Probing Higgs boson interactions at future colliders

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References

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Outline

- Introduction
- Probes of VVH interactions
- Role of longitudinal beam / final state polarization
- Use of transverse beam polarization
- Sensitivity study at higher $\sqrt{s}$
- Summary

Introduction

- Despite the dramatic success of the Standard Model (SM), an essential component of SM, Higgs Mechanism, responsible for generating masses of all the particles in the SM has not been yet directly tested.
- The Large Hadron Collider (LHC) is expected to be capable of searching the SM Higgs boson over most of the allowed range of its mass.
- The SM predicts existence of one Higgs boson, a spin-0 particle, even under charge conjugation and parity (C, P) transformation, whereas scenarios beyond the SM usually imply more than one Higgs boson with different CP and weak isospin quantum numbers.
- After the discovery of the Higgs boson at the LHC precise determination of its interactions with other particles at the International e^+e^- Linear Collider (ILC) will be necessary to establish it as *the* SM Higgs boson.
- Model independent approach is useful to analyze the most general Higgs boson interactions in an unambiguous way.

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.
- Necessary to measure the Higgs boson properties, especially the VVH couplings, because they are sensitive to the symmetry breaking physics that give rise to particle masses.
- At an e^+e^- collider (ILC), the strength and nature of VVH interactions can be studied through Gauge Boson Fusion and Bjorken process; will be discussed later.
- We have investigated, in a model independent way, the sensitivity of the ILC to probe the Higgs boson interactions with a pair of vector bosons ($V = W/Z$) with/without the use of polarized initial beams and/or the information on final state fermion polarization.

Anomalous Higgs boson interactions

Most general VVH coupling structure:

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

where,

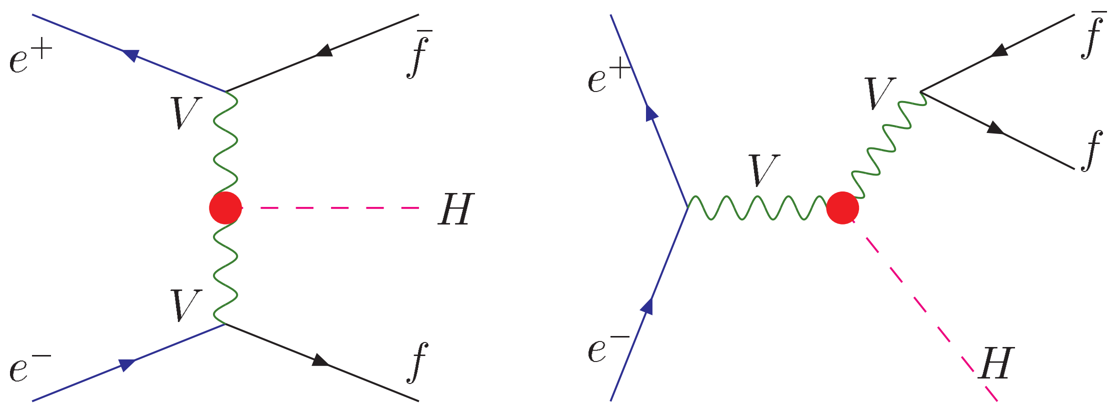
$$g_W^{SM} = e \cos\theta_w M_Z, \quad g_Z^{SM} = 2em_Z / \sin 2\theta_w,$$

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

- a_V, b_V and $\tilde{b}_V$ can be complex.
- $\tilde{b}_V$ corresponds to the coupling of a CP-odd Higgs boson.
- The Standard Model is consistent with the electroweak precision measurements.
- 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

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



(a) (b)

(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
$\Delta R_{l^- l^+}$	$\geq$	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

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

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

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

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

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

Sensitivity Limits

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

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

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

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.

Total cross sections: Probes of Δa_Z and $\Re(b_Z)$

$\sqrt{s}$ = 500 GeV; M_H = 120 GeV.

On selecting the Z-pole ($R1$ cut) cross sections in femtobarns (fb):

$$\begin{aligned}
\sigma(e^+e^-) &= 0.88 + 8.2\,\Re(b_Z) + 0.13\,\Im(b_Z) \\
\sigma(\mu^+\mu^-) &= 0.86 + 8.2\,\Re(b_Z) \\
\sigma(u\bar{u}/c\bar{c}) &= 2\ [2.9 + 27\,\Re(b_Z)] \\
\sigma(d\bar{d}/s\bar{s}) &= 2\ [3.7 + 35\,\Re(b_Z)]
\end{aligned}$$

• $\Im(b_Z)$ makes an appearance on account of the interference of the t-channel diagram with the absorptive part of the s-channel SM one.

$$\sigma(R1;\mu,q) \Rightarrow\ |\Re(b_Z)| \leq 0.49 \times 10^{-2} \quad \text{for } \mathcal{L} = 500\,\text{fb}^{-1} \text{ at } 3\sigma \text{ level.}$$

On de-selecting the Z-pole ($R2$ cut):

$$\sigma(e^+e^-) = [3.3 - 0.15\,\Re(b_Z)]\,\text{fb.}$$

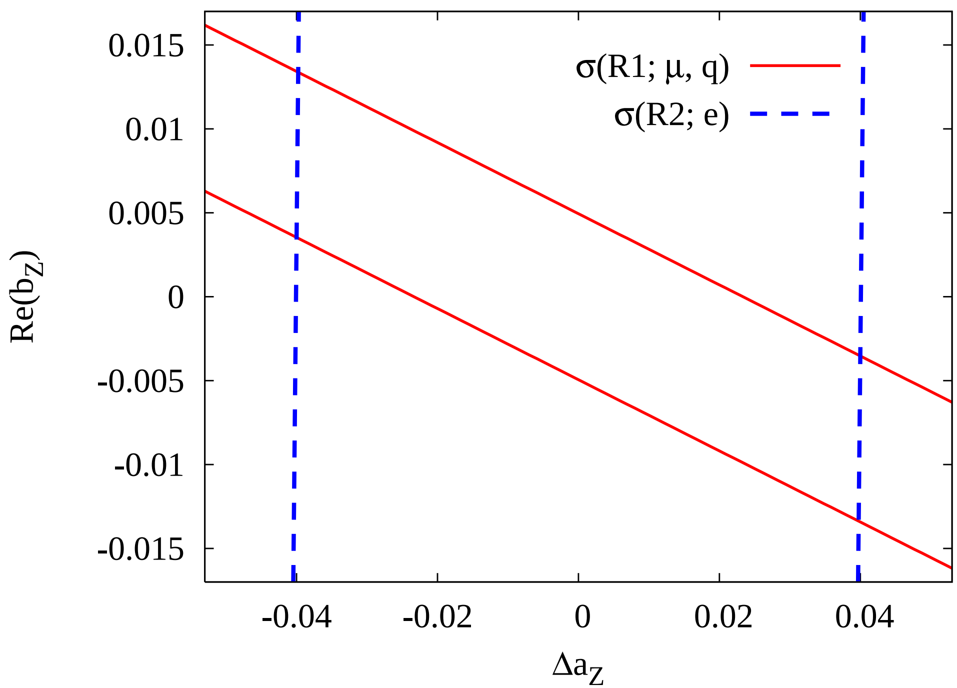
• Note: In the above expressions we have kept a_Z = 1.

Probes of Δa_Z and $\Re(b_Z)$

For $a_Z = (1 + \Delta a_Z)$, we have

$$\sigma(R1; \mu, q) = [14\ (1 + 2\Delta a_Z) + 133\ \Re(b_Z)]$$

$$\sigma(R2; e) = [3.3\ (1 + 2\Delta a_Z) - 0.15\ \Re(b_Z)]$$



$$\eta_1 \cong 2\ \Delta a_Z + 9.4\ \Re(b_Z)$$

$$|\Delta a_Z| \leq 0.04$$

$$|\eta_1| \leq 0.047$$

No independent probes of both the CP- and $\tilde{T}$-even couplings without beam polarization. Can use of beam polarization help?

Forward-backward asymmetry

• 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^-.

FB-asymmetry with $R1$-cut:

$$A_1 = A_{FB}(c_H) = \begin{cases} \dfrac{0.028\,\Re(\tilde{b}_Z) - 0.58\,\Im(\tilde{b}_Z)}{0.876} & (e^+e^-) \\ \dfrac{-0.57\,\Im(\tilde{b}_Z)}{0.86} & (\mu^+\mu^-) \\ \dfrac{-8.6\,\Im(\tilde{b}_Z)}{13.2} & (q\bar{q}) \end{cases}$$

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

$$A_{FB}(R1; \mu, q) \Rightarrow \; |\Im(\tilde{b}_Z)| \quad \leq \quad 0.064 \quad \text{for } \mathcal{L} = 500\,\text{fb}^{-1}.$$

Up-down asymmetry

- 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.

UD-asymmetry with $R2$-cut:

$$A_2 = A_{UD}(R2; e) \quad = \quad \frac{3.8\, \Re(\tilde{b}_Z)}{3.3}$$

$$A_{UD}(R2; e) \Rightarrow \ |\Re(\tilde{b}_Z)| \quad \leq \quad 0.067 \quad \text{for } \mathcal{L} = 500\,\mathrm{fb}^{-1}.$$

- Best sensitivity limit on $\Re(\tilde{b}_Z)$ is obtained using A_{UD} with $R2$-cut.
- A_{UD} for quarks in the final state cannot be used as measurement of this asymmetry requires charge determination of light quark jets.

Combined polar-azimuthal asymmetry

$\mathcal{C}_3 \equiv [\vec{P}_e \cdot \vec{p}_{_H}] * [(\vec{P}_e \times \vec{p}_{_H}) \cdot \vec{P}_f^-]$; even under CP and odd under $\tilde{T}$.

$$A_{comb} = \frac{\sigma_{FU} + \sigma_{BD} - \sigma_{FD} - \sigma_{BU}}{\sigma_{FU} + \sigma_{BD} + \sigma_{FD} + \sigma_{BU}}, \quad \text{can be sensitive to } \Im(b_Z).$$

• Combined polar-azimuthal asymmetry (A_{comb}): is a particular combination of the polar and azimuthal asymmetries, designed to increase sensitivity.

$$A_{comb}(R1;\mu) = \frac{-0.36\,\Im(b_Z)}{0.86}$$

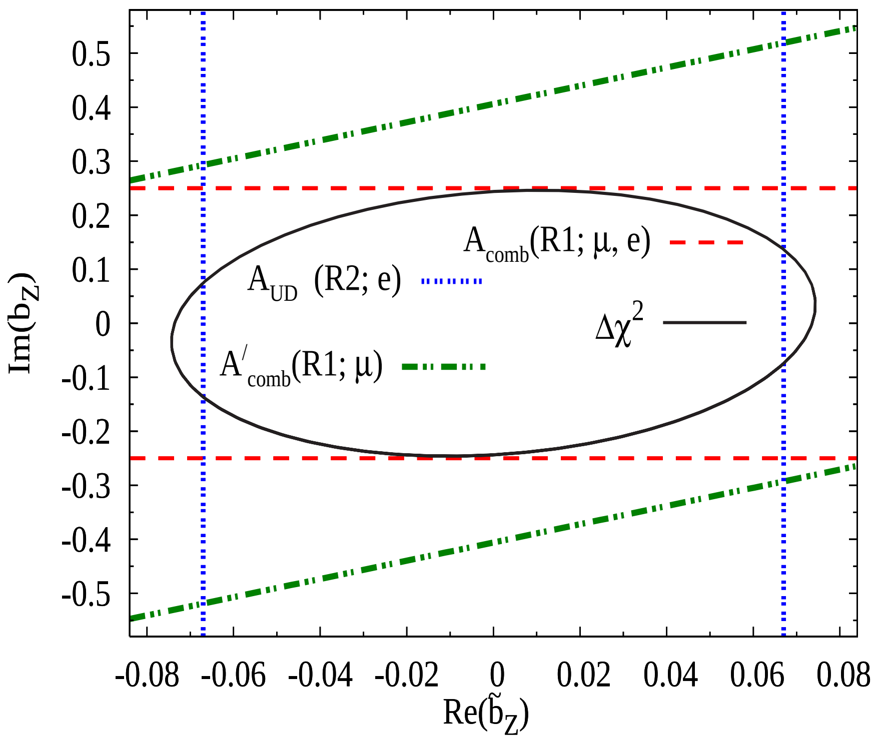
$$A_{comb}(R1;e) = \frac{-0.36\,\Im(b_Z) + 0.022\,\Re(b_Z)}{0.88}$$

$$A_{comb}(R1;\mu,e) \Rightarrow |\Im(b_Z)| \leq 0.25 \quad \text{for } \mathcal{L} = 500\,\text{fb}^{-1}.$$

• This observable requires charge measurement of the final state fermions.

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

Summary of results from: **Biswal** *et al.*, **Phys. Rev. D 73, 035001 (2006).**



Coupling	3σ Bound	Observable used
$\lvert\Delta a_Z\rvert$	0.04	$\sigma(R2;e)$
$\lvert\Re(b_Z)\rvert$	0.0049 $(\Delta a_Z = 0)$; 0.013 $(\lvert\Delta a_Z\rvert = 0.04)$	$\sigma(R1;\mu,q)$
$\lvert\Im(b_Z)\rvert$	0.25	$A_{comb}(R1;\mu,e)$
$\lvert\Re(\tilde b_Z)\rvert$	0.067	$A_{UD}(R2;e)$
$\lvert\Im(\tilde b_Z)\rvert$	0.064	$A_{FB}(R1;\mu,q)$

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

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

Observations with unpolarized states:

l_f (r_f) : left-(right-) handed coupling of the fermion to the Z-boson.

$(\ell_e^2 - r_e^2) \sim$ 1 - 4 $\sin^2\theta_W$, $\sin^2\theta_W \sim 0.23$.

$A_{FB} \propto (\ell_e^2 - r_e^2)$: A) Improvement possible using polarized beams

$A_{comb} \propto (\ell_e^2 + r_e^2)(r_f^2 - \ell_f^2)$: B) Possible gain in sensitivity with final state τ polarization

$A_{UD} \propto (\ell_e^2 - r_e^2)(r_f^2 - \ell_f^2)$: Improvement possible combining analyses A and B.

Sensitivity limits on WWH couplings

- Process: $e^+e^- \to \nu\bar{\nu}H$; Momenta of ν's cannot be used; construction of only two observables (total cross section, FB-asymmetry) are possible.

Individual limit of sensitivity

Coupling		Limit	Observable used
$\|\Delta a\|$	$\leq$	0.019	$\sigma(R2'; \nu)$
$\|\Re(b_W)\|$	$\leq$	0.10	$\sigma(R2'; \nu)$
$\|\Im(b_W)\|$	$\leq$	0.65	$\sigma(R1'; \nu)$
$\|\Re(\tilde{b}_W)\|$	$\leq$	1.7	$A_{FB}(R1'; \nu)$
$\|\Im(\tilde{b}_W)\|$	$\leq$	0.40	$A_{FB}(R2'; \nu)$

Simultaneous limit of sensitivity

Coupling		$\Delta a = 0$	$\Delta a \neq 0$
$\|\Delta a\|$	$\leq$	–	0.040
$\|\Re(b_W)\|$	$\leq$	0.11	0.32
$\|\Im(b_W)\|$	$\leq$	1.8	1.8
$\|\Re(\tilde{b}_W)\|$	$\leq$	3.3	3.3
$\|\Im(\tilde{b}_W)\|$	$\leq$	0.46	0.46

- No direct probe for $\tilde{T}$-odd WWH couplings.
- Contamination from ZZH couplings to WWH vertex determination is quite large.
- Use of beam polarization may reduce this contamination. I will discuss this aspect at a later stage of this talk.

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].

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:

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

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

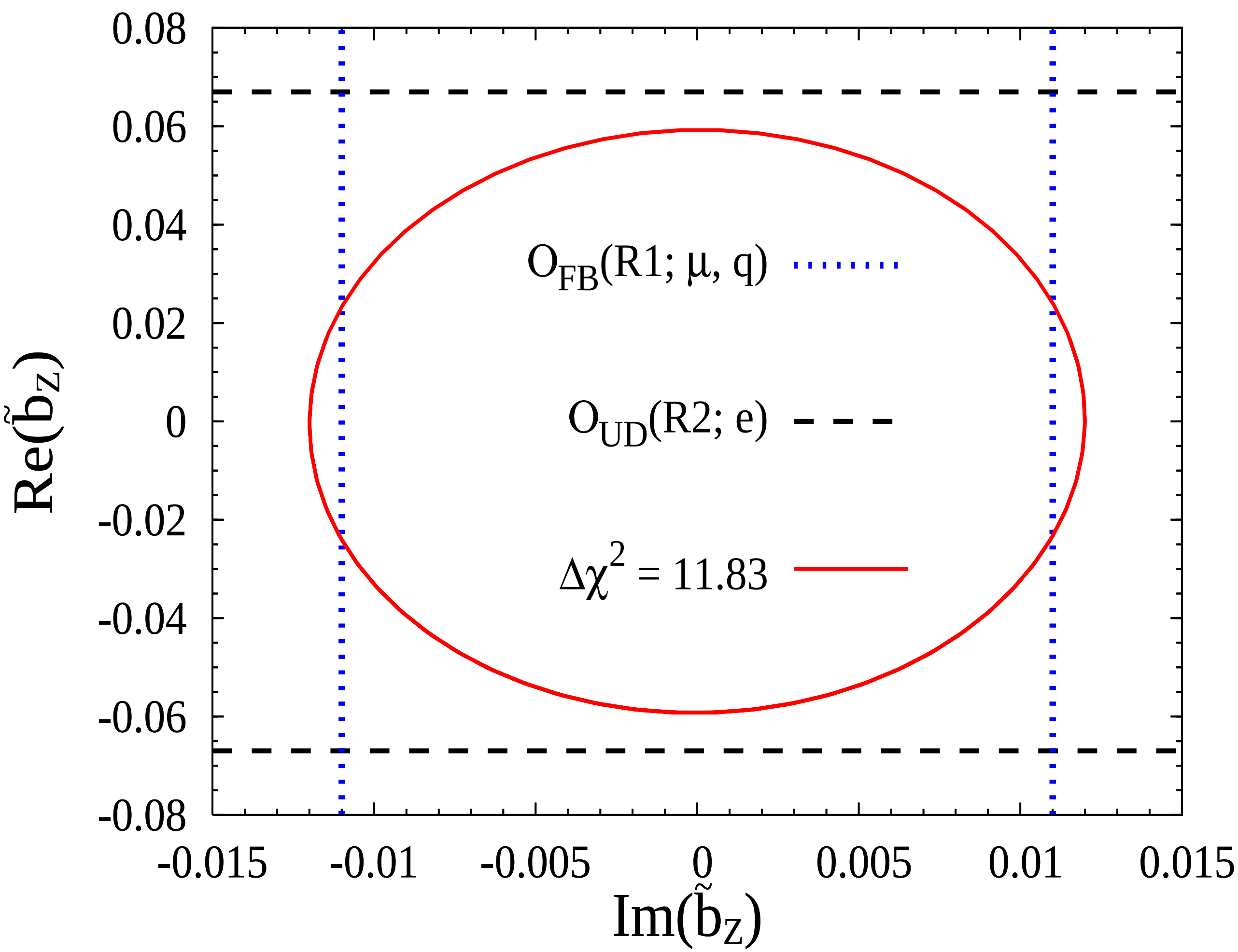
Another observable:

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

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

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

Summary of results from: **Biswal** *et al.*, **Phys. Rev. D 79, 035012 (2009).**

Using Polarized Beams			Unpolarized States	
Coupling	Limits	Observable used	Limits	Observable used
$\|\Re(\tilde{b}_Z\| \quad \leq$	0.067	$\mathcal{O}_{UD}(R2; e)$	0.067	$A_{UD}(R2; e)$
$\|\Re(\tilde{b}_Z)\| \quad \leq$	0.17	$\mathcal{O}_{UD}(R1; \mu)$	0.91	$A_{UD}(R1; \mu)$
$\|\Im(\tilde{b}_Z)\| \quad \leq$	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.

A simple understanding of the results

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

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

  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.

- 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 $\Re(\tilde{b}_Z)$.

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).
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* 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).

Use of τ Polarization with unpolarized beams

Ref: **Biswal** *et al.*, **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: $\mathcal{C}_3 = \left[[\vec{P}_e \times \vec{P}_f^{+}] \cdot \vec{P}_f^{-} \right] \left[\vec{P}_e \cdot \vec{P}_f^{+} \right]$

$$A_3 = \frac{(FU) + (BD) - (FD) - (BU)}{(FU) + (BD) + (FD) + (BU)} = A_{comb}$$

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

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.

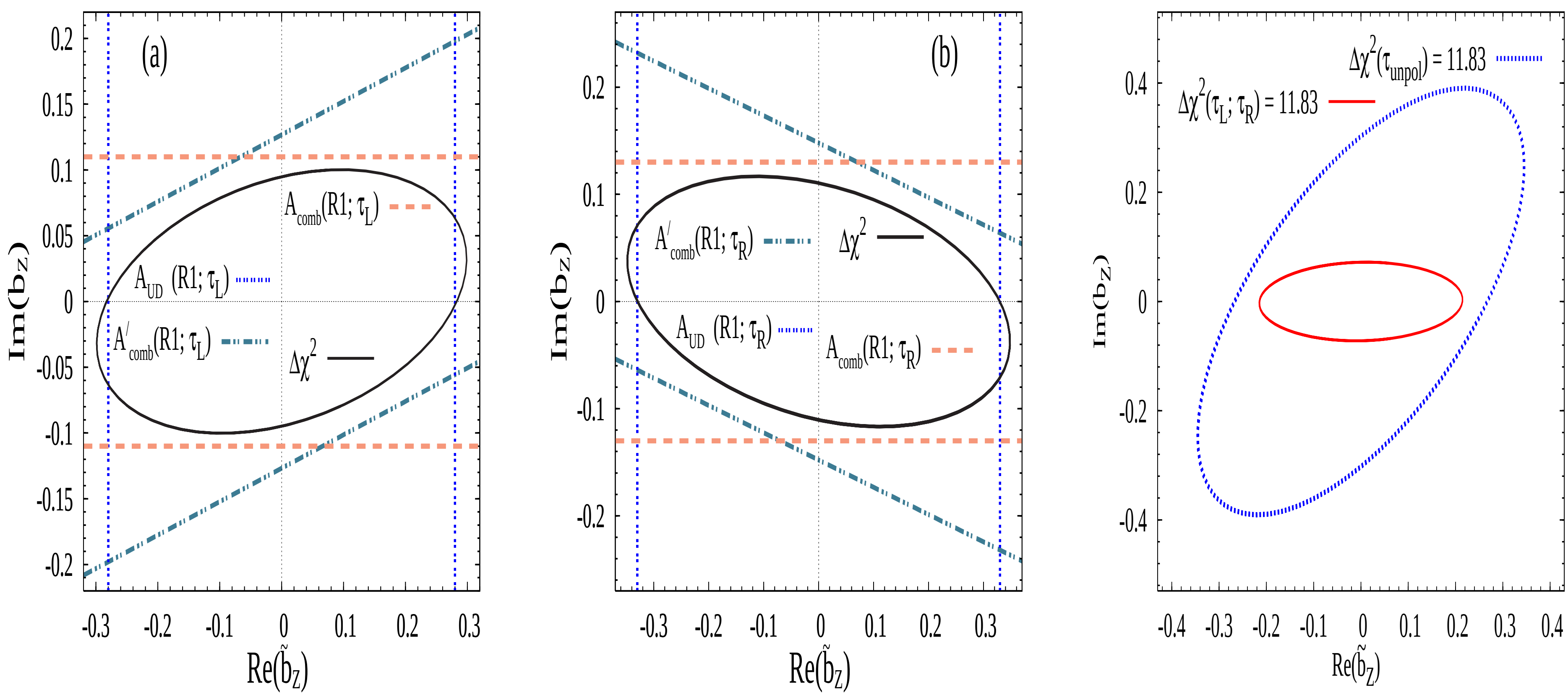
- Improvement on limits of both the $\tilde{T}$-odd couplings ($\Im(b_z)$ and $\Re(\tilde{b}_Z)$) with R1-Cut by a factor up to 3–4.

- 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 $\Re(\tilde{b}_Z)$.

Use of τ Polarization: a χ^2-analysis

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



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

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:

$$A_{UD}^{-,+}(R1;\tau_L) = \frac{-5.7\,\Re(\tilde{b}_Z)}{0.84},$$

$$A_{UD}^{-,+}(R1;\tau_R) = \frac{4.2\,\Re(\tilde{b}_Z)}{0.62}.$$

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

(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.

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.

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}	$\Im(b_Z)$

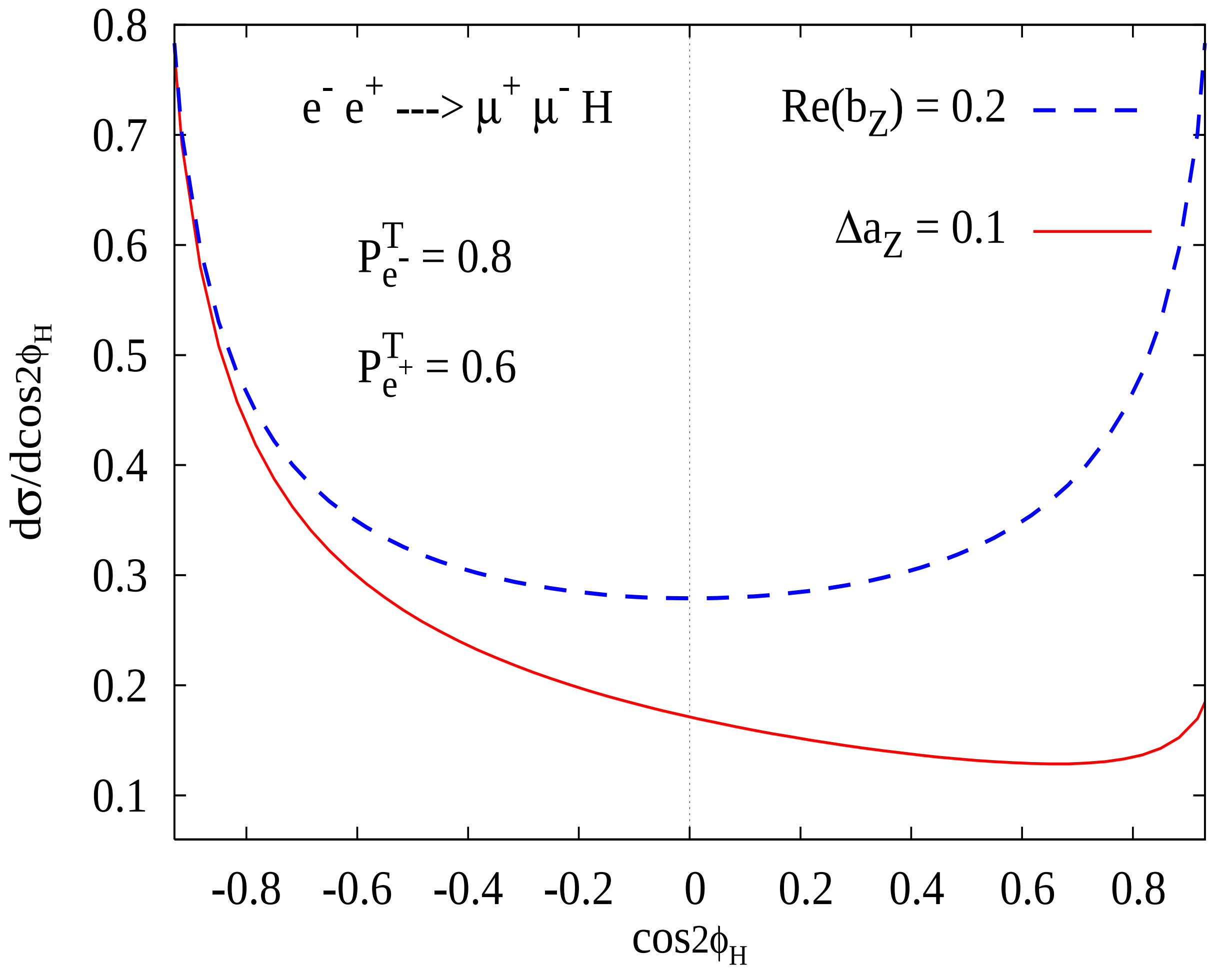
$\vec{P}_f \equiv \vec{p}_f - \vec{p}_{\bar{f}}$

- For each combination, observable can be constructed as:

$$O_i^{\mathrm{T}} = \frac{1}{\sigma_{\mathrm{SM}}} \int [\mathrm{sign}(\mathcal{C}_i^{\mathrm{T}})] \frac{d\sigma}{d^3p_H\, d^3p_f}\, d^3p_H\, d^3p_f$$

$$= \frac{\sigma(\mathcal{C}_i^{\mathrm{T}} > 0) - \sigma(\mathcal{C}_i^{\mathrm{T}} < 0)}{\sigma_{\mathrm{SM}}}$$

Independent probe for Δa_Z



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

$O_1^{\rm T}$ receives contribution ONLY from Δa_Z.

Independent probe for Δa_Z

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

$$O_1^{\rm T} = \frac{\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)}{\sigma_{SM}}$$
$$= O_1^{\rm T}(\Delta a_Z), \text{ receives contribution ONLY from } \Delta a_Z.$$

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

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

• 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 $\mathcal{C}_1^{\mathrm{T}}$ we construct an azimuthal asymmetry:

$$\mathcal{A}_1^{\mathrm{T}} = \frac{\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)}{\sigma(\cos 2\phi_H > 0) + \sigma(\cos 2\phi_H < 0)}$$

$$= \mathcal{A}_1^{\mathrm{T}}(\Re(b_Z)), \text{ receives contribution ONLY from } \Re(b_Z).$$

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

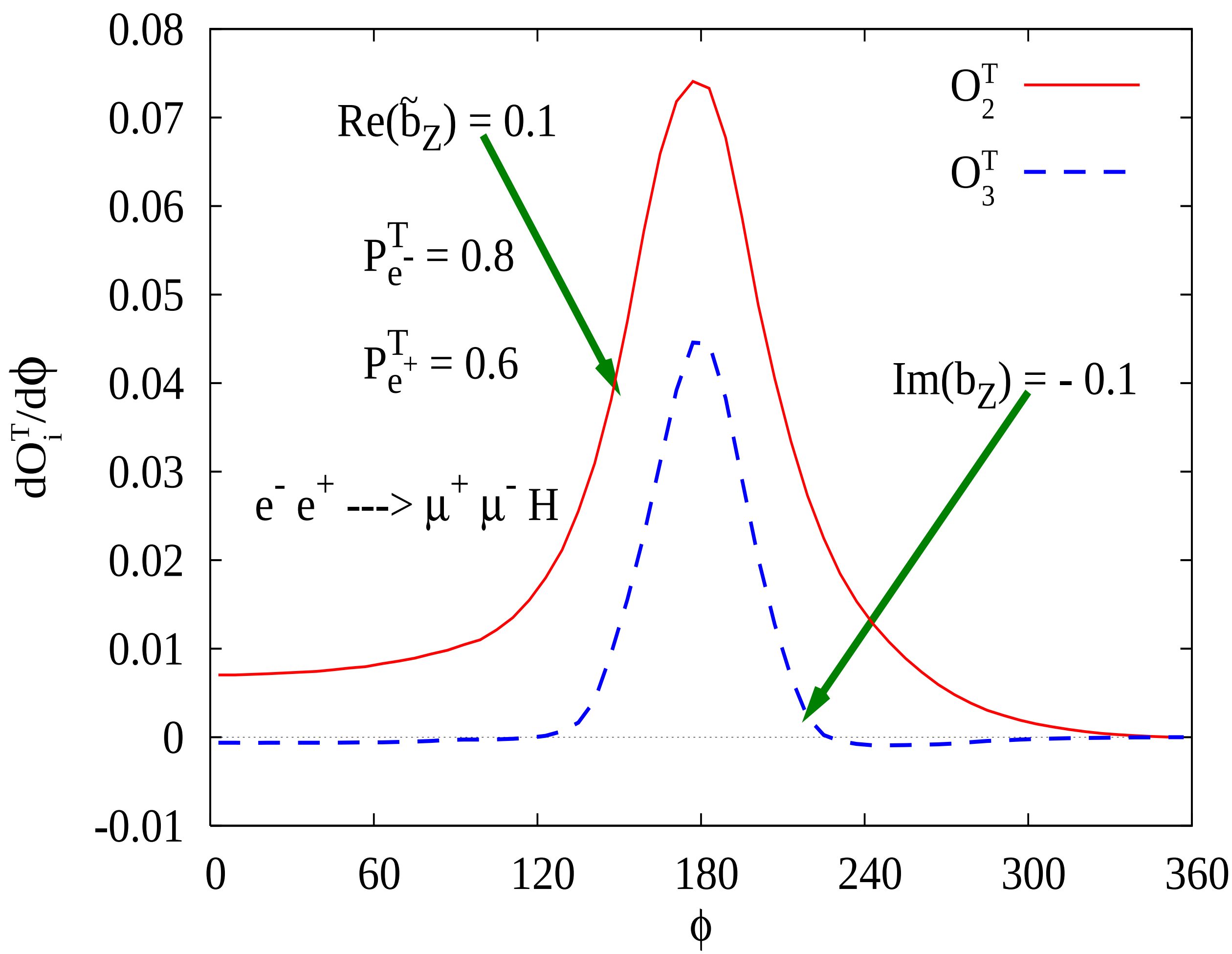
$$\simeq\ -\,0.43\,\left[\mathcal{P}_{e-}^T \mathcal{P}_{e+}^T\right]\ [1 - 9.5\,\Re(b_Z)]$$

(linear order in anomalous couplings)

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

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

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.

Going to higher $\sqrt{s}$?

- The ILC is planned to run at higher center of mass energies*.
- 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

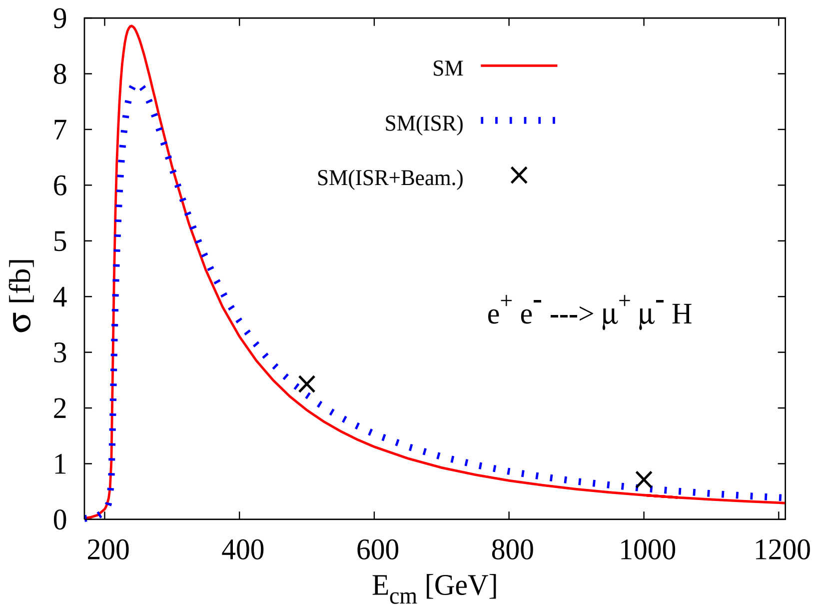
Note that No ISR/Beamstrahlung effect have been included here.

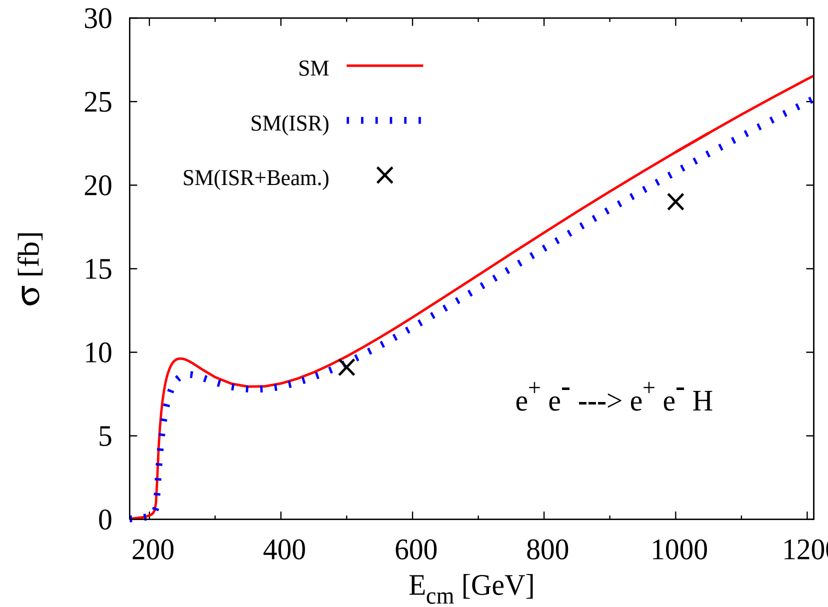
- Improvement in sensitivity to $\Re(\tilde{b}_Z)$ up to a factor 2.
- Little improvement in sensitivity to WWH anomalous couplings.
- No reduction in contamination from ZZH couplings to WWH vertex determination.

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

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.





- 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** *et al.*, **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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- **Use of τ polarization measurement can improve the sensitivity limit of one of the $\tilde{T}$-odd ZZH couplings by a factor up to 3–4.**
- Sensitivity can be enhanced using linearly polarized beams; 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.

Future Outlook

- Anomalous HVV couplings can be generated by models with an additional $U(1)$ gauge boson Z' compared to SM spectrum*.
- Anomalous trilinear gauge boson couplings in String theory models and anomalous $gt\bar{t}$ couplings in the Little Higgs model with T-parity have been analysed*.
- Anomalous coupling of the top quark and the Higgs boson has been studied in the context of the MSSM**.
- It would be worthwhile to analyse the probes of anomalous HVV, $Ht\bar{t}$ couplings using our developed procedure in the framework of a specific model.

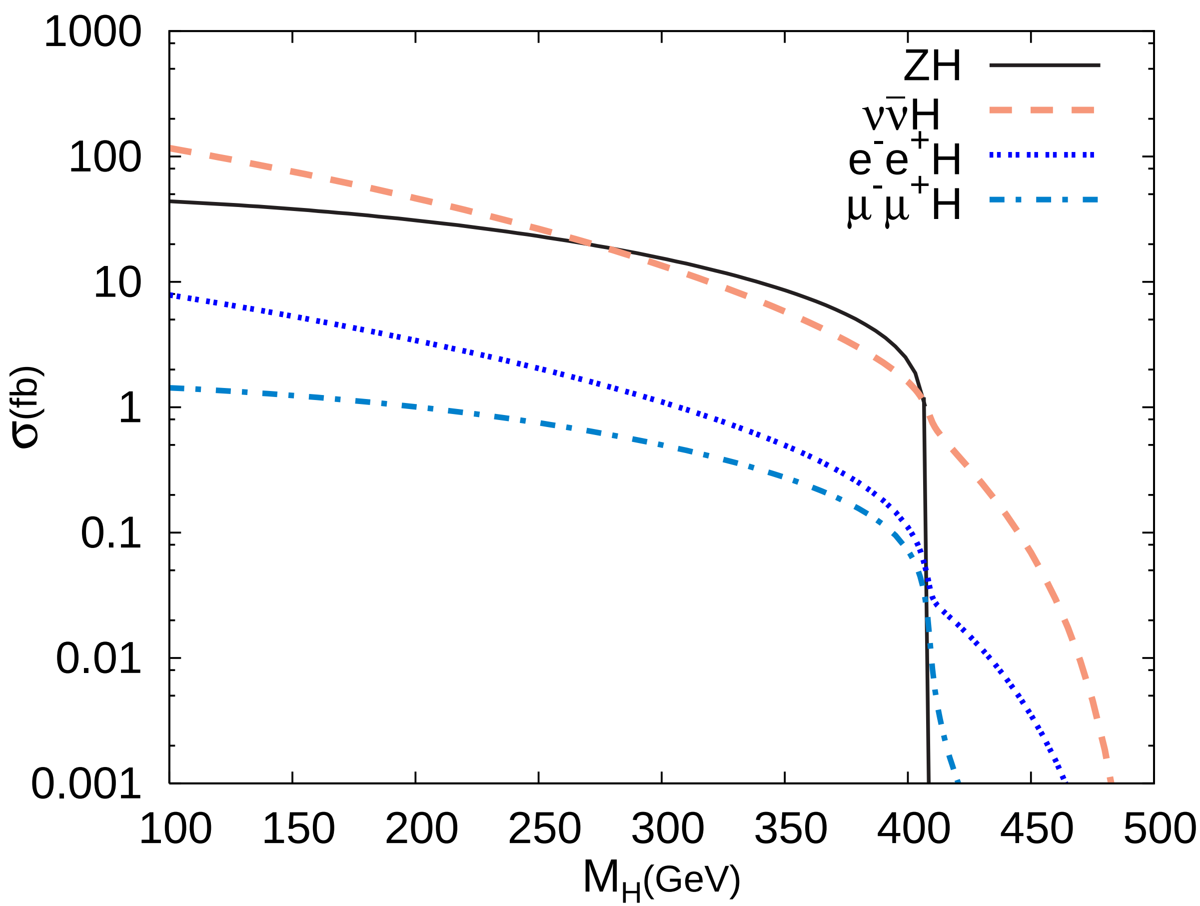
•* B. Grzadkowski and J. Wudka, Phys. Lett. B **364**, 49 (1995) [arXiv:hep-ph/9502415].

•* P. Anastasopoulos, M. Bianchi, E. Dudas and E. Kiritsis, JHEP **0611**, 057 (2006) [arXiv:hep-th/0605225]; J. Kumar, A. Rajaraman and J. D. Wells, Phys. Rev. D **77**, 066011 (2008) [arXiv:0707.3488 [hep-ph]]; R. Armillis, C. Coriano and M. Guzzi, JHEP **0805**, 015 (2008) [arXiv:0711.3424 [hep-ph]].

•** Q. H. Cao, C. R. Chen, F. Larios and C. P. Yuan, Phys. Rev. D **79**, 015004 (2009) [arXiv:0801.2998 [hep-ph]].

Higgs boson Production Rates

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



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

Observables for $R2$-cut: Transverse Beam Polarization

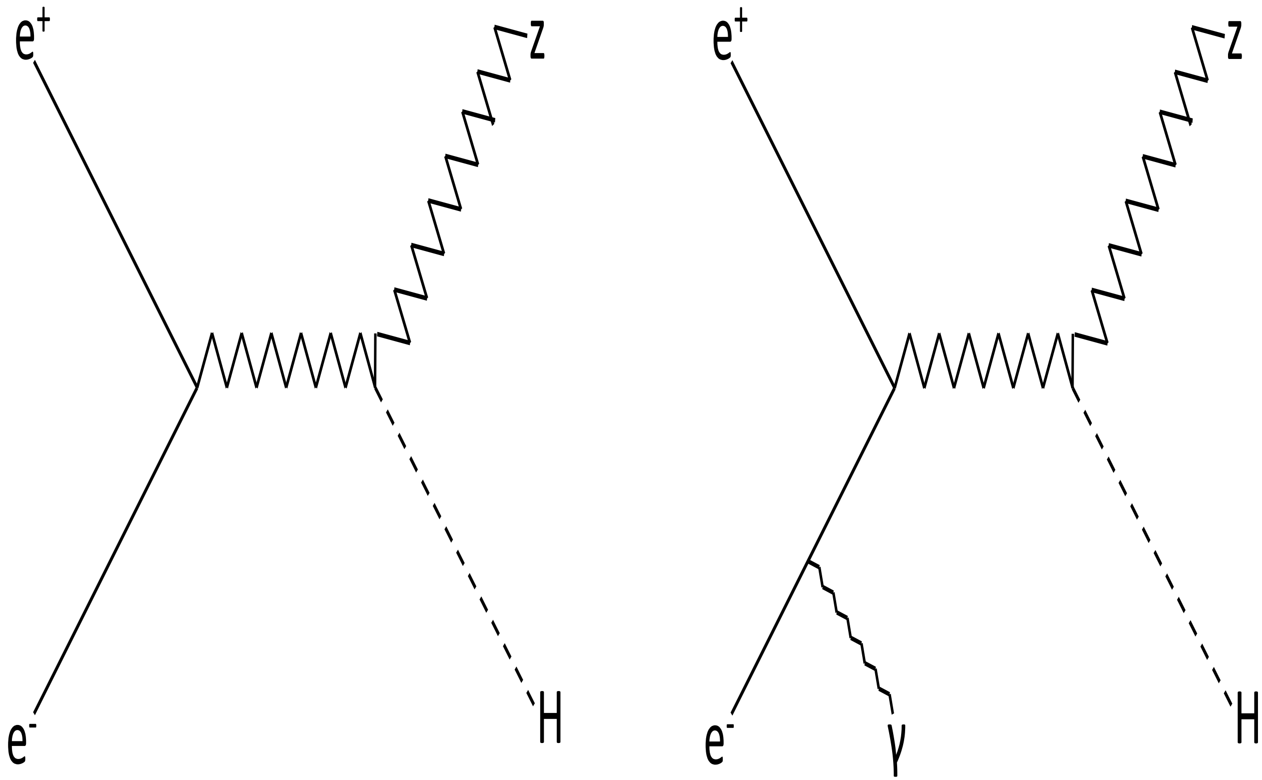
- Similar observables with $R2$-cut (de-selecting Z-pole) can be constructed using transversely polarized beams.
- The t-channel squared matrix element (MESQ) never includes both the spin projection factors $(1 + \gamma_5 \not{s}_{e^-})$ and $(1 + \gamma_5 \not{s}_{e^+})$ in the same trace.
- The MESQ for t-channel diagram does not have any transverse beam polarization dependent term*.
- The major additional contributions to the MESQ for the $R2$-cut comes from the interference of s- and t-channel diagrams.
- Observables, O^{T}_{1-3}, with $R2$-cut are less sensitive than those with $R1$-cut.

* This has been pointed out for t-channel SM diagram; can be understood as a is a consequence of electronic chiral symmetry of the SM;
K. i. Hikasa, Phys. Lett. B **143**, 266 (1984).

Effect of Transverse Beam Polarization: WWH case

- O_2^{T} and O_3^{T} require charge measurement of final state particles; cannot be considered for final state ν's.
- O_1^{T} can probe CP- and $\tilde{T}$-even anomalous WWH couplings.
- Transverse beam polarization does not affect the squared matrix element of the t-channel WW fusion diagram which includes the anomalous WWH couplings.
- Terms proportional to anomalous WWH couplings in O_1^{T} receive contribution only from the interference of t-channel diagram with the s-channel SM part.
- O_1^{T} is not expected to put stronger bounds on anomalous WWH couplings as compared to the unpolarized case.

Higgs boson production



Observations with unpolarized states

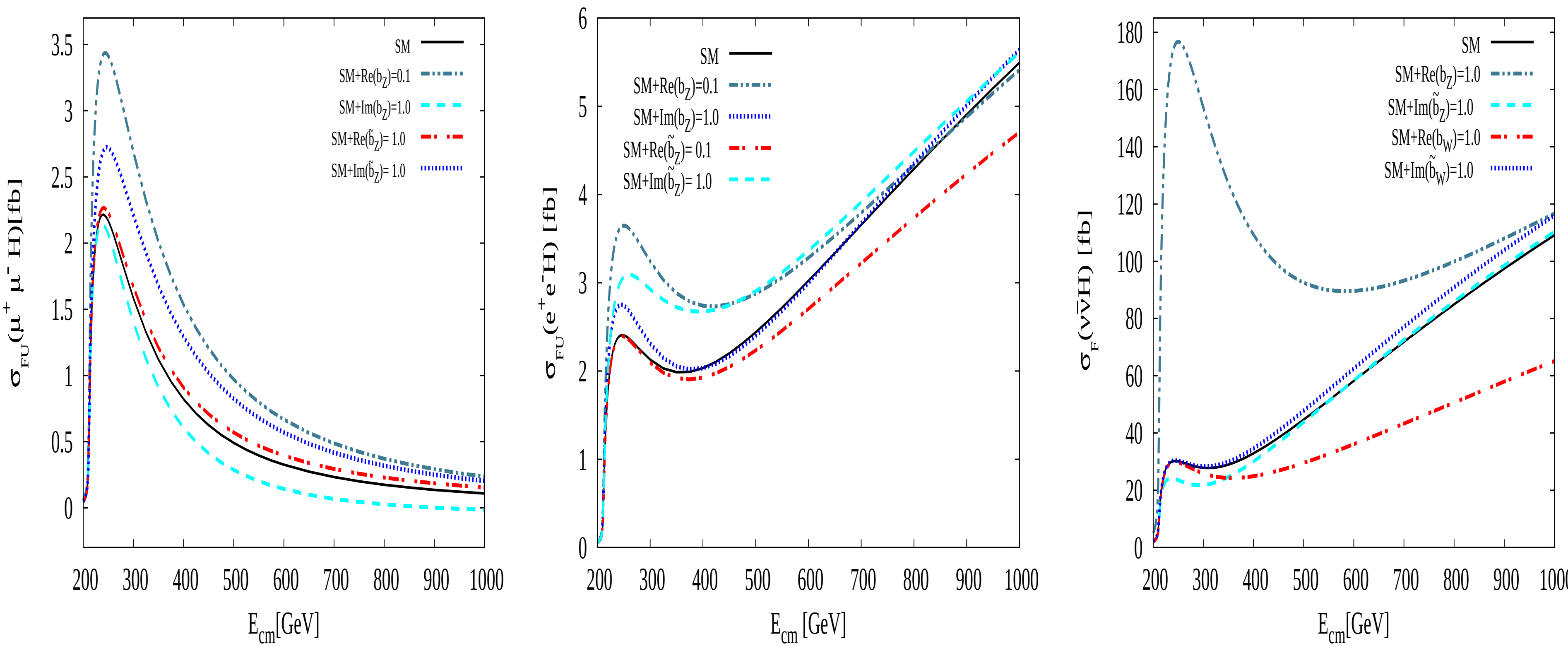
l_f (r_f) : left-(right-) handed coupling of the fermion to the Z-boson.

- For charged leptons (electron, muon, τ): $l_f \sim r_f$.

$l_e \sim$ -1 + 2 sin$^2\theta_W$, $r_e \sim$ 2 sin$^2\theta_W$, $\ell_e^2 - r_e^2 \sim$ 1 - 4 sin$^2\theta_W$.

- $A_{FB} \propto (\ell_e^2 - r_e^2)$: A) Improvement possible using polarized beams
- $A_{comb} \propto (\ell_e^2 + r_e^2)(r_f^2 - \ell_f^2)$: B) Possible gain in sensitivity with final state τ polarization
- $A_{UD} \propto (\ell_e^2 - r_e^2)(r_f^2 - \ell_f^2)$: Improvement possible combining analyses A and B

Partial cross sections

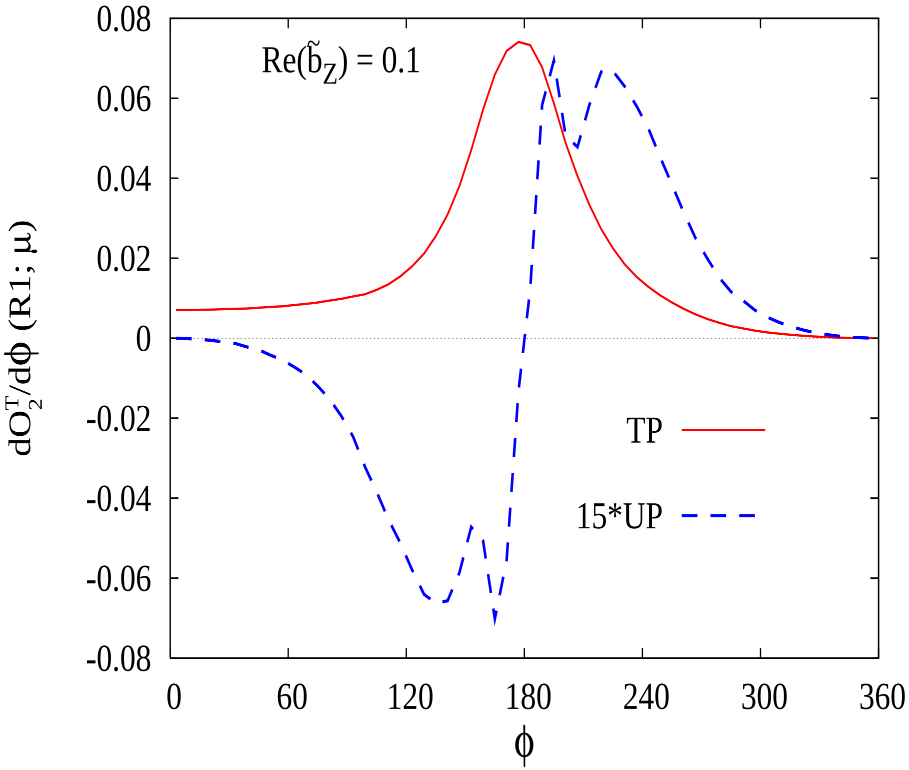


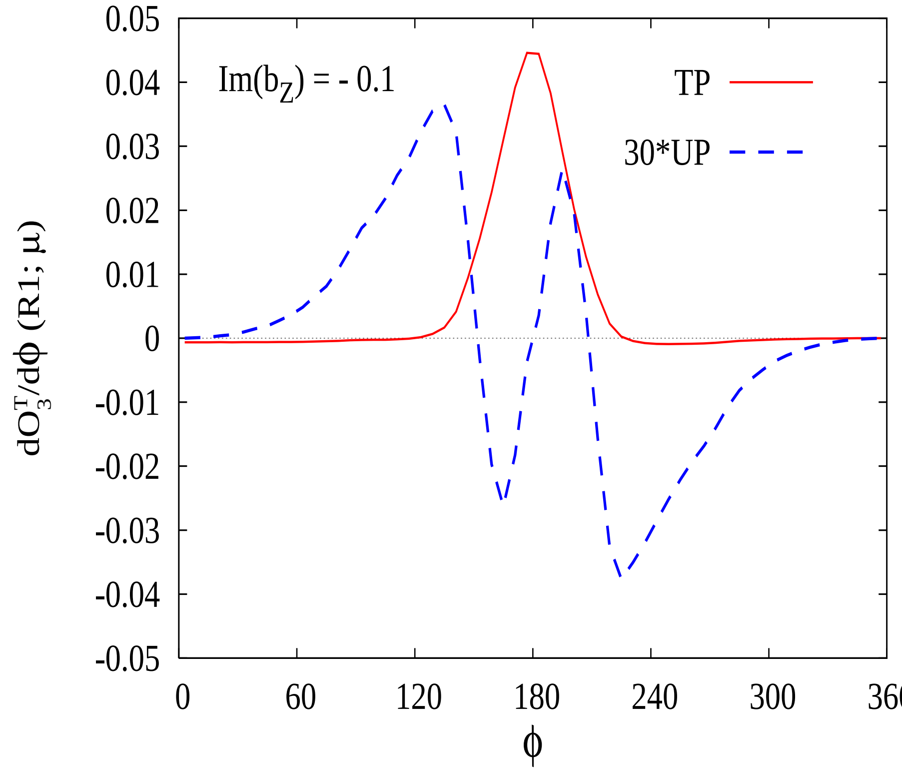
$F(B)$: H is in forward (backward) hemisphere w.r.t. the direction of initial e^-.

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

σ^{SM} = 4 σ^{SM}_{FU}, $\quad\quad$ σ^{SM} = 2 σ^{SM}_{F}.

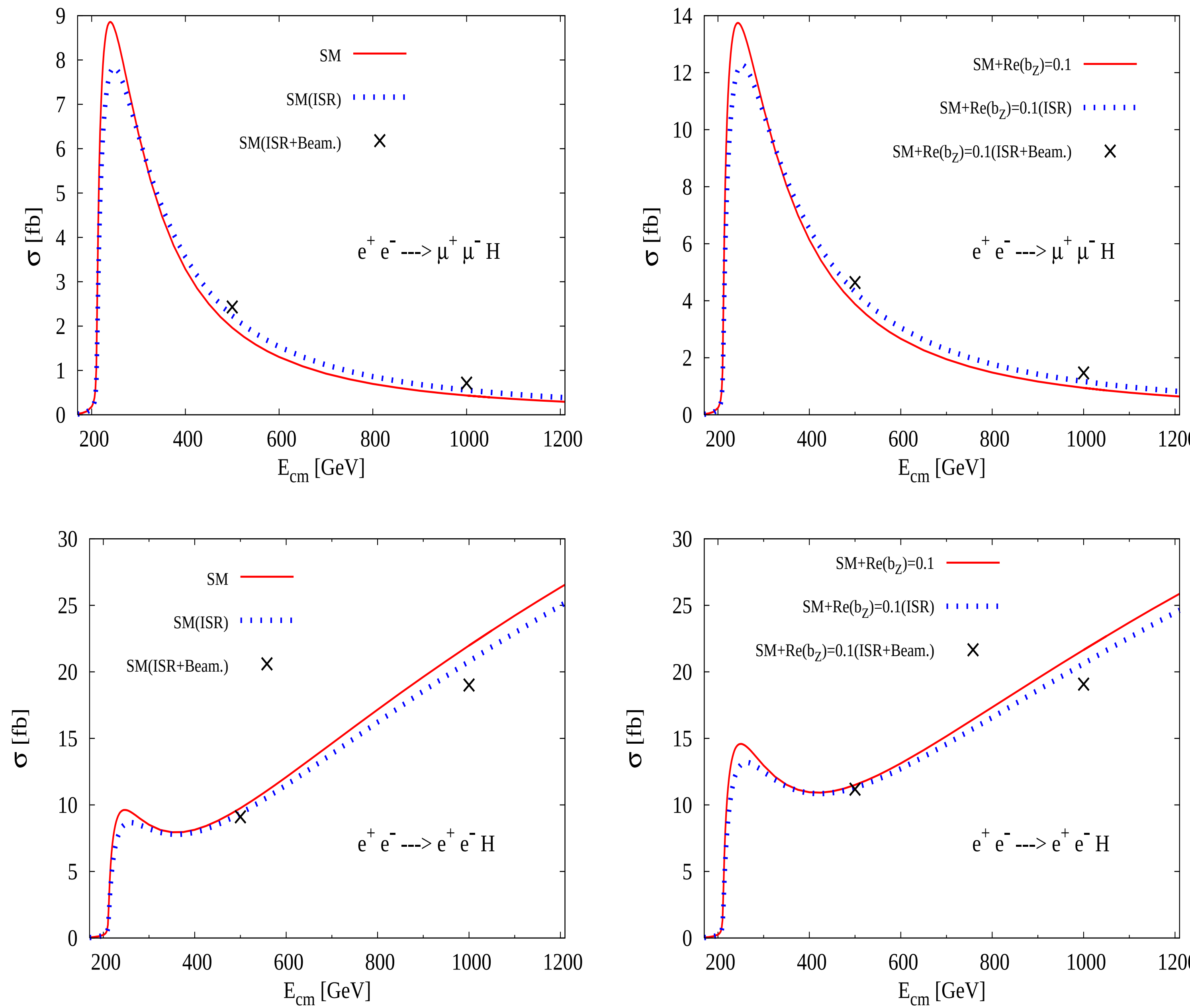
Probes for $\tilde{T}$-odd ZZH couplings





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

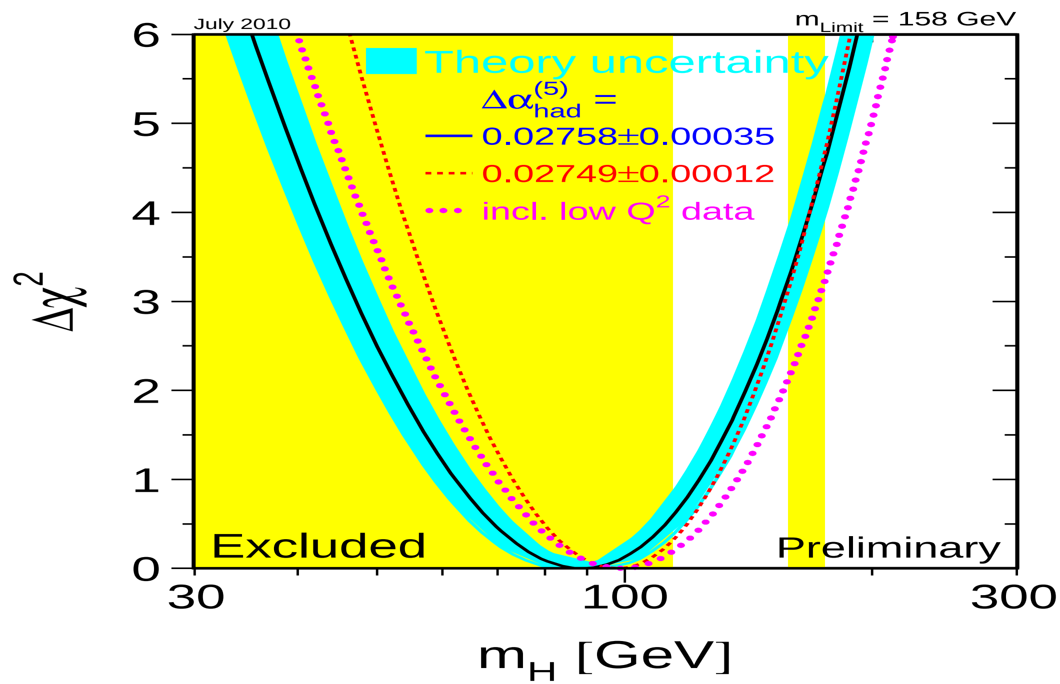
Effects of ISR and Beamstrahlung



Constraints on the mass of the SM Higgs boson

- Theoretical considerations $\Rightarrow M_H \lesssim 800$ GeV.
- Experimental informations:

- Electroweak precision measurements $\Rightarrow M_H \lesssim$ 158 GeV at 95% CL.



- Direct searches at the LEP $\Rightarrow M_H > 114.4$ GeV at 95% CL.
  Refs: Phys. Lett. B **565**, 61 (2003)[arXiv:hep-ex/0306033];
  http://lephiggs.web.cern.ch/LEPHIGGS.
- Tevatron measurements exclude $158 < M_H < 175$ GeV at 95% CL.
  Refs: arXiv:0903.4001 [hep-ex]; http://tevnphwg.fnal.gov.

Probes for WWH couplings

- Process: $e^+e^- \to \nu\bar{\nu}H$; Momenta of ν's cannot be used; construction of only two observables are possible.

Cross section:

$$\begin{aligned}
\sigma(R1';\nu) = \quad \sigma_1 \quad &= \quad [5.31 + 10.4\ \Delta a_Z + 0.207\ \Re(\Delta a_W) \\
&+ 49.7\ \Re(b_Z) - 1.26\ \Im(b_Z) + 0.331\ \Re(b_W) \\
&- 0.167\ \Im(\Delta a_W) + \ 0.525\ \Im(b_W)]\ \mathrm{fb} \\
\sigma(R2';\nu) = \quad \sigma_2 \quad &= \quad [35.6 + 0.111\ \Delta a_Z - 4.49\ \Re(b_Z) - 0.108\Im(b_Z) \\
&+ 71.0\ \Re(\Delta a_W) - \ 13.3\ \Re(b_W)]\ \mathrm{fb}
\end{aligned}$$

Forward-backward asymmetry:

$$\begin{aligned}
A_{FB}(R1';\nu) = \quad A^1_{FB}(c_H) \quad &= \quad \Big[-0.794\ \Re(\tilde{b}_Z) - 3.32\ \Im(\tilde{b}_Z) \\
&+0.197\ \Re(\tilde{b}_W) - 0.164\ \Im(\tilde{b}_W)\Big]\ /5.31 \\
A_{FB}(R2';\nu) = \quad A^2_{FB}(c_H) \quad &= \quad \Big[2.46\ \Im(\tilde{b}_Z) + 2.72\ \Im(\tilde{b}_W)\Big]\ /35.6
\end{aligned}$$