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Authors

Aad, G

Aakvaag, E

Abbott, B

et al.

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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

G. Aad *et al.*[*]
(ATLAS Collaboration)

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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 vector boson fusion $H \to \tau\tau/WW^*/\gamma\gamma$, inclusive $H \to ZZ^*$, 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 Standard Model effective field theory framework (SMEFT) 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. These limits are the most stringent constraints to date on the relevant Wilson coefficients in the SMEFT framework with minimum model dependence.

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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 the 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 [6–20]. 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 [21–24] extends the SM Lagrangian with dimension-6 operators to incorporate *CP*-violating components in HVV interactions, parametrized 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} parametrize 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 [24], 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 $c_{H\tilde{W}B}$.

[*]Full author list given at the end of the Letter.

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This Letter presents a combination of constraints on CP violation based on measurements performed in VBF $H \to \gamma\gamma$ [8], VBF $H \to \tau\tau$ [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 [25,26] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle. A software suite [27] 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 [28–33] interfaced with Pythia 8 [34] for describing SM Higgs boson production via gluon-gluon fusion (ggF), VBF, and H produced in association with a W boson (WH), with further details provided in the relevant publications [6–8,11]. BSM CP-odd Higgs bosons are generated with MadGraph [35] at leading order in QCD, using SMEFTsim3.0 [21,36] 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 $\mathcal{O}$ transforms as $CP(\mathcal{O}) = -\mathcal{O}$. If CP invariance holds, the average over the full phase space vanishes: $\langle\mathcal{O}\rangle = 0$. Any asymmetry in the distribution of $\mathcal{O}$ would then be a sign of CP violation. All analysis uses a *shape-only* approach, where the normalization 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 [37] 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 ($\mathcal{OO}$) method [38–40] is employed, as they have fully reconstructed final state particles. An $\mathcal{OO}$ 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 $\mathcal{OO}$ condenses multidimensional information into a single observable with optimal sensitivity to CP-violating contributions. The $H \to ZZ^*$ analysis in Ref. [11] constructs two $\mathcal{OO}$ for the single-parameter fit: a production observable, $OO_{jj}^{c_{H\tilde{W}}}$, used in the VBF signal region with $\mathcal{M}(VBF)$, and a decay observable, $OO_{4l}^{c_{H\tilde{W}}}$, used in a VBF-depleted signal region with $\mathcal{M}(H \to ZZ^*)$. In the simultaneous fit, two decay observables $OO_{4l}^{c_{H\tilde{W}}}$ and $OO_{4l}^{c_{H\tilde{B}}}$ 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 $\mathcal{OO}$ 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 parametrization 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 [41–43] 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. [44], 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. [44], 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 $\{[\mathbf{p}_\ell^{(W)} \cdot (\mathbf{p}_H \times \mathbf{p}_W)]/(|\mathbf{p}_\ell^{(W)}| \cdot |\mathbf{p}_H \times \mathbf{p}_W|)\}$. 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 [45,46]. The resulting cross-section measurements are shown in Fig. 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. [44], only WH production, with $W \to \ell\nu(\ell = e, \mu)$, is considered and ZH is

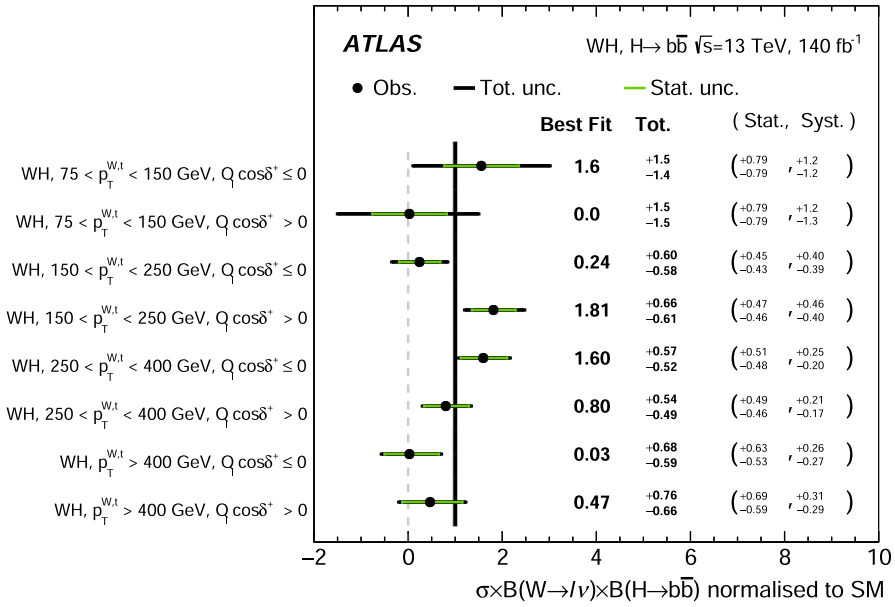


FIG. 1. Measured WH production cross sections times the $W \to \ell\nu$ and the $H \to b\bar{b}$ branching ratios normalized to their SM predictions. The best fit values and corresponding uncertainties (total as well as its statistical and systematic components) are shown for all regions. Theoretical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

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 parametrized with $c_{H\tilde{W}}$.

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 $WH, H \to b\bar{b}$ channel, and the ggF production mode in the $WH, H \to b\bar{b}$ and VBF $H \to \tau\tau$ channels, which are constrained to their respective SM prediction, since these are minor contributions. The relative ratio between VBF and ggF production in the $H \to ZZ^*$ channel is also constrained to the SM prediction, since this channel 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 nonzero Wilson coefficients were performed to verify 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 Fig. 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% C.L. 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

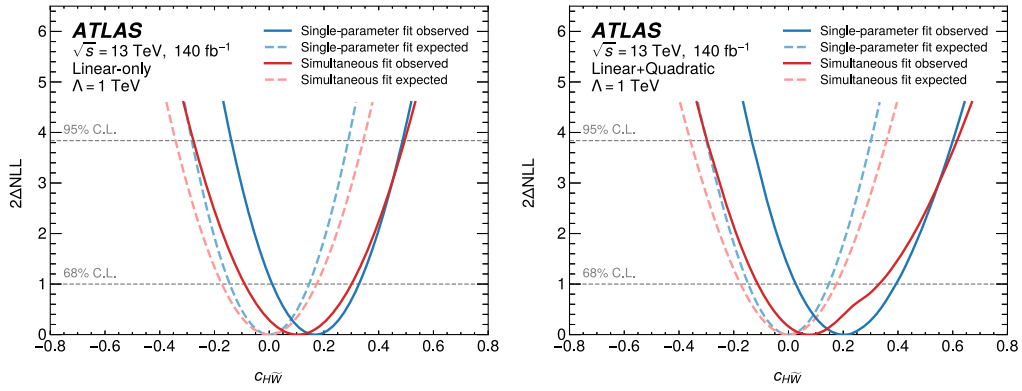


FIG. 2. Negative profile log-likelihood ratio scans are shown as a function of $c_{H\tilde{W}}$, with single-parameter fits ($c_{H\tilde{B}} = c_{H\tilde{W}B} = 0$) and simultaneous fits (all three coefficients floating), for (a) linear-only and (b) linear plus quadratic terms. Solid lines indicate the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

$c_{H\tilde{W}}$ in the single-parameter fit show an improvement of over 40% on the previous best individual channel results [6]. The expected and observed limits are primarily driven by $H \to \tau\tau$, followed by the $WH, H \to b\bar{b}$ channel.

Results of the simultaneous fits are shown in Fig. 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% C.L. contours and outside of EFT validity regions. The limits obtained in the simultaneous fit are less

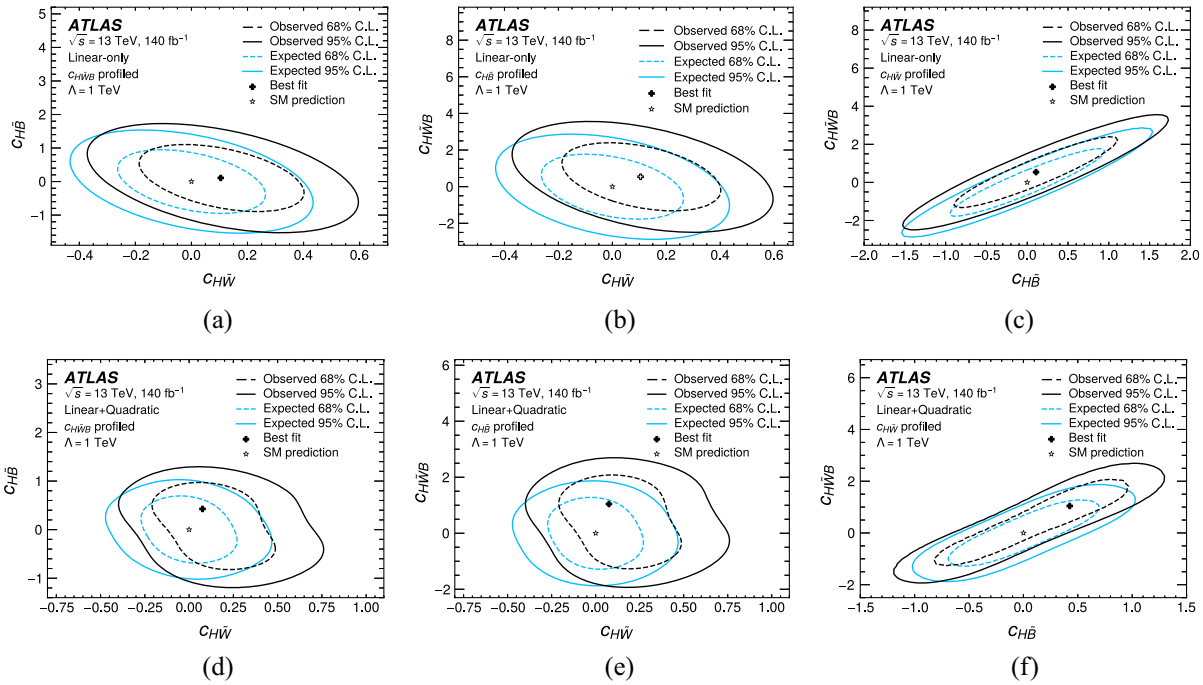


FIG. 3. Observed 68% (dashed line) and 95% (solid line) C.L. two-dimensional contours are shown for all three pairings of the Warsaw basis: (a),(d) $c_{H\tilde{W}}$ versus $c_{H\tilde{B}}$, (b),(e) $c_{H\tilde{W}}$ versus $c_{H\tilde{W}B}$, and (c),(f) $c_{H\tilde{B}}$ versus $c_{H\tilde{W}B}$ a simultaneous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

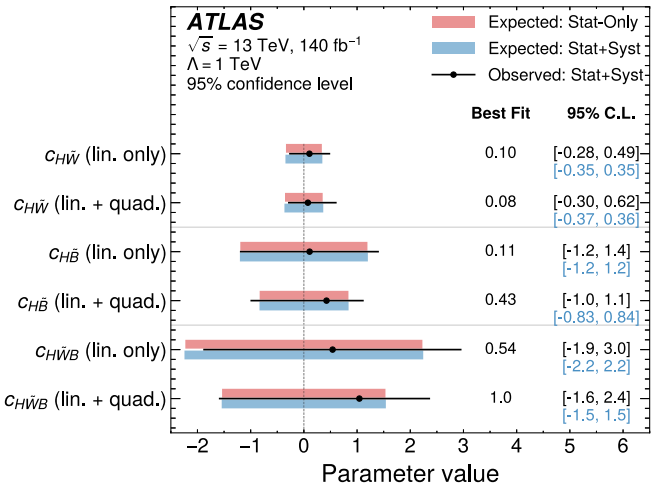


FIG. 4. Best-fit values and 95% C.L. intervals for all three Wilson coefficients obtained in a simultaneous fit to all coefficients. In both cases, linear and linear plus quadratic scenarios are shown. Expected limits using the full model and statistical only are also presented.

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.

In conclusion, constraints of Wilson coefficients of CP-violating operators in the HVV interaction within the SMEFT Warsaw basis are presented. The analysis combines five ATLAS Run 2 measurements including VBF and WH production modes, and $H \to VV$ decay channels: $H \to \tau\tau$, $H \to WW^*$, $H \to \gamma\gamma$, $H \to ZZ^*$, and $WH, H \to b\bar{b}$. 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% C.L. 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 $H \to \tau\tau$ [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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Data availability—The public release of data supporting the findings of this article will follow the CERN Open Data Policy [48]. Inquiries about plots and tables associated with this article can be addressed to atlas.publications@cern.ch.

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End Matter

Individual channel contributions to $c_{H\tilde{W}}$ constraint—The individual 2ΔNLL scans are shown in Fig. 5 for linear-only and linear plus quadratic interpretations, and the corresponding best fit values and 95% C.L. intervals are summarized in Fig. 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 nonparabolic 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 parametrized via their impact on their signal strengths μ_p (relative to the SM prediction), defined as,

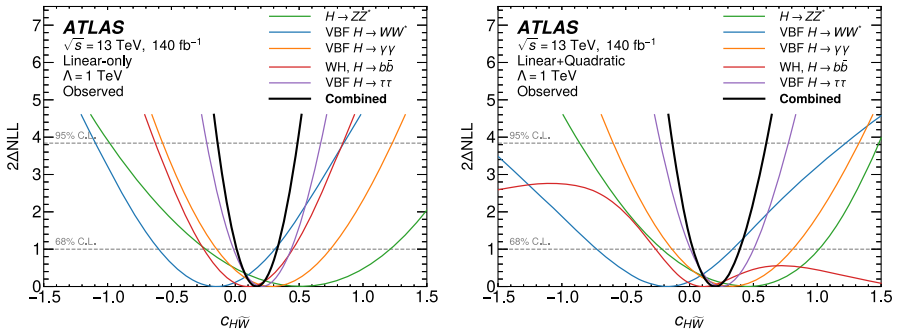


FIG. 5. Observed 2ΔNLL scans as a function of $c_{H\tilde{W}}$ considering the (a) linear-only and the (b) linear plus quadratic terms for the individual channels (in different colors) and their combination. The dashed horizontal lines show the values of ΔNLL thresholds defining the 68% and 95% confidence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

$$\mu_p \to \mu_p \times \left(1 + \sum_{j=1}^{M} A_j^p \times c_j + B_j^p \times c_j^2\right), \quad \text{(A1)}$$

where p are the STXS particle-level categories, A_j^p and B_j^p parametrize 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. (A2)]; 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. (A3)], resulting in the observed NLL behavior,

$$\text{Asym}_{p,j}^{\text{linear}} = -A_j^p \times c_j, \quad \text{(A2)}$$

$$\text{Asym}_{p,j}^{\text{linear+quadratic}} = \frac{-A_j^p \times c_j}{1 + B_j^p \times c_j^2}. \quad \text{(A3)}$$

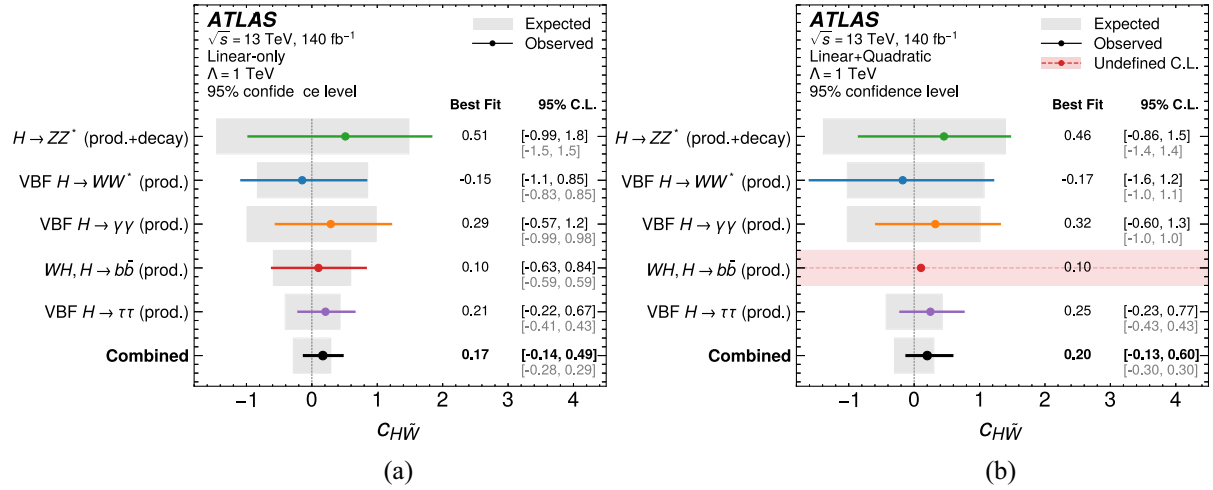


FIG. 6. Best-fit values and 95% C.L. intervals for $c_{H\tilde{W}}$ obtained in single-parameter fits for each of the individual analyses and the combined result, for both (a) linear-only and (b) linear and quadratic interpretations. For the $WH, H \to b\bar{b}$ linear and quadratic result, the best-fit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

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M. Shapiro,[18a] A. Sharma,[37] A. S. Sharma,[166] P. Sharma,[30] K. Shaw,[149] S. M. Shaw,[101] D. Shemyakin,[171] Q. Shen,[14] D. J. Sheppard,[145] P. Sherwood,[96] L. Shi,[112b] X. Shi,[14] S. Shimizu,[82] S. Shirabe,[88] M. Shiyakova,[38,mm] M. J. Shochet,[39] D. R. Shope,[126] B. Shrestha,[121] S. Shrestha,[120,nn] I. Shreyber,[38] M. J. Shroff,[104] P. Sicho,[132] A. M. Sickles,[164] E. Sideras Haddad,[34j] A. C. Sidley,[116] A. Sidoti,[24b] F. Siegert,[49] Dj. Sijacki,[16] F. Sili,[61] J. M. Silva,[51] I. Silva Ferreira,[81b] M. V. Silva Oliveira,[30] S. B. Silverstein,[46a] S. Simion,[65] R. Simoniello,[37] E. L. Simpson,[101] H. Simpson,[149] L. R. Simpson,[6] S. Simsek,[80] S. Sindhu,[54] S. N. Singh,[27] S. Singh,[30] S. Sinha,[47] S. Sinha,[101] M. Sioli,[24b,24a] K. Sioulas,[9] I. Siral,[37] E. Sitnikova,[47] J. Sjölin,[46a,46b] A. Skaf,[54] E. Skorda,[21] P. Skubic,[121] M. Slawinska,[86] I. Slazyk,[17] I. Sliusar,[126] V. Smakhtin,[171] B. H. Smart,[135] S. Yu. 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(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Türkiye*
[3b]*Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye*

[4]LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
[5]APC, Université Paris Cité, CNRS/IN2P3, Paris, France
[6]High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
[7]Department of Physics, University of Arizona, Tucson, Arizona, USA
[8]Department of Physics, University of Texas at Arlington, Arlington, Texas, USA
[9]Physics Department, National and Kapodistrian University of Athens, Athens, Greece
[10]Physics Department, National Technical University of Athens, Zografou, Greece
[11]Department of Physics, University of Texas at Austin, Austin, Texas, USA
[12]Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[13]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
[14]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[15]Physics Department, Tsinghua University, Beijing, China
[16]Institute of Physics, University of Belgrade, Belgrade, Serbia
[17]Department for Physics and Technology, University of Bergen, Bergen, Norway
[18a]Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
[18b]University of California, Berkeley, California, USA
[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[21]School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[22a]Department of Physics, Bogazici University, Istanbul, Türkiye
[22b]Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye
[22c]Department of Physics, Istanbul University, Istanbul, Türkiye
[23a]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia
[23b]Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
[24a]Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy
[24b]INFN Sezione di Bologna, Bologna, Italy
[25]Physikalisches Institut, Universität Bonn, Bonn, Germany
[26]Department of Physics, Boston University, Boston, Massachusetts, USA
[27]Department of Physics, Brandeis University, Waltham, Massachusetts, USa
[28a]Transilvania University of Brasov, Brasov, Romania
[28b]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[28c]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
[28d]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
[28e]National University of Science and Technology Politechnica, Bucharest, Romania
[28f]West University in Timisoara, Timisoara, Romania
[28g]Faculty of Physics, University of Bucharest, Bucharest, Romania
[29a]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
[29b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[30]Physics Department, Brookhaven National Laboratory, Upton, New York, USA
[31]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina
[32]California State University, Fresno, California, USA
[33]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[34a]Department of Physics, University of Cape Town, Cape Town, South Africa
[34b]iThemba Labs, Western Cape, South Africa
[34c]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
[34d]National Institute of Physics, University of the Philippines Diliman (Philippines), Quezon City, Philippines
[34e]Department of Physics, Stellenbosch University, Matieland, South Africa
[34f]University of KwaZulu-Natal, School of Agriculture and Science, Mathematics, Westville, South Africa
[34g]University of South Africa, Department of Physics, Pretoria, South Africa
[34h]University of Pretoria, Department of Mechanical and Aeronautical Engineering, Pretoria, South Africa
[34i]University of Zululand, KwaDlangezwa, South Africa
[34j]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[35]Department of Physics, Carleton University, Ottawa, Ontario, Canada
[36a]Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Casablanca, Morocco
[36b]Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
[36c]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
[36d]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco
[36e]Faculté des sciences, Université Mohammed V, Rabat, Morocco

[36f]Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco
[37]CERN, Geneva, Switzerland
[38]Affiliated with an international laboratory covered by a cooperation agreement with CERN
[39]Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
[40]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
[41]Nevis Laboratory, Columbia University, Irvington, New York, USA
[42]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[43a]Dipartimento di Fisica, Università della Calabria, Rende, Italy
[43b]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Cosenza, Italy
[44]Physics Department, Southern Methodist University, Dallas, Texas, USA
[45]National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece
[46a]Department of Physics, Stockholm University, Stockholm, Sweden
[46b]Oskar Klein Centre, Stockholm, Sweden
[47]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
[48]Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
[49]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[50]Department of Physics, Duke University, Durham, North Carolina, USA
[51]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[52]INFN e Laboratori Nazionali di Frascati, Frascati, Italy
[53]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
[54]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[55]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[56a]Dipartimento di Fisica, Università di Genova, Genova, Italy
[56b]INFN Sezione di Genova, Genova, Italy
[57]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[58]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[59]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
[60]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[61]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[62a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[62b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[63a]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[63b]Department of Physics, University of Hong Kong, Hong Kong, China
[63c]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[64]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[65]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
[66]Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain
[67]Department of Physics, Indiana University, Bloomington, Indiana, USA
[68a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
[68b]ICTP, Trieste, Italy
[68c]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
[69a]INFN Sezione di Lecce, Lecce, Italy
[69b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[70a]INFN Sezione di Milano, Milano, Italy
[70b]Dipartimento di Fisica, Università di Milano, Milano, Italy
[71a]INFN Sezione di Napoli, Napoli, Italy
[71b]Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[72a]INFN Sezione di Pavia, Pavia, Italy
[72b]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[73a]INFN Sezione di Pisa, Pisa, Italy
[73b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[74a]INFN Sezione di Roma, Roma, Italy
[74b]Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[75a]INFN Sezione di Roma Tor Vergata, Roma, Italy
[75b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[76a]INFN Sezione di Roma Tre, Roma, Italy
[76b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[77a]INFN-TIFPA, Trento, Italy

[77b]Università degli Studi di Trento, Trento, Italy
[78]Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria
[79]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[80]Istinye University, Sariyer, Istanbul, Türkiye
[81a]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
[81b]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
[81c]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
[81d]Rio de Janeiro State University, Rio de Janeiro, Brazil
[81e]Federal University of Bahia, Bahia, Brazil
[82]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[83a]Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[83b]New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
[83c]United Arab Emirates University, Al Ain, United Arab Emirates
[83d]University of Sharjah, Sharjah, United Arab Emirates
[84]Graduate School of Science, Kobe University, Kobe, Japan
[85a]AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland
[85b]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[86]Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[87]Faculty of Science, Kyoto University, Kyoto, Japan
[88]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
[89]L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France
[90]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[91]Physics Department, Lancaster University, Lancaster, United Kingdom
[92]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[93]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
[94]Department of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[95]Department of Physics, Royal Holloway University of London, Egham, United Kingdom
[96]Department of Physics and Astronomy, University College London, London, United Kingdom
[97]Louisiana Tech University, Ruston, Louisiana, USA
[98]Fysiska institutionen, Lunds universitet, Lund, Sweden
[99]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
[100]Institut für Physik, Universität Mainz, Mainz, Germany
[101]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[102]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[103]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
[104]Department of Physics, McGill University, Montreal, Quebec, Canada
[105]School of Physics, University of Melbourne, Victoria, Australia
[106]Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
[107]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[108]Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
[109]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[110]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[111]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[112a]Department of Physics, Nanjing University, Nanjing, China
[112b]School of Science, Shenzhen Campus of Sun Yat-sen University, Shenzhen, China
[112c]University of Chinese Academy of Science (UCAS), Beijing, China
[113a]School of Physics, Nankai University, Tianjin, China
[113b]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
[113c]School of Physics, Zhengzhou University, Zhengzhou City, China
[114]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[115]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
[116]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[117]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[118]Department of Physics, New York University, New York, New York, USA
[119]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
[120]Ohio State University, Columbus, Ohio, USA
[121]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[122]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA

[123]Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
[124]Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
[125]Graduate School of Science, University of Osaka, Osaka, Japan
[126]Department of Physics, University of Oslo, Oslo, Norway
[127]Department of Physics, Oxford University, Oxford, United Kingdom
[128]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
[129]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
[130]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[131a]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
[131b]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[131c]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
[131d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[131e]Departamento de Física, Escola de Ciências, Universidade do Minho, Braga, Portugal
[131f]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
[131g]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[132]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[133]Czech Technical University in Prague, Prague, Czech Republic
[134]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[135]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[136]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[137]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[138a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[138b]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile
[138c]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, La Serena, Chile
[138d]Universidad Andres Bello, Department of Physics, Santiago, Chile
[138e]Universidad San Sebastian, Recoleta, Chile
[138f]Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
[138g]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[139]Department of Physics, Institute of Science, Tokyo, Japan
[140]Department of Physics, University of Washington, Seattle, Washington, USA
[141a]State Key Laboratory of Dark Matter Physics, School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
[141b]State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China
[142]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[143]Department of Physics, Shinshu University, Nagano, Japan
[144]Department Physik, Universität Siegen, Siegen, Germany
[145]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
[146]SLAC National Accelerator Laboratory, Stanford, California, USA
[147]Department of Physics, Royal Institute of Technology, Stockholm, Sweden
[148]Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
[149]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150]School of Physics, University of Sydney, Sydney, Australia
[151]Institute of Physics, Academia Sinica, Taipei, Taiwan
[152a]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
[152b]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[152c]University of Georgia, Tbilisi, Georgia
[153]Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
[154]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[155]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[156]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
[157]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[158]Department of Physics, University of Toronto, Toronto, Ontario, Canada
[159a]TRIUMF, Vancouver, British Columbia, Canada
[159b]Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
[160]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[161]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
[162]Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
[163]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

[164]Department of Physics, University of Illinois, Urbana, Illinois, USA
[165]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
[166]Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
[167]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
[168]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
[169]Department of Physics, University of Warwick, Coventry, United Kingdom
[170]Waseda University, Tokyo, Japan
[171]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
[172]Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
[173]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[174]Department of Physics, Yale University, New Haven, Connecticut, USA
[175]Yerevan Physics Institute, Yerevan, Armenia

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[d]Also at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia.
[e]Also at Department of Physics, University of Thessaly, Greece.
[f]Also at An-Najah National University, Nablus, Palestine.
[g]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[h]Also at Department of Physics, Westmont College, Santa Barbara, California, USA.
[i]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[j]Also at University of Siena, Siena, Italy.
[k]Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN.
[l]Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[m]Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia, Bulgaria.
[n]Also at Università di Napoli Parthenope, Napoli, Italy.
[o]Also at Institute of Particle Physics (IPP), Kingston, Canada.
[p]Also at Department of Physics, Bolu Abant Izzet Baysal University, Bolu, Türkiye.
[q]Also at Faculty of Physics, University of Bucharest, Bucharest, Romania.
[r]Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
[s]Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Quezon City, Philippines.
[t]Also at TRIUMF, Vancouver, British Columbia, Canada.
[u]Also at Universita degli Studi Link, Roma, Italy.
[v]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[w]Also at University and INFN Torino, Torino, Italy.
[x]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[y]Also at Henan University, Zhengzhou, China.
[z]Also at Yeditepe University, Physics Department, Istanbul, Türkiye.
[aa]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[bb]Also at CERN, Geneva, Switzerland.
[cc]Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.
[dd]Also at Hellenic Open University, Patras, Greece.
[ee]Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China.
[ff]Also at Department of Physics, Stellenbosch University, Cape Town, South Africa.
[gg]Also at School of Physics, University of the Witwatersrand, Johannesburg, South Africa.
[hh]Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
[ii]Also at University of Colorado Boulder, Department of Physics, Colorado, Boulder, USA.
[jj]Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[kk]Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP), Braga, Portugal.
[ll]Also at Indian Institute of Technology (IIT), Jodhpur, India.
[mm]Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
[nn]Also at Washington College, Chestertown, Maryland, USA.
[oo]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[pp]Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.
[qq]Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.
[rr]Also at Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile.
[ss]Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.