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

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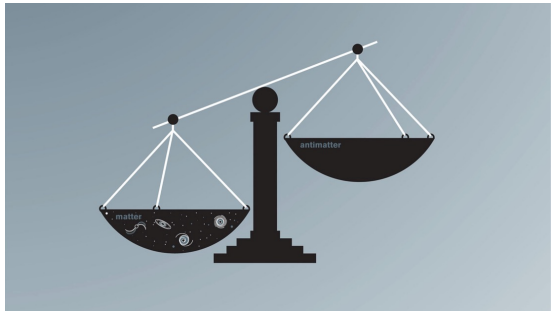
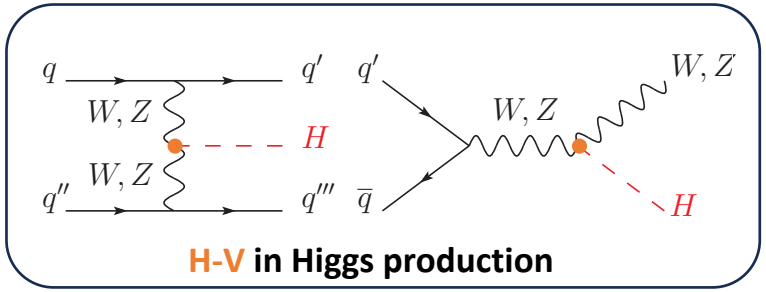
Introduction

- **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…
  - Worth to search the CPV in Higgs coupling.
    - Any evidence might be a road to NEW PHYSICS!

- **In this talk: anomalous Higgs couplings in H-V interaction**
  - Fiducial differential cross section in:
    - $H \to \gamma\gamma$, $H \to WW^*$ channels.
  - Dedicated CP analysis:
    - VBF $H \to \tau\tau$, $H \to \gamma\gamma$ channels.
    - VBF+VH $H \to ZZ$ channel.



H-V in Higgs production

H-V in Higgs decay

Introduction

- **Dimension-6 effective field theory: SMEFT framework**
  - No tree-level CPV in SM H-V interaction ⇒ $\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_k \frac{c_k}{\Lambda^2}\mathcal{O}_k$
  - Focus on CP-odd H-V operators: 3 independent c_i

Warsaw basis

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

Linear combination

Higgs basis

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

  - A simplified assumption: HISZ basis.
    - Motivated by the indistinguishable contributions from vector bosons and the absence of couplings.

      $c_{H\widetilde{W}} = c_{H\tilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d}$, $c_{H\widetilde{W}B} = 0$. $\tilde{d}$ is the only CPV parameter.
    - Used only in some CP-dedicated VBF Higgs analyses.
  - $|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\Sigma_i \frac{c_i}{\Lambda^2} Re\left(\mathcal{M}^*_{SM}\,\mathcal{M}_{BSM,i}\right) + \Sigma_i\Sigma_j \frac{c_i c_j}{\Lambda^4} Re(\mathcal{M}^*_{BSM,i}\mathcal{M}^*_{BSM,j})$

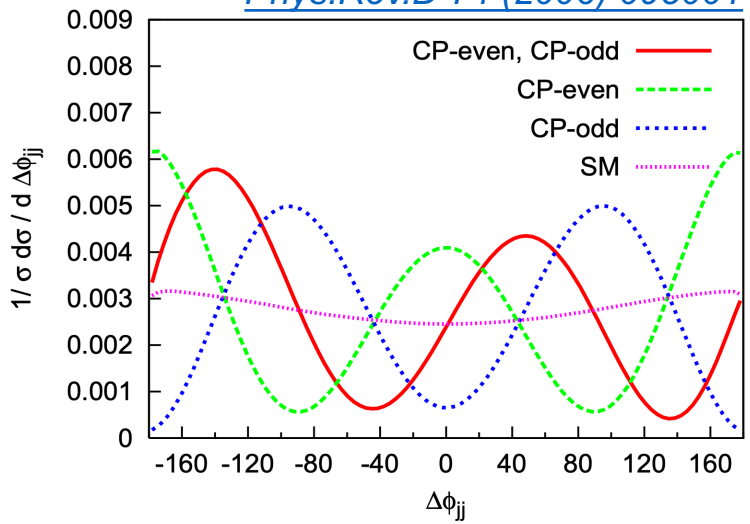
CP-odd inter. term

CP-even quad. term

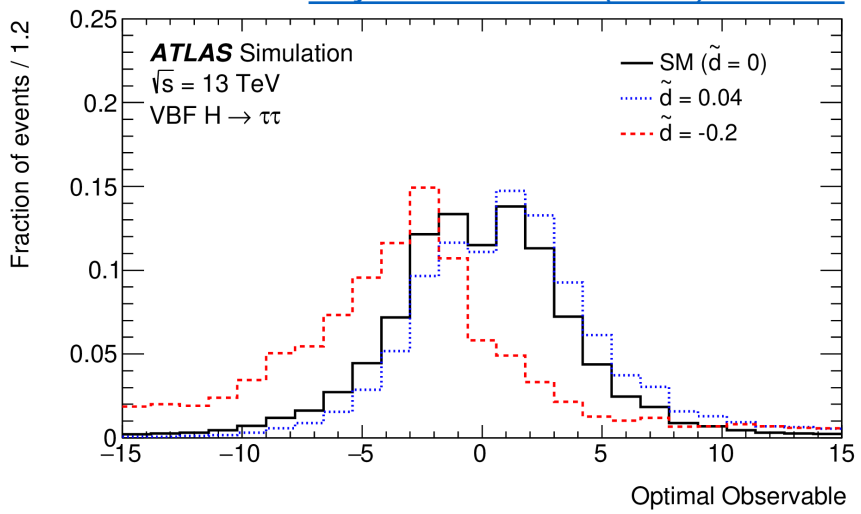
CP sensitive observables

- **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 $\Delta\phi_{jj}^{signed}$.
  - In SM, $\langle\mathcal{OO}\rangle = 0$. CP-odd effects introduce asymmetry shape in $\mathcal{OO}$.

Phys.Rev.D 74 (2006) 095001



Phys. Lett. B 805 (2020) 135426

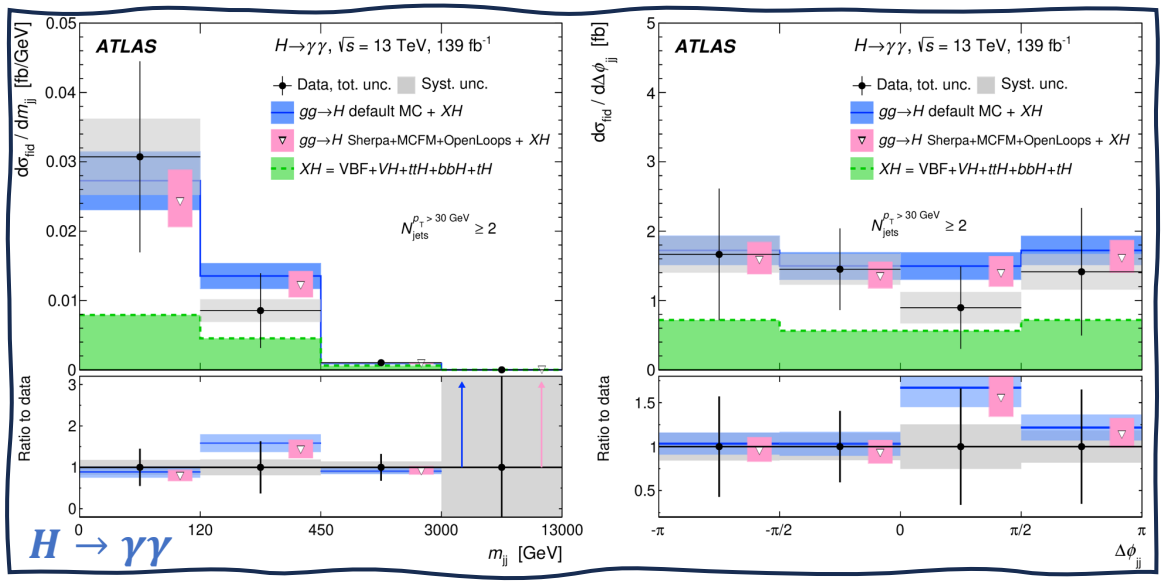


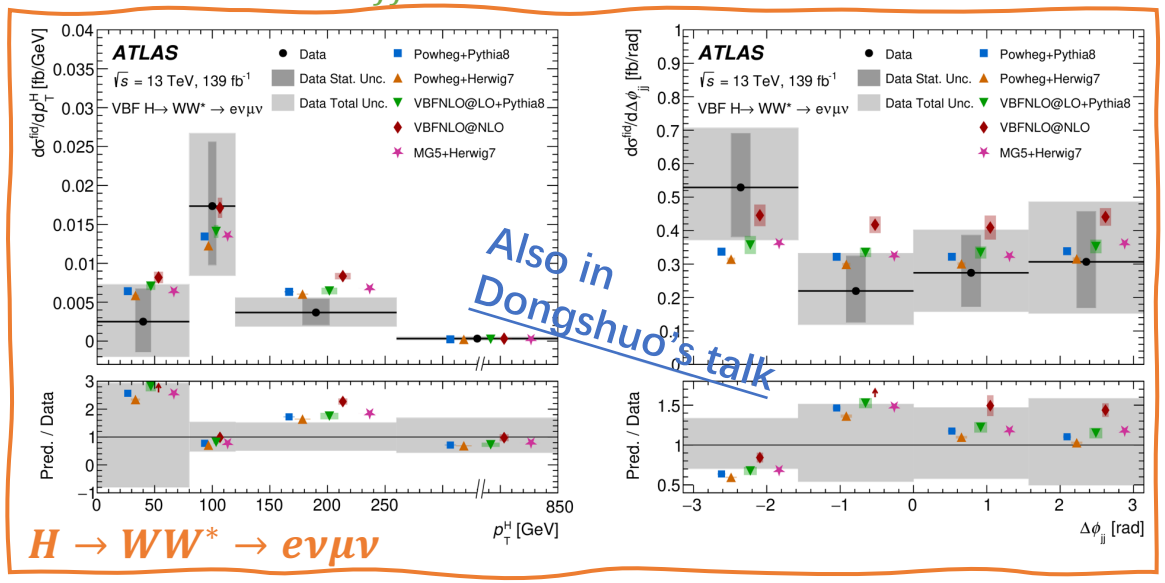
Differential fiducial XS in $H \to \gamma\gamma / WW^*$

[JHEP 08 (2022) 027](#)
[Phys. Rev. D 108, 072003](#)

- **Differential fiducial XS measurements can probe CP properties**
  - (try to be) Model independent, minimize the physics assumptions in extrapolation.
    - Flexible to be interpreted to theory models, e.g. SMEFT.
  - Measurements on observables:
    - $H \to \gamma\gamma$: diphoton kinematics (e.g. $p_T^{\gamma\gamma}$), jet multiplicities (e.g. N_{jets}), $\geq$ 1-jet observables (e.g. $p_T^{j_1}$), $p_T^{\gamma\gamma,jet\ veto}$, 2-jet observables (e.g. $\Delta\phi_{jj}$), VBF-enriched phase space observables.
    - $H \to WW^* \to e\nu\mu\nu$: Higgs-related (e.g. p_T^H), jet-related (e.g. $\Delta\phi_{jj}$).

Sensitive to CP



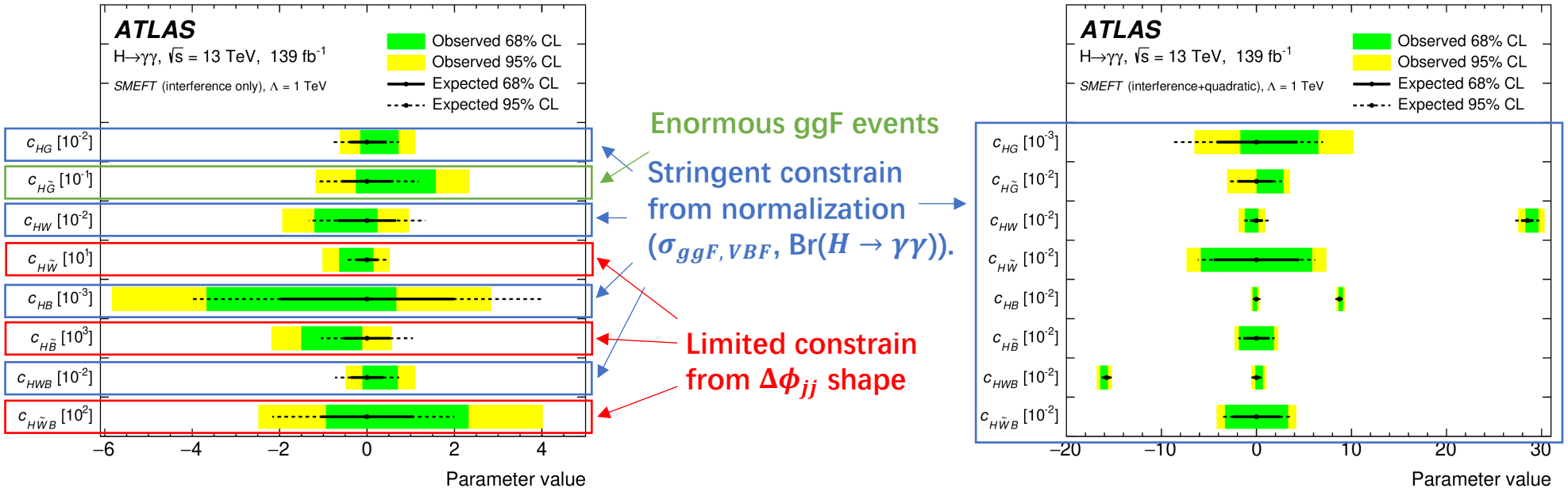


Differential fiducial XS in $H \to \gamma\gamma / WW^*$

JHEP 08 (2022) 027

- **EFT interpretation in SMEFT Warsaw basis**
  - $|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\Sigma_i \frac{c_i}{\Lambda^2} Re\left(\mathcal{M}_{SM}^* \mathcal{M}_{BSM,i}\right) + \Sigma_i \Sigma_j \frac{c_i c_j}{\Lambda^4} Re(\mathcal{M}_{BSM,i}^* \mathcal{M}_{BSM,j})$

    Observable shape (e.g. $\Delta\phi_{jj}$) — Normalized yields
  - $H \to \gamma\gamma$: simultaneous fit to 5 observables & correlations: ($p_T^{\gamma\gamma}, N_{jets}, m_{jj}, \Delta\phi_{jj}, p_T^{j_1}$).
    - For a global sets of CP-even coefficients $c_{HW,HWB,HB,HG}$ and CP-odd $c_{H\tilde{W},H\tilde{W}B,H\tilde{B},H\tilde{G}}$.



Differential fiducial XS in $H \to \gamma\gamma / WW^*$

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Phys. Rev. D 108, 072003

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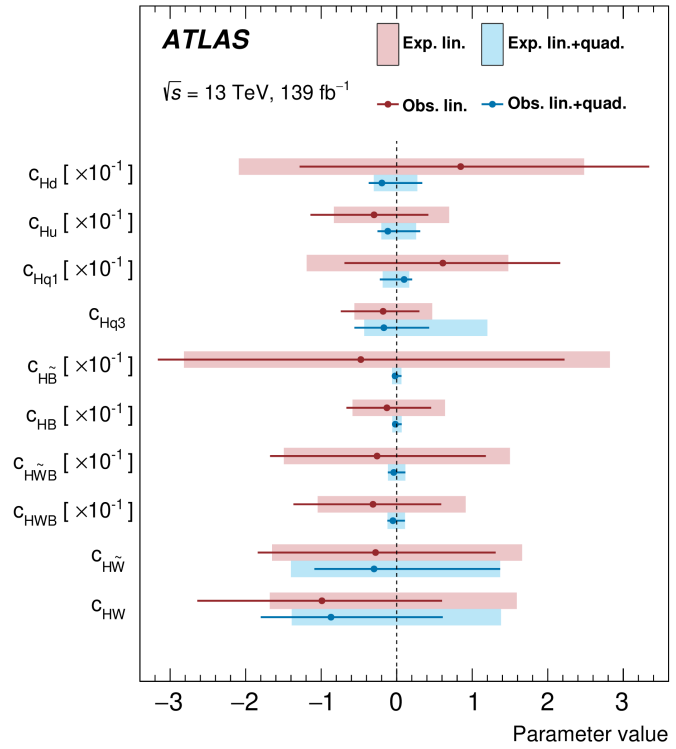
  Observable shape (e.g. $\Delta\phi_{jj}$) — Normalized yields

- $H \to WW^*$: fit to the most sensitive observables ($p_T^{j_1}$ or $\Delta\phi_{jj}$).



Wilson coefficients	Operator structure	Fit distr	Paramater order	95% Confidence interval [TeV^{-2}] Expected	Observed
c_{HW}	$H^\dagger H W^n_{\mu\nu} W^{n\mu\nu}$	$\Delta\phi_{jj}$	lin	[−1.7, 1.6]	[−2.6, 0.60]
			lin + quad	[−1.4, 1.4]	[−1.8, 0.61]
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$	lin	[−5.9, 6.4]	[−6.7, 4.6]
			lin + quad	[−0.59, 0.66]	[−0.60, 0.66]
c_{HWB}	$H^\dagger \tau^n H W^n_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$	lin	[−10, 9]	[−14, 5.9]
			lin + quad	[−1.2, 1.1]	[−1.2, 1.1]
c_{Hq1}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	p_T^{j1}	lin	[−12, 15]	[−6.9, 22]
			lin + quad	[−1.9, 1.7]	[−2.2, 2.0]
c_{Hq3}	$(H^\dagger i\overleftrightarrow{D}^n_\mu H)(\bar{q}\tau^n\gamma^\mu q)$	p_T^{j1}	lin	[−0.56, 0.47]	[−0.74, 0.30]
			lin + quad	[−0.43, 1.2]	[−0.56, 0.43]
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	p_T^{j1}	lin	[−8.3, 6.9]	[-11, 4.2]
			lin + quad	[−2.0, 2.6]	[−2.5, 3.1]
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	p_T^{j1}	lin	[−21, 25]	[−13, 33]
			lin + quad	[−3.0, 2.7]	[−3.7, 3.4]
$c_{H\tilde{W}}$	$H^\dagger H \tilde{W}^n_{\mu\nu} W^{n\mu\nu}$	$\Delta\phi_{jj}$	lin	[−1.7, 1.7]	[−1.8, 1.3]
			lin + quad	[−1.4, 1.4]	[−1.1, 1.4]
$c_{H\tilde{B}}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$	lin	[−28, 28]	[−32, 22]
			lin + quad	[−0.62, 0.62]	[−0.63, 0.63]
$c_{H\tilde{W}B}$	$H^\dagger \tau^n H \tilde{W}^n_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$	lin	[−15, 15]	[−17, 12]
			lin + quad	[−1.2, 1.1]	[−1.2, 1.1]

Excellent constrain on lin+quad c_i from yield.

Sensitivities to c_{HW} and $c_{H\widetilde{W}}$ from VBF and $H \to WW^*$ (better than $H \to \gamma\gamma$).

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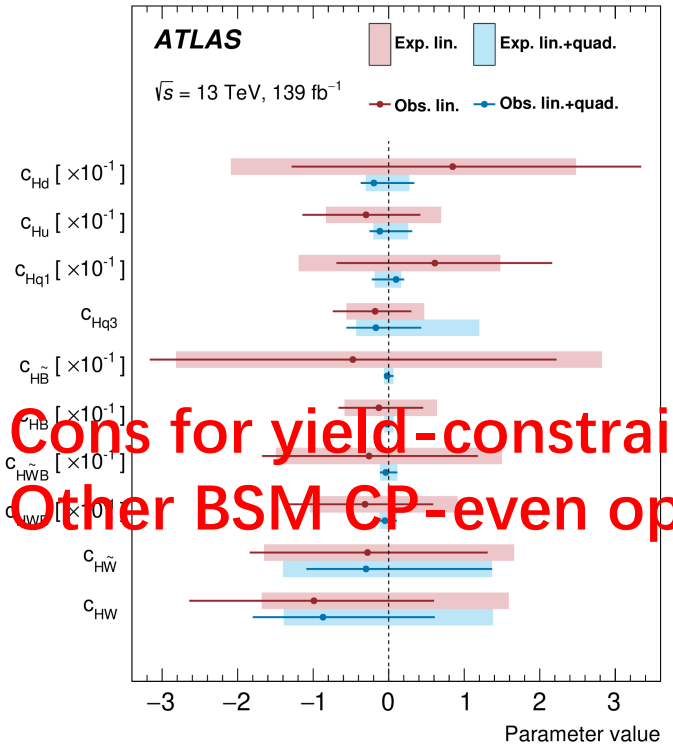
  Observable shape (e.g. $\Delta\phi_{jj}$) — Normalized yields

- $H \to WW^*$: fit to the most sensitive observables ($p_T^{j_1}$ or $\Delta\phi_{jj}$).



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Excellent constrain on lin+quad c_i from yield.

Sensitivities to c_{HW} and $c_{H\widetilde{W}}$ from VBF and $H \to WW^*$ (better than $H \to \gamma\gamma$).

Cons for yield-constrain: Not a pure CP test for H-V interaction.
Other BSM CP-even operators can also contribute.

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

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

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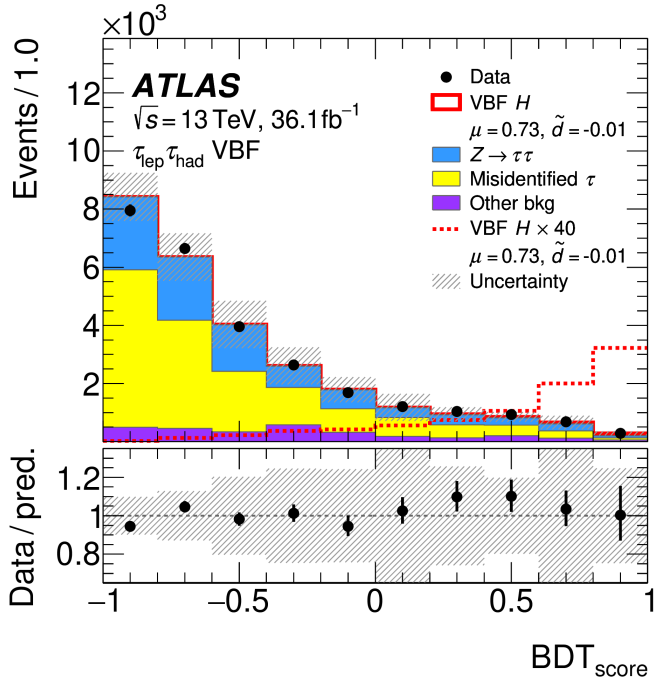
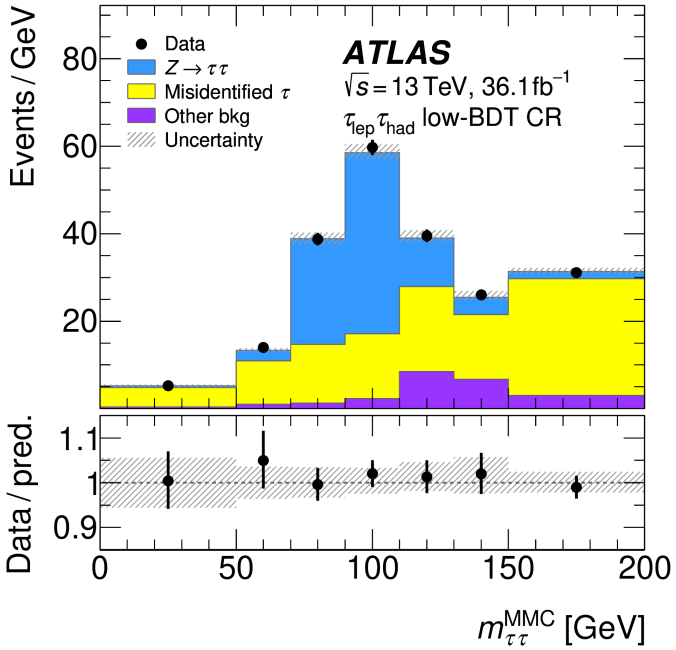
  - **Dedicated pure CP analysis** in HISZ basis ($\tilde{d}$).
  - **Shape-only fit** on CP-sensitive observable: optimal observable $\mathcal{OO}$
  - 4 analysis channels depending on τ decay: $\boldsymbol{\tau_{lep}\tau_{lep}}$ **SF**, $\boldsymbol{\tau_{lep}\tau_{lep}}$ **DF**, $\boldsymbol{\tau_{lep}\tau_{had}}$ 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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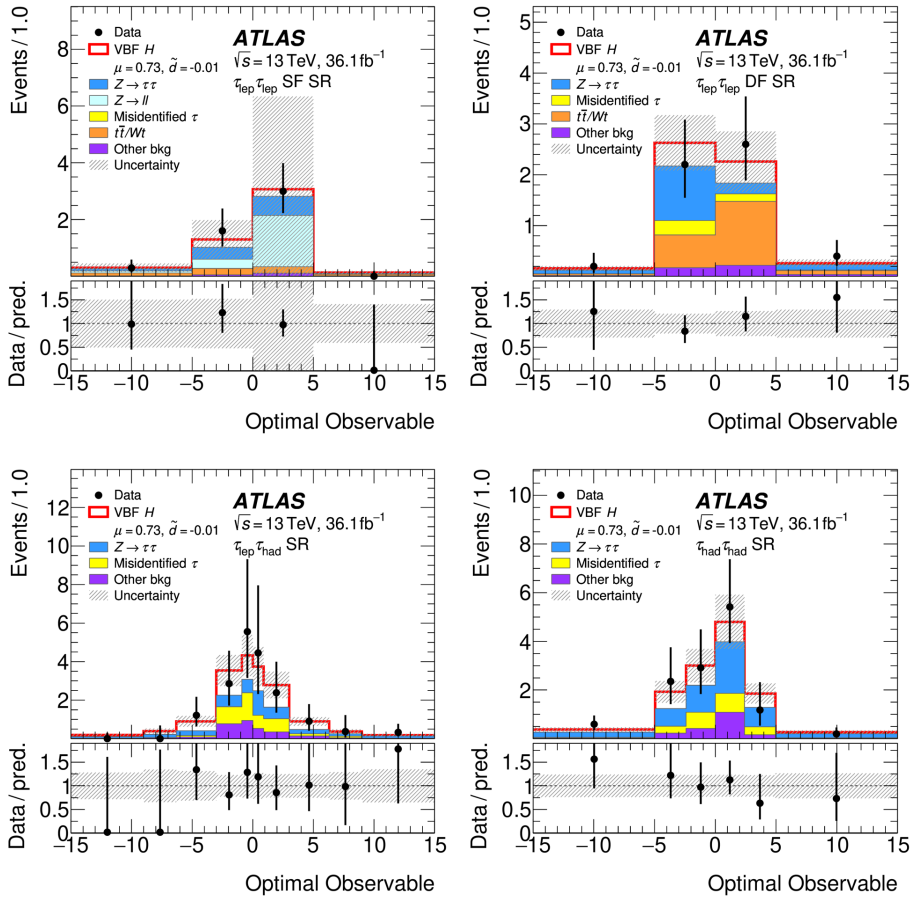
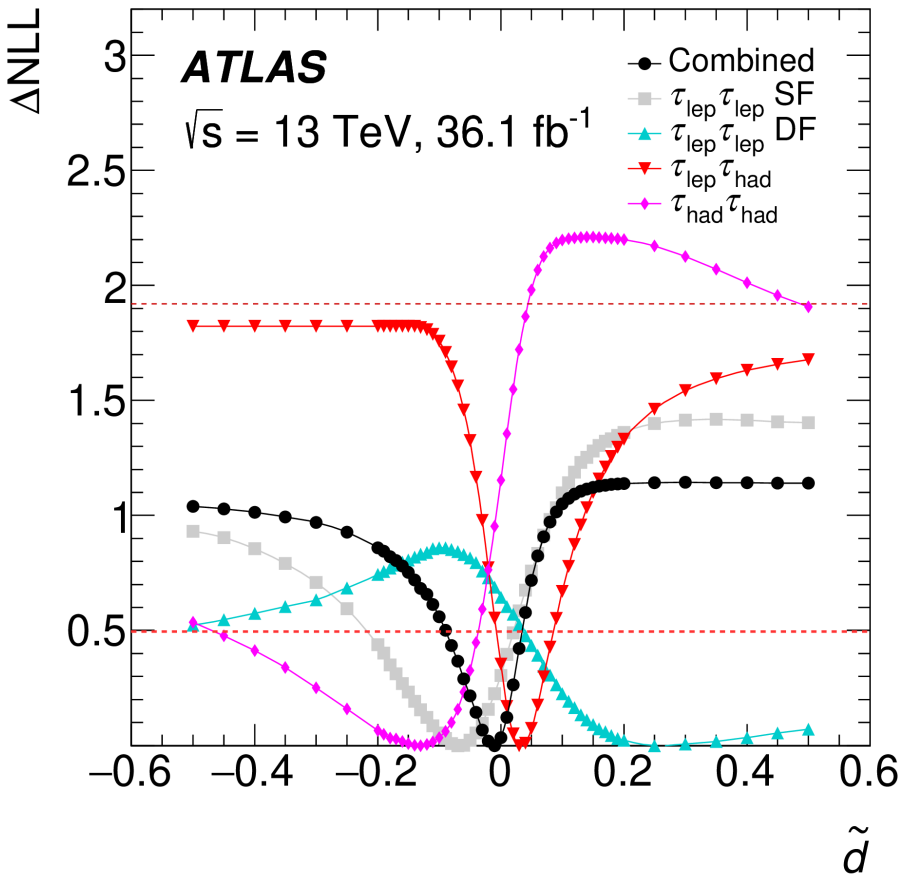
  - A template fit with $\tilde{d}$ hypotheses. Result: $\tilde{d} \in [-0.090, 0.035]$ @ 68% C.L.



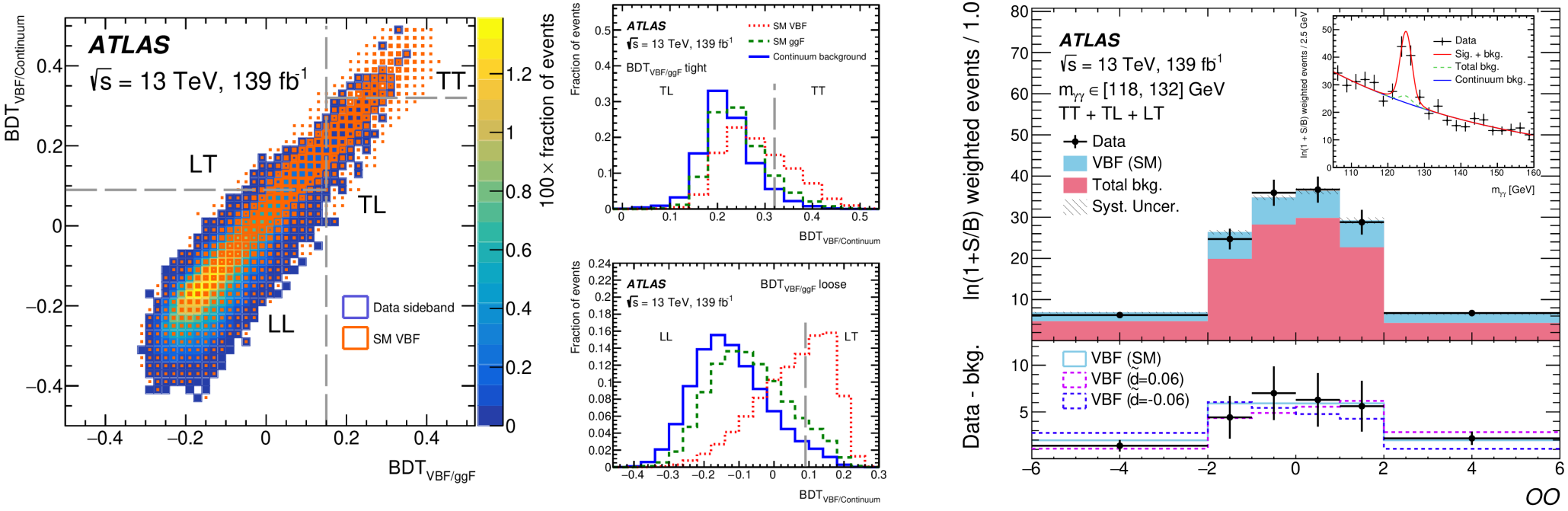


H-V CP property in VBF $H \to \gamma\gamma$

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

Phys. Rev. Lett. 131 (2023) 061802

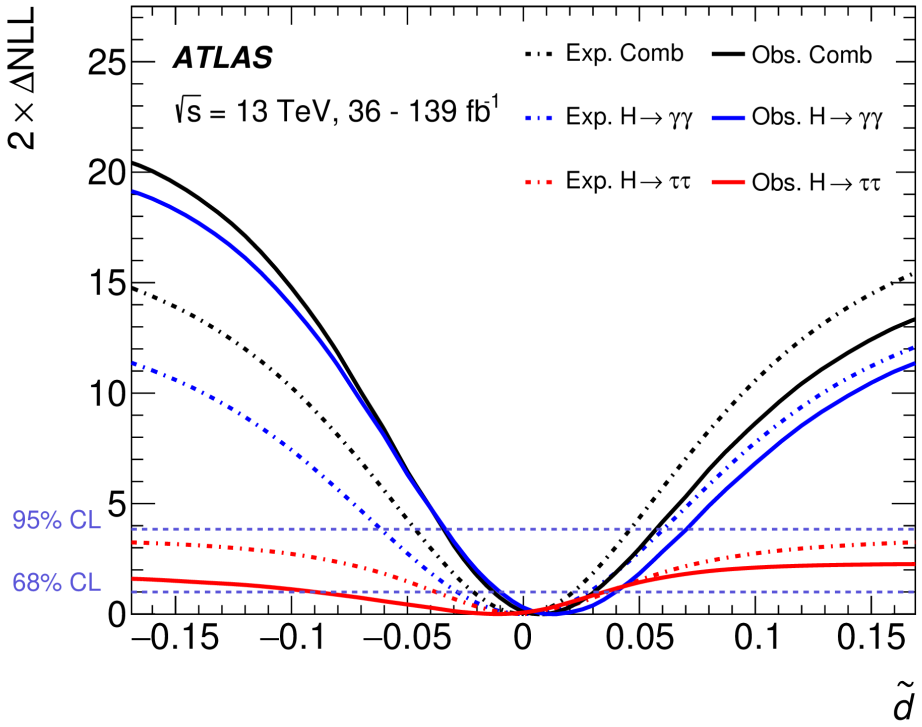
  - 2 EFT basis: $\tilde{d}$ in HISZ basis and $c_{H\widetilde{W}}$ in Warsaw basis.
  - **Shape-only fit** on CP-sensitive observable: optimal observable $\mathcal{OO}$.
  - 2 BDTs for pure VBF events: $BDT_{VBF/ggF}, BDT_{VBF/Continuum}$.
  - Extract signal and background yield from $m_{\gamma\gamma}$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

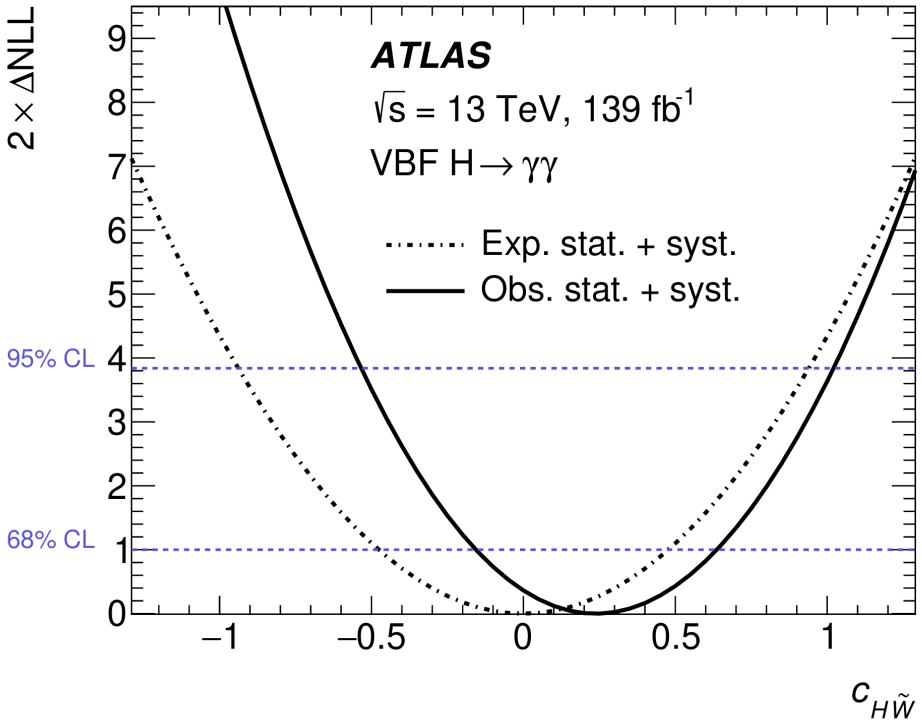


H-V CP property in VBF $H \to \gamma\gamma$

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

Phys. Rev. Lett. 131 (2023) 061802

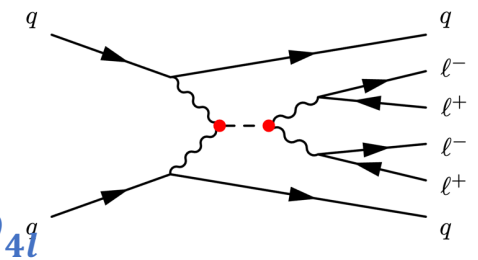




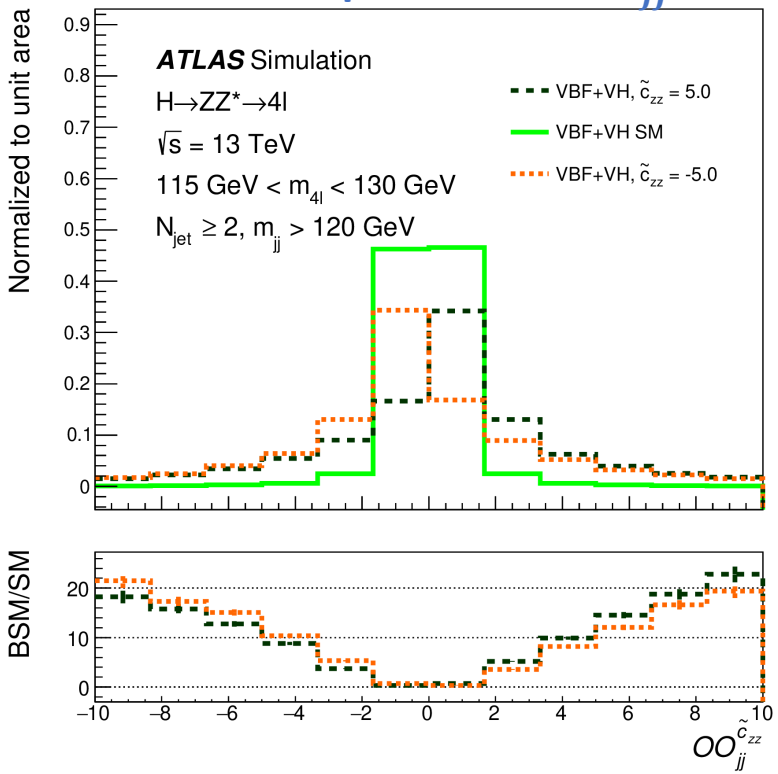
H-V CP properties in $H \to ZZ^* \to 4l$

- **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 $\mathcal{OO}_{4l}^{c_i}$

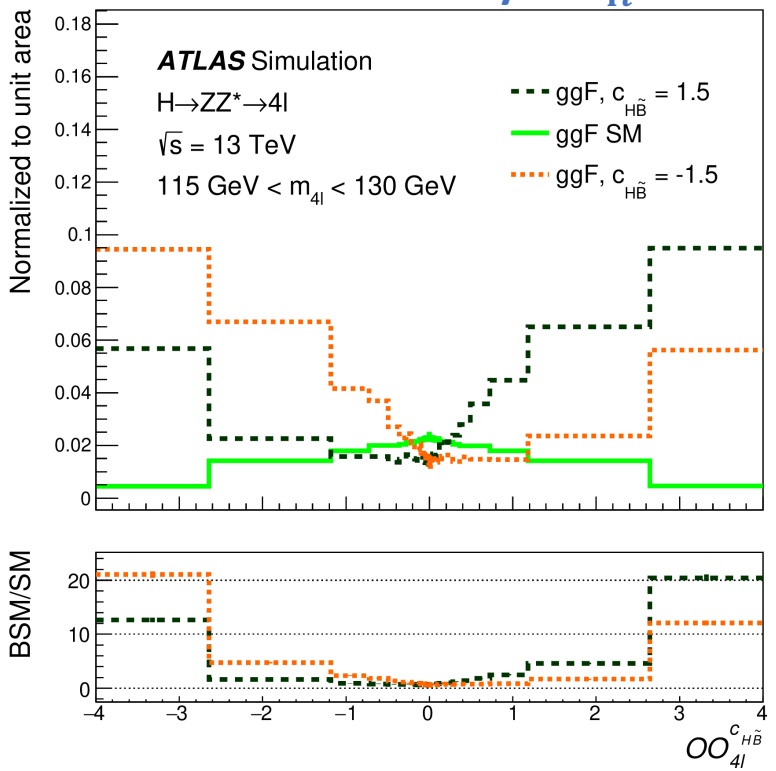
arXiv:2304.09612



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



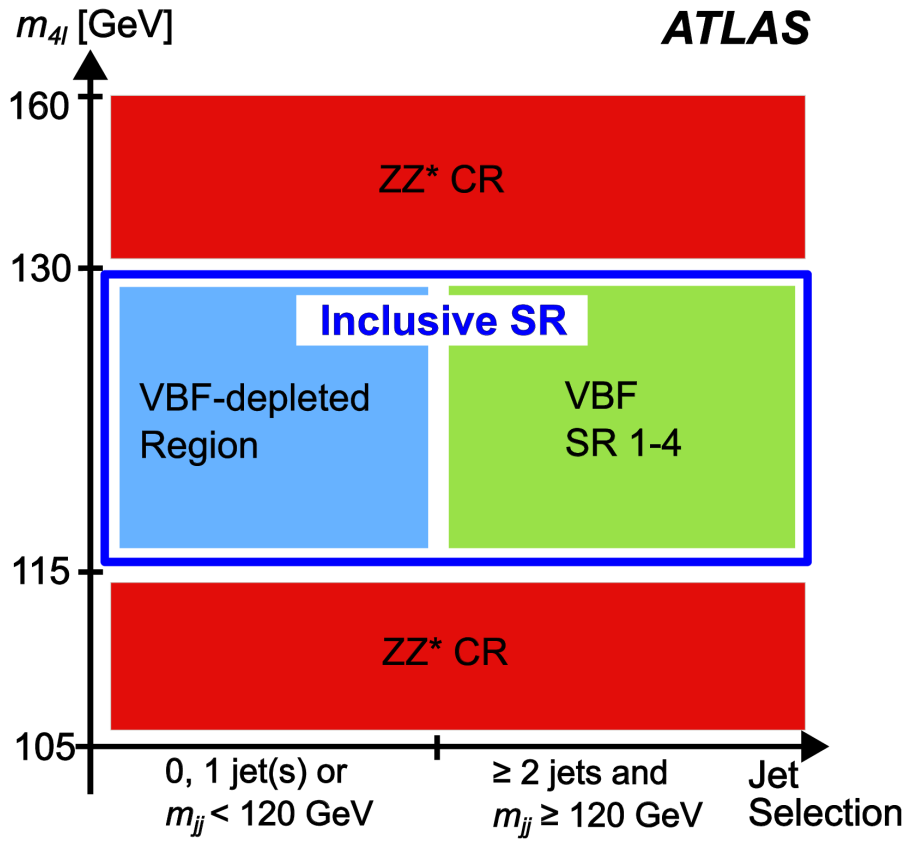
$H \to ZZ^*$ decay $\mathcal{OO}_{4l}$

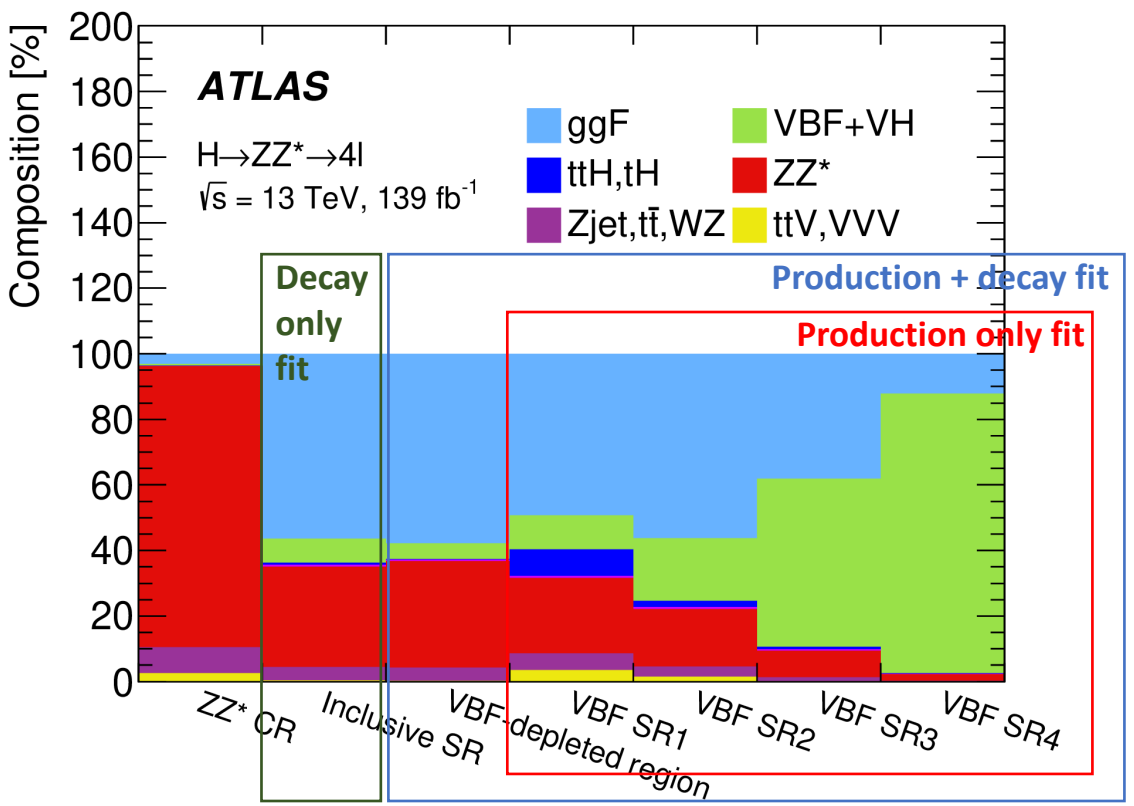


H-V CP properties in $H \to ZZ^* \to 4l$

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 $H \to ZZ$ decay (ggF dominant).

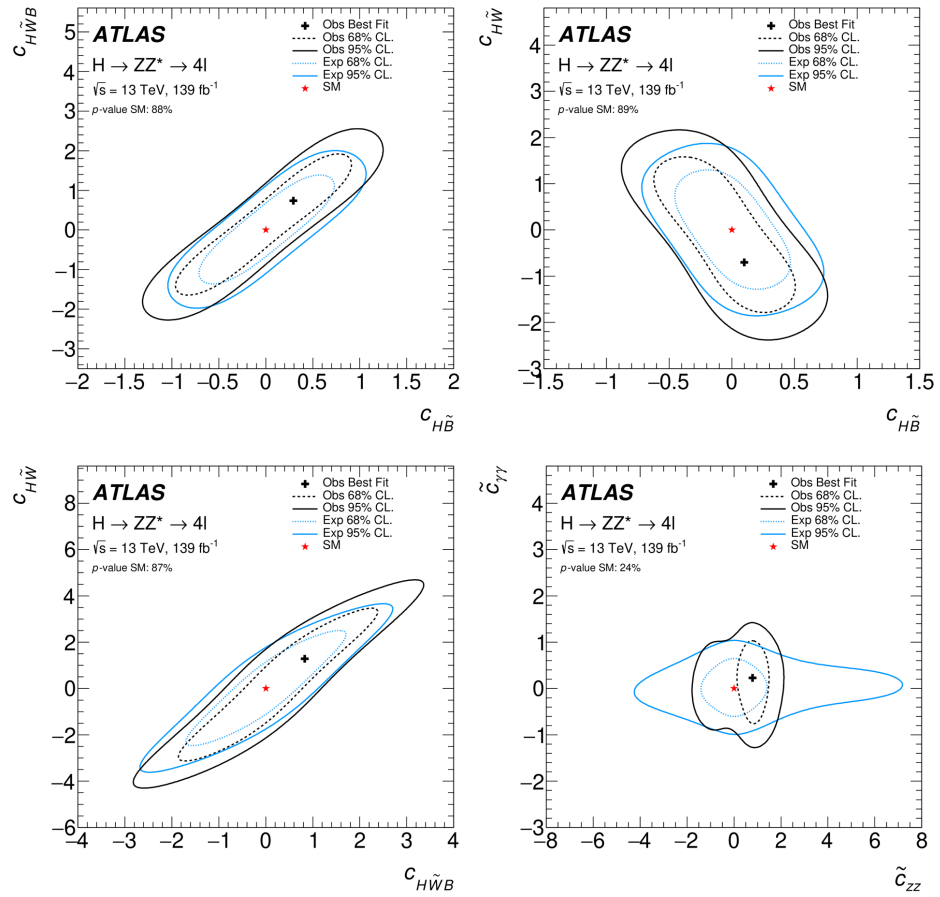


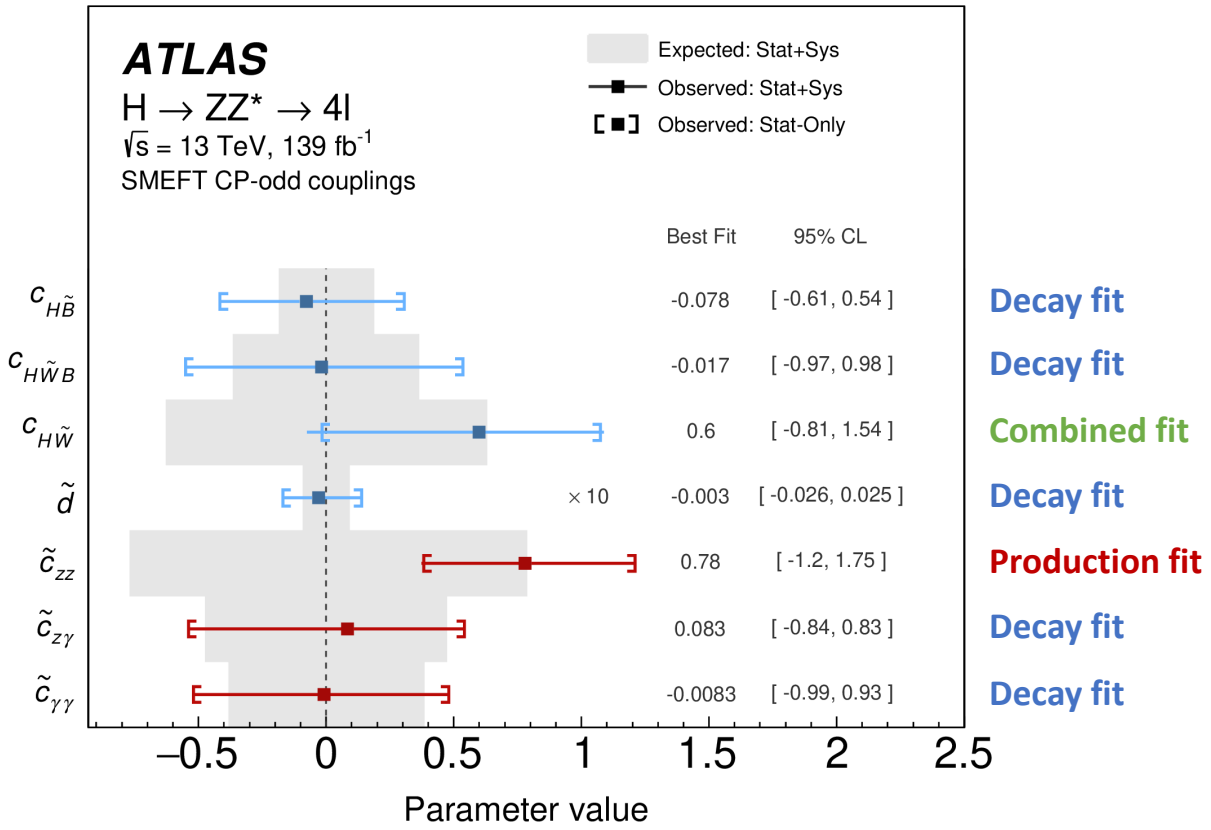


H-V CP properties in $H \to ZZ^* \to 4l$

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.
  - Mostly are statistical dominant.

- **More results are on the way, please stay tuned!**

Backup slides

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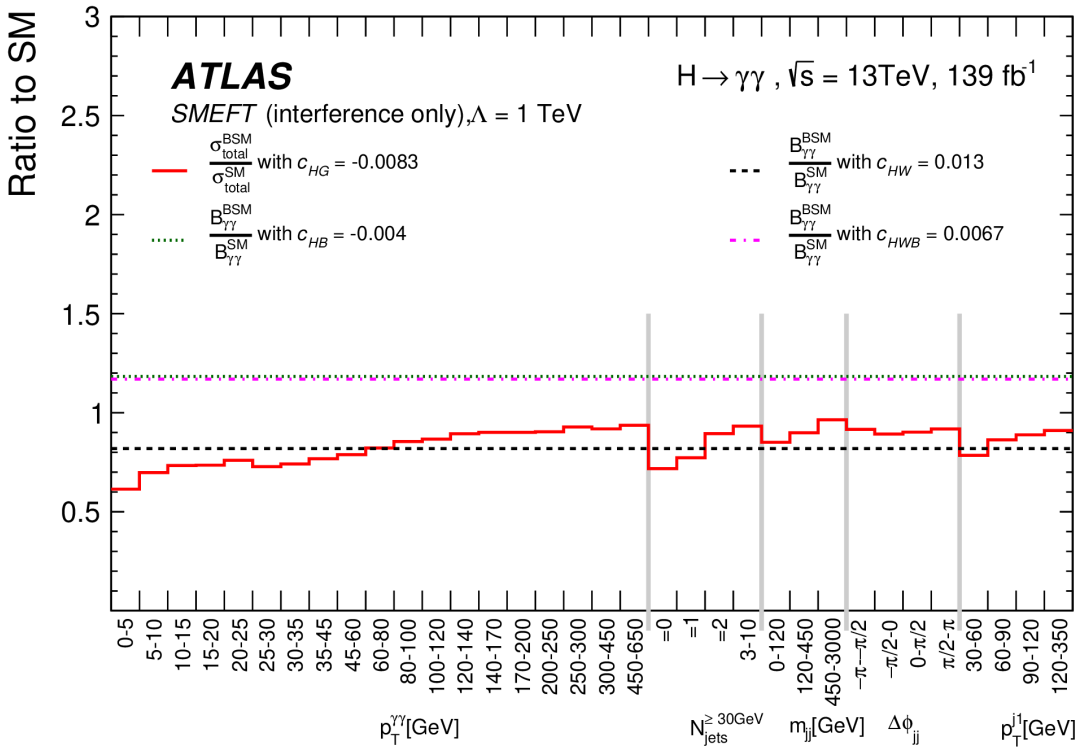
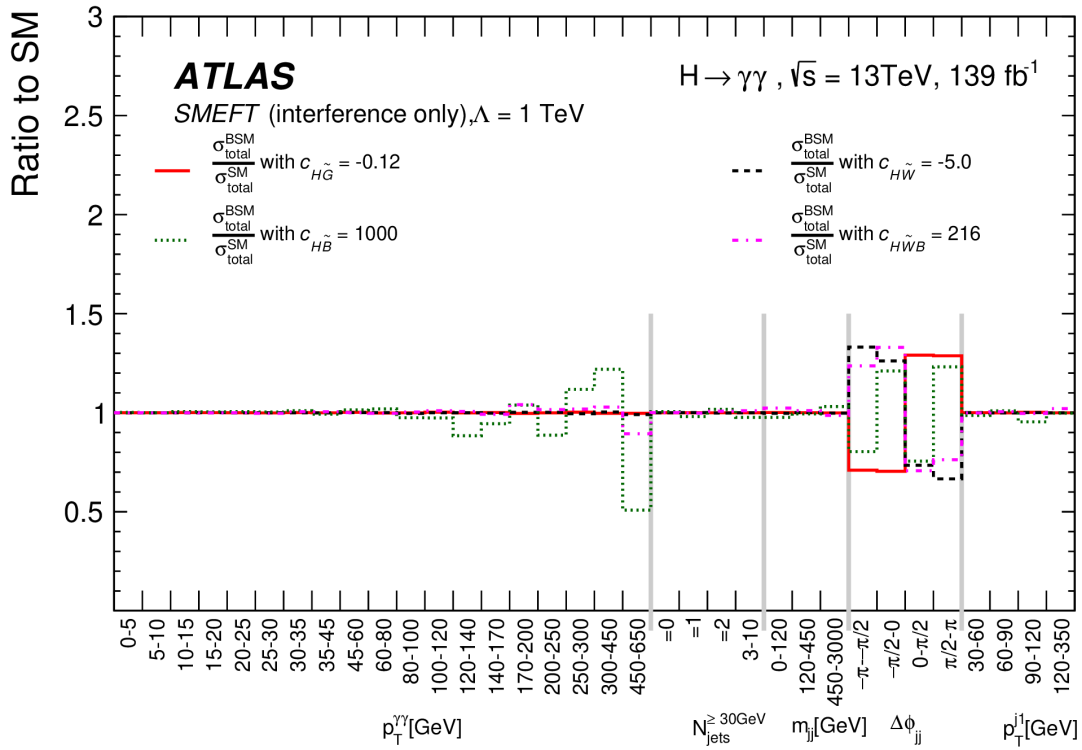
Institute of High Energy Physics Chinese Academy of Sciences

Differential fiducial XS in $H \to \gamma\gamma / WW^*$

- **Effect on the 5 distributions from CP-even and CP-odd coefficients in $H \to \gamma\gamma$**





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

- **Expected sensitivities on coefficients from production and decay.**
- **Comparison with other results.**

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	–