Study of anomalous gauge-Higgs couplings using Z boson polarization at LHC

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WG2 and WG3 Extended Higgs Sector joint meeting

Motivations of the work

- What is the exact mechanism of the Electroweak symmetry breaking (EWSB)?
- Is the observed Higgs same as the one predicted by the Standard Model?

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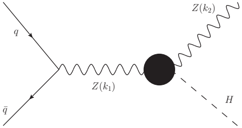
- Focus is to use the information contained in the polarization of EW gauge bosons to study its coupling to Higgs, using spin density matrix formalism.

Question:

How well can the polarization observables of a (massive) gauge boson probe the underlying physics ?

Goal of The Work

- Study anomalous ZZH vertex in the associated ZH production at LHC using the Z polarization observables



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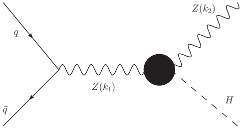

Figure: Feynman diagram for ZH production.

where the vertex $Z_\mu(k_1) \to Z_\nu(k_2)H$ takes the following Lorentz invariant structure

$$\Gamma^V_{\mu\nu} = \frac{g_w}{\cos\theta_w} m_z \left[a_z g_{\mu\nu} + \frac{b_z}{m_z^2}\left(k_{1\nu}k_{2\mu} - g_{\mu\nu}k_1.k_2\right) + \frac{\tilde{b}_z}{m_z^2}\epsilon_{\mu\nu\alpha\beta}k_1^\alpha k_2^\beta \right]$$

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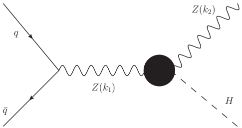

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- The form factors a_z, b_z and $\tilde{b}_z$ are in general complex. The first two couplings would correspond to CP-even terms in the interaction, while the third term is odd under CP.

Spin Density Matrix Formalism

- The 2×2 density matrix for spin-1/2 system-

$$\rho = \frac{1}{2} I + \frac{1}{2} \mathcal{P}.\sigma$$

where the Pauli matrices σ serve the basis for this expansion and $\mathcal{P}$ is called the **spin-polarization vector** for the ensemble

$$\mathcal{P} = \langle \sigma \rangle = Tr(\rho\sigma)$$

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- For spin-1, the elements of 3×3 spin density matrix written as

$$\rho = \frac{1}{3} I + \frac{1}{2} \sum_{M=-1}^{M=1} \langle S_M \rangle^* S_M + \sum_{M=-2}^{M=2} \langle T_M \rangle^* T_M$$

where $S_0 = S_3$,$S_{\pm 1} = \mp \frac{1}{\sqrt{2}}(S_1 + iS_2)$ are the spin operators in spherical basis and T_Ms are five rank 2 irreducible tensors built from S_M.

The production and decay density matrices

- For a generic process $AB \to VX$, $V \to f\bar{f}'$. Total rate with V being on-shell is given as

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_f} = \frac{2s+1}{4\pi}\sum_{\lambda,\lambda'} \mathbf{P}(\lambda,\lambda')\Gamma(\lambda,\lambda') \tag{1}$$

$\sigma = \sigma_V BR(V \to f\bar{f}')$ is the total cross section for production of V.

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- $\mathbf{P}(\lambda,\lambda')(\lambda,\lambda' = \pm 1, 0)$ is the polarization density matrix for V and in terms of a hermitian 3×3 production density matrix given as

$$\mathbf{P}(\lambda,\lambda') = \frac{1}{\sigma_v}\int \rho(\lambda,\lambda')d\Omega_v = \frac{1}{\sigma_v}\rho_T(\lambda,\lambda') \tag{3}$$

with σ_v the production cross section of V without decay.

$$\rho(\lambda,\lambda') = \frac{Phase\ space}{Flux}\mathcal{M}(\lambda)\mathcal{M}^\dagger(\lambda')$$

The production and decay density matrices

- For a generic process $AB \to VX$, $V \to f\bar{f}'$. Total rate with V being on-shell is given as

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_f} = \frac{2s+1}{4\pi}\sum_{\lambda,\lambda'} \mathbf{P}(\lambda,\lambda^{'})\Gamma(\lambda,\lambda^{'}) \quad (4)$$

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$$\rho(\lambda,\lambda^{'}) = \frac{Phase\ space}{Flux}\mathcal{M}(\lambda)\mathcal{M}^{\dagger}(\lambda^{'})$$

- **P** parametrized in terms of a vector $P = (P_x, P_y, P_z)$ and a rank 2 traceless,symmetric tensor T_{ij} (E.Leader," Spin in particle physics")

$$
\mathbf{P}(\lambda,\lambda^{'}) = \begin{bmatrix} \frac{1}{3}+\frac{P_z}{2}+\frac{T_{zz}}{\sqrt{6}} & \frac{P_x-iP_y}{2\sqrt{2}}+\frac{T_{xz}-iT_{yz}}{\sqrt{3}} & \frac{T_{xx}-T_{yy}-2iT_{yz}}{\sqrt{6}} \\ \frac{P_x+iP_y}{2\sqrt{2}}+\frac{T_{xz}+iT_{yz}}{\sqrt{3}} & \frac{1}{3}-\frac{2T_{zz}}{\sqrt{6}} & \frac{P_x-iP_y}{2\sqrt{2}}-\frac{T_{xz}-iT_{yz}}{\sqrt{3}} \\ \frac{T_{xx}-T_{yy}-2iT_{xy}}{\sqrt{6}} & \frac{P_x+iP_y}{2\sqrt{2}}-\frac{T_{xz}+iT_{yz}}{\sqrt{3}} & \frac{1}{3}-\frac{P_z}{2}+\frac{T_{zz}}{\sqrt{6}} \end{bmatrix} \quad (6)
$$

The decay density matrix with the interaction vertex $Vf\bar{f} : \gamma^{\mu}(c_L^f P_L + c_R^f P_R)$ in its rest frame is given by

$$
\Gamma(\lambda,\lambda^{'}) = \begin{bmatrix} \frac{(1+\cos^2\theta+2\alpha\cos\theta}{4} & \frac{\sin\theta(\alpha+\cos\theta)e^{i\phi}}{2\sqrt{2}} & \frac{(1-\cos\theta^2)e^{2i\phi}}{4} \\ \frac{\sin\theta(\alpha+\cos\theta)e^{-i\phi}}{2\sqrt{2}} & \frac{\sin^2\theta}{2} & \frac{\sin\theta(\alpha-\cos\theta)e^{i\phi}}{2\sqrt{2}} \\ \frac{(1-\cos\theta^2)e^{-2i\phi}}{4} & \frac{\sin\theta(\alpha-\cos\theta)e^{-i\phi}}{2\sqrt{2}} & \frac{(1+\cos^2\theta-2\alpha\cos\theta}{4} \end{bmatrix} \quad (7)
$$

$\alpha \rightarrow \frac{c_R^2-c_L^2}{c_R^2+c_L^2}$ for massless final state fermions

Therefore the angular distribution of the fermion in the rest frame of V

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_f} = \frac{3}{8\pi}[(\frac{2}{3} - \frac{T_{zz}}{\sqrt{6}}) - P_z \cos\theta] \tag{8}$$

$$+\sqrt{\frac{3}{2}}T_{zz}\cos^2\theta + (-P_x + 2\sqrt{\frac{2}{3}}T_{xz}\cos\theta)\sin\theta\cos\phi$$

$$+(-P_y + 2\sqrt{\frac{2}{3}}T_{yz}\cos\theta)\sin\theta\sin\phi$$

$$+(\frac{T_{xx} - T_{yy}}{\sqrt{6}})\sin^2\theta\cos 2\phi + \sqrt{\frac{2}{3}}T_{xy}\sin^2\theta\sin 2\phi$$

Extracting the various polarization parameters of V -

- At production level, by using the polarization matrix elements (R.Rahaman and R.K.Singh, Eur.Phys.J. C76 (2016) no.10, 539)

$$
\begin{aligned}
P_x &= \frac{\{\rho_T(+,0) + \rho_T(+,0)\} + \{\rho_T(0,-) + \rho_T(-,0)\}}{\sqrt{2}\sigma_v} \\
P_y &= \frac{-i\{[\rho_T(0,+) - \rho_T(+,0)] + [\rho_T(-,0) - \rho_T(0,-)]\}}{\sqrt{2}\sigma_v} \\
P_z &= \frac{[\rho_T(+,+)] - [\rho_T(-,-)]}{2\sigma_v}
\end{aligned}
$$

$$
\begin{aligned}
T_{xy} &= \frac{-i\sqrt{6}[\rho_T(-,+) - \rho_T(+,-)]}{4\sigma_v} \\
T_{xz} &= \frac{\sqrt{3}\{[\rho_T(+,0) + \rho_T(+,0)] - [\rho_T(0,-) + \rho_T(-,0)]\}}{\sqrt{2}\sigma_v} \\
T_{yz} &= \frac{-i\sqrt{3}\{[\rho_T(0,+) - \rho_T(+,0)] - [\rho_T(-,0) - \rho_T(0,-)]\}}{\sqrt{2}\sigma_v} \\
T_{xx} - T_{yy} &= \frac{\sqrt{6}[\rho_T(-,+) - \rho_T(+,-)]}{2\sigma_v} \\
T_{zz} &= \frac{\sqrt{6}}{2}\left\{\frac{[\rho_T(+,+)] - [\rho_T(-,-)]}{\sigma_v} - \frac{2}{3}\right\} = \frac{\sqrt{6}}{2}\left[\frac{1}{3} - \frac{\rho_T(0,0)}{\sigma_v}\right]
\end{aligned}
$$

Here T_{xx} and T_{yy} can be separately calculated by using the tracelessness property of T_{ij}.

- At decay level, by using partial integration of the differential distribution (**Eq. 4**) and then constructing various asymmetries.(R.Rahaman and R.K.Singh, Eur.Phys.J. C76 (2016) no.10, 539)

$$A_x = \frac{3\alpha P_x}{4} \equiv \frac{\sigma(\cos\phi > 0) - \sigma(\cos\phi < 0)}{\sigma(\cos\phi > 0) + \sigma(\cos\phi < 0)}$$

$$A_y = \frac{3\alpha P_y}{4} \equiv \frac{\sigma(\sin\phi > 0) - \sigma(\sin\phi < 0)}{\sigma(\sin\phi > 0) + \sigma(\sin\phi < 0)}$$

$$A_z = \frac{3\alpha P_z}{4} \equiv \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

$$A_{xz} = \frac{-2}{\pi}\sqrt{\frac{2}{3}}T_{xz} \equiv \frac{\sigma(\cos\theta\cos\phi < 0) - \sigma(\cos\theta\cos\phi > 0)}{\sigma(\cos\theta\cos\phi > 0) + \sigma(\cos\theta\cos\phi < 0)}$$

$$A_{yz} = \frac{2}{\pi}\sqrt{\frac{2}{3}}T_{yz} \equiv \frac{\sigma(\cos\theta\sin\phi > 0) - \sigma(\cos\theta\sin\phi < 0)}{\sigma(\cos\theta\sin\phi > 0) + \sigma(\cos\theta\sin\phi < 0)}$$

$$A_{x^2-y^2} = \frac{1}{\pi}\sqrt{\frac{2}{3}}(T_{xx} - T_{yy}) \equiv \frac{\sigma(\cos 2\phi > 0) - \sigma(\cos 2\phi < 0)}{\sigma(\cos 2\phi > 0) + \sigma(\cos 2\phi < 0)}$$

$$A_{xy} = \frac{2}{\pi}\sqrt{\frac{2}{3}}T_{xy} \equiv \frac{\sigma(\sin 2\phi > 0) - \sigma(\sin 2\phi < 0)}{\sigma(\sin 2\phi > 0) + \sigma(\sin 2\phi < 0)}$$

$$A_{zz} = \frac{3}{8}\sqrt{\frac{3}{2}}T_{zz} \equiv \frac{\sigma(\sin 3\theta > 0) - \sigma(\sin 3\theta < 0)}{\sigma(\sin 3\theta > 0) + \sigma(\sin 3\theta < 0)}$$

Helicity Amplitudes for $q + \bar{q} \to Z^{\alpha}(p) + H(k)$

$$q(p_1) + \bar{q}(p_2) \to Z^{\alpha}(p) + H(k)$$

In the limit of massless initial states

$$\begin{aligned}
M(-,+,\pm) &= \frac{g_w^2 m_z \sqrt{s}}{\cos^2\theta_w((s-m_z^2)+i\Gamma_z m_z)} \frac{(c_v+c_a)}{2} \left[1 - \frac{\sqrt{s}}{m_z^2}(E_z b_z \pm i\tilde{b_z} P_z)\right] \\
&\times \frac{(1 \mp \cos\theta)}{\sqrt{2}} \\
M(\mp,\pm,0) &= \frac{g_w^2 \sqrt{s}}{\cos^2\theta_w((s-m_z^2)+i\Gamma_z m_z)} \frac{(c_v \pm c_a)}{2} \left[E_z - \sqrt{s} b_z\right] \sin\theta \\
M(+,-,\pm) &= \frac{g_w^2 m_z \sqrt{s}}{\cos^2\theta_w((s-m_z^2)+i\Gamma_z m_z)} \frac{(c_v-c_a)}{2} \left[-1 + \frac{\sqrt{s}}{m_z^2}(E_z b_z \pm i\tilde{b_z} P_z)\right] \\
&\times \frac{(1 \pm \cos\theta)}{\sqrt{2}}
\end{aligned}$$

where the first two entries in M denote the helicities $+1/2$ and $-1/2$ of the quark and anti-quark respectively

$\sqrt{s}$ = total center of mass energy , $C_v = -0.5 + \sin^2\theta_w$, $C_a = -0.5$ where θ_w is the weak mixing angle.

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- we adopt the following representations for the polarization vectors of Z

$$\varepsilon_\mu(s = \pm 1) = \mp\frac{1}{\sqrt{2}}(0, -\cos\theta, \mp i, \sin\theta) \tag{9}$$

$$\varepsilon_\mu(s = 0) = \frac{1}{m_z}(\mid p_z \mid, -E_z\sin\theta, 0, -E_z\cos\theta) \tag{10}$$

where E_z,$\mid p_z \mid$ are the energy and momentum of the Z respectively,with θ being the polar angle made by Z with respect to quark momentum taken to be along the positive z axis.

$$
\begin{aligned}
\rho(\pm,\pm) &= \frac{g^4 m_Z^2 s}{8\cos^4\theta_W(\hat{s}-m_Z^2)^2}\left[(c_V+c_A)^2(1\mp\cos\theta)^2\right. \\
&\quad \left.+(c_V-c_A)^2(1\pm\cos\theta)^2\right]\left[1-2(\mathrm{Re}\ b_Z \mp \beta_Z \mathrm{Im}\ \tilde{b}_Z)\frac{E_Z\sqrt{\hat{s}}}{m_Z^2}\right. \\
&\quad +\frac{E_Z^2\hat{s}}{m_Z^4}|b_Z|^2 \mp \frac{2E_Z P_Z \hat{s}}{m_Z^4}(\mathrm{Im}\ \tilde{b}_Z\ \mathrm{Re}\ b_Z - \mathrm{Im}\ b_Z\ \mathrm{Re}\ \tilde{b}_Z) \\
&\quad \left.+\frac{P_Z^2\hat{s}}{m_Z^4}|\tilde{b}_Z|^2\right] \qquad (11) \\
\rho(0,0) &= \frac{g^4 E_Z^2 s}{2\cos^4\theta_W(s-m_Z^2)^2}\sin^2\theta\,(c_V^2+c_A^2)\left[1-2\mathrm{Re}\ b_Z\frac{\sqrt{s}}{E_Z}\right. \\
&\quad \left.+\frac{\hat{s}}{E_Z^2}|b_Z|^2\right] \qquad (12) \\
& \qquad (13)
\end{aligned}
$$

$$\rho(\pm,\mp) = \frac{g^4 m_Z^2 s}{4\cos^4\theta_W(\hat{s}-m_Z^2)^2}\sin^2\theta\,(c_V^2+c_A^2) \times \Bigg[1-2(\mathrm{Re}\ b_Z \pm i\beta_Z \mathrm{Re}\ \tilde{b}_Z)\frac{E_Z\sqrt{s}}{m_Z^2}+\frac{E_Z^2\hat{s}}{m_Z^4}|b_Z|^2 \pm i\frac{2E_Z P_Z\hat{s}}{m_Z^4} (\mathrm{Im}\ \tilde{b}_Z\ \mathrm{Im}\ b_Z + \mathrm{Re}\ b_Z\ \mathrm{Re}\ \tilde{b}_Z) - \frac{2P_Z^2\hat{s}}{m_Z^4}|\tilde{b}_Z|^2\Bigg] \quad (14)$$

$$\rho(\pm,0) = \frac{g^4 m_Z E_Z s}{4\sqrt{2}\cos^4\theta_W(\hat{s}-m_Z^2)^2}\sin\theta \times \left[(c_V+c_A)^2(1\mp\cos\theta)-(c_V-c_A)^2(1\pm\cos\theta)\right] \times \Bigg[1-\mathrm{Re}\ b_Z\sqrt{\hat{s}}\frac{(E_Z^2+m_Z^2)}{E_Z m_Z^2} - i\sqrt{\hat{s}}\frac{E_Z}{m_Z^2}\left(\mathrm{Im}\ b_Z\ \beta_Z^2 \pm \tilde{b}_Z\beta_Z\right) \mp\frac{\hat{s}}{m_Z^2}|b_Z|^2 \pm \frac{\hat{s}P_Z}{m_Z^2 E_Z}(\mathrm{Im}\ b_Z + i\mathrm{Re}\ b_Z)(\mathrm{Re}\ \tilde{b}_Z + i\mathrm{Im}\ \tilde{b}_Z)\Bigg] \quad (15)$$

where $\beta_Z = |\vec{p}_Z|/E_Z$ is the velocity of the Z in the c.m frame.

Sensitivities at $\sqrt{s} = 14$ TeV LHC

Observable	Coupling	Limit ($\times 10^{-3}$)
σ	Re b_Z	0.70
A_x	Re b_Z	136
A_y	Re $\tilde{b}_Z$	37.9
A_z	Im $\tilde{b}_Z$	13.5
A_{xy}	Re $\tilde{b}_Z$	9.53
A_{yz}	Im b_Z	16.5
A_{xz}	Im $\tilde{b}_Z$	13.3
$A_{x^2-y^2}$	Re b_Z	24.4
A_{zz}	Re b_Z	6.88

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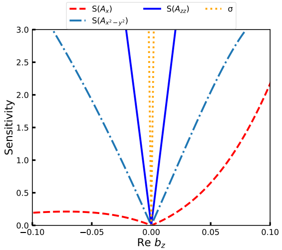
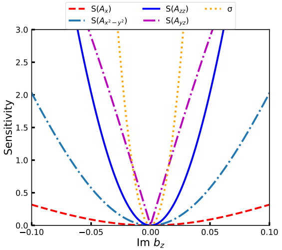
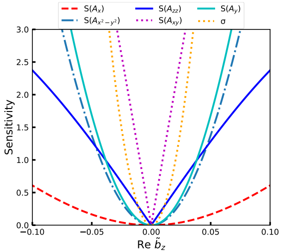
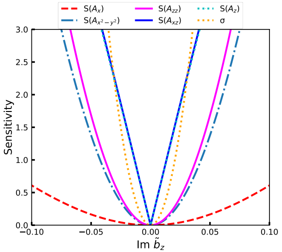
- Redefine the z-axis as reconstructed momentum of ZH system
- In SM, only three asymmetries are non-zero *viz.* A_x , $A_{x^2-y^2}$, A_{zz}.

Sensitivities at $\sqrt{s} = 14$ TeV and $\int \mathcal{L} dt = 1000$ fb^{-1}









Observable	Coupling	Limit ($\times 10^{-3}$)
σ	$\|\text{Re } b_Z\|$	0.70
σ	$\|\text{Im } b_Z\|$	15.9
A_{xy}	$\|\text{Re } \tilde{b}_Z\|$	9.54
A_{xz}, A_z	$\|\text{Im } \tilde{b}_Z\|$	13.3

TABLE: The best 1σ limit on couplings and the corresponding observables at $\sqrt{s} = 14$ TeV

(K.Rao, S.D.Rindani, P.Sarmah, Nucl.Phys.B 964 115317 (2021))

Summary

- Studied anomalous ZZH vertex by making use of the full density matrix of Z boson at the e^+e^- and LHC. The 8 angular asymmetries corresponding to different polarization states of Z, help probing all the anomalous couplings.
- $\sqrt{s} = 14$ TeV LHC with $\int \mathcal{L} dt = 1000$ fb^{-1} could provide a limit on the couplings Reb_z in the interval $[-0.7, 0.7] \times 10^{-3}$ and Imb_z in the interval $[-15.9, 15.9] \times 10^{-3}$.
- Couplings Re$\tilde{b}_z$ and Im$\tilde{b}_z$ get a best bound of $|\text{Re}\tilde{b}_z| \leq 9.54 \times 10^{-3}$ and $|\text{Im}\tilde{b}_z| \leq 13.3 \times 10^{-3}$respectively.

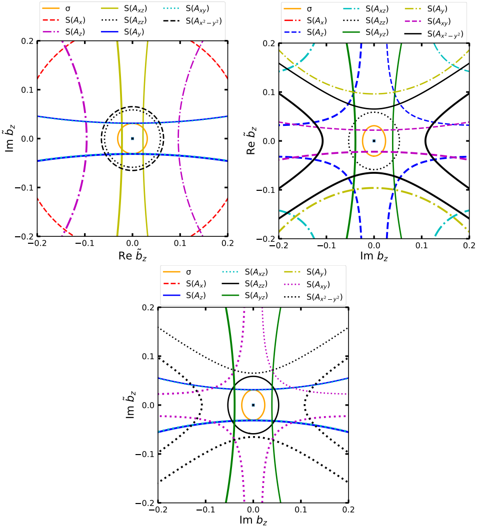
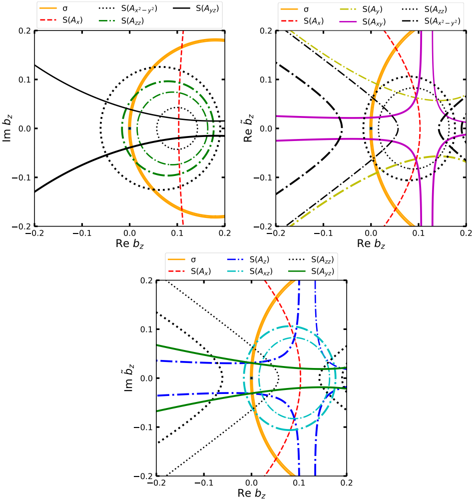


FIGURE: 1σ sensitivity contours for cross-section and asymmetries obtained by varying two parameters simultaneously.



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