Signatures of anomalous VVH interactions at a Linear Collider

via Gauge Boson Fusion and Bjorken Process

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WWH/ZZH interactions

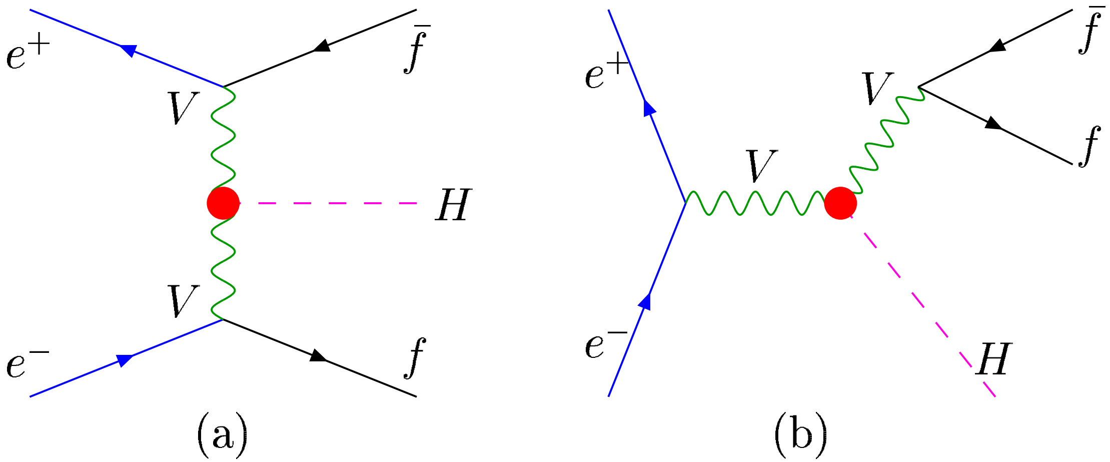
- VVH and $VVHH$ interactions are generated from the kinetic term of the Higgs field after symmetry breaking.

- The strength and structure of VVH interaction depends upon the quantum number of the Higgs field, such as CP, iso-spin, hypercharge etc.

- At a LC, the strength and nature of WWH and ZZH can be studied through Gauge Boson Fusion and Bjorken process.

Higgs production at e^+e^- collider

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



$M_H = 120$ GeV, $Br(H \rightarrow b\bar{b}) \approx 0.9$

b-quark detection efficiency $= 0.7$

$\sqrt{s} = 500$ GeV

Anomalous Higgs interactions

Most general VVH coupling structure:

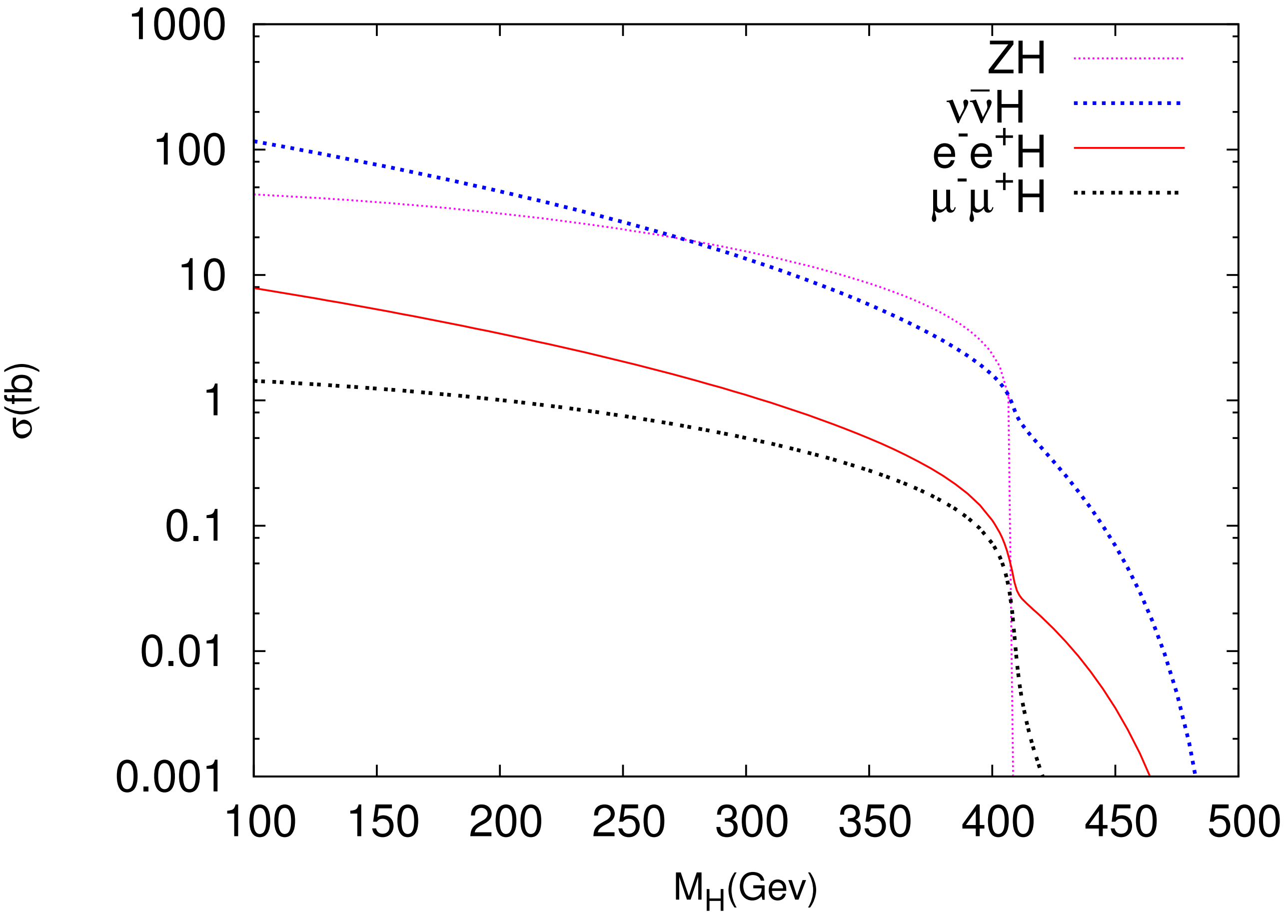
$$\Gamma_{\mu\nu} \;=\; g\left[a_V\; g_{\mu\nu} \;+\; \frac{b_V}{M^2}\,(k^1_\nu k^2_\mu - g_{\mu\nu}k^1.k^2) \;+\; \frac{\tilde{b}_V}{M^2}\,\epsilon_{\mu\nu\alpha\beta}k^{1\alpha}k^{2\beta}\right]$$

where,
$g_W^{SM} = e\cos\theta_w M_Z$ and $g_Z^{SM} = 2em_Z/\sin 2\theta_w$
$a_W^{SM} = a_Z^{SM} = 1.$

b_V and $\tilde{b}_V$ are complex in general and they are treated as small parameters i.e. terms quadratic in them are dropped.

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.

$e^+e^- \rightarrow \nu_e \bar{\nu}_e H$

- Final state has two neutrinos (missing energy). Only a few observables can be constructed.

- Interference of SM part of W fusion diagram with non-standard Bjorken diagram is large even away form Z pole. Cannot be separated by cutting out Z pole.

- Set of non-standard couplings involved

$$\{\Re(b_W), \Im(b_W), \Re(\tilde{b}_W), \Im(\tilde{b}_W), \Re(b_Z), \Im(b_Z), \Re(\tilde{b}_Z), \Im(\tilde{b}_Z)\}$$

- Need to fix/constrain b_Z and $\tilde{b}_Z$ using Bjorken process before studying WWH vertex.

Kinematical cuts

Variable		Limit	Description
θ_0	$=$	5°	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 to be detectable
$p_T^{\rm miss}$	$\geq$	15 GeV	For neutrinos to be detectable
$\Delta R_{q_1 q_2}$	$\geq$	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 have,

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

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

Momentum 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, $\Re(b_V)$
$\mathcal{C}_1$	$\vec{P}_e \cdot \vec{P}_f^+$	$-$	$+$	$-$	$+$	$-$	$\Im(\tilde{b}_V)$
$\mathcal{C}_2$	$[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-$	$+$	$-$	$-$	$-$	$+$	$\Re(\tilde{b}_V)$
$\mathcal{C}_3$	$\left[[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-\right]\left[\vec{P}_e \cdot \vec{P}_f^+\right]$	$-$	$-$	$+$	$-$	$-$	$\Im(b_V)$
$\mathcal{C}_4$	$\left[[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-\right]\left[\vec{P}_e \cdot \vec{p}_f\right]$	$\times$	$-$	$\times$	$-$	$\times$	$\Im(b_V)$, $\Re(\tilde{b}_V)$

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

Cross-sections

Cross-section in fb With $R1$ cut,

$$\begin{aligned}
\sigma(e^+e^-) &= 1.28 + 12.0\,\Re(b_Z) + 0.189\,\Im(b_Z) \\
\sigma(\mu^+\mu^-) &= 1.25 + 11.9\,\Re(b_Z) \\
\sigma(u\bar{u}/c\bar{c}) &= 2\;[4.25 + 40.2\,\Re(b_Z)] \\
\sigma(d\bar{d}/s\bar{s}) &= 2\;[5.45 + 51.6\,\Re(b_Z)]
\end{aligned}$$

Cross-section in fb with $R2$ cut,

$$\sigma(e^+e^-) = [4.76 - 0.147\,\Re(b_Z)]$$

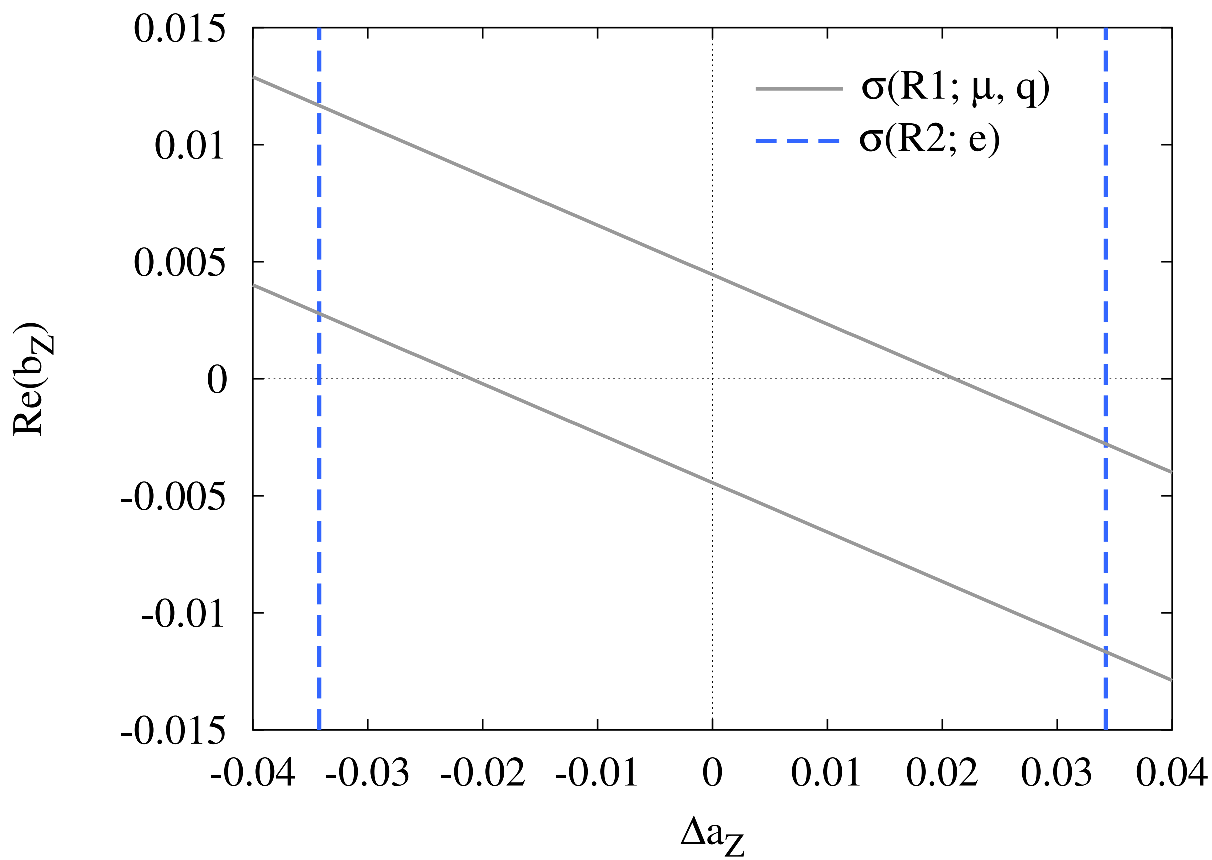
Using $\sigma(R1;\mu,q)$ cut, we get a 3σ limit with $L = 500$ fb^{-1}

$$|\Re(b_Z)| \leq 0.44 \times 10^{-2}$$

Cross-sections

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

$$\begin{aligned} \sigma(R1;\mu,q) &= [20.7\,(1+2\Delta a_Z) + 196\,\Re(b_Z)] = [20.7\,(1+\eta_1)] \\ \sigma(R2;e) &= [4.76\,(1+2\Delta a_Z) - 0.147\,\Re(b_Z)] \end{aligned}$$



$|\Delta a_Z| \le 0.034$

$|\eta_1| \le 0.042$

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

$$A^1 = A_{FB}(c_H) = \begin{cases} \dfrac{0.059\,\Re(\tilde{b}_Z) - 1.22\,\Im(\tilde{b}_Z)}{1.28} & (e^+e^-) \\ \dfrac{-1.2\,\Im(\tilde{b}_Z)}{1.25} & (\mu^+\mu^-) \\ \dfrac{-18.5\,\Im(\tilde{b}_Z)}{19.4} & (q\bar{q}) \end{cases}$$

For final state with μ and light quarks,
$\Rightarrow 3\sigma$ limit with $L = 500$ fb^{-1}

$$|\Im(\tilde{b}_Z)| \leq 0.038$$

Up-down asymmetry

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

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

$$A_{UD}(\phi_{e^-}) = \frac{-0.354\ \Re(\tilde{b}_Z) - 0.226\ \Im(\tilde{b}_Z)}{1.28}$$

$$A_{UD}(\phi_{\mu^-}) = \frac{-0.430\ \Re(\tilde{b}_Z)}{1.25}$$

$$A_{UD}(\phi_u) = \frac{-4.62\ \Re(\tilde{b}_Z)}{4.25}$$

$$A_{UD}(\phi_d) = \frac{-7.98\ \Re(\tilde{b}_Z)}{5.45}$$

$$A_{UD}^{R2}(\phi_{e^-}) = \frac{5.48\ \Re(\tilde{b}_Z)}{4.76}$$

$A_{UD}^{R2}(\phi_{e^-}) \Rightarrow 3\sigma$ limit with $L = 500$ fb^{-1} $|\Re(\tilde{b}_Z)| \leq 0.057$.

Polar-azimuthal asymmetry

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

$$A^3 \quad = \quad \frac{(FU) + (BD) - (FD) - (BU)}{(FU) + (BD) + (FD) + (BU)}$$

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.

Polar-azimuthal asymmetry

Correlator: $\mathcal{C}_4 = [[\vec{P}_e \times \vec{P}_f^+] \cdot \vec{P}_f^-][\vec{P}_e \cdot \vec{p}_f]$

$\tilde{T}$-odd, does not have a definite CP .

$\Re(\tilde{b}_z)$ and $\Im(b_Z)$ can be constrained simultaneously.

$$A^4 \quad = \quad \frac{(F'U) + (B'D) - (F'D) - (B'U)}{(F'U) + (B'D) + (F'D) + (B'U)}$$

$F'(B')$: Final state f 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.

Polar-azimuthal asymmetry

$$A_4^\mu = \frac{0.659\ \Im(b_Z) - 0.762\ \Re(\tilde{b}_Z)}{1.25} \equiv A(\theta_\mu, \phi_\mu)$$

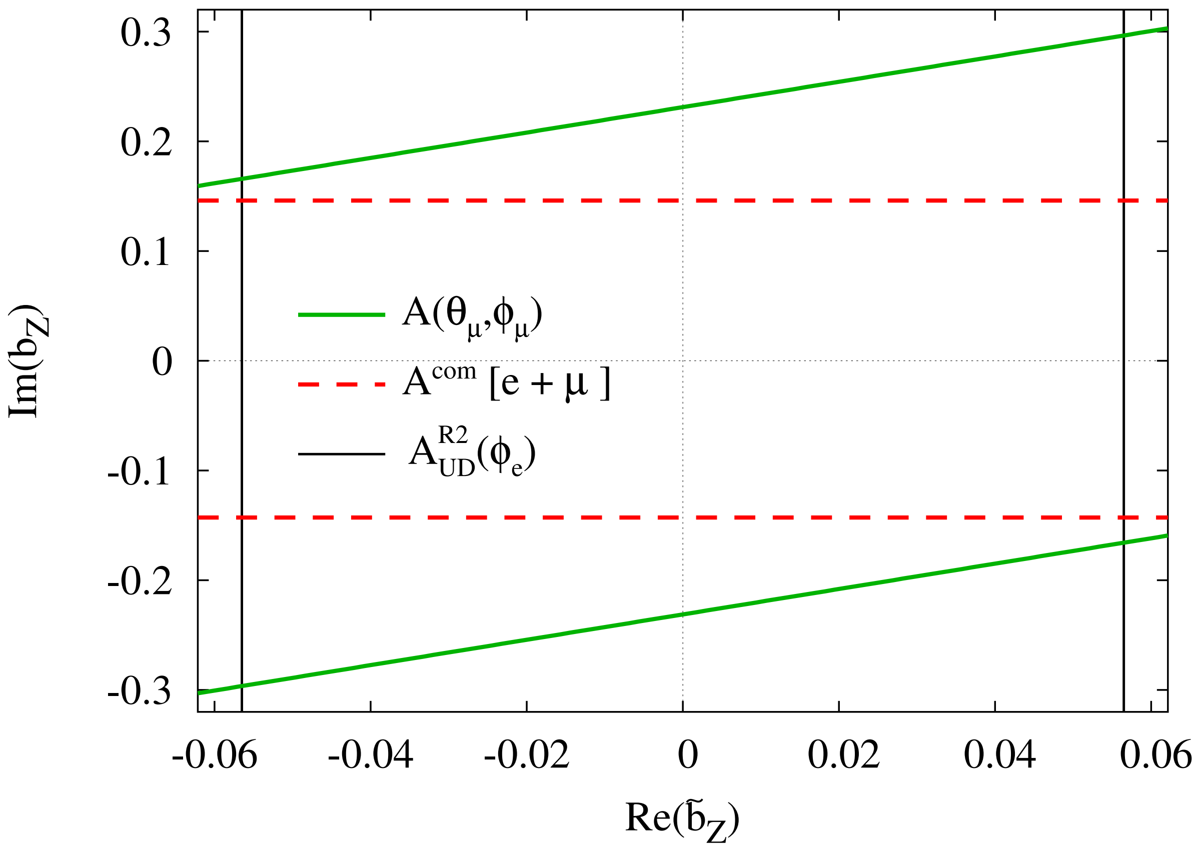
$$A_3^\mu = \frac{0.766\ \Im(b_Z)}{1.25} \equiv A^{com}(\mu)$$

$$A_3^e = \frac{0.757\ \Im(b_Z) - 0.048\ \Re(b_Z)}{1.28} \equiv A^{com}(e)$$

A_3^e and $A_3^\mu \Rightarrow 3\sigma$ limit with $L = 500$ fb^{-1}

$$|\Im(b_Z)| \leq 0.14,$$

Polar-azimuthal asymmetry



Limits on ZZH coupling

Coupling	3σ Bound	Observable used
$\lvert\Delta a_Z\rvert$	0.034	σ with $R2$ cut; $f = e^-$
$\lvert\Re(b_Z)\rvert$	0.0044 $(\Delta a_Z = 0)$; 0.012 $(\lvert\Delta a_Z\rvert = 0.034)$	σ with $R1$ cut; $f = \mu, q$
$\lvert\Im(b_Z)\rvert$	0.14	A_3 with $R1$ cut; $f = \mu^-, e^-$
$\lvert\Re(\tilde{b}_Z)\rvert$	0.057	$A_{UD}(\phi_{e^-})$ with $R2$ cut
$\lvert\Im(\tilde{b}_Z)\rvert$	0.038	$A_{FB}(c_H)$ with $R1$ cut; $f = \mu, q$

Limits on WWH coupling

Cross-section :

$$\begin{aligned}
\sigma_{R1} &= [7.69\,(1+\eta_1) - 1.89\,\Im(b_Z) + 0.458\,\Re(b_W) + 0.786\,\Im(b_W)] \\
\sigma_{R2} &= [52.1\,(1+2\,\Delta a) - 6.99\,\Re(b_Z) - 0.162\,\Im(b_Z) - 19.5\,\Re(b_W)] \\
\eta_1 &= 2\Delta a + 9.46\Re(b_z)
\end{aligned}$$

Forward-backward asymmetry :

$$\begin{aligned}
A^1_{FB}(c_H) &= \left[-1.20\,\Re(\tilde{b}_Z) - 7.11\,\Im(\tilde{b}_Z) + 0.294\,\Re(\tilde{b}_W) - 0.242\,\Im(\tilde{b}_W)\right]/7.69 \\
A^2_{FB}(c_H) &= \left[3.55\,\Im(\tilde{b}_Z) + 4.00\,\Im(\tilde{b}_W)\right]/52.1
\end{aligned}$$

Limits on WWH coupling

Coupling		Limit	Observable used
$\|\Delta a\|$	$\leq$	0.017	σ_{R2}
$\|\Re(b_W)\|$	$\leq$	0.094	σ_{R2}
$\|\Im(b_W)\|$	$\leq$	0.56	σ_{R1}
$\|\Re(\tilde{b}_W)\|$	$\leq$	1.4	$A^1_{FB}(c_H)$
$\|\Im(\tilde{b}_W)\|$	$\leq$	0.37	$A^2_{FB}(c_H)$

Coupling		$\Delta a = 0$	$\Delta a \neq 0$
$\|\Delta a\|$	$\leq$	–	0.034
$\|\Re(b_W)\|$	$\leq$	0.097	0.28
$\|\Im(b_W)\|$	$\leq$	1.4	1.4
$\|\Re(\tilde{b}_W)\|$	$\leq$	2.8	2.8
$\|\Im(\tilde{b}_W)\|$	$\leq$	0.40	0.40

Summary

- For ZZH vertex, coupling for the $\tilde{T}$ even operators can be constrained stongly using total rates, various asymmeries.

- The $\tilde{T}$ odd observables require charge mesurement of the final state fermions. Due to lack of light quark channels, we receive a relatively poor limit for $\tilde{T}$ odd couplings.

- For W boson fusion process, due to missing ν one cannot probe couplings of $\tilde{T}$ odd operators and we have limits only on couplings of $\tilde{T}$ even operators. Need transverse polarization of e^+/e^- beams to probe $\tilde{T}$-odd WWH couplings.

Thank you !