
CMS Physics Analysis Summary

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Constraints on Effective Field Theory operators from multiboson production measurements at $\sqrt{s} = 13$ TeV

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Abstract

A search for new physics in electroweak multiboson production is performed through a statistical combination of ten CMS measurements using proton-proton collision data collected at $\sqrt{s} = 13$ TeV during 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} . The combination encompasses six vector boson scattering channels: same-sign WW production in fully leptonic and $\ell\tau_h$ final states, opposite-sign WW, WZ, and two VBS channels with a hadronically decaying vector boson (WV and ZV); two vector boson fusion channels (Wjj and Zjj), inclusive W^+W^- diboson production, and triboson VVV (no γ) production. Within the standard model effective field theory framework, potential contributions from physics beyond the standard model are parameterized in terms of six CP-even bosonic dimension-six operators of the Warsaw basis: $\mathcal{O}_W$, $\mathcal{O}_{HW}$, $\mathcal{O}_{HWB}$, $\mathcal{O}_{H\Box}$, $\mathcal{O}_{HB}$, and $\mathcal{O}_{HD}$. Their effects are introduced through event-by-event reweighting of leading-order Monte Carlo simulations, enabling a consistent propagation of EFT effects to detector level with a consistent treatment of systematic uncertainties. Constraints on the associated Wilson coefficients are extracted using a binned profile likelihood fit, in scenarios ranging from individual coefficients to the fully profiled six-dimensional fit. No significant deviations from the standard model are observed. The combination improves substantially upon any individual analysis and constitutes the first detector-level combination of direct EFT measurements targeting bosonic dimension-six operators at the LHC.

1 Introduction

The standard model effective field theory (SMEFT) [1, 2] is a theoretical framework that extends the standard model (SM) of particle physics by systematically incorporating the effects of new physics at a mass scale Λ that is large in comparison to the electroweak (EW) scale and beyond the reach of current experiments. Predictions for experimental observables are then provided in terms of a systematic expansion of the SM Lagrangian in inverse powers of Λ , obtained by including higher-dimensional operators $\mathcal{O}_i^{(d)}$, with dimension $d > 4$, that respect the SM symmetries but introduce interactions that do not exist in the original theory. The effect of the SMEFT operators is gauged by a dimensionless parameter called Wilson coefficient $c_i^{(d)}$ and tamed by inverse powers of the new energy scale $\Lambda^{-(d-4)}$:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}. \quad (1)$$

Comparing these predictions with observations provides constraints on the Wilson coefficients, offering insight into BSM physics. The effective field theory interpretations of experimental results have been explored by both ATLAS and CMS [3–6]. Assuming baryon and lepton number conservation, only operators of even dimension are allowed. This study is restricted to the leading term in the tower expansion, namely dimension-6 operators.

This study presents a statistical combination of ten CMS analyses, interpreted in the framework of SMEFT, to constrain the Wilson coefficients of six purely bosonic dimension-six operators. The operators are defined in the Warsaw basis [2], which provides a complete and non-redundant operator set. Their definitions are listed in Table 1. The SMEFT effects are incorporated through event-by-event reweighting of leading-order SM matrix elements, consistently propagating both normalization and kinematic modifications to detector level in each analysis. SMEFT-induced propagator corrections, which arise from operator contributions to the total decay widths of the W , Z , and H bosons and are largest near the boson mass peaks, are not included in the simulation. These corrections are most significant for operators entering $\delta\Gamma_W$ and $\delta\Gamma_Z$ through fermionic decays; for the purely bosonic operators considered here, their impact on the extracted constraints has been verified to be negligible [7]. The combination includes the latest CMS measurements of EW production of one, two, and three vector bosons in proton-proton collisions at the LHC. The input analyses probe complementary, non-overlapping regions of phase space and are interpreted using a common SMEFT implementation and flavor-symmetry assumptions. The SMEFT effects are assumed to modify only EW interactions among gauge bosons and fermions, providing a coherent probe of possible new physics in the EW symmetry-breaking sector. The analyses included in the combination are listed in Table 2.

The six Wilson coefficients considered in this combination correspond to the complete set of CP-even, purely bosonic dimension-six operators of the Warsaw basis that contribute at tree level to the EW diagrams entering the vector-boson-scattering (VBS), vector-boson-fusion (VBF), di-boson, and triboson final states studied here. $\mathcal{O}_W$ modifies the triple and quartic EW gauge-boson self-couplings; $\mathcal{O}_{HW}$, $\mathcal{O}_{HB}$, and $\mathcal{O}_{HWB}$ modify the HVV vertex, with $\mathcal{O}_{HWB}$ additionally inducing a momentum-dependent $WW\gamma$ / WWZ coupling; and $\mathcal{O}_{H\Box}$ and $\mathcal{O}_{HD}$ enter through corrections to the Higgs kinetic term and the EW input parameters. Together, these six operators span the complete set of tree-level modifications accessible to the EW gauge and Higgs sectors probed by the final states considered in this combination.

Depending on their Lorentz structure, the operators listed in Table 1 affect the kinematics of

Table 1: The subset of Warsaw basis operators considered in this work, following the definitions of [1, 2]. Repeated indices are summed over. These purely bosonic operators are independent of the flavour symmetry imposed on the SMEFT Lagrangian. The symbol H refers to the Higgs doublet; D_μ is a covariant derivative and $\square = D^\mu D_\mu$ the d'Alembert operator; $W_{\mu\nu}^i$ and $B_{\mu\nu}$ are the $SU(2)_L$ and $U(1)_Y$ field strength tensors; i, j, k are $SU(2)$ adjoint indices.

Class	Operator Name	Definition
X^3	$\mathcal{O}_W$	$\epsilon^{ijk} W_\mu^{iv} W_\nu^{j\rho} W_\rho^{k\mu}$
$H^4 D^2$	$\mathcal{O}_{H\square}$	$(H^\dagger H) \square (H^\dagger H)$
	$\mathcal{O}_{HD}$	$(H^\dagger D_\mu H) (H^\dagger D^\mu H)$
	$\mathcal{O}_{HWB}$	$(H^\dagger \sigma^i H) W_{\mu\nu}^i B^{\mu\nu}$
$X^4 H^2$	$\mathcal{O}_{HB}$	$(H^\dagger H) B_{\mu\nu} B^{\mu\nu}$
	$\mathcal{O}_{HW}$	$(H^\dagger H) W_{\mu\nu}^i W^{i\mu\nu}$

the processes considered in qualitatively different ways. $\mathcal{O}_{HD}$ is built solely from covariant derivatives acting on the Higgs doublet and contains no gauge field-strength tensor; in the SMEFTSIM implementation used in this combination, its effect after EW symmetry breaking can therefore be reabsorbed into a redefinition of the EW input parameters. As a result, it rescales the predicted cross sections without altering the shape of the kinematic distributions, and acts effectively as a normalization operator. The remaining operators – $\mathcal{O}_W$, $\mathcal{O}_{HW}$, $\mathcal{O}_{HB}$, and $\mathcal{O}_{HWB}$ – all contain explicit gauge field-strength tensors ($W_{\mu\nu}^i$ and/or $B_{\mu\nu}$), which introduce new derivative couplings among gauge bosons, or between the Higgs boson and gauge bosons, that are absent in the SM Lagrangian and cannot be reabsorbed in the same way; in particular, $\mathcal{O}_{HWB}$ modifies the $WW\gamma$ and WWZ vertices with a momentum-dependent structure equivalent to a shift of the anomalous coupling $\Delta\kappa_\gamma$. $\mathcal{O}_{H\square}$ similarly cannot be reabsorbed into the input parameters, modifying instead the HVV vertex. Since these couplings are absent at tree level in the SM, their contribution to the amplitude grows with the energy of the hard-scattering process, distorting the shape of the kinematic distributions used in the fit; visible shape effects are indeed observed for $\mathcal{O}_{H\square}$ in the $SSWW$ and WZ channels, and for $\mathcal{O}_{HWB}$ in the diboson W^+W^- and VBF channels.

In this note, we consider the detector-level results of the latest CMS data analyses on the EW production of one, two, and three vector bosons at the LHC, and statistically combine them. This study focuses on processes that are non-overlapping in terms of the covered portions of the physics phase space, using a consistent definition of the SMEFT operators based on their defining basis and the flavor symmetries imposed upon them. The SMEFT effects under investigation are assumed to modify only the EW couplings among bosons and fermions, to capture BSM effects in the EW symmetry breaking across different key EW processes. The list of the individual analyses considered in this note is reported in Table 2.

In the remainder of this note, Section 2 describes the CMS detector, Section 3 presents the inputs to the combination, Section 4 illustrates the methods for simulating events. In Section 5 and Section 6 respectively we discuss the statistical procedure employed to measure the Wilson coefficients and modeling of systematic uncertainties. The SMEFT interpretation results are given in Section 8, and we conclude with a summary in Section 9.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within this magnetic field volume are a silicon pixel and silicon strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass-and-scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the coverage in pseudorapidity η provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [8].

The silicon tracker used in 2016 measured charged particles within the range $|\eta| < 2.5$. For nonisolated particles of transverse momentum p_T in the range $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions were typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter. For isolated particles with $p_T = 100$ GeV emitted at $|\eta| < 1.4$, the resolutions are approximately 2.8% in p_T , and in impact parameter 10 μm (transverse) and 30 μm (longitudinal) [9]. At the start of 2017, a new pixel detector was installed [10]; the upgraded tracker measured particles up to $|\eta| < 3.0$ with typical resolutions of 1.5% in p_T and 20–75 μm in the transverse impact parameter for nonisolated particles of $1 < p_T < 10$ GeV [11].

Events of interest are selected using a two-tiered trigger system [12]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software, optimized for fast processing that reduces the event rate to a few kHz before data storage.

3 Input analyses

For this study we consider the results of ten analyses, as outlined in Table 2. Six vector boson scattering (VBS) channels are included, four of them with a fully leptonic final state: the scattering of two W bosons with same electric charge (SSWW) with electrons or muons in the final state (e, μ), or with one hadronically decaying τ lepton (τ_h); the scattering of two W bosons with opposite electric charge (OSWW); and the scattering of a WZ pair. Two further VBS analyses are included in which one of the two vector bosons decays hadronically ($V \rightarrow q\bar{q}$): $WV \rightarrow \ell^\pm \nu jj$ and $ZV \rightarrow \ell^+ \ell^- jj$, where $V = Z, W$. The EW production of a vector boson Vjj through vector boson fusion (VBF), where $V = W, Z$, is also considered. One diboson process W^+W^- , targeting the electron-muon final state to suppress the Drell–Yan background, with leptonic decay of both W bosons ($W^+W^- \rightarrow e^\pm \mu^\mp \nu \nu$), and one triboson process (VVV/γ), targeting the production of three massive gauge bosons VVV with $V = W, Z$ and excluding final states with a photon, complete the picture. The triboson analysis includes multiple final states from 0 up to 2 charged leptons. All analyses considered in the combination are based on pp collisions data collected between 2016 and 2018 with the CMS detector, corresponding to an integrated luminosity of 138 fb^{-1} . The VBS SSWW(τ_h) and VVV/ γ analyses are the only ones targeting final states that include a hadronically decaying τ lepton. Details about the generation of the SM and SMEFT terms are described in Section 4. Representative SM diagrams for the EW production mechanism and final state of each analysis are shown in Fig. 1, with the shaded blob denoting the EW production amplitude, which receives contributions from multiple diagrams; the dimension-six operators of Table 1 can affect both this production amplitude and the subsequent decay vertices of the vector bosons.

Table 2: Summary of the analyses considered in the combination and the reference to the specific CMS study on that final state. The final state for each analysis is specified, where $\ell^\pm$ denotes a light lepton (e, μ) and τ_h represents a hadronically decaying τ lepton. The last two columns indicate the operators contributing as vertex corrections to the diagrams associated with each specific final state and the single CMS publication on that final state.

Analysis	Final state	Operators	Ref.
VBS-SSWW(e, μ)	$\ell^\pm \ell^\pm 2\nu jj$	$\mathcal{O}_{HD}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_{H\Box}, \mathcal{O}_W$	[13]
VBS-SSWW(τ_h)	$\ell^\pm \tau_h^\pm 2\nu jj$	$\mathcal{O}_{HD}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_{H\Box}, \mathcal{O}_W$	[14]
VBS-OSWW	$\ell^\pm \ell^\mp 2\nu jj$	$\mathcal{O}_{HD}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_{H\Box}, \mathcal{O}_W$	[15]
VBS-WZ	$\ell^+ \ell^- \ell^\pm \nu jj$	$\mathcal{O}_{HD}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_{H\Box}, \mathcal{O}_W$	[13]
VBS-WV	$\ell^\pm \nu jjjj$	$\mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_{H\Box}, \mathcal{O}_W$	[16]
VBS-ZV	$\ell^+ \ell^- jjjj$	$\mathcal{O}_{HD}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_{H\Box}, \mathcal{O}_W$	[17]
VBF-W	$\ell^\pm \nu jj$	$\mathcal{O}_{HD}, \mathcal{O}_{HWB}, \mathcal{O}_W$	[18]
VBF-Z	$\ell^+ \ell^- jj$	$\mathcal{O}_{HD}, \mathcal{O}_{HWB}, \mathcal{O}_W$	[19]
WW	$\ell^+ \ell^- 2\nu$	$\mathcal{O}_{HWB}, \mathcal{O}_W$	[20]
VVV/ γ	$6j, \ell^\pm \nu jjjj, \ell^+ \ell^- jjjj,$ $\ell^+ \ell^- 2\nu jj, \ell^\pm \ell^\pm 2\nu jj$ $\ell^\pm \tau_h^\pm 2\nu jj, \ell^+ \ell^- \tau_h^\pm 3\nu$	$\mathcal{O}_{HB}, \mathcal{O}_{HD}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_{H\Box}, \mathcal{O}_W$	[21]

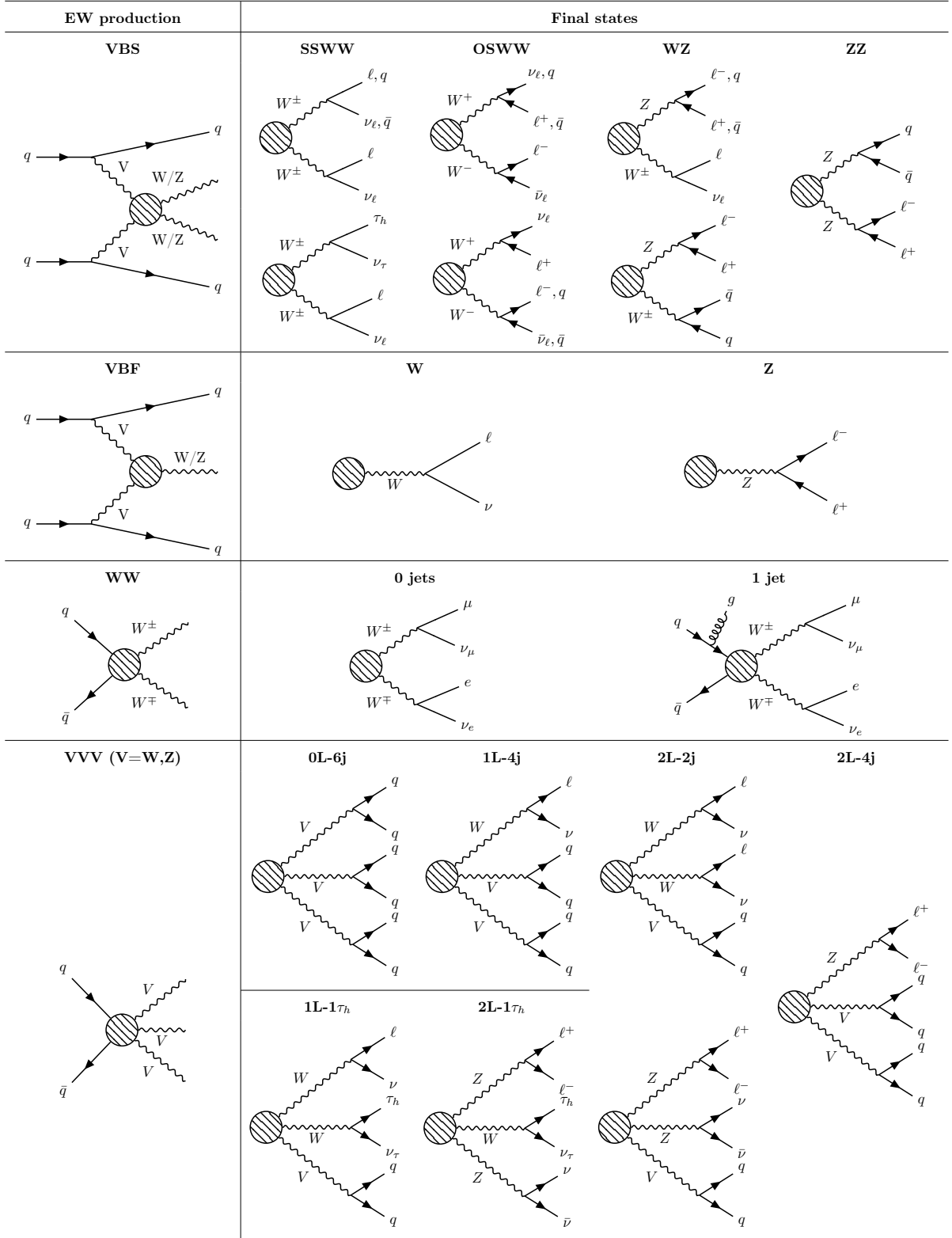


Figure 1: Representative SM diagrams for the EW production processes considered in this combination. Each row corresponds to one of the four production mechanisms entering the combination – VBS, VBF, diboson W^+W^- , and triboson VVV – with the generic production diagram shown on the left; the shaded blob denotes the EW production amplitude, summing the multiple diagrams contributing to each process. The dimension-six operators of Table 1 can affect both this production amplitude and the subsequent decay vertices of the vector bosons. The columns on the right show the specific decay topologies corresponding to the final states of each analysis listed in Table 2.

4 Signal and background samples

Monte Carlo (MC) simulation is used throughout the combination to design the event selection, evaluate signal efficiencies, and estimate background contributions. The VBS, VBF, diboson, and triboson SMEFT signal samples are all generated at leading order (LO) with MADGRAPH5_aMC@NLO v2.6.5 [22]; the generation syntax used by each analysis is reported in Table 5 in the appendix. Further details on the signal simulation can be found in the documentation of each individual analysis. The SMEFT simulation is performed at LO using the SMEFTSIM package [23, 24]. For each analysis considered in this combination, a single set of events is generated with all six CP-even operators of interest simultaneously active at unit coupling. The MADGRAPH5_aMC@NLO reweighting functionality is then used to assign each event a weight corresponding to a given new physics hypothesis, from which the full SMEFT parametrization is recovered: the SM hypothesis, each operator individually set to $c_i = \pm 1$, and each pair of operators simultaneously set to $c_i = c_j = 1$. The closure of this reweighting procedure has been validated, on a per-analysis basis, against the direct generation of the linear and quadratic amplitude components implemented in SMEFTSIM.

SMEFTSIM is used exclusively to generate the SMEFT contributions to the EW signal processes; all background processes are instead simulated using their SM-only matrix elements, as described below.

The strategies to estimate the background contributions vary across input channels and include both data-driven estimations and MC simulation techniques. Backgrounds that are reducible or poorly simulated, such as non-prompt leptons, charge-misidentification electrons, and Vector Boson + Jets processes, are constrained through dedicated control regions (CRs) in data. Most irreducible backgrounds are instead modeled using MC simulation, as described in the following lines. In the VBS channels, the QCD-induced backgrounds and EW-QCD interference are simulated at leading order (LO) with MADGRAPH5_aMC@NLO v2.6.5 and using MADSPIN [25] to simulate the decay of the vector bosons. In the case of OSWW, quark- and gluon-induced WW backgrounds are instead simulated using POWHEG v2 [26–28]. W/Z +jets, $W\gamma$, QCD-induced diboson, and VBF production are simulated with MADGRAPH5_aMC@NLO at LO, while triboson processes are simulated at next-to-leading order (NLO). $Z\gamma$, Wg and Zg are generated at LO or NLO depending on the input channel. Resonant diboson EW or QCD production is generated through MADGRAPH5_aMC@NLO (LO) and PYTHIA [29]. Processes involving top quarks are generated mainly with POWHEG at NLO and MADGRAPH5_aMC@NLO at NLO, depending on the input analysis. W +Jets and Z +Jets are estimated through data-driven methods in some analyses, namely VBS-ZV, VBS-WV, VBF-Z, while in the others they are generated via MADGRAPH5_aMC@NLO at LO with MLM jet matching [30]. The same matching strategy is used also for QCD multijet and diboson events. Higgs boson production processes, in particular gluon-gluon fusion, VBF, and WH production, are generated through POWHEG or JHUGEN [31] at NLO, with reweighting to next-to-NLO [32], where applicable.

The NNPDF3.1 next-to-NLO [33] parton distribution functions (PDFs) are used in the simulation of the background and signal samples.

The generators used for signal and background processes are interfaced with the PYTHIA program, in versions 8.306 or 8.230 depending on the analysis, with the CP5 tune [34], to model parton showering, hadronization and underlying events.

Additional collisions in the same or adjacent bunch crossings (pileup) are taken into account by superimposing simulated minimum bias interactions onto the hard-scattering process, with a multiplicity distribution matching the one that is observed in the data. Simulated events

are propagated through the full GEANT4-based simulation [35] of the CMS detector. The object reconstruction is performed with the CMS Particle-flow algorithm [36] both in data and simulation.

5 Statistical procedure

The statistical interpretation of the data follows the methodology shared by the ATLAS and CMS Collaborations [37, 38]. The results were derived using the CMS statistical analysis tool, COMBINE [39], which is based on the ROOFIT [40] and ROOSTATS [41] frameworks. A profile likelihood ratio q is used as a test statistic in order to measure the Wilson coefficients $\vec{c}$ and their associated confidence intervals. By denoting $\vec{x}$ the measurements and $\vec{\theta}$ the nuisance parameters modeling various source of uncertainties the test statistics is defined as:

$$q(\vec{c}) = -2 \log \frac{L(\vec{x}|\vec{c}, \hat{\vec{\theta}})}{L(\vec{x}|\hat{\vec{c}}, \hat{\vec{\theta}})} \quad (2)$$

Where L represents the likelihood function, $\hat{\vec{c}}$ and $\hat{\vec{\theta}}$ in the denominator are the maximum likelihood estimators for the parameters of interest and nuisance parameters, respectively. The term $\hat{\vec{\theta}}$ in the numerator denotes the value of $\vec{\theta}$ that maximizes L for a given $\vec{c}$, making it a function of $\vec{c}$. The binned likelihood function L is constructed as the product of Poisson probabilities for each bin of the input templates. It incorporates systematic uncertainties and their correlations, which are described by likelihood functions (π) associated with the estimation of the corresponding parameters. The formulation of the likelihood function for a specific phase space is detailed in Eq. 3. Given the statistical independence of the data points $\vec{x}$ across different phase spaces included in the combination, the complete likelihood is obtained as the product of the individual per-channel likelihoods.

$$L(\vec{x}|\vec{c}, \vec{\theta}) = \prod_{\text{bin}=k} \frac{(N_k(\vec{c}) + b_k)^{n_k}}{n_k!} e^{-(N_k(\vec{c}) + b_k)} \times \prod_{\text{syst}=j} \pi(\vec{\theta}_j|\theta_j) \quad (3)$$

The effect of the Wilson coefficients is to scale quadratically the normalization of the purely EW-induced signal processes of interest. The expected number of events in a bin k of a differential distribution is the sum of the expected background yield b_k , assumed to be independent of the SMEFT parameters, and of the expected signal yield $N_k(\vec{c})$ that depends quadratically on the Wilson coefficients as follows

$$\begin{aligned} N_k(\vec{c}) \propto |\mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{BSM}}|_k^2 &= |\mathcal{A}_{\text{SM}}|_k^2 + \sum_i \left[\frac{c_i}{\Lambda^2} 2 \text{Re} |\mathcal{A}_{\text{SM}}^* \mathcal{A}_{\mathcal{O}_i}|_k + \frac{c_i^2}{\Lambda^4} |\mathcal{A}_{\mathcal{O}_i}|_k^2 \right] \\ &+ \sum_{n \neq m} \frac{c_n c_m}{\Lambda^4} \text{Re} |\mathcal{A}_{\mathcal{O}_n}^* \mathcal{A}_{\mathcal{O}_m}|_k, \end{aligned} \quad (4)$$

Terms scaling linearly or quadratically as a function of a specific Wilson coefficient c_i are respectively referred to as Linear ($N_{\text{Lin},k}^i = 2 \text{Re} |\mathcal{A}_{\text{SM}}^* \mathcal{A}_{\mathcal{O}_i}|_k$) and Quadratic ($N_{\text{Quad},k}^i = |\mathcal{A}_{\mathcal{O}_i}|_k^2$) components. Terms scaling as the product of two different Wilson coefficients are referred to as Mixed quadratic contributions ($N_{\text{Mix},k}^{n,m} = 2 \text{Re} |\mathcal{A}_{\mathcal{O}_n}^* \mathcal{A}_{\mathcal{O}_m}|_k$)

Different kinds of fits are performed with the same dataset, addressing increasing levels of generality in the SMEFT description. An individual fit to a Wilson coefficient c_i is performed by floating the corresponding c_i while setting the remaining SMEFT parameters to their SM expectation, so that the set of Wilson coefficients may be represented as $\vec{c} = \{0, \dots, c_i, 0, \dots, 0\}$. In this case, the expected number of signal events reads as:

$$N_k(c_i) = N_{\text{SM},k} + c_i/\Lambda^2 \cdot N_{\text{Lin},k}^i + c_i^2/\Lambda^4 \cdot N_{\text{Quad},k}^i. \quad (5)$$

Two-dimensional fits can be performed by freely floating pairs of Wilson coefficients while setting the remaining SMEFT parameters to their SM expectation ($\vec{c} = \{0, \dots, c_i, c_j, 0, \dots, 0\}$). In this case, the expected number of signal events receives contributions from linear, quadratic, and mixed quadratic components:

$$N_k(c_i, c_j) = N_{\text{SM},k} + c_i/\Lambda^2 \cdot N_{\text{Lin},k}^i + c_j/\Lambda^2 \cdot N_{\text{Lin},k}^j + c_i^2/\Lambda^4 \cdot N_{\text{Quad},k}^i \quad (6)$$

$$+ c_j^2/\Lambda^4 \cdot N_{\text{Quad},k}^j + c_i c_j/\Lambda^4 \cdot N_{\text{Mix},k}^{ij}. \quad (7)$$

In the most general case, where all the operators under study are present simultaneously with non-zero Wilson coefficients, the expected number of signal events follows Eq. 4. In this configuration, the one-dimensional likelihood scan for a specific coefficient can be derived by profiling over all the other ones.

For all configurations the estimated values of the Wilson coefficients $\hat{c}$ are computed from a maximum likelihood fit of the corresponding parameters of interest. Confidence intervals at one and two standard deviations, corresponding to 68.3% and 95.4% confidence level (CL) respectively, are identified, under the assumption that Wilks' theorem holds, as the Wilson coefficients values for which $q < 1$ and $q < 4$ respectively in the case of one-dimensional fits and $q < 2.3$, $q < 6.18$ for two-dimensional ones.

To quantify the sensitivity of each input channel to a given Wilson coefficient, the expected uncertainty $\sigma_{c_j}^\alpha$ on c_j is evaluated separately for each channel α , using that channel alone. The fractional contribution of channel α to the combined constraint on c_j , shown in Fig. 2, is then defined as

$$f_j^\alpha = \frac{1/(\sigma_{c_j}^\alpha)^2}{\sum_\beta 1/(\sigma_{c_j}^\beta)^2}, \quad (8)$$

where the sum runs over all input channels β entering the combination.

6 Systematic uncertainties

Systematic uncertainties from both experimental and theoretical sources are taken into account in the combination, implemented as nuisance parameters in the binned maximum likelihood fit to the dimension-6 Wilson coefficients. All uncertainties affecting the SM EW component of the signal in a specific analysis are also considered on the SMEFT prediction and fully correlated across all bins and channels. Theoretical uncertainties are treated as correlated across analyses and between signal and background samples wherever appropriate. Experimental uncertainties are also correlated across analyses when justified. The adopted correlation scheme has been tested for robustness, with the results showing only limited sensitivity to variations in the correlation assumptions. The systematic uncertainties are globally treated

as either normalization-only or shape-affecting, depending on their impact on the predicted yields and distributions.

The integrated luminosity of the 2016, 2017, and 2018 datasets is measured with uncertainties of 1.2, 2.3, and 2.5%, respectively, resulting in an overall uncertainty of 1.6% [42–44].

Reconstruction and identification efficiencies of electrons and muons, alongside with their momentum scale and resolution uncertainties, are evaluated using dedicated studies [45]. Similarly, statistical uncertainties related to the τ lepton identification, energy scale and resolution are accounted for [46]. Depending on the analysis, specific uncertainties are computed to account for differences between measurement and signal regions in the modeling of the non-prompt lepton background or the charge misidentification electrons background, which are data-driven estimation techniques [13].

Trigger efficiency uncertainties are derived from measurements based on control samples in data and propagated to the predicted yields.

Jet energy scale and resolution uncertainties are assessed through the variation of the jet momenta within their $\pm 1\sigma$ uncertainties, which in turn affects jet multiplicities and p_T^{miss} [47]. For small- and large-radius jets, additional uncertainties in the jet mass scale and resolution are considered, particularly in channels targeting boosted topologies. Multiplicative factors are applied to all simulated samples to correct the discrepancies in jet pileup identification between data and simulation. These corrections affect only analyses with jets of $p_T < 50$ GeV and are uncorrelated through years, correlated across processes. Efficiencies for b tagging are adjusted using corrections based on control samples in data [45]. Pileup modeling uncertainties are estimated by varying the total inelastic pp cross section by 4.6% [48].

Theoretical uncertainties are propagated by varying renormalization and factorization scales by a factor of two, excluding the two extreme and opposite variations, and by evaluating uncertainties from PDFs and the strong coupling α_s following the PDF4LHC prescription [49]. Parton shower modeling uncertainties are derived by varying initial- and final-state radiation weights in the simulated samples.

7 Combined fit inputs and uncertainty correlations

Table 3 summarizes the signal regions (SRs) and input distributions entering the combined maximum-likelihood fit. Several analyses further split their SRs into finer categories in order to maximize sensitivity to the SMEFT signal.

In the VBS-OSWW analysis, the two SRs are separated by the Zeppenfeld variable [50] of the dilepton system, $Z_{\ell\ell} = 0.5 |Z_{\ell_1} + Z_{\ell_2}|$, with $Z_\ell = \eta_\ell - 0.5 (\eta_{j_1} + \eta_{j_2})$, as defined in Ref. [15], and are fit in the dijet invariant mass m_{jj} . The VBS-SSWW(e, μ) and VBS-WZ analyses use a single SR each, fit in a two-dimensional distribution of m_{jj} and $m_{\ell\ell}$, or of m_{jj} and the transverse mass m_T^{WZ} of the diboson system for VBS-WZ, flattened into a one-dimensional array of bins. The VBS-SSWW(τ_h) analysis uses a single SR fit in an SMEFT-sensitive DNN score. The VBF-W and VBF-Z analyses are fit in the azimuthal separation $\Delta\phi_{jj}$ between the two tagging jets, uniformly binned for VBF-W and further split into windows of DNN score, flattened into a single array, for VBF-Z. The VBS-WV SRs are split by the value of a DNN discriminant trained to separate the EW signal from the backgrounds, and are fit in the diboson invariant mass m_{WV} ; the VBS-ZV SRs are instead split according to the number of b-tagged jets (b-veto or b-tag), and are fit in m_{ZV} .

The VVV/ γ analysis defines the largest number of SRs, split according to the number of charged leptons, the number of hadronically decaying τ leptons (τ_h), and the number of large-radius, V-tagged jets (VTJ). Categories with two charged leptons are further split by the leptons' relative electric charge – same-sign (SS) or opposite-sign (OS) – by their flavor – opposite-flavor (OF) or same-flavor (SF) – and, for same-flavor pairs, by whether the dilepton invariant mass lies close to the Z boson mass (Z) or away from it (noZ). Most SRs are fit in the scalar sum of the transverse momenta of the reconstructed objects, S_T . In the categories with one hadronically decaying τ_h , a boosted decision tree (BDT) trained to separate the SMEFT signal from the background is used instead of S_T as the discriminating variable, with the working point separating the low- and high-BDT-score regions ranging from 0.95 to 0.98 depending on the data-taking year; the high-BDT, low- S_T region is excluded from the fit due to its limited event yield. Finally, the diboson W^+W^- analysis (WW) merges the 0- and 1-jet SRs, fit in the dilepton invariant mass $m_{\ell\ell}$.

The combined fit spans 163 signal and control regions, corresponding to 912 bins of the discriminating distributions used in the likelihood, with 3.39 million events observed in total. Systematic uncertainties are implemented through 562 independent nuisance parameters, profiled in the fit; several background normalizations are additionally left free to float and constrained directly by data rather than assigned an external uncertainty.

The correlation pattern of the systematic uncertainties is assigned according to their physical origin rather than by region. Approximately 30% of the nuisance parameters are shared between two or more regions and are thus treated as fully correlated wherever they appear; the remaining 70% affect a single region and are left uncorrelated with the rest of the combination. The correlated component is dominated by sources common to the detector or to the theoretical modeling: jet energy scale and resolution, b-tagging efficiency, pileup modeling, and lepton reconstruction/identification efficiencies are correlated across all regions and years in which the same calibration applies, as are parton distribution function and QCD renormalization and factorization scale uncertainties for shared background processes. The integrated luminosity uncertainty follows the standard LHC Run 2 decomposition into a component uncorrelated between years, a component correlated only between the last two years of data-taking, and a component fully correlated across the entire dataset. Conversely, uncertainties on backgrounds estimated with region-specific data-driven techniques, such as nonprompt-lepton contributions, are treated as fully uncorrelated between regions, since they arise from measurements specific to each selection. Statistical uncertainties of the MC simulations are treated independently in every bin of every region and are never correlated.

The SMEFT signal, is not assigned its own independent set of systematic uncertainties. Instead, every nuisance parameter that affects the SM component of a signal process is applied identically to all of its associated SMEFT interference and quadratic components, so that the whole SMEFT parameterization of a given process responds coherently to a systematic shift, exactly as if it were a single template. Since the linear, quadratic, and mixed terms are obtained analytically from a common set of simulated samples rather than being independently generated, no separate MC statistical uncertainty is assigned to them: bin-by-bin statistical uncertainties are propagated only for the SM signal template and the background templates, not for the SMEFT-dependent pieces individually.

8 Results

The result of the fit performed on single Wilson coefficients according to the model of Eq. 5 is shown in Fig. 8 and 9, where the resulting $-2\ln\Delta\mathcal{L}$ profile for the six bosonic operators is

Table 3: Summary of the signal regions (SRs) entering the combined fit. Some rows merge multiple SRs sharing an identical discriminating variable and binning, with yields summed accordingly. SRs are further split by the Zeppenfeld variable [50] (VBS-OSWW), DNN score or b-tag multiplicity (VBS-WV/ZV), and, for VVV/ γ , by lepton/ τ_h /VTJ multiplicity, lepton charge (SS: same-sign, OS: opposite-sign), flavor (OF: opposite-, SF: same-flavor), and $m_{\ell\ell}$ proximity to the Z pole (Z/noZ); a BDT separates signal in the τ_h channels. Full definitions are given in the original references of Table 2. The second column gives the discriminating variable, with a colon for bidimensional observables; m/m_T denote invariant/transverse mass of the sub/superscripted system. Remaining columns: number of bins and edges, nuisance parameters (NP), and observed events.

Region	Discr. variable(s)	Bins	Bin edges	NP	Obs.
VBS-OSWW					
$Z_{\ell\ell} \geq / < 1$ SRs (17+18)	m_{jj}	8	300, 550, 750, 1000, 1250, 1500, 1750, 2000, 4000 GeV	73	1155
$Z_{\ell\ell} \geq / < 1$ SRs (16)	m_{jj}	5	500, 750, 1000, 1500, 2000, 4000 GeV	48	186
VBS-SSWW(e, μ)					
SR	$m_{jj} : m_{\ell\ell}$	12	[500, 800, 1200, 1800]:[20, 150, 300, 450, 600] GeV	98	481
VBS-WZ					
SR	$m_T^{WZ} : m_{jj}$	6	[0, 300, 600, 1000]:[500, 1200, 3000] GeV	94	188
VBS-SSWW(τ_h)					
SR	SMEFT DNN score	5	0, 0.264, 0.405, 0.517, 0.608, 1.0	82	1047
VBF-W					
SR	$\Delta\phi_{jj}$	10	uniform, $[0, \pi]$	151	26948
VBF-Z					
SR	$\Delta\phi_{jj} : \text{DNN score}$	25	[0.0, 0.2, 0.4, 0.6, 0.8, 1.0]:[0, 0.38, 0.96, 1.58, 2.29, π]	168	1359831
VBS-WV					
SM DNN $\geq / < 0.5$ SRs	m_{WV}	8	200, 400, 600, 800, 1000, 1200, 1500, 2000, 3000 GeV	216	16835
VBS-ZV					
b-veto+ b-tag SRs	m_{ZV}	12	200, 300, 400, 500, 600, 700, 800, 900, 1000, 1250, 1500, 2000, 2500 GeV	152	2848
VVV/γ					
SR-0 ℓ -2VTJ	$S_T = \sum p_T^j$	5	1100, 1500, 2000, 2500, 3000, 3500 GeV	19	5172
SR-0 ℓ -3VTJ	$S_T = \sum p_T^j$	7	1250, 1500, 1750, 2000, 2250, 2500, 3000, 4000 GeV	19	1706
SR-1 ℓ -1 τ_h -1VTJ	BDT : $S_T = \sum p_T^{\ell,j,\tau}$	3	[low, high]:[< 600, $\geq$ 600]	33	330
SR-1 ℓ -2VTJ	$m_{jj\ell\nu}$	4	0, 1600, 2400, 3400, 4000 GeV	22	885
SR-2 ℓ -1 τ_h -0VTJ	BDT : $S_T = \sum p_T^{\ell,j,\tau}$	3	[low, high]:[< 300, $\geq$ 300]	35	6169
SR-2 ℓ -OS-2VTJ	$S_T = \sum p_T^{j,\ell} + p_T^{\text{miss}}$	3	0, 800, 1900, 10000 GeV	27	25
SR-2 ℓ -OS-1VTJ (OF)	$S_T = \sum p_T^{j,\ell}$	3	200, 800, 1350, 5000 GeV	24	193
SR-2 ℓ -OS-1VTJ (SFnoZ)	$S_T = \sum p_T^{j,\ell}$	3	200, 800, 1300, 5000 GeV	28	2996
SR-2 ℓ -OS-1VTJ (SFZ)	$S_T = \sum p_T^{j,\ell}$	3	200, 800, 1050, 5000 GeV	26	589
SR-2 ℓ -SS-1VTJ	$S_T = \sum p_T^{j,\ell} + p_T^{\text{miss}}$	3	0, 1000, 1600, 2000 GeV	30	71
WW					
0-jet + 1-jet SRs	$m_{\ell\ell}$	5	100, 330, 560, 790, 1020, 1250 GeV	115	85893

reported, as well as the breakdown of such results into the individual contributions of each channel. For each operator, only the sensitive channels are shown. The expected 68% and 95% confidence intervals on the Wilson coefficients are extracted from the scan and reported in Table 4.

In the combined fit, the most constrained coefficient is c_W , which modifies both the triple and quartic gauge couplings; the strongest constraints on c_W originate from the triboson, diboson WW, and VBF channels, where momentum-enhanced effects in the boson transverse momenta increase the sensitivity. The coefficient c_{HD} enters only through corrections to the EW input parameters, rescaling the overall cross sections without affecting the kinematic distributions; it is therefore predominantly constrained by VBF and diboson processes thanks to the higher cross-section. The coefficient c_{HWB} modifies the WW γ and WWZ vertices with a momentum-dependent structure and is similarly best constrained by the VBF and diboson WW channels, which are directly sensitive to the resulting shape distortions. The coefficients $c_{H\Box}$ and c_{HW} modify the HVV couplings and are mainly constrained by the VBS-WV channel, by VBS-SSWW, where a t -channel Higgs boson exchange contributes, and by the triboson channel. The coefficient c_{HB} affects only Higgs couplings to the Z boson and the photon, and is therefore unconstrained by the diboson and VBF channels, being instead set mainly by the VBS and triboson channels, which probe off-shell Higgs contributions.

Fig. 8 and 9 show the observed results, obtained by fitting each of the operators individually to data while fixing all the others to zero. The corresponding expected results, obtained under the SM-only hypothesis, are also shown for reference.

A summary of the expected and observed limits are shown in Fig. 2, together with the fractional contribution of each analysis to the constraint on each Wilson coefficient and with the limits on the energy scale Λ . The observed 68% and 95% CL intervals are reported in Table 4.

For most operators, the one-dimensional sensitivity is dominated by the quadratic SMEFT term, consistent with what is observed in the individual VBS analyses. The exceptions are c_{HWB} and c_{HD} , for which the linear term dominates, driven by the VBF channels.

The ranking of the input channels' fractional contribution f_j^α , shown in the central panel of Fig. 2, also shifts between the linear-only and the linear+quadratic fits. For c_W and c_{HWB} , the linear fit is dominated by the VBF-W and VBF-Z channels, while in the linear+quadratic fit the leading contribution shifts to the diboson WW channel, with the triboson channel also becoming relevant for c_W . For c_{HD} , the VBF channels dominate both fits, with VBF-W alone accounting for most of the linear+quadratic constraint. The VBS-WV channel dominates both fits for c_{HW} , although the linear fit receives a sizeable additional contribution from the VBS-OSWW and VBS-SSWW(e, μ) channels that becomes negligible in the linear+quadratic fit. For c_{HB} , the linear constraint is spread fairly evenly across most channels, whereas the linear+quadratic constraint is almost entirely set by the VBS-WV channel. For $c_{H\Box}$, the VBS-OSWW channel dominates the linear fit, while in the linear+quadratic fit the constraint is shared between the OSWW and VBS-WV channels.

All of the operators are found to be compatible with the SM expectation of zero, within one standard deviation. As observed already with the expected results, the tightest constraint is set on c_W , particularly constrained by the diboson WW, triboson, VBF-W, and VBS-WV analyses. The coefficients c_{HD} and c_{HWB} are predominantly constrained by the VBF and diboson channels, while $c_{H\Box}$ and c_{HW} are primarily constrained by the VBS-WV channel. The coefficient c_{HB} is mainly constrained by the VBS and triboson channels.

The results of the fit performed according to the two-coefficient model of Eq. 6 are reported

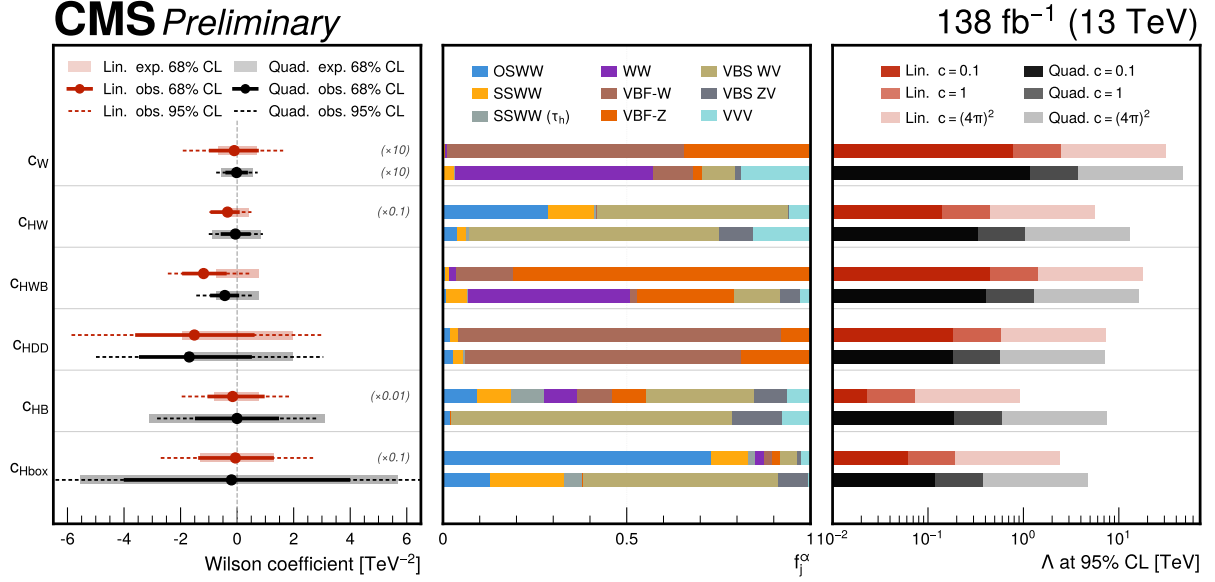


Figure 2: Summary of the expected and observed one-dimensional 68% and 95% CL intervals, considering both linear-only and linear + quadratic SMEFT contributions (left panel). Results for the Wilson coefficient under analysis are obtained by fixing to zero the coefficients of the rest of the operators. The central panel shows the fractional contribution f_j^α of each analysis α to the combined limit on each Wilson coefficient c_j , while the right panel shows the limits on the energy scale Λ .

Table 4: Observed 68% and 95% 1D confidence level (CL) intervals on the Wilson coefficients associated with the SMEFT dim-6 operators considered. All CL are reported for the fits including both linear and quadratic SMEFT components. The results reported here are obtained by fixing the Wilson coefficients other than the one of interest to their SM values in the fit procedure.

Wilson coefficient Lin+Quad	68% CL interval [TeV^{-2}]		95% CL interval [TeV^{-2}]	
	Expected	Observed	Expected	Observed
c_W	$[-0.06, 0.05]$	$[-0.04, 0.04]$	$[-0.09, 0.09]$	$[-0.07, 0.07]$
c_{HW}	$[-0.88, 0.85]$	$[-0.58, 0.48]$	$[-1.31, 1.28]$	$[-0.99, 0.90]$
c_{HWB}	$[-0.72, 0.77]$	$[-0.95, 0.07]$	$[-1.35, 1.49]$	$[-1.42, 0.58]$
c_{HD}	$[-1.85, 1.96]$	$[-3.47, 0.52]$	$[-3.40, 3.71]$	$[-4.93, 2.95]$
$c_{H\Box}$	$[-5.57, 5.68]$	$[-4.01, 4.00]$	$[-8.54, 8.59]$	$[-6.99, 6.96]$
c_{HB}	$[-3.10, 3.10]$	$[-1.49, 1.48]$	$[-4.74, 4.75]$	$[-2.78, 2.77]$

in Fig. 3, where two-dimensional likelihood scans are reported for all possible Wilson coefficient pairings. The two-dimensional contours show the correlation patterns expected between pairs of operators, reflecting the interference structure of the corresponding amplitudes; in general, the contours have an elliptical shape, with their orientation driven by the interference between the operators considered in each pair. Because the one- and two-dimensional confidence regions are defined with a different number of degrees of freedom, their boundaries are not directly comparable.

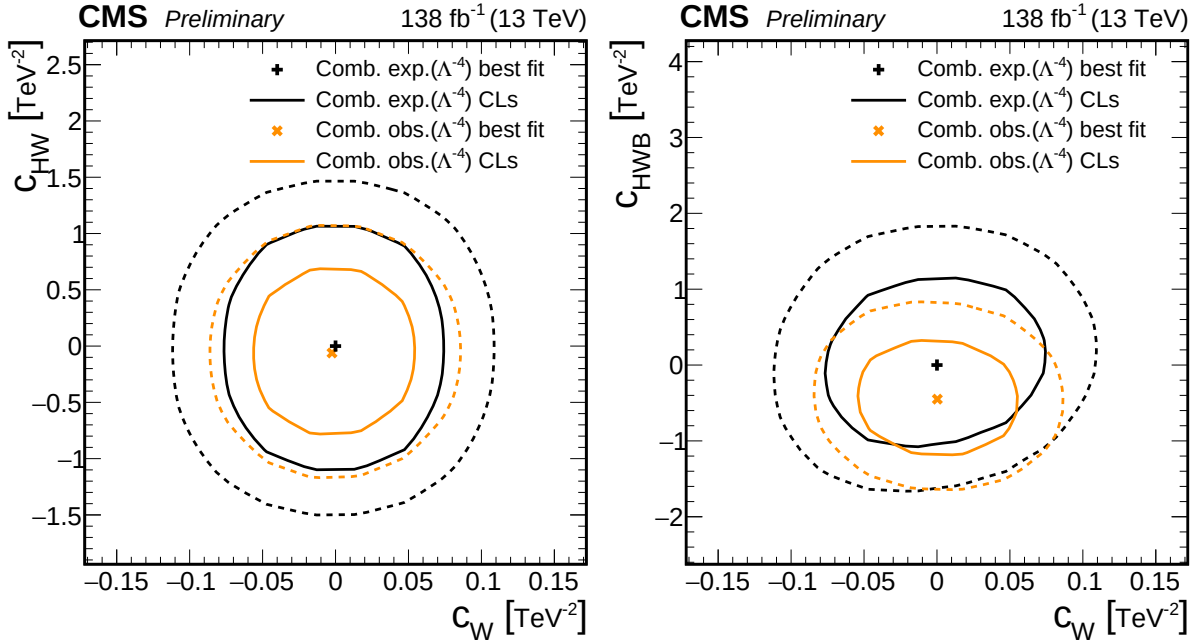


Figure 3: 68% (solid line) and 95% (dashed line) CL contours for $-2\ln\Delta\mathcal{L}$ as functions of the reported dim-6 Wilson coefficient pairs, both expected (black) and observed (orange). All results are obtained by considering the combination of all the channels, fixing the operators not under analysis to zero. A full table showing all pairs of operators is reported in appendix F.

Fig. 4 shows the fully profiled observed combination fits, obtained by leaving all of the operators not under study freely floating, together with all of the nuisance parameters, and considering the contribution of all analyses. Owing to the complexity of these fits, only the observed profiled results are presented; the fits are found to be smooth, stable, and well behaved despite the high dimensionality of the problem. Overall, the profiled and individual likelihood profiles are very similar, consistent with the absence of significant correlations, as already observed in the two-dimensional fits.

9 Summary

A search for physics beyond the standard model is performed in the framework of the standard model effective field theory (SMEFT) through a statistical combination of ten CMS measurements of electroweak (EW) processes. The combination includes vector boson scattering (VBS), vector boson fusion (VBF), diboson, and triboson production, probing final states with one, two, and three EW gauge bosons. The analyses use the full Run 2 proton-proton collision dataset recorded by the CMS experiment at the CERN LHC at $\sqrt{s} = 13\text{TeV}$, corresponding to an integrated luminosity of 138 fb^{-1} . For all measurements, the SMEFT parametrization is propagated directly to detector level through event-by-event reweighting, allowing a consistent

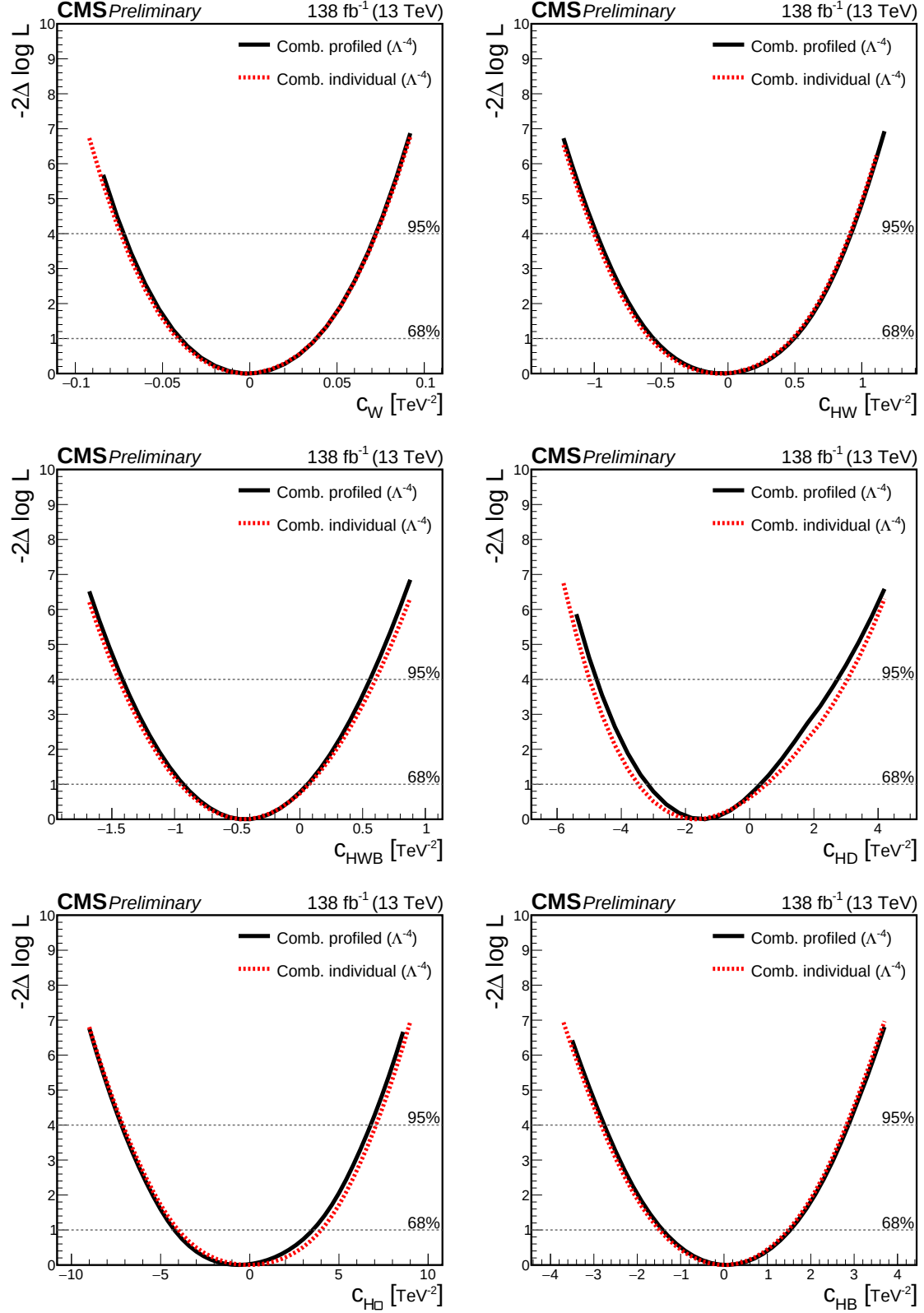


Figure 4: $-2 \ln \Delta \mathcal{L}$ observed scans for the six bosonic operators, fully profiled. The profiled combination fits (solid black line) were performed leaving all of the operators not under study freely floating, as well as all of the nuisance parameters. They are shown in comparison to the individual fit (red dashed line), in which all of the operators not under study are fixed to zero. Horizontal lines represent the 95% and 68% CL.

treatment of detector effects and systematic uncertainties while avoiding the model assumptions required by unfolding. Six Wilson coefficients associated with bosonic dimension-six operators are constrained: c_W , c_{HW} , c_{HWB} , $c_{H\Box}$, c_{HB} , and c_{HD} . Limits are extracted in single-parameter, two-parameter, and global profiling scenarios. The combination significantly improves the sensitivity to all six operators compared with the individual measurements, with no single analysis dominating any constraint. The strongest limit is obtained for c_W , while the remaining coefficients are constrained through complementary sensitivity of the VBS, VBF, diboson, and triboson channels. No evidence for deviations from the standard model is observed. These results provide competitive constraints on bosonic dimension-six operators and constitute the first statistical combination of direct detector-level SMEFT measurements of bosonic operators.

References

- [1] W. Buchmüller and D. Wyler, “Effective lagrangian analysis of new interactions and flavour conservation”, *Nucl. Phys. B* **268** (1986) 621, doi:10.1016/0550-3213(86)90262-2.
- [2] B. Grzadkowski, M. Iskrzyński, M. Misiak, and J. Rosiek, “Dimension-six terms in the Standard Model Lagrangian”, *JHEP* **10** (2010) 085, doi:10.1007/JHEP10(2010)085, arXiv:1008.4884.
- [3] ATLAS Collaboration, “Effective field theory interpretation of ATLAS measurements involving the Higgs boson, electroweak bosons and the top quark”, 2026. arXiv:2604.21670.
- [4] ATLAS Collaboration, “Top EFT summary plots April 2024”, technical report, CERN, Geneva, 2024. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2024-004>.
- [5] R. Covarelli, M. Pellen, and M. Zaro, “Vector-Boson scattering at the LHC: Unraveling the electroweak sector”, *Int. J. Mod. Phys. A* **36** (2021) 2130009, doi:10.1142/S0217751X2130009X, arXiv:2102.10991.
- [6] CMS Collaboration, “Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark, and multijet measurements”, *Eur. Phys. J. C* **86** (2026) 331, doi:10.1140/epjc/s10052-025-14997-y, arXiv:2504.02958.
- [7] R. Bellan et al., “A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC”, *JHEP* **05** (2022) 039, doi:10.1007/JHEP05(2022)039, arXiv:2108.03199.
- [8] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) 8004, doi:10.1088/1748-0221/3/08/S08004.
- [9] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) 10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
- [10] CMS Tracker Group Collaboration, “The CMS phase-1 pixel detector upgrade”, *JINST* **16** (2021) P02027, doi:10.1088/1748-0221/16/02/P02027, arXiv:2012.14304.

- [11] CMS Collaboration, “Track impact parameter resolution for the full pseudo rapidity coverage in the 2017 dataset with the CMS phase-1 pixel detector”, CMS Detector Performance Summary CMS-DP-2020-049, CERN, 2020.
- [12] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [13] CMS Collaboration, “Measurements of production cross sections of WZ and same-sign WW boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **809** (2020) 135710, doi:10.1016/j.physletb.2020.135710, arXiv:2005.01173.
- [14] CMS Collaboration, “Study of same-sign W boson scattering and anomalous couplings in events with one tau lepton from pp collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **10** (2025) 219, doi:10.1007/JHEP10(2025)219, arXiv:2410.04210.
- [15] CMS Collaboration, “Observation of electroweak $W+W-$ pair production in association with two jets in proton-proton collisions at $s=13\text{TeV}$ ”, *Phys. Lett. B* **841** (2023) 137495, doi:10.1016/j.physletb.2022.137495, arXiv:2205.05711.
- [16] CMS Collaboration, “Evidence for WW/WZ vector boson scattering in the decay channel $\ell\nu qq$ produced in association with two jets in proton-proton collisions at $s=13\text{TeV}$ ”, *Phys. Lett. B* **834** (2022) 137438, doi:10.1016/j.physletb.2022.137438, arXiv:2112.05259.
- [17] CMS Collaboration, “Vector boson scattering and anomalous quartic couplings in final states with $\ell\nu qq$ or $\ell\ell qq$ plus jets using proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **03** (2026) 022, doi:10.1007/JHEP03(2026)022, arXiv:2510.00118.
- [18] CMS Collaboration, “Measurement of electroweak production of a W boson and two forward jets in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **11** (2016) 147, doi:10.1007/JHEP11(2016)147, arXiv:1607.06975.
- [19] CMS Collaboration, “Electroweak production of two jets in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **78** (2018) 589, doi:10.1140/epjc/s10052-018-6049-9, arXiv:1712.09814.
- [20] CMS Collaboration, “ W^+W^- boson pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. D* **102** (2020) 092001, doi:10.1103/PhysRevD.102.092001, arXiv:2009.00119.
- [21] CMS Collaboration, “Search for new physics in triple boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV using the effective field theory approach”, 2026. arXiv:2605.15023.
- [22] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [23] I. Brivio, “SMEFTsim 3.0 — a practical guide”, *JHEP* **04** (2021) 073, doi:10.1007/JHEP04(2021)073, arXiv:2012.11343.
- [24] I. Brivio, Y. Jiang, and M. Trott, “The SMEFTsim package, theory and tools”, *JHEP* **12** (2017) 070, doi:10.1007/JHEP12(2017)070, arXiv:1709.06492.

-
- [25] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, “Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations”, *JHEP* **03** (2013) 015, doi:10.1007/JHEP03(2013)015, arXiv:1212.3460.
- [26] P. Nason, “A New method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [27] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [28] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [29] C. Bierlich et al., “A comprehensive guide to the physics and usage of PYTHIA 8.3”, *SciPost Phys. Codeb.* **2022** (2022) 8, doi:10.21468/SciPostPhysCodeb.8, arXiv:2203.11601.
- [30] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [31] S. Bolognesi et al., “On the Spin and Parity of a Single-Produced Resonance at the LHC”, *Phys. Rev. D* **86** (2012) 095031, doi:10.1103/PhysRevD.86.095031, arXiv:1208.4018.
- [32] K. Hamilton, P. Nason, and G. Zanderighi, “Finite quark-mass effects in the NNLOPS POWHEG+MiNLO Higgs generator”, *JHEP* **05** (2015) 140, doi:10.1007/JHEP05(2015)140, arXiv:1501.04637.
- [33] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [34] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [35] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [36] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [37] ATLAS and CMS Collaborations, and the LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in summer 2011”, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, CERN, 2011.
- [38] ATLAS, CMS Collaboration, “Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV”, *JHEP* **08** (2016) 045, doi:10.1007/JHEP08(2016)045, arXiv:1606.02266.

- [39] CMS Collaboration, “The CMS statistical analysis and combination tool: COMBINE”, 2024. arXiv:2404.06614. Submitted to *Comput. Softw. Big Sci.*
- [40] W. Verkerke and D. P. Kirkby, “The RooFit toolkit for data modeling”, 2003. arXiv:physics/0306116.
- [41] L. Moneta et al., “The RooStats Project”, 2010. arXiv:1009.1003. doi:10.22323/1.093.0057.
- [42] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [43] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, CERN, 2018.
- [44] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, CERN, 2019.
- [45] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [46] CMS Collaboration, “Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.
- [47] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [48] CMS Collaboration, “Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.
- [49] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
- [50] D. L. Rainwater, R. Szalapski, and D. Zeppenfeld, “Probing color singlet exchange in $Z +$ two jet events at the CERN LHC”, *Phys. Rev. D* **54** (1996) 6680, doi:10.1103/PhysRevD.54.6680, arXiv:hep-ph/9605444.
- [51] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [52] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [53] CMS Collaboration, “Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **81** (2021) 378, doi:10.1140/epjc/s10052-021-09014-x, arXiv:2011.03652.

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- [54] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [55] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [56] D. Bertolini, P. Harris, M. Low, and N. Tran, “Pileup per particle identification”, *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.
- [57] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.
- [58] E. Bols et al., “Jet Flavour Classification Using DeepJet”, *JINST* **15** (2020) P12012, doi:10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.
- [59] CMS Collaboration, “Performance of the DeepJet b tagging algorithm using 41.9 fb⁻¹ of data from proton-proton collisions at 13 TeV with Phase 1 CMS detector”, CMS Detector Performance Summary CMS-DP-2018-058, CERN, 2018.
- [60] P. F. Monni et al., “MiNNLO_{PS}: a new method to match NNLO QCD to parton showers”, *JHEP* **05** (2020) 143, doi:10.1007/JHEP05(2020)143, arXiv:1908.06987. [Erratum: doi:10.1007/JHEP02(2022)031].
- [61] P. F. Monni, E. Re, and M. Wiesemann, “MiNNLO_{PS}: optimizing 2 → 1 hadronic processes”, *Eur. Phys. J. C* **80** (2020) 1075, doi:10.1140/epjc/s10052-020-08658-5, arXiv:2006.04133.
- [62] M. Grazzini et al., “NNLO QCD + NLO EW with Matrix+OpenLoops: precise predictions for vector-boson pair production”, *JHEP* **02** (2020) 087, doi:10.1007/JHEP02(2020)087, arXiv:1912.00068.
- [63] M. Grazzini, S. Kallweit, and M. Wiesemann, “Fully differential NNLO computations with MATRIX”, *Eur. Phys. J. C* **78** (2018) 537, doi:10.1140/epjc/s10052-018-5771-7, arXiv:1711.06631.
- [64] J. M. Campbell and R. K. Ellis, “MCFM for the Tevatron and the LHC”, *Nucl. Phys. B Proc. Suppl.* **205-206** (2010) 10, doi:10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.
- [65] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.

A Diboson W^+W^-

The diboson W^+W^- analysis targets leptonic W boson decays, $W^+W^- \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$ with $\ell = e, \mu$. The background composition depends strongly on the lepton-flavour final state: same-flavour events ($ee, \mu\mu$) are dominated by Drell–Yan production, while different-flavour events ($e\mu$) are dominated by top-quark processes. To maximize sensitivity to SMEFT effects, only the different-flavour ($e\mu$) category is considered, further split by jet multiplicity ($N_{\text{jets}} = 0, 1$). The analysis uses the full 2016–2018 CMS dataset, corresponding to an integrated luminosity of 138 fb^{-1} .

Events are preselected using single-lepton or dilepton triggers, requiring at least one isolated electron or muon, or two isolated leptons (electrons and/or muons), respectively.

Leptons are further selected offline using tight MVA-based identification [51–53] and isolation criteria, together with track-based constraints consistent with the primary vertex.

Jets are reconstructed with the anti- k_T [54, 55] algorithm using a distance parameter of $R = 0.4$, and are required to satisfy $p_T^j > 30 \text{ GeV}$ and $|\eta^j| < 4.7$. The p_T^{miss} is computed with the PUPPI algorithm [56, 57]. Jets from b quark fragmentation are identified among jets with $p_T^j > 30 \text{ GeV}$ and $|\eta^j| < 2.5$, using the medium working point of the DeepJet algorithm [58, 59].

The leading and subleading leptons are required to have opposite charge and flavour, with $p_T > 25$ and 20 GeV , respectively. Events with an additional lepton satisfying loose identification and $p_T > 10 \text{ GeV}$ are rejected to suppress other diboson backgrounds. $p_T^{\text{miss}} > 20 \text{ GeV}$ is required to account for the undetected neutrinos. Contributions from nonprompt leptons are suppressed by requiring $p_T^{\ell\ell} > 30 \text{ GeV}$ and $m_{\ell\ell} > 20 \text{ GeV}$.

Two regions are defined: a signal region, enriched in electroweak W^+W^- production by vetoing b-tagged jets with $p_T > 20 \text{ GeV}$ and requiring $m_T^{W^+W^-} > 60 \text{ GeV}$ and $m_T^{W^2} > 30 \text{ GeV}$ (the transverse mass built from the subleading- p_T lepton); and a $t\bar{t}$ -enriched control region, used to constrain its normalization from data, requiring $m_{\ell\ell} > 50 \text{ GeV}$, $m_T^{W^2} > 30 \text{ GeV}$, and at least one b-tagged jet.

All SM backgrounds and the W^+W^- signal are simulated, except for nonprompt leptons, which mainly arise from W +jets events where a jet is misidentified as the second lepton. These are estimated with a data-driven fake-rate method [20]: misidentification and prompt rates, measured in multijet and Drell–Yan control samples and parametrized in lepton p_T and η , define a transfer factor applied to a loose-lepton data sample to predict the nonprompt contribution passing the tight selection. The quark-induced W^+W^- production is simulated with POWHEG v2.0 at next-to-NLO accuracy in QCD using the MiNNLO_{PS} method [60, 61], with higher-order EW corrections computed at NLO with MATRIX v2.1.0 [62, 63]; a shape-only correction in p_T^{WW} is applied to the MiNNLO_{PS} sample. The non-resonant gluon-induced W^+W^- production, treated as part of the signal, is modelled with MCFM v7.0 [64]. The dominant top-induced backgrounds ($t\bar{t}$, tW , and t -channel single top quark) are simulated with POWHEG v2.0 at NLO in QCD, with top quark decays modelled by MADSPIN; the s -channel single top contribution is generated with MADGRAPH5_aMC@NLO v2.6.5 at NLO in QCD. Drell–Yan production enters the different-flavour region mainly via residual $Z \rightarrow \tau^+\tau^-$ decays and is generated at NLO in QCD with MADGRAPH5_aMC@NLO with up to two additional partons. Remaining minor backgrounds (diboson and triboson EW production, and Higgs-mediated resonant W^+W^- production) are generated with either MADGRAPH5_aMC@NLO or POWHEG.

Among the six dimension-six operators considered in the combination, the diboson W^+W^-

channel is sensitive only to $\mathcal{O}_W$ and $\mathcal{O}_{\text{HWB}}$, with subleading sensitivity to $\mathcal{O}_{\text{HD}}$ that is neglected, as this operator is expected to be more strongly constrained by the VBF channels (Section B). Detector-level parametrizations are derived by interfacing SMEFTSIM predictions at LO in QCD with PYTHIA and GEANT4 in a full CMS simulation, including only SMEFT contributions to the production and decay of the quark-induced W^+W^- process. Since a LO sample is used, two additional uncertainties are included: a normalization uncertainty from comparing the SMEFTSIM SM prediction with MINNLO_{PS}, and a shape uncertainty accounting for the known LO mismodelling of p_T^{WW} . Uncorrelated between the 0- and 1-jet regions, these constitute the dominant uncertainty in the measurement of the Wilson coefficients.

The dilepton invariant mass $m_{\ell\ell}$ is used as the observable to constrain SMEFT effects, binned as [100, 330, 560, 790, 1020, ∞] GeV. This choice is motivated by its sensitivity to shape operators in the high-mass tail and its small correlation with the poorly modelled p_T^{WW} .

Figure 5 shows the post-fit distributions of the final discriminants in the signal regions of the W^+W^- analysis.

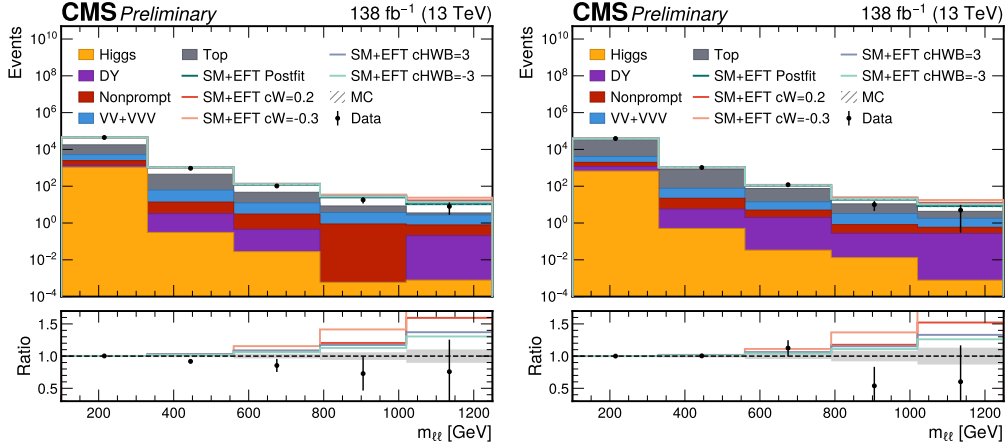


Figure 5: Distributions of the dilepton invariant mass $m_{\ell\ell}$ used to extract the SMEFT signal in the W^+W^- analysis. Left: the $m_{\ell\ell}$ distribution in the 0-jet signal region after the combined fit. Right: the $m_{\ell\ell}$ distribution in the 1-jet signal region after the combined fit. The lower panels show the ratio to the best-fit prediction. Different SMEFT scenarios, each corresponding to a distinct value of a Wilson coefficient, are shown as solid coloured lines.

B VBF analyses

The VBF-W and VBF-Z analyses target the electroweak production of a single massive vector boson in association with two jets, where the boson decays leptonically. These processes provide complementary sensitivity to the bosonic SMEFT operators considered in this combination, in particular to c_{HD} , c_{HWB} , and c_W . Their characteristic topology consists of two energetic jets with large invariant mass and large pseudorapidity separation, together with a centrally produced massive vector boson.

Events are reconstructed using the CMS particle-flow algorithm [36]. Electrons and muons are required to satisfy identification and isolation criteria optimized for high-purity prompt-lepton selection [51, 52]. Jets are reconstructed with the anti- k_T algorithm and are corrected for detector response, pileup contamination, and residual data-to-simulation differences [47, 57]. Missing transverse momentum [65] is used in the VBF-W analysis to reconstruct the leptonic W boson decay, while the VBF-Z analysis uses a pair of opposite electric charge, same-flavour leptons compatible with the Z boson mass. Events containing additional leptons or b-tagged jets [45, 58, 59] are rejected in order to suppress diboson and top-quark backgrounds.

The VBF-W analysis selects events with exactly one isolated electron or muon, significant missing transverse momentum, and at least two jets. The two leading jets are required to satisfy VBF-like requirements on their invariant mass and pseudorapidity separation. Additional selections on the lepton kinematics, the transverse mass of the W boson, and the event topology are applied to reduce the dominant W+jets and top-quark backgrounds. A Deep Neural Network (DNN) is used to enhance the separation between the electroweak VBF-W signal and the dominant backgrounds. The signal-enriched region is defined by requiring the DNN output to be larger than 0.5, and the azimuthal separation between the two tagging jets, $\Delta\phi_{jj}$, is used as the final discriminating observable in the fit. Dedicated control regions enriched in W+jets and top-quark events are included in the likelihood to constrain the corresponding background normalizations in data.

The VBF-Z analysis selects events with two isolated, oppositely charged electrons or muons and at least two jets with high pseudorapidity separation and high invariant mass. A DNN is trained to separate the SM signal from the background, which is dominated by DY+jets production. The $\Delta\phi_{jj}$ distribution is found to be the observable most sensitive to SMEFT contributions relative to the SM VBF signal. To maximize sensitivity to the SMEFT signal while suppressing the SM background, the $\Delta\phi_{jj}$ distribution is therefore fit within windows of the DNN score.

The selected signal and control regions are combined in a simultaneous binned maximum-likelihood fit. The observables entering the fit are chosen to maximise the discrimination between the electroweak signal and the dominant backgrounds while retaining sensitivity to possible SMEFT-induced deviations from the Standard Model. Figure 6 shows the post-fit distributions of the final discriminants in the signal regions of the VBF-W and VBF-Z analyses.

The dominant systematic uncertainties arise from the modelling of the V+jets background, renormalisation and factorisation scale variations, PDFs, jet energy scale and resolution. These uncertainties are propagated to the final discriminant distributions and included in the likelihood fit as nuisance parameters.

The VBF channels are particularly important in the combined SMEFT interpretation because of their large signal yields and their direct sensitivity to modifications of electroweak input-parameter relations. As a result, they provide some of the strongest constraints on c_{HD} and c_{HWB} , while also contributing to the sensitivity to c_W through momentum-enhanced effects in the VBF phase space.

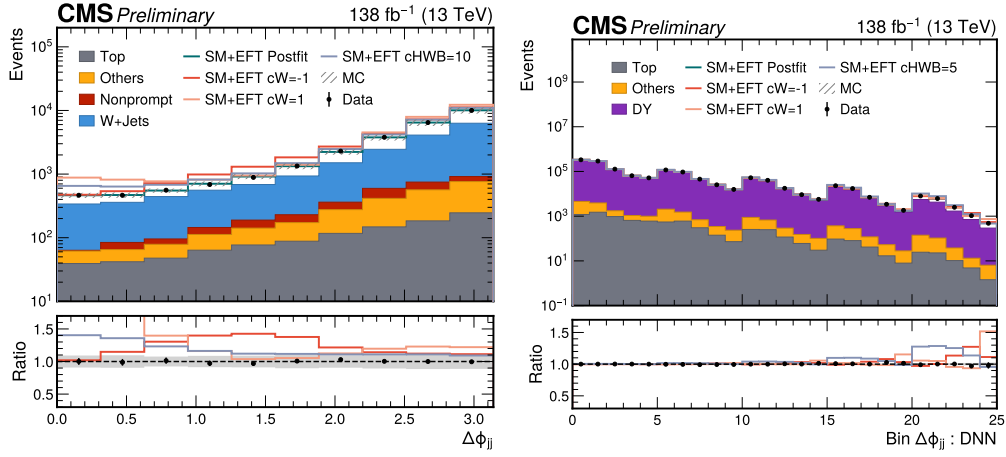


Figure 6: Distributions of the observables used to extract the SMEFT signal in the VBF analyses. Left: the $\Delta\phi_{jj}$ distribution in the VBF-W signal region after the combined fit. Right: the $\Delta\phi_{jj}$ distribution in windows of DNN score used to discriminate the VBF signal from the SM backgrounds in the VBF-Z analysis. The lower panels show the ratio to the best-fit prediction. Different SMEFT scenarios, each corresponding to a distinct value of a Wilson coefficient, are shown as solid coloured lines.

C VBS-SSWW(e, μ), WZ, and OSWW analyses

The VBS-SSWW(e, μ), -WZ, and -OSWW analyses target the production of a pair of massive vector bosons in association with two jets. Only leptonic decays of the Z and W to e and μ and the associated neutrinos are considered. They provide sensitivity to a wide range of the SMEFT operators considered, namely $c_W, c_{HW}, c_{HWB}, c_{HD}$ and $c_{H\Box}$ for SSWW and WZ and $c_W, c_{HW}, c_{HWB}, c_{HD}, c_{H\Box}$ and c_{HB} for OSWW. Such studies are SMEFT reinterpretations of Run-2 CMS results [13] and [15]. The analysis strategy here employed follows closely that of the public results, with few notable exceptions. In particular, the SMEFT reinterpretations employ a tighter lepton ID strategy based on a multivariate analysis, which grants better discrimination against fake leptons.

Similarly to the VBF analyses described in section B, the VBS analyses use most up-to-date reconstruction for 2016–2018, which provides improved and consistent detector calibrations and object reconstruction across the data-taking period. Events are reconstructed using the CMS particle-flow algorithm [36]. Electrons and muons are required to satisfy identification and isolation criteria optimized for high-purity prompt-lepton selection [51, 52]. Jets are reconstructed with the anti- k_T algorithm and are corrected for detector response, pileup contamination, and residual data-to-simulation differences [47, 57]. Missing transverse momentum [65] is used in to reconstruct the leptonic W boson decay. Events containing additional leptons or b-tagged jets [45, 58, 59] are rejected in order to suppress top-quark backgrounds in the SSWW and WZ analyses. A veto on τ particles is employed in the SSWW analysis[46].

To isolate the signal-enriched phase space, the analyses employ a set of kinematic selections on the final state objects. All the three analyses require the presence of at least two jets, with high invariant mass (m_{jj}) and high pseudorapidity separation, and the presence of missing transverse energy due to the presence of neutrinos from the W boson. Furthermore, the VBS SSWW signal region is designed to select a pair of same-sign leptons (e or μ), while OSWW requires two opposite electric charge, opposite flavour leptons (e and μ). To increase sensitivity, the 2018 and 2017 OSWW signal region is further divided into two subcategories based on the dilepton system centrality with respect to the tagging jets. For 2016 data, due to the lower statistics, events are considered into a single category due to the lack of statistics. The VBS WZ analysis, on the other hand, requires three leptons, two of which must be of opposite electric charge and same flavour.

Backgrounds are estimated using a combination of simulation and data-driven techniques. The main background contribution for SSWW stems from nonprompt leptons, which are estimated through data-driven techniques. For WZ, the main contributions come from QCD-induced WZ production, estimated through MC simulation, and from the $tV + q$ background, constrained in a dedicated control region. The main background to OSWW arises from top-quark pair production, where both top quarks decay leptonically. This background is normalized using a dedicated control region. The same strategy is used to constrain also the DY process, which represents a subdominant background contribution. All other background processes are estimated through MC simulations.

The statistical analysis is performed using a binned maximum likelihood fit to the distribution of meaningful kinematic variables, and systematic uncertainties are incorporated as nuisance parameters. In particular, for SSWW a bidimensional combination of the invariant mass of the two leading jets (m_{jj}) and the invariant mass of the dilepton system ($m_{\ell\ell}$) is used. For WZ, the transverse mass of the WZ system is used, combined with m_{jj} . For OSWW, the invariant mass of the di-jet system m_{jj} is used. Such variables are displayed in Figure 7.

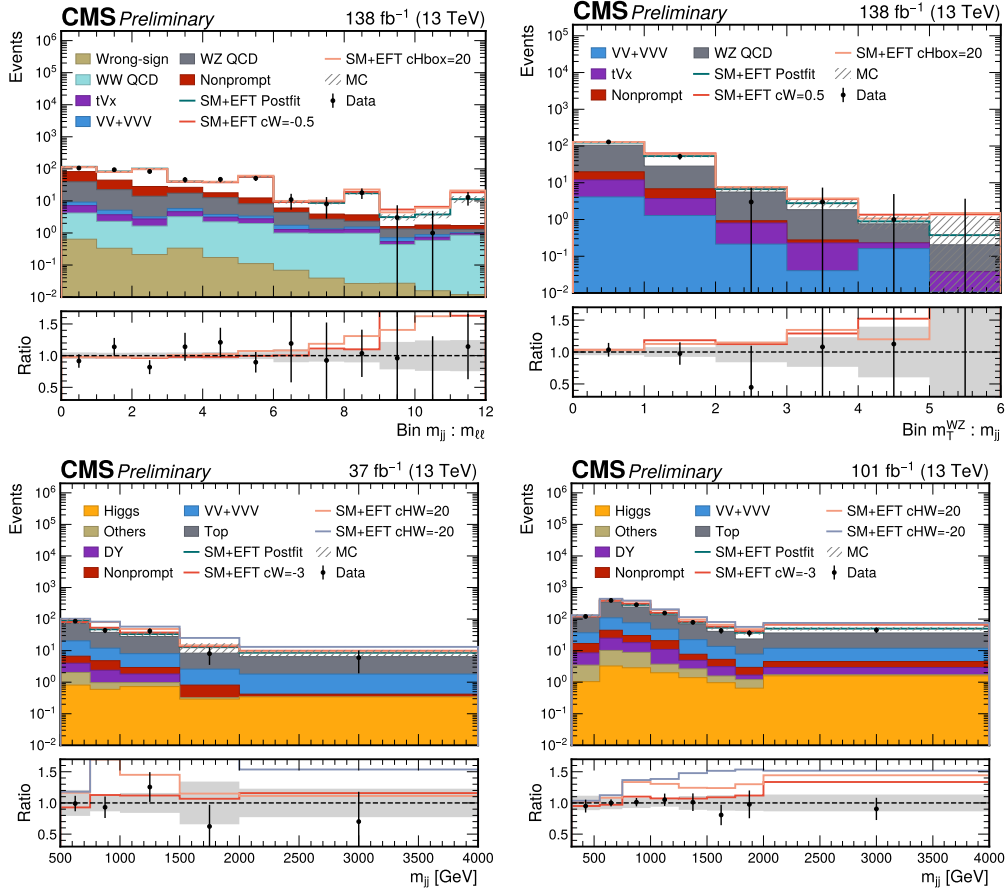


Figure 7: Distributions of the observables used to extract the SMEFT signal in the SSWW, WZ and OSWW analyses. Top left: the m_{jj} distribution in windows of $m_{\ell\ell}$ in the SSWW signal region, after the combined fit. Top right: the m_T^{WZ} distribution in windows of m_{jj} in the WZ signal region, after the combined fit. Bottom: the m_{jj} distribution in the OSWW signal region, for the 2016 data taking period (left) and 2017 and 2018 (right). The lower panels of each plot show the ratio to the best-fit prediction. Different SMEFT scenarios, each corresponding to a distinct value of a Wilson coefficient, are shown as solid coloured lines.

D Monte Carlo samples generation commands

Table 5 shows the MADGRAPH5_aMC@NLO commands used to generate the SM components of the processes of interest.

Table 5: MADGRAPH5_aMC@NLO commands for generating SM components of the processes of interest. Where relevant, charge conjugate processes were included. The shortcut l^- stands for electron, muon, or tau lepton.

Process	Interaction	Command
VBS-SSWW(e, μ) VBS-SSWW(τ_h)	EW	generate p p > l+ vl l+ vl j j SMHLOOP=0 QCD=0 add process p p > l- vl l- vl j j SMHLOOP=0 QCD=0
VBS-OSWW	EW	generate p p > e+ ve mu- vm j j SMHLOOP=0 QCD=0 add process p p > e- ve mu+ vm j j SMHLOOP=0 QCD=0
VBS-WZ	EW	generate p p > w+ z j j SMHLOOP=0 QCD=0 NP=1 Decays: (w+ > l+ vl, z > l+ l- w/madspin) add process p p > w- z j j SMHLOOP=0 QCD=0 NP=1 Decays: (w- > l- vl, z > l+ l- w/madspin)
VBS-WV	EW	generate p p > l+ vl j j j j NP=1 SMHLOOP=0 QCD=0 add process p p > l- vl j j j j NP=1 SMHLOOP=0 QCD=0
VBS-ZV	EW	generate p p > w+ z j j NP=1 SMHLOOP=0 QCD=0 Decays: (z > l+ l-, w+ > j j w/madspin) generate p p > w- z j j NP=1 SMHLOOP=0 QCD=0 Decays: (z > l+ l-, w- > j j w/madspin) generate p p > z z j j NP=1 SMHLOOP=0 QCD=0 Decays: (z > l+ l-, z > j j w/madspin)
VBF-W	EW	generate p p > l+ vl j j SMHLOOP=0 QCD=0 add process p p > l- vl j j SMHLOOP=0 QCD=0
VBF-Z	EW	generate p p > l+ l- j j SMHLOOP=0 QCD=0
WW	EW	generate p p > l+ vl l- vl SMHLOOP=0 QCD=0
VVV/g	EW QCD	generate p p > v v v \$ t t~ add process p p > v v v j \$ t t~

E Likelihood Scans profiles

Figures 8 and 9 show the likelihood scans for the six bosonic operators considered in this combination, obtained by fixing all of the other operators to their SM values.

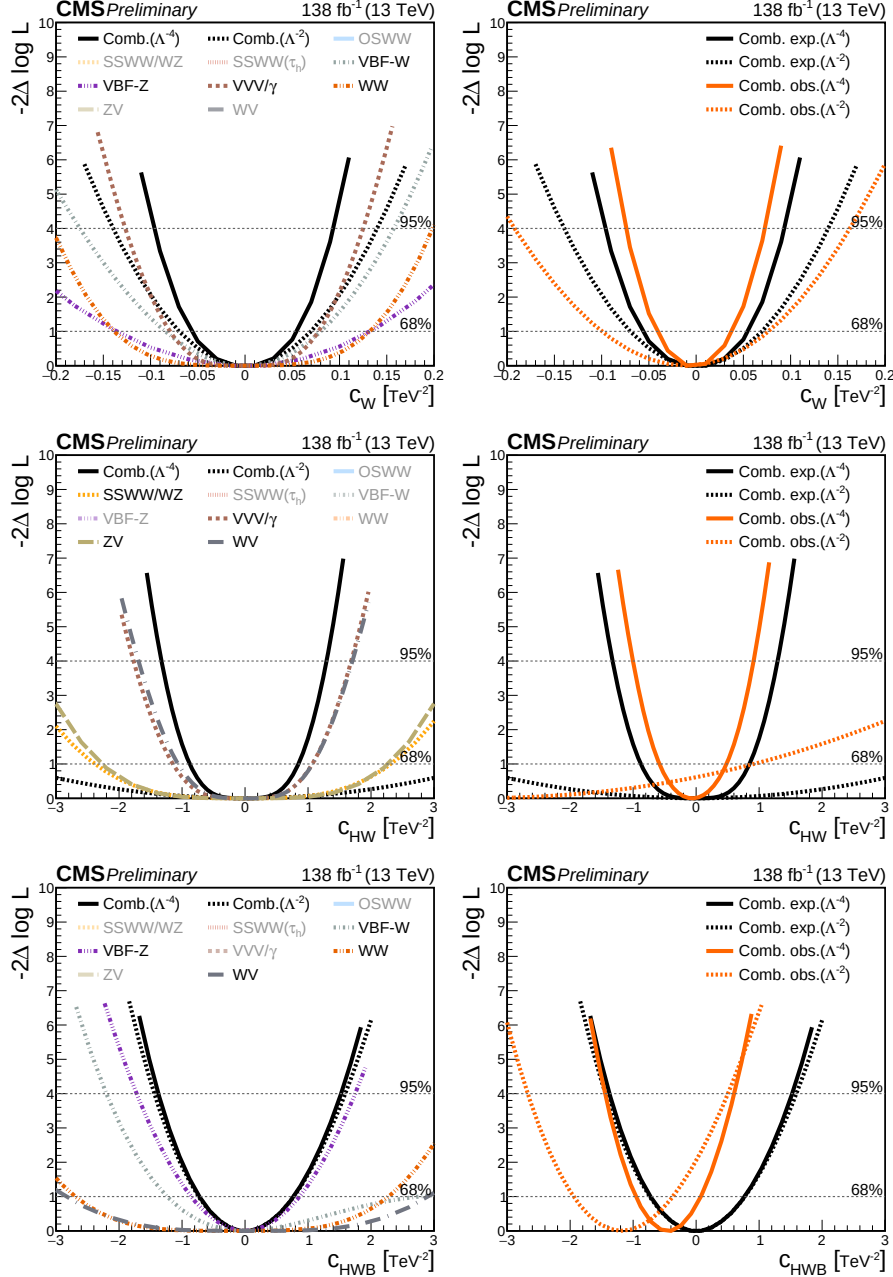


Figure 8: $-2\ln\Delta\mathcal{L}$ profiles for individual bosonic operators. On the left, the combined fits (black solid line) are compared to the individual fits in each channel (colored lines). Only the likelihood scans of the most sensitive channels are shown. On the right, the observed fits (orange lines) are compared to the expected fits (black lines), both considering the linear+quadratic (solid) and linear (dashed) SMEFT contributions. Horizontal lines represent the 95% and 68% CL. Results for the Wilson coefficient under analysis are obtained by fixing to zero the coefficients of the rest of the operators.

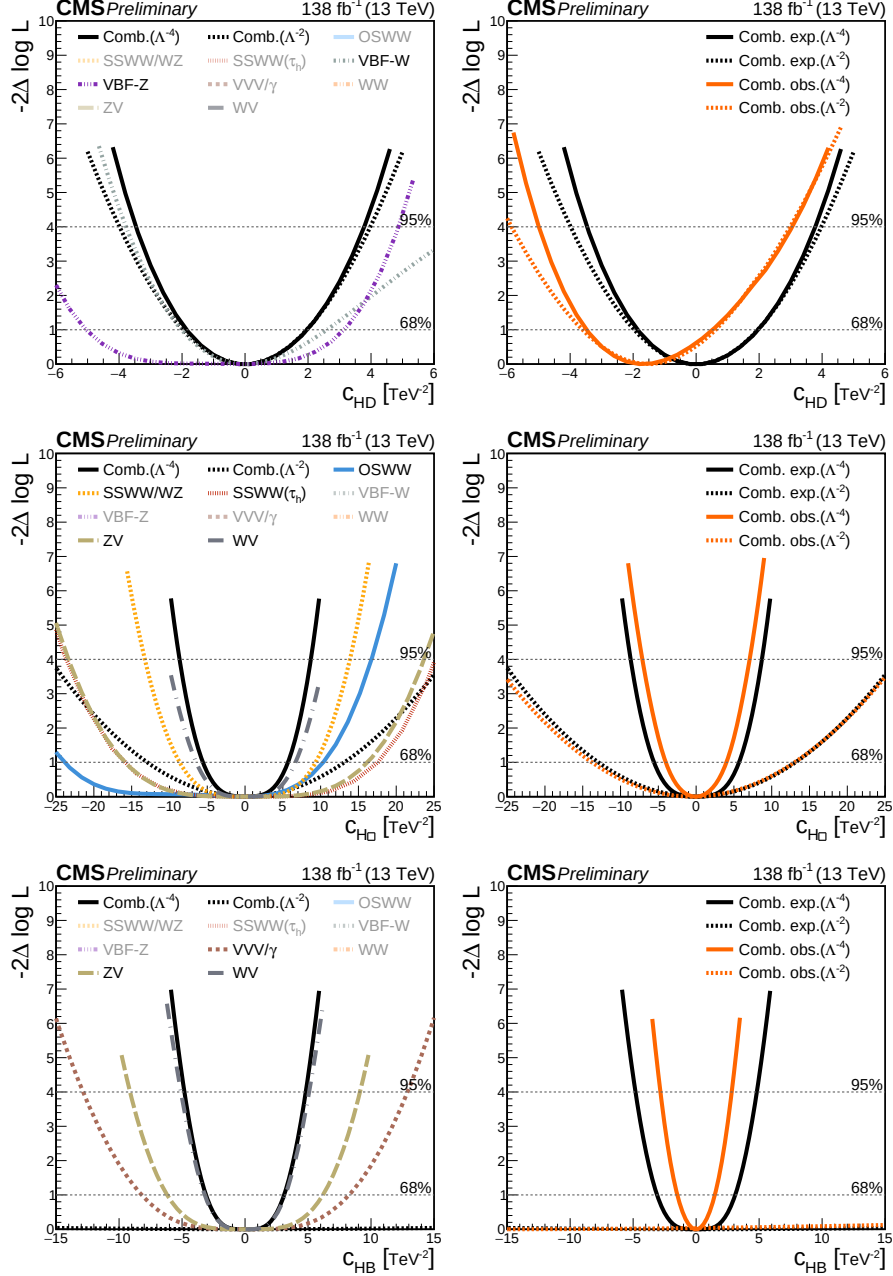


Figure 9: $-2 \ln \Delta \mathcal{L}$ profiles for individual bosonic operators. On the left, the combined fits (black solid line) are compared to the individual fits in each channel (colored lines). Only the likelihood scans of the most sensitive channels are shown. On the right, the observed fits (orange lines) are compared to the expected fits (black lines), both considering the linear+quadratic (solid) and linear (dashed) SMEFT contributions. Horizontal lines represent the 95% and 68% CL. Results for the Wilson coefficient under analysis are obtained by fixing to zero the coefficients of the rest of the operators.

F Two-dimensional likelihood scans

Figure 10 shows the two-dimensional likelihood scans for all possible pairs of Wilson coefficients, obtained by fixing all of the other operators to their SM values. The expected and observed 68% and 95% CL contours are reported for each pair of operators.

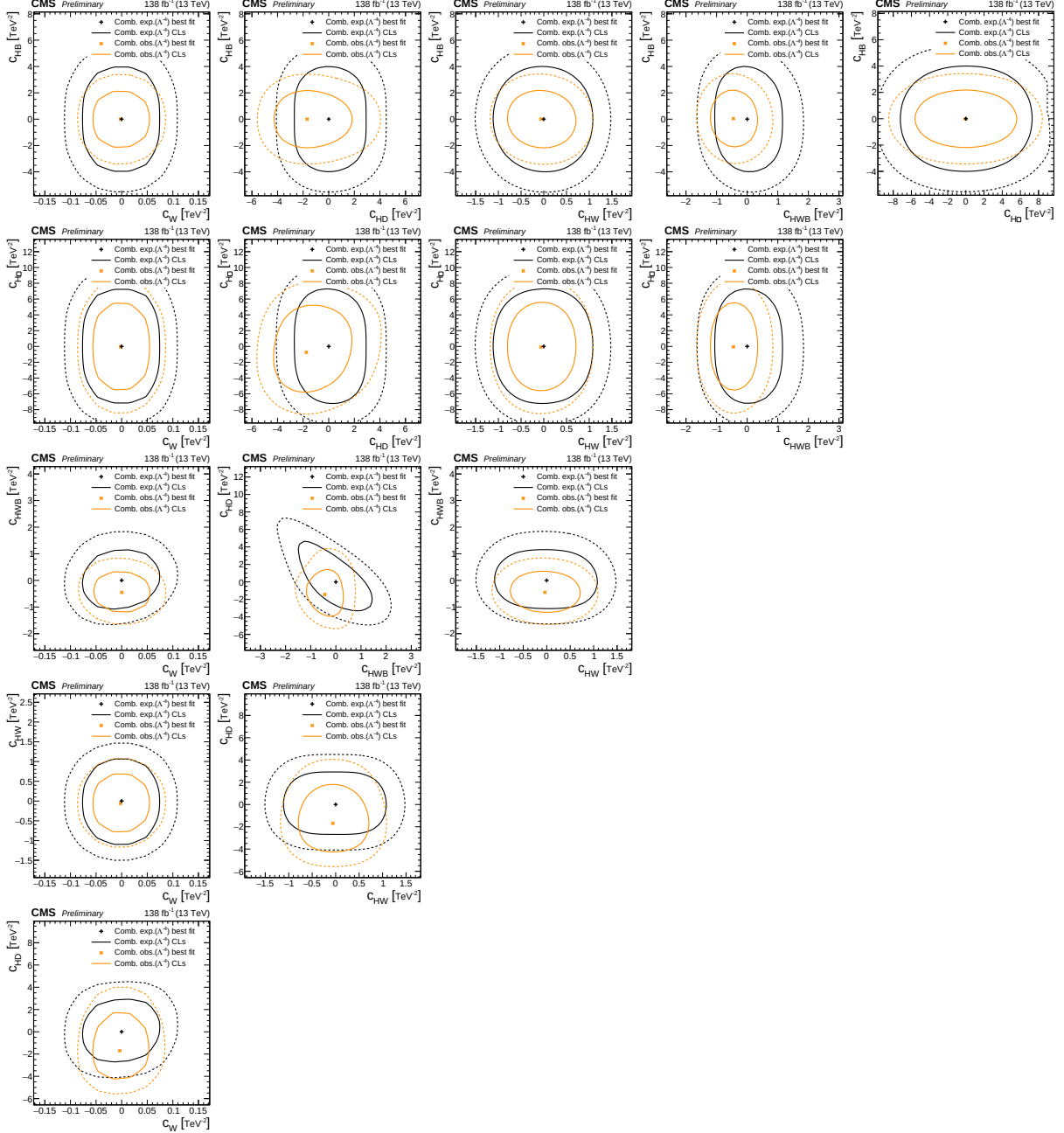


Figure 10: 68% (solid line) and 95% (dashed line) CL contours for $-2 \ln \Delta \mathcal{L}$ as functions of the reported dim-6 Wilson coefficient pairs. Expected results are reported in black, while observed ones are reported in orange. All results are obtained by considering the combination of all the channels, fixing the operators not under analysis to zero.