Measurement of CP properties of the Higgs boson couplings to weak bosons at the ATLAS experiment

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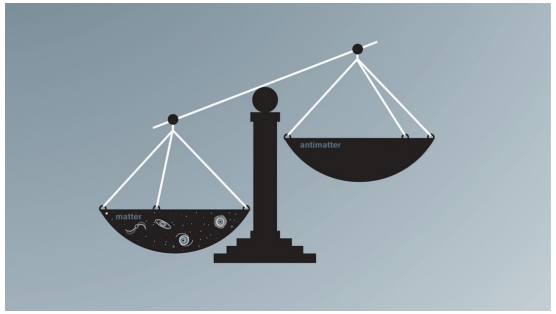
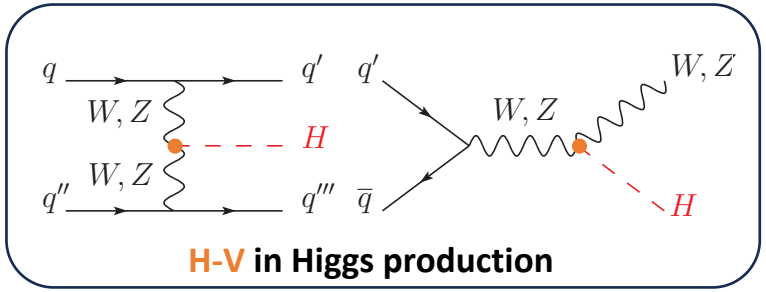
Introduction

- **CP violation: one of key conditions in baryon asymmetry.**
  - Existing CPV in SM: CKM, PMNS matrices, but NOT sufficient.
  - **Where is the other CP-violation source?**



- **11 years after Higgs discovery:**
  - Significant achievements from ATLAS & CMS: Higgs mass, width, coupling strength…
  - A (new) yield for CPV search: in Higgs coupling.

- **In this talk: anomalous Higgs couplings in H-V interaction**
  - Through production: $VBF,\ VH$.
    - Independent with decay mode: $H \to \tau\tau/\gamma\gamma/ZZ/WW$.
  - Through decay: $H \to ZZ, H \to WW$.



H-V in Higgs production

H-V in Higgs decay

Introduction

- **Dimension-6 effective field theory: SMEFT framework**
  - $\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_k \frac{c_k}{\Lambda^2}\mathcal{O}_k$
  - Focus on CP-odd H-V operators: 3 independent c_i

Warsaw basis

Operator	Structure	Coupling
$\mathcal{O}_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^{\mathrm{I}}_{\mu\nu}\mathrm{W}^{\mu\nu\mathrm{I}}$	$c_{H\tilde{W}}$
$\mathcal{O}_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^{\mathrm{I}}_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{W}B}$
$\mathcal{O}_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{B}}$

Linear combination

Higgs basis

Operator	Structure	Coupling
$\mathcal{O}_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$\mathcal{O}_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$\mathcal{O}_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

- Experimental assumption: different contributions can not be distinguished
  - HISZ base: $c_{H\tilde{W}} = c_{H\tilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d}$, $c_{H\tilde{W}B} = 0$. $\tilde{d}$ is the only CPV parameter.
  - Used in VBF Higgs analyses.

3 sets of parameters to represent the H-V CP violation effects.

CP sensitive observables

- **Signed $\Delta\phi_{jj}$**
  - Angular information in production process.
  - Used in early spin/CP and differential fiducial cross section analysis.
- **Optimal observable**
  - Matrix element based observable: $\mathcal{OO} = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$. More sensitive than $\Delta\phi_{jj}^{signed}$.
  - CP-odd effects introduce asymmetry shape in OO.

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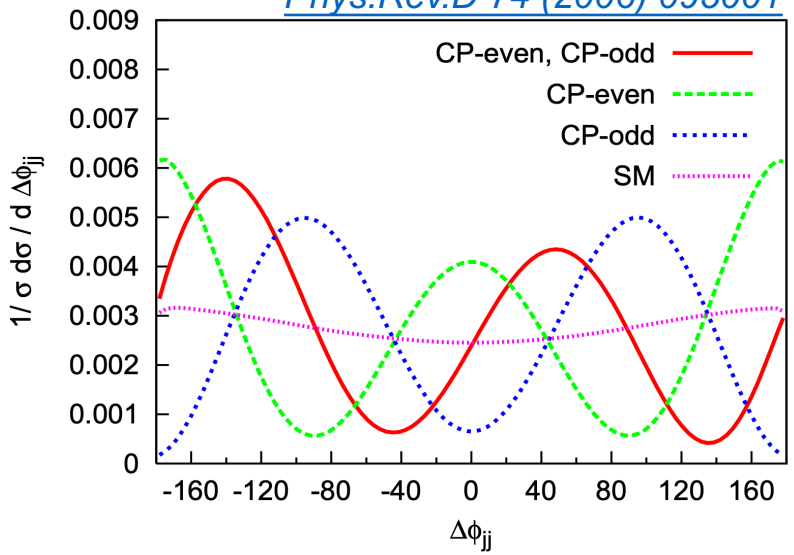

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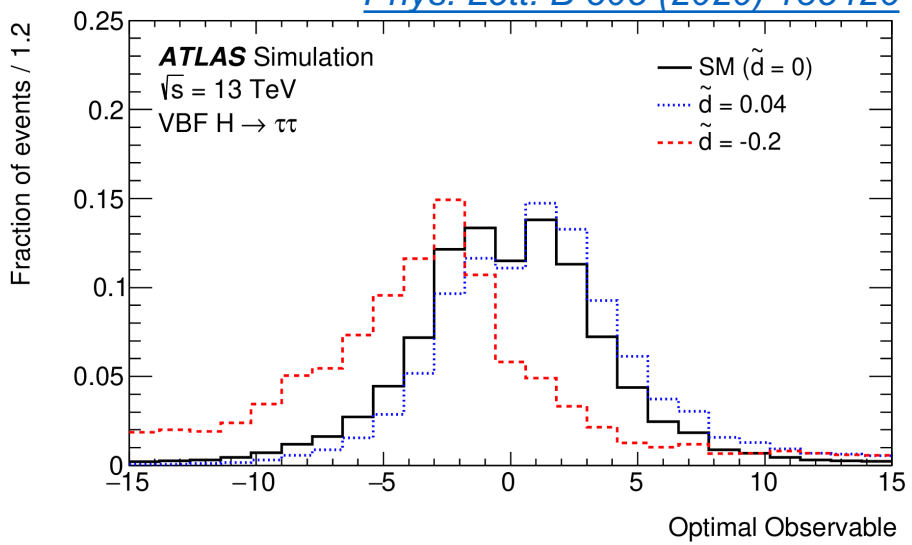

Fiducial differential XS in $H \to \gamma\gamma / WW^*$

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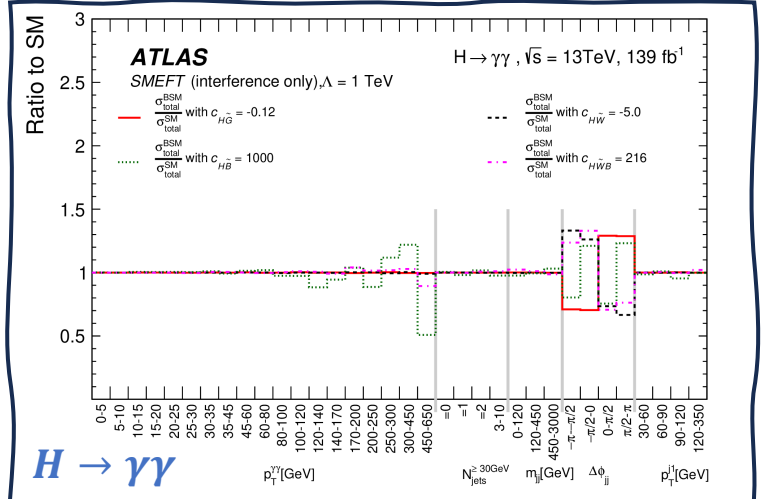
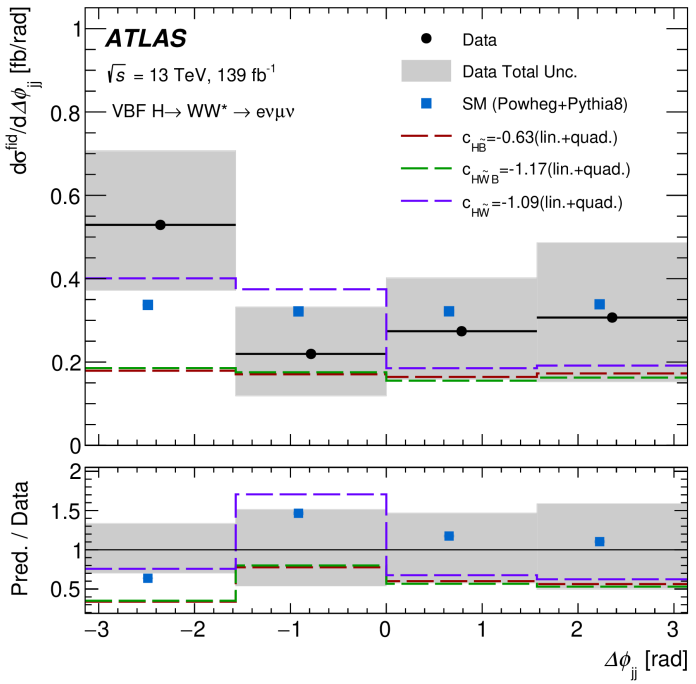
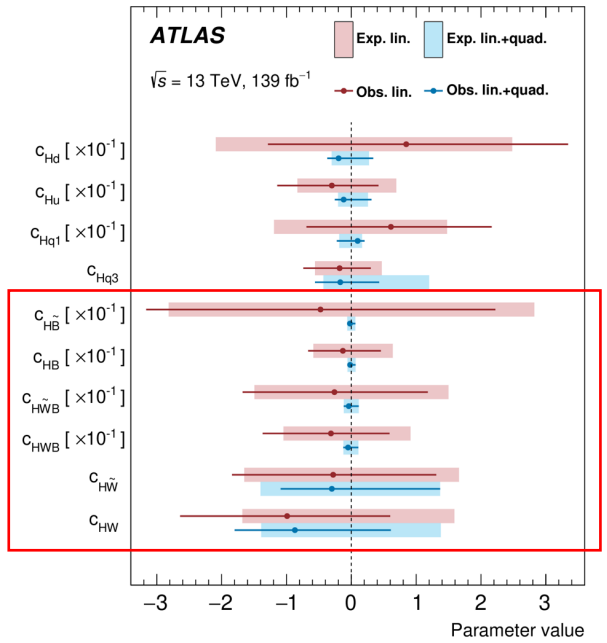
- **EFT interpretation in SMEFT Warsaw basis ($c_{H\widetilde{W}}, c_{H\widetilde{W}B}, c_{H\widetilde{B}}$)**
  - $H \to \gamma\gamma$: simultaneous fit to 5 observables & correlations: ($p_T^{\gamma\gamma}, N_{jets}, m_{jj}, \Delta\phi_{jj}, p_T^{j_1}$).
  - $H \to WW^* \to e\nu\mu\nu$: constrain with $\Delta\phi_{jj}$.
  - Interference only and interference + quadratic constraints from **shape + yield info.**



Coefficient	95% CL, interference-only terms	95% CL, interference and quadratic terms
c_{HG}	$[-6.1, 11.0] \times 10^{-3}$	$[-6.5, 10.2] \times 10^{-3}$
$c_{H\widetilde{G}}$	$[-0.12, 0.23]$	$[-3.1, 3.5] \times 10^{-2}$
c_{HW}	$[-1.9, 0.9] \times 10^{-2}$	$[-1.8, 1.0] \times 10^{-2} \cup [0.28, 0.30]$
$c_{H\widetilde{W}}$	$[-10.2, 5.2]$	$[-7.3, 7.3] \times 10^{-2}$
c_{HB}	$[-5.8, 2.8] \times 10^{-3}$	$[-5.5, 3.0] \times 10^{-3} \cup [8.4, 9.3] \times 10^{-2}$
$c_{H\widetilde{B}}$	$[-21.8, 5.7] \times 10^{2}$	$[-2.3, 2.3] \times 10^{-2}$
c_{HWB}	$[-5.2, 10.7] \times 10^{-3}$	$[-0.17, -0.15] \cup [-5.5, 9.8] \times 10^{-3}$
$c_{H\widetilde{W}B}$	$[-2.5, 4.0] \times 10^{2}$	$[-4.0, 4.0] \times 10^{-2}$





$H \to WW^* \to e\nu\mu\nu$

H-V CP property in VBF $H \to \tau\tau$

- **Probe HVV interaction in VBF enriched region**

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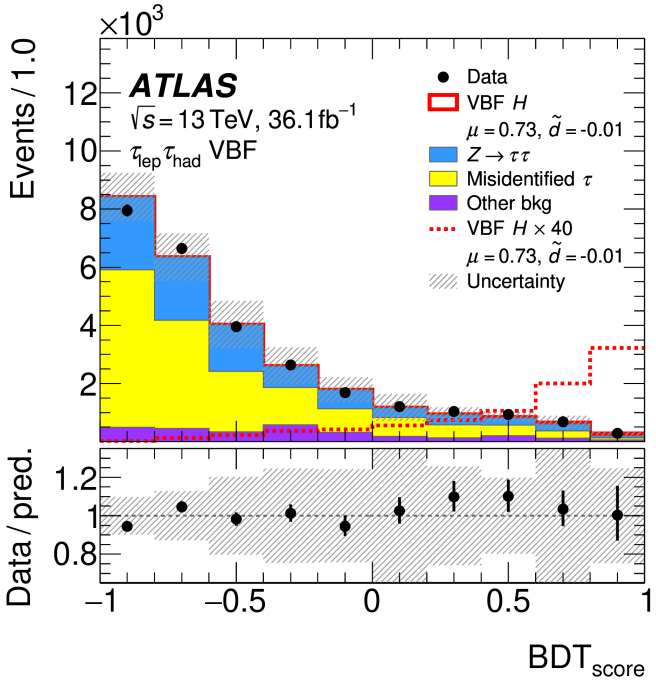
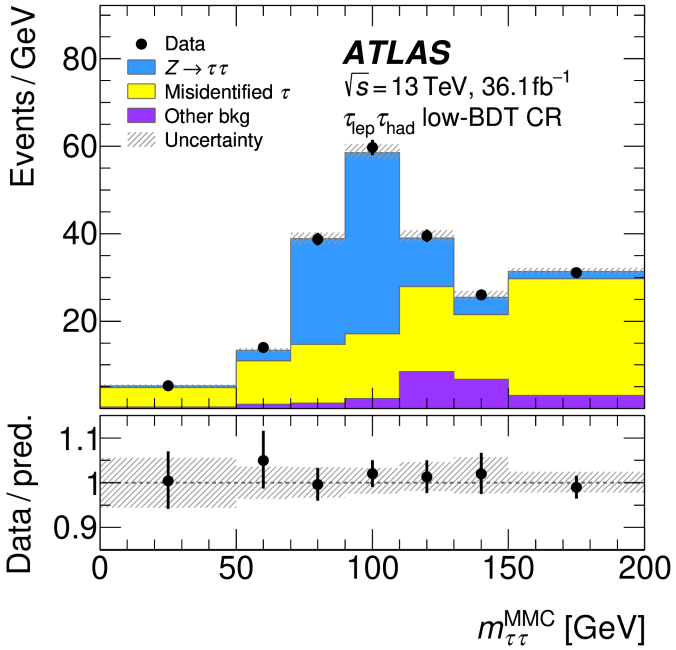
  - Dedicated pure CP analysis in HISZ basis ($\tilde{d}$).
  - **Shape-only fit** on CP-sensitive observable: optimal observable $\mathcal{OO}$
  - 4 analysis channels depending on τ decay: $\boldsymbol{\tau_{lep}\tau_{lep}}$ **SF**, $\boldsymbol{\tau_{lep}\tau_{lep}}$ **DF**, $\boldsymbol{\tau_{lep}\tau_{had}}$ and $\boldsymbol{\tau_{had}\tau_{had}}$
  - BDT-based classification + $m_{\tau\tau}^{MMC}$ background estimation.





H-V CP property in VBF $H \to \tau\tau$

- **Maximum likelihood fit in binned $\mathcal{OO}$**

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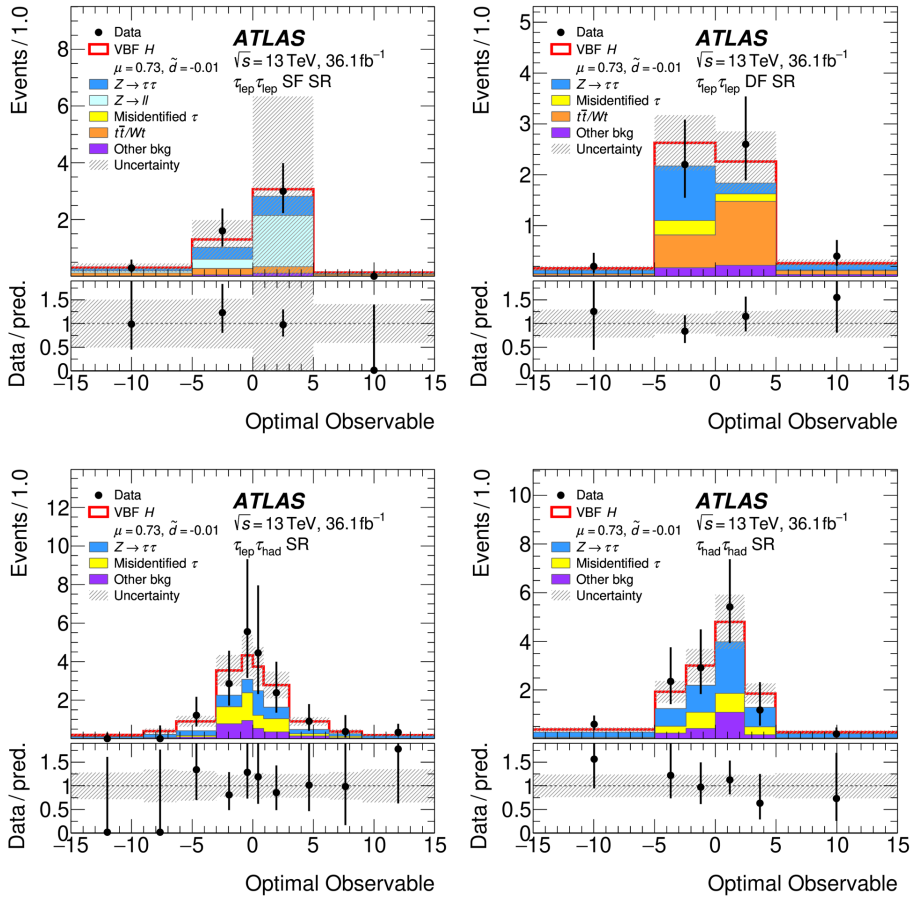
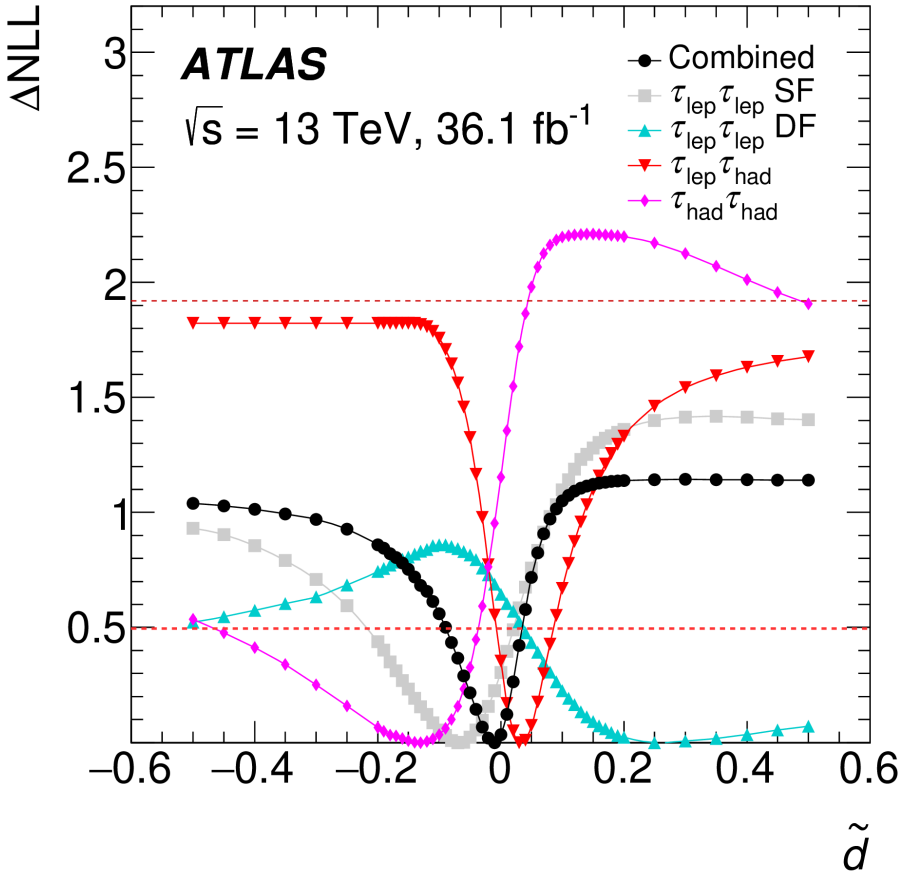
  - A template fit with $\tilde{d}$ hypotheses. Result: $\tilde{d} \in [-0.090, 0.035]$ @ 68% C.L.



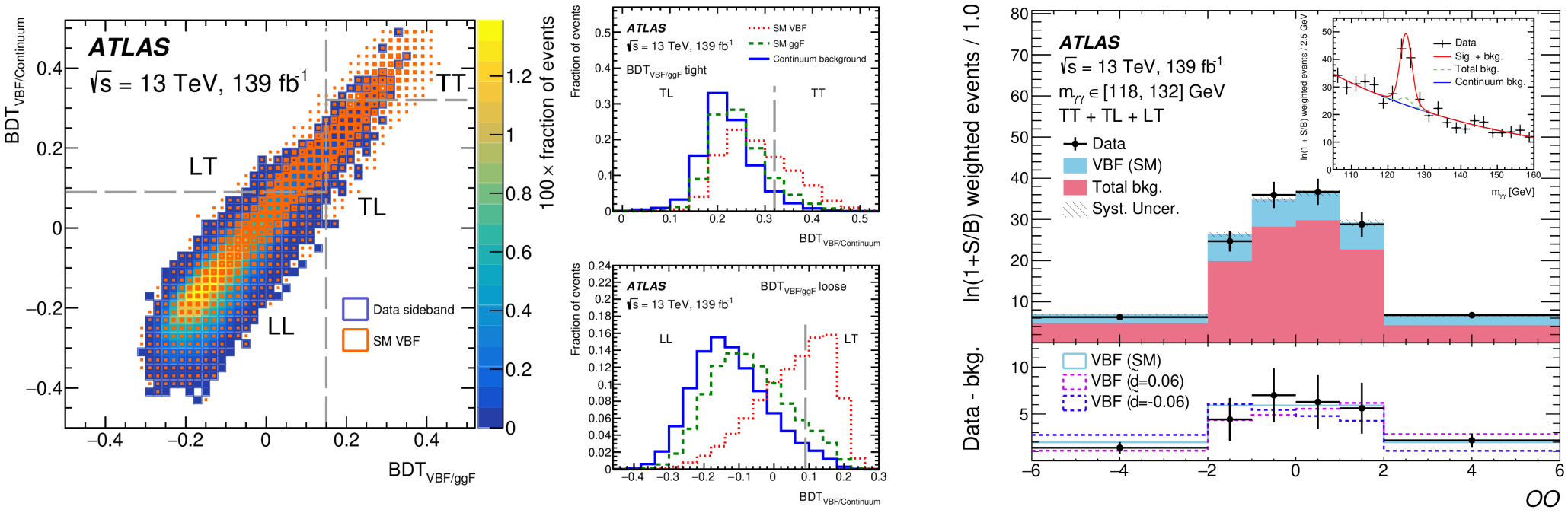


H-V CP property in VBF $H \to \gamma\gamma$

- **Similar strategy with $H \to \tau\tau$**

Phys. Rev. Lett. 131 (2023) 061802

  - 2 EFT basis: $\tilde{d}$ in HISZ basis and $c_{H\widetilde{W}}$ in Warsaw basis.
  - **Shape-only fit** on CP-sensitive observable: optimal observable $\mathcal{OO}$.
  - 2 BDTs for pure VBF events: $BDT_{VBF/ggF}, BDT_{VBF/Continuum}$.
  - Extract signal and background yield from $m_{\gamma\gamma}$ distribution: **better background estimation.**



H-V CP property in VBF $H \to \gamma\gamma$

- **Fit in 3 categories and 6 $\mathcal{OO}$ bins**
  - Float the VBF normalization for shape-only fit.
  - Results are combined with $H \to \tau\tau$.
  - Most stringent pure CPV constraint on $c_{H\tilde{W}}$: [-0.55, 1.07] @ 95% C.L. (inter + quad.)

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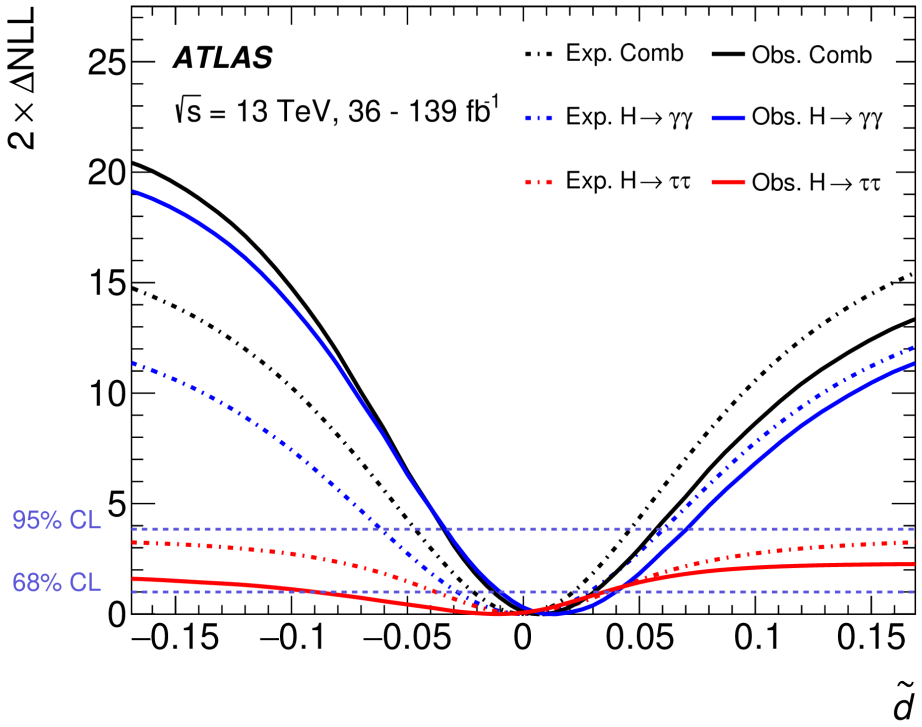
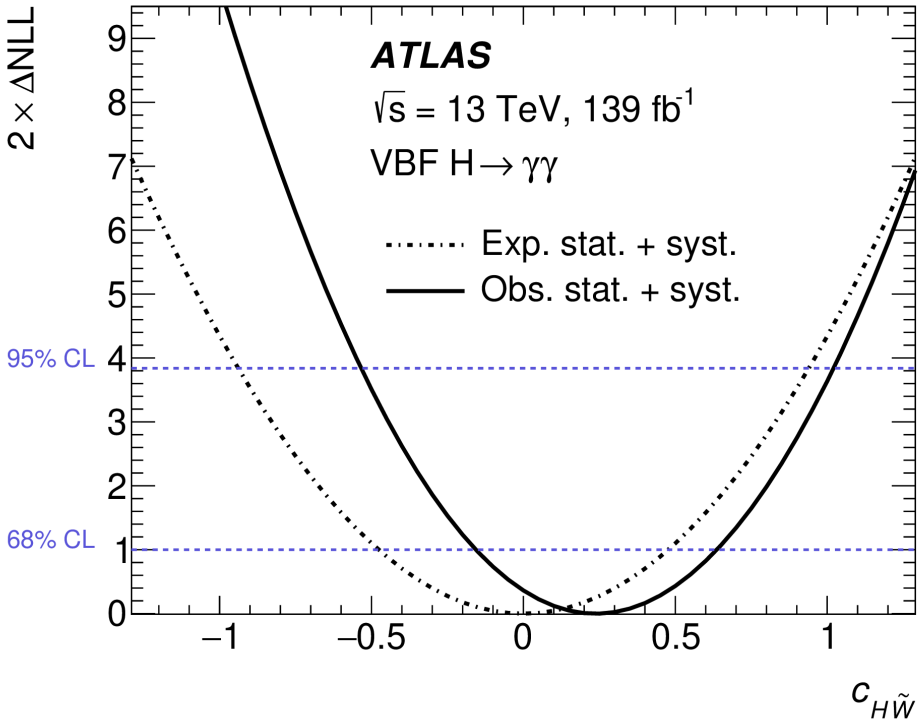
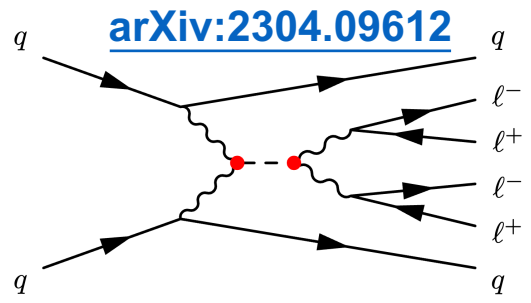


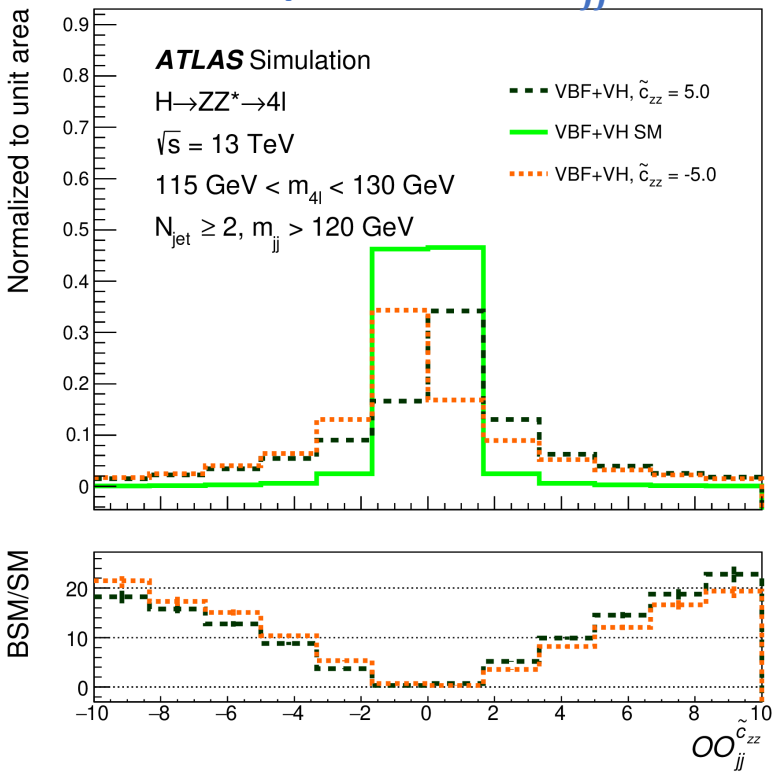


H-V CP properties in VBF+VH $H \to ZZ^* \to 4l$

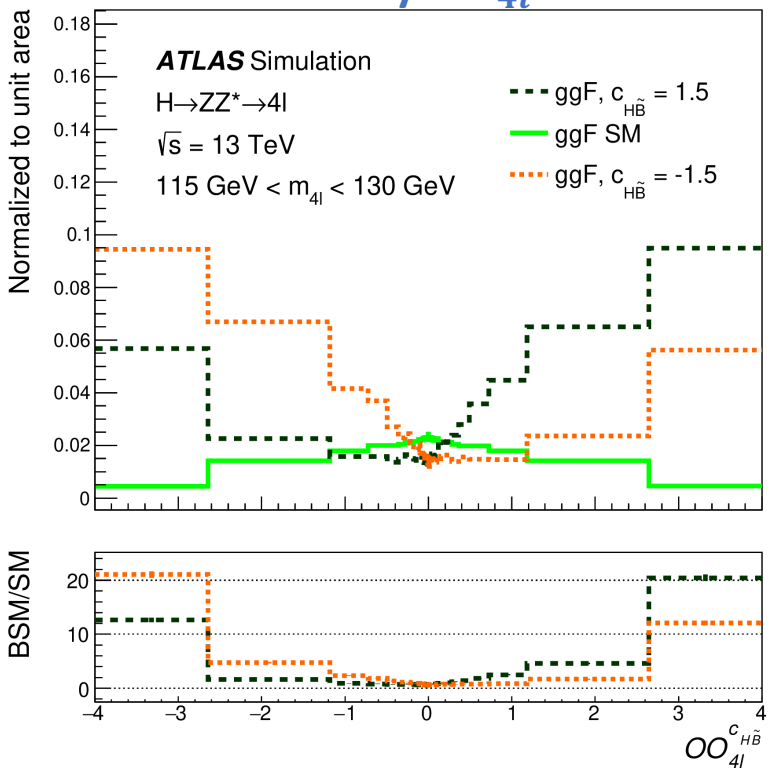
- **Constrain H-V CP-odd effects from both production and decay.**
  - In all 3 representations: $\tilde{d}$ in HISZ basis, Warsaw basis and Higgs basis.
  - $\mathcal{OO}$ for each coefficients and vertices: $\mathcal{OO}_{jj}^{c_i}$ and $\mathcal{OO}_{4l}^{c_i}$



VBF+VH production $\mathcal{OO}_{jj}$



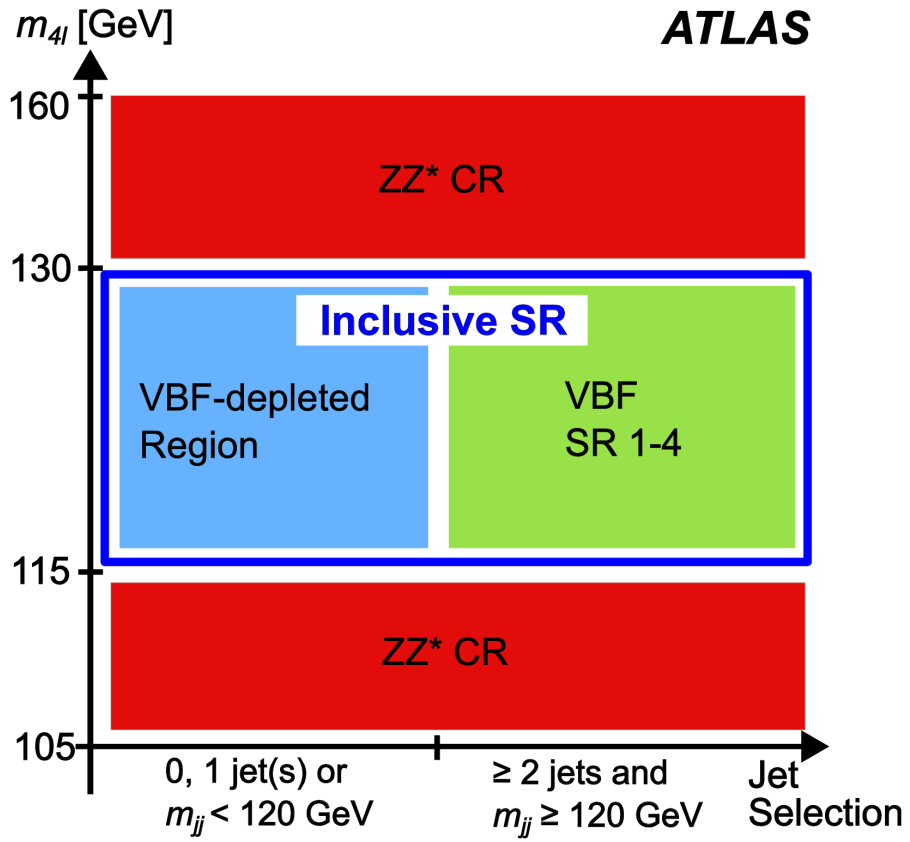
$H \to ZZ^*$ decay $\mathcal{OO}_{4l}$

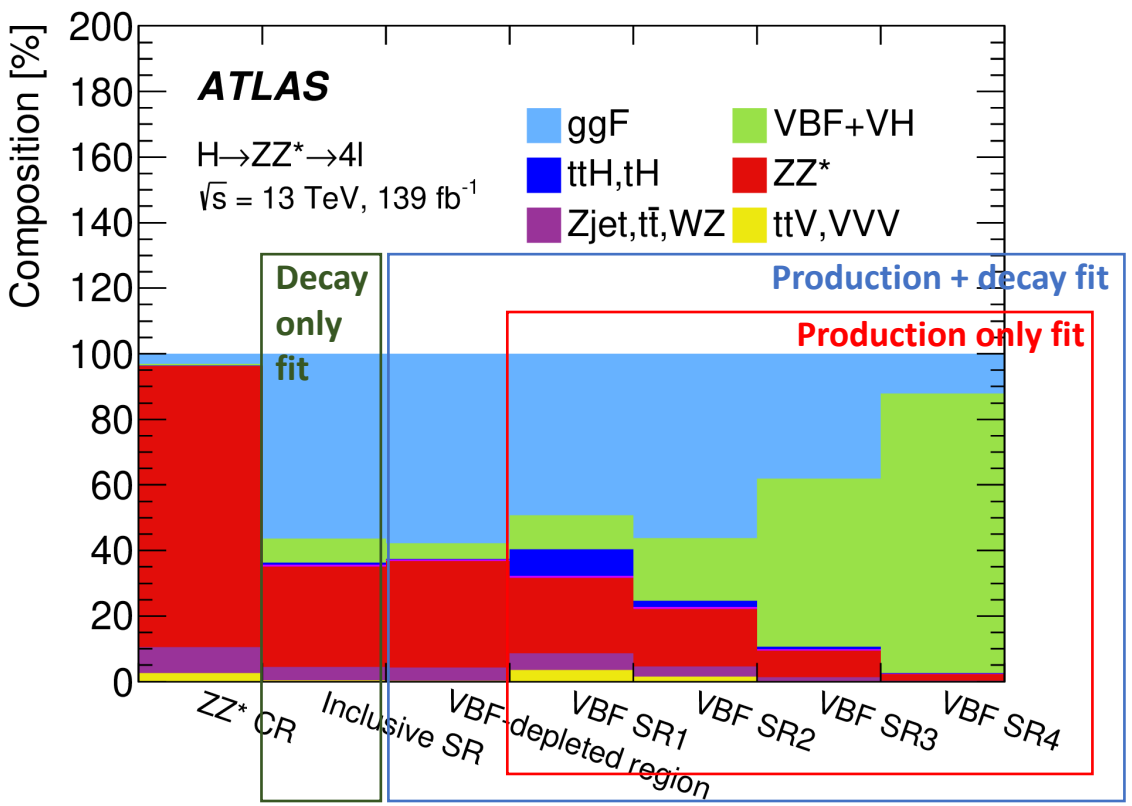


H-V CP properties in VBF+VH $H \rightarrow ZZ^* \rightarrow 4l$

arXiv:2304.09612

- **Analysis strategy: for 2 targets**
  - 3-class NN classification to distinguish VBF, VH and ggF.
  - 4 VBF SRs for VBF production, 1 VBF-depleted region for $H \rightarrow ZZ$ decay (ggF dominant).

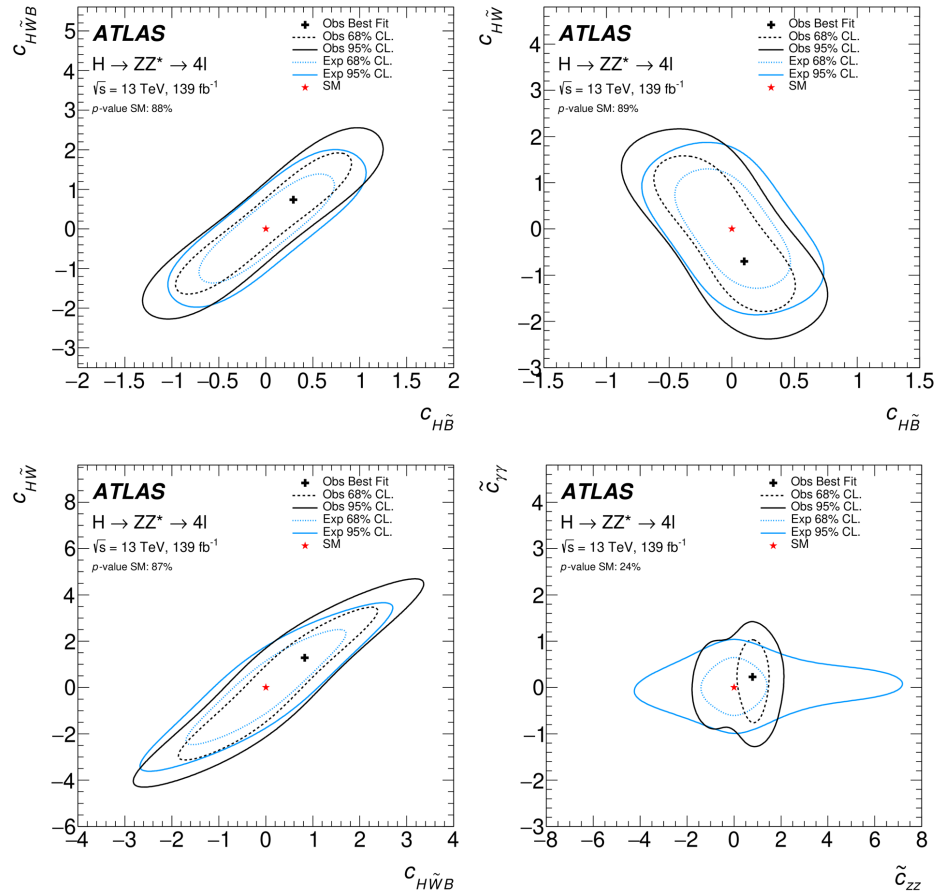


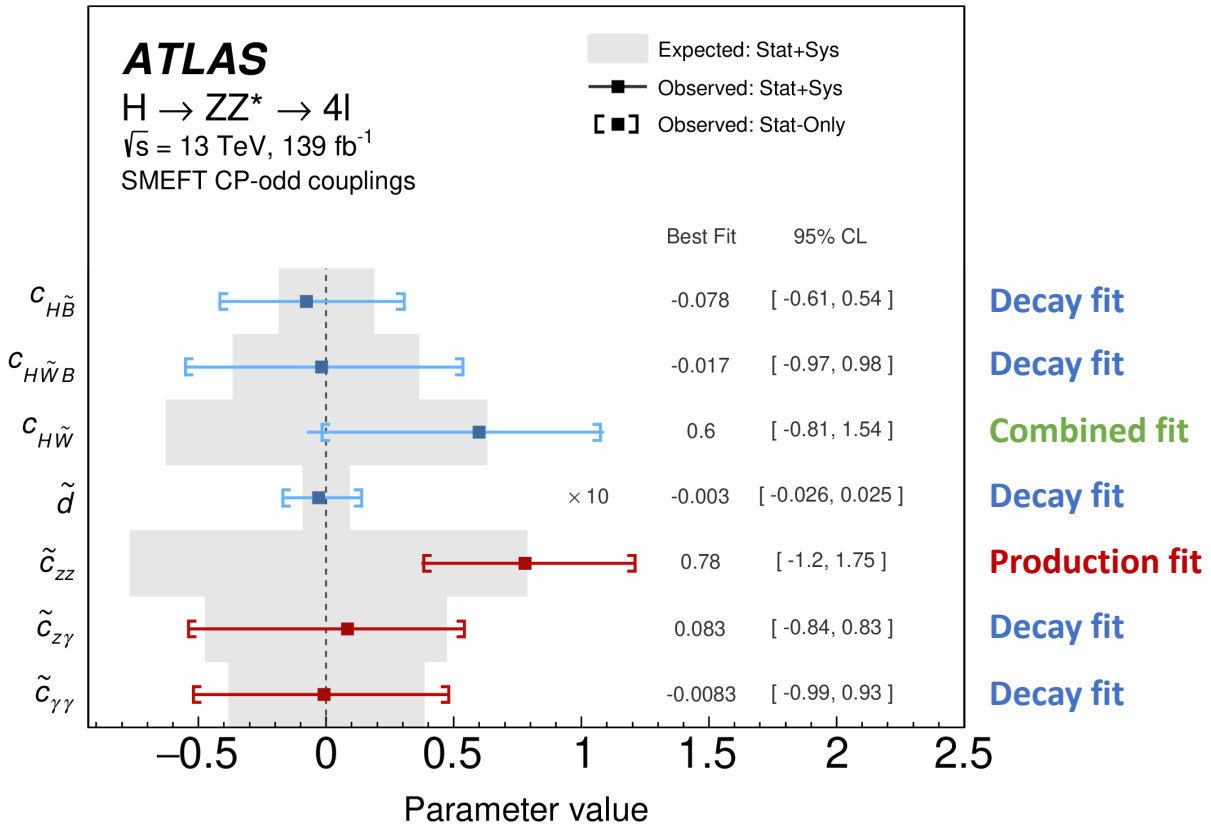


H-V CP properties in VBF+VH $H \rightarrow ZZ^* \rightarrow 4l$

arXiv:2304.09612

- **Results: 1D and 2D constraints**
  - Full set of H-V CP-odd coefficients. Compatible with SM.





Decay fit
Decay fit
Combined fit
Decay fit
Production fit
Decay fit
Decay fit

Summary

- **We are looking for new CP-violation sources beyond SM**
  - Is well-motivated by the baryon asymmetry puzzle.
  - H-V interaction is a precious window to study EW and search the new physics.

- **A series of analyses targeting H-V CP properties are performed**
  - From both production mode and decay mode, covers many possibilities.
  - Provide stringent limits on CP-violation, with Warsaw and Higgs basis.
  - Optimal observable is commonly used and shows great sensitivity.
  - All results are compatible with the SM.

- **More results are on the way, please stay tuned!**
  - $H \to \tau\tau$, $H \to WW$ channels with full Run 2 data.
  - Combination between channels.
  - New round analyses in Run 3.