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Combination of measurements of CP properties of Higgs boson interactions with vector bosons using proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

A combination of measurements of the CP properties of Higgs boson interactions with electroweak gauge bosons is presented, using 140 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 13 TeV recorded by the ATLAS detector. Results from $H \to \tau\tau$, $H \to WW^*$, $H \to \gamma\gamma$, $H \to ZZ^*$, and $WH, H \to b\bar{b}$ channels are combined. No evidence of CP violation is observed, and constrains on the CP-violating operators in the SMEFT framework are set in the Warsaw basis. The results from the combination improve by over 40% on previous individual limits on $c_{H\tilde{W}}$ and, for the first time, simultaneous constraints on three coefficients $c_{H\tilde{W}}$, $c_{H\tilde{B}}$, and $c_{H\tilde{W}B}$ are set. This limits are the most stringent constraints to date on the relevant Wilson coefficients in the SMEFT framework with minimum model dependence.

The Standard Model (SM) of particle physics is unable to explain the observed baryon asymmetry of the universe. One of the three Sakharov conditions [1] required to generate this asymmetry is the violation of charge–parity (CP) symmetry. In the SM, CP violation arises from the complex phase of the quark mixing matrix [2, 3], and possibly the phase of neutrino mixing. However these effects are insufficient to account for the observed baryon asymmetry, and additional beyond-the-SM (BSM) sources of CP violation are needed. The discovery in 2012 [4, 5] of the Higgs boson (H) has opened new possibilities for search of new CP-violating interactions. The Higgs boson is predicted by the SM to be a CP-even scalar and its CP properties were extensively studied [6–19]. Current measurements are consistent with SM expectations, but experimental results cannot fully exclude the possibility of CP-violating interactions. Measuring the CP structure of Higgs boson couplings to electroweak gauge bosons constitutes a crucial test of the SM since any deviation from the SM prediction would be a clear sign of BSM.

CP-violating interactions between the Higgs boson and electroweak gauge bosons (HVV, $V = W^{\pm}, Z$) can be probed experimentally through vector boson fusion (VBF), associated production (VH), and Higgs boson decays into ZZ^* and WW^*. The Standard Model Effective Field Theory (SMEFT) formalism [20–23] extends the SM Lagrangian with dimension-6 operators to incorporate CP-violating components in HVV interactions, parameterized by Wilson coefficients c_i and a new physics scale Λ. The resulting cross-section consists of three components: the SM contribution, a linear term in c_i describing CP-odd interference between SM and BSM amplitudes that is suppressed by $1/\Lambda^2$, and a quadratic term in c_i describing CP-even BSM contributions suppressed by $1/\Lambda^4$. In addition, cross-terms from different operators can be present. The linear term affects the shapes of CP-odd observables while the quadratic term impacts CP-even observables such as inclusive cross-sections. The SMEFT cross-section can be decomposed as:

$$O = O^{\mathrm{SM}}\left(1 + \sum_i A_i \frac{c_i}{\Lambda^2} + \sum_i B_i \frac{c_i^2}{\Lambda^4} + \sum_{i<j} C_{ij} \frac{c_i c_j}{\Lambda^4}\right), \quad (1)$$

where O^{SM} is the corresponding SM prediction. The indices i, j run through the BSM operators considered, while A_i, B_i, and C_{ij} parameterize the linear, quadratic, and cross-term contributions, respectively, defined relative to the SM expectation. Constraints on Wilson coefficients of CP-violating operators are derived in two scenarios: using linear-only or both linear and quadratic terms. While the linear-only scenario provides a direct CP-violation test via the measurement of asymmetries in CP-odd observables, the linear plus quadratic scenario provides a more complete assessment of the BSM impact and the validity of the SMEFT truncation. In the Warsaw basis [23], considering only CP-violating operators that conserve lepton and baryon number, HVV interactions are described by three Wilson coefficients: $c_{H\tilde{W}}$, $c_{H\tilde{B}}$, and $c_{H\tilde{W}B}$.

This Letter presents a combination of constraints on CP violation based on measurements performed in $H \to \gamma\gamma$ [8], $H \to \tau\tau$ [6], $H \to WW^*$ [7], and $H \to ZZ^*$ [11], and a new measurement of associated production in $WH, H \to b\bar{b}$, using 140 fb^{-1} proton–proton collision data at $\sqrt{s} = 13$ TeV recorded during Run 2 of the LHC with the ATLAS detector from 2015 to 2018. The results include single-parameter fits for individual constraints on $c_{H\tilde{W}}$ while fixing $c_{H\tilde{B}}$ and $c_{H\tilde{W}B}$ to zero, and simultaneous fits for constraining the coefficients $c_{H\tilde{W}}$, $c_{H\tilde{B}}$, and $c_{H\tilde{W}B}$.

ATLAS [24, 25] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle. A software suite [26] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

In all input measurements the signal is modeled using Monte Carlo (MC) simulations from Powheg Box v2 [27–32] interfaced with Pythia 8 [33] for describing SM Higgs boson production via gluon–gluon fusion (ggF), VBF and WH, with further details provided in the relevant publications [6–8, 11]. BSM CP-odd Higgs boson are generated with MadGraph [34] at leading-order (LO) in QCD, using SMEFTsim3.0 [20, 35] in the top flavor assumption and the m_W, m_Z, G_F input scheme. The scale Λ is set to 1 TeV following convention.

Tests of CP-invariance are performed by all analysis with the use of CP-odd observables. Under CP conjugation, a CP-odd observable O transforms as $CP(O) = -O$. If CP-invariance holds, the average over the full phase space vanishes: $\langle O \rangle = 0$. Any asymmetry in the distribution of O would then be a sign of CP-violation. All analysis use a *shape-only* approach, where the normalisation of the signal sample is added as a free floating parameter. In this way, the analyses are not sensitive to overall changes of the total cross-section from CP-even terms, higher-order BSM corrections [36] can be factored out. Only the differences in the shape of the CP-sensitive variables are considered.

In the following paragraphs, the main characteristics of each input channel are summarized, and a previously unpublished analysis in the $WH, H \to b\bar{b}$ channel is described.

In $H \to \gamma\gamma$, $H \to \tau\tau$, and $H \to ZZ^*$ channels, the Optimal Observable (OO) method [37–39] is employed, as they have fully reconstructed final state particles. An OO is defined as $2\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}})/|\mathcal{M}_{\mathrm{SM}}|^2$, where $\mathcal{M}_{\mathrm{SM}}$ and $\mathcal{M}_{\mathrm{BSM}}$ denote SM and BSM matrix elements respectively. The OO condenses multidimensional information into a single observable with optimal sensitivity to CP-violating contributions. The $H \to ZZ^*$ analysis in Ref. [11] constructs two OO for the single-parameter fit: a production observable, $OO^{c_{H\tilde{W}}}_{jj}$, used in the VBF signal region with $\mathcal{M}(VBF)$, and a decay observable, $OO^{c_{H\tilde{W}}}_{4l}$, used in a VBF-depleted signal region with $\mathcal{M}(H \to ZZ^*)$. In the simultaneous fit, two decay observables $OO^{c_{H\tilde{W}}}_{4l}$ and $OO^{c_{H\tilde{B}}}_{4l}$ related to the two coefficients $c_{H\tilde{W}}$, $c_{H\tilde{B}}$ are regarded as observables in the inclusive $H \to ZZ^*$ signal region, providing optimal sensitivity to the three Wilson coefficients. In addition to what was published in Ref. [11], a linear-only interpretation is also performed here. For the single-parameter linear-only fit of $c_{H\tilde{W}}$, the OO distributions are rebinned to avoid bins in which the negative interference contribution exceeds the total background yield, reducing the expected sensitivity by up to 8%. For $H \to \tau\tau$, an additional simultaneous parameterization of $c_{H\tilde{W}}$, $c_{H\tilde{B}}$, and $c_{H\tilde{W}B}$ is performed compared with Ref. [6], including interference terms between the different CP-violating amplitudes.

The $H \to WW^*$ and $WH, H \to b\bar{b}$ analyses rely on modifications to the simplified template cross-section (STXS) formalism [40–42] with dedicated angular observables sensitive to the CP structure of the HVV coupling. In $H \to WW^*$ the CP-sensitive variable is the pseudorapidity-ordered azimuthal angular difference between the two leading jets, $\Delta\phi_{jj}$, sensitive only to the structure of the interaction at the production vertex. In contrast to the result in Ref. [7], a single-parameter fit of $c_{H\tilde{W}}$ is performed, with the remaining coefficients set to zero. In addition, the quadratic parametrization of $c_{H\tilde{W}}$ in the single-parameter fit, as well as the quadratic and cross terms in the simultaneous fit, are included only in this combination.

The $WH, H \to b\bar{b}$ analysis is based on the measurement in Ref. [43], where events are selected to reconstruct a leptonic W-boson decay and a H decay into b-quarks. To reconstruct the Higgs boson decay products, small-radius jets are used for $p_T^W < 400$ GeV and large-radius jets for $p_T^W > 400$ GeV, where p_T^W is the transverse momentum of the W boson. The W-boson four-vector is reconstructed as the vector sum of the charged lepton and the neutrino, where the transverse component of the neutrino is identified with the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the longitudinal component is obtained by applying a W-mass constraint to the lepton-neutrino system. MC simulated samples model most of the SM background processes, and dedicated control regions are used to constrain the main backgrounds (W+jets and top quark production). Compared with the STXS categories used in Ref. [43], the regions are further split into two bins of an angular variable, $Q_\ell \cos\delta^+$, where Q_ℓ is the lepton charge and $\cos\delta^+$ is an angular observable defined as $\frac{\mathbf{p}_\ell^{(W)}\cdot(\mathbf{p}_H\times\mathbf{p}_W)}{|\mathbf{p}_\ell^{(W)}|\cdot|\mathbf{p}_H\times\mathbf{p}_W|}$. Here, $\mathbf{p}_\ell^{(W)}$ is the three-momentum of the charged lepton in the W-boson rest frame, and $\mathbf{p}_W$ and $\mathbf{p}_H$ are the three-momenta of the W and Higgs bosons, respectively, in the laboratory frame [44, 45]. The resulting cross-section measurements are shown in Figure 1 in bins of the particle-level transverse momentum of the W boson, $p_T^{W,t}$, and $Q_\ell \cos\delta^+$. Compared with the result in Ref. [43], only WH production, with $W \to \ell\nu$ ($\ell = e, \mu$), is considered and ZH is treated as a background. Events with hadronically decaying τ-leptons are vetoed, and only one p_T^W bin above 400 GeV is considered to reduce the impact of statistical uncertainties.

The EFT interpretation is performed by only considering the $Q_\ell \cos\delta^+$ shape effect from $c_{H\tilde{W}}$. One signal normalization factor is applied per p_T^W bins and profiled in fitting, while the normalization factors in negative and positive $Q_\ell \cos\delta^+$ bins are parameterized with $c_{H\tilde{W}}$.

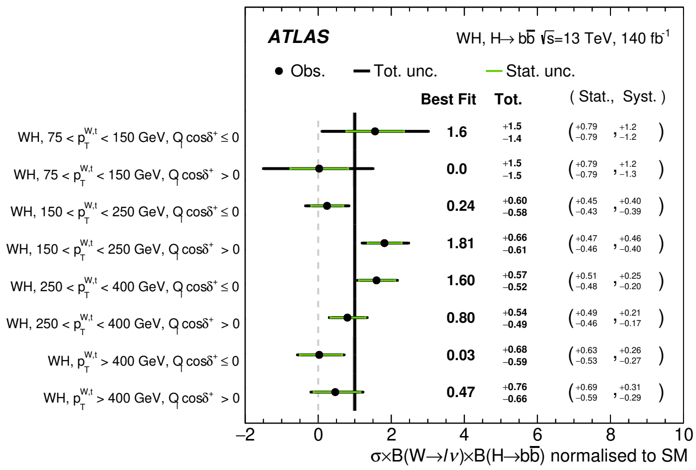
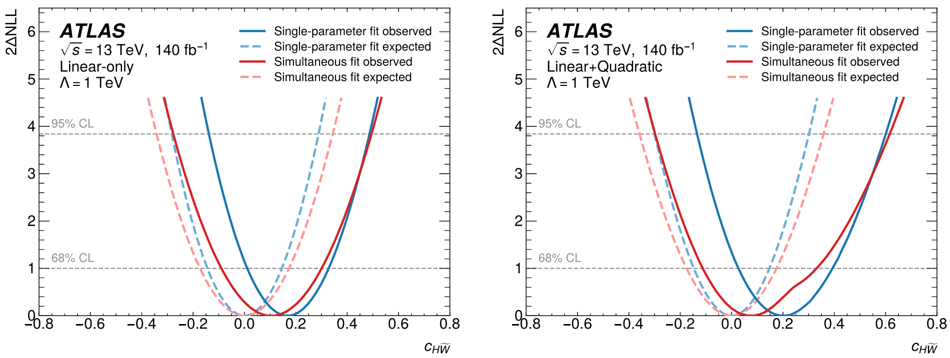


Figure 1: Measured WH production cross-sections times the $W \to \ell\nu$ and the $H \to b\bar{b}$ branching ratios normalized to their SM predictions. The best fit values and corresponding uncertainties (total as well as its statistical and systematic components) are shown for all regions. Theoretical uncertainties on the predictions are not shown as they are too small to be visible.

Combination results are presented using single-parameter fits for individual constraints on $c_{H\tilde{W}}$ (with $c_{H\tilde{B}} = c_{H\tilde{W}B} = 0$) and simultaneous fits for constraining $c_{H\tilde{W}}$, $c_{H\tilde{B}}$ and $c_{H\tilde{W}B}$. The VBF production process is mainly sensitive to $c_{H\tilde{W}}$, with subleading contributions from $c_{H\tilde{W}B}$ and $c_{H\tilde{B}}$, while WH production depends only on $c_{H\tilde{W}}$. The simultaneous fits combine all channels except for $H \to \gamma\gamma$, which has very limited sensitivity to the additional operators and has a negligible impact on the simultaneous fit results. The normalization factors are treated as free parameters for all production modes for all channels. The exceptions are the normalization of ZH production in the $WH, H \to b\bar{b}$, the ggF production in $WH, H \to b\bar{b}$ and $H \to \tau\tau$, which are constrained to the their respective SM prediction, since these are minor contributions. The relative ratio between VBF and ggF production in $H \to ZZ^*$ is also constrained to the SM prediction, since it only uses the decay information. All free normalization factors are uncorrelated across channels. Event overlap between channels is negligible due to their distinct final states and selection criteria. Signal injection tests with non-zero Wilson coefficients were performed to varify the extraction of Wilson coefficients is unbiased in this shape-only approach.

The combined likelihood is constructed as the product of the individual analyses likelihoods, incorporating correlations of systematic uncertainties where applicable. The treatment of systematic uncertainties follows that of the individual analyses [6–8, 11], with experimental uncertainties related to luminosity, object reconstruction and calibration considered fully correlated across all channels. Theoretical uncertainties affecting signal modeling are correlated among analyses targeting the same production mode, while background modeling uncertainties are treated as uncorrelated due to their analysis-specific nature. The impact of systematic uncertainties in the presented results is small compared to the statistical uncertainties. In each fit, the confidence intervals for the Wilson coefficients are determined using a profile likelihood ratio test statistic as in Ref. [11].

No evidence of CP-violation is observed, and constraints on the Wilson coefficients are set. The observed and expected negative log-likelihood ratio (2ΔNLL) scans as a function of the $c_{H\tilde{W}}$ are shown in Figure 2 for the single-parameter fit ($c_{H\tilde{B}} = c_{H\tilde{W}B} = 0$), separately for linear-only and linear plus quadratic scenarios. Additionally, the scans obtained in simultaneous fits with all coefficients floating are also shown. The sensitivity to $c_{H\tilde{W}}$ in this case is impacted by the negative correlation with the remaining coefficients. In the single-parameter fit, observed (expected) 95% CL intervals of $[-0.14, 0.49]$ ($[-0.28, 0.29]$) and $[-0.13, 0.60]$ ($[-0.30, 0.30]$) at $\Lambda = 1$ TeV are obtained for the linear-only and linear plus quadratic scenarios, respectively. The limits obtained on $c_{H\tilde{W}}$ in the single-parameter fit show an improvement of over 40% on the previous best individual channel results. The expected and observed limits are primarily driven by $H \to \tau\tau$, followed by the $WH, H \to b\bar{b}$ channel.



(a) (b)

Figure 2: Negative profile log-likelihood ratio scans are shown as a function of $c_{H\tilde{W}}$, with single-parameter fits ($c_{H\tilde{B}} = c_{H\tilde{W}B} = 0$) and simultaneous fits (all three coefficients floating), for (a) linear-only and (b) linear plus quadratic terms. Solid lines indicate the observed scans, while dashed lines show the expected results. The dashed horizontal lines show the thresholds defining the 68% and 95% confidence intervals, assuming the asymptotic approximation.

Results of the simultaneous fits are shown in Figure 3 in terms of two-dimensional contours for each pair of Wilson coefficients, profiling over the third coefficient. There is a large correlation between the $c_{H\tilde{B}}$ and $c_{H\tilde{W}B}$ coefficients caused by similar effects to the CP-odd observables in the $H \to ZZ^*$, $H \to WW^*$ and $H \to \tau\tau$ channels. On the other hand, $c_{H\tilde{W}}$ is positively correlated with $c_{H\tilde{W}B}$ and negatively correlated with $c_{H\tilde{B}}$ in the $H \to ZZ^*$ channel, negatively correlated with both coefficients in $H \to WW^*$ and $H \to \tau\tau$, and independent in the $WH, H \to b\bar{b}$ channel. There are parameter-space regions where the linear-only terms lead to negative cross-sections; however, these are outside the observed 95% CL contours and outside of EFT validity regions. The limits obtained in the simultaneous fit are less stringent than those obtained in the single-parameter fit, due to the negative correlation between $c_{H\tilde{W}}$ and the remaining coefficients.

Figure 4 summarizes the observed results obtained for each Wilson coefficient when profiling the other two for both linear-only and linear plus quadratic scenarios.

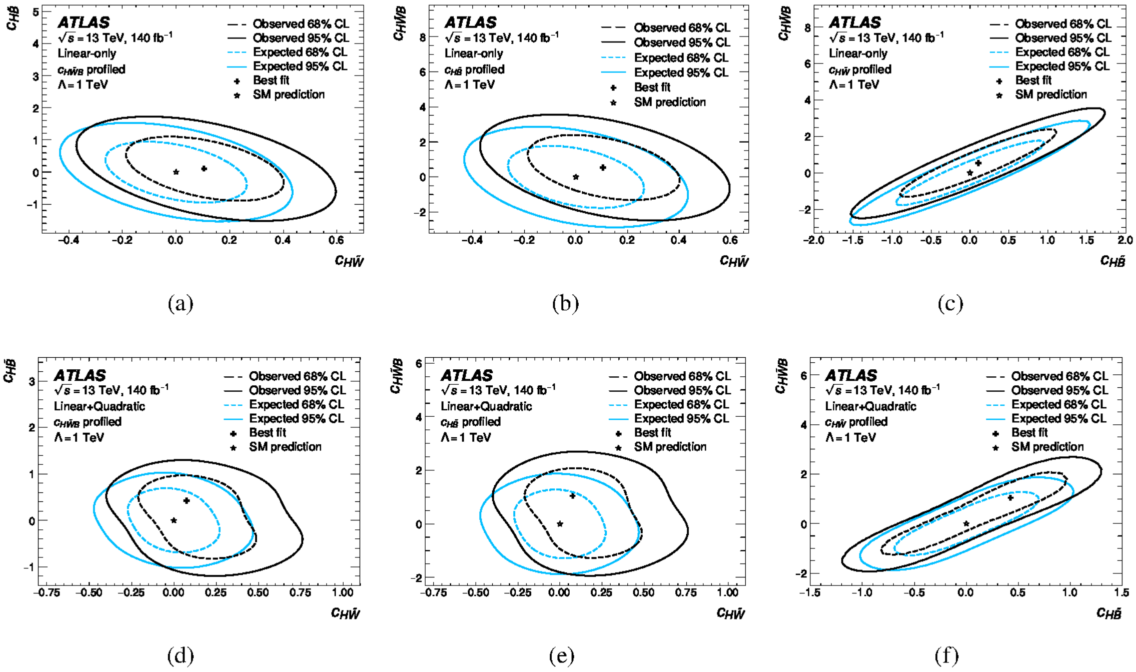


Figure 3: The observed 68% (dashed line) and 95% (solid line) CL two-dimensional contours are shown for all three pairings of the Warsaw basis: (a, d) $c_{H\tilde{W}}$ versus $c_{H\tilde{B}}$, (b, e) $c_{H\tilde{W}}$ versus $c_{H\tilde{W}B}$, and (c, f) $c_{H\tilde{B}}$ versus $c_{H\tilde{W}B}$ a simultaneous fit, for (a, b, c) linear-only and (d, e, f) linear plus quadratic terms interpretations. Expected contour lines are also shown. All couplings scale as $1/\Lambda^2$ with $\Lambda = 1$ TeV.

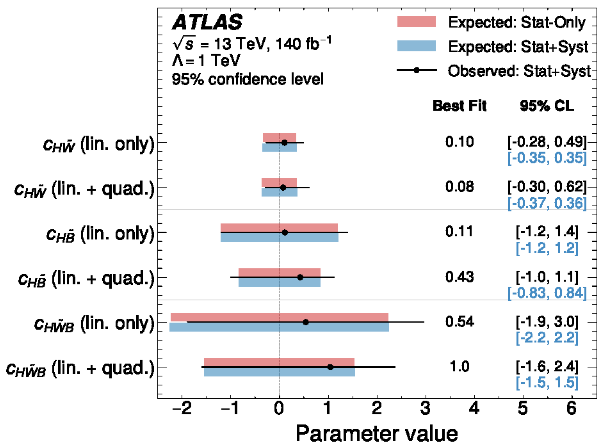


Figure 4: Best-fit values and 95% CL intervals for all three Wilson coefficients obtained in a simultaneous fit to all coefficients. In both cases, linear and linear plus quadratic scenarios are shown. Expected limits using the full model and statistical-only are also presented.

In conclusion, constraints of Wilson coefficients of CP-violating operators in the *HVV* interaction within the SMEFT Warsaw basis is presented. The analysis combines five ATLAS Run 2 measurements including

VBF and WH production modes, and $H \rightarrow VV$ decay channels: $H \rightarrow \tau\tau$, $H \rightarrow WW^*$, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, and $WH, H \rightarrow b\bar{b}$. Shape-based measurements of CP-odd sensitive observables are used to constrain CP-violating effects. A single-parameter fit was performed constraining the $c_{H\tilde{W}}$ Wilson coefficient while the remaining coefficients are set to zero. No significant deviations from the Standard Model are observed. The single-parameter fit yields an observed (expected) 95% CL interval for $c_{H\tilde{W}}$ of $[-0.14, 0.49]$ ($[-0.28, 0.29]$) at $\Lambda = 1$ TeV for the linear-only and $[-0.13, 0.60]$ ($[-0.30, 0.30]$) for the linear plus quadratic interpretation. The compatibility between the limits in both scenarios is an indication of the validity of the EFT truncation to dimension-six operators. The limits presented on $c_{H\tilde{W}}$ from the single-parameter fit improve upon previous best individual channel results from $H \rightarrow \tau\tau$ [6] by over 40%. The combination further enabled, for the first time, a simultaneous fit constraining the coefficients of three CP-violating operators ($c_{H\tilde{W}}$, $c_{H\tilde{B}}$, $c_{H\tilde{W}B}$). These combined results deliver the most stringent constraints to date on Wilson coefficients of CP-violating operators in the SMEFT framework.

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End Matter

Individual channel contributions to $c_{H\tilde{W}}$ constraint: The individual negative log-likelihood ratio (2ΔNLL) scans are shown in Figure 5 for linear-only and linear plus quadratic interpretations, and the corresponding best fit values and 95% CL intervals are summarized in Figure 6, along with the combination results. The introduction of the quadratic term results in a loss of sensitivity at higher Wilson coefficient values, which is visible for $WH, H \to b\bar{b}$ and to a lesser extent $H \to WW^*$, but is true for all channels. For $WH, H \to b\bar{b}$ in particular, this results in undefined confidence intervals.

To understand the non-parabolic behavior of the NLL scans, it is helpful to consider the particular cases of $WH, H \to b\bar{b}$ and $H \to WW^*$. In these two channels, the impact of the CP-odd operators on the corresponding differential cross-section measurements is parameterized via their impact on their signal strengths μ_p (relative to the SM prediction), defined as:

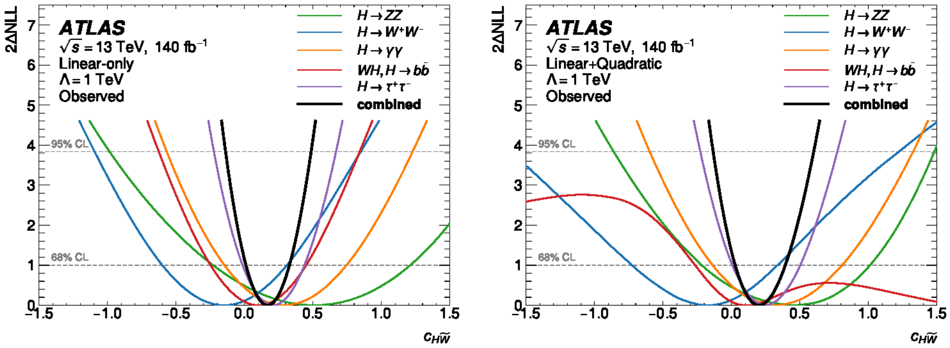
$$\mu_p \to \mu_p \times (1 + \sum_{j=1}^{M} A_j^p \times c_j + B_j^p \times c_j^2), \tag{2}$$

where p are the STXS particle-level categories, A_j^p and B_j^p parameterize the linear and quadratic contributions in STXS region p, and j runs through the number M of CP-odd operators considered. The relative asymmetry across bins of an angular observable can be formulated as $(\mu_{q^+} - \mu_{q^-})/(\mu_{q^+} + \mu_{q^-})$, where $q^\pm$ stands for STXS regions in the same CP-even bin (e.g., p_T^W) and symmetric angular observable bins.

The observed effect in the linear plus quadratic NLL scans is related to how this relative asymmetry depends on the Wilson coefficients. In the linear-only interpretation, this asymmetry grows linearly with $c_{H\tilde{W}}$ (Eq. 3); however, in the linear plus quadratic scenario this asymmetry grows approximately linearly only for small values of $c_{H\tilde{W}}$ and is then much reduced (and even inverted) as the absolute value of the coefficient grows (Eq. 4), resulting in the observed NLL behavior.

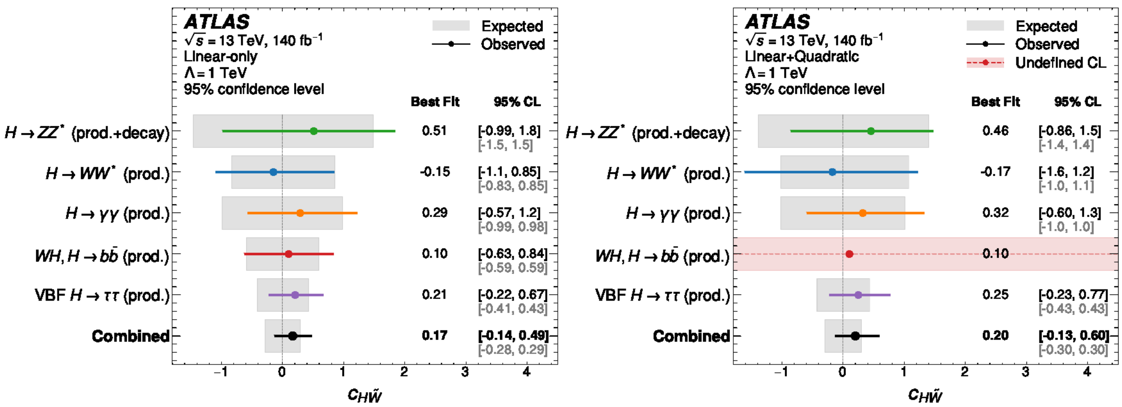
$$\text{Asym}_{p,j}^{\text{linear}} = -A_j^p \times c_j \tag{3}$$

$$\text{Asym}_{p,j}^{\text{linear+quadratic}} = \frac{-A_j^p \times c_j}{1 + B_j^p \times c_j^2} \tag{4}$$



(a) (b)

Figure 5: Observed negative log-likelihood ratio (2ΔNLL) scans as a function of $c_{H\tilde{W}}$ considering the (a) linear-only and the (b) linear plus quadratic terms for the individual channels (in different colors) and their combination. The dashed horizontal lines show the values of ΔNLL thresholds defining the 68% and 95% confidence intervals, assuming the asymptotic approximation.



(a) (b)

Figure 6: Best-fit values and 95% CL intervals for $c_{H\tilde{W}}$ obtained in single-parameter fits for each of the individual analyses and the combined result, for both (a) linear-only and (b) linear and quadratic interpretations. For the $WH, H \to b\bar{b}$ linear and quadratic result, the best-fit value is valid in the $c_{H\tilde{W}}$ range $[-1.5, 1.5]$ and no 95% CL interval is defined, as explained in the text.

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