & (q\bar{q}) \end{cases}$$

For final state with μ and light quarks,

3σ Limit $\Rightarrow |\Im(\tilde{b}_Z)| \leq 0.0079$

Up-down asymmetry

Probe for $\Re(\tilde{b}_Z)$,

Correlator: $\mathcal{C}_2 = [\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-$, CP odd and $\tilde{T}$ odd

$$A_{UD}(\phi) = \frac{\sigma(\sin\phi > 0) - \sigma(\sin\phi < 0)}{\sigma(\sin\phi > 0) + \sigma(\sin\phi < 0)}$$

$U(D)$: Final state f is above (below) the H-production plane.

This observable requires charge measurement of the final state fermions.

Up-down asymmetry

$$A^{2^{-,+}}(R1;e) = A_{UD}^{-,+}(\phi_{e^-}) \;=\; \frac{-2.48\,\Re(\tilde{b}_Z) + 0.35\,\Im(\tilde{b}_Z)}{1.72}$$

$$A^{2^{-,+}}(R1;\mu) = A_{UD}^{-,+}(\phi_{\mu^-}) \;=\; \frac{-2.54\,\Re(\tilde{b}_Z)}{1.69}$$

$$A^{2^{-,+}}(R2;e) = A_{UD}^{-,+R2}(\phi_{e^-}) \;=\; \frac{5.09\,\Re(\tilde{b}_Z)}{4.85}$$

For final state μ with R1-Cut,
3σ Limit $\Rightarrow |\Re(\tilde{b}_Z)| \leq 0.070.$

For final state e^- with R2-Cut,
3σ Limit $\Rightarrow |\Re(\tilde{b}_Z)| \leq 0.062.$

Some of the correlators

$$\vec{P}_e = \vec{p}_{e^-} - \vec{p}_{e^+}, \qquad \vec{P}_f^- = \vec{p}_f - \vec{p}_{\bar{f}}, \qquad \vec{P}_f^+ = \vec{p}_f + \vec{p}_{\bar{f}} = -\vec{p}_H$$

	Correlator	C	P	CP	$\tilde{T}$	$CP\tilde{T}$	Probe of
$\mathcal{C}'_0$	1	$+$	$+$	$+$	$+$	$+$	a_V, $\Re(b_V)$
$\mathcal{C}'_1$	$\vec{P}_e \cdot \vec{P}_f^+$	$-$	$+$	$-$	$+$	$-$	$\Im(\tilde{b}_V)$
$\mathcal{C}'_2$	$[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-$	$+$	$-$	$-$	$-$	$+$	$\Re(\tilde{b}_V)$
$\mathcal{C}'_3$	$\left[[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-\right]\left[\vec{P}_e \cdot \vec{P}_f^+\right]$	$-$	$-$	$+$	$-$	$-$	$\Im(b_V)$

$$A'_i = \frac{\sigma(\mathcal{C}'_i > 0) - \sigma(\mathcal{C}'_i < 0)}{\sigma(\mathcal{C}'_i > 0) + \sigma(\mathcal{C}'_i < 0)} \qquad \text{for } i \neq 0.$$

- We constructed 10 combinations in total.

Polar-azimuthal asymmetry

Correlator: $\mathcal{C}'_3 = [[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-][\vec{P}_e \cdot \vec{P}_f^+]$

$$A'_3 = \frac{(FU) + (BD) - (FD) - (BU)}{(FU) + (BD) + (FD) + (BU)}$$

CP even and $\tilde{T}$ odd observable; probe for $\Im(b_Z)$.

$F(B)$: H is in forward (backward) hemisphere w.r.t. the direction of initial e^-.

$U(D)$: Final state f is above (below) the H-production plane.

Limits on $\Im(b_Z)$ and $\Re(\tilde{b}_Z)$

$$A_3^{\prime L}(R1;\tau) \;=\; \frac{1.60\;\Im(b_Z)}{0.578} \equiv A^{com}(\tau)$$

$$A_3^{\prime L} \Rightarrow |\Im(b_Z)| \le 0.064.$$

Up-down asymmetry

$$A_2^{\prime L}(R1;\tau) = A_{UD}^{\prime L}(\phi_{\tau^-}) \;=\; \frac{-0.90\;\Re(\tilde{b}_Z)}{0.578}$$

$A_{UD}^{\prime L}(\phi_{\tau^-})$ with R1-Cut $\Rightarrow |\Re(\tilde{b}_Z)| \le 0.11.$