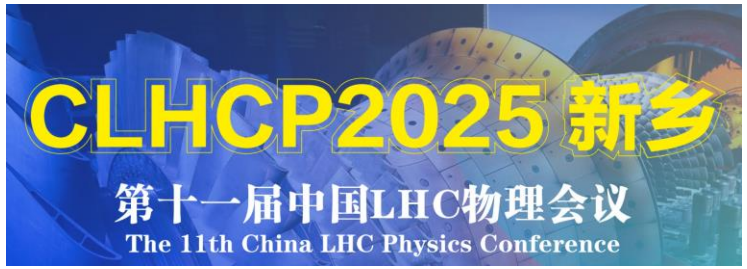

Search for CP-violation in Higgs interaction with vector bosons with the ATLAS detector

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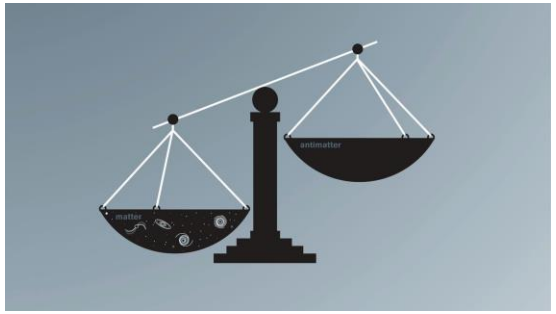
11th China LHC Physics Conference

Oct 29th – Nov 2nd 2025, Xinxiang

中国高等科学技术中心
China Center of Advanced Science and Technology
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Introduction

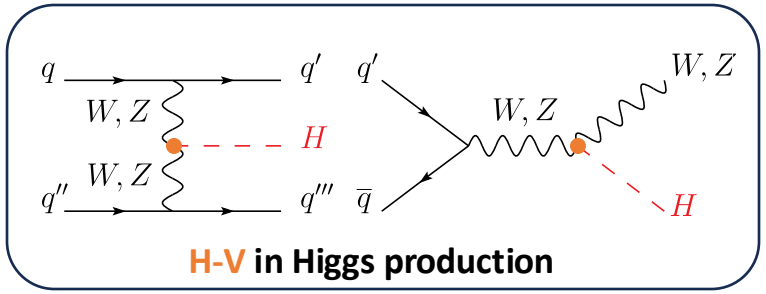
- **CP violation: one of key conditions in baryon asymmetry.**
  - Existing CPV in SM: CKM, PMNS matrices, but NOT sufficient.
  - **Where is the other CP-violation source?**



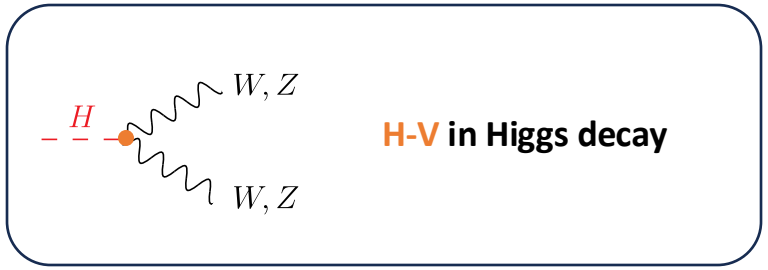
- **Higgs boson: a portal for BSM CPV source search.**
  - Higgs interactions in the SM: CP-even.
  - Any observation of CP-violation indicates new physics!

- **In this talk: CPV search in Higgs - EW boson couplings**

Channel	HVV interaction in
$H \to ZZ^* \to 4l$ (JHEP05(2024)105)	VBF production, $H \to ZZ$ decay
$H \to WW^* \to lvlv$ (arxiv: 2504.07686) **New**	VBF production
VBF $H \to \gamma\gamma$ (PhysRevLett.131.061802)	VBF production
VBF $H \to \tau\tau$ (JHEP10(2025)092) **New**	VBF production
WH $H \to bb$ (ATL-PHYS-PUB-2025-022) **New**	WH production



H-V in Higgs production



H-V in Higgs decay

Introduction

- **Effective Field Theory: theoretical model for BSM search**
  - Consider commonly used interpretation **SMEFT Warsaw basis** with dimension-6 operators:

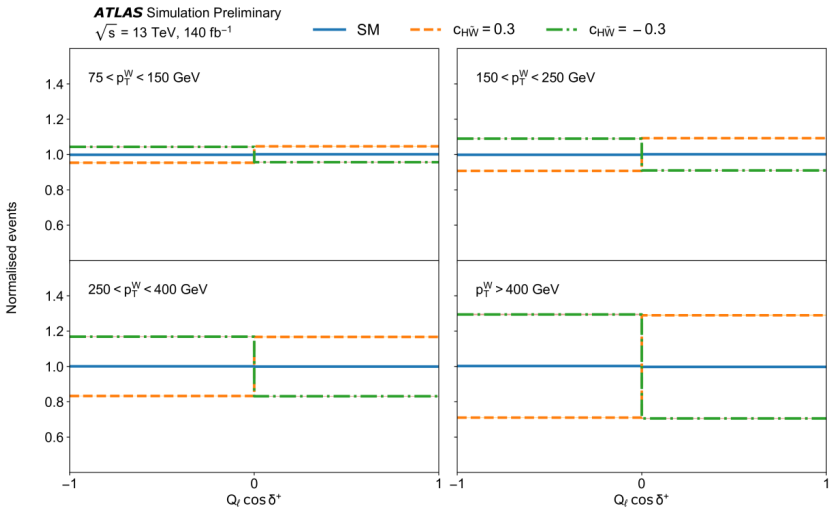
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \cdots + \frac{c_{H\widetilde{W}}}{\Lambda^2}\mathcal{O}_{\Phi\widetilde{W}} + \frac{c_{H\widetilde{B}}}{\Lambda^2}\mathcal{O}_{\Phi\widetilde{B}} + \frac{c_{H\widetilde{W}B}}{\Lambda^2}\mathcal{O}_{\Phi\widetilde{W}B} + \cdots$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + \underbrace{\frac{c_i}{\Lambda^2}2\mathcal{R}e(\mathcal{M}^*_{CP-odd}\mathcal{M}_{SM})}_{\text{CP-odd}} + \underbrace{\frac{c_i^2}{\Lambda^4}|\mathcal{M}_{CP-odd}|^2}_{\text{CP-even}}$$

  - Other EFT interpretations (SMEFT Higgs basis, HISZ basis) and other coefficients are considered in channels.

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

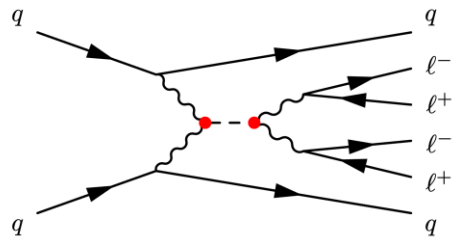
- **CP sensitive observable:**
  - Optimal Observable: $\mathcal{OO} = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$
  - Angular observable: $\Delta\phi^{\pm}_{jj}$, $Q_l\cos\delta^+ = Q_l\frac{\boldsymbol{p}_l^{(W)}\cdot(\boldsymbol{p}_H\times\boldsymbol{p}_W)}{|\boldsymbol{p}_l^W|\cdot|\boldsymbol{p}_H\times\boldsymbol{p}_W|}$
  - **Shape-only analysis to exclude the contribution from CP-even BSM term.**



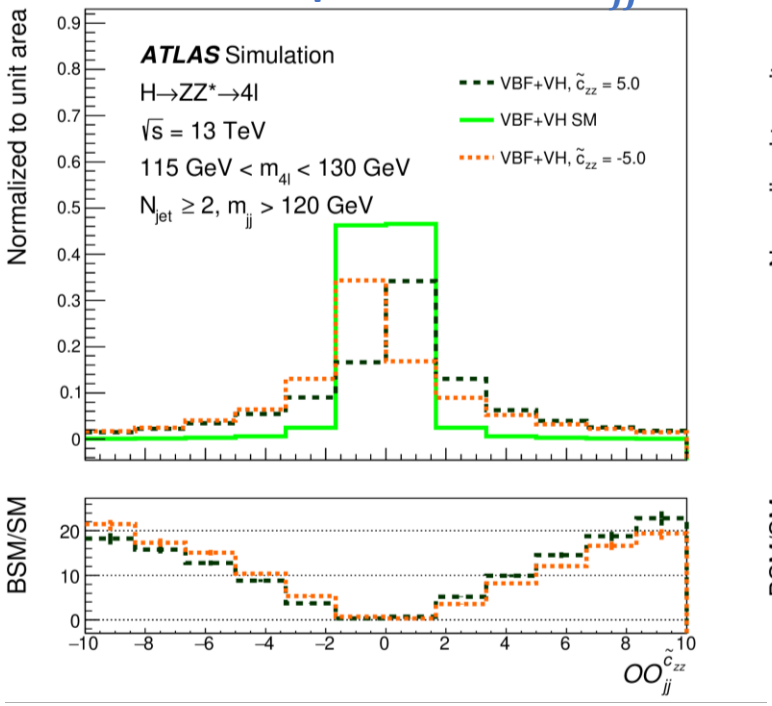
$H \to ZZ^* \to 4l$

JHEP05(2024)105

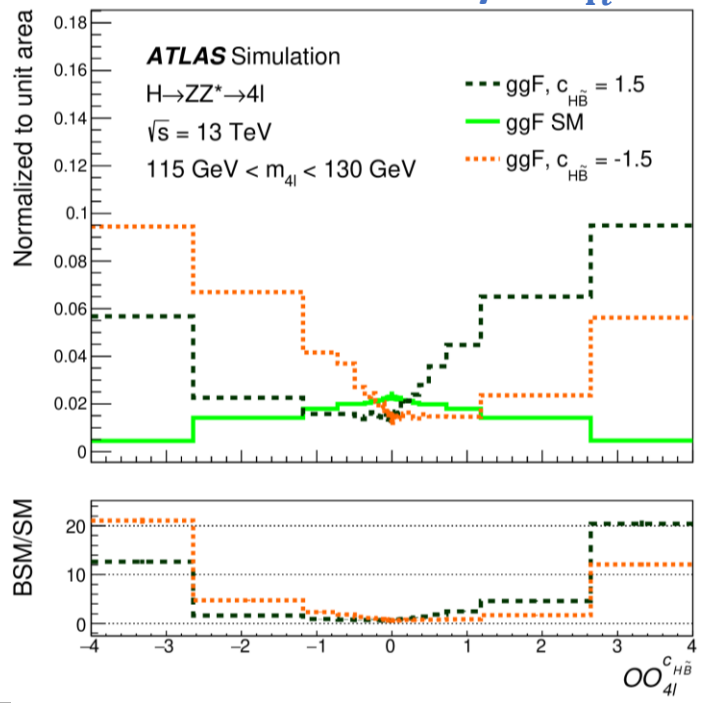
- **Constrain H-V CP-odd effects from VBF production and $H \to ZZ$ decay.**
  - $\mathcal{OO}$ for each coefficients and vertices: $\mathcal{OO}_{jj}^{c_i}$ and $\mathcal{OO}_{4l}^{c_i}$
  - Categorization design: 4 VBF SRs for VBF production, 1 VBF-depleted region for $H \to ZZ$ decay (ggF dominant).

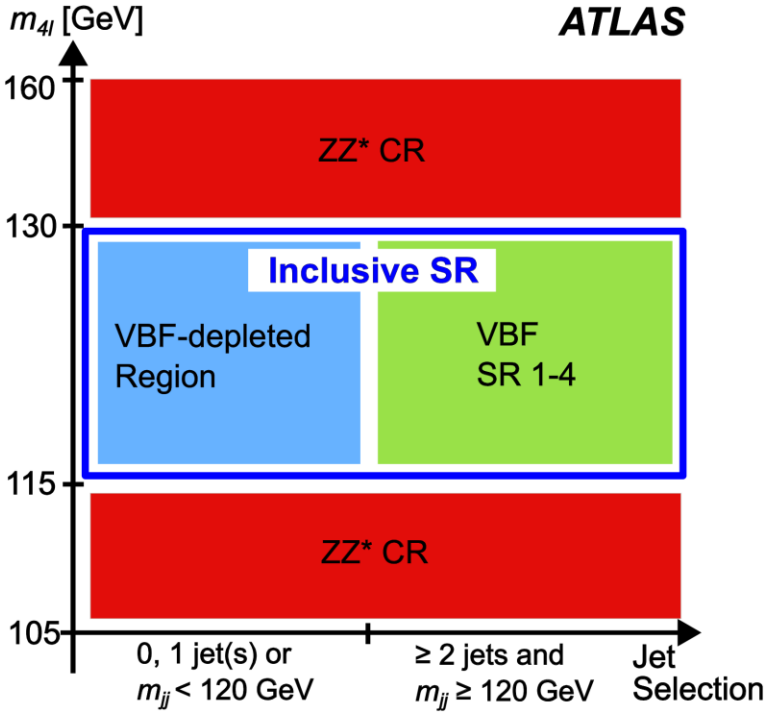


VBF+VH production $\mathcal{OO}_{jj}$



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

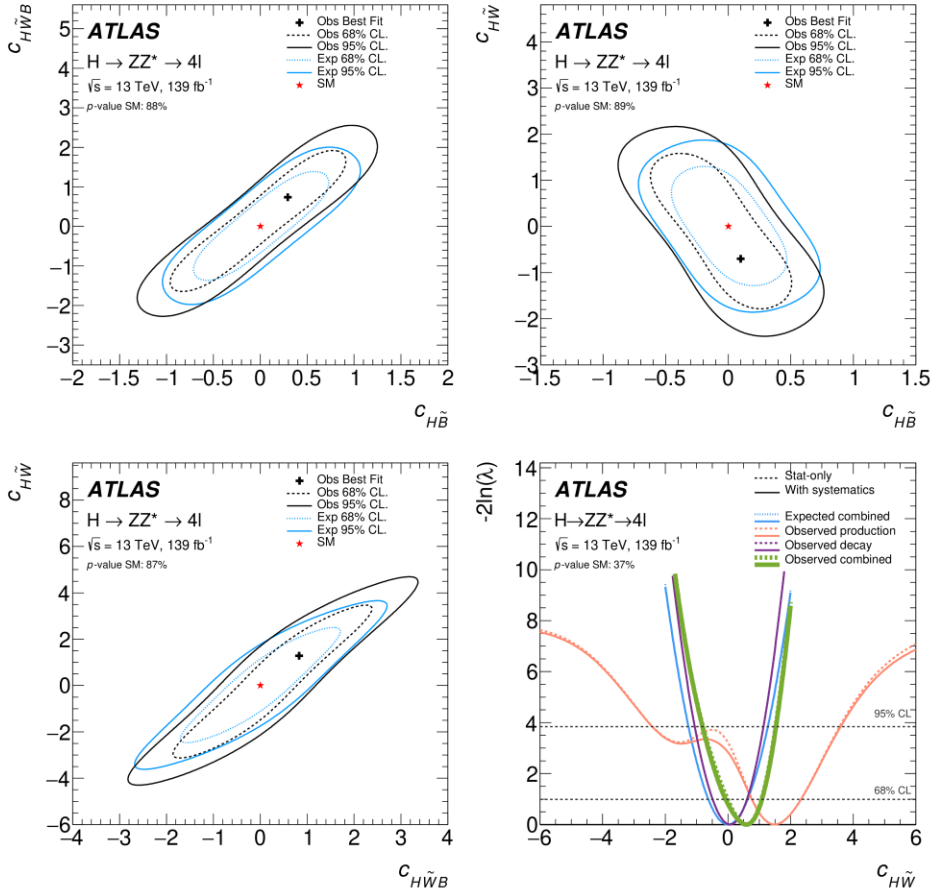


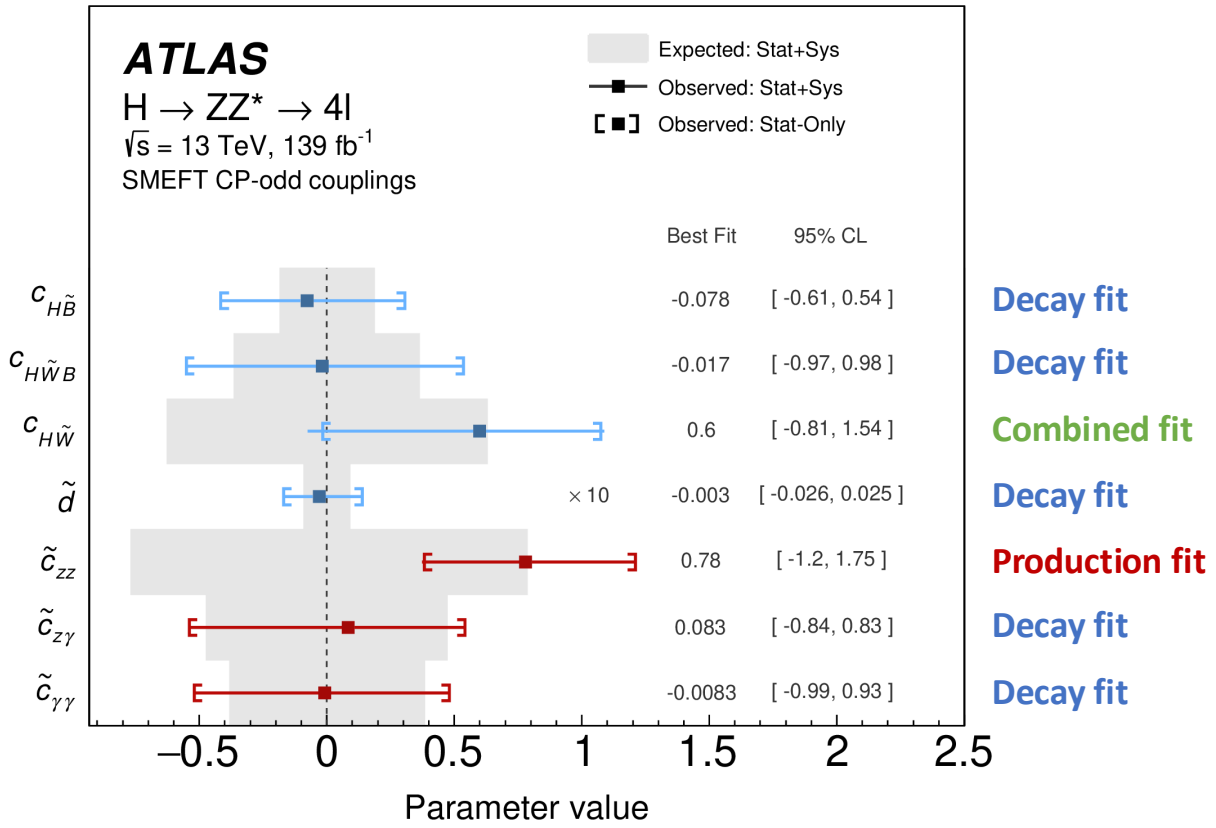


$H \to ZZ^* \to 4l$

JHEP05(2024)105

- **Results: 1D and 2D constraints on interference + quadratic term**
  - Full set of H-V CP-odd coefficients ($c_{H\tilde{W}}$, $c_{H\tilde{B}}$, $c_{H\tilde{W}B}$). **Compatible with SM.**



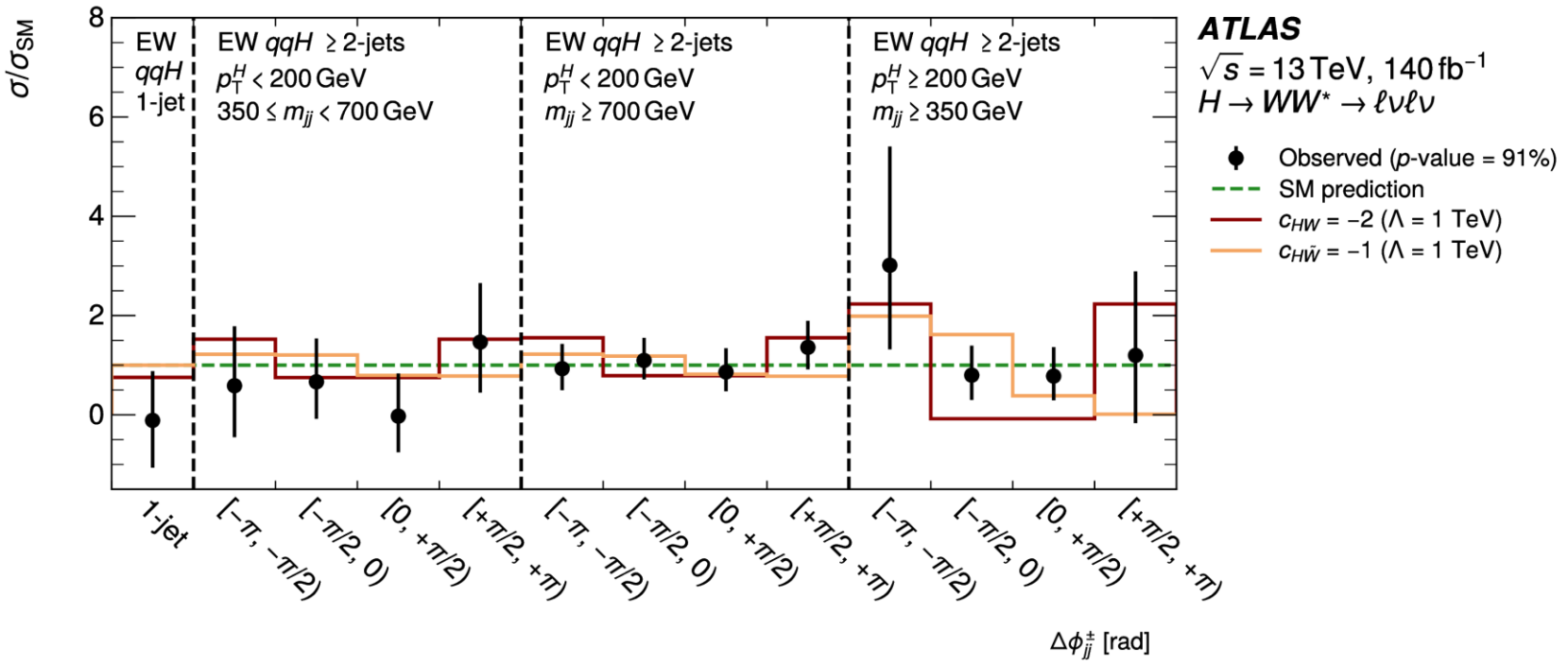


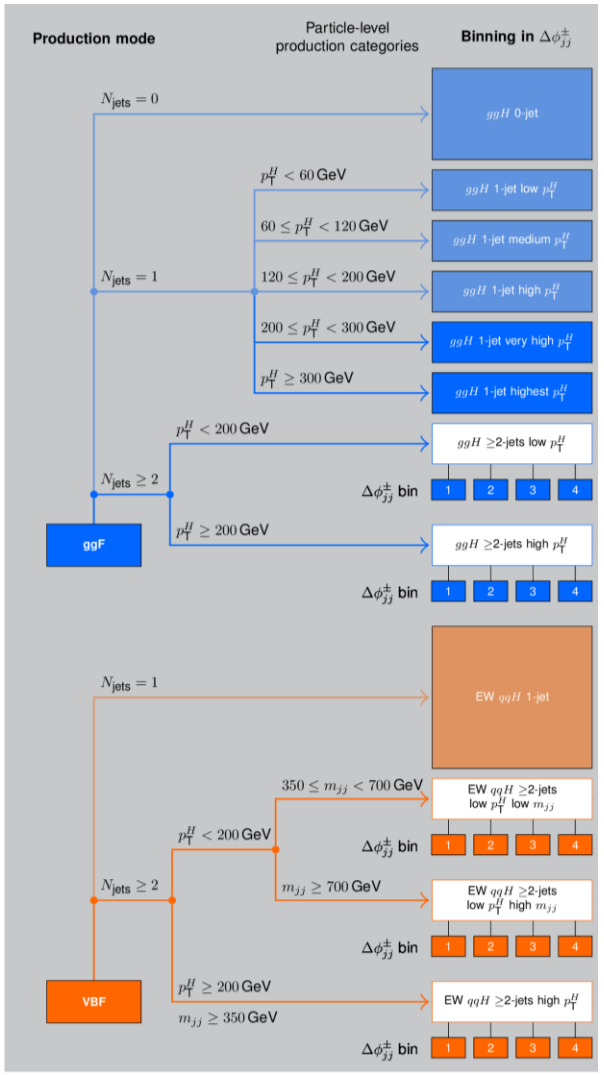
Decay fit
Decay fit
Combined fit
Decay fit
Production fit
Decay fit
Decay fit

$H \to WW^* \to l\nu l\nu$

arxiv: 2504.07686 (accepted by EPJC)

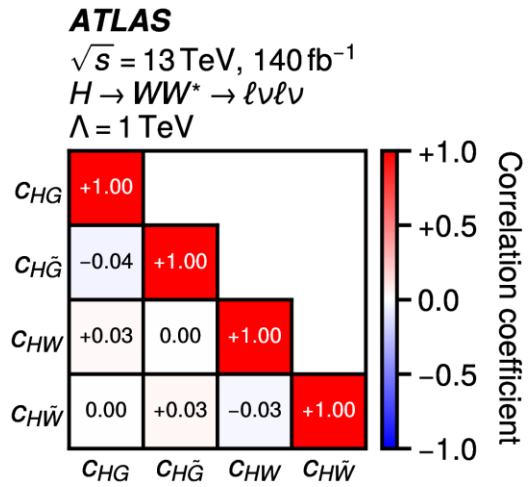
- **STXS-based analysis with dedicated CP bins $\Delta\phi_{jj}^{\pm}$**
  - Only sensitive to VBF vertex. $H \to WW$ vertex is not exploited.
  - Signal region defined with N_{jets}, p_T^H and m_{jj} bins
  - A DNN is used to identify signals in each SR.

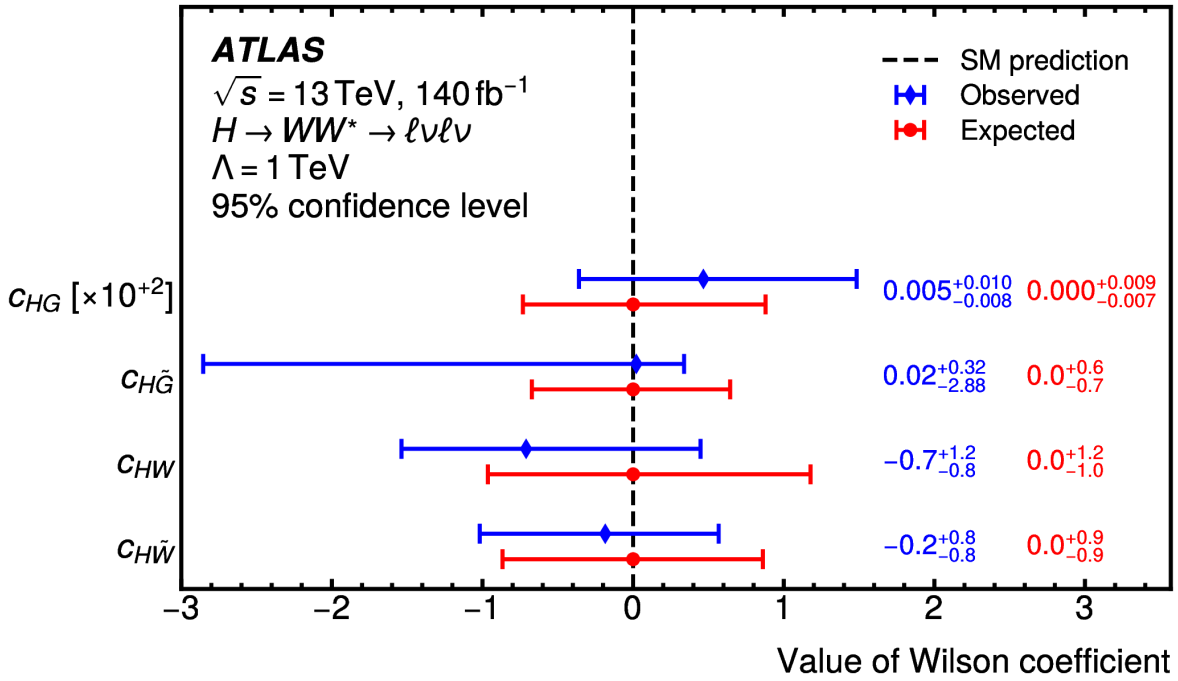


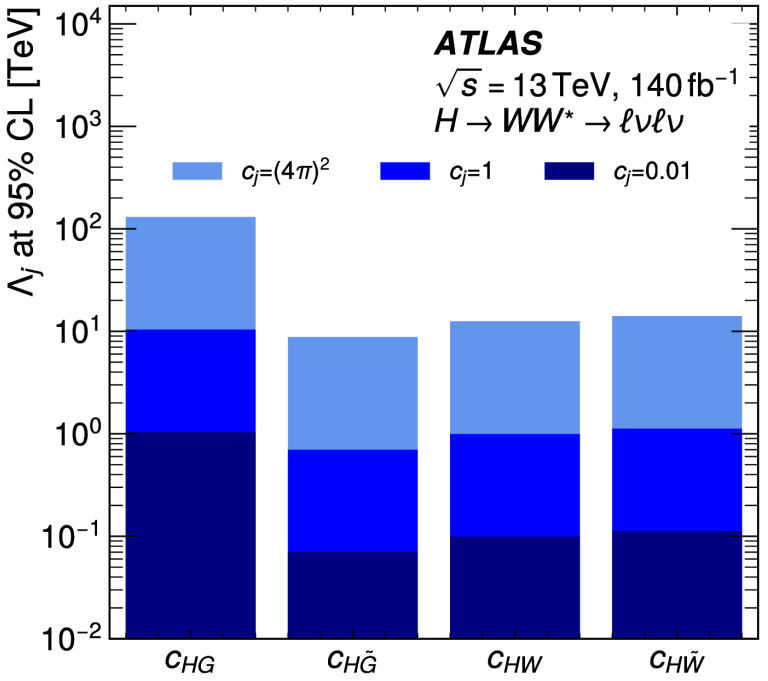


$H \to WW^* \to l\nu l\nu$

- **EFT interpretation: interference order CP-even and CP-odd terms**
  - Simultaneous constrain $c_{HW}, c_{H\tilde{W}}, c_{HG}$ and $c_{H\tilde{G}}$ from VBF and ggF.
  - Correlations between different Wilson coefficients are less than 5%.
  - New physics scale $\Lambda \sim 1 - 10$ TeV if $c_i = 1$.
  - **Compatible with SM.**







VBF $H \to \gamma\gamma$

- **Explore HVV CP structure in VBF production**

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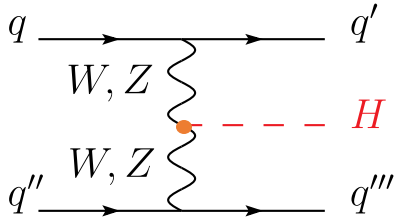
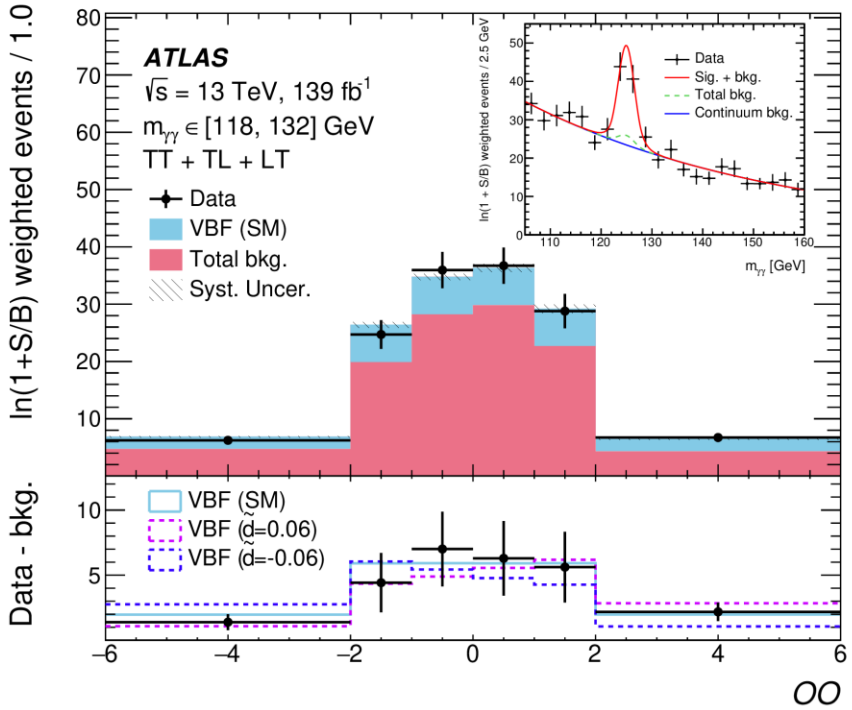
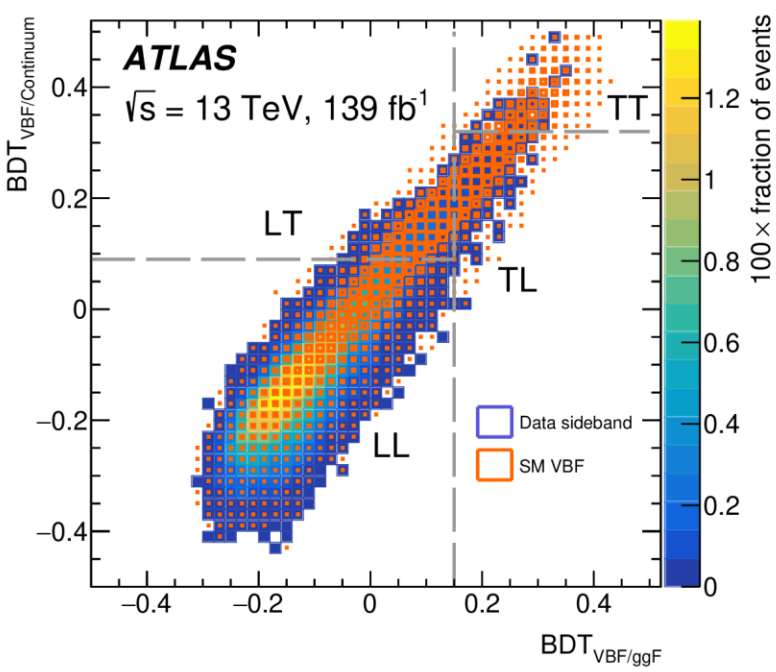
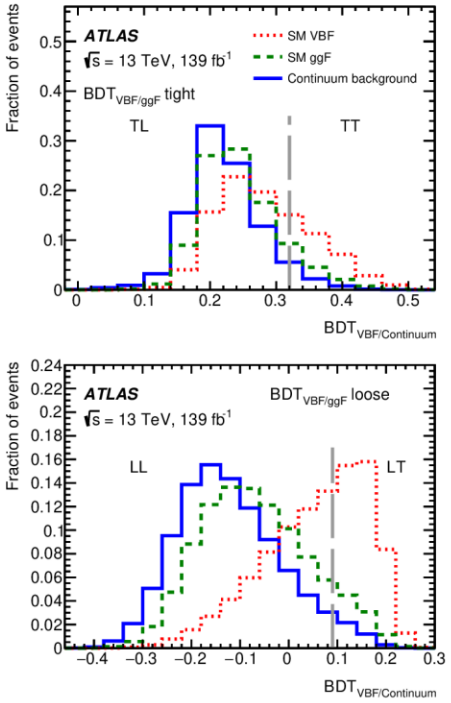
  - Consider $c_{H\tilde{W}}$ and $\tilde{d}$ in interference and interference + quadratic order.
  - Shape-only fit on VBF $\mathcal{OO}$, yield from $m_{\gamma\gamma}$ fit for better background estimation.
  - 2 BDTs for signal - background separation: VBF vs ggF, VBF vs diphoton.









VBF $H \to \gamma\gamma$

- **Results: constraints on $c_{H\widetilde{W}}$ and $\widetilde{d}$**

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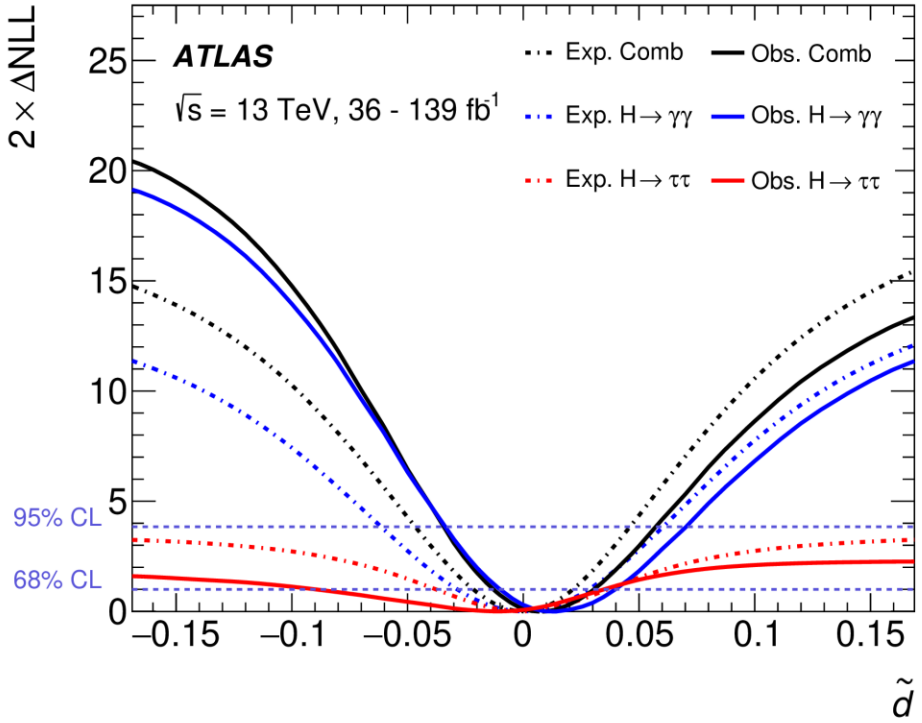
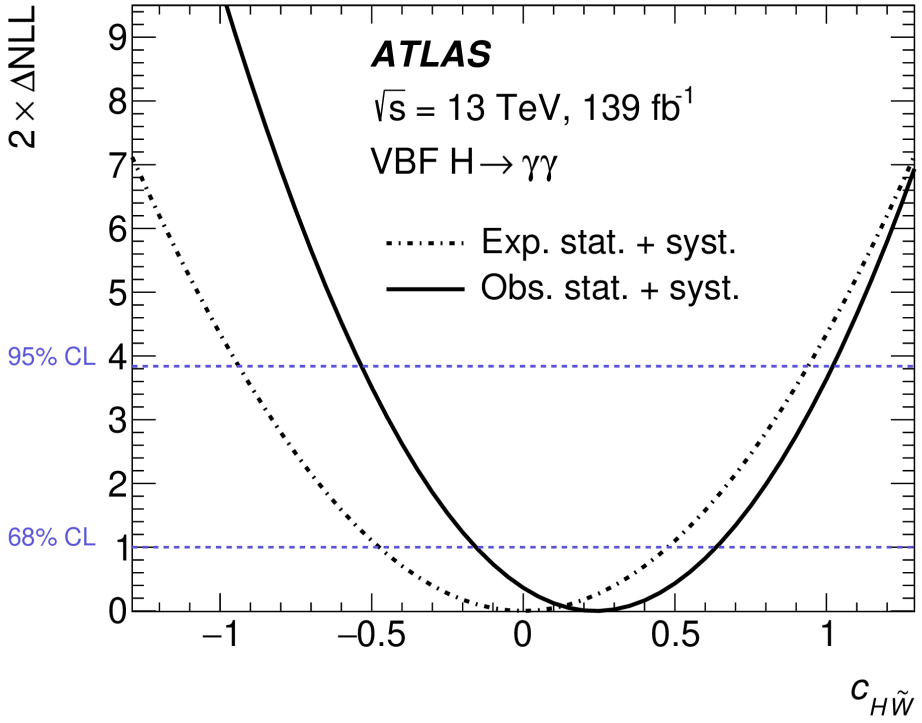
  - Simultaneous fit to $m_{\gamma\gamma}$ in each $\mathcal{OO}$ bin in all SRs, with μ_{VBF} floated.
  - Combined with partial Run-2 $H \to \tau\tau$ results in $\tilde{d}$.
  - **Compatible with SM.**





VBF $H \to \tau\tau$

- **Similar strategy as $H \to \gamma\gamma$ but ×20 larger branching ratio**
  - $c_{H\widetilde{W}}$ and $\tilde{d}$ in interference and interference + quadratic order.
  - Compare 3 CP observables and $\mathcal{OO}$ is selected.
  - 3 sub-channels with di-τ final state, NN for SR construction.

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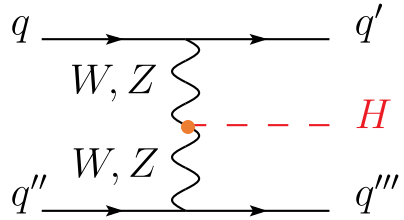

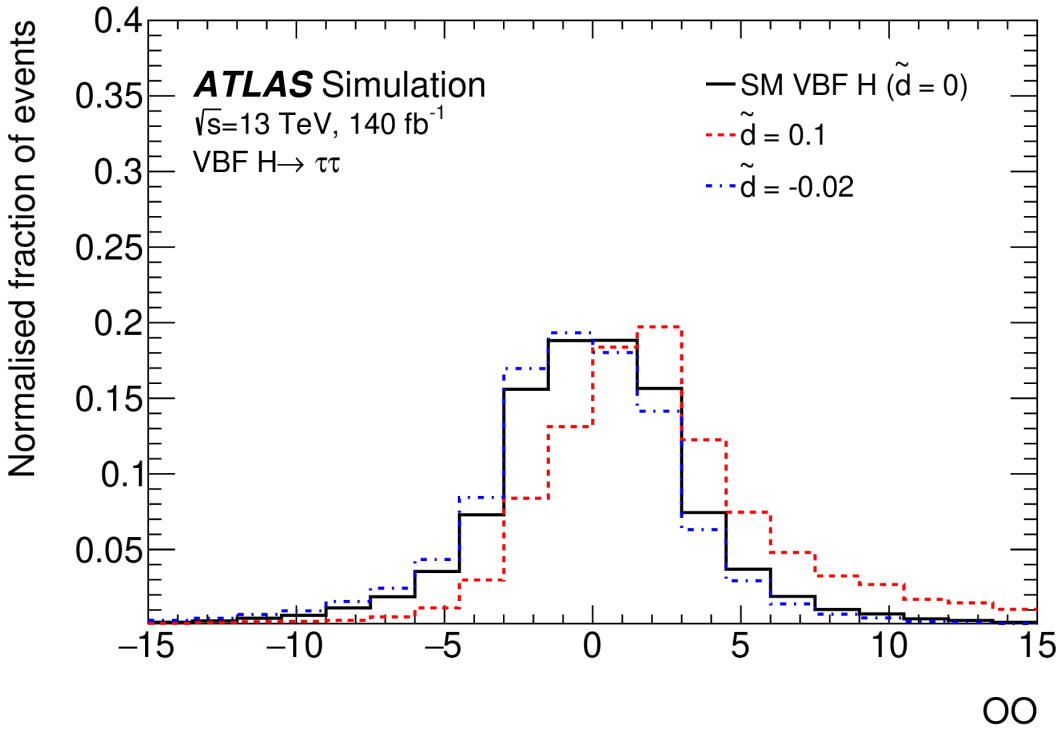

Channel	Region	NN signal score	$s/\sqrt{s+b}$
$\tau_{\text{lep}}\tau_{\text{lep}}$	$\text{SR}^{\text{HighNN}}$	> 0.91	3.50
	SR^{LowNN}	$0.67 - 0.91$	1.98
	VR^{LowNN}	< 0.67	0.51
$\tau_{\text{lep}}\tau_{\text{had}}$	$\text{SR}^{\text{HighNN}}$	> 0.91	6.93
	SR^{LowNN}	$0.63 - 0.91$	2.69
	VR^{LowNN}	< 0.63	0.30
$\tau_{\text{had}}\tau_{\text{had}}$	$\text{SR}^{\text{HighNN}}$	> 0.93	6.86
	SR^{LowNN}	$0.60 - 0.93$	2.42
	VR^{LowNN}	< 0.60	0.34

Also in Antonio's report

VBF $H \to \tau\tau$

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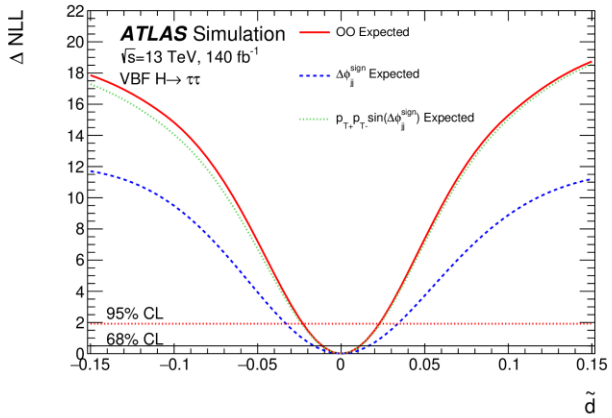
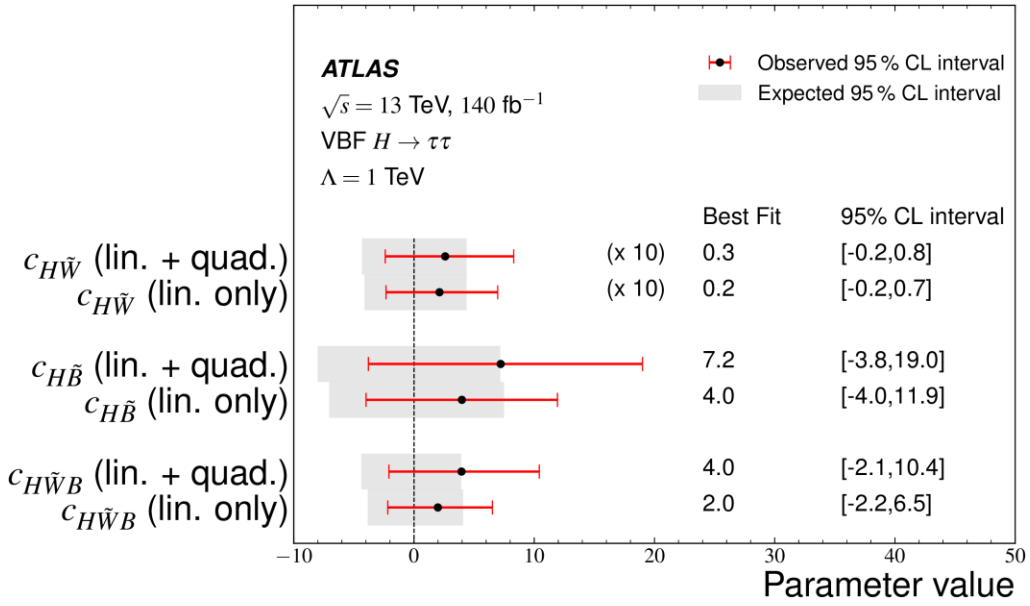
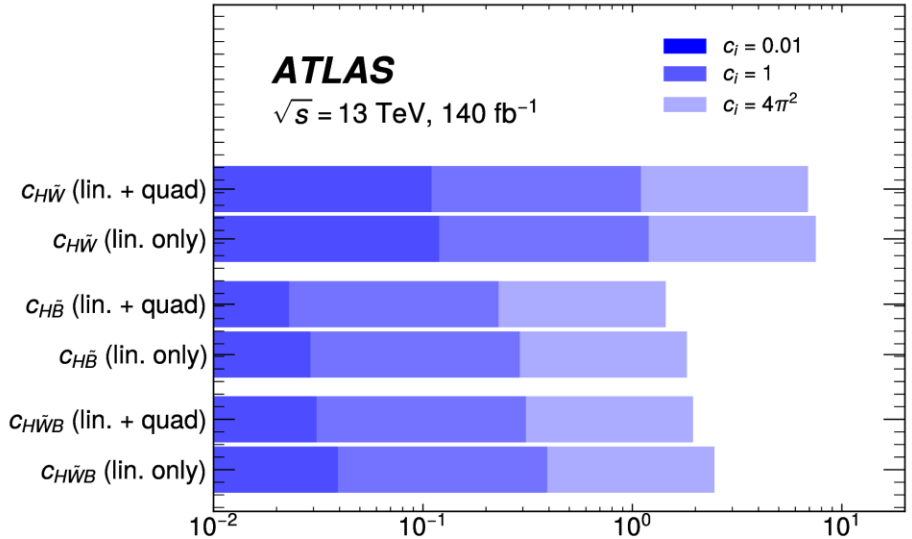
- **Results:**
  - Set **the most stringent constraint on $c_{H\widetilde{W}}$** from shape-only analysis. Constraints on $c_{H\tilde{B}}$ and $c_{H\widetilde{W}B}$ are also set.
  - $\mathcal{OO}$ has ~30% better constraint than $\Delta\phi_{jj}^{sign}$, ~5% better than $p_{T+}p_{T-}\sin(\Delta\phi_{jj}^{sign})$.
  - **Compatible with SM.**







Also in Antonio's report

WH $H \to b\bar{b}$

- **First dedicated CP study in WH vertex:**
  - Pure probe to HWW vertex, only sensitive to $c_{H\tilde{W}}$.
  - STXS measurement on **CP bins $Q_l \cos\delta^+ \times p_T^W$** based on $VH, H \to b\bar{b}$/cc analysis.
  - BDT for event selection and categorization.

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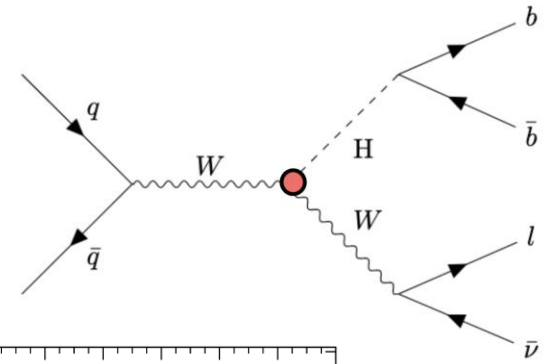

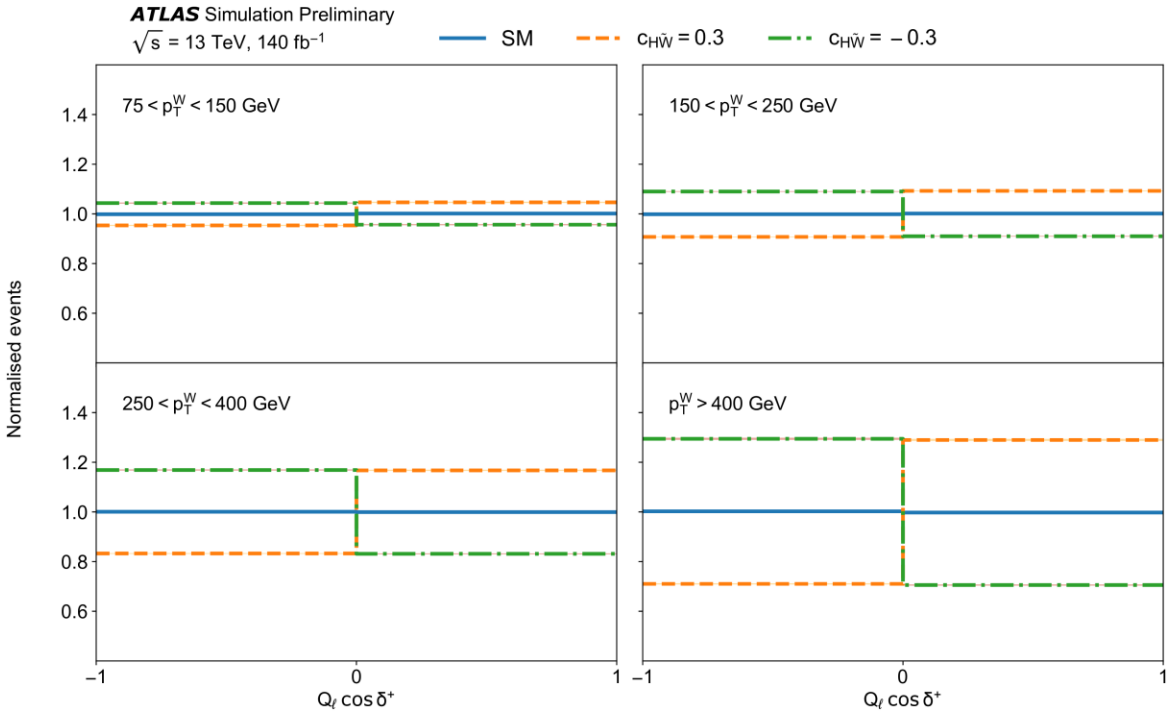

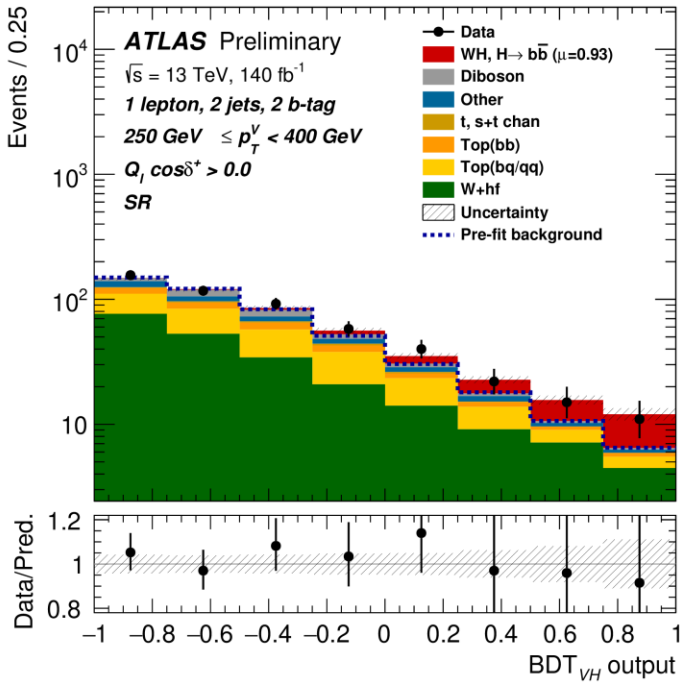

WH $H \to b\bar{b}$

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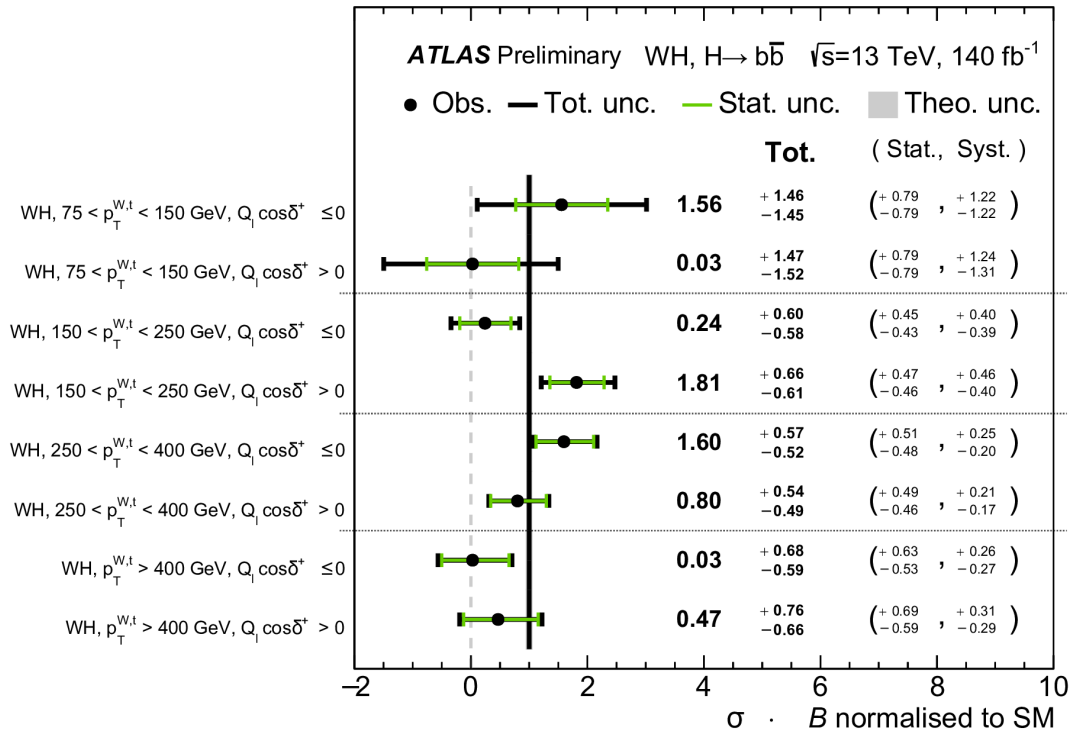
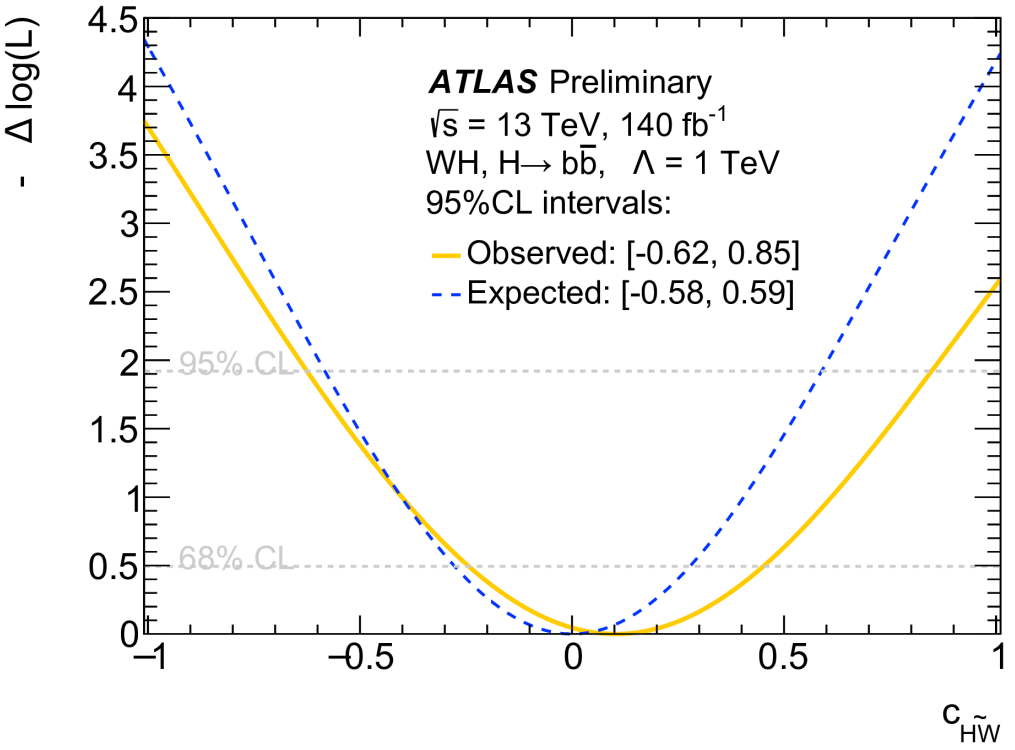
- **Results: constraint on interference order $c_{H\widetilde{W}}$**
  - Shape-only fit on $Q_l \cos\delta^+$.
  - **Compatible with SM.**
  - New physics scale $\Lambda > 1.2\ (14.6)$ TeV if $c_{H\widetilde{W}} = 1\ ((4\pi)^2)$.





Summary

- **Fruitful HVV CP analyses with ATLAS Run-2 data**
  - Including new results in 2025: $H \to WW^* \to l\nu l\nu$, VBF $H \to \tau\tau$ and WH $H \to bb$.
  - No evidence for CP-violation was observed, results are consistent between channels.
  - Combined measurement and Run-3 analyses are on-going, please stay tuned!