

# Z POLARIZATION AS A PROBE OF ANOMALOUS GAUGE-HIGGS COUPLINGS

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# PLAN OF THE TALK

- ▶ Motivation of the work
- ▶ Spin Density Matrix
- ▶ Helicity Amplitudes for the process
- ▶ Asymmetries and Sensitivities
- ▶ Summary

# MOTIVATIONS OF THE WORK

- ▶ Precise measurement of the couplings of the Higgs to electroweak gauge bosons is needed to uncover the exact mechanism of EWSB.
- ▶ Apart from the usual observables namely total cross section, angular distribution, observables like spin polarizations can provide deeper insight into underlying physics.
- ▶ 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.

## GOAL OF THE WORK

- ▶ Study anomalous  $ZZH$  vertex in the associated  $ZH$  production at the  $e^+e^-$  (K.Rao, S.D.Rindani, P.Sarmah, Nucl.Phys.B 950 114840 (2020)) and LHC using the  $Z$  polarization observables.

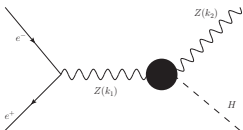


FIGURE: Feynman diagram for  $ZH$  production.

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

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

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.

# FORMALISM

## Polarization Parameters of Z boson

The  $2 \times 2$  density matrix for spin-1/2 system-

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

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

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

For spin-1, the elements of  $3 \times 3$  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  $T_M$ s are five rank 2 irreducible tensors built from  $S_M$ .

## THE PRODUCTION AND DECAY DENSITY MATRICES

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

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

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

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

$$\mathbf{P}(\lambda, \lambda') = \frac{1}{\sigma_V} \int \rho(\lambda, \lambda') d\Omega_V = \frac{1}{\sigma_V} \rho_T(\lambda, \lambda') \quad (2)$$

with  $\sigma_V$  the production cross section of  $V$  without decay.

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

$\mathbf{P}$  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")

# THE PRODUCTION AND DECAY DENSITY MATRICES

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

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

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

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

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

$$\begin{aligned}
 \frac{1}{\sigma} \frac{d\sigma}{d\Omega_f} = & \frac{3}{8\pi} \left[ \left( \frac{2}{3} - \frac{T_{zz}}{\sqrt{6}} \right) - P_z \cos \theta \right] \\
 & + \sqrt{\frac{3}{2}} T_{zz} \cos^2 \theta + (-P_x + 2\sqrt{\frac{2}{3}} T_{xz} \cos \theta) \sin \theta \cos \phi \\
 & + (-P_y + 2\sqrt{\frac{2}{3}} T_{yz} \cos \theta) \sin \theta \sin \phi \\
 & + \left( \frac{T_{xx} - T_{yy}}{\sqrt{6}} \right) \sin^2 \theta \cos 2\phi + \sqrt{\frac{2}{3}} T_{xy} \sin^2 \theta \sin 2\phi
 \end{aligned} \tag{5}$$



Extracting the various polarization parameters of  $Z$  -

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

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

$$T_{xy} = \frac{-i\sqrt{6}[\rho_T(-,+) - \rho_T(+,-)]}{4\sigma_v}$$

$$T_{xz} = \frac{\sqrt{3}\{[\rho_T(+,0) + \rho_T(+,0)] - [\rho_T(0,-) + \rho_T(-,0)]\}}{\sqrt{2}\sigma_v}$$

$$T_{yz} = \frac{-i\sqrt{3}\{[\rho_T(0,+) - \rho_T(+,0)] - [\rho_T(-,0) - \rho_T(0,-)]\}}{\sqrt{2}\sigma_v}$$

$$T_{xx} - T_{yy} = \frac{\sqrt{6}[\rho_T(-,+) - \rho_T(+,-)]}{2\sigma_v}$$

$$T_{zz} = \frac{\sqrt{6}}{2} \left\{ \frac{[\rho_T(+,+) - \rho_T(-,-)]}{\sigma_v} - \frac{2}{3} \right\} = \frac{\sqrt{6}}{2} \left[ \frac{1}{3} - \frac{\rho_T(0,0)}{\sigma_v} \right]$$

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 (**equation(5)**) 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 $e^- + e^+ \rightarrow Z + H$

$$e^-(p_1) + e^+(p_2) \rightarrow Z^\alpha(k_2) + H(k)$$

In the limit of massless initial states

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

$$M(\mp, \pm, 0) = \frac{g_w^2 \sqrt{s}}{\cos^2 \theta_w ((s - m_z^2) + i\Gamma_z m_z)} \frac{(c_v \pm c_a)}{2} [E_z - \sqrt{s} b_z] \sin \theta$$

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

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

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

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

$$\varepsilon_\mu(s = \pm 1) = \mp \frac{1}{\sqrt{2}}(0, -\cos \theta, \mp i, \sin \theta) \quad (6)$$

$$\varepsilon_\mu(s = 0) = \frac{1}{m_z}(|p_z|, -E_z \sin \theta, 0, -E_z \cos \theta) \quad (7)$$

where  $E_z, |p_z|$  are the energy and momentum of the  $Z$  respectively, with  $\theta$  being the polar angle made by  $Z$  with respect to the  $e^-$  coming along the positive  $z$  axis.

Sensitivities at  $\sqrt{s} = 500\text{GeV}$ ,  $\int \mathcal{L} dt = 500 \text{ fb}^{-1}$  for unpolarized and polarized beams

Observable	Coupling	Limit ( $\times 10^{-3}$ ) for	
		$P_L = 0$ $\bar{P}_L = 0$	$P_L = -0.8$ $\bar{P}_L = 0.3$
$\sigma$	Re $b_z$	3.32	2.8
$A_x$	Re $b_z$	394	54.2
$A_y$	Re $\tilde{b}_z$	204	28.2
$A_z$	Im $\tilde{b}_z$	47.9	40.4
$A_{xy}$	Re $\tilde{b}_z$	33.7	28.5
$A_{yz}$	Im $b_z$	77.7	10.7
$A_{xz}$	Im $\tilde{b}_z$	72.0	9.93
$A_{x^2-y^2}$	Re $b_z$	46.7	39.4
$A_{zz}$	Re $b_z$	12.8	10.8

- ▶  $\sigma$  sensitive to only Re  $b_z$  and  $A_x, A_{x^2-y^2}, A_{zz}$  being CP even observables depend on CP even Re  $b_z$
- ▶ Remaining asymmetries being either CP even and T odd or CP odd, has dependence on the CP odd coupling (Im  $b_z, \tilde{b}_z$ )

(K.Rao, S.D. Rindani, P.Sarmah, Nucl.Phys.B 950 114840 (2020))

Sensitivities at  $\sqrt{s} = 250\text{GeV}$ ,  $\int \mathcal{L} dt = 2 \text{ ab}^{-1}$  for unpolarized and polarized beams

Observable	Coupling	Limit ( $\times 10^{-3}$ ) for	
		$P_L = 0$ $\bar{P}_L = 0$	$P_L = -0.8$ $\bar{P}_L = 0.3$
$\sigma$	Re $b_z$	1.36	1.15
$A_x$	Re $b_z$	3480	478
$A_y$	Re $\tilde{b}_z$	303	41.7
$A_z$	Im $\tilde{b}_z$	32.3	27.2
$A_{xy}$	Re $\tilde{b}_z$	22.7	19.2
$A_{yz}$	Im $b_z$	189	26.1
$A_{xz}$	Im $\tilde{b}_z$	107	14.7
$A_{x^2-y^2}$	Re $b_z$	94.5	80.2
$A_{zz}$	Re $b_z$	26.8	22.8

- ▶ Better sensitivities for oppositely polarized beams
- ▶ Slight improvement on limits with increasing c.m. energy
- ▶ Minimal acceptance cut leads to 1% change in all the observables

(K.Rao, S.D. Rindani, P.Sarmah, Nucl.Phys.B 950 114840 (2020))



# ASYMMETRIES AND SENSITIVITIES AT LHC

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

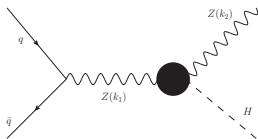


FIGURE: Feynman diagram for  $ZH$  production.

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

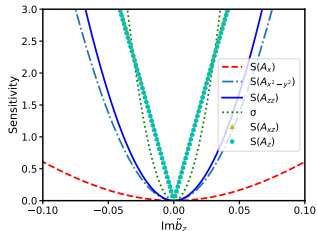
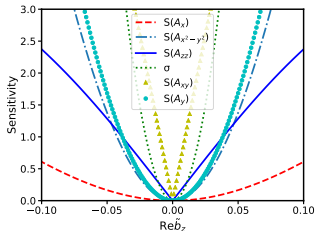
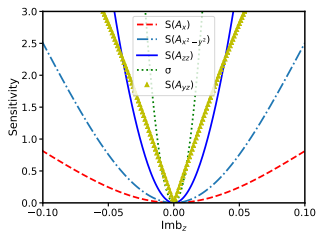
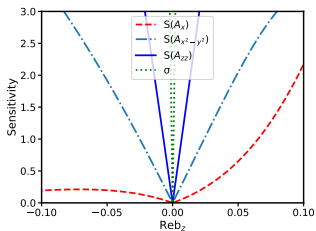
$$\Gamma_{\mu\nu}^V = \frac{g_w}{\cos\theta_w} m_Z \left[ a_z g_{\mu\nu} + \frac{b_z}{m_Z^2} (k_{1\nu} k_{2\mu} - g_{\mu\nu} k_1 \cdot k_2) + \frac{\tilde{b}_z}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} k_1^\alpha k_2^\beta \right]$$

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

Observable	Coupling	Limit ( $\times 10^{-3}$ )
$\sigma$	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

**TABLE:**  $1\sigma$  limit obtained from cross section and various leptonic asymmetries calculated upto linear order in couplings at  $\sqrt{s} = 14$  TeV with integrated luminosity  $\int \mathcal{L} dt = 1000$  fb $^{-1}$ .

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

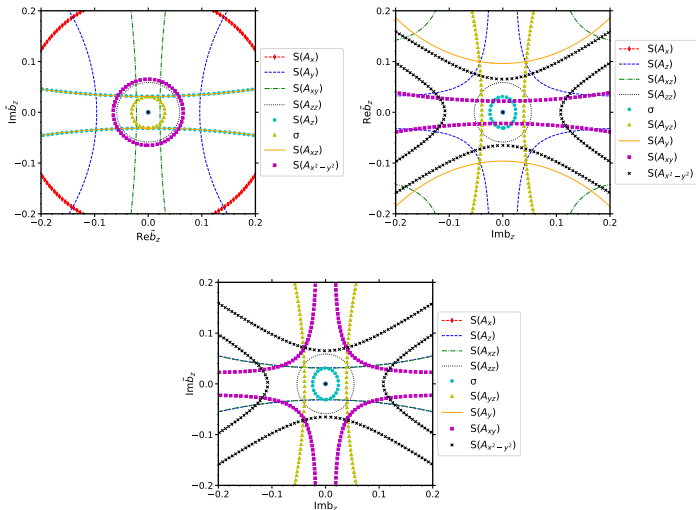


Observable	Coupling	Limit ( $\times 10^{-3}$ )
$\sigma$	$ \text{Re } b_Z $	0.70
$\sigma$	$ \text{Im } b_Z $	15.9
$A_{xy}$	$ \text{Re } \tilde{b}_Z $	9.54
$A_{xz}, A_z$	$ \text{Im } \tilde{b}_Z $	13.3

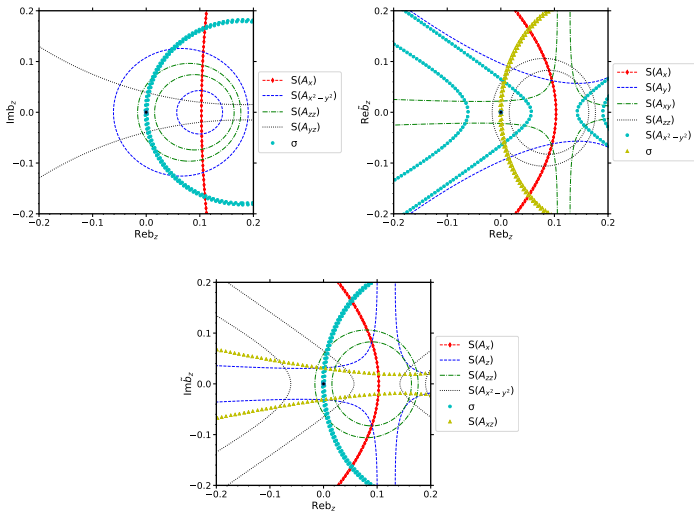
**TABLE:** The best  $1\sigma$  limit on couplings and the corresponding observables at  $\sqrt{s} = 14$  TeV

## 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.
- ▶ We see that most of the  $1\sigma$  limits are of the order of a few times  $10^{-3}$  for 500 GeV  $e^+e^-$  colliders and find that beams with opposite polarization provides better limits on the couplings.
- ▶  $\sqrt{s} = 14$  TeV LHC with  $\int \mathcal{L} dt = 1000 \text{ fb}^{-1}$  could provide a limit on the couplings  $\text{Re}b_z$  in the interval  $[-0.7, 0.7] \times 10^{-3}$  and  $\text{Im}b_z$  in the interval  $[-15.9, 15.9] \times 10^{-3}$ .
- ▶ Couplings  $\text{Re}\tilde{b}_z$  and  $\text{Im}\tilde{b}_z$  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:**  $1\sigma$  sensitivity contours for cross-section and asymmetries obtained by varying two parameters simultaneously.



**FIGURE:**  $1\sigma$  sensitivity contours for cross-section and asymmetries obtained by varying two parameters simultaneously.