Probing Higgs boson interactions at an e^+e^- linear collider using polarized beams and information on final state fermion polarization

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in collaboration with

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HVV interactions

- VVH and $VVHH$ interactions are 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.
- After discovery of the Higgs boson the determination of its couplings will be essential to establish it as the SM Higgs boson.
- At an e^+e^- collider, the strength and nature of VVH interactions can be studied through Gauge Boson Fusion and Bjorken process.

Anomalous Higgs boson interactions

Most general VVH coupling structure:

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

where,

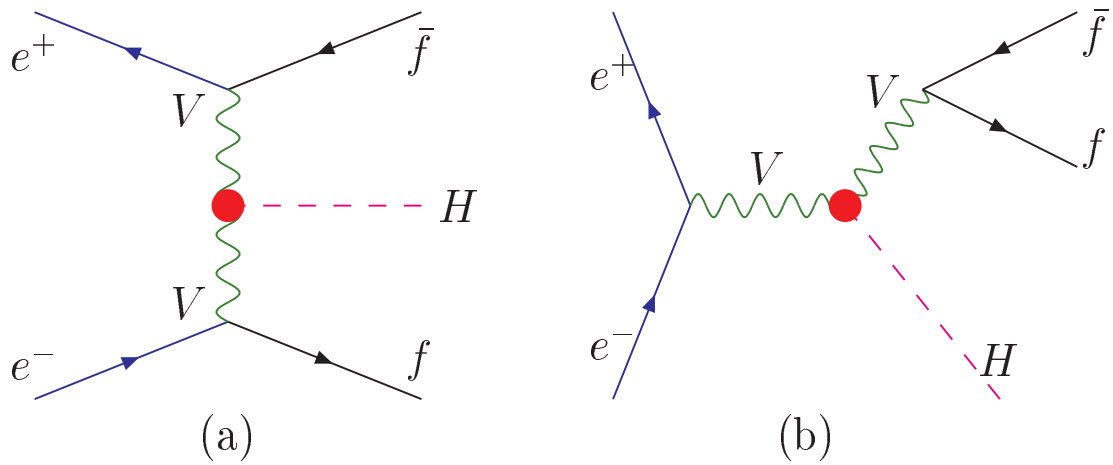
$$g_W^{SM} = e \cos\theta_w M_Z, \quad g_Z^{SM} = 2em_Z / \sin 2\theta_w,$$

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

- a_V, b_V and $\tilde{b}_V$ can be complex.
- $\tilde{b}_V$ corresponds to the coupling of a CP-odd Higgs boson.
- We treat Δa_V, b_V and $\tilde{b}_V$ to be small parameters, i.e. quadratic terms are dropped.

Higgs production at e^+e^- collider

$$
\begin{array}{lclcll}
e^+e^- & \to & e^+e^-Z^*Z^* & \to & e^+e^-H(b\bar{b}) & (Z\text{-fusion}) \\
 & \to & \nu_e\bar{\nu}_e W^*W^* & \to & \nu_e\bar{\nu}_e H(b\bar{b}) & (W\text{-fusion}) \\
 & \to & ZH & \to & f\bar{f}H(b\bar{b}) & (\text{Bjorken})
\end{array}
$$



(a) Gauge Boson Fusion (b) Bjorken

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

b-quark detection efficiency $= 0.7$

$\sqrt{s}$ = 0.5–1 TeV, $\mathcal{L}$ = 500 fb^{-1}

We explore the use of polarized beams and/or information on final state fermion polarization in probing HVV interactions.

Some comments

- The process $e^+e^- \to \nu_e\bar{\nu}_e H$ has the highest rate for an intermediate mass Higgs boson.
- All the non-standard couplings ($ZZH + WWH$) are involved.
- But final state has two neutrinos. Only a few observables can be constructed.
- Interference of SM part of W fusion diagram with non-standard part of Bjorken diagram is large and cannot be simply separated by imposing cuts on invariant mass of the $f\bar{f}$ system ($M_{f\bar{f}}$).
- Need to fix/constrain b_Z and $\tilde{b}_Z$ using Bjorken process before going to study WWH vertex using the process $e^+e^- \to \nu_e\bar{\nu}_e H$.

Asymmetries

• Plan: construct observables with definite $CP/\tilde{T}$ transformation properties using beam/final state polarizations and other kinematic variables to probe the anomalous couplings.

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

	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.

• For each combination, asymmetry can be constructed as:

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

• Measurement of A_{UD} and A_{comb} require charge determination of light quark jets; these asymmetries for quarks in the final state cannot be used.
• Total cross section (CP-even, $\tilde{T}$-even) can probe a_V and $\Re(b_V)$.

Kinematical cuts

- Need to devise kinematical 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
ΔR_{l-l+}	$\geq$	0.2	Leptonic jet resolution
ΔR_{l+b}, $\Delta R_{l+\bar{b}}$, ΔR_{l-b}, $\Delta R_{l-\bar{b}}$	$\geq$	0.4	Lepton-hadron resolution

$$(\Delta R)^2 \equiv (\Delta\phi)^2 + (\Delta\eta)^2,$$

$\Delta\phi$ and $\Delta\eta$ being the separation between the two entities in azimuthal angle and rapidity respectively.

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

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

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

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.

• Note: Total luminosity 500 fb^{-1} is divided equally among different polarization states.

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

Observations with unpolarized & longitudinally polarized beams

With unpolarized beams:
Ref: **Biswal, Choudhury, Godbole and Singh, Phys. Rev. D 73, 035001 (2006).**

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

Use of longitudinal beam polarization:
Ref: **Biswal, Choudhury, Godbole and Mamta, Phys. Rev. D 79, 035012 (2009).**

- Improves sensitivity to $\Im(\tilde{b}_Z)$ by a factor up to 5–6.
- Reduces contamination from ZZH couplings in measurement of WWH vertex.
- Cannot probe a_Z, $\Re(b_Z)$ independently.

• Completely independent probes of $\Re(b_Z)$ and a_Z possible using transversely polarized beams; discussed later.

A simple understanding of the results

- Unpolarized beam for Bjorken processes (R1-Cut):

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

  l_f : left handed coupling of the fermion to the Z-boson.

  $\ell_e^2 > r_e^2 \Rightarrow$ observables constructed using $|M(-,+)|^2$ are more sensitive.

  $\ell_\tau^2 > r_\tau^2 \Rightarrow$ observables for final state τ in -ve helicity are more sensitive.

- Longitudinal beam polarization gives improvement on limits of both the CP-odd couplings ($\Re(\tilde{b}_Z)$, $\Im(\tilde{b}_Z)$) for R1-Cut by a factor up to 5–6.

- Limit on $\Im(\tilde{b}_Z)$ improves up to a factor of 5-6 as compared to the unpolarized case.

- Sensitivity to $\Re(\tilde{b}_Z)$ is comparable to that obtained with unpolarized beams with R2-cut; longitudinal beam polarization leads to more than one independent probe for $\Re(\tilde{b}_Z)$.

- The RL amplitude gets contribution only from s-channel diagram. Using longitudinally polarized beams probes for $\tilde{T}$-even WWH couplings independent of the anomalous ZZH couplings can be constructed.

Possible improvements ?

We investigate:

- Improvement possible using final state τ Polarization.
- Use of final state τ Polarization for polarized beams.
- Use of transverse beam polarization.
- Sensitivity at higher $\sqrt{s}$.

Use of τ Polarization: ZZH case

- Observables are constructed for τ's of definite helicity state.
- Analysis has been made assuming 40% and 20% efficiency of detecting final state τ's with a definite helicity state.

Use of τ Polarization with unpolarized beams

Ref: **Biswal, Choudhury, Godbole and Mamta, Phys. Rev. D 79, 035012 (2009).**

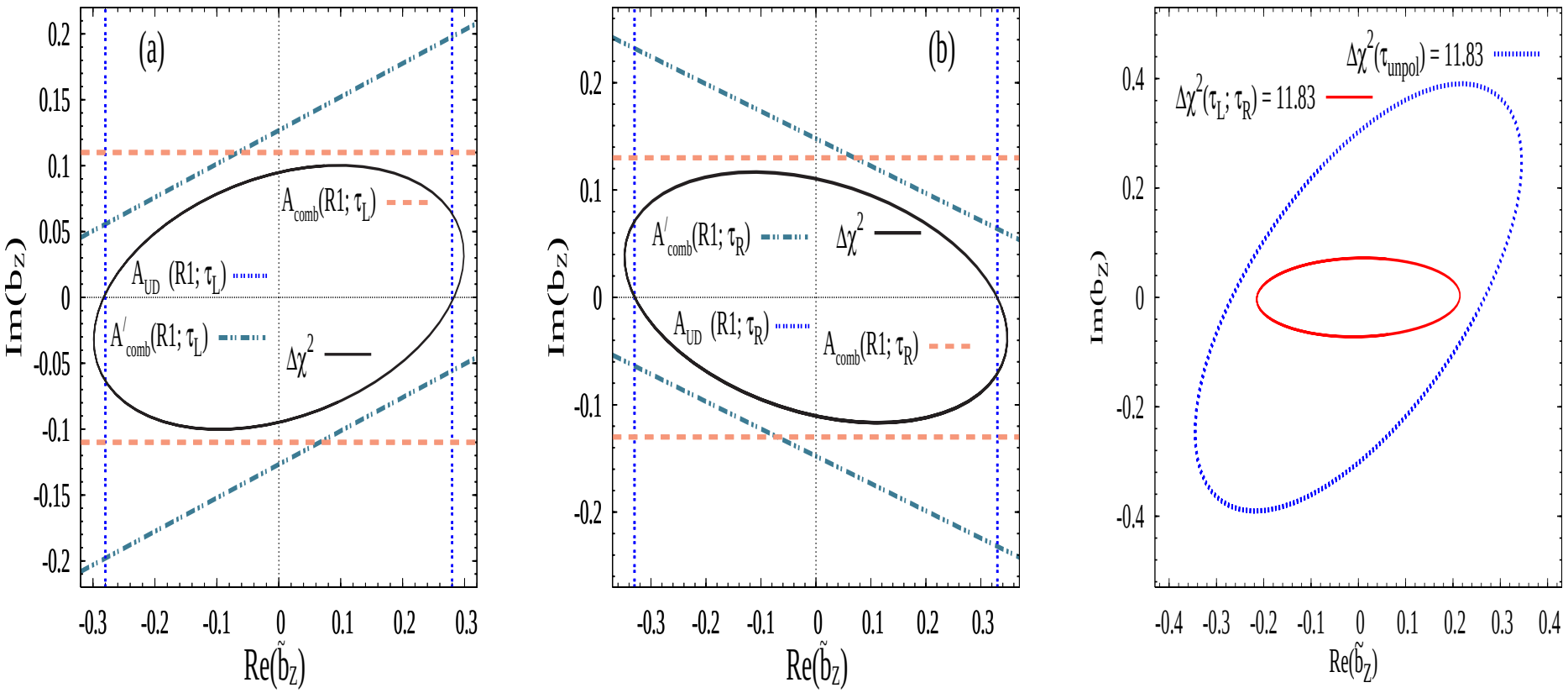
	Using Pol. of final state τ^-			Unpolarized τ's	
Coupling	Limits		Observable	Limits	Observable
	40% eff.	20% eff.			
$\lvert\Im(b_z)\rvert \quad \leq$	0.11	0.15	A^L_{comb}	0.35	A_{comb}
$\lvert\Re(\tilde{b}_z)\rvert \quad \leq$	0.28	0.40	A^L_{UD}	0.91	A_{UD}

Combination: $\mathcal{C}_3 = \left[[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-\right]\left[\vec{P}_e \cdot \vec{P}_f^+\right]$; $\quad A_3 = \frac{(FU)+(BD)-(FD)-(BU)}{(FU)+(BD)+(FD)+(BU)} = A_{comb}$

- Improvement on limits of both the $\tilde{T}$-odd couplings ($\Im(b_z)$ and $\Re(\tilde{b}_Z)$) with R1-Cut by a factor up to 3–4.
- Limit on $\Im(b_z)$ improves up to a factor of 2 assuming the efficiency of isolating events with τ's of -ve helicity state to be 20%.
- Unpolarized measurements with eeH final state for $R2$-cut gives a better sensitivity to $\Re(\tilde{b}_Z)$.

Use of τ Polarization: a χ^2-analysis

Ref: **Biswal, Choudhury, Godbole and Mamta, Phys. Rev. D 79, 035012 (2009).**



$$\Im(b_z) \;:\; A_{comb}; \quad \Re(\tilde{b}_z) \;:\; A_{UD}; \quad \Im(b_z), \Re(\tilde{b}_z) \;:\; A'_{comb}.$$

Combining analyses A and B

- Use of A) longitudinal beam polarization or B) final state τ polarization improves the sensitivity to $\Re(\tilde{b}_Z)$. What happens if A + B ?
- Unpolarized initial states for Bjorken processes (R1-Cut):

$$A_{UD} \propto (\ell_e^2 - r_e^2)(\ell_\tau^2 - r_\tau^2).$$

  l_e : left handed coupling of the electron to the Z-boson.

- Use of final state τ polarization for longitudinally polarized beams can enhance A_{UD}. Up-down asymmetry:

$$\begin{aligned} A_{UD}^{-,+}(R1;\tau_L) &= \frac{-5.7\,\Re(\tilde{b}_Z)}{0.84}, \\ A_{UD}^{-,+}(R1;\tau_R) &= \frac{4.2\,\Re(\tilde{b}_Z)}{0.62}. \end{aligned}$$

$$a\ \chi^2 - analysis \ \Rightarrow\ |\Re(\tilde{b}_Z)| \quad \leq \quad 0.032$$

(for $\mathcal{L}$ = 125 fb^{-1} with 40% isolation efficiency).

- Use of final state τ polarization measurement along with longitudinally polarized beams can improve on the sensitivity for $\Re(\tilde{b}_Z)$ by a factor of about 2 as compared to the case of unpolarized states/ polarized beams/ polarized final state τ.

Use of transverse beam polarization: OBSERVABLES

Ref: **Biswal and Godbole, Phys. Lett. B 680, 81 (2009).**

New observables with transverse beam polarization:

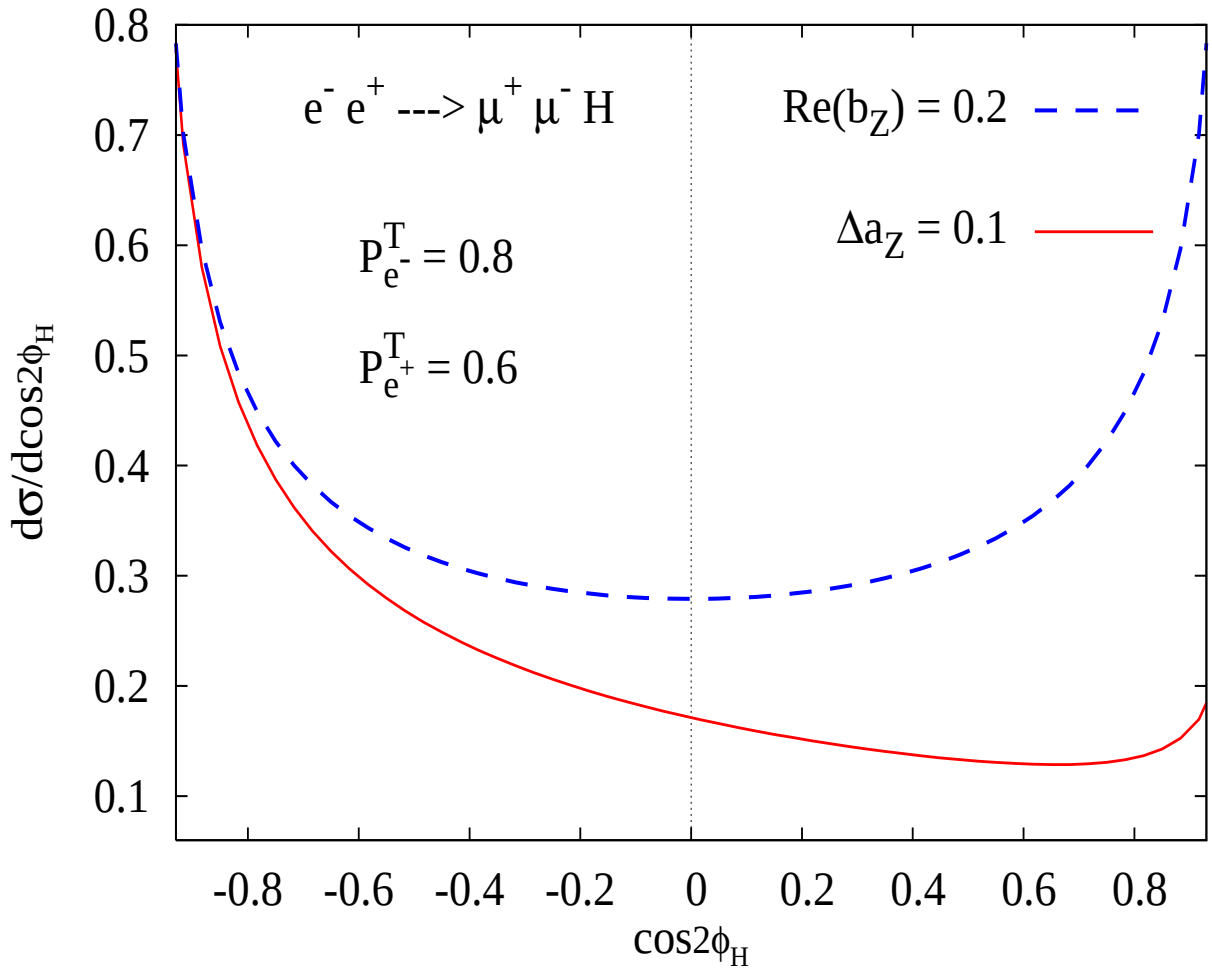
ID	$\mathcal{C}_i^{\mathrm{T}}$	C	P	CP	$\tilde{T}$	$CP\tilde{T}$	Observable (O_i^{T})	Coupling
1	$(\vec{p}_H)_x^2 - (\vec{p}_H)_y^2$	$+$	$+$	$+$	$+$	$+$	O_1^{T}	a_V, $\Re(b_V)$
2	$(\vec{P}_f)_x * (\vec{P}_f)_y * (\vec{p}_H)_z$	$+$	$-$	$-$	$-$	$+$	O_2^{T}	$\Re(\tilde{b}_Z)$
3	$(\vec{p}_H)_x * (\vec{p}_H)_y * (\vec{P}_f)_z$	$-$	$-$	$+$	$-$	$-$	O_3^{T}	$\Im(b_Z)$

$\vec{P}_f \equiv \vec{p}_f - \vec{p}_{\bar{f}}$

- For each combination, observable can be constructed as:

$$
\begin{aligned}
O_i^{\mathrm{T}} &= \frac{1}{\sigma_{\mathrm{SM}}} \int [\mathrm{sign}(\mathcal{C}_i^{\mathrm{T}})] \frac{d\sigma}{d^3p_H\, d^3p_f}\, d^3p_H\, d^3p_f \\
&= \frac{\sigma(\mathcal{C}_i^{\mathrm{T}} > 0) - \sigma(\mathcal{C}_i^{\mathrm{T}} < 0)}{\sigma_{\mathrm{SM}}}
\end{aligned}
$$

Independent probe for Δa_Z



$$O_1^{\mathrm{T}} \quad \propto \quad [\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)] \Rightarrow O_1^{\mathrm{T}}(\Delta a_Z) : \text{Probe of } \Delta \mathrm{a_Z}$$

O_1^{T} receives contribution ONLY from Δa_Z.

Independent probe for Δa_Z

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$$O_1^{\mathrm{T}} = \frac{\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)}{\sigma_{SM}}$$

$$= O_1^{\mathrm{T}}(\Delta a_Z),$$ receives contribution ONLY from Δa_Z.

$$O_1^{\mathrm{T}}(R1-\mathrm{cut}) = \begin{cases} \dfrac{[\mathcal{P}_{e^-}^T \mathcal{P}_{e^+}^T]^* \, [-0.37\,(\,1\,+\,2\,\Delta a_Z)]}{0.86} & (\mu^+\mu^- H) \\ \dfrac{[\mathcal{P}_{e^-}^T \mathcal{P}_{e^+}^T]^* \, [-0.57\,(\,1\,+\,2\,\Delta a_Z)]}{1.32} & (q\bar{q}H) \end{cases}$$

$$|\Delta a_Z| \leq 0.1 \quad \text{for } \mathcal{L} = 500\,\mathrm{fb}^{-1}.$$

- e^- and e^+ transverse beam polarization are considered to be 80% and 60% respectively; sensitivity limit is obtained at 3 σ level.

*The proportionality factor ($\mathcal{P}_{e^-}^T \mathcal{P}_{e^+}^T$) can be understood as a consequence of electronic chiral symmetry mentioned in: K. i. Hikasa, Phys. Rev. D **33**, 3203 (1986).

Independent probes for CP- and $\tilde{T}$-even ZZH couplings

Ref: **Biswal and Godbole, Phys. Lett. B 680, 81 (2009).**

- Using $\mathcal{C}_1^{\rm T}$ we construct an azimuthal asymmetry:

$$\begin{aligned}\mathcal{A}_1^{\rm T} &= \frac{\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)}{\sigma(\cos 2\phi_H > 0) + \sigma(\cos 2\phi_H < 0)} \\ &= \mathcal{A}_1^{\rm T}(\Re(b_Z)),\ \text{receives contribution ONLY from } \Re(b_Z).\end{aligned}$$

$$\mathcal{A}_1^{\rm T}(R1-{\rm cut}) = \begin{cases} \dfrac{[\mathcal{P}_{e^-}^T \mathcal{P}_{e^+}^T]\,[-0.37\,(\,1\,+\,2\,\Delta a_Z)]}{[0.86\,(\,1\,+\,2\,\Delta a_Z)\,+\,8.2\,\Re(b_Z)]} & (\mu^+\mu^- H) \\[2ex] \dfrac{[\mathcal{P}_{e^-}^T \mathcal{P}_{e^+}^T]\,[-0.57\,(\,1\,+\,2\,\Delta a_Z)]}{[1.32\,(\,1\,+\,2\,\Delta a_Z)\,+\,12.5\,\Re(b_Z)]} & (q\bar{q}H) \end{cases}$$

$$\simeq -0.43\,\left[\mathcal{P}_{e^-}^T \mathcal{P}_{e^+}^T\right]\,[1 - 9.5\,\Re(b_Z)]$$

(linear order in anomalous couplings)

$$\mathcal{A}_1^{\rm T}(R1;\ \mu, q) \Rightarrow |\Re(b_Z)| \leq 0.021 \quad \text{for } \mathcal{L} = 500\,{\rm fb}^{-1}.$$

- Both the CP- and $\tilde{T}$-even couplings, $\Re(b_Z)$ and Δa_Z, can be probed independently using $\mathcal{A}_1^{\rm T}$ and $O_1^{\rm T}$ respectively, which was not possible with unpolarized and/or linearly polarized beams.

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

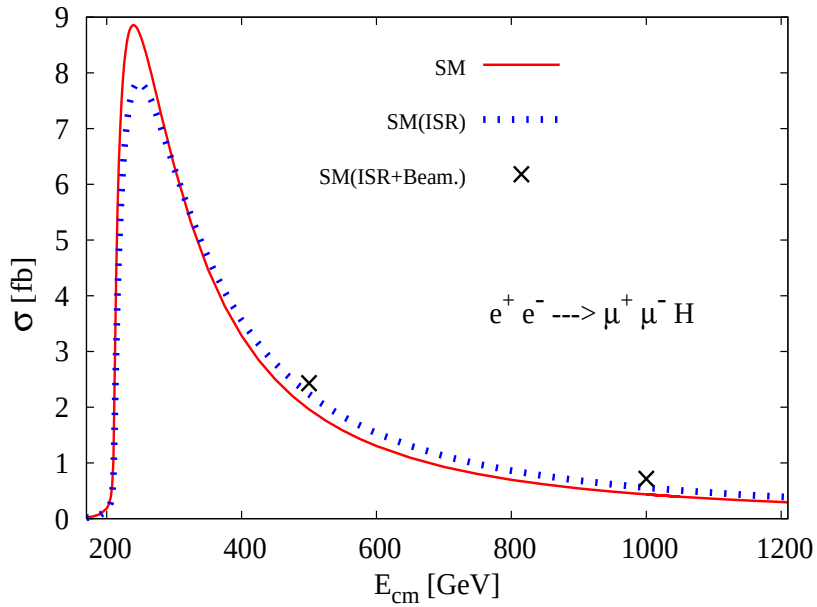
Coupling		E = 500 GeV	E = 1 TeV
$\lvert\Re(\tilde{b}_Z)\rvert$	$\leq$	0.067	0.028
$\lvert\Re(b_W)\rvert$	$\leq$	0.10	0.082
$\lvert\Re(\tilde{b}_W)\rvert$	$\leq$	0.40	0.42

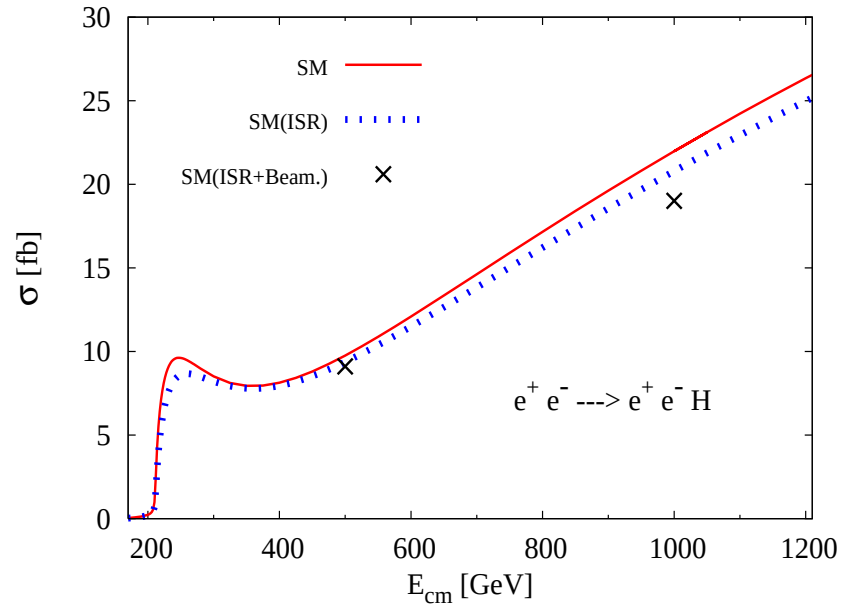
Note that No ISR/Beamstrahlung effect have been included here.

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

Effects of ISR and Beamstrahlung

• Beamstrahlung: Radiation from the beam particles due to its interaction with the strong electromagnetic fields caused by the dense bunches of opposite charge in a collider environment.





Ref: **Biswal, Choudhury, Godbole and Mamta, Phys. Rev. D 79, 035012 (2009).**

- ISR has effects on the SM part as well as on the anomalous parts of the cross sections.
- (a) Crossover in cross section at high c.m. energy due to s-channel suppression.
- (b) No crossover in cross section for final state electrons because of t-channel enhancement in σ at higher $\sqrt{s}$.

Effects of ISR and Beamstrahlung

Ref: **Biswal, Choudhury, Godbole and Mamta, Phys. Rev. D 79, 035012 (2009).**

- 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),

$$|\Re(\tilde{b}_Z)| \leq 0.028, \quad \text{No ISR \& No Beamst}$$
$$|\Re(\tilde{b}_Z)| \leq 0.032, \quad \text{With ISR \& Beamst}$$

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- Longitudinally polarized beams improve the sensitivity to both the CP-odd couplings ($\Re(\tilde{b}_z)$, $\Im(\tilde{b}_z)$) up to a factor of 5-6 *.

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- **With the use of transverse beam polarization it is possible to probe ALL the different anomalous parts of the general HZZ vertex independently.**
- No significant gain in sensitivity at higher $\sqrt{s}$.
- Running the collider at lower energies (say at 500 GeV), but with polarized beams is more beneficial to study these interactions.

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

Thank you !

Effect of longitudinal 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. , $P_{e^-} = +1$, $P_{e^+} = -1$.

- 80%(60%) polarization for e^-(e^+) seem possible at the ILC*.

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

* G. Aarons *et al.* [ILC Collaboration], arXiv:0709.1893 [hep-ph].

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 40% and 20% efficiency of detecting final state τ's with a definite helicity state.

  L (R): τ^- is in -ve (+ve) helicity state, λ_τ = - 1 (+1).

* K. Hagiwara, A. D. Martin and D. Zeppenfeld, Phys. Lett. B **235**, 198 (1990).

* D. P. Roy, Phys. Lett. B **277** (1992) 183.

* K. Hagiwara, S. Ishihara, J. Kamoshita and B. A. Kniehl, Eur. Phys. J. C **14**, 457 (2000).

* R. M. Godbole, M. Guchait and D. P. Roy, Phys. Lett. B **618**, 193 (2005).

A simple understanding of the results

- Unpolarized initial and final states:

$$A_{comb} \propto (\ell_e^2 + r_e^2)(r_\tau^2 - \ell_\tau^2)$$

$$A_{UD} \propto (\ell_e^2 - r_e^2)(r_\tau^2 - \ell_\tau^2)$$

  $\ell_\tau^2 > r_\tau^2 \Rightarrow$ 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 by a factor up to 3–4.

- Limit on $\Im(b_z)$ improves up to a factor of 2 assuming the efficiency of isolating events with τ's of -ve helicity state to be 20%.

- Unpolarized measurements with eeH final state for $R2$-cut gives a better sensitivity to $\Re(\tilde{b}_Z)$.

Probe for $\Im(\tilde{b}_Z)$

- Forward-backward (FB) asymmetry:

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

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

Observable:

$$\begin{aligned} \mathcal{O}_{FB}(R1;\mu,q) &= A_{FB}^{-,+}(R1;\mu) + A_{FB}^{-,+}(R1;q) \\ &- A_{FB}^{+,-}(R1;\mu) - A_{FB}^{+,-}(R1;q) \\ &= -16.3\,\Im(\tilde{b}_Z) \end{aligned}$$

$$\mathcal{O}_{FB}(R1;\mu,q) \Rightarrow |\Im(\tilde{b}_Z)| \leq 0.011 \quad \text{for } \mathcal{L} = 125\,\text{fb}^{-1}.$$

- Note: Total luminosity 500 fb^{-1} is divided equally among different polarization states.

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

- Up-down (UD) asymmetry:

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

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

Observable:

$$\begin{aligned}\mathcal{O}_{UD}(R1;\mu) \equiv A_{UD}^{-,+}(R1;\mu) - A_{UD}^{+,-}(R1;\mu) \\ = -2\,\Re(\tilde{b}_Z)\ ,\end{aligned}$$

$$\mathcal{O}_{UD}(R1;\mu) \Rightarrow\ |\Re(\tilde{b}_Z)| \quad \leq \quad 0.17 \quad \text{for } \mathcal{L} = 125\,\text{fb}^{-1}.$$

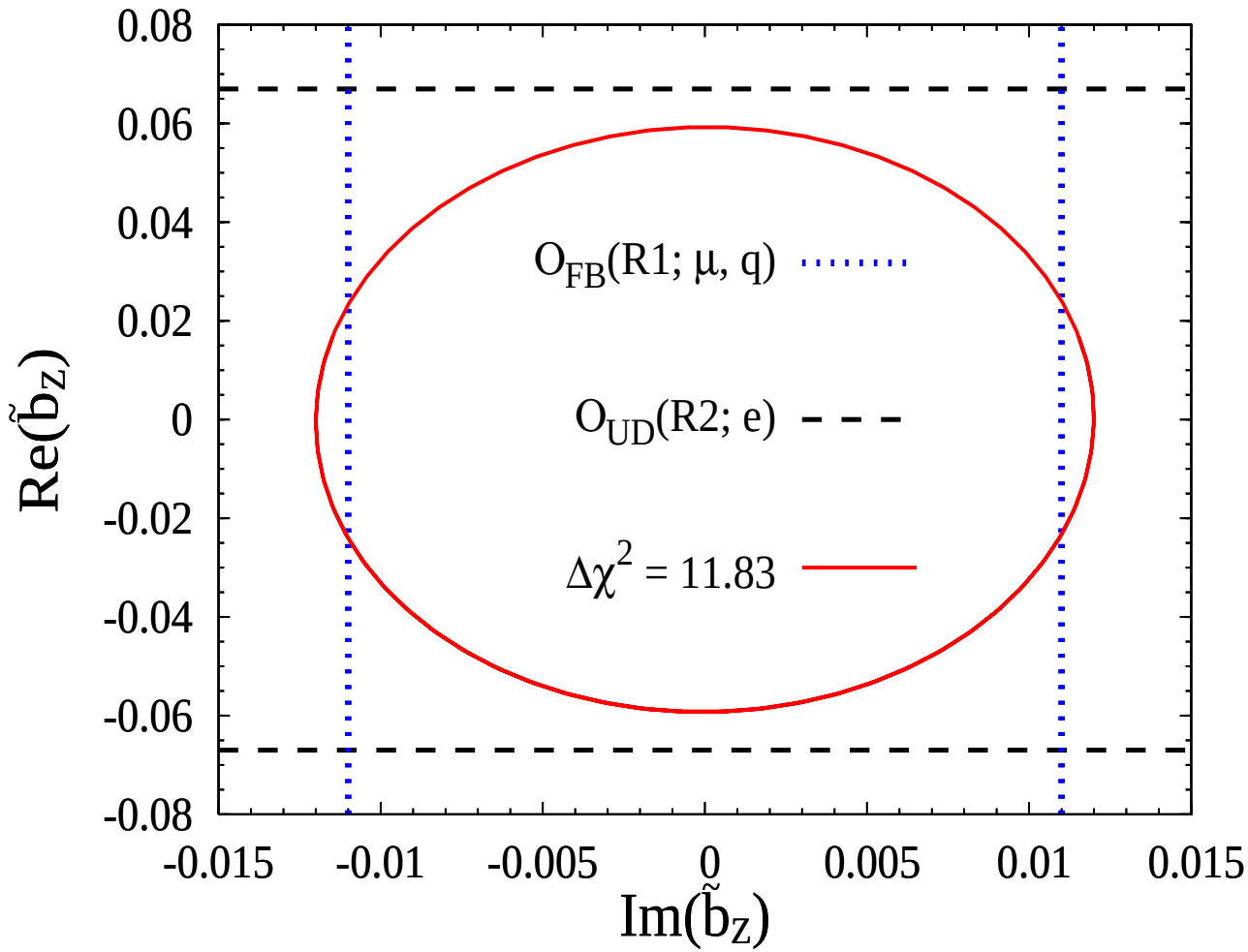
Another observable:

$$\begin{aligned}\mathcal{O}_{UD}(R2;e) &= 2\,A_{UD}^{-,+}(R2;e) + A_{UD}^{+,-}(R2;e) + A_{UD}^{-,-}(R2;e) + A_{UD}^{+,+}(R2;e) \\ &= 5.7\,\Re(\tilde{b}_Z) - 0.005\,\Im(b_Z)\end{aligned}$$

$$\mathcal{O}_{UD}(R2;e) \Rightarrow\ |\Re(\tilde{b}_Z)| \quad \leq \quad 0.067 \quad \text{for } \mathcal{L} = 125\,\text{fb}^{-1}.$$

Constraints on CP-odd ZZH-couplings: a χ^2-analysis

Ref: **Biswal** *et al.*, **Phys. Rev. D 79, 035012 (2009).**



Effect of longitudinal beam polarization: ZZH case

Using Polarized Beams			Unpolarized States	
Coupling	Limits	Observable used	Limits	Observable used
$\lvert\Re(\tilde{b}_Z\rvert \quad \leq$	0.067	$\mathcal{O}_{UD}(R2;e)$	0.067	$A_{UD}(R2;e)$
$\lvert\Re(\tilde{b}_Z)\rvert \quad \leq$	0.17	$\mathcal{O}_{UD}(R1;\mu)$	0.91	$A_{UD}(R1;\mu)$
$\lvert\Im(\tilde{b}_Z)\rvert \quad \leq$	0.011	$\mathcal{O}_{FB}(R1;\mu,q)$	0.064	$A_{FB}(R1;\mu,q)$

- Note: 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).

Probe for $\Im(\tilde{b}_Z)$

$$A_{FB}^{-,+}(R1-\text{cut}) = \begin{cases} \dfrac{0.174\,\Re(\tilde{b}_Z) - 6.14\,\Im(\tilde{b}_Z)}{1.48} & (e^+e^-H) \\ \dfrac{-6.07\,\Im(\tilde{b}_Z)}{1.46} & (\mu^+\mu^-H) \\ \dfrac{-92.8\,\Im(\tilde{b}_Z)}{22.4} & (q\bar{q}H) \end{cases}$$

- $\Re(\tilde{b}_Z)$ makes an appearance on account of the interference of the t-channel diagram with the absorptive part of the s-channel SM one.

$$A_{FB}^{+,-}(R1-\text{cut}) = \begin{cases} \dfrac{-0.0911\,\Re(\tilde{b}_Z) + 4.43\,\Im(\tilde{b}_Z)}{1.11} & (e^+e^-H) \\ \dfrac{4.4\,\Im(\tilde{b}_Z)}{1.09} & (\mu^+\mu^-H) \\ \dfrac{67.2\,\Im(\tilde{b}_Z)}{16.8} & (q\bar{q}H) \end{cases}$$

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

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

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

$$A_{UD}^{-,+}(R1-\text{cut}) = \begin{cases} \dfrac{-1.43\,\Re(\tilde{b}_Z) - 0.286\,\Im(\tilde{b}_Z)}{1.48} & (e^+e^-H) \\ \dfrac{-1.49\,\Re(\tilde{b}_Z)}{1.46} & (\mu^+\mu^-H) \end{cases}$$

$$A_{UD}^{+,-}(R1-\text{cut}) = \begin{cases} \dfrac{1.12\,\Re(\tilde{b}_Z) - 0.161\,\Im(\tilde{b}_Z)}{1.11} & (e^+e^-H) \\ \dfrac{1.08\,\Re(\tilde{b}_Z)}{1.09} & (\mu^+\mu^-H) \end{cases}$$

$$A_{UD}^{-,+}(R2;e) = \frac{4.3\,\Re(\tilde{b}_Z) + 0.227\,\Im(b_Z)}{4.04},$$

$$A_{UD}^{+,-}(R2;e) = \frac{3\,\Re(\tilde{b}_Z) - 0.227\,\Im(b_Z)}{2.64},$$

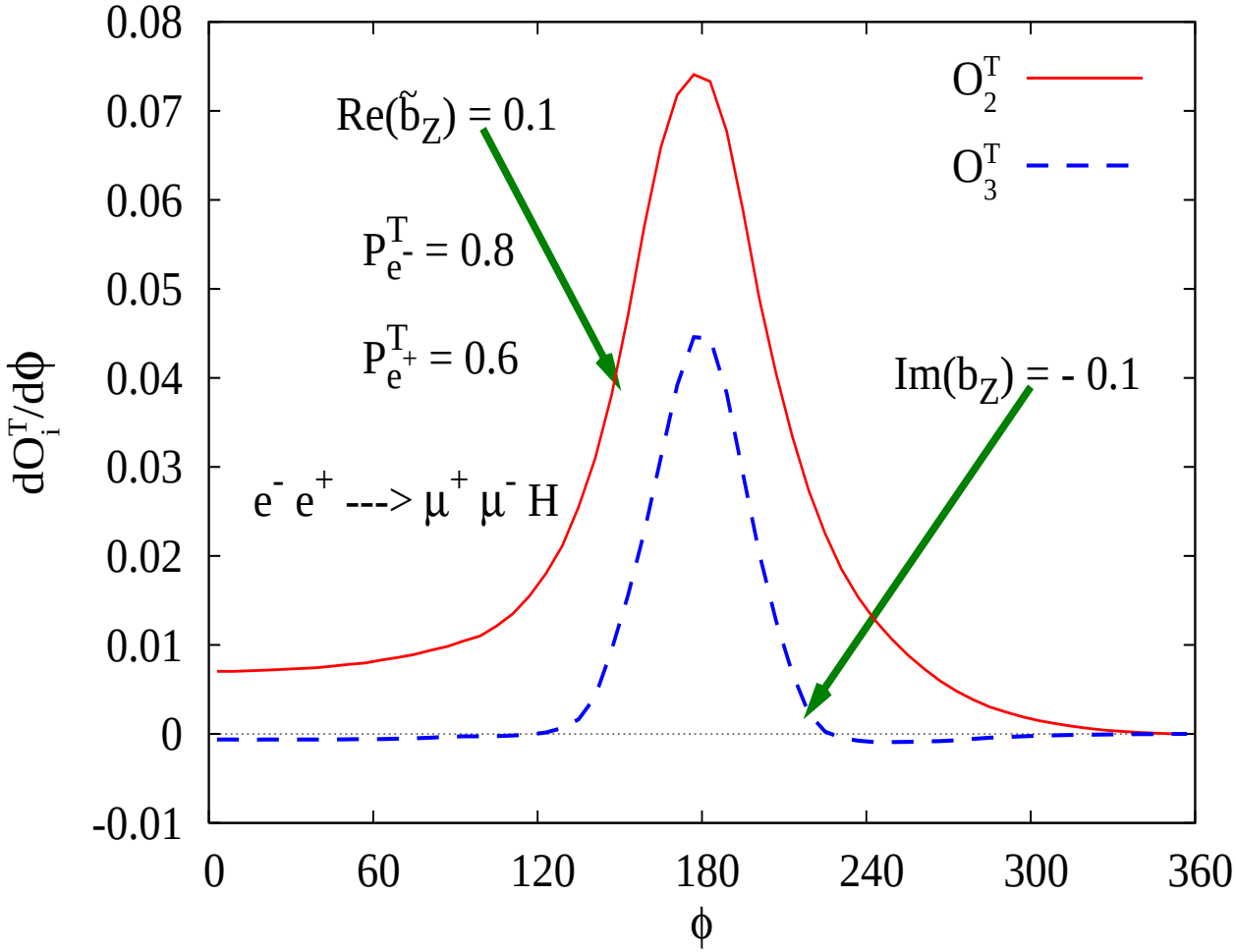
$$A_{UD}^{-,-}(R2;e) = \frac{4.01\,\Re(\tilde{b}_Z) + 1.59\,\Im(b_Z)}{3.29},$$

$$A_{UD}^{+,+}(R2;e) = \frac{3.82\,\Re(\tilde{b}_Z) - 1.59\,\Im(b_Z)}{3.09}.$$

Effect of longitudinal 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. Longitudinal beam polarization may help to decrease the contamination coming from ZZH couplings.
- Using longitudinally polarized beams probes for $\tilde{T}$-even WWH couplings independent of the anomalous ZZH couplings can be constructed.

Probes for $\tilde{T}$-odd ZZH couplings



ϕ: is defined with respect to Higgs boson production plane.

More observations with transverse polarization

- Observables with transversely polarized beams for R1-Cut:

$$O_2^{\mathrm{T}} \propto l_e\, r_e\, (\ell_f^2 + r_f^2),$$
$$O_3^{\mathrm{T}} \propto l_e\, r_e\, (\ell_f^2 - r_f^2).$$

  l_f : left handed coupling of the fermion to the Z-boson.

- Using O_2^{T} for $R1$-cut (select Z-pole events) the sensitivity limit of $\Re(\tilde{b}_Z)$ can be improved by a factor of 4-5.

- Isolation of events with final state τ's in definite helicity state with an efficiency of 40% can increase the sensitivity of O_3^{T} to probe $\Im(b_Z)$ by 30% as compared to the unpolarized case.

- Transverse beam polarization does not affect the squared matrix element of the t-channel WW fusion diagram which includes the anomalous WWH couplings.

- O_1^{T} is not expected to put stronger bounds on anomalous WWH couplings as compared to the unpolarized case.

Observables for $R2$-cut

- Similar observables using transversely polarized beams for $R2$-cut (de-selecting Z-pole) can be constructed.
- The t-channel squared matrix element (MESQ) does not include the spin projection factors $(1+\gamma_5 \not{s}_{e^-})$ and $(1+\gamma_5 \not{s}_{e^+})$ in the same trace.
- The MESQ for t-channel diagram does not have transverse beam polarization dependence factors*.
- The major additional contribution in the MESQ for $R2$-cut comes from the interference of s- and t-channel diagrams.
- Observables: O_1^{T}, O_2^{T} and O_3^{T} for $R2$-cut are less sensitive than those for $R1$-cut.

* This has been pointed out for t-channel SM diagram;
K. i. Hikasa, Phys. Lett. B **143**, 266 (1984).