Probing of anomalous HZZ interactions at high energy colliders

Signaling the Arrival of the LHC Era

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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 (HVV, $Ht\bar{t}$) will be essential to establish it as the SM Higgs boson.
- The HZZ coupling can be explored at the LHC in the process: $H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$
- The tensor structure of HZZ and HWW couplings can also be studied in vector boson fusion and gluon fusion processes.

Anomalous Higgs interactions

- Most general HZZ coupling structure:

$$V_{\mu\nu}^{HZZ} = \frac{igm_Z}{\cos\theta_W}\left[a\,g_{\mu\nu} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\,\epsilon_{\mu\nu\alpha\beta}\,\frac{p^\alpha k^\beta}{m_Z^2}\right],$$

  where $p = q_1 + q_2$ and $k = q_1 - q_2$; q_1 and q_2 are the four-momenta of two Z bosons respectively.

- At tree-level SM, $a = 1$ and $b = c = 0$.

- a and b: associated with the coupling of a CP-even Higgs boson; c: associated with the CP-odd one.

- b and c can be complex in general.

Discrete transformation properties of couplings

	a	$\Re e(b)$	$\Im m(b)$	$\Re e(c)$	$\Im m(c)$
CP	$+$	$+$	$+$	$-$	$-$
$\tilde{T}$	$+$	$+$	$-$	$-$	$+$

- a and b are even under CP whereas c is odd under CP.
- a, $\Re e(b)$ and $\Im m(c)$ are even under $\tilde{\mathrm{T}}$ while $\Im m(b)$ and $\Re e(c)$ are odd under $\tilde{\mathrm{T}}$.

Strategy to construct asymmetries

- Strategy: Construct observables (asymmetries) with a given CP and $\tilde{\mathrm{T}}$ transformation properties that are sensitive to a single anomalous part of the HZZ vertex with the same CP and $\tilde{\mathrm{T}}$ transformation properties.
- For each momentum combination($\mathcal{C}_i$), asymmetry can be constructed as:

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

$\mathcal{C}_i$'s have definite CP and $\tilde{\mathrm{T}}$ transformation properties.

Probes of HZZ interaction

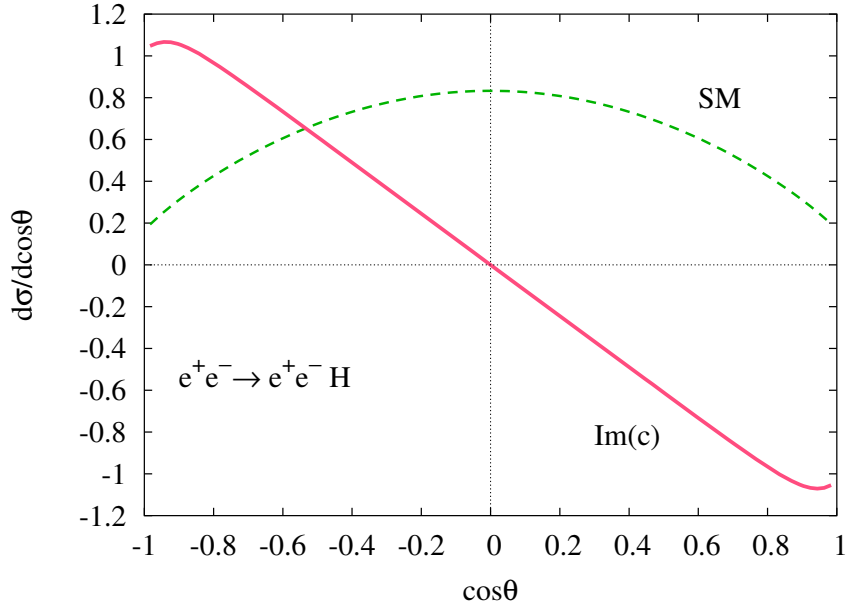
- We have developed general methods to probe the HVV interactions at the e^+e^- colliders with/without beam polarization*.
- The same strategy has been used in the context of the LHC**.

* **Biswal, Choudhury, Godbole et al, Phys. Rev. D 73, 035001 (2006)[arXiv:hep-ph/0509070]; arXiv:0809.0202 [hep-ph], submitted to Phys. Rev. D.**

** *Aspects of CP violation in the HZZ coupling at the LHC*, Godbole, Miller and Muhlleitner, JHEP **0712**, 031 (2007), [arXiv:0708.0458 [hep-ph]]

Example: Probe of HZZ interactions at the ILC

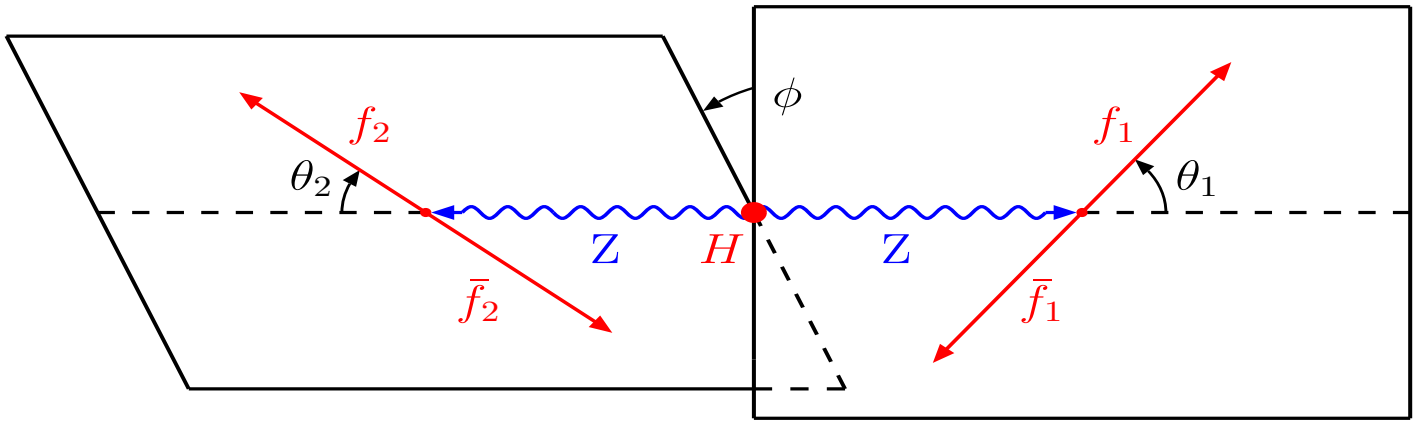
- Process: $e^+e^- \to f\bar{f}H$*.
- Combination: $[\vec{p}_{e^-} - \vec{p}_{e^+}] \cdot \vec{p}_H$ (CP-odd, $\tilde{T}$-even)
- Asymmetry: $A_{FB}(\cos\theta_H) = \frac{\sigma(\cos\theta_H>0)-\sigma(\cos\theta_H<0)}{\sigma(\cos\theta_H>0)+\sigma(\cos\theta_H<0)}$; can probe $\Im m(c)$. $F(B)$: H is in forward (backward) hemisphere w.r.t. the direction of initial e^-.



* Biswal, Choudhury, Godbole et al, Phys. Rev. D 73, 035001 (2006)[arXiv:hep-ph/0509070]

Example: Probes of HZZ interactions at the LHC

- Process: $H \to ZZ^{(*)} \to [f_1(p_1)\bar{f}_1(p_2)][f_2(p_3)\bar{f}_2(p_4)]$
- Notation:



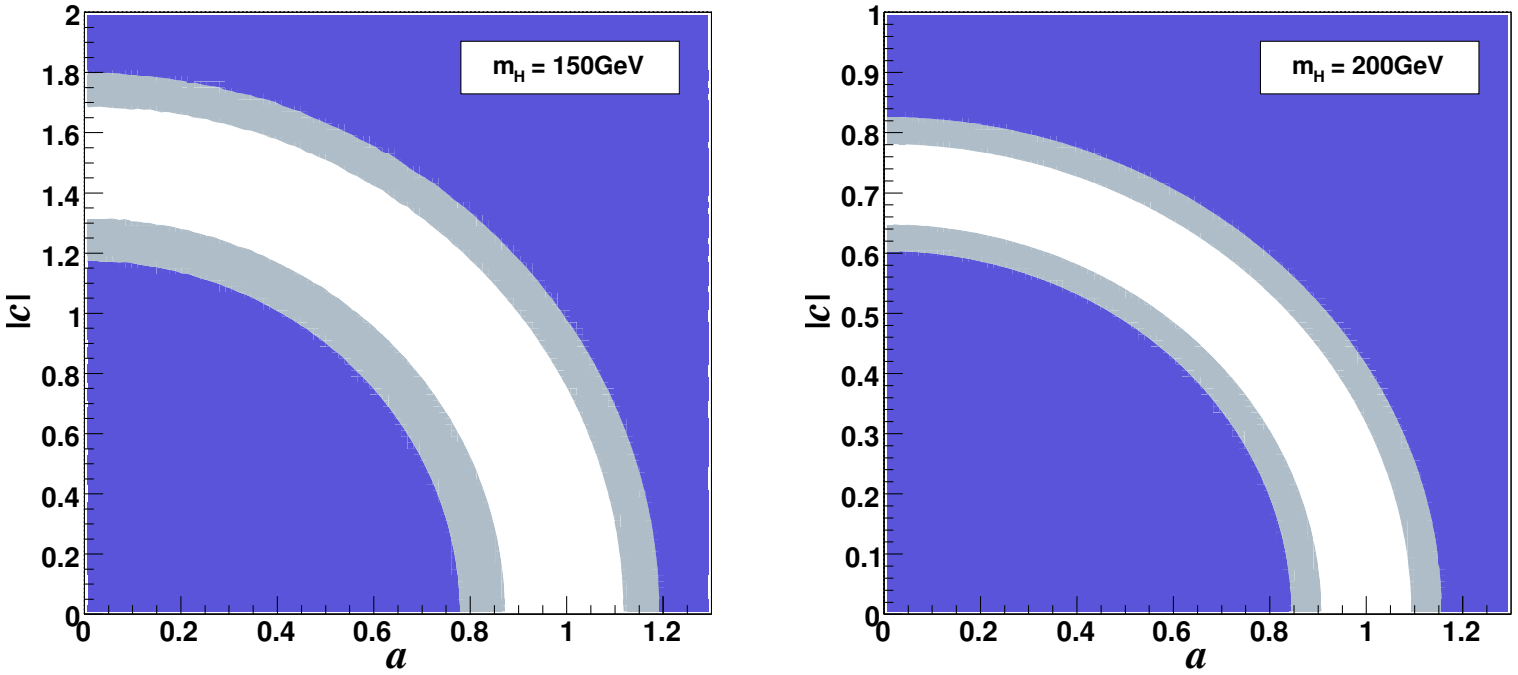
θ_1 and θ_2: polar angles of the fermions f_1, f_2 in the rest frame of the parent Z boson.

ϕ: azimuthal angle between the planes formed from the fermion pairs in the Higgs boson rest frame.

Sensitivity of total production

Dominant Higgs production process at the LHC:

$gg \to H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$, with $f = e$ or μ.



- In the white region one cannot distinguish the corresponding a, c values from the SM case $a = 1$, $c = 0$ at a significance more than $3\,\sigma$.
- Asymmetries are required to probe specific parts of the anomalous couplings directly.

Probe of $\Im m(c)$

- Process: $H \to ZZ^{(*)} \to [f_1(p_1)\bar{f}_1(p_2)][f_2(p_3)\bar{f}_2(p_4)]$
- Combination:

$$\mathcal{C}_1 \equiv \frac{(\vec{p}_{2Z} - \vec{p}_{1Z}) \cdot (\vec{p}_{3H} + \vec{p}_{4H})}{|\vec{p}_{2Z} - \vec{p}_{1Z}||\vec{p}_{3H} + \vec{p}_{4H}|} = \cos\theta_1 \ ,$$

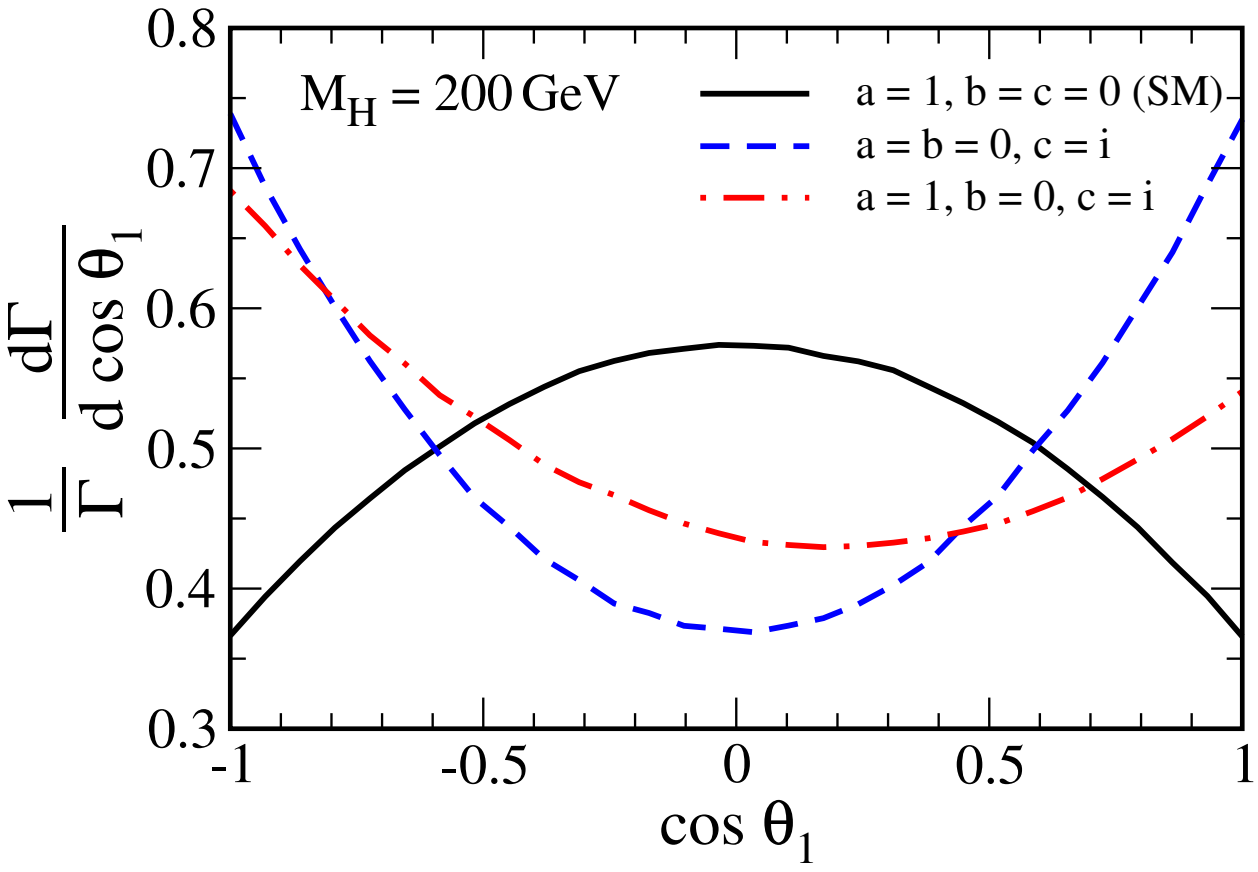
  $\vec{p}_{Z/H}$: is defined in the Z boson or Higgs boson rest frame.

- Asymmetry:

$$\mathcal{A}_1 = \frac{\Gamma(\cos\theta_1 > 0) - \Gamma(\cos\theta_1 < 0)}{\Gamma(\cos\theta_1 > 0) + \Gamma(\cos\theta_1 < 0)} \ .$$

- $\mathcal{A}_1$ is CP-odd and $\tilde{\mathrm{T}}$-even; probe of $\Im m(c)$.

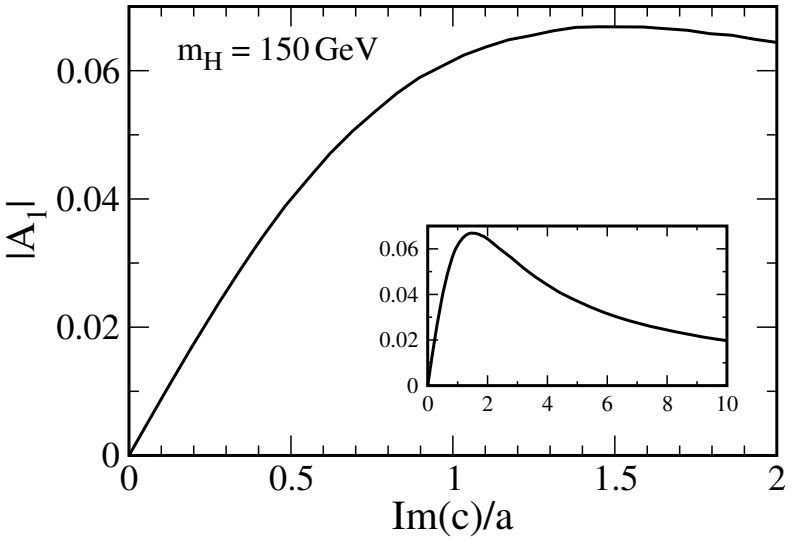
An asymmetry to probe $\Im m(c)$

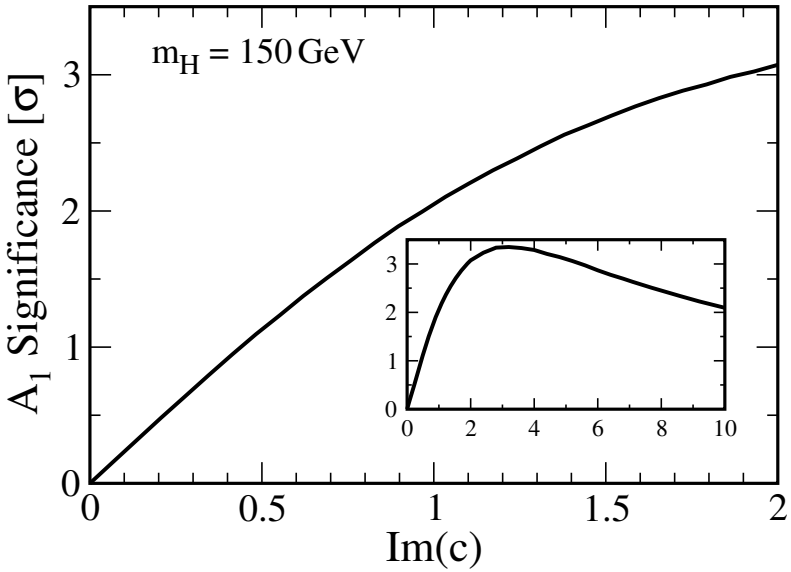


- An asymmetry about $\cos\theta_1 = 0$ for the CP violating case $(a = 1,\, b = 0,\, c = i)$.

Size & significance of the asymmetry ($\mathcal{A}_1$)

- Size of the asymmetry:





- $\mathcal{A}_1$ may provide *evidence* for CP violation (> $3\,\sigma$ deviation from the SM) if $\Im m(c) \gtrsim 1.9$ for $m_H = 150$GeV.
- Use of $b\bar{b}$ final state (i.e. $H \to ZZ \to l^+l^-jj$) can increase the sensitivity of $\mathcal{A}_1$.

An additional observable

- One can construct simple observables using scalar product/ scalar triple product of momenta of particles.
- Some of these observables are suppressed by small vector coupling of fermion to Z-boson.
- At the e^+e^- colliders we have used longitudinal beam polarization to overcome this suppression*.
- At the LHC one needs to construct more complicated observables to study the HZZ vertex**.

* **Biswal, Choudhury, Godbole and Mamta, arXiv:0809.0202 [hep-ph], submitted to Phys. Rev. D.**

** Godbole, Miller and Muhlleitner, JHEP **0712**, 031 (2007), [arXiv:0708.0458 [hep-ph]]

Observable to probe $\Re e(c)$

- One more combination:

$$\begin{aligned}\mathcal{C}_4 &= \sin^2\theta_1 \sin^2\theta_2 \sin\phi\cos\phi \ (\propto \ \sin 2\phi) \\ &= \frac{[(\vec{p}_{3H}\times\vec{p}_{4H})\cdot\vec{p}_{1H}][(\vec{p}_{3H}\times\vec{p}_{4H})\cdot(\vec{p}_{1H}\times\vec{p}_{2H})]}{|\vec{p}_{3H}+\vec{p}_{4H}|^2|\vec{p}_{1H}+\vec{p}_{2H}||\vec{p}_{3Z}-\vec{p}_{4Z}|^2|\vec{p}_{1Z}-\vec{p}_{2Z}|^2/16} \ .\end{aligned}$$

- Asymmetry:

$$\mathcal{A}_4 = \frac{\Gamma(\mathcal{C}_4>0)-\Gamma(\mathcal{C}_4<0)}{\Gamma(\mathcal{C}_4>0)+\Gamma(\mathcal{C}_4<0)}$$

- $\mathcal{A}_4$ is CP-odd and $\tilde{\mathrm{T}}$-odd; probe of $\Re e(c)$.

Dependence of the asymmetries on a, b, c

- List of observables(*):

Asymmetry	a	$\Re e(b)$	$\Im m(b)$	$\Re e(c)$	$\Im m(c)$
$\mathcal{A}_1$	x				x
$\mathcal{A}_2$	x	(x)	(x)	x	(x)
$\mathcal{A}_3$	x	(x)	(x)	x	(x)
$\mathcal{A}_4$	x			x	
$\mathcal{A}_5$	x	(x)	(x)	x	(x)
$\mathcal{A}_6$	x		x		

- (x) denotes a dependence which is suppressed if the additional form factors are small.

* **Table 1:** Godbole et al, JHEP **0712**, 031 (2007), [arXiv:0708.0458 [hep-ph]]

Summary

- We have developed general methods to probe the HVV interactions.
- Observables are constructed with a given CP and $\tilde{\mathrm{T}}$ transformation properties that can probe a single anomalous part of the HZZ vertex with the same CP and $\tilde{\mathrm{T}}$ transformation properties.
- General strategy has been used to probe the anomalous Higgs boson interactions at the LHC and at the e^+e^- colliders.
- Similar procedure has been followed to study the contact e^+e^-HZ interactions*.
- We have further studied the HVV interactions with transverse beam polarization.

* Rao and Rindani, Phys. Rev. D **77**, 015009 (2008) [arXiv:0709.2591 [hep-ph]].

Thank you !