

Higgs CP Properties and EFT Measurements from ATLAS

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(On behalf of the ATLAS Collaboration)



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- Introduction of Higgs CP and EFT framework
- CP of Higgs Couplings to Fermions and Bosons
 - Higgs-tau coupling: $H \rightarrow \tau\tau$
 - Higgs-top coupling (ttH/tH)
 - $H \rightarrow \gamma\gamma$
 - $H \rightarrow bb$
 - Higgs-VV coupling and EFT measurements
 - $H \rightarrow WW^* \rightarrow l\nu l\nu$
 - VBF $H \rightarrow \tau\tau$
 - VBF $H \rightarrow \gamma\gamma$
 - $H \rightarrow ZZ^* \rightarrow 4l$
 - WH, $H \rightarrow bb$
 - $HH \rightarrow bbbb, bb\tau\tau, bb\gamma\gamma$

➤ Summary

- SM predicts Higgs boson to be a CP-even particle ($J^{CP} = 0^{++}$, scalar)
- Higgs CP-odd has already been excluded ($> 3\sigma$)
- Known CP violation cannot explain matter-antimatter asymmetry in the universe
- **Anomalous Higgs coupling may introduce additional CP violation, any signs of CP-mixed Higgs couplings to SM particles would be a hint of new physics**
- Higgs CP measurements through its couplings to fermions and bosons
 - Higgs-tau coupling, $H \rightarrow \tau\tau$
 - Higgs-top coupling, $H \rightarrow \gamma\gamma$, $H \rightarrow bb$
 - Higgs-VV coupling and EFT measurements, $H \rightarrow WW^* \rightarrow l\nu l\nu$, VBF $H \rightarrow \tau\tau$,
VBF $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, WH, $H \rightarrow bb$

- **Effective Field Theory (EFT)**, SM (Wilson coeff. $c_i=0$) + BSM operators
- Constrain BSM operators (e.g. Dimension-6) in CP violation test

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots,$$

- **HISZ basis:** $\tilde{d} = \tilde{d}_B$

$$\tilde{c}_{H\gamma\gamma} = \frac{g}{2m_W} (\tilde{d} \sin^2 \theta_W + \tilde{d}_B \cos^2 \theta_W) \quad \tilde{c}_{H\gamma Z} = \frac{g}{2m_W} \sin 2\theta_W (\tilde{d} - \tilde{d}_B)$$

$$\tilde{c}_{HZZ} = \frac{g}{2m_W} (\tilde{d} \cos^2 \theta_W + \tilde{d}_B \sin^2 \theta_W) \quad \tilde{c}_{HWW} = \frac{g}{m_W} \tilde{d},$$

- **Warsaw basis:** three CP-odd terms contribute to the HVV vertex ($c_{H\tilde{W}}, c_{H\tilde{B}}, c_{H\tilde{W}B}$)

$$c_{H\tilde{W}} = c_{H\tilde{B}} \text{ and } c_{H\tilde{W}B} = 0$$

$$\tilde{d} = \frac{v^2}{\Lambda^2} c_{H\tilde{W}} = \frac{v^2}{\Lambda^2} c_{H\tilde{B}}$$

- Run2 139/fb $H \rightarrow \tau\tau$ semileptonic ($\tau_{lep} - \tau_{had}$) or hadronic ($\tau_{had} - \tau_{had}$) tau decays
- CP-sensitive observable: signed acoplanarity angle ϕ_{CP}^* of 2 τ decay planes.

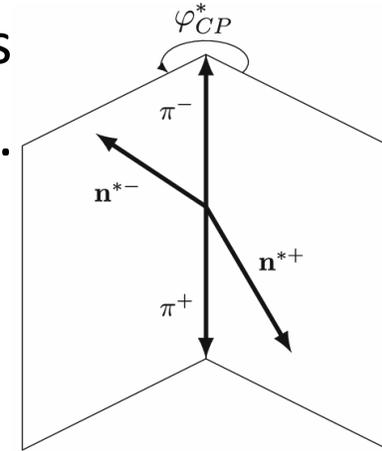
Higgs-tau coupling:

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v} \kappa_\tau (\cos \phi_\tau \bar{\tau}\tau + \sin \phi_\tau \bar{\tau}i\gamma_5\tau)H$$

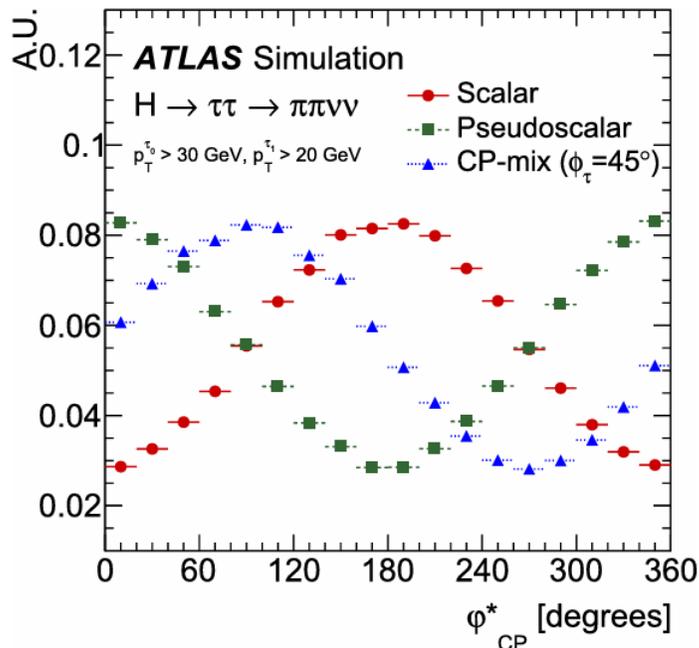
ϕ_τ is CP-mixing angle: relative contributions of CP-even/odd components

- **1D likelihood fit of CP-mixing angle $\phi_\tau = 9^\circ \pm 16^\circ$ (68% CL)**

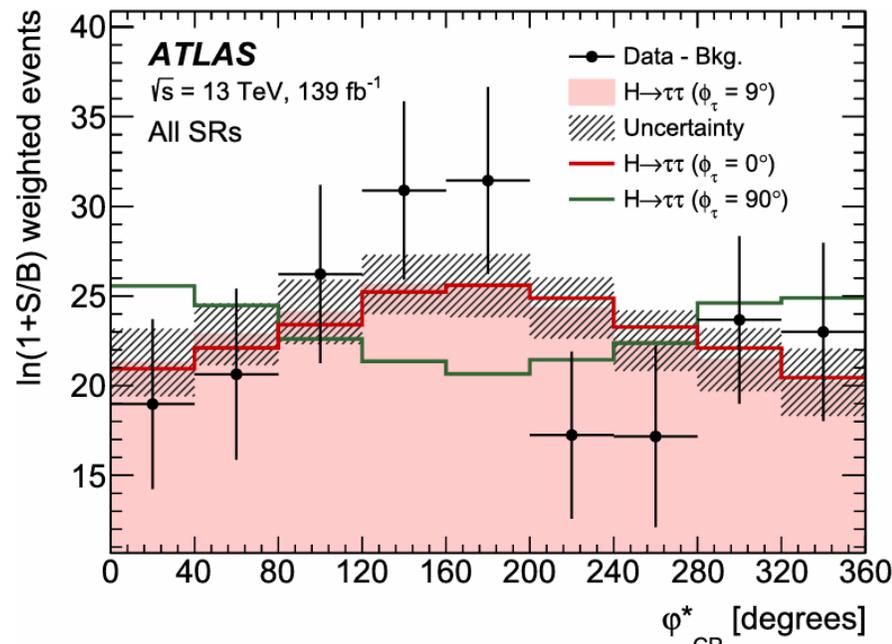
- **Pure CP-odd hypothesis is excluded at 3.4σ**



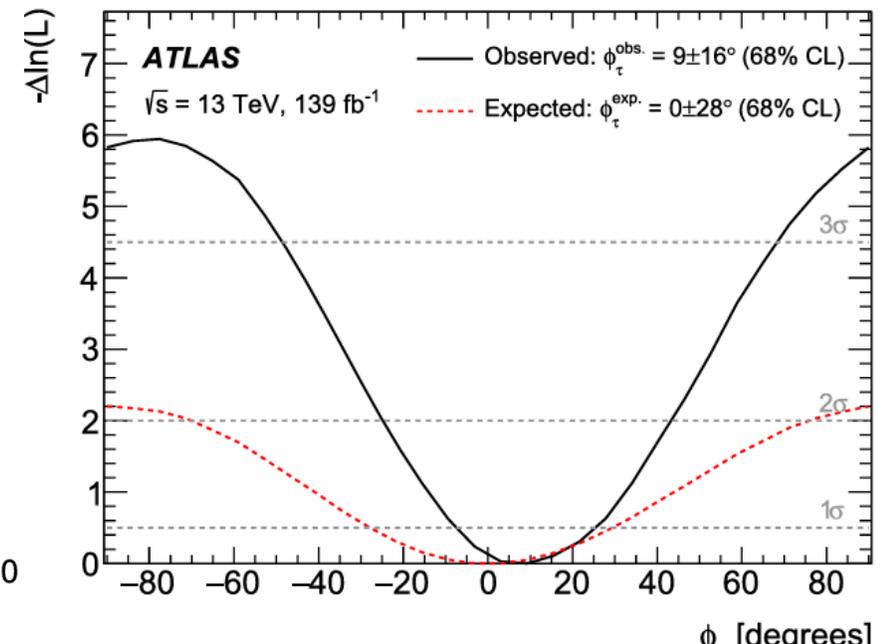
(a) $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + 2\nu$



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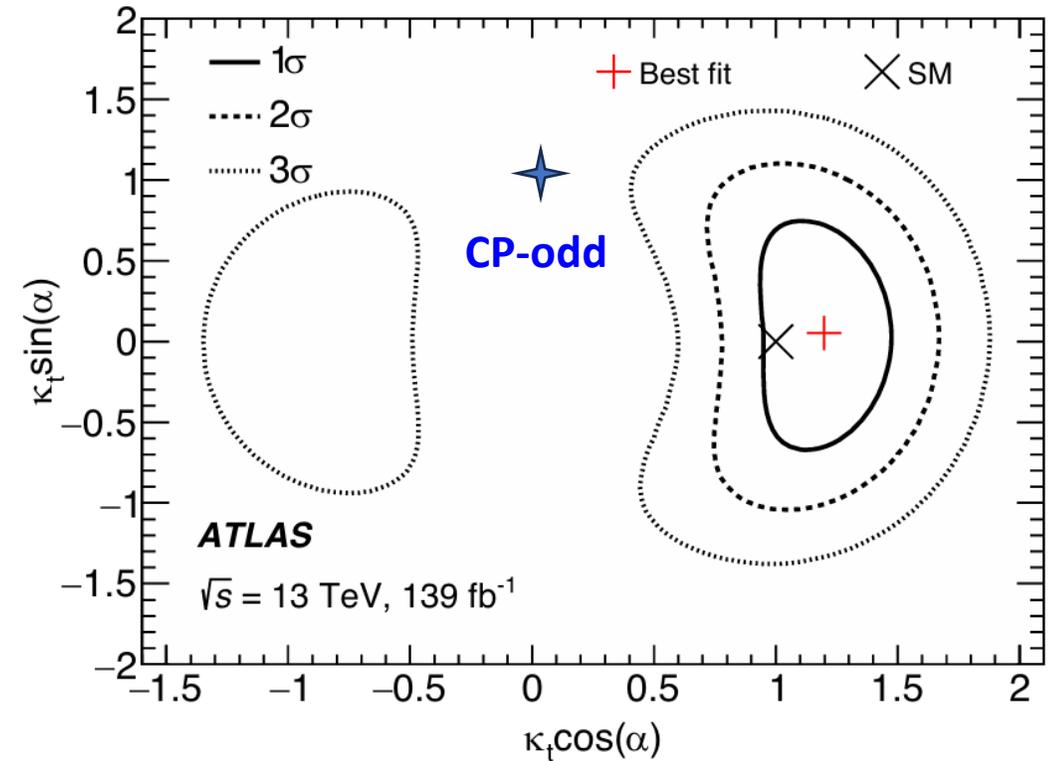
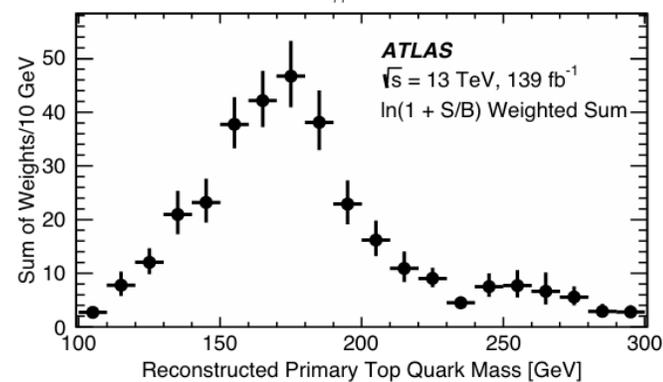
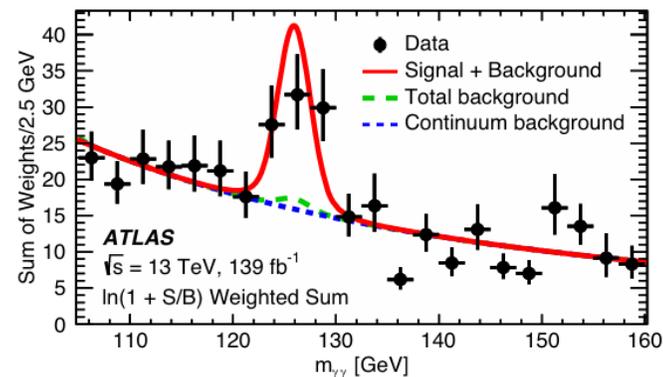
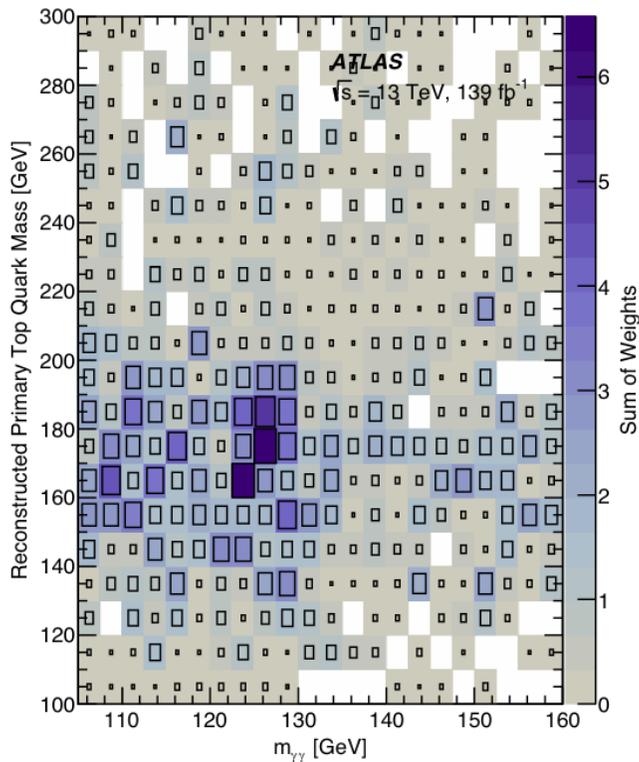
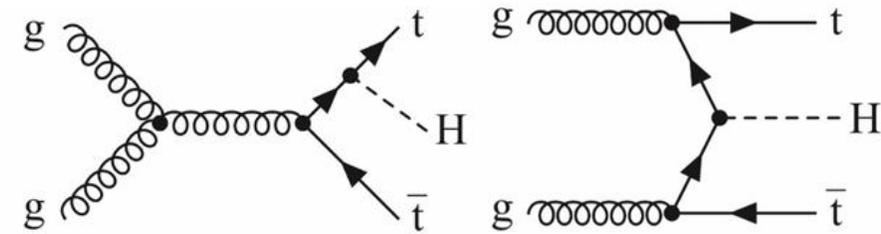


Acoplanarity angle ϕ_{CP}^*



CP-mixing angle

- Using Run2 139/fb data, $t\bar{t}H$ was observed at 5.2σ assuming CP-even coupling
- CP of H-top Yukawa coupling can be probed via $t\bar{t}H/tH$
- **Pure CP-odd ($\alpha = 90^\circ$) is excluded at 3.9σ**
- **$|\alpha| > 43^\circ$ is excluded at 95% CL**

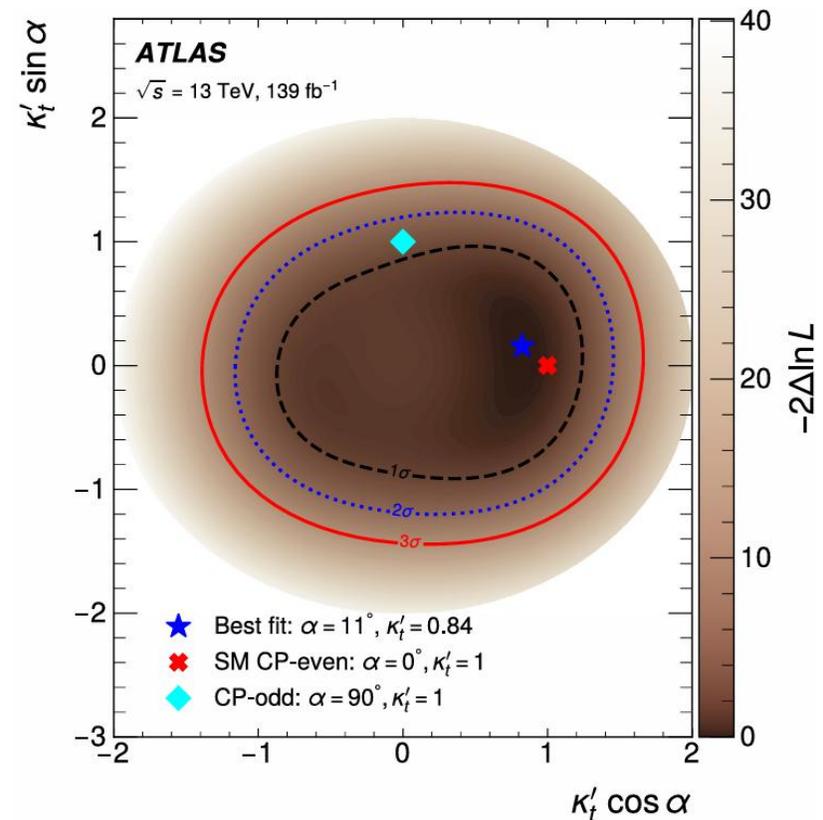
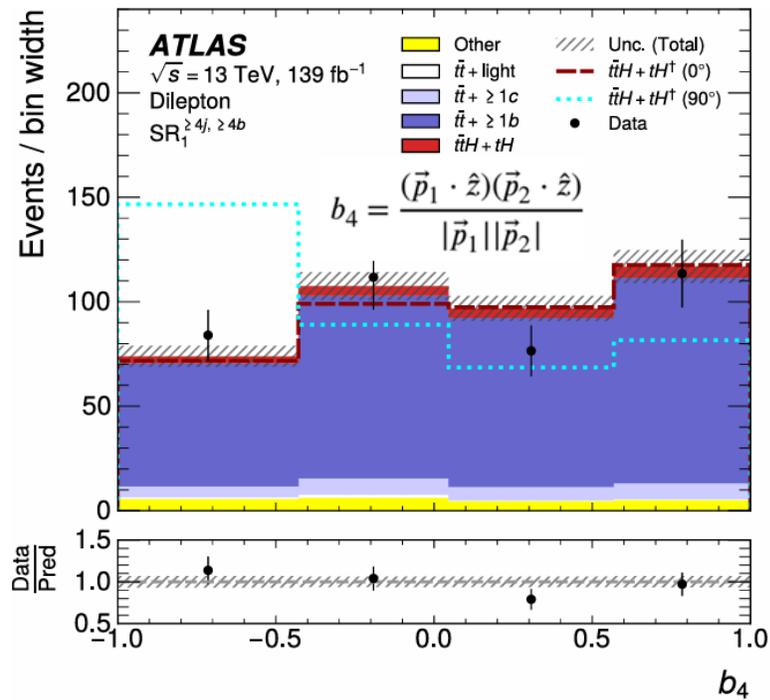
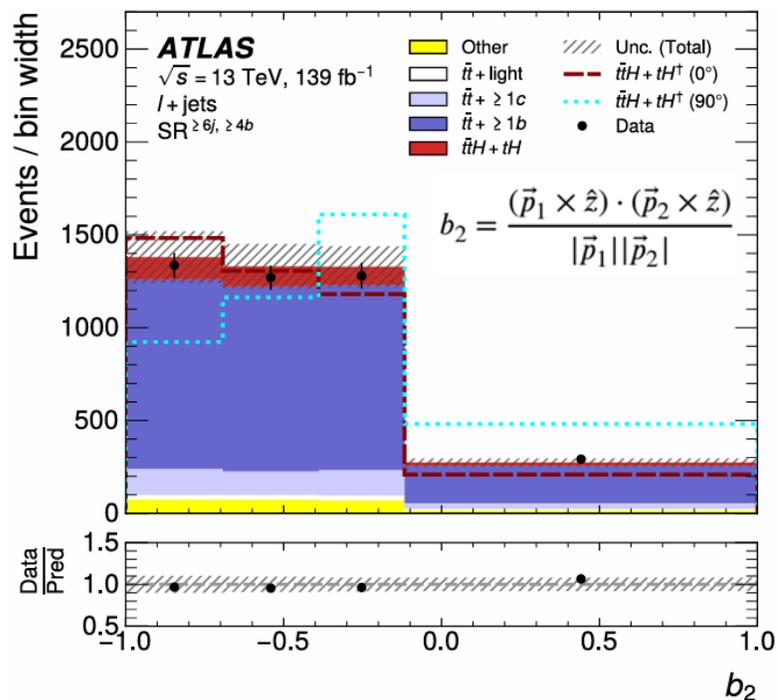


Rec. top mass vs $m_{\gamma\gamma}$

➤ CP properties of H-top Yukawa coupling can be probed via ttH/tH processes

➤ **Pure CP-odd ($\alpha = 90^\circ$) is disfavored at 1.2σ**

➤ **Best-fit CP-mixing angle $\alpha = 11^{+52}_{-73}^\circ$ and Higgs-top coupling strength $\kappa_t' = 0.84^{+0.30}_{-0.46}$**



Two CP observables: \vec{p}_i is top momentum, \hat{z} unit vector in beam direction

- b_2 : enhanced for narrower azimuthal separation of top quarks in CP-odd case
- b_4 : enhanced for tops in opposite directions and closer to beamline in CP-odd case

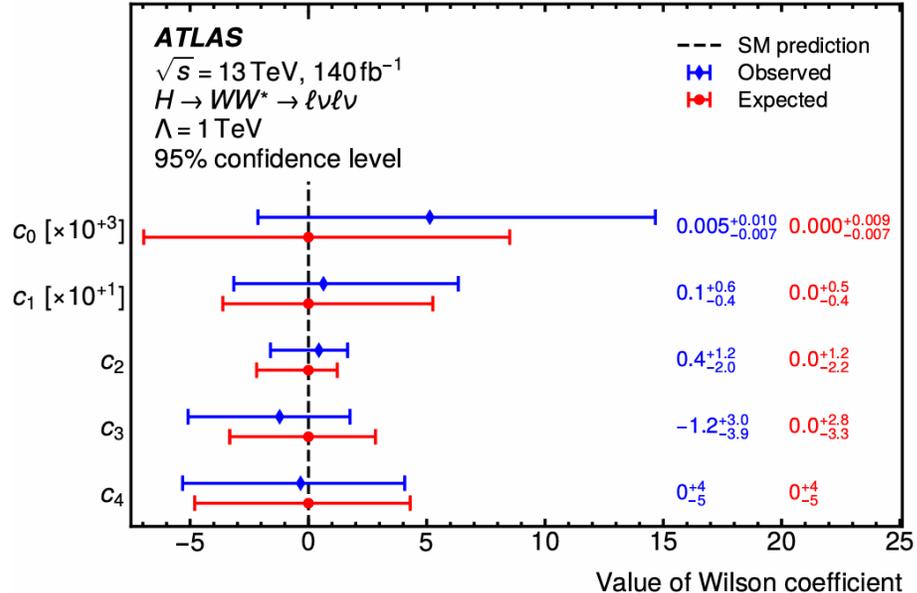
EFT: Higgs-VV coupling ($H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$)

- $d = 6$ operators (Warsaw-basis, 16 operators) considered by EFT interpretation in a CP-violating scenario.
- A reduced set of five operators in a rotated basis.

ATLAS
 $\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$
 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
 $\Lambda = 1 \text{ TeV}$

Rotated-basis Wilson coefficient	Warsaw-basis Wilson coefficient																Component of eigenvector
c_0 (σ_{exp} 0.004)	+0.003	-0.001	+0.999	+0.002	-0.001	-0.002	-0.002	-0.002	0.000	0.000	-0.001	0.000	0.000	-0.003	-0.035	+0.002	+1.0
c_1 (σ_{exp} 0.213)	+0.108	-0.008	-0.002	+0.076	+0.047	-0.041	-0.148	-0.148	-0.012	+0.078	-0.957	-0.046	+0.008	+0.001	+0.004	+0.098	+0.5
c_2 (σ_{exp} 0.767)	-0.317	+0.042	+0.003	-0.228	+0.574	+0.149	+0.429	+0.428	+0.035	+0.103	-0.186	-0.001	-0.012	+0.002	-0.023	-0.283	0.0
c_3 (σ_{exp} 1.467)	-0.021	-0.017	-0.032	-0.027	-0.320	-0.029	+0.142	+0.142	+0.006	-0.008	-0.075	-0.001	+0.002	-0.129	-0.909	-0.073	-0.5
c_4 (σ_{exp} 2.223)	+0.245	-0.037	-0.015	+0.214	+0.749	-0.107	-0.244	-0.243	-0.032	-0.029	+0.176	+0.006	0.000	-0.071	-0.365	+0.173	-1.0

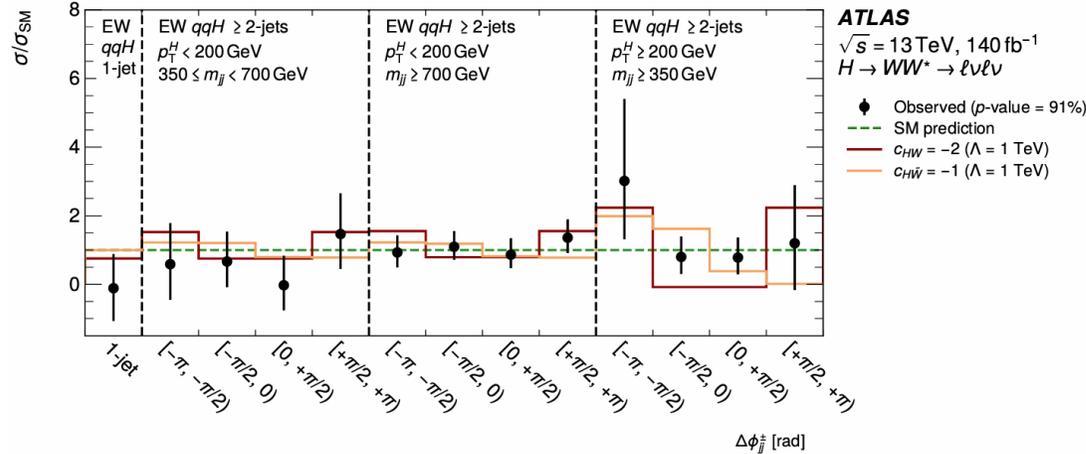
Wilson coefficient	Operator	Effect or affected diagram
c_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G_{\mu\nu}^A$	
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$	
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^L H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Rescales all Higgs boson couplings
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	
c_{HB}	$H^\dagger H B_{\mu\nu}B^{\mu\nu}$	
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	
$c_{HI,11}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^L H)(\bar{l}_1\tau^I\gamma^\mu l_1)$	
$c_{HI,22}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^L H)(\bar{l}_2\tau^I\gamma^\mu l_2)$	
$c_{HI,33}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^L H)(\bar{l}_3\tau^I\gamma^\mu l_3)$	
$c_{H,1221}^{(3)}$	$(\bar{l}_1\gamma_\mu l_2)(\bar{l}_2\gamma^\mu l_1)$	Rescales Fermi constant



$c_0 \rightarrow c_{HG}$
 $c_3 \rightarrow c_{tG}$
 $c_1 \rightarrow c_{Hq}^{(3)}$
 $c_4 \rightarrow c_{HW}$

EFT: Higgs-VV coupling ($H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$)

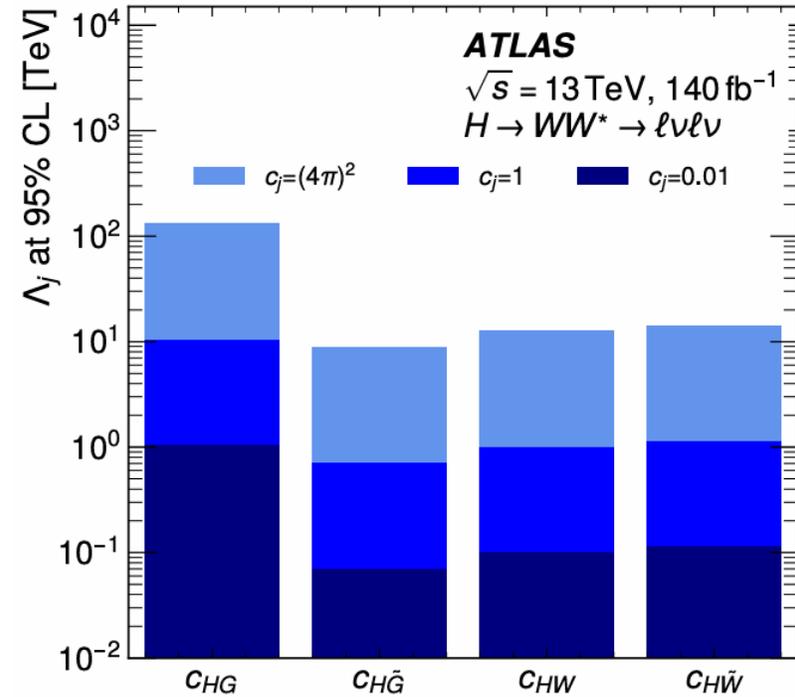
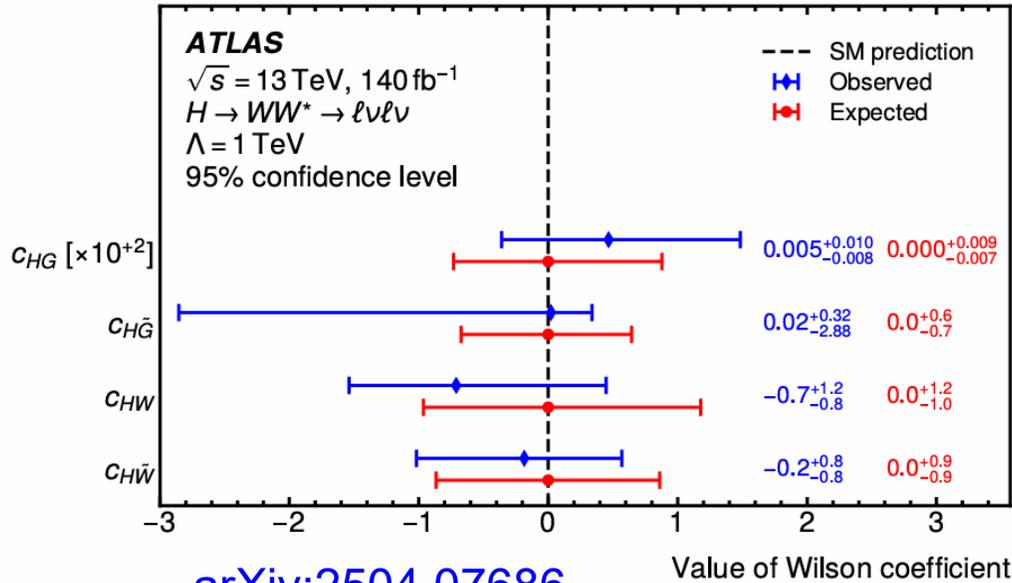
- Wilson coefficients for CP-even / CP-odd scenarios related to H-gluon, HVV couplings
- Result is compatible with SM (p-value of 91%); CP-odd $c_{H\tilde{W}} \in [-1.0, 0.6]$ at 95% CL



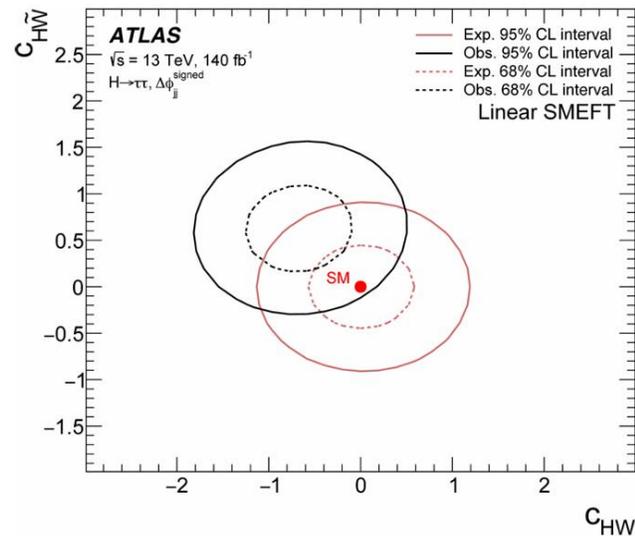
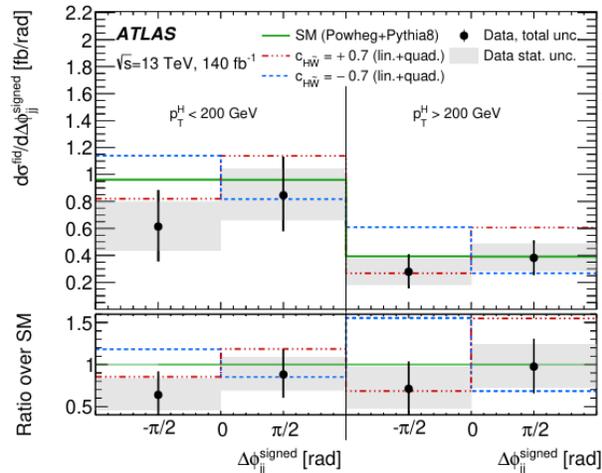
- CP-even →
- CP-odd →
- CP-even →
- CP-odd →

Wilson coefficient	Operator
c_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$
$c_{H\tilde{G}}$	$H^\dagger H \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$
$c_{H\tilde{W}}$	$H^\dagger H \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$

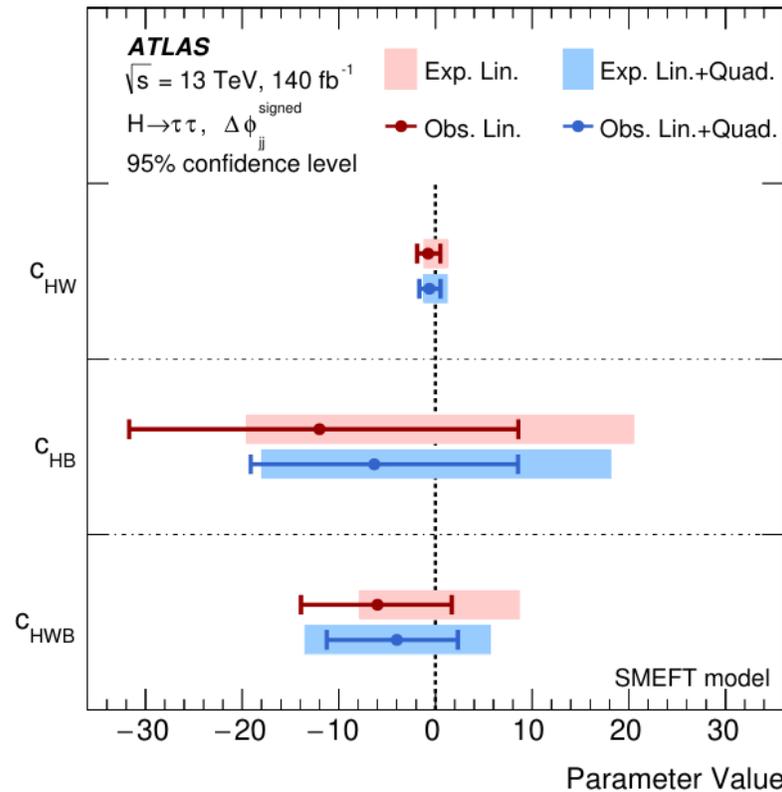
H-g (green text)
HVV (blue text)



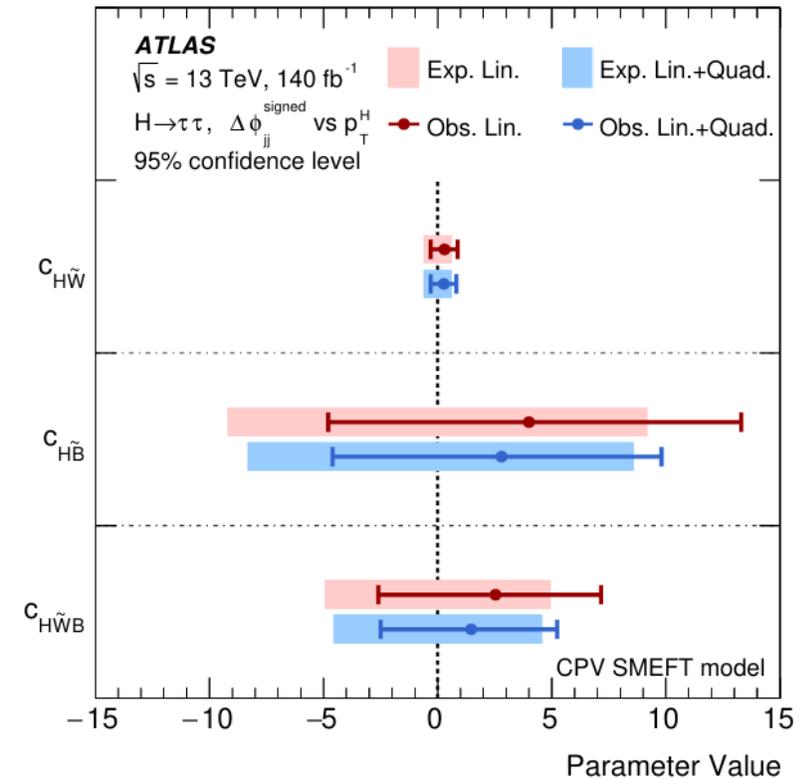
- Using 140/fb VBF $H \rightarrow \tau\tau$ to probe CP violation of HVV couplings in EFT framework
- $\Delta\phi_{jj}$ is a sensitive observable to CP, **no evidence of CP violation is observed**



CP-even, $c_{HW} \in [-1.90, +0.51]$
 Expected limit $[-1.19, +1.21]$



CP-odd, $c_{H\tilde{W}} \in [-0.31, +0.88]$
 Expected limit $[-0.60, +0.60]$



EFT: Higgs-VV Coupling (VBF $H \rightarrow \tau\tau$)

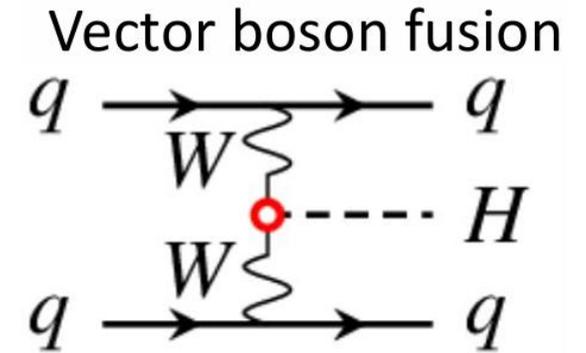
- Using 140/fb data, VBF $H \rightarrow \tau\tau$ decay mode to probe CP-violating HVV interactions in the EFT framework

➤ Optimal Observable (OO):

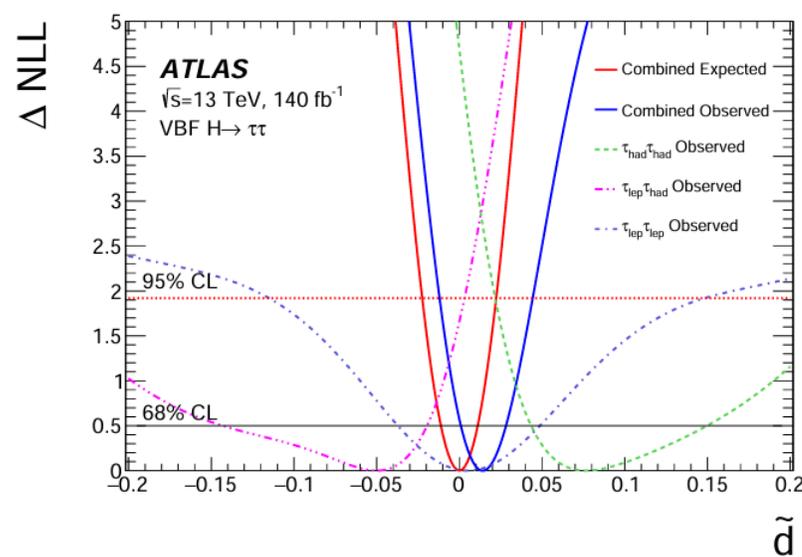
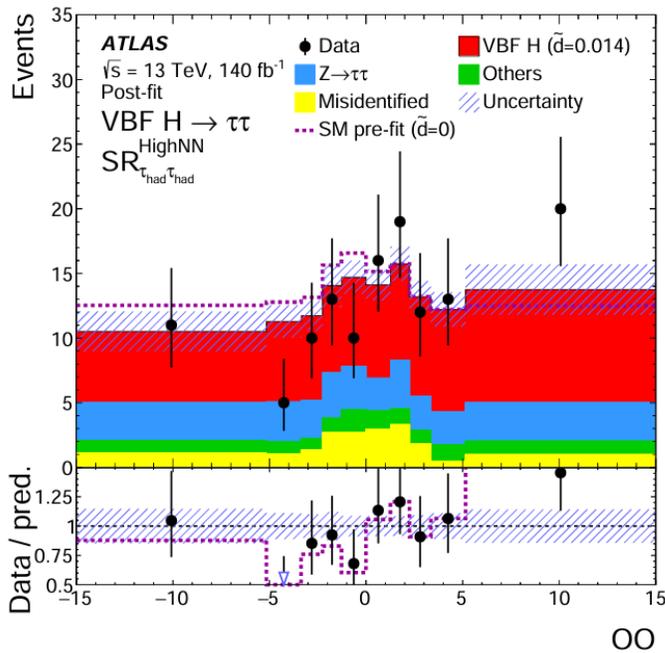
~30% stronger limit than those obtained with $\Delta\phi_{jj}^{\text{sign}}$

$$OO = \frac{2\Re(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

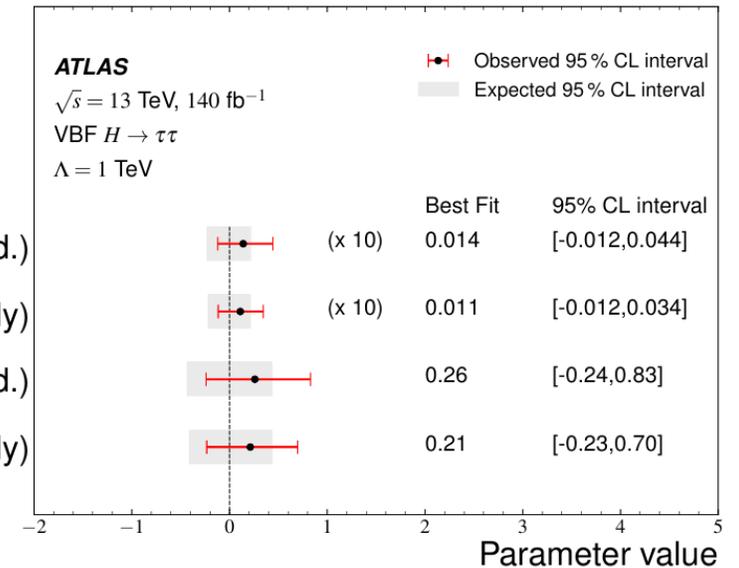
NEW!



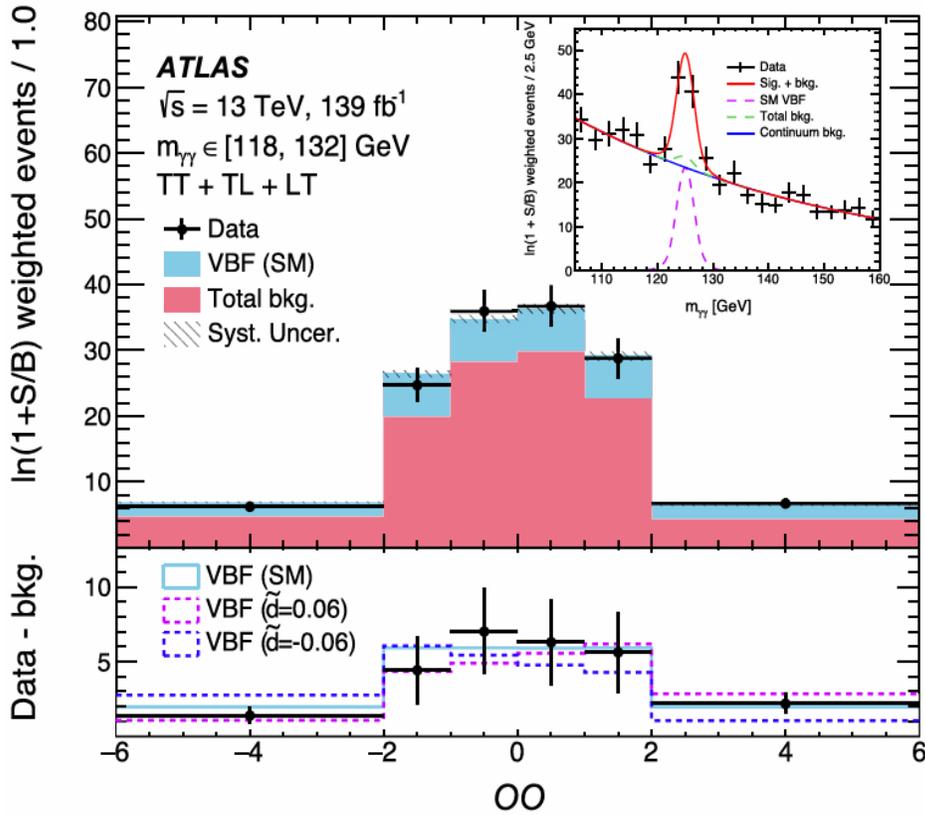
$\tilde{d} \in [-0.012, 0.034]$ at 95%CL
 $c_{H\tilde{W}} \in [-0.23, 0.70]$ at 95%CL
The most stringent limit !



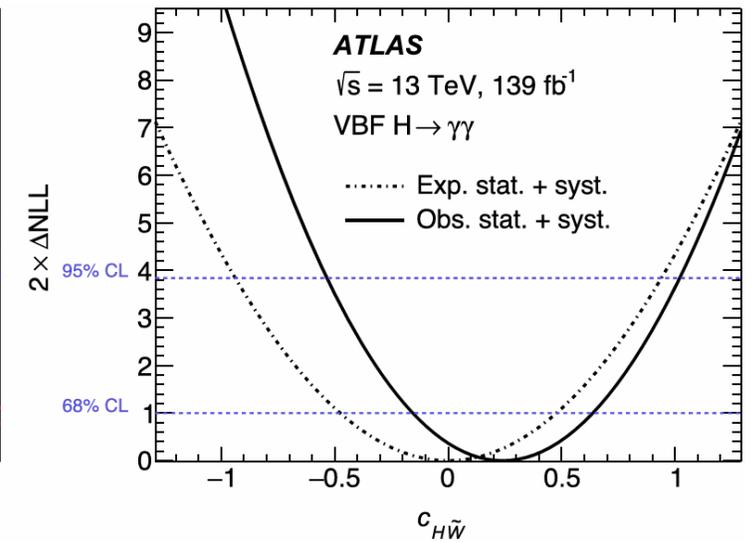
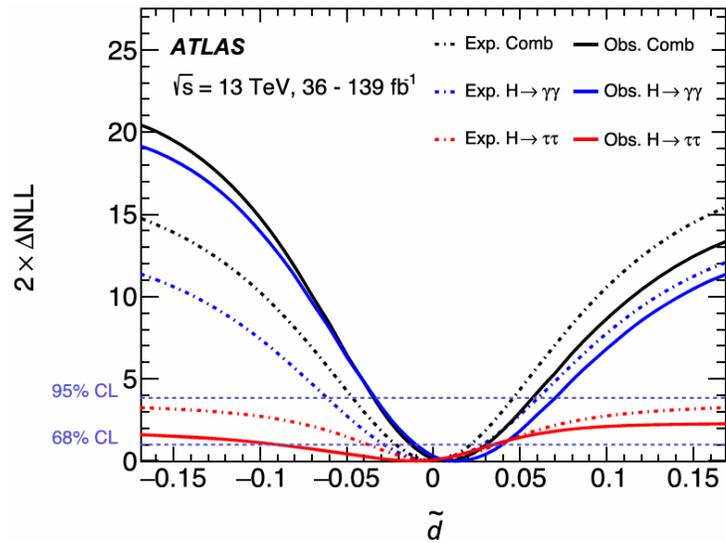
\tilde{d} (lin. + quad.)
 \tilde{d} (lin. only)
 $c_{H\tilde{W}}$ (lin. + quad.)
 $c_{H\tilde{W}}$ (lin. only)



- Using 139/fb data, VBF $H \rightarrow \gamma\gamma$ to probe Higgs CP-violating in EFT framework
- Optimal observable (OO) is constructed to distinguish CP property.
- **Observed limits $\tilde{d} \in [-0.032, 0.059]$, CP-odd $c_{H\tilde{W}} \in [-0.53, 1.02]$ at 95% CL**



	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
\tilde{d} (inter. only)	$[-0.027, 0.027]$	$[-0.055, 0.055]$	$[-0.011, 0.036]$	$[-0.032, 0.059]$
\tilde{d} (inter. + quad.)	$[-0.028, 0.028]$	$[-0.061, 0.060]$	$[-0.010, 0.040]$	$[-0.034, 0.071]$
\tilde{d} from $H \rightarrow \tau\tau$	$[-0.038, 0.036]$...	$[-0.090, 0.035]$...
Combined \tilde{d}	$[-0.022, 0.021]$	$[-0.046, 0.045]$	$[-0.012, 0.030]$	$[-0.034, 0.057]$
$c_{H\tilde{W}}$ (inter. only)	$[-0.48, 0.48]$	$[-0.94, 0.94]$	$[-0.16, 0.64]$	$[-0.53, 1.02]$
$c_{H\tilde{W}}$ (inter. + quad.)	$[-0.48, 0.48]$	$[-0.95, 0.95]$	$[-0.15, 0.67]$	$[-0.55, 1.07]$

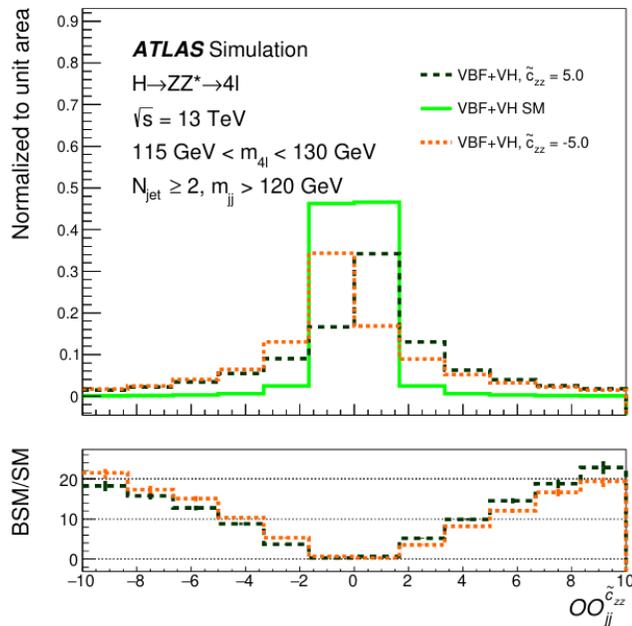


➤ Using 139/fb data, $H \rightarrow ZZ^* \rightarrow 4l$ to probe Higgs CP-violating in EFT framework

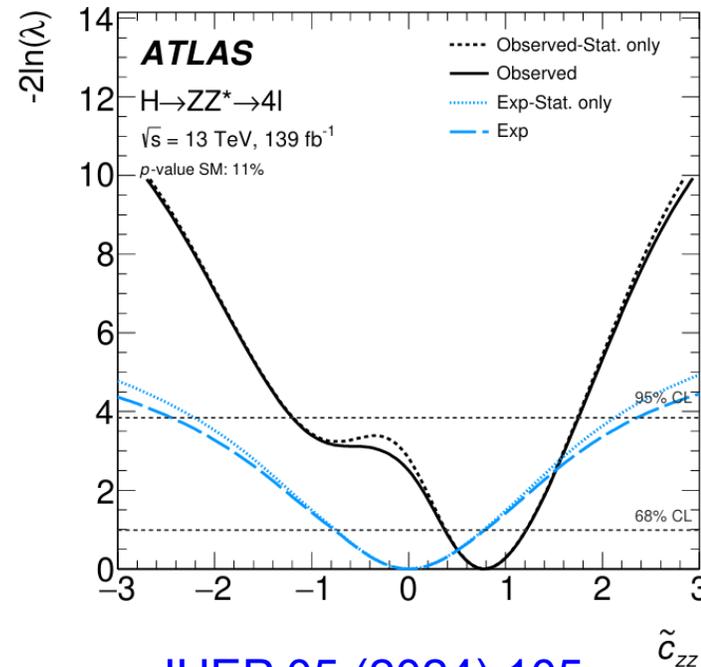
Operator	Structure	Coupling
Warsaw Basis		
$O_{\Phi\tilde{W}}$	$\Phi^\dagger \Phi \tilde{W}_{\mu\nu}^I W^{\mu\nu I}$	$c_{H\tilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger \tau^I \Phi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$c_{H\tilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger \Phi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$
Higgs Basis		
$O_{hZ\tilde{Z}}$	$h Z_{\mu\nu} \tilde{Z}^{\mu\nu}$	\tilde{c}_{zz}
$O_{hZ\tilde{A}}$	$h Z_{\mu\nu} \tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$h A_{\mu\nu} \tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{HW}	$HH^\dagger W_{\mu\nu}^l W^{\mu\nu l}$	c_{HW}	$O_{H\tilde{W}}$	$HH^\dagger \tilde{W}_{\mu\nu}^l W^{\mu\nu l}$	$c_{H\tilde{W}}$	VBF, VH	HZZ
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$	VBF, VH	HZZ
O_{HWB}	$HH^\dagger \tau^l W_{\mu\nu}^l B^{\mu\nu}$	c_{HWB}	$O_{H\tilde{W}B}$	$HH^\dagger \tau^l \tilde{W}_{\mu\nu}^l B^{\mu\nu}$	$c_{H\tilde{W}B}$	VBF, VH	HZZ

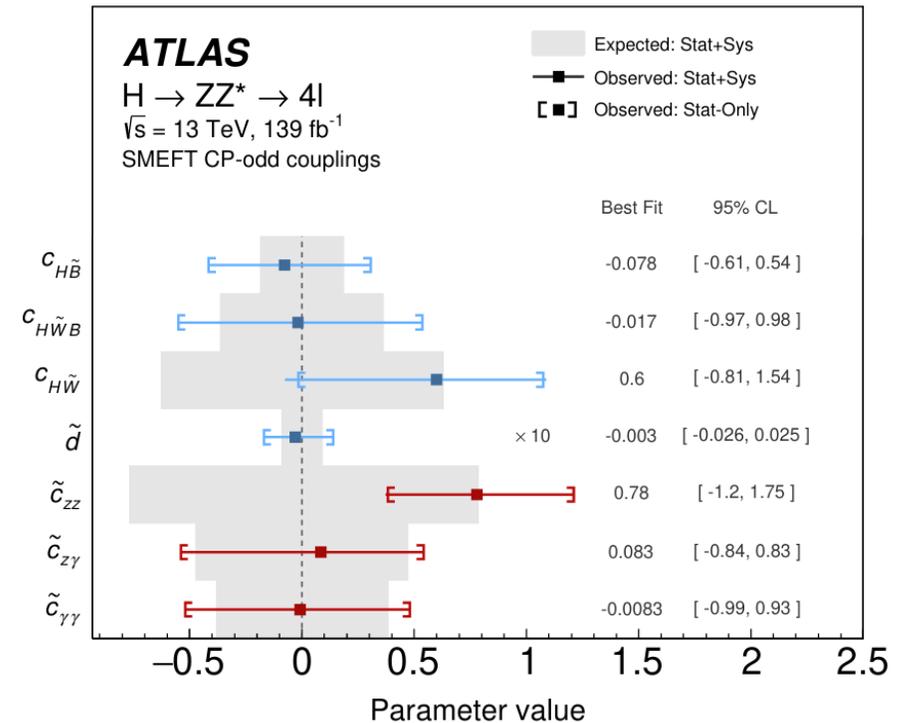
No deviation from SM observed



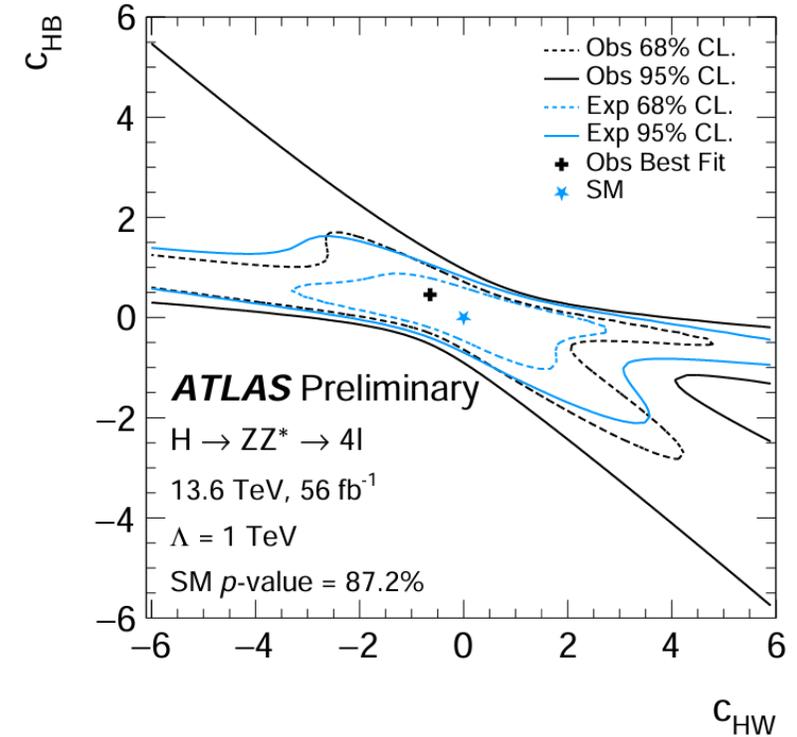
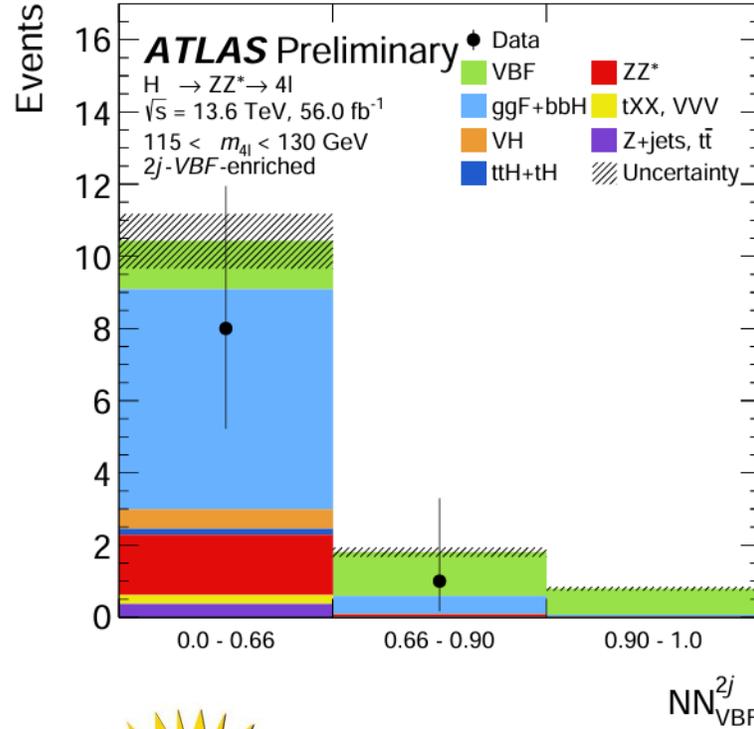
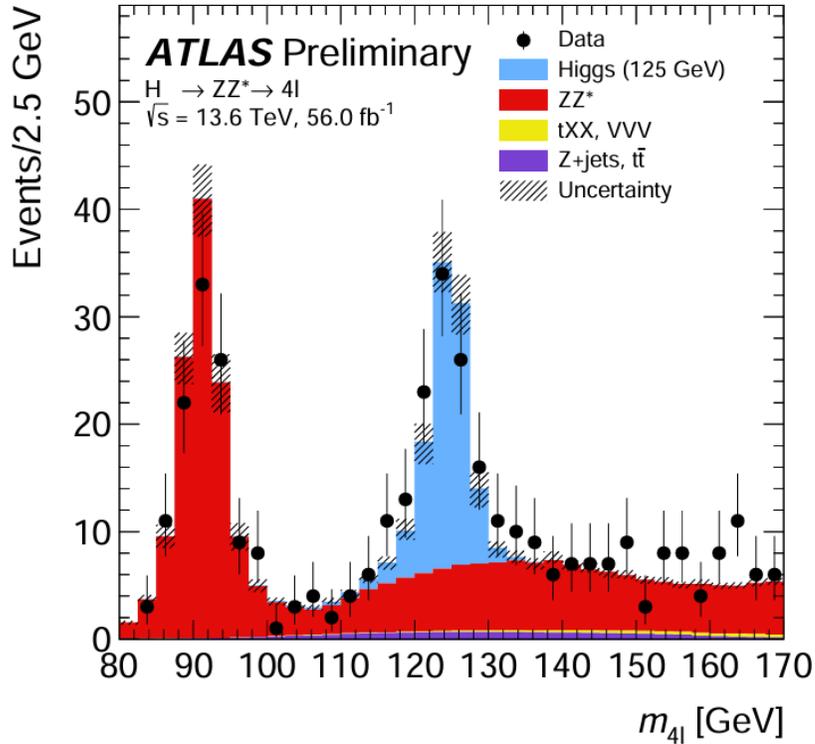
$OO_{jj}(\tilde{c}_{zz})$ for VBF Higgs



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➤ Using Run3 data (56/fb) at 13.6 TeV, $H \rightarrow ZZ^* \rightarrow 4\ell$ to probe Higgs CP-violating



NEW!

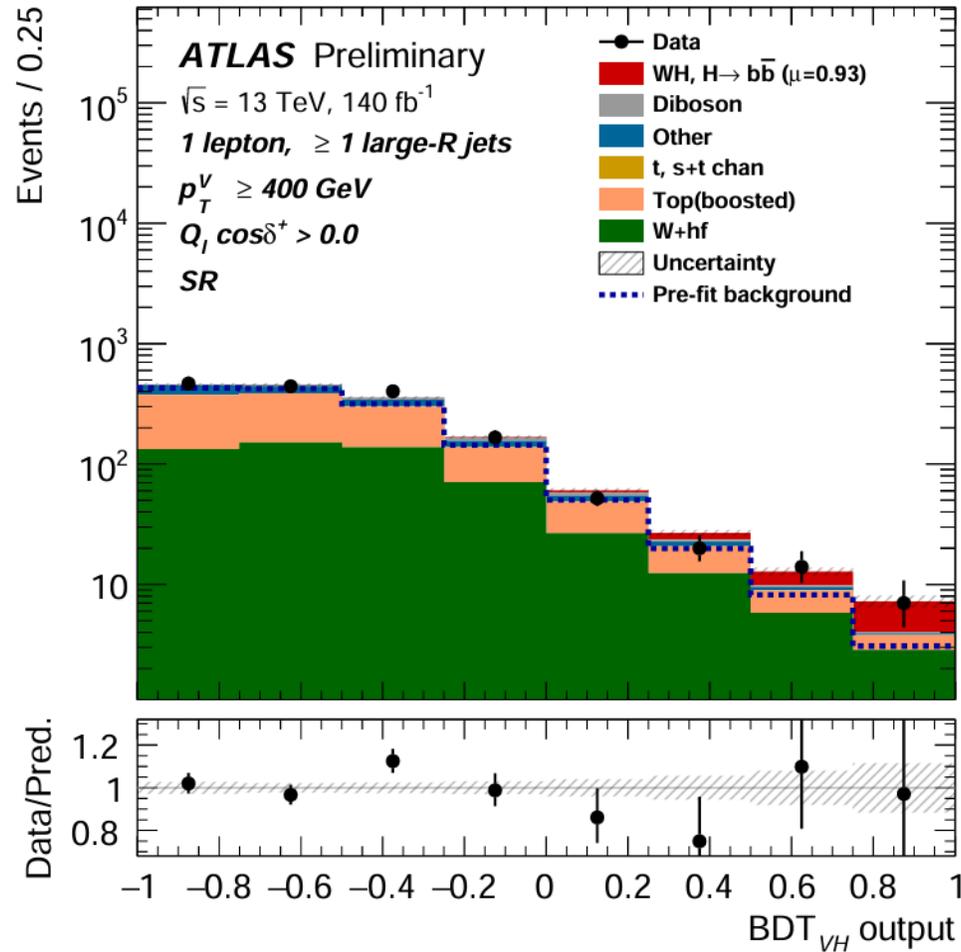
$$\sigma_{\text{fid}} \equiv \sigma \cdot \mathcal{B}(H \rightarrow ZZ^* \rightarrow 4\ell)$$

$$= [3.5 \pm 0.5(\text{stat.}) \text{ } ^{+0.3}_{-0.2}(\text{sys.})] \text{ fb}$$

SM prediction of $\sigma_{\text{fid}}^{\text{SM}} = 3.7 \pm 0.1 \text{ fb}$

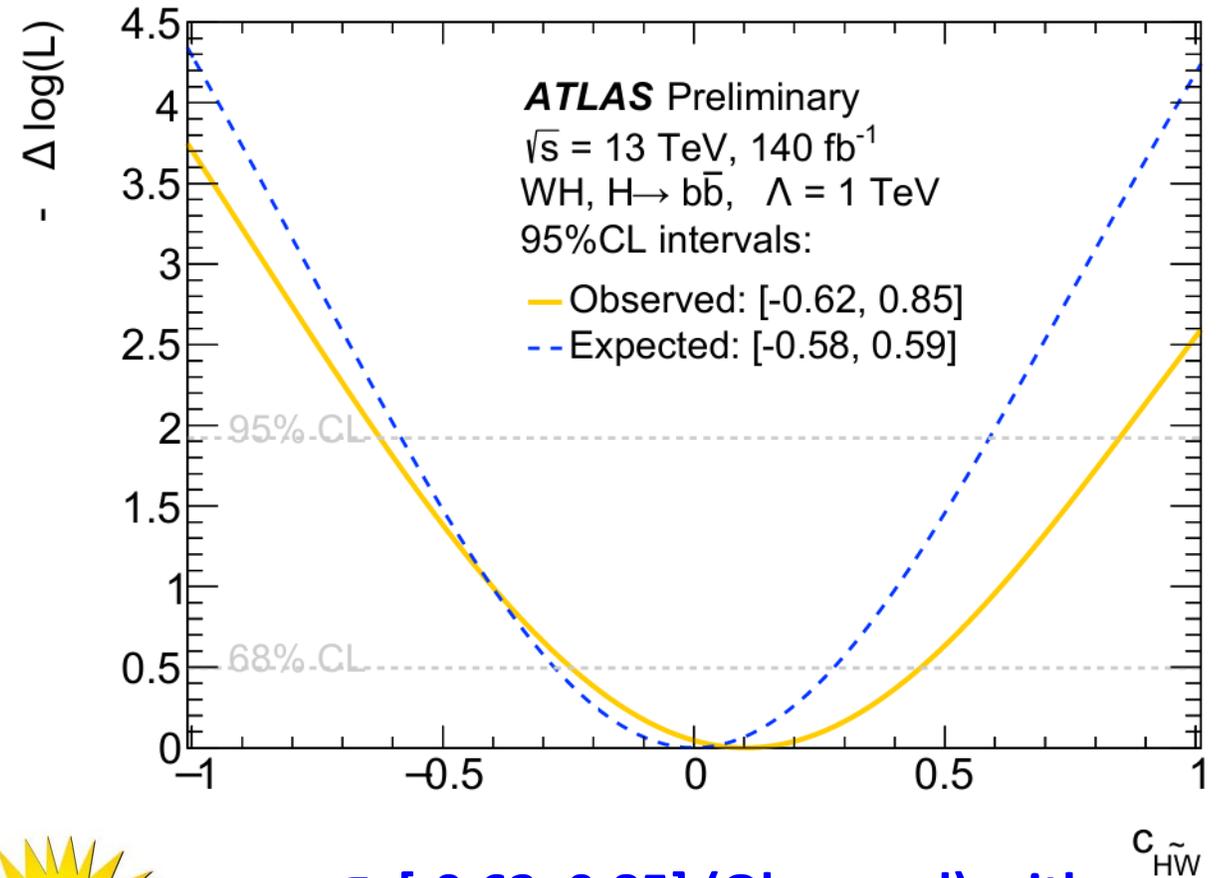
Wilson coefficient	Expected		Observed		Best-fit value
	68% CL	95% CL	68% CL	95% CL	
c_{HW}	[-1.2, 1.4]	[-2.1, 2.3]	[-1.7, 1.5]	[-2.8, 2.7]	-0.9
c_{HB}	[-0.4, 0.4]	[-0.7, 0.6]	[-0.6, 0.5]	[-0.9, 0.7]	-0.3
c_{HWB}	[-0.9, 0.7]	[-1.3, 1.1]	[-1.0, 0.9]	[-1.5, 1.4]	0.5

➤ Using 140/fb WH, H→bb to probe Higgs CP-violating in the EFT framework



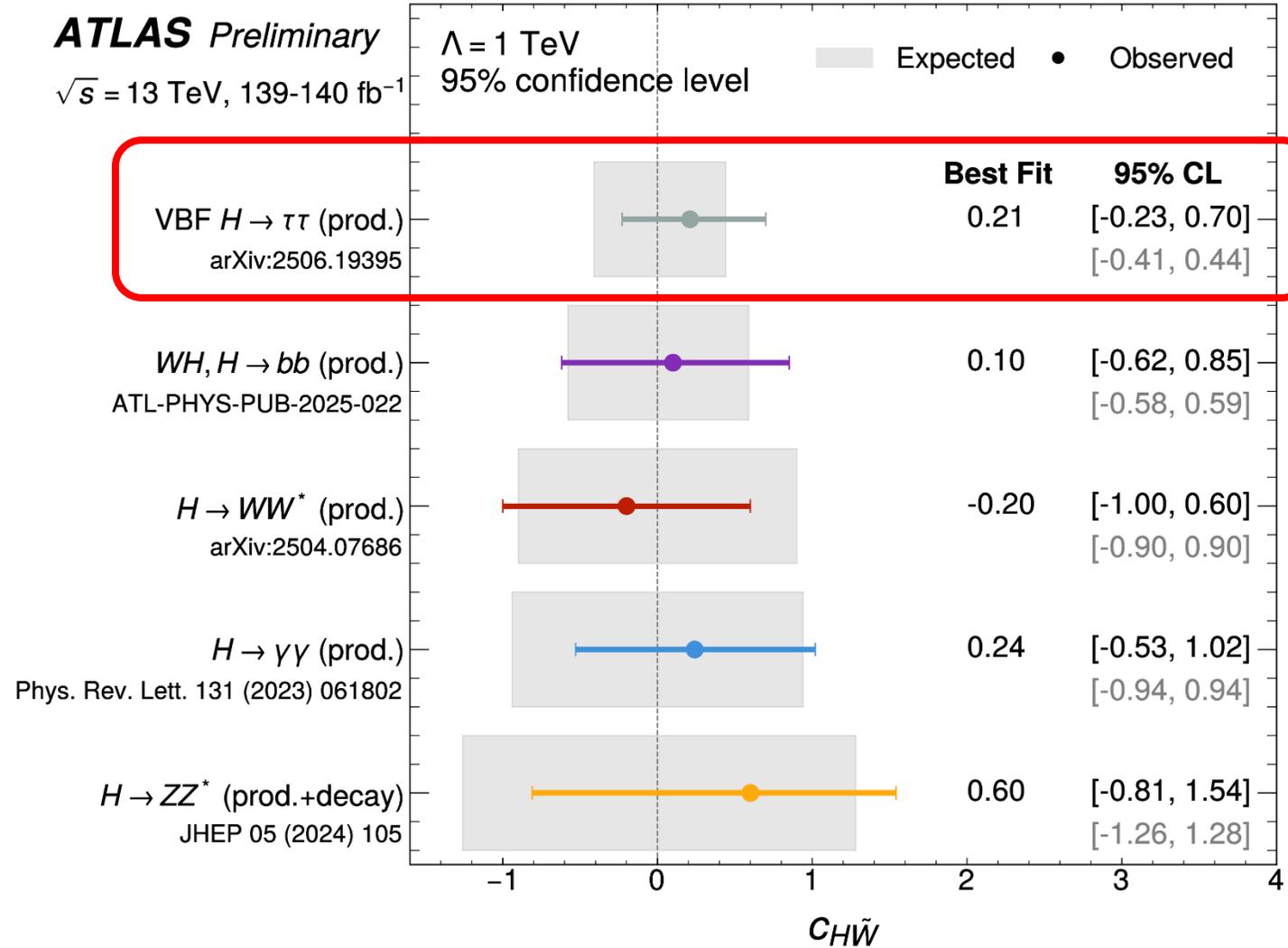
Observed (expected): 4.7 σ (5.0 σ)

$$\mu_{WH}^{bb} = 0.93_{-0.21}^{+0.22} = 0.93_{-0.15}^{+0.15} (\text{stat.})_{-0.15}^{+0.16} (\text{syst.})$$



$c_{\widetilde{HW}} \in [-0.62, 0.85]$ (Observed) with expected limit [-0.58, 0.59] at 95% CL

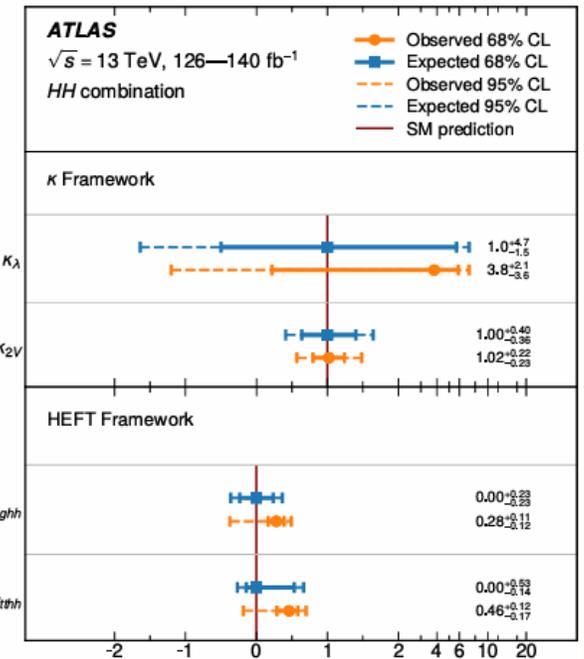
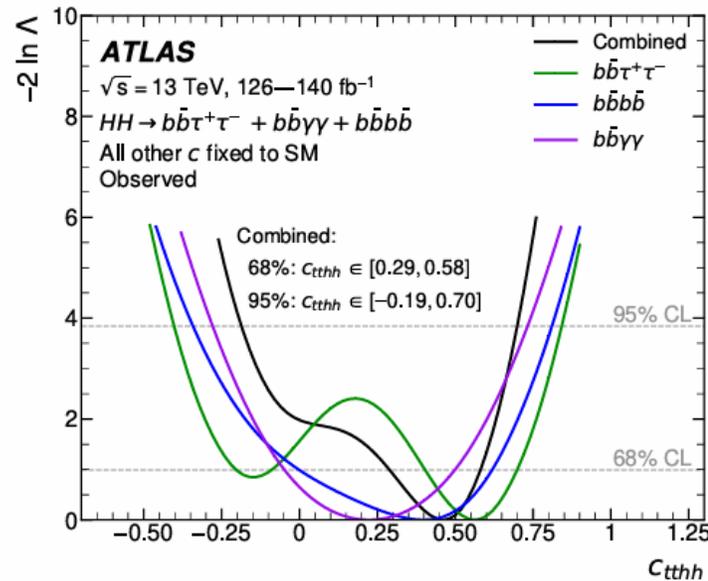
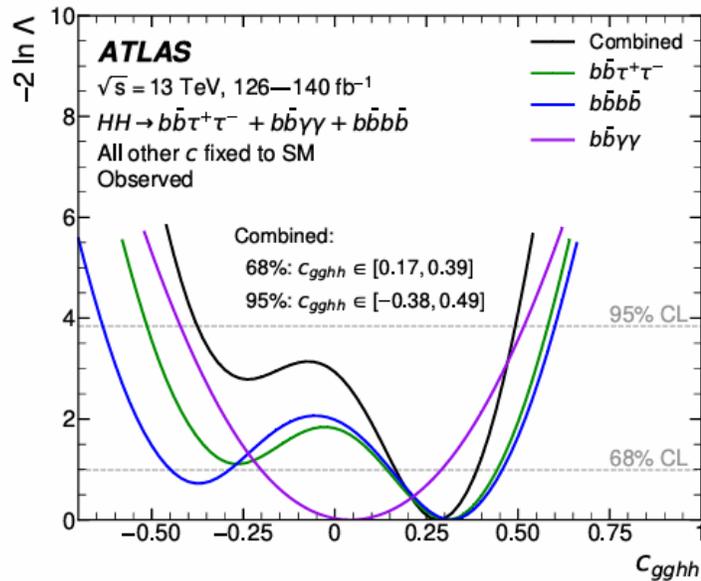
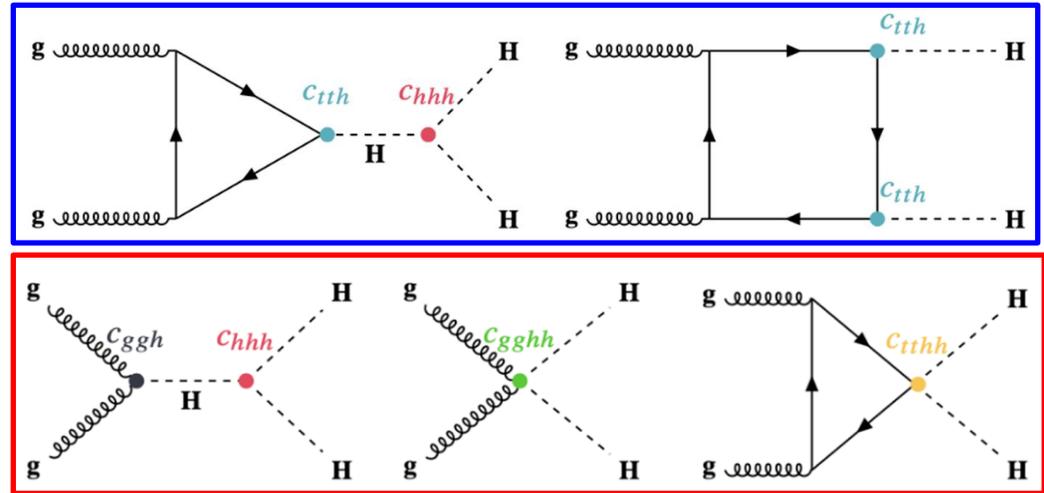
→ CP-violating parameter $C_{H\tilde{W}}$ in EFT is consistent with SM value.



→ Most stringent limit !

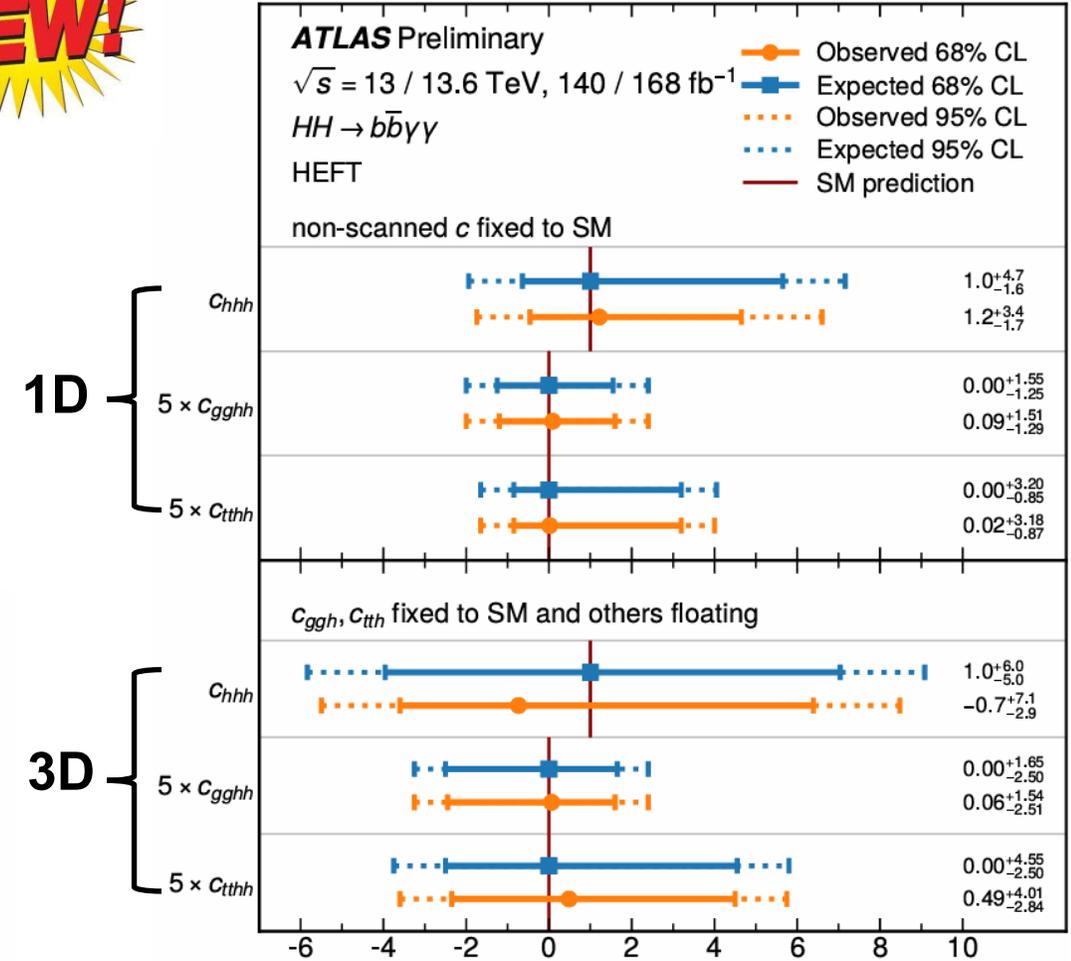
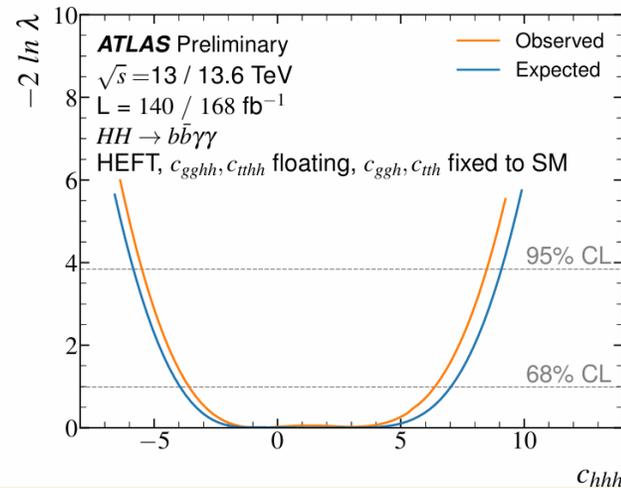
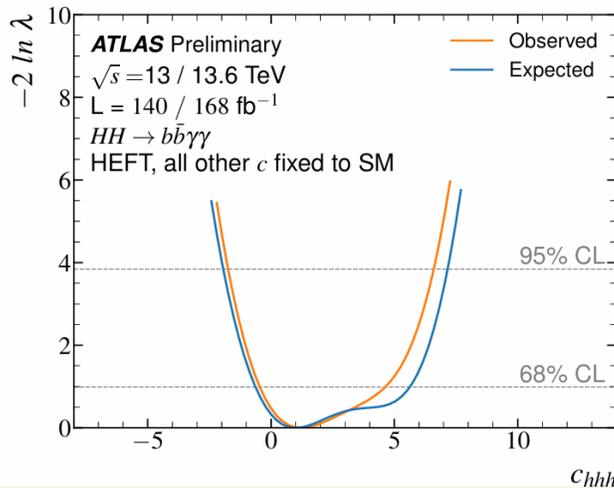


→ ATLAS has performed HEFT interpretation of Run2 HH searches
 → Constraints on the c_{gghh} and c_{tthh} anomalous couplings, all others are set to their SM value



- ➔ Run2 (140/fb) and Run3 (168/fb)
- HH → bb̄γγ interpretation in HEFT
- ➔ Include the EFT effects on VBF HH
- ➔ 1D constraints are comparable to those obtained in the Run2 HH combination
- ➔ Large differences between 1D and 3D constraints show important correlations of three HEFT operators on HH signal.

NEW!



- Higgs boson is considered as a portal to explore new physics beyond the SM via CP violation and EFT framework.
- **Higgs has CP-even nature, NO evidence of CP violation observed so far.**
- New CP measurements set limits on admixture scenarios and constraints to CP violation, the best limit: $c_{H\widetilde{W}} \in [-0.23, 0.70]$ (VBF $H \rightarrow \tau\tau$) @ 95% CL
- It's important to keep searching for various Higgs productions & decay modes with larger statistics and more coverage, providing more inputs to global EFT fits.

Please stay tuned, thanks !

➤ CP of Higgs Couplings to Fermions and Bosons

➤ Higgs-tau coupling: $H \rightarrow \tau\tau$ [EPJC 83 (2023) 563]

➤ Higgs-top coupling (ttH/tH)

○ $H \rightarrow \gamma\gamma$ [PRL 125 (2020) 061802]

○ $H \rightarrow bb$ [PLB 849 (2024) 138469]

➤ Higgs-VV coupling and EFT measurements

○ $H \rightarrow WW^* \rightarrow l\nu l\nu$ [arXiv:2504.07686]

○ VBF $H \rightarrow \tau\tau$ [JHEP 03 (2025) 010]

○ VBF $H \rightarrow \gamma\gamma$ [PRL 131 (2023) 061802]

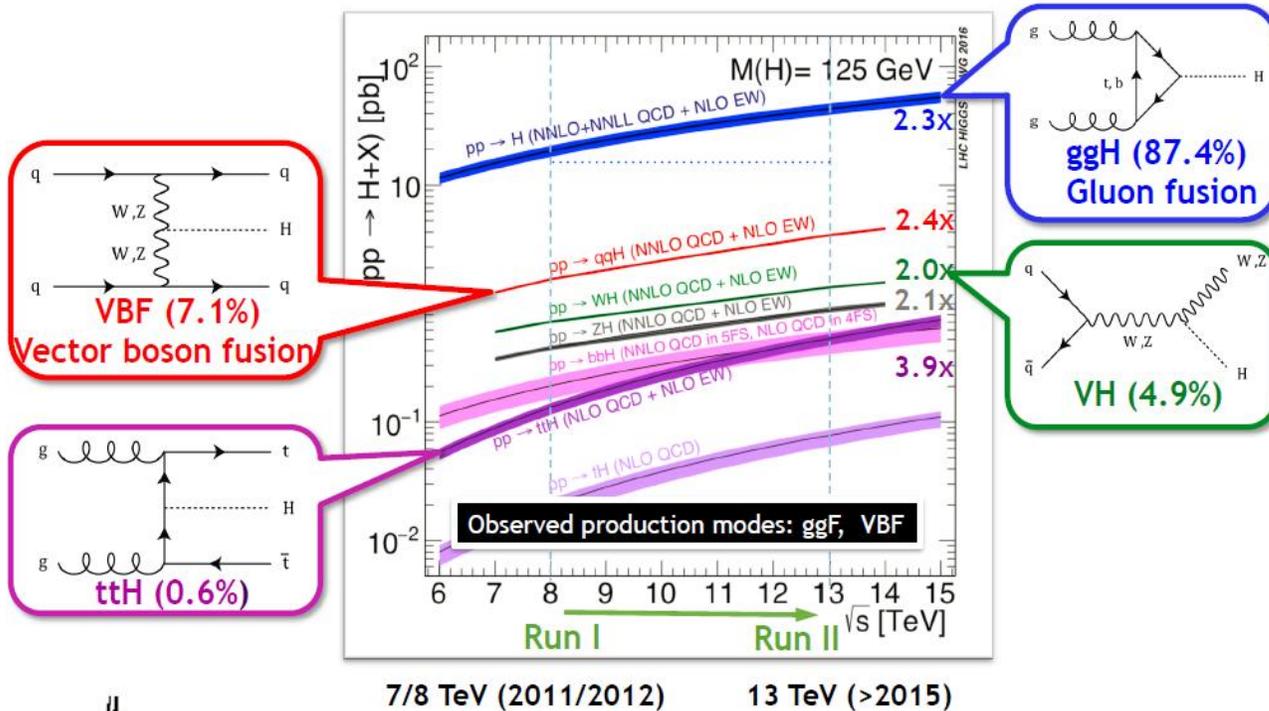
○ $H \rightarrow ZZ^* \rightarrow 4l$ [JHEP 05 (2024) 105, ATLAS-CONF-2025-002]

○ WH, $H \rightarrow bb$ [ATL-PHYS-PUB-2025-022]

○ $HH \rightarrow bbbb, bb\tau\tau, bb\gamma\gamma$ [Phys. Rev. Lett. 133 (2024) 101801, ATL-CONF-2025-05]

Higgs Productions

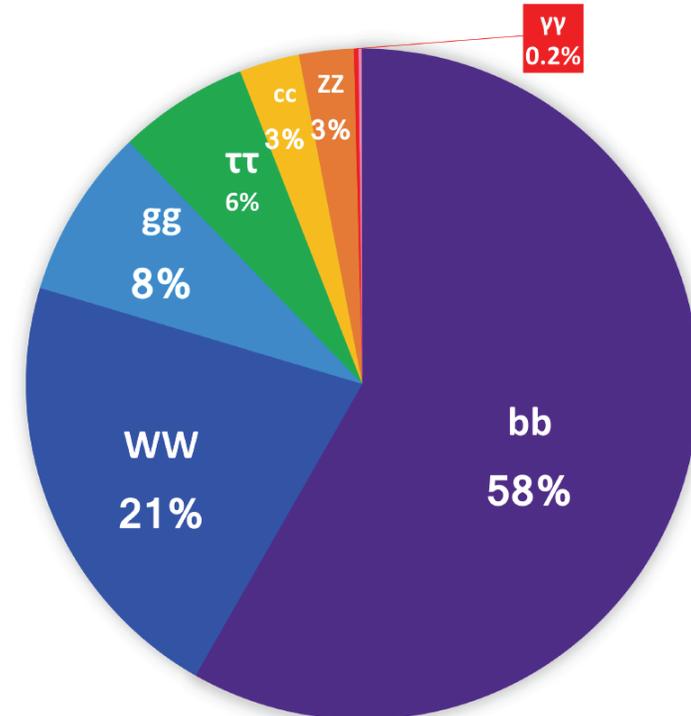
proton-proton →



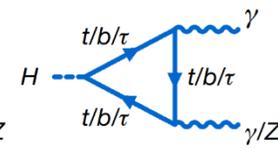
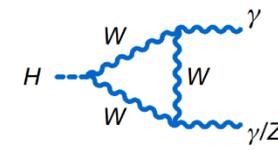
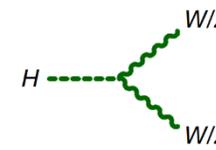
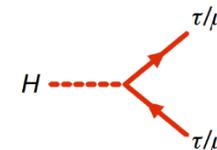
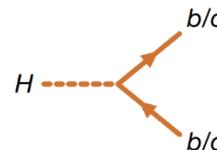
Higgs Decays



→ SM



$\rightarrow \sigma_{ggF} = 48.6 \text{ pb}, \sigma_{VBF} = 3.78 \text{ pb}$
 $\rightarrow \sigma_{VH} = 2.25 \text{ pb}, \sigma_{ttH} = 0.51 \text{ pb}$



Process	Matrix element	PDF set	UE/PS model	Prediction order
$ggF H$	POWHEG BOX v2 (MADGRAPH5_AMC@NLO)	PDF4LHC15NNLO	PYTHIA 8.212 (HERWIG 7.13)	N ³ LO QCD + NLO EW
$VBF H$	POWHEG BOX v2 (MADGRAPH5_AMC@NLO)	PDF4LHC15NNLO	PYTHIA 8.230 (HERWIG 7.13)	NNLO QCD + NLO EW
VH	POWHEG BOX v2	PDF4LHC15NNLO	PYTHIA 8.212	NNLO QCD + NLO EW
$gg \rightarrow ZH$	POWHEG BOX v2	PDF4LHC15NNLO	PYTHIA 8.212	NLO + NLL
$t\bar{t}H$	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	NLO QCD + NLO EW
$Z/\gamma^* \rightarrow ee/\mu\mu$	SHERPA 2.2.11	NNPDF3.0NNLO	SHERPA 2.2.11	NNLO
$Z/\gamma^* \rightarrow \tau\tau$	SHERPA 2.2.14	NNPDF3.0NNLO	SHERPA 2.2.14	NNLO
$VV/V\gamma^*$	SHERPA 2.2.11/2.2.12	NNPDF3.0NNLO	SHERPA 2.2.12	NLO
$V+\gamma$	SHERPA 2.2.8	NNPDF3.0NNLO	SHERPA 2.2.8	NLO
$gg \rightarrow VV$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	NLO
VVV	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	NLO
$EW Zjj$	HERWIG 7.1.3/7.2.0	MMHT2014NLO	HERWIG 7.1.3/7.2.0	NLO
$EW VVjj$	MADGRAPH	NNPDF3.0NLO	PYTHIA 8	LO
$t\bar{t}$	POWHEG BOX v2 (POWHEG BOX v2, $p_T^{\text{hard}} = 1$)	NNPDF3.0NLO	PYTHIA 8.230 (HERWIG 7.04)	NNLO + NNLL
Wt	POWHEG BOX v2 (POWHEG BOX v2, $p_T^{\text{hard}} = 1$)	NNPDF3.0NLO	PYTHIA 8.230 (HERWIG 7.04)	NLO + NNLL

For $d = 6$ operators, the expected

- Higgs production cross-sections (σ_i)
- Higgs partial width ($\Gamma_{H \rightarrow WW^*}$)
- Higgs total width (Γ_H)
- Signal strength (μ_{ij})

are linear function of Wilson coefficients

$$\sigma_i \rightarrow \sigma_i \times \left(1 + \sum_{j=1}^M A_j^{\sigma_i} \times c_j \right) \forall i = 1, \dots, N,$$

$$\Gamma^{H \rightarrow WW^*} \rightarrow \Gamma^{H \rightarrow WW^*} \times \left(1 + \sum_{j=1}^M A_j^{\Gamma^{H \rightarrow WW^*}} \times c_j \right)$$

$$\Gamma^H \rightarrow \Gamma^H \times \left(1 + \sum_{j=1}^M A_j^{\Gamma^H} \times c_j \right),$$

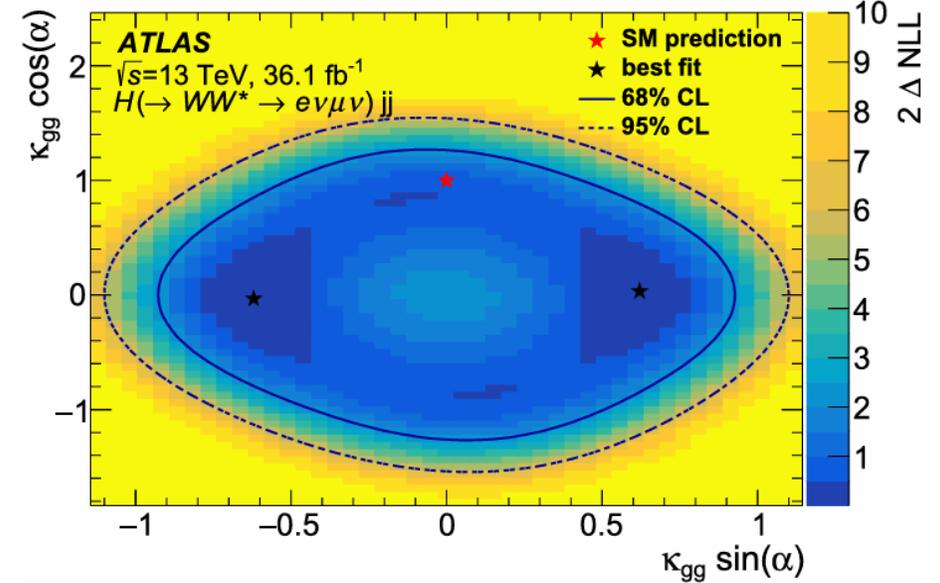
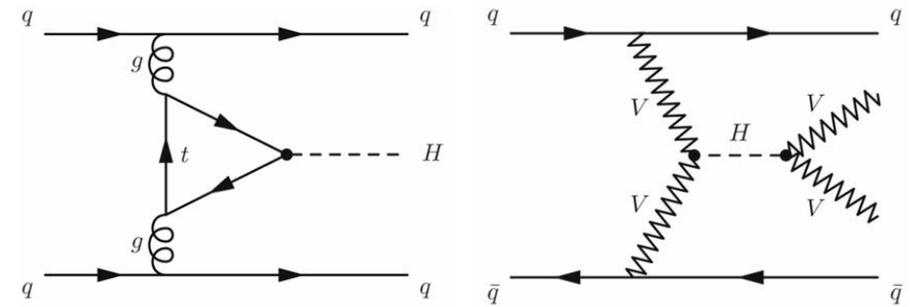
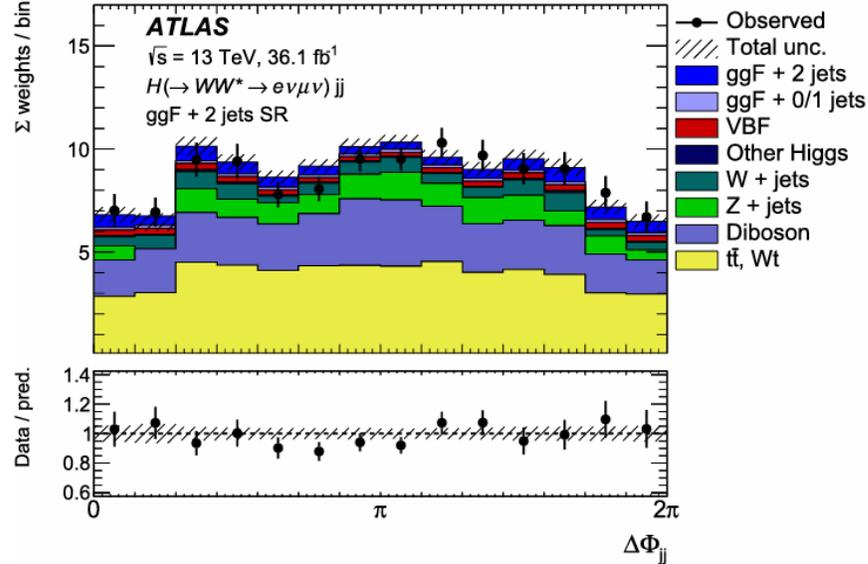
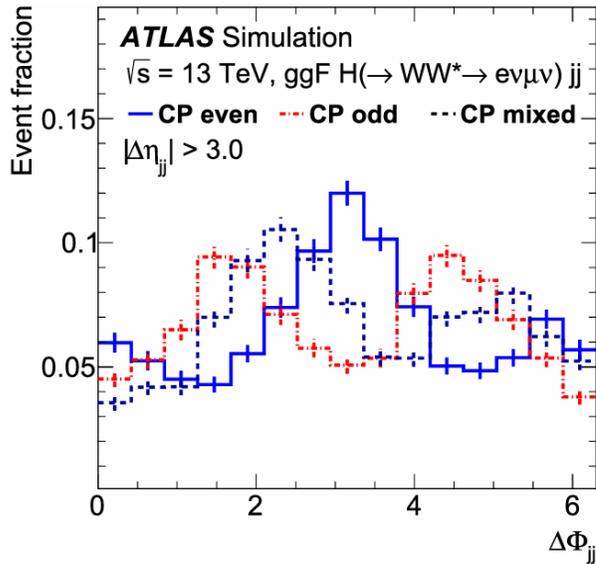
$$\mu_{ij} \rightarrow \mu_{ij} \times \mu_i^{\text{NF}} \times \frac{\left(1 + \sum_k (A_k^{\sigma_{ij}} + A_k^{\Gamma^{H \rightarrow WW^*}}) \times c_k \right)}{1 + \sum_k A_k^{\Gamma^H} \times c_k}$$

- **Principal Component Analysis (PCA)** : BSM couplings may have similar impacts on signal strengths in STXS categories, resulting in highly correlated Wilson coefficients. This may lead to poor convergence of the fit. Therefore, a rotation of Warsaw basis is performed to identify the directions, i.e. the set of mutually orthogonal linear combinations of Wilson coefficients for which the analysis has the greatest sensitivity, a procedure known as PCA.
- Covariance matrix of the Wilson coefficients, $\mathbf{C}_{\text{SMEFT}}$, is obtained by transforming the expected covariance matrix of the STXS signal strengths, \mathbf{C}_{STXS} :

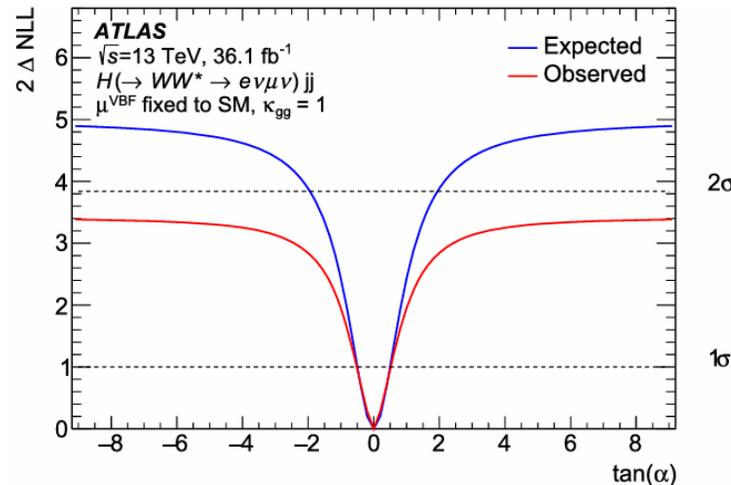
$$[\mathbf{P}]_{ij} \equiv P_{ij} = A_j^{\sigma_i} + A_j^{\Gamma^{H \rightarrow WW^*}} - A_j^{\Gamma^H}$$

$$\mathbf{C}_{\text{SMEFT}}^{-1} = \mathbf{P}^T \mathbf{C}_{\text{STXS}}^{-1} \mathbf{P}$$

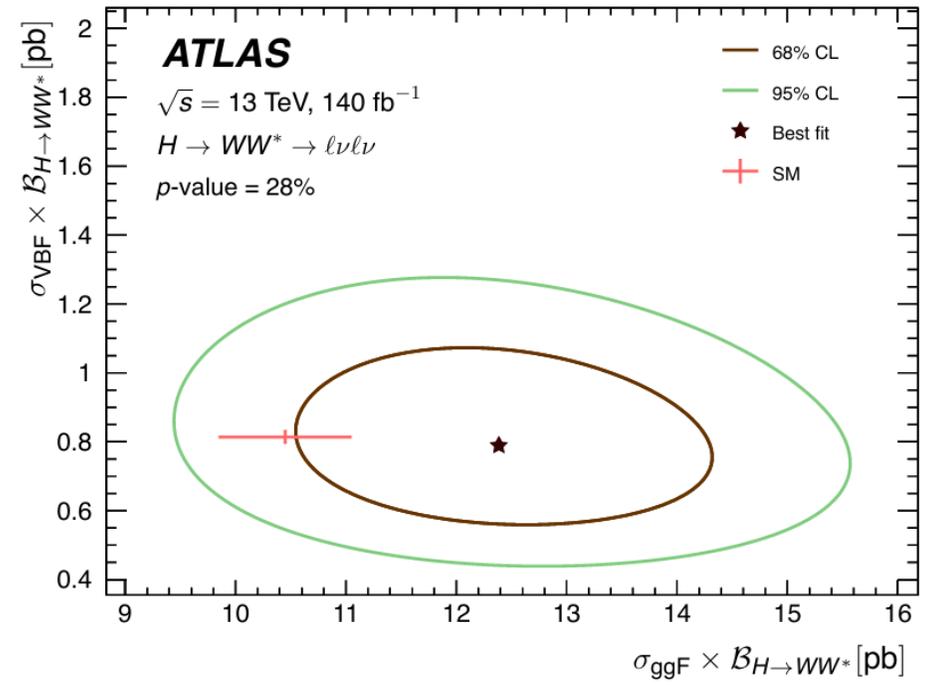
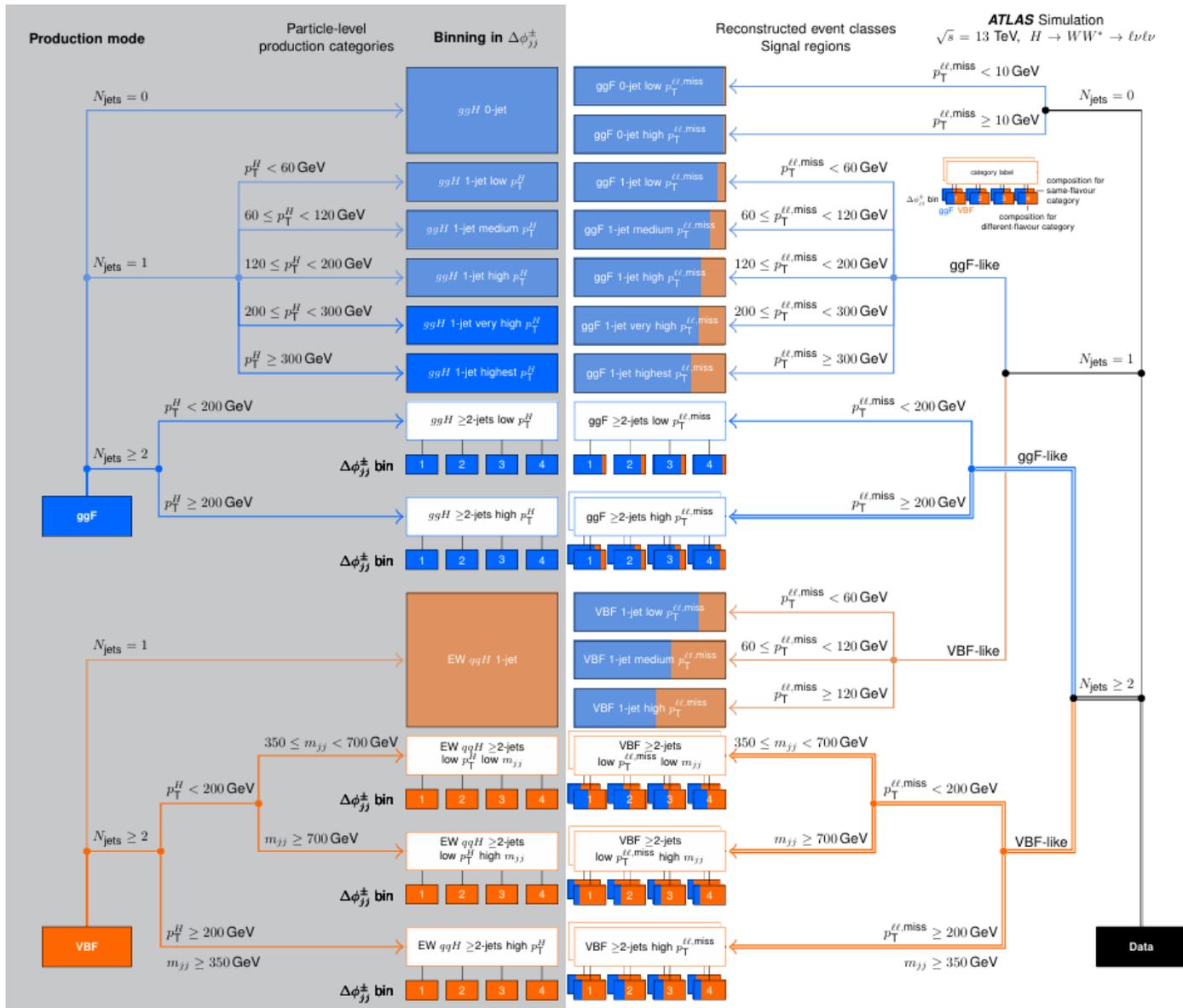
➤ CP-odd is primarily sensitive to the $\Delta\Phi_{jj}$



- Best-fit values agree with SM at 68% CL
- $|\kappa_{gg} \cos(\alpha)| > 1.6$ and $|\kappa_{gg} \sin(\alpha)| > 1.1$ are excluded at 95% CL



➤ CP mixing angle:
 $\tan(\alpha) = 0.0 \pm 0.4(\text{stat.}) \pm 0.3(\text{syst.})$



$$\sigma_{\text{ggF}} \times \mathcal{B}_{H \rightarrow WW^*} = 12.4^{+1.3}_{-1.2} \text{ pb}$$

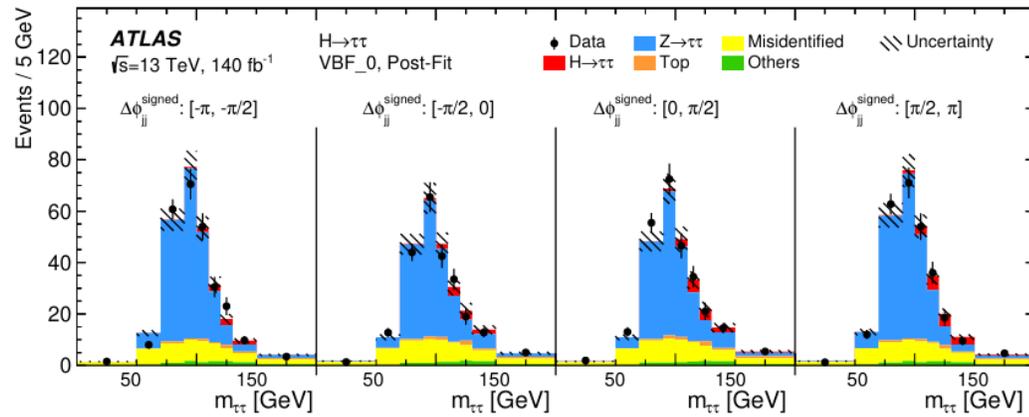
$$= 12.4 \pm 0.6 \text{ (stat.)} \pm 0.9 \text{ (exp. syst.)}$$

$$\sigma_{\text{VBF}} \times \mathcal{B}_{H \rightarrow WW^*} = 0.79^{+0.18}_{-0.16} \text{ pb}$$

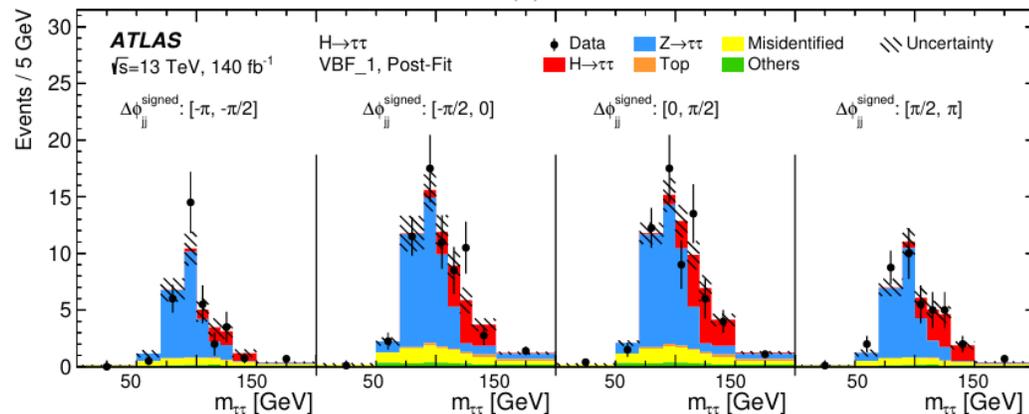
$$= 0.79 \pm 0.11 \text{ (stat.)}^{+0.07}_{-0.06} \text{ (exp. syst.)}$$

- Using VBF $H \rightarrow \tau\tau$ to probe CP-violating of HVV couplings in EFT framework
- $\Delta\phi_{jj}$ is a sensitive observable to CPV.

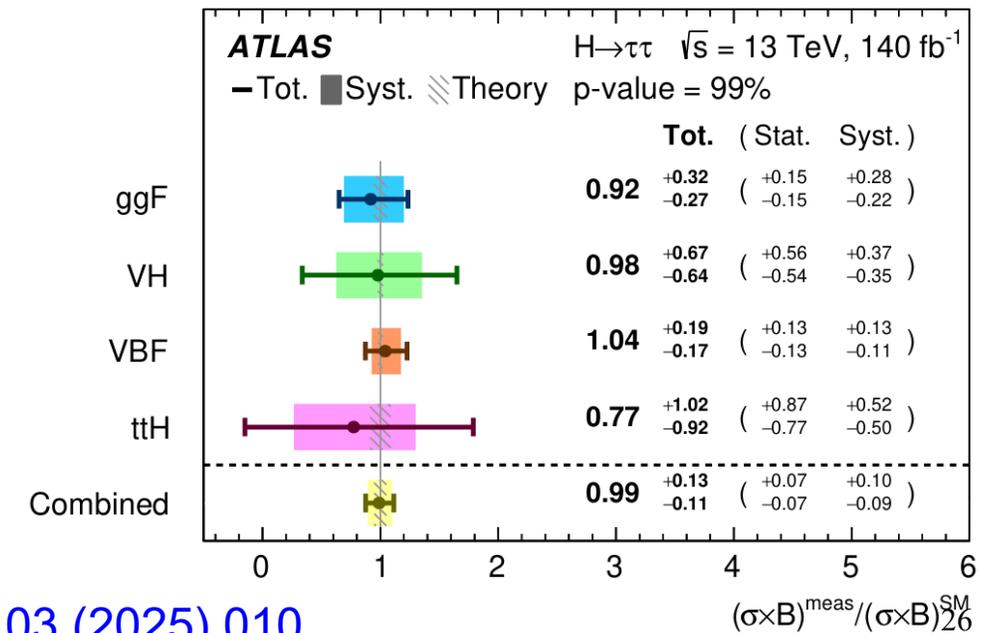
$$\sigma_{\text{SM+EFT}}^k = \sigma_{\text{SM}}^k \left(1 + \alpha_{ik} \frac{c_i}{\Lambda^2} + \beta_{ik} \left(\frac{c_i}{\Lambda^2} \right)^2 \right)$$



(a)



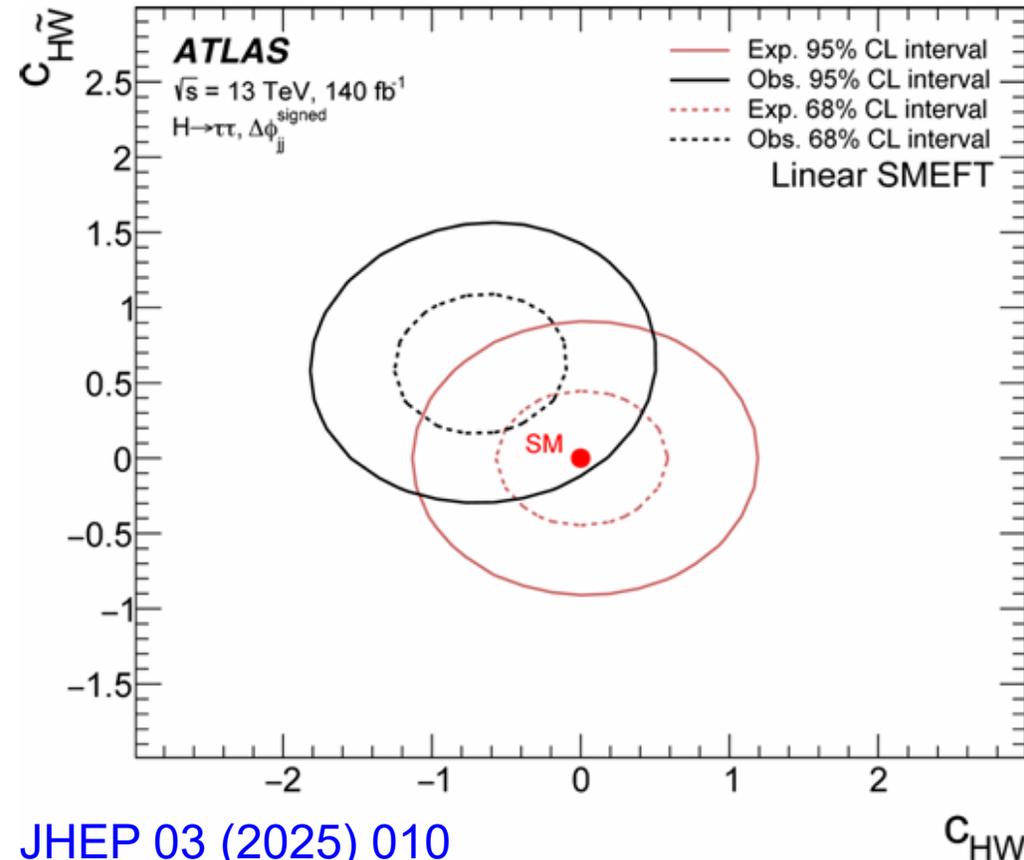
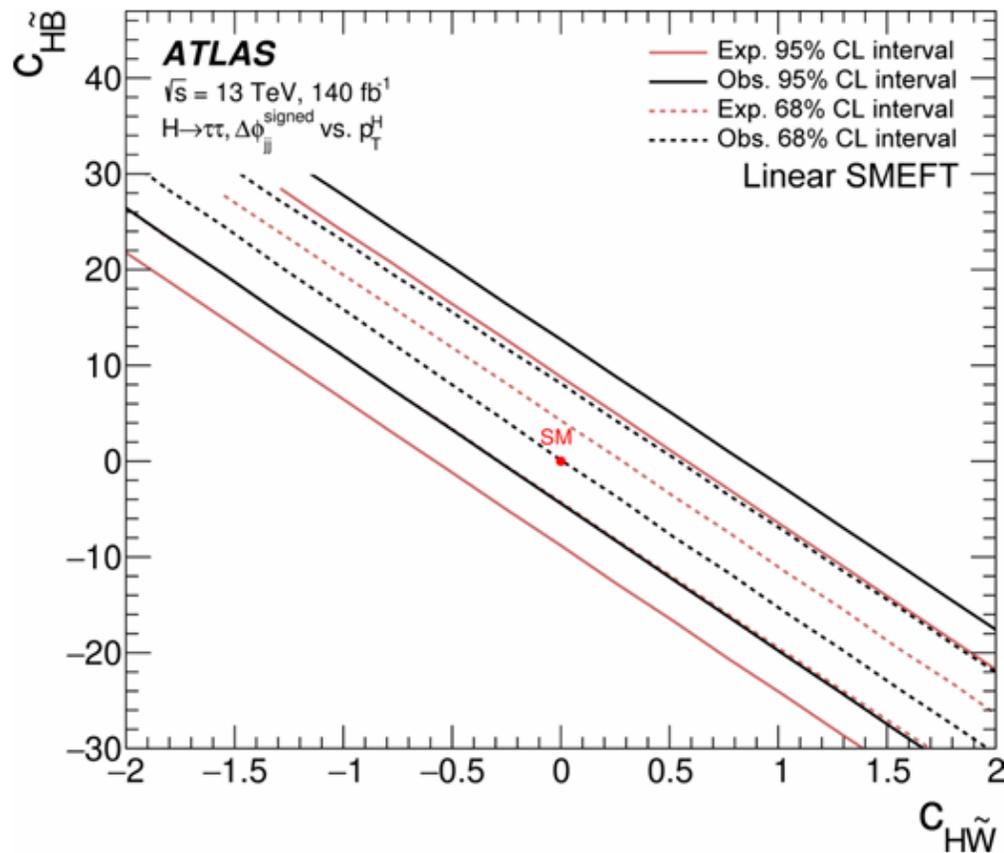
Production mode	$\sigma_H \times B(H \rightarrow \tau\tau)$ [pb]	
	SM prediction	Measurement
ggF	2.77 ± 0.09	2.5 ± 0.8
VH	0.117 ± 0.003	0.11 ± 0.08
VBF	0.220 ± 0.005	0.23 ± 0.04
$t\bar{t}H$	0.031 ± 0.003	0.02 ± 0.03



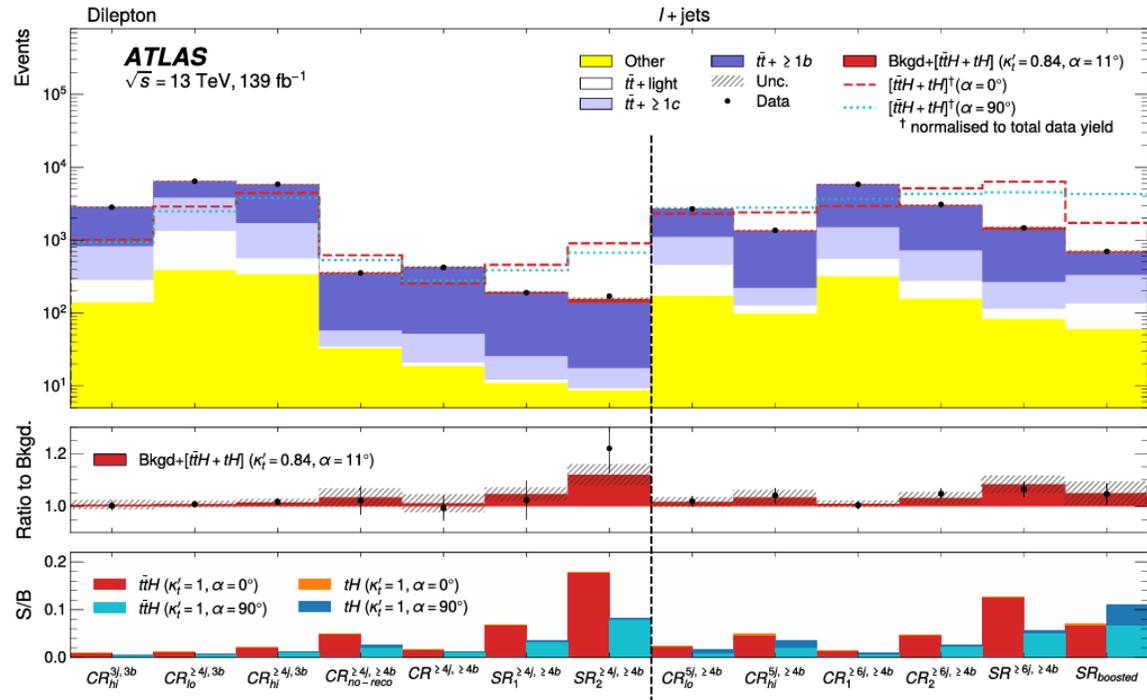
- Using VBF H → ττ to probe CP-violating of HVV couplings in EFT framework
- $\Delta\phi_{jj}$ is a sensitive observable to CPV.

$$\sigma_{\text{SM+EFT}}^k = \sigma_{\text{SM}}^k \left(1 + \alpha_{ik} \frac{c_i}{\Lambda^2} + \beta_{ik} \left(\frac{c_i}{\Lambda^2} \right)^2 \right)$$

	CP-even		
Operator $\mathcal{O}_i^{(d=6)}$	$H^\dagger H W_{\mu\nu}^n W^{n\mu\nu}$	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$H^\dagger \tau^n H W_{\mu\nu}^n B^{\mu\nu}$
Wilson coefficient	c_{HW}	c_{HB}	c_{HWB}
	CP-odd		
Operator $\mathcal{O}_i^{(d=6)}$	$H^\dagger H \tilde{W}_{\mu\nu}^n W^{n\mu\nu}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$H^\dagger \tau^n H \tilde{W}_{\mu\nu}^n B^{\mu\nu}$
Wilson coefficient	$c_{H\tilde{W}}$	$c_{H\tilde{B}}$	$c_{H\tilde{W}B}$



CP: Higgs-Top coupling ($t\bar{t}H/tH, H \rightarrow bb$)

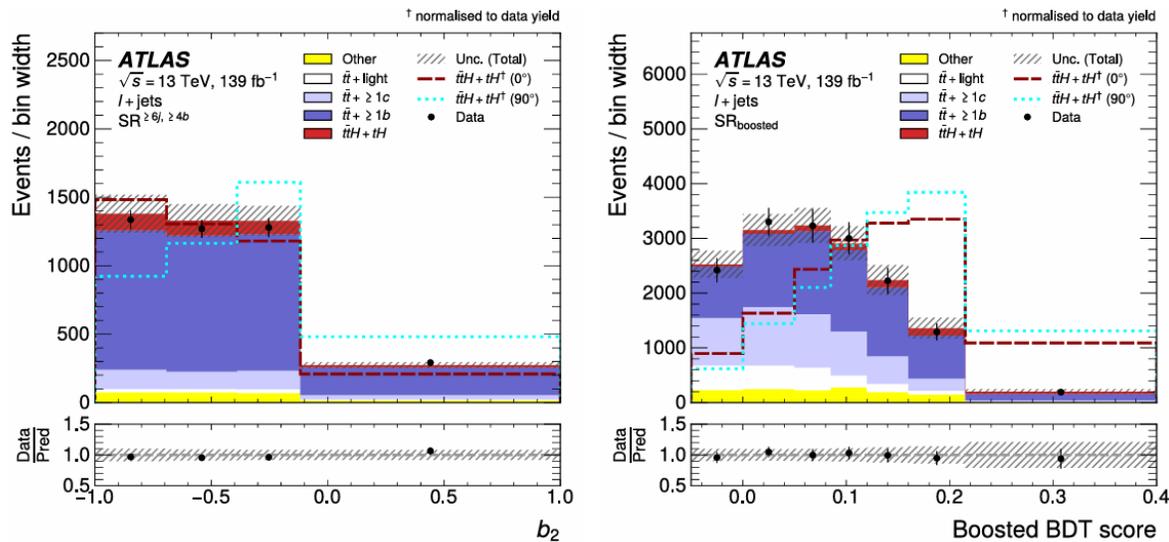


➤ $t\bar{t}H/tH, H \rightarrow bb$ in lepton + jet channel

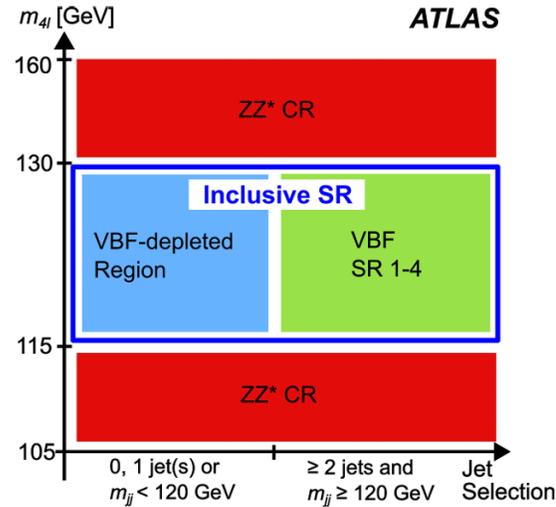
	$CR_{lo}^{5j, \geq 4b}$	$CR_{hi}^{5j, \geq 4b}$	$CR_1^{\geq 6j, \geq 4b}$	$CR_2^{\geq 6j, \geq 4b}$	$SR^{\geq 6j, \geq 4b}$	$SR_{boosted}$
$t\bar{t}H (1, 0^\circ)$	60 ± 9	63 ± 10	78 ± 11	139 ± 18	173 ± 26	46 ± 6
$tH (1, 0^\circ)$	3.5 ± 0.5	3.8 ± 0.6	3.3 ± 0.6	2.3 ± 0.6	1.3 ± 0.4	1.9 ± 0.4
$t\bar{t}H (1, 90^\circ)$	28 ± 6	28 ± 6	45 ± 11	61 ± 12	68 ± 16	45 ± 6
$tH (1, 90^\circ)$	19.0 ± 2.8	19.4 ± 3.1	17.4 ± 3.1	13.1 ± 3.5	10 ± 4	29 ± 6
$t\bar{t}H (0.84, 11^\circ)$	40 ± 30	41 ± 31	50 ± 40	90 ± 70	110 ± 80	30 ± 22
$tH (0.84, 11^\circ)$	3 ± 4	3.9 ± 1.9	3.1 ± 1.9	1.9 ± 0.8	1.3 ± 1.7	3 ± 5
$t\bar{t} + \geq 1b$	1530 ± 80	1090 ± 60	4300 ± 120	2220 ± 120	1110 ± 110	335 ± 30
$t\bar{t} + \geq 1c$	650 ± 50	96 ± 11	950 ± 80	450 ± 40	153 ± 15	196 ± 22
$t\bar{t} + \text{light}$	280 ± 40	28 ± 8	230 ± 60	117 ± 26	32 ± 11	76 ± 15
Other	173 ± 30	99 ± 20	320 ± 50	159 ± 21	83 ± 11	60 ± 11
Total	2690 ± 50	1350 ± 40	5870 ± 80	3040 ± 70	1500 ± 50	701 ± 31
Data	2696	1363	5837	3090	1470	699

➤ $t\bar{t}H/tH, H \rightarrow bb$ in di-lepton channel

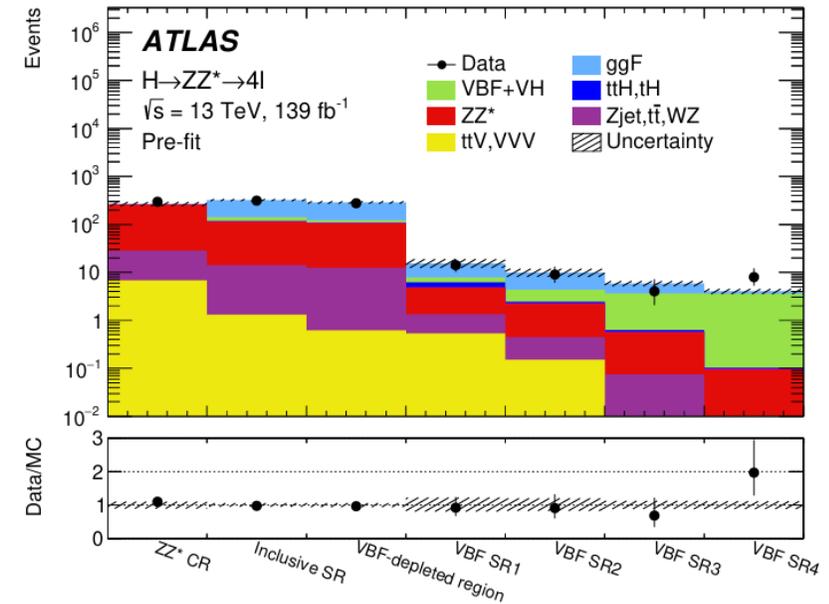
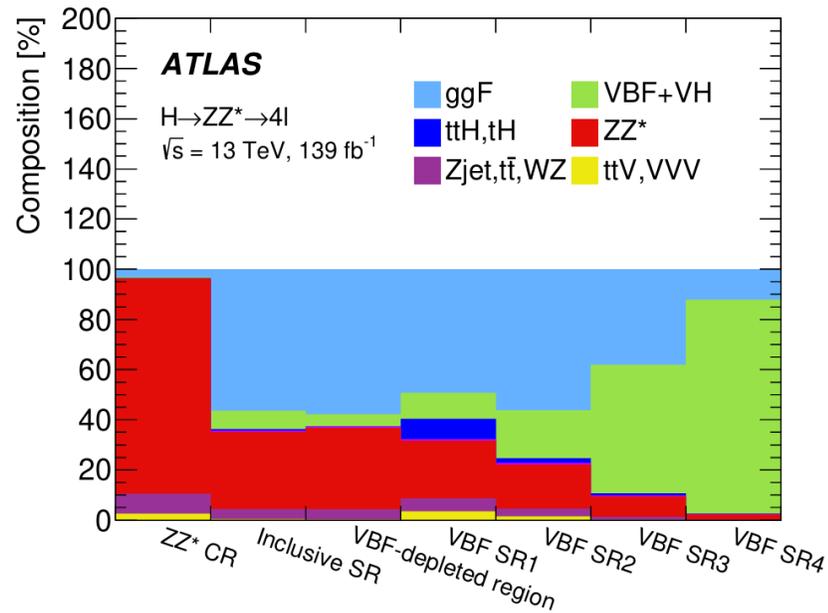
	$CR_{hi}^{3j, 3b}$	$CR_{lo}^{\geq 4j, 3b}$	$CR_{hi}^{\geq 4j, 3b}$	$CR_{no-reco}^{\geq 4j, \geq 4b}$	$CR^{\geq 4j, \geq 4b}$	$SR_1^{\geq 4j, \geq 4b}$	$SR_2^{\geq 4j, \geq 4b}$
$t\bar{t}H (1, 0^\circ)$	26 ± 4	79 ± 8	120 ± 12	16.9 ± 2.1	6.9 ± 1.1	12.5 ± 1.5	24.8 ± 2.9
$tH (1, 0^\circ)$	1.12 ± 0.13	0.90 ± 0.13	1.74 ± 0.20	0.19 ± 0.08	0.087 ± 0.035	0.100 ± 0.033	0.09 ± 0.06
$t\bar{t}H (1, 90^\circ)$	10.6 ± 1.6	35.6 ± 3.5	54 ± 5	7.2 ± 0.9	4.3 ± 0.6	6.1 ± 0.7	10.9 ± 1.3
$tH (1, 90^\circ)$	5.4 ± 0.6	7.0 ± 1.0	10.7 ± 1.2	1.8 ± 0.8	0.48 ± 0.19	0.48 ± 0.16	0.5 ± 0.4
$t\bar{t}H (0.84, 11^\circ)$	18 ± 14	50 ± 40	80 ± 60	11 ± 9	4.7 ± 3.4	8 ± 6	17 ± 12
$tH (0.84, 11^\circ)$	0.9 ± 0.5	1.0 ± 1.9	1.5 ± 1.3	0.17 ± 0.16	0.068 ± 0.016	0.08 ± 0.14	0.07 ± 0.09
$t\bar{t} + \geq 1b$	1990 ± 80	2520 ± 110	4040 ± 130	288 ± 15	371 ± 16	160 ± 8	122 ± 11
$t\bar{t} + \geq 1c$	550 ± 50	2510 ± 150	1160 ± 90	23 ± 4	31.1 ± 2.5	13.4 ± 1.6	8.2 ± 1.0
$t\bar{t} + \text{light}$	143 ± 27	960 ± 130	230 ± 40	1.7 ± 0.4	2.3 ± 0.8	1.4 ± 0.8	0.57 ± 0.25
Other	140 ± 11	390 ± 19	340 ± 40	33 ± 8	18.6 ± 2.5	10.9 ± 1.3	8.7 ± 1.0
Total	2840 ± 50	6430 ± 80	5850 ± 80	358 ± 12	428 ± 15	194 ± 5	156 ± 6
Data	2827	6429	5865	354	420	190	170

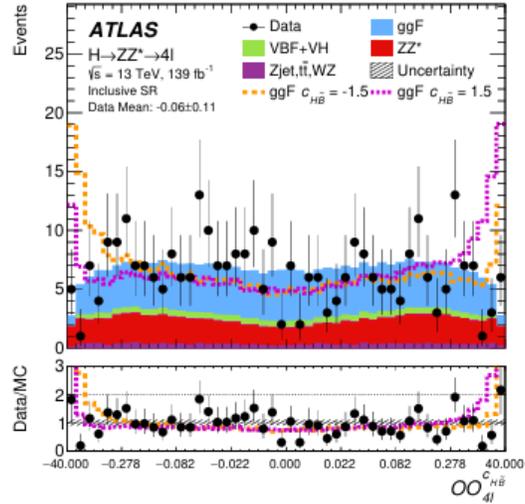


→ Events composition in various categories used for direct EFT coupling measurements.

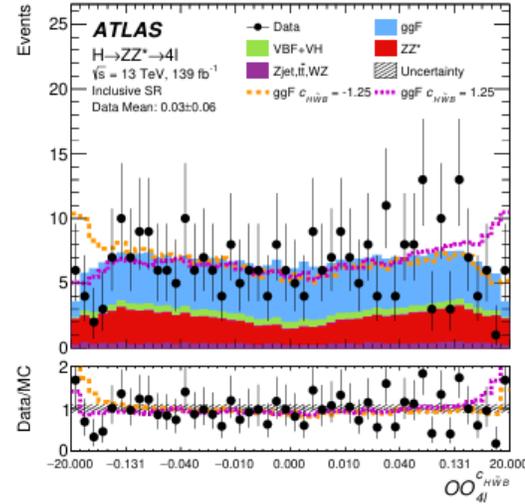


	ZZ* CR	Inclusive SR	VBF-depleted Region	SR1	SR2	SR3	SR4
ggF	8.2 ± 1.3	181 ± 12	165 ± 12	$7.5^{+3.0}_{-2.4}$	$5.6^{+1.8}_{-1.5}$	2.2 ± 0.6	0.49 ± 0.17
bbH	$0.087^{+0.016}_{-0.015}$	1.85 ± 0.05	1.65 ± 0.05	0.11 ± 0.01	$0.072^{+0.010}_{-0.009}$	$0.020^{+0.005}_{-0.003}$	< 0.01
VBF/VH	1.39 ± 0.16	23.8 ± 0.7	13.8 ± 0.6	$1.60^{+0.09}_{-0.08}$	1.89 ± 0.11	3.01 ± 0.18	3.5 ± 0.4
ttH, tH	$0.22^{+0.03}_{-0.04}$	$1.89^{+0.21}_{-0.22}$	0.44 ± 0.05	1.22 ± 0.14	0.179 ± 0.023	$0.046^{+0.009}_{-0.010}$	< 0.01
ttV, VVV	6.79 ± 0.13	1.31 ± 0.06	0.62 ± 0.04	0.53 ± 0.04	0.150 ± 0.020	< 0.01	< 0.01
ZZ*	229^{+20}_{-25}	98^{+6}_{-9}	92^{+6}_{-8}	$3.5^{+1.3}_{-1.7}$	1.7 ± 0.6	$0.48^{+0.16}_{-0.15}$	$0.086^{+0.025}_{-0.028}$
Zjet, $t\bar{t}, WZ$	21 ± 5	13 ± 4	12 ± 3	0.8 ± 0.9	0.3 ± 0.6	0.07 ± 0.26	0.01 ± 0.09
Total SM	267^{+21}_{-26}	321^{+14}_{-15}	286^{+14}_{-15}	15 ± 3	$9.9^{+2.0}_{-1.7}$	5.9 ± 0.7	4.1 ± 0.5
Data	294	311	276	14	9	4	8

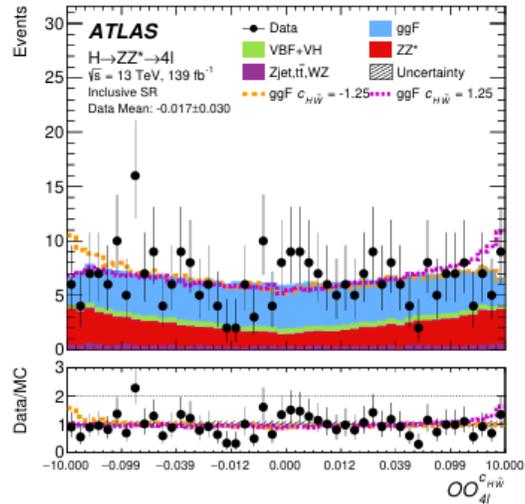




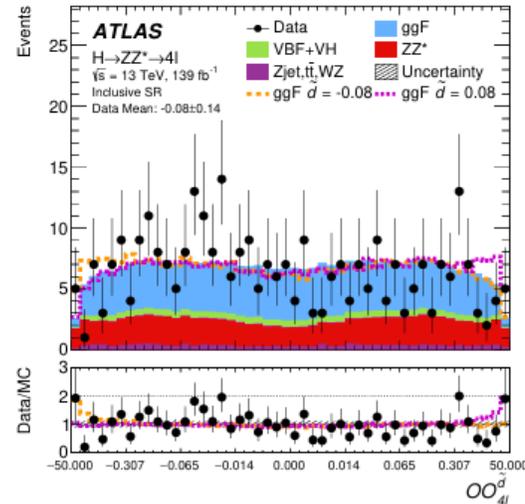
(a) $OO_{4l}^{c_{H\tilde{B}}}$



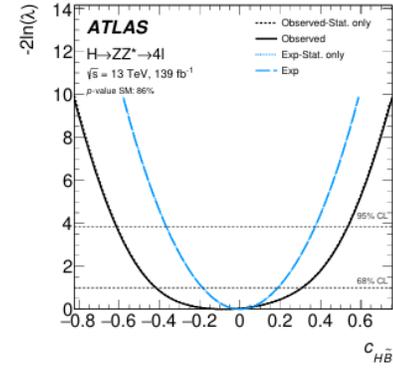
(b) $OO_{4l}^{c_{H\tilde{W}B}}$



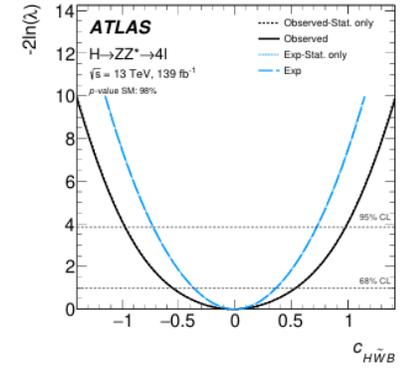
(c) $OO_{4l}^{c_{H\tilde{W}}}$



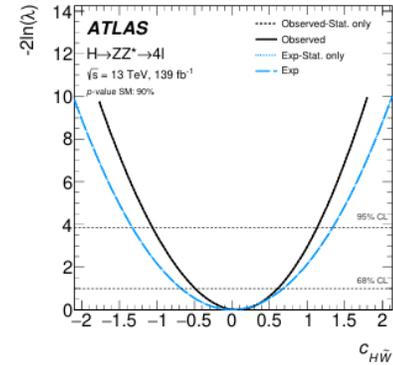
(d) $OO_{4l}^{\tilde{d}}$



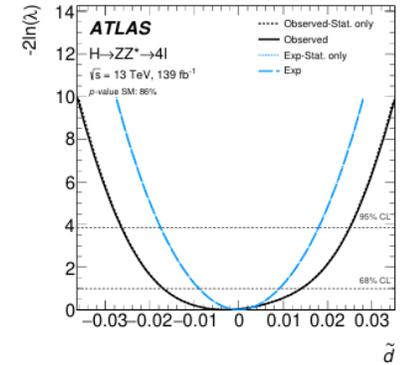
(a) $c_{H\tilde{B}}$



(b) $c_{H\tilde{W}B}$



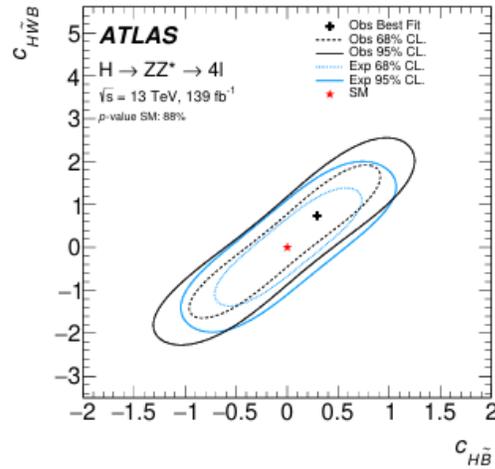
(c) $c_{H\tilde{W}}$



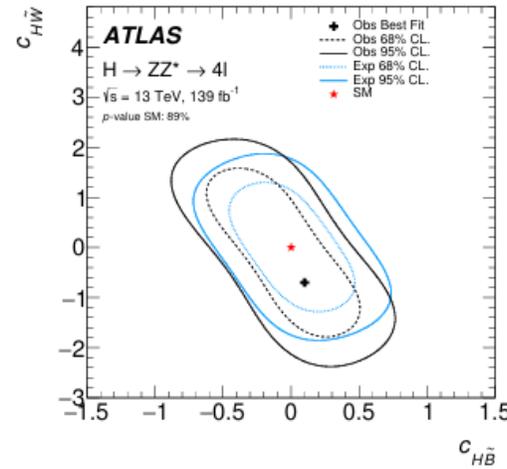
(d) \tilde{d}

EFT coupling parameter	Expected		Observed		Best-fit value	SM p -value	Fit type
	68% C.L.	95% C.L.	68% C.L.	95% C.L.			
$c_{H\tilde{B}}$	[-0.18, 0.19]	[-0.37, 0.37]	[-0.42, 0.31]	[-0.61, 0.54]	-0.078	0.86	decay
$c_{H\tilde{W}B}$	[-0.36, 0.36]	[-0.72, 0.72]	[-0.56, 0.53]	[-0.97, 0.98]	-0.017	0.99	decay
$c_{H\tilde{W}}$	[-0.63, 0.63]	[-1.26, 1.28]	[-0.07, 1.09]	[-0.81, 1.54]	0.60	0.37	comb
\tilde{d}	[-0.009, 0.009]	[-0.018, 0.018]	[-0.017, 0.014]	[-0.026, 0.025]	-0.003	0.86	decay
\tilde{c}_{zz}	[-0.77, 0.79]	[-2.4, 2.4]	[0.37, 1.21]	[-1.20, 1.75]	0.78	0.11	prod
$\tilde{c}_{z\gamma}$	[-0.47, 0.47]	[-0.76, 0.76]	[-0.54, 0.54]	[-0.84, 0.83]	0.083	0.93	decay
$\tilde{c}_{\gamma\gamma}$	[-0.38, 0.38]	[-0.76, 0.77]	[-0.52, 0.48]	[-0.99, 0.93]	-0.01	0.99	decay

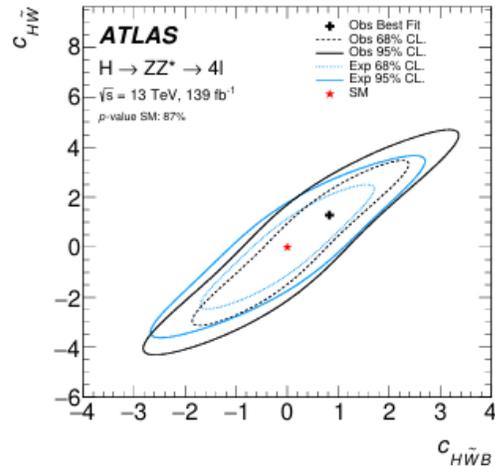
➤ Using $H \rightarrow ZZ^* \rightarrow 4l$ to probe Higgs CP-violating in the EFT framework



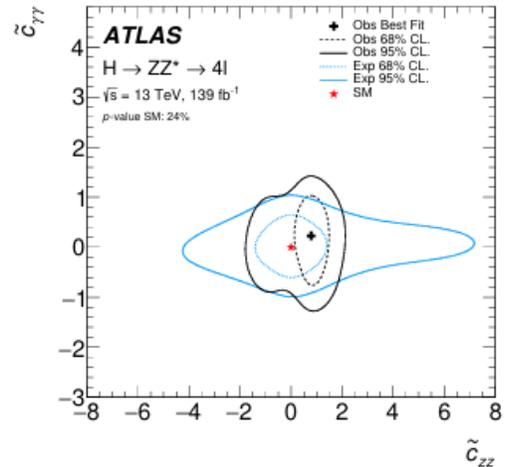
(a) $c_{H\tilde{W}B}$ vs. $c_{H\tilde{B}}$



(b) $c_{H\tilde{W}}$ vs. $c_{H\tilde{B}}$

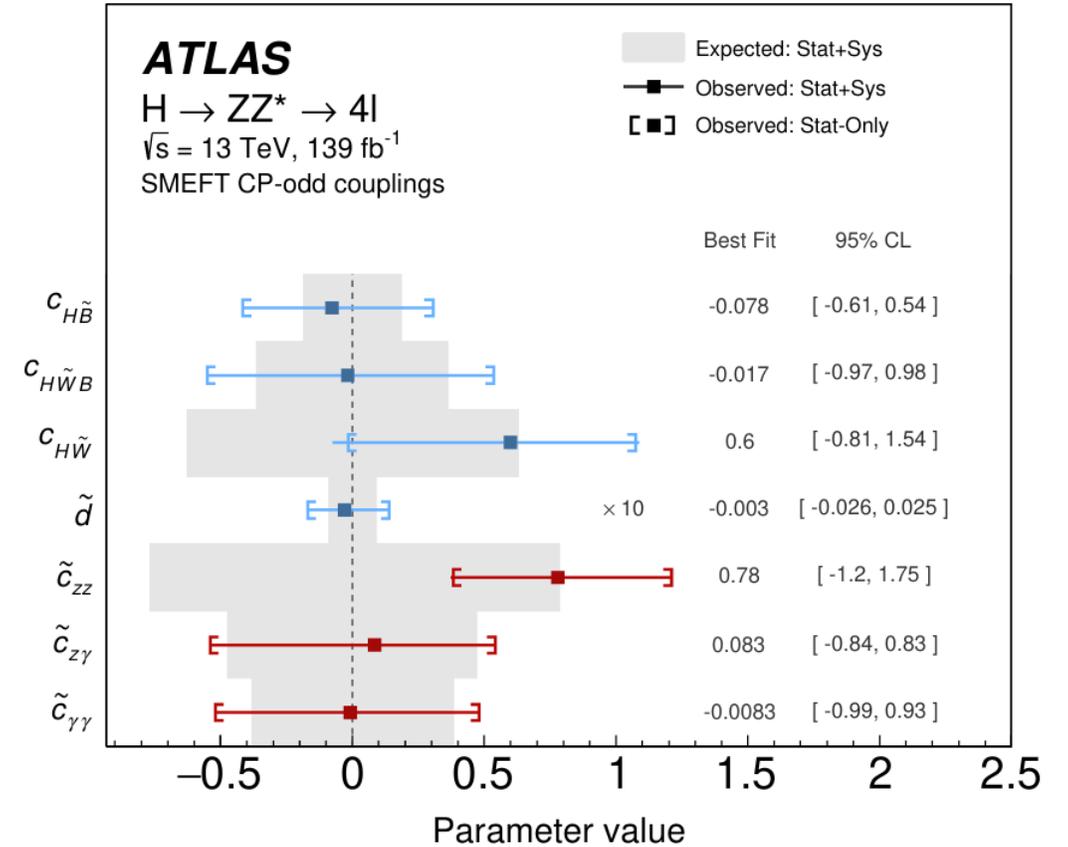


(c) $c_{H\tilde{W}}$ vs. $c_{H\tilde{W}B}$

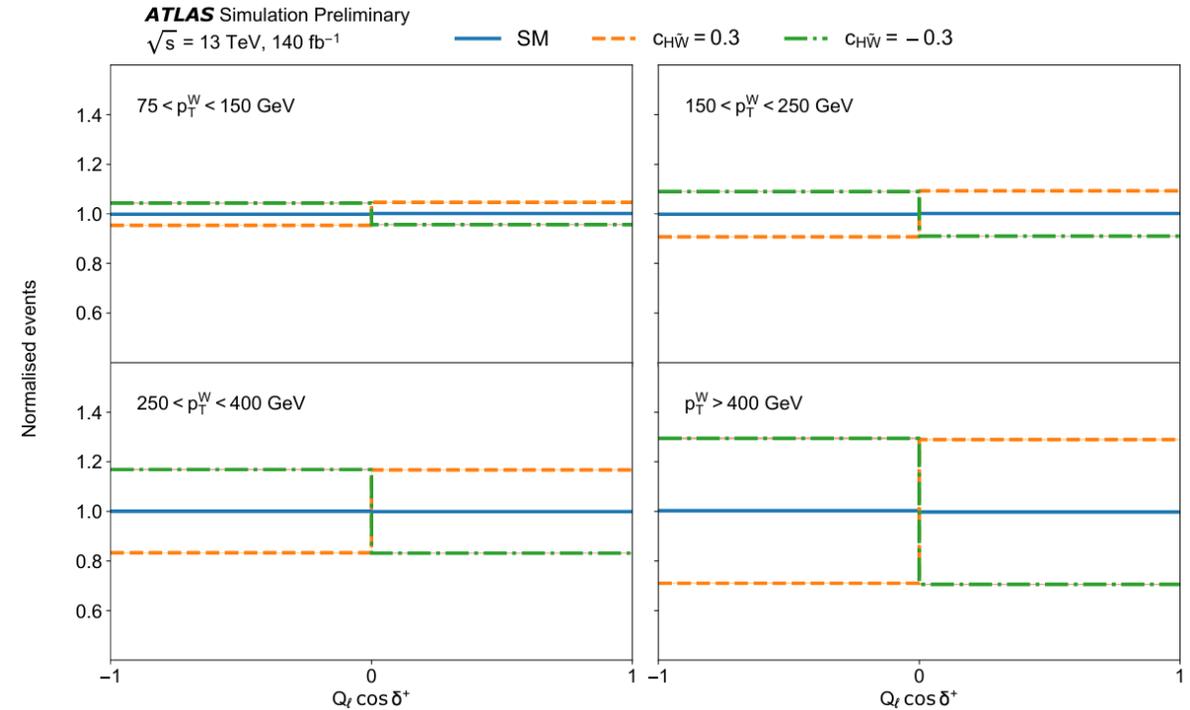
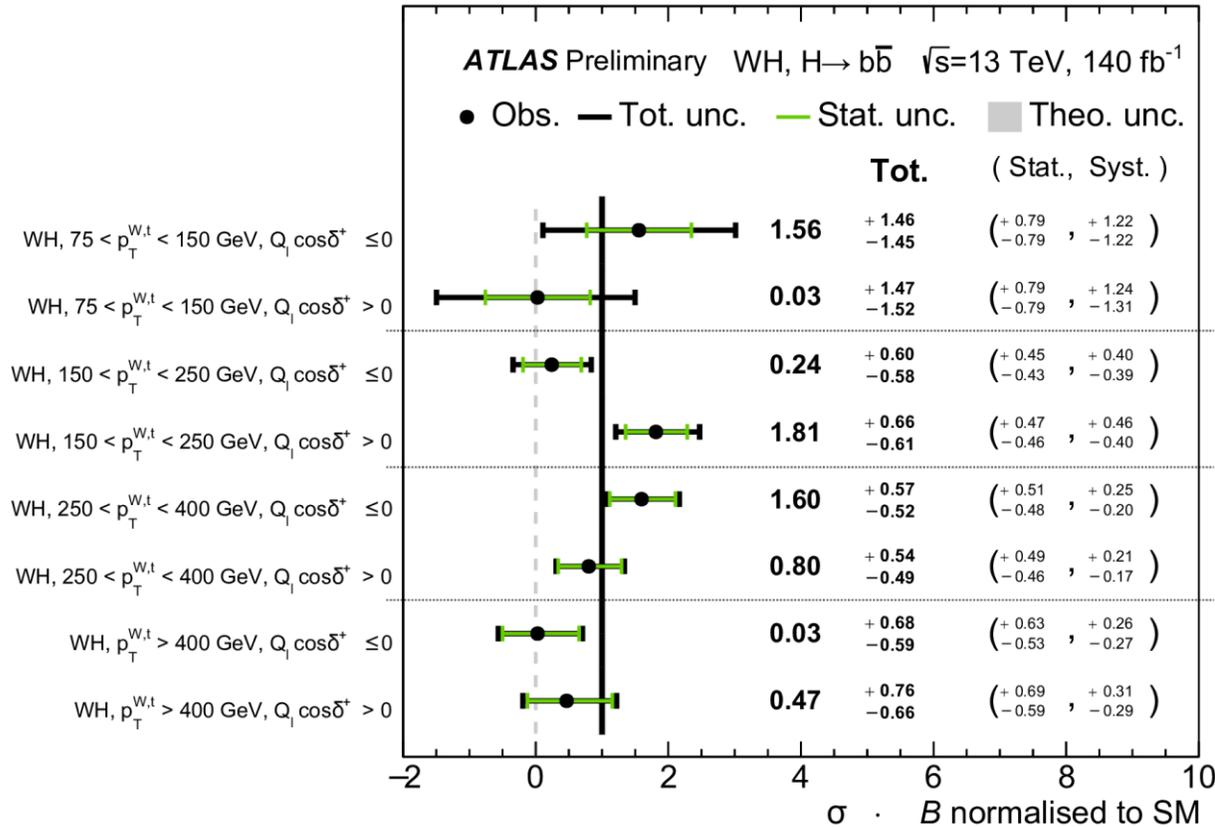


(d) $\tilde{c}_{\gamma\gamma}$ vs. \tilde{c}_{ZZ}

Results are consistent with a CP-even Higgs.
No significant CP-odd contribution observed.



➤ Using 140/fb WH, H → bb to probe Higgs CP-violating in the SMEFT framework



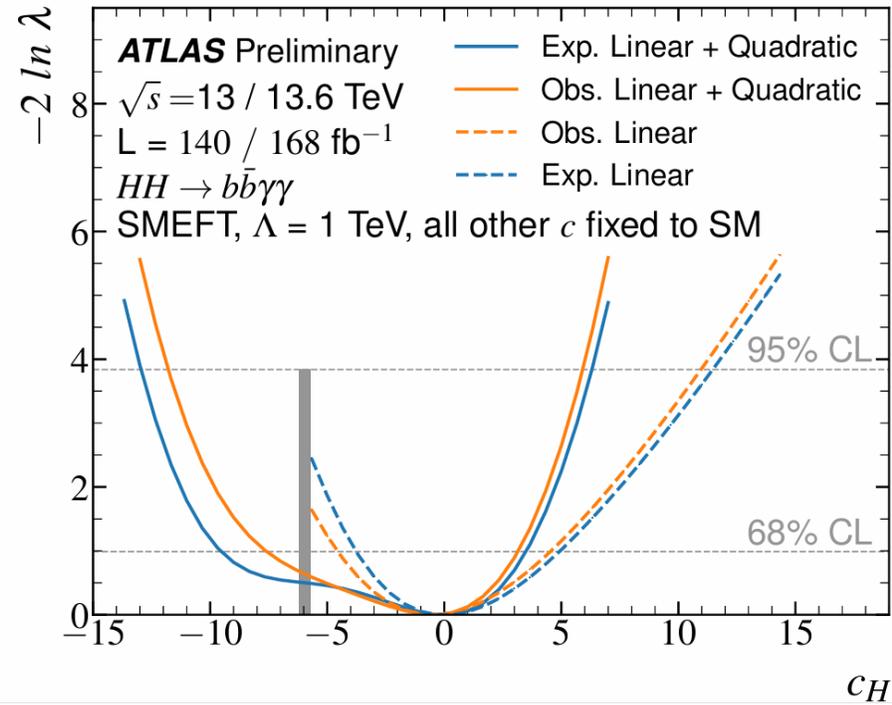
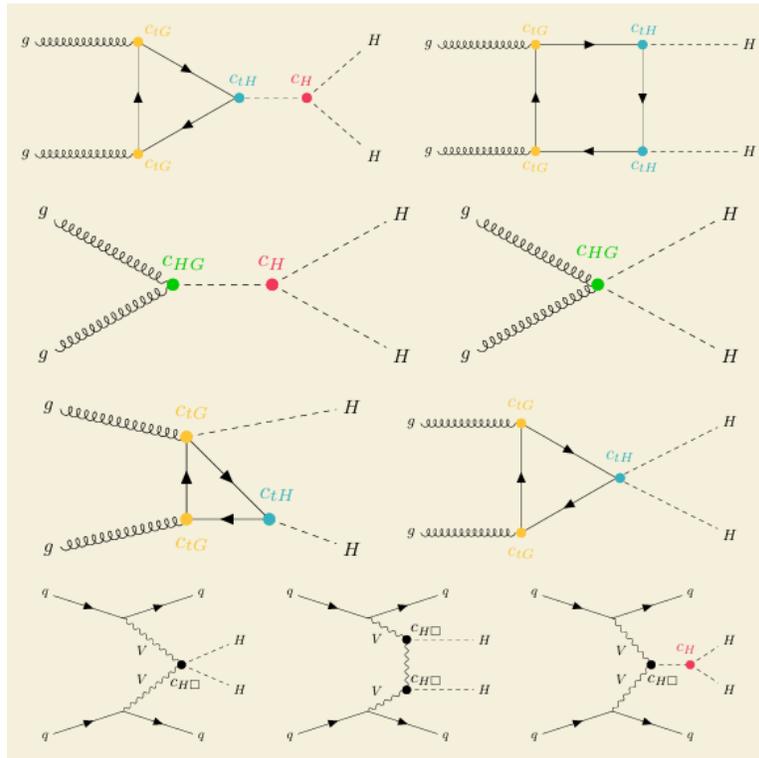
Observed (expected): 4.7σ (5.0σ)

$$\mu_{WH}^{bb} = 0.93_{-0.21}^{+0.22} = 0.93_{-0.15}^{+0.15}(\text{stat.})_{-0.15}^{+0.16}(\text{syst.})$$



$$\cos \delta^+ = \frac{\mathbf{p}_\ell^{(W)} \cdot (\mathbf{p}_H \times \mathbf{p}_W)}{|\mathbf{p}_\ell^{(W)}| \cdot |\mathbf{p}_H \times \mathbf{p}_W|}$$

➔ Run2 (140/fb) and Run3 (168/fb) $HH \rightarrow b\bar{b}\gamma\gamma$ interpretation in SMEFT



➔ Gray bar indicates one of ggF HH category yields become negative.

NEW!

