ECFA focus topic on ZH angular distributions and CP studies

4 ZHang — Zh angular distributions and CP studies

Expert Team: Cheng Li, Chris Hays, Gudrid Moortgat-Pick, Ivanka Bozovic, Ken Mimasu, Markus Klute, Sandra Kortner

Angular distributions in Zh production can be used to increase sensitivity to both CP-even and CP-odd interactions of the Higgs boson. The Higgs self-coupling vertex appears at next-to-leading order in Zh production, and a global analysis of CP-even interactions including angular distributions from this process can improve the sensitivity to the self-coupling. The presence of a CP-odd component in Higgs-boson interactions can be probed by reconstructing the Higgs and Z boson decay planes, or by measuring and utilizing the polarizations of the Higgs-boson decay particles. These CP-odd interactions could provide an ingredient to explain the observed matter-antimatter asymmetry in the universe. Prior analyses of Zh production have found good sensitivity to CP-odd interactions, and a further understanding of this sensitivity is a primary goal of this topic.

Chris Hays, Oxford University

18 March 2024

ZH angular distributions and CP studies

15 focus topics have been defined as a central element of the next ECFA report
Expert teams formed to develop a work plan for the topics
Now documented in arXiv:2401.07564

Areas of study for the “ZHang” focus topic:

1 CP-odd HZZ interactions
- using fully simulated samples
- in an asymmetric colllider
- with polarized beams
- joint constraints with CP-even interactions

2 Connecting CP-odd constraints to specific models

3 CP-odd $H\tau\tau$ interactions

4 Higgs self-coupling from angular distributions

5 Global SMEFT analysis extended to NLO, dimension-8 operators

6 Quantum entanglement observables

First meeting

ECFA meeting on e+e- to ZH angular measurements

Tuesday 12 Dec 2023, 14:00 → 17:00 Europe/Zurich

Videoconference ZHAng focus topic Join

14:00 → 14:10 **Introduction** 10m
Speaker: Chris Hays (University of Oxford (GB))

14:20 → 14:40 **Probing the Higgs with angular observables at future e+e- colliders** 20m
Speakers: Jiayin Gu (IHEP, CAS), Jiayin Gu (Fudan University)

1 CP-odd HZZ interactions
- joint constraints with CP-even interactions

14:50 → 15:10 **FCC-ee ZH CP studies** 20m
Speaker: Nicholas Pinto (Johns Hopkins University)
FCC-ee CP Studies.... FCC-ee CP Studies....

1 CP-odd HZZ interactions
- using fully simulated samples

15:20 → 15:40 **Sensitivity to CP-odd HVV interactions at the 1 TeV ILC** 20m
Speaker: Ivanka Bozovic-Jelisavcic (University of Belgrade (RS))

15:50 → 16:10 **Higgs self-coupling sensitivity in ZH production (theory)** 20m
Speaker: Johannes Braathen (DESY)

4 Higgs self-coupling from angular distributions

Today's meeting

ECFA meeting on e+e- to ZH angular measurements

Monday 18 Mar 2024, 14:00 → 17:00 Europe/Zurich

Videoconference ECFA meeting on e+e- to ZH angular measurements — Join

14:00 → 14:05 **Introduction** (5m)
Speaker: Chris Hays (University of Oxford (GB))

14:10 → 14:30 **ZH polarisation for self-coupling** (20m)
Speakers: BALBEER SINGH (Physical Research Laboratory), Balbeer Singh (University of South Dakota)

4 Higgs self-coupling from angular distributions

14:40 → 15:00 **Entanglement with e+e- sqrt(s)=240/250 GeV collisions** (20m)
Speaker: Alan Barr (University of Oxford (GB))

6 Quantum entanglement observables

15:10 → 15:30 **FCC-ee ZH CP studies** (20m)
Speaker: Nicholas Pinto (Johns Hopkins University)

1 CP-odd HZZ interactions
- using fully simulated samples

15:40 → 16:00 **LHC CP prospects** (20m)
Speaker: Sandra Kortner (Max Planck Society (DE))

CP-odd interactions: hVV status

Snowmass 2021 quantified sensitivity in terms of the CP-odd fraction f_{CP}

$$A(hV_1V_2) = \frac{1}{v}\left[a_1^{hVV} m_{V_1}^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + a_2^{hVV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{2} a_3^{hVV} \epsilon^{\mu\nu\rho\sigma} f_{\mu\nu}^{*(1)} f_{\rho\sigma}^{*(2)}\right]$$

$$f_{\rm CP}^{hVV} = \frac{|a_3^{hVV}|^2}{\sum_i |a_i^{hVV}|^2 (\sigma_i/\sigma_3)}$$

Target of $f_{CP} < 10^{-5}$ based on a benchmark model point of the 2HDM

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1300	125	125	3000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1000	250	20	1000	
hZZ/hWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$

e^+e^- expectations use leptonic Z decays and assume equivalent sensitivity with quarks

pp expectations based on CMS projections using VBF production

2209.07510

CP-odd interactions: hVV possibilities

Joint analysis of SMEFT constraints on SU(2), U(1), and mixing operators (c_{HW}, c_{HB}, c_{HWB})

Complementarity with LHC VBF, Wh, Zh measurements

Include hZZ and hWW* decays*

Joint analysis of CP-odd and CP-even constraints

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1300	125	125	3000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1000	250	20	1000	
hZZ/hWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$

Experimental sensitivity at FCC-ee with 5/ab per experiment including backgrounds

Experimental sensitivity at ILC including beam polarization scenarios including backgrounds

Sensitivity at proposed HALHF collider

Potential gains from optimal observables or other multivariate methods

CP-odd interactions: Polarization for hVV

Decay-lepton correlations as probes of anomalous *ZZH* and γZH interactions in $e^+e^- \to HZ$ with polarized beams

Saurabh D. Rindani *, Pankaj Sharma

PLB 693, 134 (2010)

2. Polarization effects in the process $e^+e^- \to HZ$

We consider the process

$$e^-(p_1) + e^+(p_2) \to Z^\alpha(q) + H(k) \to \ell^+(p_{l^+}) + \ell^-(p_{l^-}) + H(k), \qquad (2)$$

Table 1
The 95% CL limits on the anomalous *ZZH* and γZH couplings, chosen nonzero one at a time, from various observables with unpolarized and longitudinally polarized beams.

	Observable	Coupling	Limits for polarizations		
			$P_L = 0.0$ $\bar{P}_L = 0.0$	$P_L = 0.8$ $\bar{P}_L = 0.6$	$P_L = 0.8$ $\bar{P}_L = -0.6$
X_1	$(p_1 - p_2).q$	$\mathrm{Im}\,\tilde{b}_Z$	4.11×10^{-2}	8.69×10^{-2}	9.94×10^{-3}
		$\mathrm{Im}\,\tilde{b}_\gamma$	1.49×10^{-2}	2.06×10^{-2}	1.22×10^{-2}
X_2	$P.(p_{l^-} - p_{l^+})$	$\mathrm{Im}\,\tilde{b}_Z$	4.12×10^{-2}	5.99×10^{-2}	3.84×10^{-2}
		$\mathrm{Im}\,\tilde{b}_\gamma$	5.23×10^{-1}	3.12×10^{-1}	5.52×10^{-2}
X_3	$(\vec{p}_{l^-} \times \vec{p}_{l^+})_z$	$\mathrm{Re}\,\tilde{b}_Z$	1.41×10^{-1}	2.97×10^{-1}	3.40×10^{-2}
		$\mathrm{Re}\,\tilde{b}_\gamma$	5.09×10^{-2}	7.05×10^{-2}	4.15×10^{-2}
X_4	$(p_1 - p_2).(p_{l^-} - p_{l^+}) \times (\vec{p}_{l^-} \times \vec{p}_{l^+})_z$	$\mathrm{Re}\,\tilde{b}_Z$	2.95×10^{-2}	4.29×10^{-2}	2.75×10^{-2}
		$\mathrm{Re}\,\tilde{b}_\gamma$	3.81×10^{-1}	2.24×10^{-1}	3.95×10^{-2}
X_5	$(p_1 - p_2).q(\vec{p}_{l^-} \times \vec{p}_{l^+})_z$	$\mathrm{Im}\,b_Z$	7.12×10^{-2}	1.04×10^{-1}	6.64×10^{-2}
		$\mathrm{Im}\,b_\gamma$	9.10×10^{-1}	5.42×10^{-1}	9.53×10^{-2}
X_6	$P.(p_{l^-} - p_{l^+})(\vec{p}_{l^-} \times \vec{p}_{l^+})_z$	$\mathrm{Im}\,b_Z$	7.12×10^{-2}	1.50×10^{-1}	1.72×10^{-2}
		$\mathrm{Im}\,b_\gamma$	2.58×10^{-2}	3.57×10^{-2}	2.10×10^{-2}
X_7	$[(p_1 - p_2).q]^2$	$\mathrm{Re}\,b_Z$	1.75×10^{-2}	2.54×10^{-2}	1.63×10^{-2}
		$\mathrm{Re}\,b_\gamma$	2.23×10^{-1}	1.34×10^{-1}	2.35×10^{-2}
X_8	$[(p_1 - p_2).(p_{l^-} - p_{l^+})]^2$	$\mathrm{Re}\,b_Z$	1.53×10^{-2}	2.22×10^{-2}	1.42×10^{-2}
		$\mathrm{Re}\,b_\gamma$	1.94×10^{-1}	1.16×10^{-1}	2.04×10^{-2}

CP-odd interactions: hff & loop-induced

Target of $f_{CP} < 10^{-2}$ based on a benchmark model point of the 2HDM

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1300	125	125	3000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1000	250	20	1000	
$h\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$hZ\gamma$	–	~ 1	✓	–	–	–	~ 1	–	–	–	–	$< 10^{-2}$
hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$h\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$h\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Possibilities:

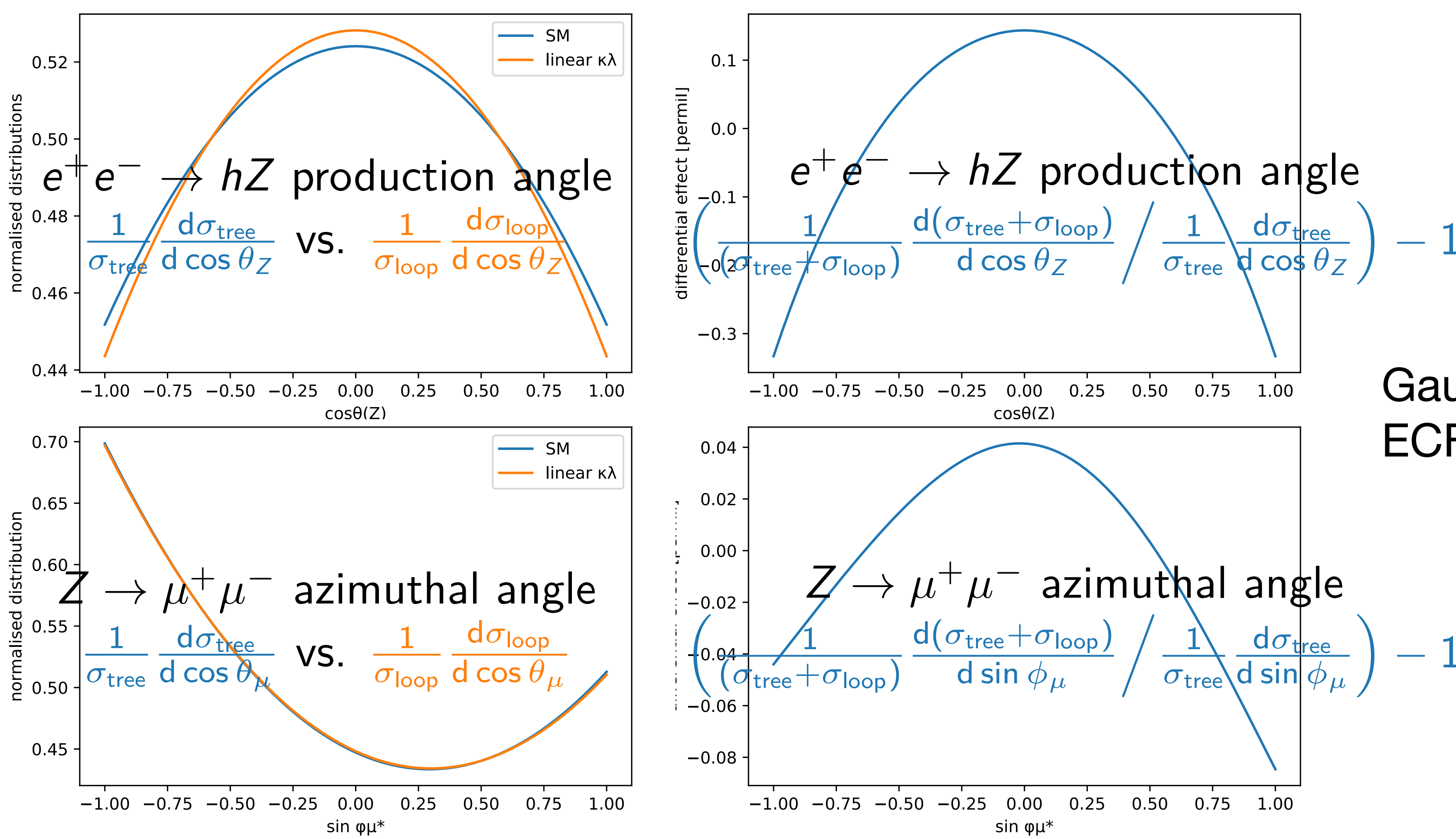
Complete experimental analysis of $h \to \tau\tau$ including uncertainties
$hZ\gamma$ and $h\gamma\gamma$ sensitivity
Joint SMEFT CP-even + CP-odd analysis
Extend benchmark models

CP-even interactions

Zh has sensitivity to self-coupling through NLO loop

Can angular information improve sensitivity?
How does sensitivity change in a global NLO SMEFT analysis?
Can we extend a global SMEFT analysis to dimension-8 and $1/\Lambda^4$?

ZZh loop κ_λ vertex: $F_a(p_i^2)\ (\epsilon_1 \cdot \epsilon_2) + F_b(p_i^2)\ (p_1 \cdot \epsilon_2)(p_2 \cdot \epsilon_1)$
with $F_b/F_a \sim 10^{-2}$ so only $\lesssim 10^{-4}$ differential effect



Gauthier Durieux, ECFA HTE meeting

Rindani & Sharma

2. Polarization effects in the process $e^+e^- \to HZ$

We consider the process

$$e^-(p_1) + e^+(p_2) \to Z^\alpha(q) + H(k) \to \ell^+(p_{l^+}) + \ell^-(p_{l^-}) + H(k), \quad (2)$$

3. Observables

We have evaluated the expectation values of observables X_i $(i = 1, 2, \ldots, 8)$ for unpolarized and longitudinally polarized beams, and observables Y_i $(i = 1, 2, \ldots, 6)$ for transversely polarized beams. The observables X_i and Y_i are respectively sensitive to longitudinal transverse beam polarizations. The definitions of X_i and Y_i are found respectively in Tables 1 and 3.

Table 1
The 95% CL limits on the anomalous ZZH and γZH couplings, chosen nonzero one at a time, from various observables with unpolarized and longitudinally polarized beams.

	Observable	Coupling	Limits for polarizations		
			$P_L = 0.0$, $\bar{P}_L = 0.0$	$P_L = 0.8$, $\bar{P}_L = 0.6$	$P_L = 0.8$, $\bar{P}_L = -0.6$
X_1	$(p_1 - p_2).q$	$\mathrm{Im}\,\tilde{b}_Z$	4.11×10^{-2}	8.69×10^{-2}	9.94×10^{-3}
		$\mathrm{Im}\,\tilde{b}_\gamma$	1.49×10^{-2}	2.06×10^{-2}	1.22×10^{-2}
X_2	$P.(p_{l^-} - p_{l^+})$	$\mathrm{Im}\,\tilde{b}_Z$	4.12×10^{-2}	5.99×10^{-2}	3.84×10^{-2}
		$\mathrm{Im}\,\tilde{b}_\gamma$	5.23×10^{-1}	3.12×10^{-1}	5.52×10^{-2}
X_3	$(\vec{p}_{l^-} \times \vec{p}_{l^+})_z$	$\mathrm{Re}\,\tilde{b}_Z$	1.41×10^{-1}	2.97×10^{-1}	3.40×10^{-2}
		$\mathrm{Re}\,\tilde{b}_\gamma$	5.09×10^{-2}	7.05×10^{-2}	4.15×10^{-2}
X_4	$(p_1 - p_2).(p_{l^-} - p_{l^+}) \times (\vec{p}_{l^-} \times \vec{p}_{l^+})_z$	$\mathrm{Re}\,\tilde{b}_Z$	2.95×10^{-2}	4.29×10^{-2}	2.75×10^{-2}
		$\mathrm{Re}\,\tilde{b}_\gamma$	3.81×10^{-1}	2.24×10^{-1}	3.95×10^{-2}
X_5	$(p_1 - p_2).q(\vec{p}_{l^-} \times \vec{p}_{l^+})_z$	$\mathrm{Im}\,b_Z$	7.12×10^{-2}	1.04×10^{-1}	6.64×10^{-2}
		$\mathrm{Im}\,b_\gamma$	9.10×10^{-1}	5.42×10^{-1}	9.53×10^{-2}
X_6	$P.(p_{l^-} - p_{l^+})(\vec{p}_{l^-} \times \vec{p}_{l^+})_z$	$\mathrm{Im}\,b_Z$	7.12×10^{-2}	1.50×10^{-1}	1.72×10^{-2}
		$\mathrm{Im}\,b_\gamma$	2.58×10^{-2}	3.57×10^{-2}	2.10×10^{-2}
X_7	$[(p_1 - p_2).q]^2$	$\mathrm{Re}\,b_Z$	1.75×10^{-2}	2.54×10^{-2}	1.63×10^{-2}
		$\mathrm{Re}\,b_\gamma$	2.23×10^{-1}	1.34×10^{-1}	2.35×10^{-2}
X_8	$[(p_1 - p_2).(p_{l^-} - p_{l^+})]^2$	$\mathrm{Re}\,b_Z$	1.53×10^{-2}	2.22×10^{-2}	1.42×10^{-2}
		$\mathrm{Re}\,b_\gamma$	1.94×10^{-1}	1.16×10^{-1}	2.04×10^{-2}

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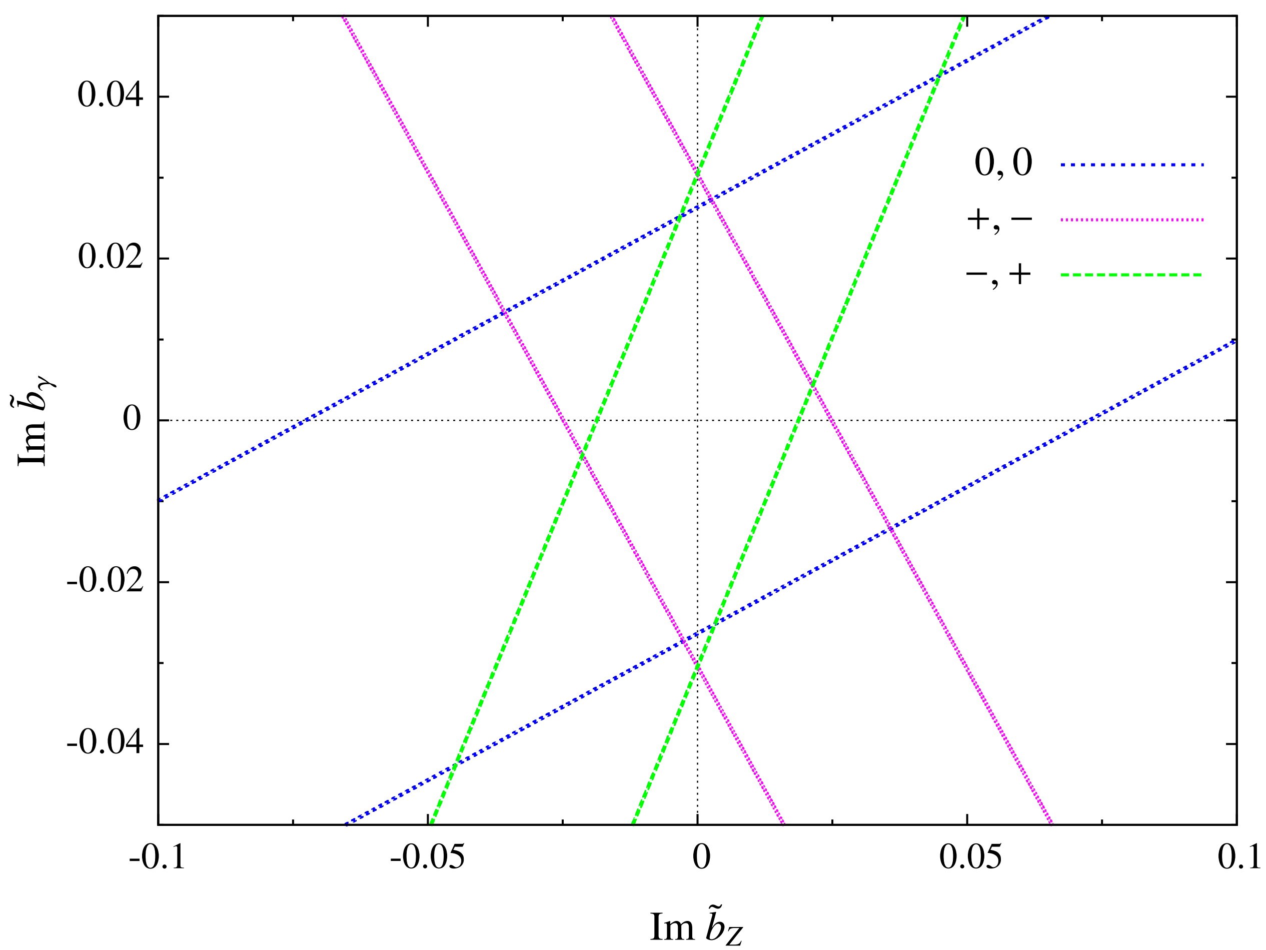

Fig. 1. The region in the $\mathrm{Im}\,\tilde{b}_Z$–$\mathrm{Im}\,\tilde{b}_\gamma$ plane accessible at the 95% CL with observable X_1 with different longitudinal beam polarization configurations.

Table 2
Simultaneous 95% CL limits on anomalous ZZH and γZH couplings from various observables using different longitudinal polarization combinations $(0,0)$, i.e., $P_L = 0$, $\bar{P}_L = 0$, $(\pm,\mp)$, i.e., $(P_L = \pm 0.8, \bar{P}_L = \mp 0.6)$.

Observable	Coupling	Limit on coupling for the polarization combination		
		$(0,0)$, $(-,+)$	$(0,0)$, $(+,-)$	$(-,+)$, $(+,-)$
X_1	$\mathrm{Im}\,\tilde{b}_Z$	4.50×10^{-2}	3.59×10^{-2}	2.14×10^{-2}
	$\mathrm{Im}\,\tilde{b}_\gamma$	4.28×10^{-2}	2.74×10^{-2}	3.04×10^{-2}
X_2	$\mathrm{Im}\,\tilde{b}_Z$	9.73×10^{-2}	7.56×10^{-2}	8.54×10^{-2}
	$\mathrm{Im}\,\tilde{b}_\gamma$	3.06×10^{-1}	2.19×10^{-1}	1.37×10^{-1}
X_3	$\mathrm{Re}\,\tilde{b}_Z$	1.54×10^{-1}	1.22×10^{-1}	7.29×10^{-2}
	$\mathrm{Re}\,\tilde{b}_\gamma$	1.46×10^{-1}	9.31×10^{-2}	1.08×10^{-1}
X_4	$\mathrm{Re}\,\tilde{b}_Z$	5.37×10^{-2}	6.89×10^{-2}	6.10×10^{-2}
	$\mathrm{Re}\,\tilde{b}_\gamma$	1.56×10^{-1}	2.18×10^{-1}	9.78×10^{-2}
X_5	$\mathrm{Im}\,b_Z$	1.67×10^{-1}	1.29×10^{-1}	1.48×10^{-1}
	$\mathrm{Im}\,b_\gamma$	5.27×10^{-1}	3.76×10^{-1}	2.36×10^{-1}
X_6	$\mathrm{Im}\,b_Z$	7.79×10^{-2}	6.18×10^{-2}	3.69×10^{-2}
	$\mathrm{Im}\,b_\gamma$	7.39×10^{-2}	4.72×10^{-2}	5.27×10^{-2}
X_7	$\mathrm{Re}\,b_Z$	2.53×10^{-2}	1.27×10^{-2}	3.11×10^{-2}
	$\mathrm{Re}\,b_\gamma$	1.05×10^{-1}	5.74×10^{-2}	5.11×10^{-2}
X_8	$\mathrm{Re}\,b_Z$	2.58×10^{-2}	2.05×10^{-2}	3.37×10^{-2}
	$\mathrm{Re}\,b_\gamma$	1.15×10^{-1}	6.33×10^{-2}	5.26×10^{-2}