ZH angular focus topic introduction

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
for the focus topic expert team

ECFA ZH angular measurements meeting
18 June 2024

e-group: ECFA-WHF-FT-ZHANG

ZH angular distributions and CP studies

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

European strategy update and ECFA input

Deadline for input to the next European Particle Physics Strategy Update (EPPSU) is March 31, 2025

ECFA aims to provide a report summarizing results since Snowmass to the community by mid-December

Details to be worked out soon

Anyone wishing to provide input should provide an overview by the October 9-11 workshop in Paris

https://indico.in2p3.fr/event/32629/overview

Higgs/Top/EW presentations

1 Electroweak interactions

A Photon interactions
a Spin asymmetry with transversely polarized beams
b Neutrino anomalous magnetic moment

B Z boson interactions
a AFB of quarks at the ILC
b AFB of b-quarks at the FCC
c Flavour changing Z & H decays
d Other exotic Z boson decays

C Gauge boson self-couplings
a Theory
b LHC
c Optimal observables at e+e- colliders
d Polarization and CP

2 Four-fermion interactions
a Charged-lepton and quark constraints from ILC
b Nonstandard neutrino interactions

3 ZH production and angular studies

A CP-odd coupling sensitivity
a CP violation in the Higgs sector
b CP at LHC
c HZZ CP at FCC
d CP at CEPC
e HVV CP at 1 TeV ILC
f Polarized beams for CP tests
g CP in H->tau-tau

B CP-even coupling sensitivity
a Models with CP-even interactions
i. H->Zy in the 3HDM
ii. Additional Higgs bosons
b Coupling measurements at the LHC
c HZZ coupling at the ILC
d HZZ coupling sensitivity to angular observables

C Entanglement sensitivity
a Entanglement in H->VV
b Entanglement in H->tau-tau

4 Rare Higgs couplings

A Hss
a Modelling parton shower and hadronization
i. The challenge of fragmentation modelling
ii. LHC constraints on hadronization models
iii. ALICE charm fragmentation measurements
iv. ATLAS b fragmentation measurements
v. Constraining parton shower models in e+e-
b Strange tagging
i. Flavour tagging at the LHC
ii. Flavour tagging at e+e- colliders
1. Detector design
2. PID reconstruction
c Sensitivity
ii. H->ss branching fractions
ii. Obstacles in Higgs-strange-coupling interpretation
iii. Higgs-strange-coupling projections

B Hee
a FCC sensitivity
b Energy recovery Linacs

C Invisible Higgs decays
a ILC

D Flavour-violating Higgs decays
a Quark flavour violating SUSY
b Flavour changing H decays at the FCC

5 Higgs self coupling

A Theory & models
a Self-coupling in the 2HDM at ILC
b BSM self-coupling at the ILC
c Self-couping predictions in arbitrary models

B Experiment
a Polarization for self-coupling
b ILC and C^3 prospects

6 Top-quark interactions
a FCNC in top-quark interactions
b CP sensitivity in top decays

Today's meeting

ECFA meeting on e+e- to ZH angular measurements

Tuesday 18 Jun 2024, 14:00 → 17:30 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 **CP violation in the Higgs sector** 20m
Speaker: Henning Bahl

14:35 → 14:55 **CP and entanglement in H to VV decays** 20m
Speaker: Juan Antonio Aguilar Saavedra (Consejo Superior de Investigaciones Científicas (ES))

15:00 → 15:20 **Polarized beams for CP tests** 20m
Speaker: Cheng Li

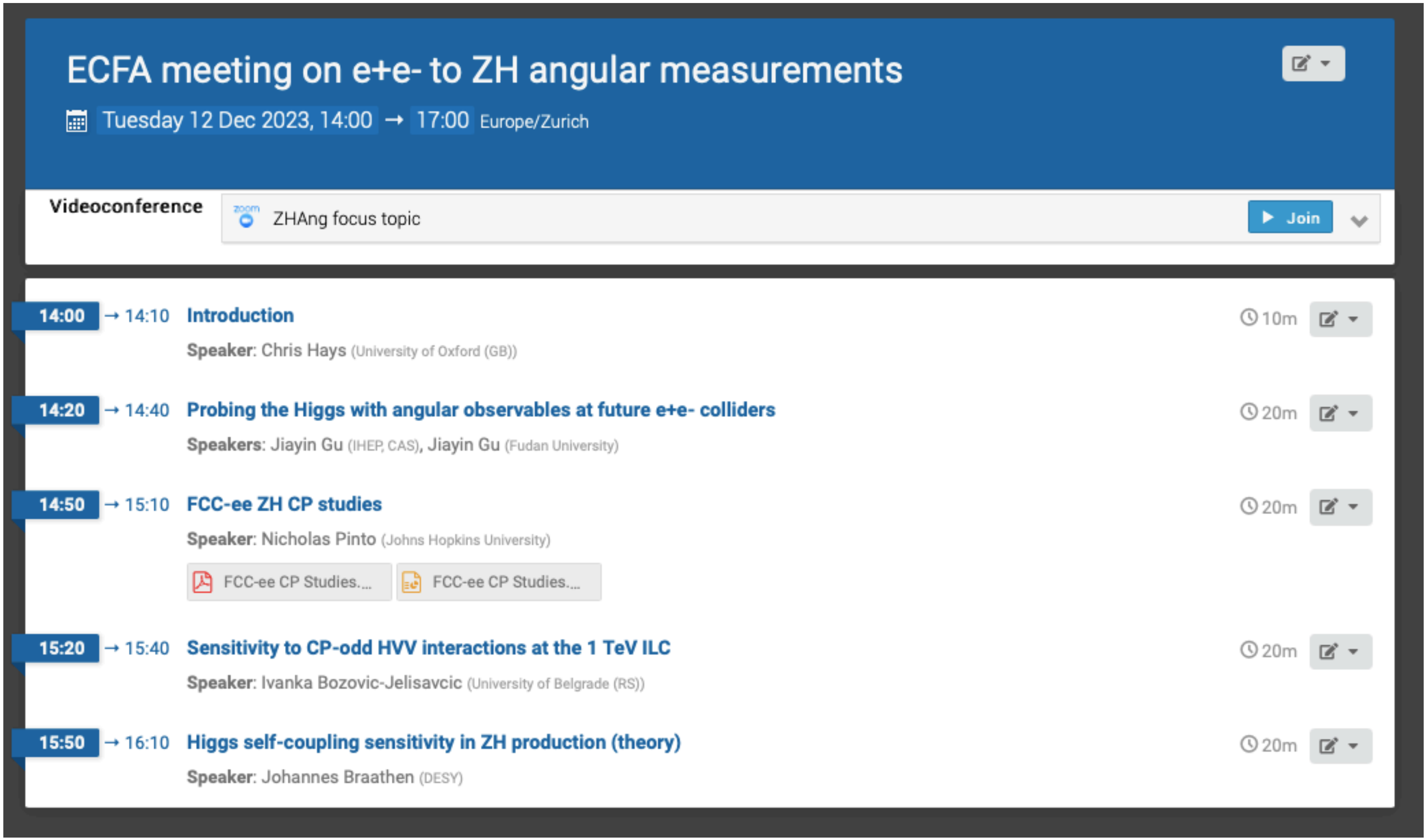
15:25 → 15:45 **Beam polarization at CEPC** 20m
Speaker: Duan,Zhe duanz

15:50 → 16:10 **CP at CEPC** 20m
Speaker: Qiyu Sha (Chinese Academy of Sciences (CN))

16:15 → 16:35 **FCC-ee ZH CP studies** 20m
Speaker: Valdis Slokenbergs (Johns Hopkins University (US))

16:40 → 17:00 **Higgs self-coupling sensitivity at the ILC** 20m
Speaker: Bryan Bliewert (Deutsches Elektronen-Synchrotron (DE))

First meeting



Second 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)

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

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

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}

$$A(hV_1V_2) = \frac{1}{v}\left[a_1^{hVV} m_{V_1}^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + a_2^{hVV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{2} a_3^{hVV} \epsilon^{\mu\nu\rho\sigma} f_{\mu\nu}^{*(1)} f_{\rho\sigma}^{*(2)}\right] \qquad f_{CP}^{hVV} = \frac{|a_3^{hVV}|^2}{\sum_i |a_i^{hVV}|^2 (\sigma_i/\sigma_3)}$$

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	$4\cdot 10^{-5}$	$2.5\cdot 10^{-6}$	✓	$3.9\cdot 10^{-5}$	$2.9\cdot 10^{-5}$	$1.3\cdot 10^{-5}$	$3.0\cdot 10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$

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

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

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