Role of polarization in probing anomalous VVH interactions at the ILC

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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 (ILC), the strength and nature of VVH interactions 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,

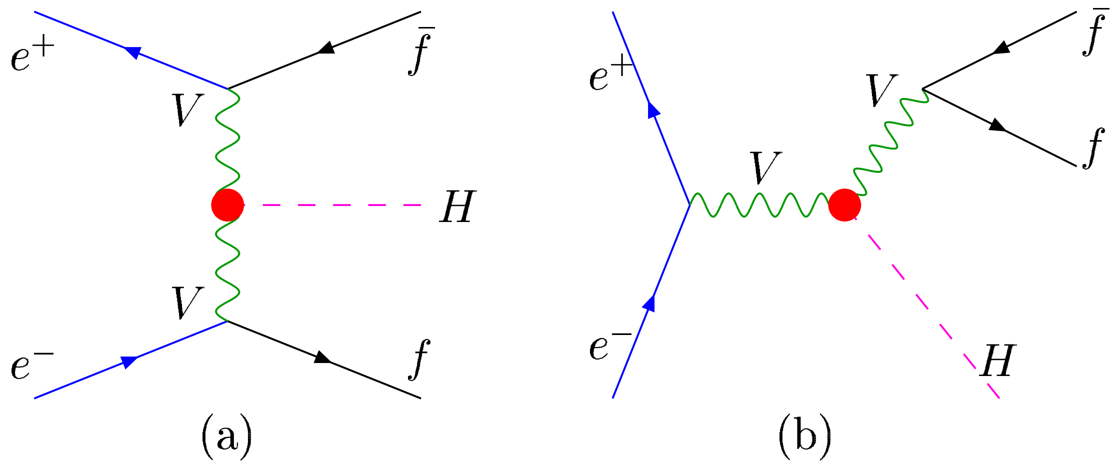
$$g_W^{SM} = e \cos\theta_w M_Z, \quad g_Z^{SM} = 2em_Z / \sin 2\theta_w,$$

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

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

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



$M_H = 120$ 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 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 $e^+e^- \to \nu_e \bar{\nu}_e H$.

Observations with Unpolarized states

Summary of results from:

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 $\Im(\tilde{b}_W)$.

Possible improvements ?

In this work we investigate:

- Use of Initial Beam Polarization.
- Improvement possible using final state τ Polarization.
- Use of final state τ Polarization for polarized beams.

An advance summary of our results:

- Use of longitudinal beam polarization improves sensitivity to $\Im(\tilde{b}_Z)$ by a factor up to 5–6.
- Using longitudinally polarized beams contamination from ZZH couplings in measurement of WWH vertex can be reduced.
- Use of transverse beam polarization helps to construct an independent probe of one of the CP- and $\tilde{T}$-even coupling.
- Measurement of final state τ polarization helps to obtain stronger limit on $\Im(b_Z)$ by a factor of about 3.
- Use of longitudinal (transverse) beam polarization along with measurement of final state τ polarization can improve on the sensitivity for $\Re(\tilde{b}_Z)$ ($\Im(b_Z)$).

Note: All the results are compared with unpolarized case*.

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

Kinematical cuts

- Plan: construct observables with definite $CP/\tilde{T}$ transformation properties using beam/final state polarizations and other kinematic variables to probe the anomalous couplings.
- 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^{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 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. , $P_{e^-} = +1$, $P_{e^+} = -1$.

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

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.

- For each combination, asymmetry can be constructed as:

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

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.

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:

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

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

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:

$$\begin{aligned} \mathcal{O}_{UD}(R1;\mu) \equiv A_{UD}^{-,+}(R1;\mu) - A_{UD}^{+,-}(R1;\mu) \\ = -\,2.01\,\Re(\tilde{b}_Z)\ , \end{aligned}$$

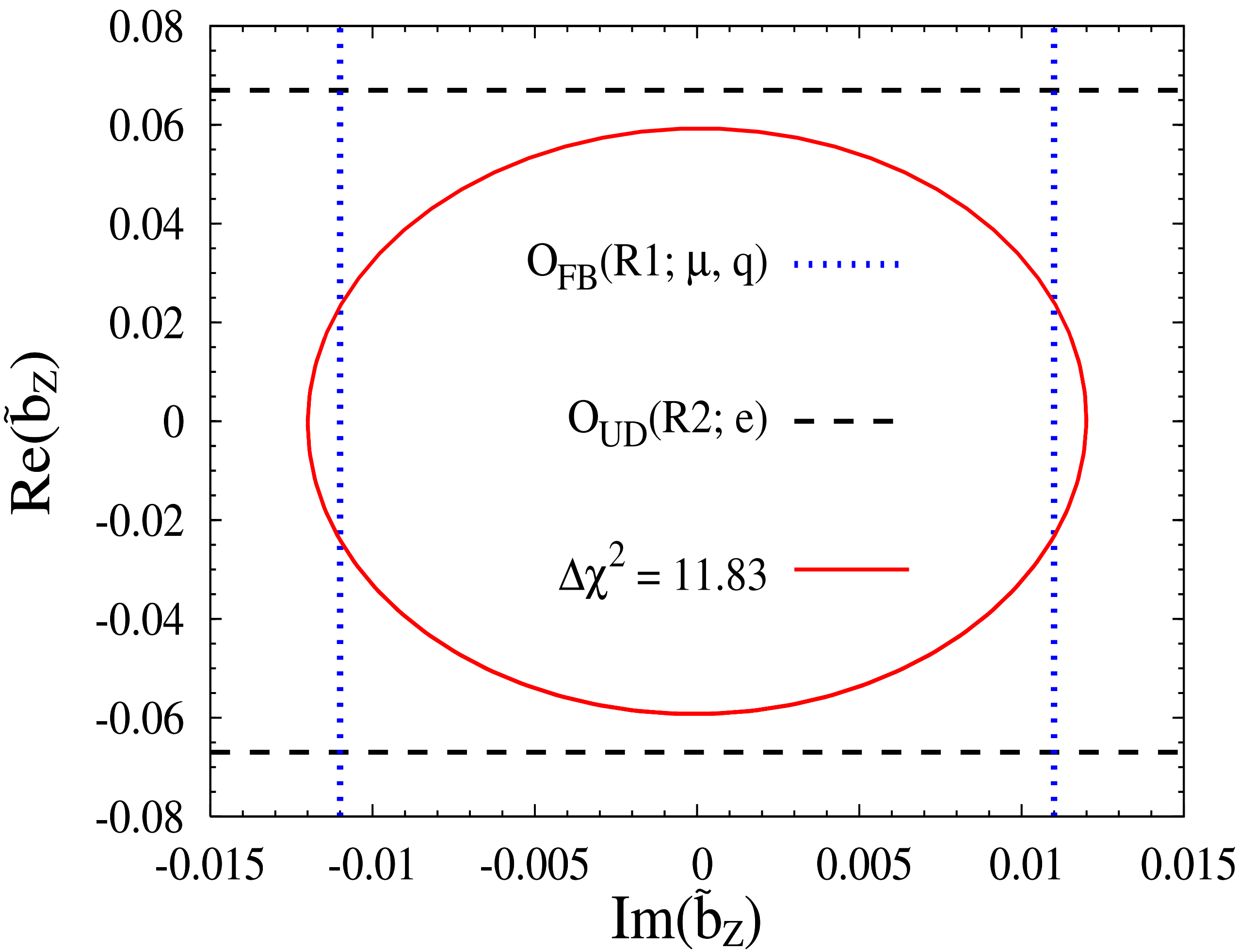
$$\mathcal{O}_{UD}(R1;\mu) => \ |\Re(\tilde{b}_Z)| \quad \leq \quad 0.17 \quad \text{for } \mathcal{L} = 125\,\text{fb}^{-1}.$$

Another observable:

$$\begin{aligned} \mathcal{O}_{UD}(R2;e) &= 2\,A_{UD}^{-,+}(R2;e) + A_{UD}^{+,-}(R2;e) + A_{UD}^{-,-}(R2;e) + A_{UD}^{+,+}(R2;e) \\ &= 5.72\,\Re(\tilde{b}_Z) - 0.005\,\Im(b_Z) \end{aligned}$$

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

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



Effect of longitudinal beam polarization: ZZH case

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

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).
  * 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).

Use of τ Polarization with unpolarized beams

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

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

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

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

A simple understanding of the results

- Unpolarized initial and final states:

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

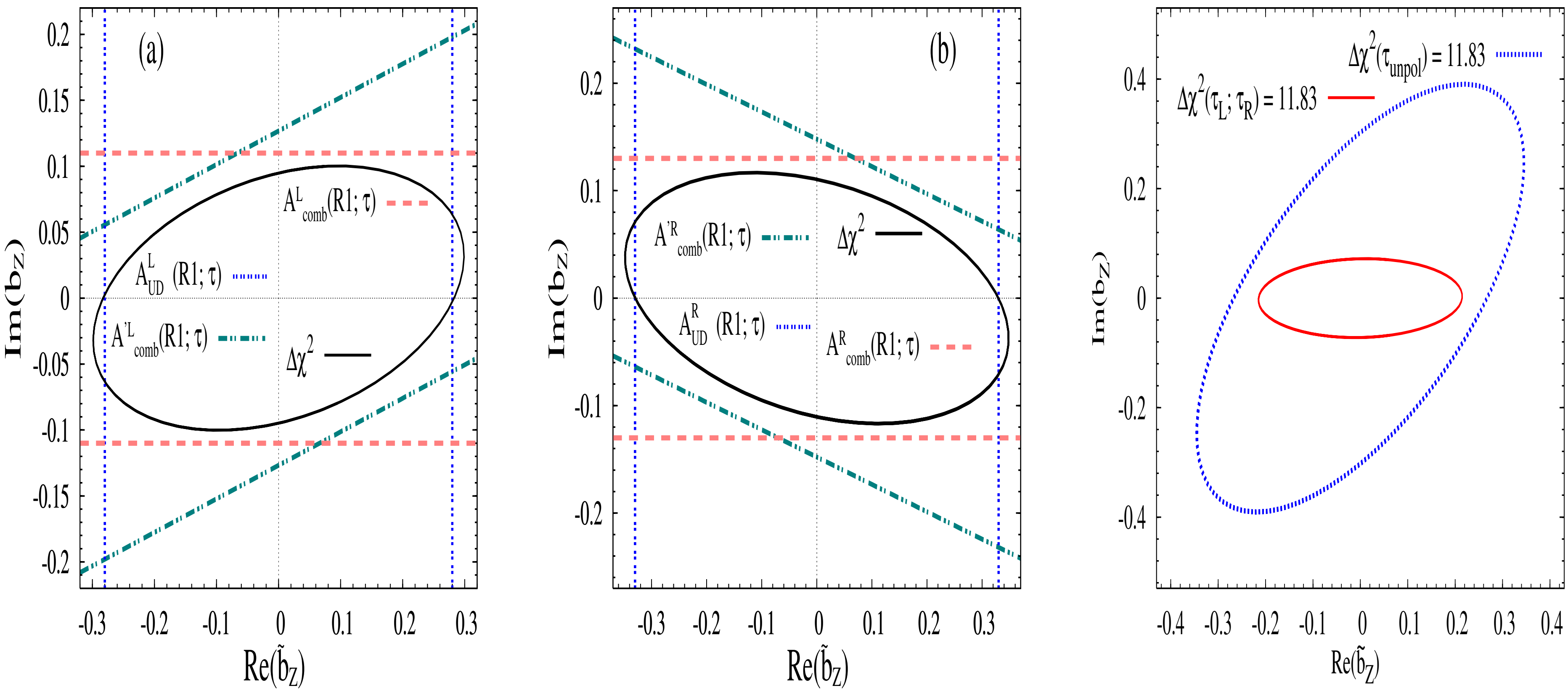
$$A_{UD} \propto (\ell_e^2 - r_e^2)(r_\tau^2 - \ell_\tau^2)$$

$\ell_\tau^2 > r_\tau^2 \Rightarrow$ 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 $\Re(\tilde{b}_Z)$*.

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

Use of τ Polarization: a χ^2-analysis



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

Combining analysis 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:

$$A_{UD}^{-;+}(R1;\tau_L) = \frac{-5.66\,\Re(\tilde{b}_Z)}{0.836},$$

$$A_{UD}^{-;+}(R1;\tau_R) = \frac{4.17\,\Re(\tilde{b}_Z)}{0.617}.$$

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

(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.

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

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

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

ID	$\mathcal{C}_i^{'}$	C	P	CP	$\tilde{T}$	$CP\tilde{T}$	Observable(O_i^{T})	Coupling
1	$(\vec{P}_f)_x * (\vec{P}_f)_y * (\vec{p}_H)_z$	$+$	$-$	$-$	$-$	$+$	O_1^{T}	$\Re(\tilde{b}_V)$
2	$(\vec{p}_H)_x * (\vec{p}_H)_y * (\vec{P}_f)_z$	$-$	$-$	$+$	$-$	$-$	O_2^{T}	$\Im(b_V)$
3	$(\vec{p}_H)_x^2 - (\vec{p}_H)_y^2$	$+$	$+$	$+$	$+$	$+$	O_3^{T}	a_V

- For each combination, asymmetry can be constructed as:

$$O_i^{\mathrm{T}} = \frac{1}{\sigma_{\mathrm{SM}}} \int [\mathrm{sign}(\mathcal{C}_i^{'})] \frac{d\sigma}{d^3p_H \, d^3p_f} \, d^3p_H \, d^3p_f$$

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

Asymmetries

Combination: $\mathcal{C}_3^{'} \equiv [(\vec{p}_{_H})_x^2 \ - \ (\vec{p}_{_H})_y^2]$ $(\propto \cos 2\phi_H)$: Probe for a_V.

Azimuthal asymmetry:

$$O_3^{\rm T} = \frac{\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)}{\sigma(\cos 2\phi_H > 0) + \sigma(\cos 2\phi_H < 0)} = \frac{\sigma(\mathcal{C}_3^{'} > 0) - \sigma(\mathcal{C}_3^{'} < 0)}{\sigma_{\rm SM}},$$

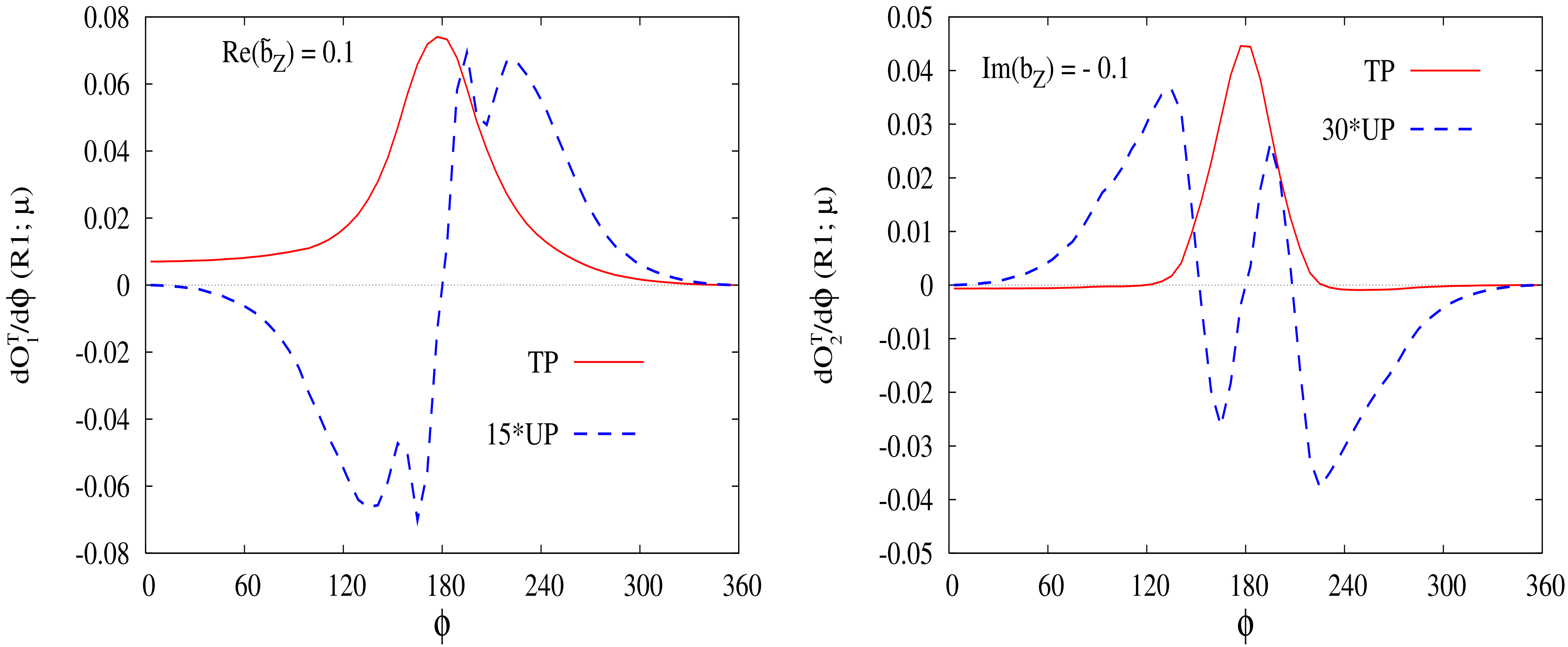
ϕ_H is the azimuthal angle of $\vec{p}_H$ defined with respect to XZ-plane.

$\mathcal{C}_2^{'} = (\vec{p}_{_H})_x * (\vec{p}_{_H})_y * (\vec{P}_f)_z$
$\propto [\vec{S}_e \cdot \vec{p}_H] * [(\vec{S}_e \times \vec{P}_e) \cdot \vec{p}_H] * [\vec{P}_e \cdot \vec{P}_f]$ is CP-even and $\tilde{T}$-odd;
$O_2^{\rm T}$ can probe $\Im(b_Z)$.

$\mathcal{C}_1^{'} = (\vec{P}_f)_x * (\vec{P}_f)_y * (\vec{p}_{_H})_z$
$\propto [\vec{S}_e \cdot \vec{P}_f] * [(\vec{S}_e \times \vec{P}_e) \cdot \vec{P}_f] * [\vec{P}_e \cdot \vec{p_H}]$ is CP-odd and $\tilde{T}$-odd;
$O_1^{\rm T}$ can constrain $\Re(\tilde{b}_Z)$.

$\vec{P}_e \equiv \vec{p}_{e^-} - \vec{p}_{e^+}$, $\vec{P}_f \equiv \vec{p}_f - \vec{p}_{\bar{f}}$, $\vec{S}_e \equiv \vec{s}_{e^-} - \vec{s}_{e^+}$.

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



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

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

- $$O_1^{\mathrm{T}}(R1 - \mathrm{cut}) \quad = \quad \begin{cases} \dfrac{[\mathcal{P}^T_{e^-}\,\mathcal{P}^T_{e^+}]^{*}\ [1.19\ \Re(\tilde{b}_Z) + 0.0236\ \Im(\tilde{b}_Z)]}{0.876} & (e^+e^-H) \\[2ex] \dfrac{[\mathcal{P}^T_{e^-}\,\mathcal{P}^T_{e^+}]\ [1.19\ \Re(\tilde{b}_Z)]}{0.861} & (\mu^+\mu^-H) \end{cases}$$

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

$$O_1^{\mathrm{T}}(R1;\mu) => \ |\Re(\tilde{b}_Z)| \quad \leq \quad 0.22 \quad \text{for } \mathcal{L} = 500\,\mathrm{fb}^{-1}.$$

$$O_2^{\mathrm{T}}(R1;\ \mu) \quad = \quad \frac{[\mathcal{P}^T_{e^-}\,\mathcal{P}^T_{e^+}]\ [-0.341\ \Im(b_Z)]}{0.861}$$

$$O_2^{\mathrm{T}}(R1;\mu) => \ |\Im(b_Z)| \quad \leq \quad 0.77 \quad \text{for } \mathcal{L} = 500\,\mathrm{fb}^{-1}.$$

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

A simple understanding of the results

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

$$A_{UD}\text{: Probe for } \Re(\tilde{b}_Z) : \propto (\ell_e^2 - r_e^2)(r_f^2 - \ell_f^2),$$
$$A_{comb}\text{: Probe for } \Im(b_Z)\text{: } \propto (\ell_e^2 + r_e^2)(r_f^2 - \ell_f^2).$$

- Observables with transversely polarized beams for R1-Cut:

$$O_1^{\mathrm{T}} \propto l_e\, r_e\, (\ell_f^2 + r_f^2),$$
$$O_2^{\mathrm{T}} \propto l_e\, r_e\, (\ell_f^2 - r_f^2).$$

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

- Using O_1^{T} for $R1$-cut (select Z-pole events) the sensitivity limit of $\Re(\tilde{b}_Z)$ can be improved by a a factor of 4-5.

- Note: Unpolarized measurements with $e^- e^+ H$ final state, with $R2$-cut (de-select Z-pole events) gives a better sensitivity to $\Re(\tilde{b}_Z)$*.

- But transverse beam polarization helps to construct an additional independent probe for $\Re(\tilde{b}_Z)$.

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

* This was for unpolarized initial and final states.

Independent probe for Δa_Z

- Combination: $\mathcal{C}_3' \equiv [(\vec{p}_H)_x^2 \;-\; (\vec{p}_H)_y^2]$ $(\propto \cos 2\phi_H)$: Probe for a_V.
  Azimuthal asymmetry:

$$O_3^{\rm T} \;=\; \frac{\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)}{\sigma(\cos 2\phi_H > 0) + \sigma(\cos 2\phi_H < 0)}$$
$$\;=\; \frac{1}{\sigma_{\rm SM}} \int [{\rm sign}(\mathcal{C}_3')] \frac{d\sigma}{d^3p_H d^3p_f} d^3p_H d^3p_f,$$

$$O_3^{\rm T}(R1;\ \mu) \;=\; \frac{[\mathcal{P}_{e^-}^T \mathcal{P}_{e^+}^T]\,[-0.368\,(\,1\;+\;2\,\Delta a_Z)]}{0.861}$$

$$|\Delta a_Z| \;\leq\; 0.35 \quad {\rm for}\ \mathcal{L} = 500\,{\rm fb}^{-1}.$$

- $O_3^{\rm T}$ receives contribution only from Δa_Z (not from $\Re(b_Z)$)*. This was not possible either with/without longitudinally polarized beams*.
- Quark final states can be considered to enhance the sensitivity of this observable by a factor of about 3 compared to that for final state μ's.

* **Biswal, Choudhury, Godbole and Mamta, Phys. Rev. D 79, 035012 (2009); for longitudinally polarized beams.**

* **Biswal, Choudhury, Godbole and Singh, Phys. Rev. D 73, 035001 (2006); for unpolarized states.**

* This has been also observed for the process $e^+e^- \rightarrow ZH$;
S. D. Rindani and P. Sharma, arXiv:0901.2821 [hep-ph].

Use of final state τ polarization for transversely polarized beams

- $O_2^{\rm T}$ for final state τ is proportional to $l_e\, r_e\, (\ell_\tau^2 - r_\tau^2)$ and is suppressed.
- Simultaneous use of transverse beam polarization and measurement of final state polarization may improve the sensitivity of this observable*.

$$O_2^{\rm T}(R1;\ \tau_L) \quad = \quad \frac{[\mathcal{P}^T_{e^-}\,\mathcal{P}^T_{e^+}]\ [-1.13\ \Im(b_Z)]}{0.495}$$

$$O_2^{\rm T}(R1;\ \tau_L) => \ |\Im(b_Z)| \quad \leq \quad 0.24 \quad \text{for} \ \ \text{40\% isolation efficiency.}$$

- Isolation of events with final state τ's in definite helicity state from events of transversely polarized beams with an efficiency of 40% can improve the sensitivity limit of $\Im(b_Z)$ by 30% as compared to the unpolarized case* .
- A similar discussion for a different observable using longitudinal beam polarization and measurement of final state τ polarization to probe ZZH vertex has been made before*.

* **Biswal, Choudhury, Godbole and Mamta, Phys. Rev. D 79, 035012 (2009); for longitudinally polarized beams.**

* **Biswal, Choudhury, Godbole and Singh, Phys. Rev. D 73, 035001 (2006); for unpolarized states.**

Effect of Transverse Beam Polarization: WWH case

- O_1^{T} and O_2^{T} are constructed using momenta of all the final state particles (f, $\bar{f}$, H); cannot be considered for final state ν's.
- O_3^{T} can constrain CP- and $\tilde{T}$-even anomalous WWH couplings.
- 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 of the t-channel WW fusion diagram which includes the anomalous WWH couplings does not have transverse beam polarization dependence factors*.
- Terms proportional to anomalous WWH couplings in O_3^{T} receive contribution only from the interference of t-channel diagram with the s-channel SM part.
- O_3^{T} is not expected to put stronger bounds on anomalous WWH couplings as compared to the unpolarized case.

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

Summary

- 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 *.

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

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Summary

- 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 *.
- Use of longitudinal beam polarization allows to construct probes for $\tilde{T}$-even WWH couplings virtually independent of the anomalous ZZH couplings.

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- Use of τ polarization measurement improves the limit of $\Im(b_Z)$ by a factor up to 3–4.
- The sensitivity limit on $\Re(\tilde{b}_Z)$ can be improved by a factor of about 2 with the use of final state τ polarization measurement along with longitudinally polarized beams.
- Using transversely polarized beams we can construct an independent probe of Δa_Z*.
- Use of transverse beam polarization along with measurement of final state polarization can improve the sensitivity of probe of $\Im(b_Z)$ as compared to the unpolarized case.

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Thank you !

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

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

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

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

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.

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

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

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

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

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

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

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_{T}, O'_{T} and $O^3{}_{\mathrm{T}}$ 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).