Test of CP invariance in Higgs Boson VBF production using the $H \to \gamma\gamma$ channel with the ATLAS Detector

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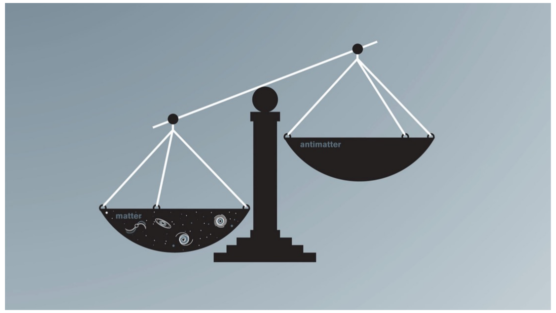
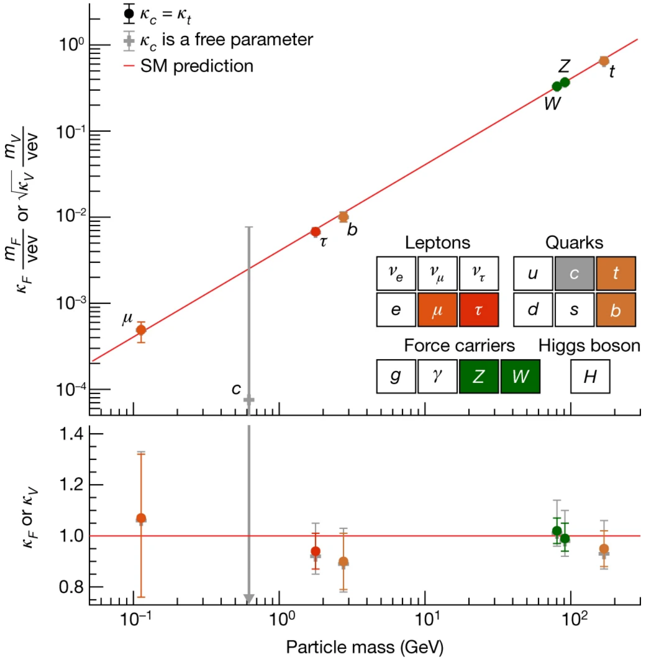
Introduction

- **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:**
  - H-V interaction CP property in VBF $H \rightarrow \gamma\gamma$ channel [*Phys. Rev. Lett. 131, 061802*].
  - Comparison with latest results in other channels.

Introduction

- **Theoretic model: SMEFT framework**
  - $\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_k \frac{c_k}{\Lambda^2}\mathcal{O}_k$ in dimention-6.
  - Warsaw basis: in unbroken gauge symmetry

    $\mathcal{L}_{SMEFT}^{CP-odd} \supset \frac{c_{H\widetilde{W}}}{\Lambda^2} H^\dagger H W_{\mu\nu}^I W^{\mu\nu I} + \frac{c_{H\widetilde{B}}}{\Lambda^2} H^\dagger H B_{\mu\nu}^A B^{\mu\nu} + \frac{c_{H\widetilde{W}B}}{\Lambda^2} H^\dagger \sigma^I H W_{\mu\nu}^I B^{\mu\nu}.$

    VBF process is only sensitive to $c_{H\widetilde{W}}$.

  - HISZ basis: based on the mass eigenstates after SSB.

    $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \tilde{g}_{HAA} HAA + \tilde{g}_{HAZ} HAZ + \tilde{g}_{HZZ} HZZ + \tilde{g}_{HWW} HWW$

    Assumption: *various HVV processes can not be distinguished experimentally in VBF*

    $\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}, \tilde{g}_{HAZ} = 0$. Make $\tilde{d}$ as the ONLY CP-violation parameter.

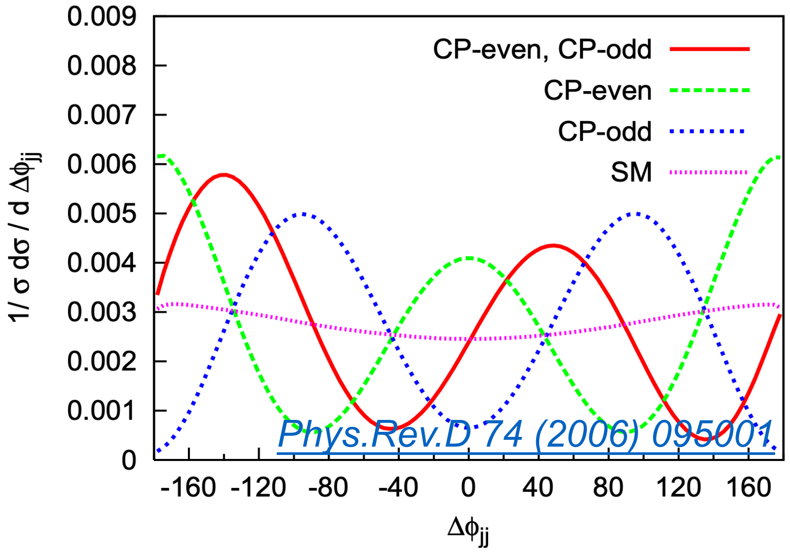
  - Matrix element:

    $|\mathcal{M}_{VBF}|^2 = |\mathcal{M}_{SM}|^2 + c_i \cdot 2Re(\mathcal{M}_{SM}^* \mathcal{M}_{CP-odd}) + c_i^2 \cdot |\mathcal{M}_{CP-odd}|^2$

    Compatible for the *Optimal Observable* definition.

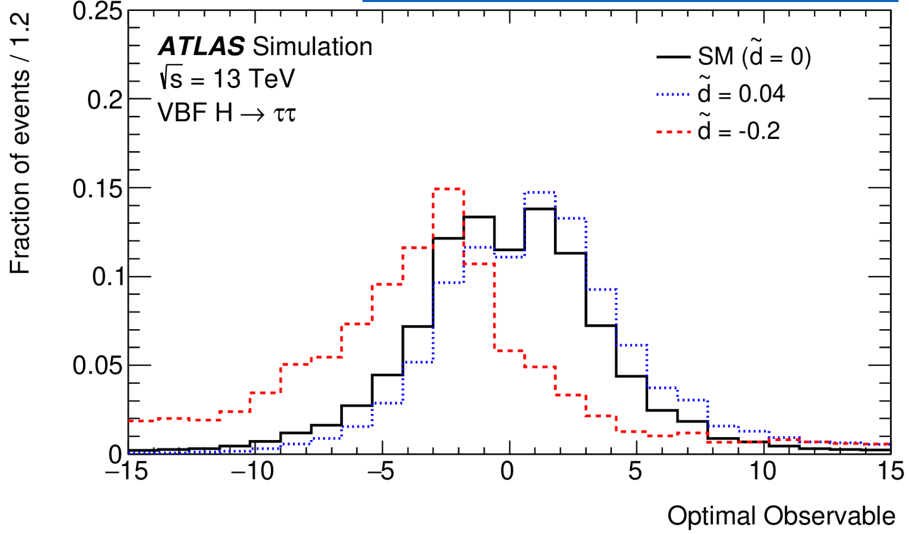
CP sensitive observables

- **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.



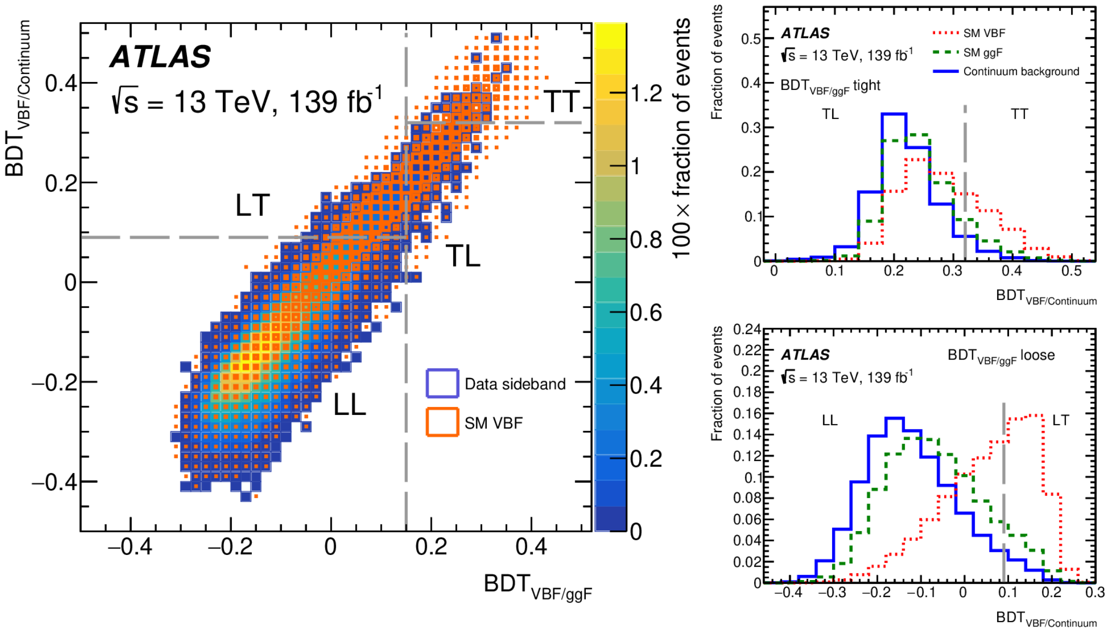
Phys.Rev.D 74 (2006) 095001

Phys. Lett. B 805 (2020) 135426



Analysis strategy

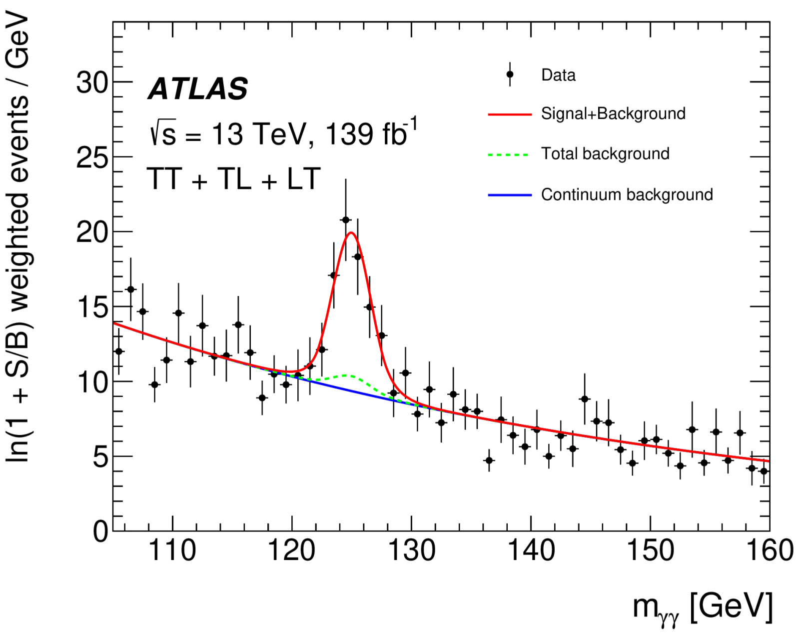
- **Object definition and pre-selection:**
  - Follows common $H \rightarrow \gamma\gamma$ analysis.
- **Event categorization: 2 BDTs**
  - VBF vs. ggF, VBF vs. continuum background.
  - 7 Training variables: $m_{jj}, \Delta\eta_{jj}, \Delta\Phi_{\gamma\gamma,jj}, \eta^{Zepp}, \Delta R_{\gamma,j}^{min}, pTt_{\gamma\gamma}, pT_{Hjj}$.

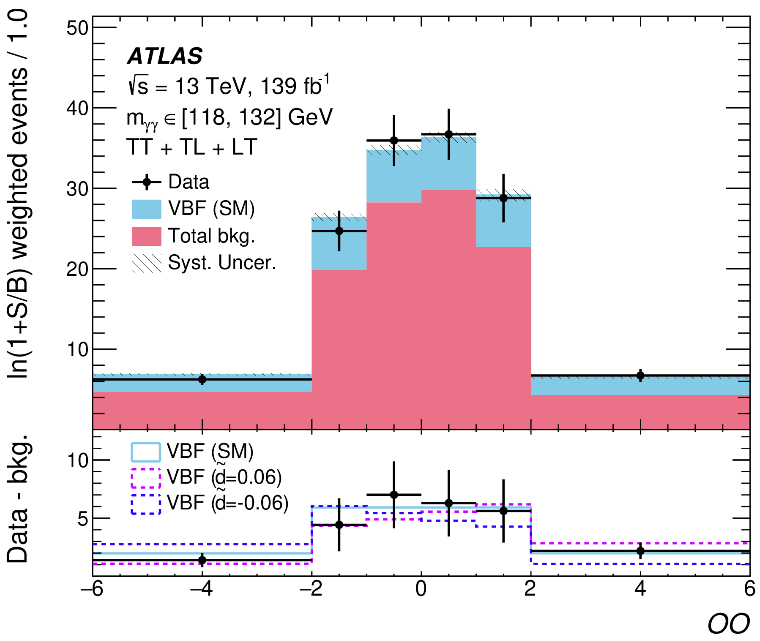


Ensure a high VBF purity (>85%) in TT and TL category

Analysis strategy

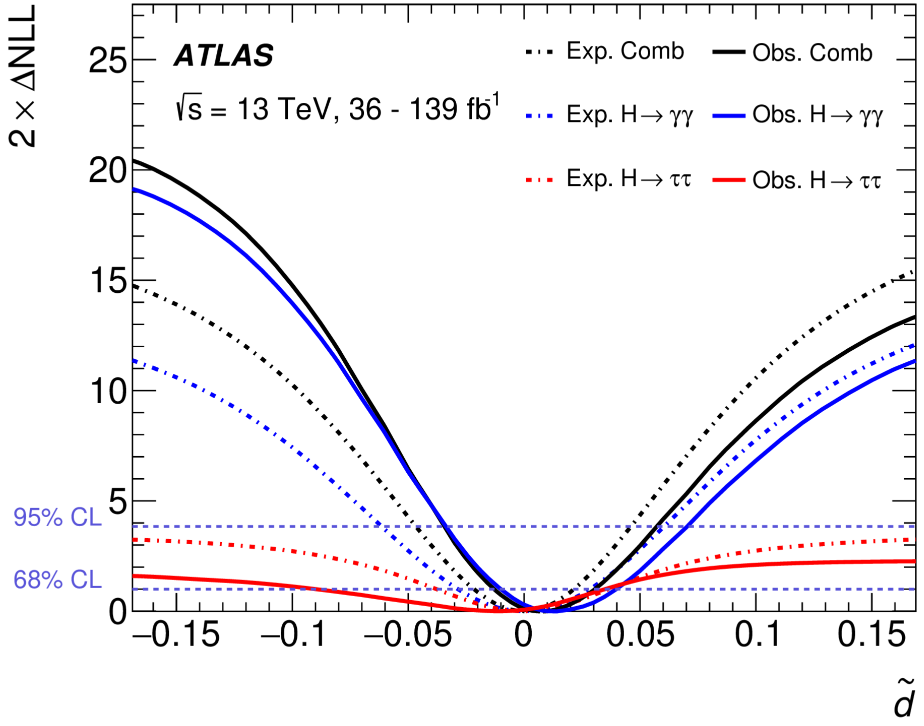
- **Statistical model:**
  - Extract event yields from $m_{\gamma\gamma}$ distribution.
    - Better and simpler background control
  - Likelihood constructed from the fit on 3 categories and 6 OO bins.
    - Float signal strength to have shape-only CP constraint.
    - Template fit for serios of $c_{H\tilde{W}}$ / $\tilde{d}$ hypotheses.

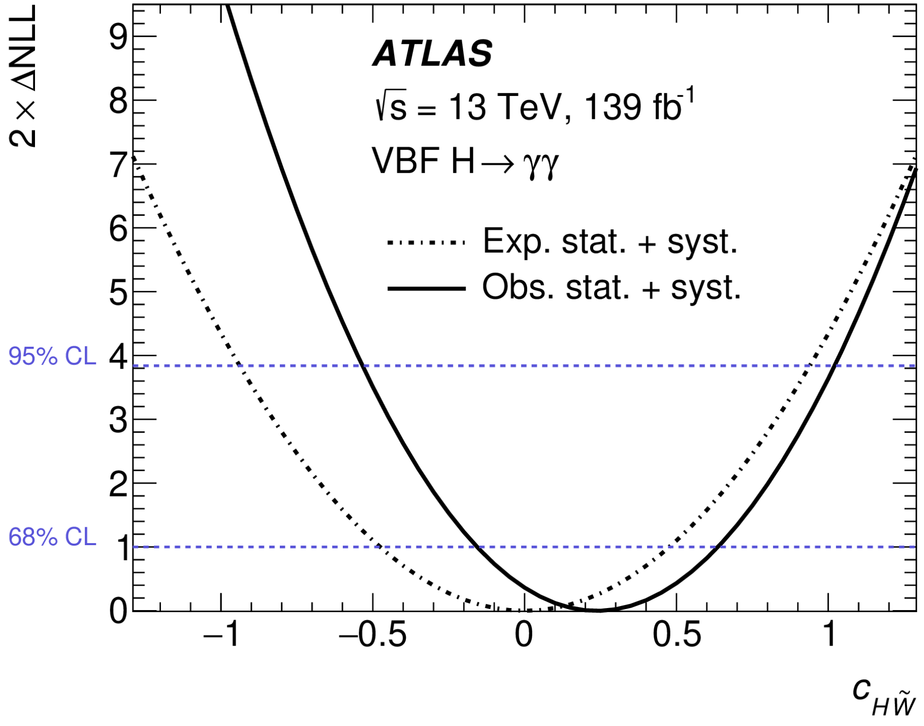




Results

- **Constraints on H-V CP violation effect**
  - Most stringent pure CPV constraint on $c_{H\tilde{W}}$: [-0.55, 1.07] @ 95% C.L. (inter + quad.)
  - No sign of CP violation observed.
  - $\tilde{d}$ measurement combined with $H \rightarrow \tau\tau$ result.

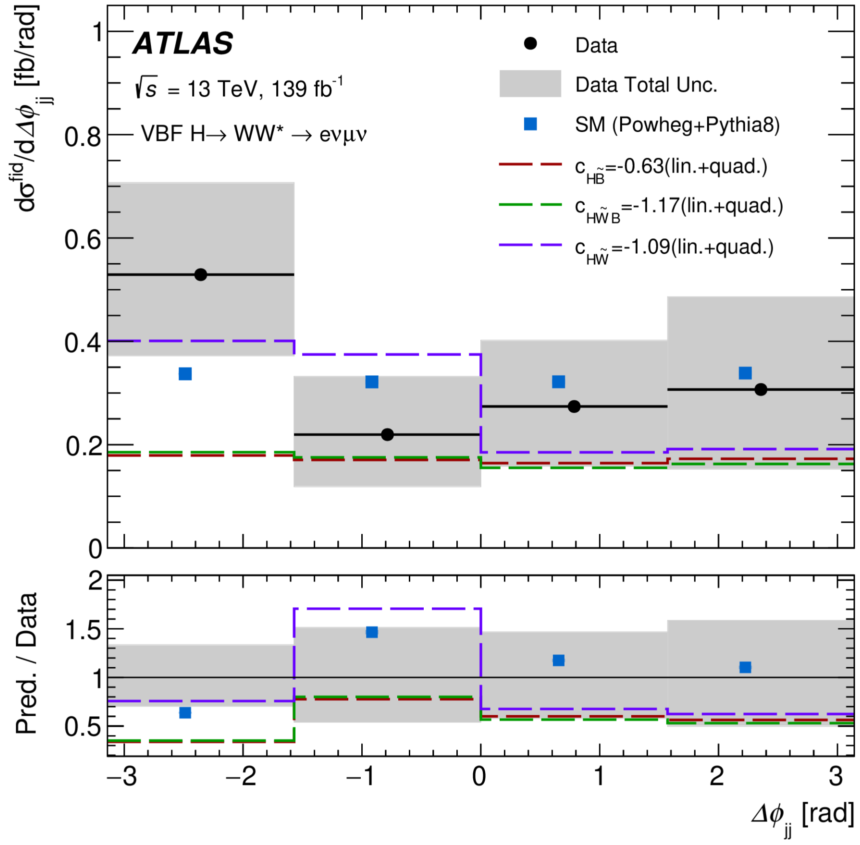


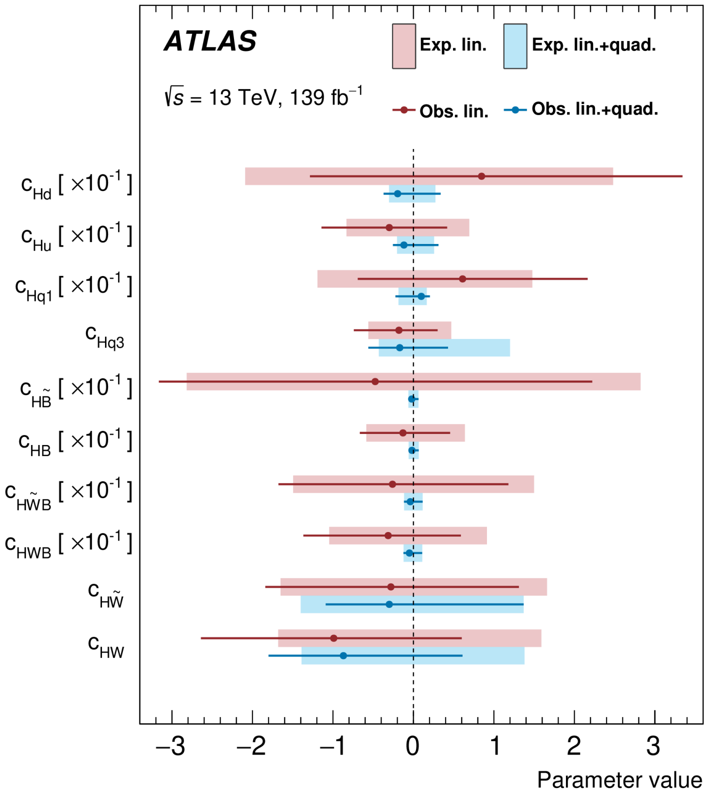


Results in other channels

Phys. Rev. D 108, 072003

- **EFT interpretation VBF $H \to WW^*$ differential fiducial cross section on $\Delta\phi_{jj}$**
  - SMEFT basis ($c_{H\widetilde{W}}, c_{H\widetilde{W}B}, c_{H\tilde{B}}$), main sensitivity from VBF process and **event yields.**

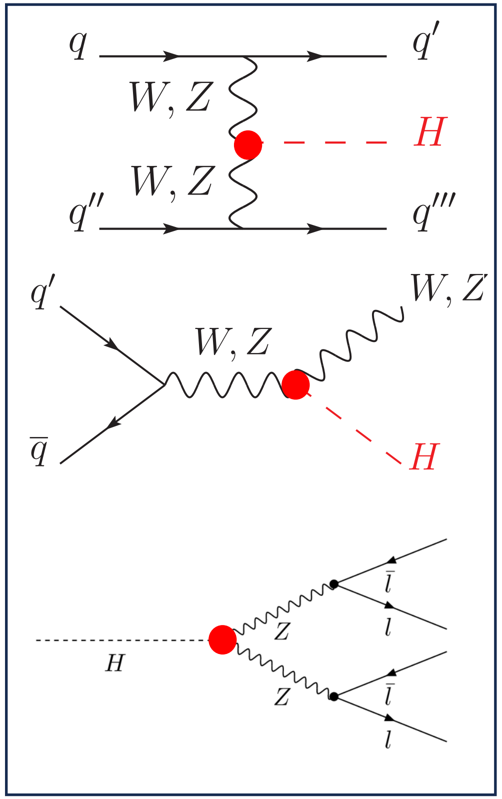




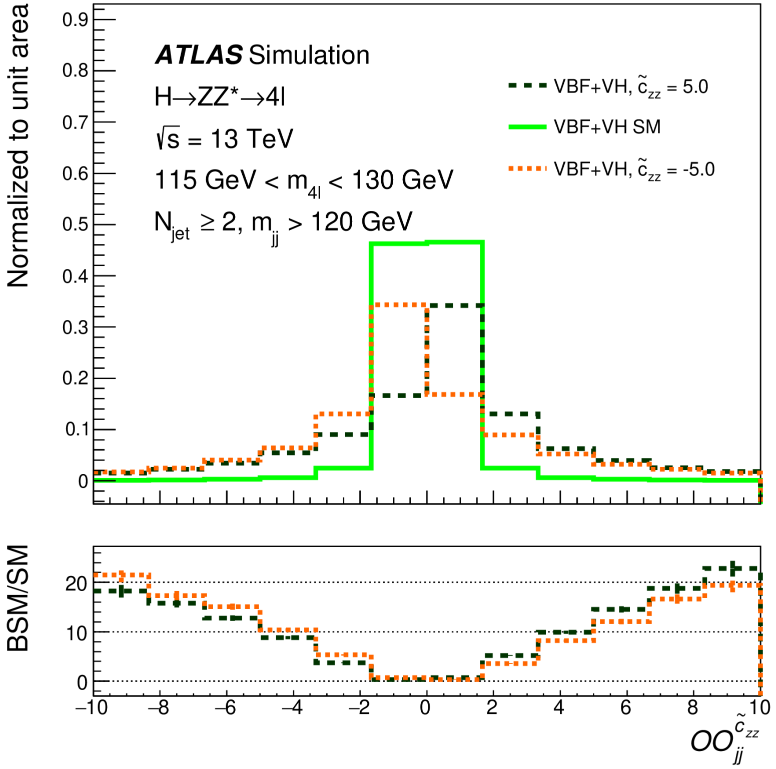
Results in other channels

[arXiv:2304.09612](https://arxiv.org/abs/2304.09612)

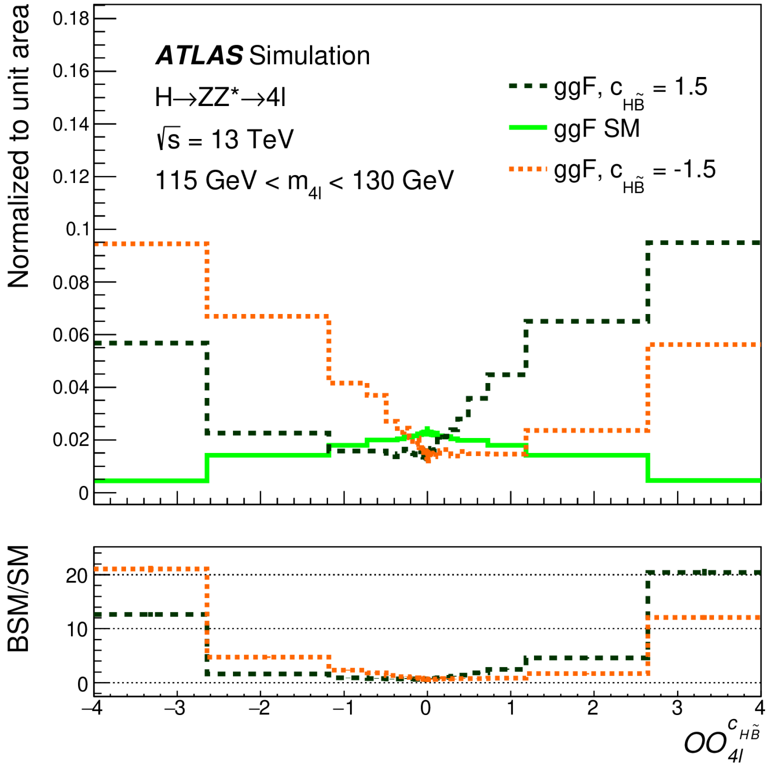
- **VBF $H \rightarrow ZZ^* \rightarrow 4l$ CP analysis**
  - Sensitive to all 3 CP-violation coefficients from VBF production and $H \rightarrow ZZ$ decay.
  - $\mathcal{OO}$ for each coefficients and vertices: $\mathcal{OO}_{jj}^{c_i}$ and $\mathcal{OO}_{4l}^{c_i}$



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



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



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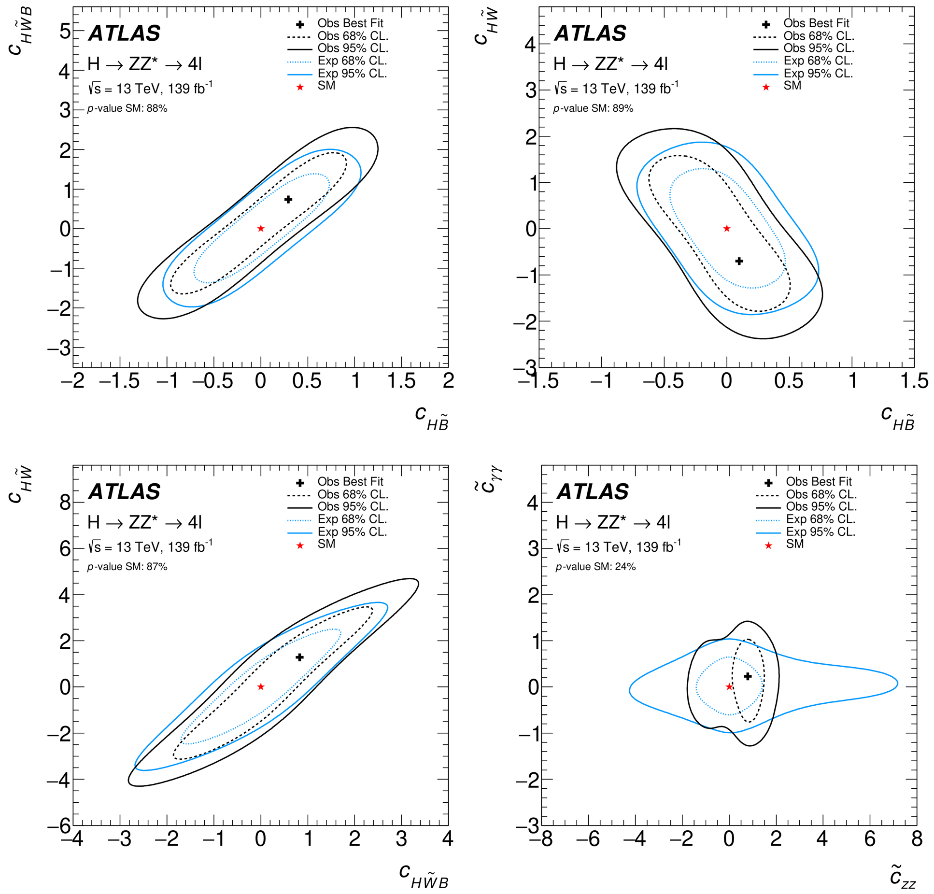
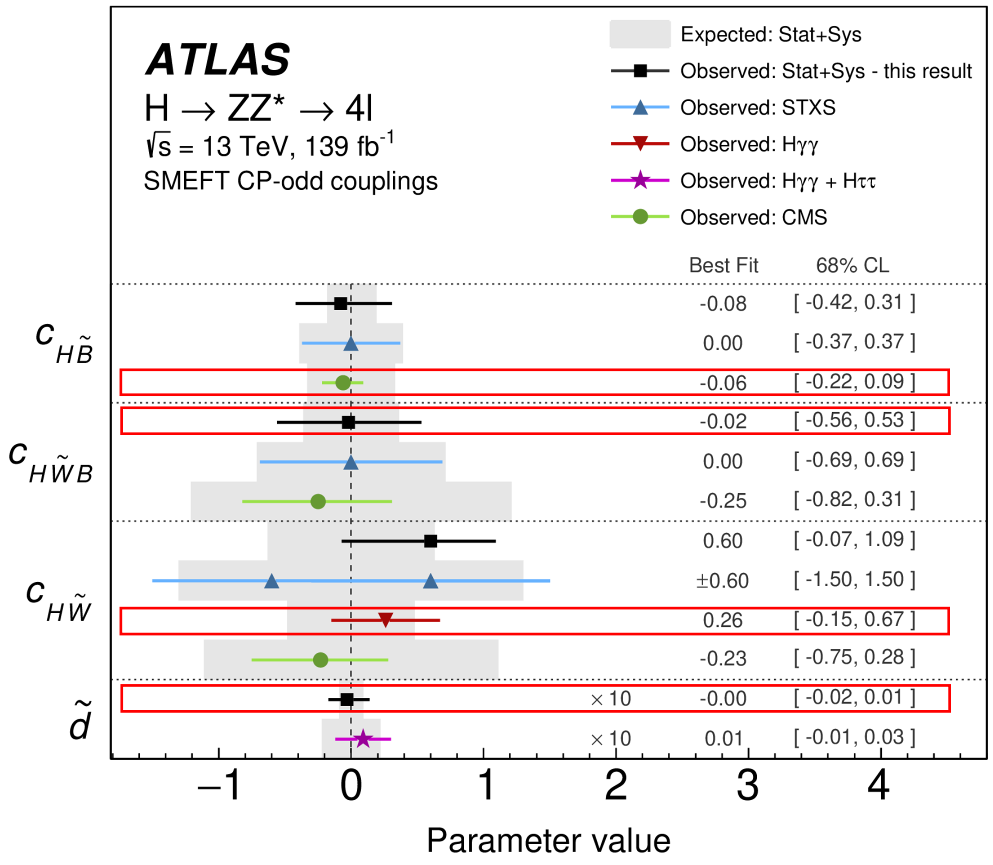
- **1D and 2D constraints for H-V CP properties**





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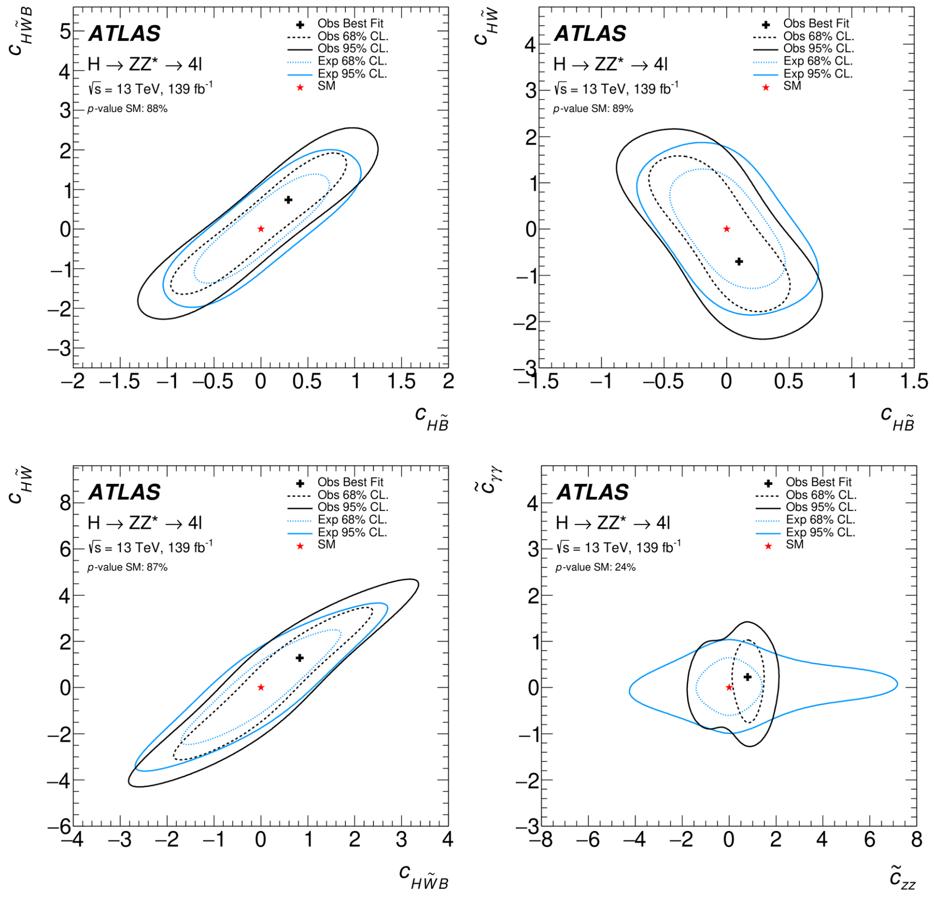

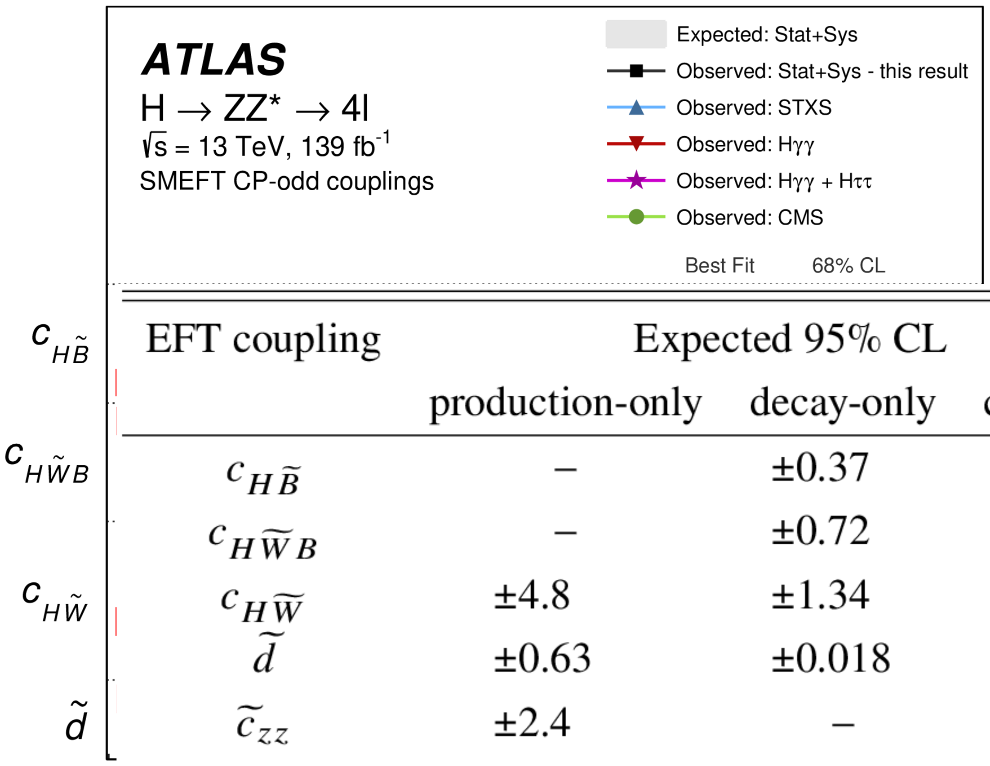

EFT coupling	Expected 95% CL		
	production-only	decay-only	combined
$c_{H\tilde{B}}$	–	±0.37	–
$c_{H\tilde{W}B}$	–	±0.72	–
$c_{H\tilde{W}}$	±4.8	±1.34	±1.27
$\tilde{d}$	±0.63	±0.018	±0.019
$\tilde{c}_{zz}$	±2.4	–	–
$\tilde{c}_{z\gamma}$	±6.6	±0.76	±0.80
$\tilde{c}_{\gamma\gamma}$	–	±0.76	–

ur result)

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.

- **Study of CP property in VBF $H \to \gamma\gamma$ channel in ATLAS Run 2 is done**
  - Results are compatible with the SM.
  - Still the most stringent constraint on $c_{H\widetilde{W}}$ now.

- **Future**
  - Combination with other channels.
    - Analysis is kicked-off. Significant improvement can be expected.
  - Going forward to Run 3.