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Indirect Probes of Electroweak Interactions in the Top-Quark Sector: Recent SMEFT Results from CMS

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Abstract: The absence of direct evidence for new particles at the LHC has shifted the emphasis of the experimental program toward precision measurements as indirect probes of new interactions. The top-quark sector provides a particularly sensitive laboratory within the Standard Model Effective Field Theory (SMEFT) framework. This article reviews three recent CMS results that constrain electroweak interactions of the top quark: a search for CP violation in associated $t\bar{t}Z$ and tZq production using CP-odd observables, a multilepton measurement probing the flavor structure of electroweak SMEFT couplings, and a Run 2 statistical combination of complementary top+X analyses. Their interpretation is discussed with explicit attention to EFT truncation, interference versus quadratic contributions, and the role of dimension-eight effects. Prospects for global SMEFT interpretations at the High-Luminosity LHC are examined.

Keywords: top quark; SMEFT; electroweak interactions; CP violation; multilepton final states; High-Luminosity LHC

1. Introduction

Effective field theories (EFTs) provide low-energy descriptions of physical systems when the relevant heavy degrees of freedom are not resolved explicitly. Familiar examples in high-energy physics include Fermi's theory of weak interactions, chiral effective theory for hadronic processes, and low-energy effective descriptions below the electroweak scale [1,2]. At the LHC, when new degrees of freedom are assumed to lie above the energies directly probed, the natural framework is the Standard Model Effective Field Theory (SMEFT), which extends the Standard Model (SM) using operators built from SM fields and respecting the SM gauge symmetries [3–5]. The present article focuses on the experimental interpretation of recent CMS results; broader theoretical foundations, operator constructions, and EFT-systematics details are described in the references cited above and in the review-oriented references added in Section 6.

In the SMEFT framework, the effective Lagrangian is written as

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \mathcal{O}\left(\frac{1}{\Lambda^6}\right). \quad (1)$$

Equation (1) makes explicit that dimension-six and dimension-eight operators appear at successive orders in the $1/\Lambda$ expansion. In practice, most experimental analyses in the top-quark sector truncate the expansion at dimension six. This choice reflects a pragmatic compromise: dimension-six operators capture the leading phenomenological deviations while preserving interpretability in a manageable parameter space; including a general dimension-eight basis would substantially enlarge the fit space and dilute the connection to concrete experimental observables.

The top quark plays a central role in this program. Owing to its large mass and sizable Yukawa coupling, it is particularly sensitive to modifications of electroweak symmetry breaking dynamics and gauge interactions. In addition, processes involving top quarks in association with electroweak bosons probe third-generation gauge couplings directly and complement constraints derived from Higgs and diboson measurements. A coherent SMEFT strategy therefore relies on a portfolio of measurements with different sensitivity patterns, acceptance, and dominant systematic uncertainties.

This article reviews three recent CMS results that illustrate complementary components of this strategy. Its purpose is to present the experimental results in a unified way and to discuss their broader interpretation within the SMEFT framework. First, a CP-violation search in $t\bar{t}Z$ and tZq production employs CP-odd observables designed to isolate the interference between SM and CP-odd SMEFT amplitudes. Second, a multilepton measurement constrains the flavor structure of electroweak SMEFT couplings by combining sensitivity from top-associated and diboson production. Third, a Run 2 multi-channel combination demonstrates the gains achievable through unified likelihood interpretations across heterogeneous final states. Beyond summarizing these results, I discuss how they should be interpreted in view of EFT truncation, including the interplay between linear and quadratic terms, the potential impact of dimension-eight effects, and the role of high-energy tails.

2. SMEFT Framework and Interpretation Strategy

At fixed order in the EFT expansion, the dependence of an observable on Wilson coefficients, i.e., the numerical coefficients multiplying the higher-dimensional operators in Equation (1), is polynomial. For inclusive cross sections or binned differential distributions, one may write schematically

$$\sigma = \sigma_{\mathrm{SM}} + \sum_i c_i\, \sigma_i^{\mathrm{int}} + \sum_{i,j} c_i c_j\, \sigma_{ij}^{\mathrm{quad}}, \tag{2}$$

where the linear term arises from interference between the SM and dimension-six amplitudes and scales as $1/\Lambda^2$, while the quadratic term scales as $1/\Lambda^4$. The quadratic term is therefore parametrically of the same order as contributions from dimension-eight operators in Equation (1).

2.1. Linear Versus Quadratic Interpretations

Retaining only the linear term yields a formally consistent prediction at $\mathcal{O}(1/\Lambda^2)$. In this regime, sensitivity arises exclusively from interference effects and, for many observables, manifests as shape distortions rather than overall rate changes. This is particularly attractive experimentally because it reduces reliance on absolute rate normalizations that are often limited by theory and modeling uncertainties.

Including quadratic terms typically increases sensitivity and guarantees that predicted yields remain positive for all values of the coefficients. The resulting constraints, however, should be interpreted with the implicit assumption that neglected dimension-eight contributions are subleading in the probed phase space. Operationally, this assumption is more credible when the inferred scale Λ associated with the constraint is well above the typical momentum transfer in the events that dominate the sensitivity. Conversely, in extreme tails where the typical scale approaches the fitted Λ, the interpretation may be less robust and should be accompanied by additional validity arguments.

2.2. Energy Growth and Phase-Space Sensitivity

Several operators relevant for top-associated production, in particular electroweak dipoles, generate amplitudes that grow with the characteristic energy scale of the process. This implies that differential measurements targeting high-p_T regions can increase sensitivity relative to inclusive rates. However, enhanced sensitivity in the tails typically comes with increased dependence on detector modeling, jet and lepton reconstruction at high momentum, and theoretical uncertainties affecting the shape of distributions. A balanced SMEFT program therefore leverages both inclusive control regions and tail-enhanced categories.

2.3. Statistical Interpretation in Multi-Parameter Fits

As SMEFT analyses move beyond one-operator scans, correlations among Wilson coefficients become increasingly relevant. Degeneracies may arise when different operators induce similar distortions in the measured observables or when acceptance effects mimic EFT-induced shape changes. Multi-channel combinations help reduce such degeneracies by providing orthogonal information, but they also demand careful propagation of correlated systematic uncertainties and robust treatment of nuisance parameters. These considerations motivate designs where sensitivity arises from multiple observables and multiple phase-space regions rather than a single tail-dominated bin.

The relation between these interpretation regimes is summarized in Figure 1.

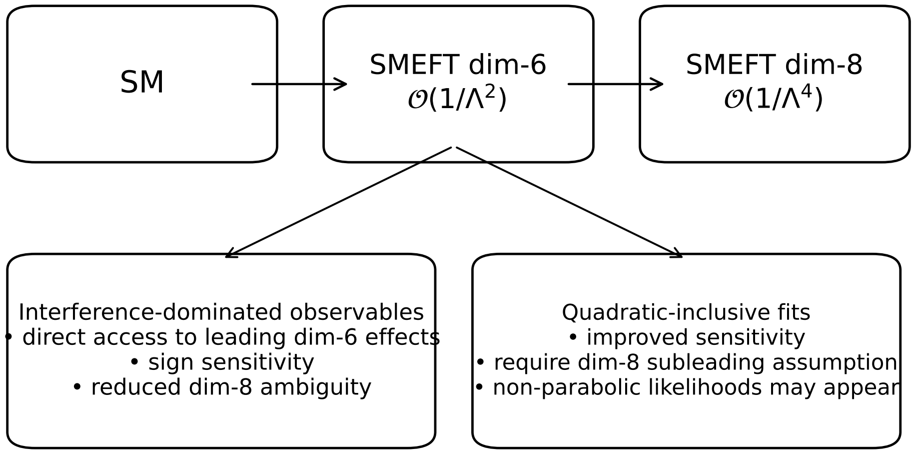

Figure 1. Conceptual summary of SMEFT interpretation regimes used in this article. Interference-dominated observables probe the leading $\mathcal{O}(1/\Lambda^2)$ contribution, while quadratic terms improve sensitivity but are formally of the same order as dimension-eight effects.

3. CP Violation in $t\bar{t}Z$ and tZq Production

The violation of charge-parity (CP) symmetry remains a central open question in particle physics. While CP violation is accommodated in the SM through the quark mixing matrix, its magnitude is insufficient to account for the observed baryon asymmetry of the Universe. Searches for additional sources of CP violation are therefore a key component of indirect new-physics programs. The top-quark sector is an attractive arena for such searches because CP-odd effects can appear in electroweak dipole interactions and can be probed using kinematic correlations in final states with multiple reconstructed objects.

In associated production with a Z boson, both $t\bar{t}Z$ (top–antitop production with an associated Z boson) and tZq (single-top production with a Z boson and a light quark) channels provide sensitivity to electroweak dipole operators. Within SMEFT, CP-odd effects arise from the imaginary parts of these dipole couplings, commonly parameterized by Wilson coefficients such as c^I_{tZ} and c^I_{tW}. These coefficients modify the amplitude in a way that can generate measurable asymmetries in CP-odd observables.

3.1. Why CP-Odd Observables Are Special

A defining feature of CP-odd operators is that their interference with the SM generates contributions that are odd under a CP transformation. For a generic CP-odd Wilson coefficient $c^I_{\rm CP}$, suitably constructed CP-odd observables $O_{\rm CP}$ have an SM expectation that is symmetric around zero, while a nonzero coefficient induces an asymmetry:

$$A_{\rm CP} \equiv \frac{N(O_{\rm CP} > 0) - N(O_{\rm CP} < 0)}{N(O_{\rm CP} > 0) + N(O_{\rm CP} < 0)} \propto c^I_{\rm CP} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right). \quad (3)$$

Crucially, quadratic contributions from CP-odd operators are CP-even and therefore do not contribute to such asymmetries. This implies that CP-odd observables isolate the interference term and provide direct access to the leading $\mathcal{O}(1/\Lambda^2)$ contribution. As a consequence, these measurements retain sensitivity to the sign of the corresponding Wilson coefficients and are comparatively robust against assumptions about higher-order terms, including dimension-eight contamination.

In addition, CP-odd observables tend to be less sensitive to overall rate uncertainties because the key information is encoded in an antisymmetric distortion of the distribution rather than a shift in its normalization. In realistic analyses, this can translate into reduced impact from theory uncertainties that enter primarily through the overall cross section normalization, although shape-related uncertainties remain relevant.

3.2. Measurement Strategy and Interpretive Impact

Within the current CMS Collaboration strategy, the CP-odd discriminant distributions are interpreted through a binned likelihood fit performed in categories enriched in $t\bar{t}Z$ and tZq production. The analysis emphasizes symmetry: the CP-odd observable is binned symmetrically around zero so that a genuine CP-violating signal manifests as an antisymmetric distortion. This construction reduces sensitivity to common normalization effects and focuses the inference on the interference term between the SM amplitude and the CP-odd SMEFT contribution.

From an interpretive standpoint, the key impact of this result is that it constrains directions in parameter space that are poorly accessed by CP-even measurements. In global SMEFT fits, CP-even observables often admit approximate sign degeneracies (e.g. $c \to -c$ when quadratic terms dominate). CP-odd observables break these degeneracies by preserving sign information through interference. They also provide a consistency handle: because quadratic terms from CP-odd operators are CP-even, they do not contribute to the measured asymmetry at leading order, making the constraint comparatively robust against ambiguities associated with $\mathcal{O}(1/\Lambda^4)$ truncation.

As datasets grow, the same methodology can be extended by incorporating multiple CP-odd observables and by performing differential fits in kinematic regions with enhanced sensitivity, while maintaining explicit control of potential detector-induced asymmetries through dedicated validation regions and symmetry cross-checks.

3.3. Experimental Systematics and Robustness Considerations

In CP-odd measurements, many systematic effects that act predominantly as overall yield normalizations cancel to first order in asymmetries, but several important sources remain. These include detector-induced charge asymmetries, residual mis-modeling of kinematic correlations entering the CP-odd observable, and background composition uncertainties that can introduce small antisymmetric components when projected onto a limited acceptance. By symmetric binning we mean that positive and negative values of the CP-odd observable are grouped into mirrored bins with identical boundaries. This makes antisymmetric distortions directly visible in the fit and helps disentangle genuine CP-violating effects from normalization shifts or other contributions that are symmetric in the observable. In practice, these effects are controlled by symmetric binning, data-driven background constraints in dedicated control regions, and explicit nuisance-parameter treatments that allow for antisymmetric deformations when warranted by validation studies.

In multi-parameter fits, antisymmetric distortions provide information that is qualitatively different from CP-even rate shifts and can therefore help stabilize the interpretation when several coefficients and nuisance parameters are varied simultaneously. This complementary information becomes increasingly valuable as the dimension of the EFT parameter space expands and as the experimental program moves toward simultaneous constraints on several electroweak and Yukawa directions.

Representative likelihood scans from the CP-violation analysis are shown in Figure 2.

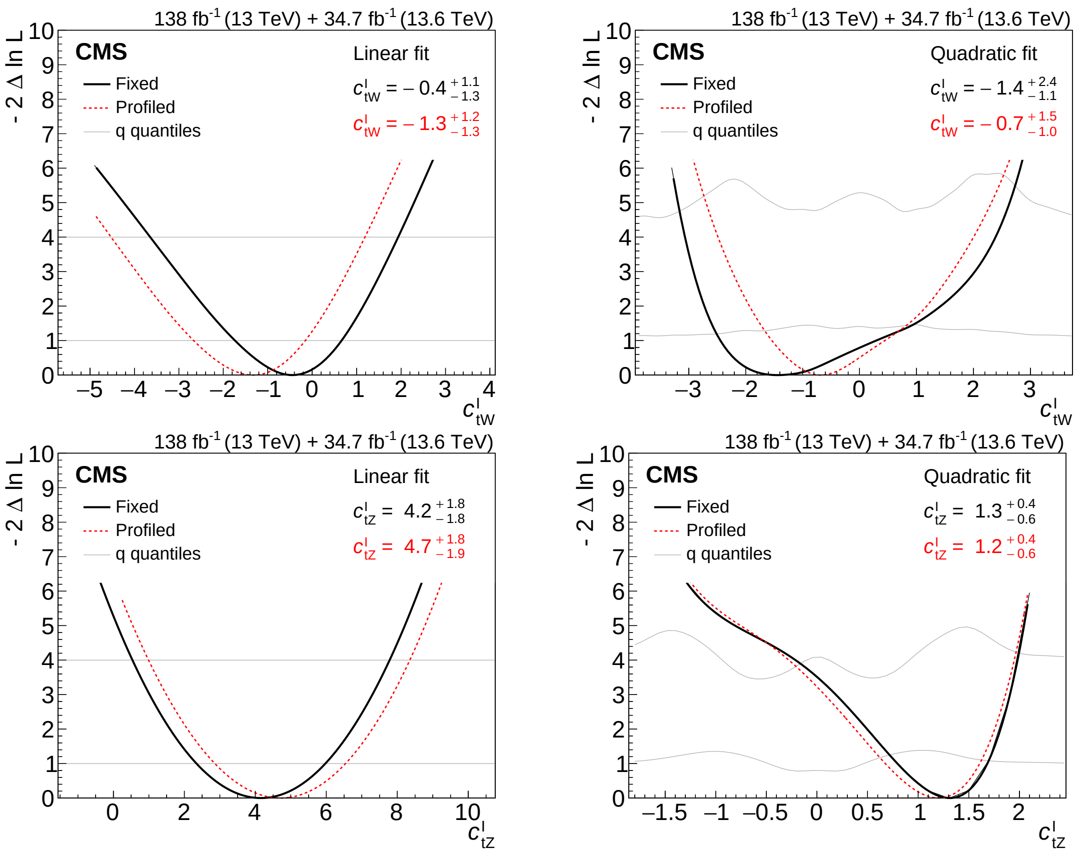

Figure 2. Likelihood scans for selected CP-odd dipole couplings from the CP-violation analysis in $t\bar{t}Z$ and tZq production (from Ref. [6]).

4. Flavor Structure in Multilepton Final States

A key question in SMEFT interpretations concerns the flavor structure of the underlying operators. Several dimension-six operators modify the couplings of quarks to the Z boson and can be defined separately for light generations and for the third generation. Relaxing flavor-universality assumptions increases the dimensionality of the parameter space but enables more realistic global interpretations, especially when combining information from processes with different initial-state compositions.

Operator Interpretation and Degeneracy Lifting

In this context, the analysis is formulated in the Warsaw basis, a complete and non-redundant basis of dimension-six SMEFT operators that is widely used in collider interpretations [7]. In the Warsaw basis, modifications of Z couplings arise from operators such as $\mathcal{O}_{\phi q}^{(1)}$, $\mathcal{O}_{\phi q}^{(3)}$, $\mathcal{O}_{\phi u}$, and $\mathcal{O}_{\phi d}$, which can be instantiated for each quark generation. Allowing independent coefficients for light and third-generation quarks increases the number of degrees of freedom and introduces approximate flat directions, namely parameter combinations that are only weakly constrained by a given dataset, if only a single process is considered. The CMS strategy addresses this by using the different sensitivity patterns of $t\bar{t}Z$ and diboson production: diboson channels constrain light-quark directions, while $t\bar{t}Z$ anchors third-generation interactions. Differential information, especially the Z boson transverse momentum, further reduces degeneracies by exploiting the distinct energy scaling of different operator structures.

A key outcome of this approach is a fit that remains stable when flavor assumptions are relaxed. This is an important methodological step beyond "one-operator-at-a-time" interpretations and provides a template for future global combinations where top-associated, Higgs, and diboson measurements are analyzed jointly.

The measurement performed by the CMS Collaboration simultaneously probes light- and heavy-quark contributions by combining sensitivity from $t\bar{t}Z$ production and diboson channels. In diboson production, light-quark couplings enter predominantly through the initial state, while in $t\bar{t}Z$ production the couplings of the top quark are probed directly. Differential information, in particular the p_T of the Z boson, enhances sensitivity to energy-growing operator effects and helps reduce degeneracies among coefficients. Conceptually, this strategy can be viewed as using diboson channels to anchor light-quark directions in parameter space while top-associated production provides direct access to third-generation couplings.

Representative best-fit intervals from the flavor-structure analysis are shown in Figure 3.

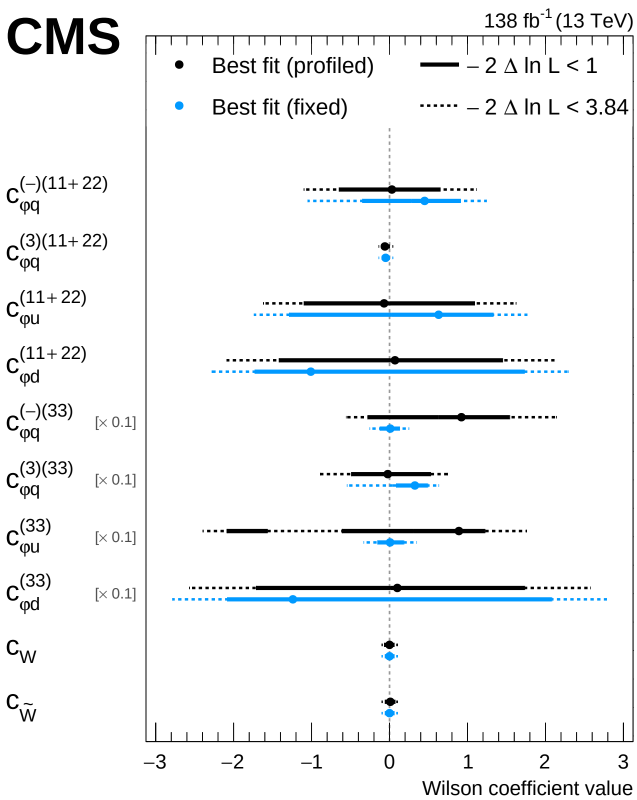

Figure 3. Best-fit values and confidence intervals for selected Wilson coefficients in the flavor-structure analysis (from Ref. [8]).

Interpretively, the main point is that jointly analyzing top-associated and non-top processes reduces the risk of attributing deviations to third-generation interactions when they could instead arise from modified light-quark couplings. This provides a more robust foundation for global SMEFT combinations.

5. Run 2 Combinations and Multi-Channel Interpretations

As the number of measured final states and observables grows, SMEFT interpretations naturally evolve toward multi-channel and multi-parameter likelihood fits. The CMS Collaboration has performed Run 2 combinations that integrate complementary channels, e.g. a boosted analysis targeting hadronic boson decays at high transverse momentum and a multilepton analysis relying on clean leptonic signatures.

Interpretive Value Beyond Sensitivity Gains

While the most visible numerical improvement in one-dimensional intervals may be at the $\mathcal{O}(10\%)$ level, the more consequential impact of combinations is qualitative. By combining channels with different dominant backgrounds, acceptance, and systematics, the fit gains resilience against modeling limitations in any single region. In higher-dimensional EFT parameter spaces, this reduces the risk that a constraint is driven by a single tail bin or by a single nuisance-parameter configuration. Furthermore, combinations provide a natural environment to propagate correlated theoretical uncertainties consistently across channels, which becomes essential when interpreting results in terms of common Wilson coefficients.

In the longer term, such combined likelihoods are a stepping stone toward global SMEFT interpretations that incorporate multiple production modes and decay topologies. They also help identify which observables provide the orthogonal information needed to break degeneracies in future HL-LHC analyses.

The three measurements summarized in Table 1 illustrate complementary facets of the CMS SMEFT program in the top-quark sector, spanning interference-driven CP-sensitive observables, flavor-resolved electroweak couplings, and multi-channel global interpretations.

Constraints from the Run 2 combination are shown in Figure 4.

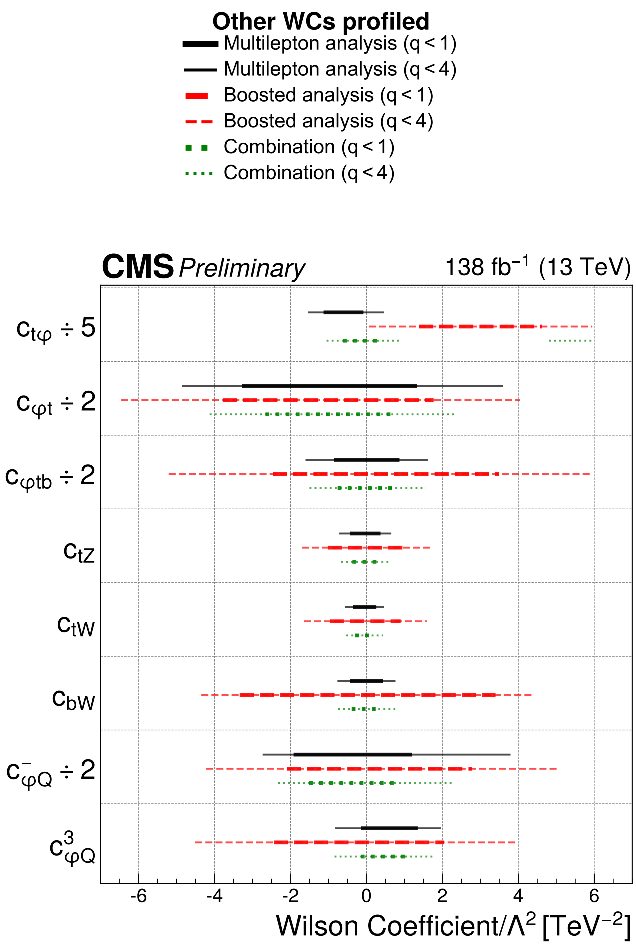

Figure 4. Wilson-coefficient constraints from the Run 2 combination (from Ref. [9]).

Table 1. Summary of the CMS SMEFT measurements discussed in this article. The original study references are repeated explicitly in the last column.

Measurement	Final State	Operators Probed	Sensitivity Type	Interpretation	Key Feature	Ref.
CP violation in $t\bar{t}Z$, tZq	$\geq$ 3 leptons + jets	CP-odd dipoles c^I_{tW}, c^I_{tZ}	CP-odd asymmetries	Linear and quadratic	Interference isolation; sign sensitivity	[6]
Flavor structure in multilepton final states	$\geq$ 3 leptons	Flavor-resolved Z couplings ($\mathcal{O}^{(1,3)}_{\phi q}$, $\mathcal{O}_{\phi u}$, $\mathcal{O}_{\phi d}$)	Differential p^Z_T	Multi-parameter fit	Light vs. third generation disentangling	[8]
Run 2 top+X combination	Boosted + multilepton	Multiple electroweak/top operators	Multi-channel likelihood	Quadratic multi-parameter	Reduced degeneracies and improved robustness	[9]

6. EFT Consistency and Interpretation Considerations

The inclusion of quadratic terms in Equation (2) improves numerical sensitivity but introduces contributions formally of the same order as neglected dimension-eight operators; see, e.g., the LHC EFT WG note on truncation and validity and related discussions [3, 10, 11]. In practice, bounds derived from purely quadratic fits should be interpreted with the implicit assumption that dimension-eight contributions are subleading in the explored phase space.

6.1. Truncation, Sensitivity, and Robustness

When interference is experimentally accessible, interference-dominated observables provide theoretically cleaner constraints within a truncated SMEFT expansion. This is particularly clear for CP-odd observables: by construction, they isolate the interference term and thus reduce dependence on assumptions about $\mathcal{O}(1/\Lambda^4)$ effects. Conversely, for directions in parameter space where interference is suppressed, quadratic terms can dominate, and resulting limits should be interpreted as conditional on the smallness of dimension-eight contributions and on the validity of the EFT in the probed kinematics.

6.2. Energy Tails and Validity Criteria

Energy-growing operator effects motivate the use of high-p_T tails, but they also raise the question of EFT validity. A practical approach is to compare the typical momentum transfer in the selected region to the inferred Λ associated with the constraint. Energy-binned fits and the reporting of constraints as a function of a maximum probed scale are increasingly used to make this connection explicit. At the HL-LHC, where statistical uncertainties will be reduced, such validity criteria will become increasingly important for robust interpretations.

6.3. Likelihood Boundaries in Quadratic Fits

Practical aspects of SMEFT simulation and event reweighting, including potential biases when separating squared terms, are discussed in the LHC EFT WG note on SMEFT predictions and reweighting [12]. In directions where the SM–dimension-six interference is suppressed, the leading deviation from the SM can be dominated by quadratic terms. In such cases, the likelihood as a function of a Wilson coefficient may become non-parabolic near the SM point: the best fit can occur away from zero, and confidence intervals can appear "bounded" by an effective sensitivity floor. This behavior is not a pathology of the fit but a direct consequence of the polynomial dependence of the prediction on EFT parameters, cf. Equation (2).

Practically, this motivates two reporting choices. First, when feasible, provide both linear-only and quadratic-inclusive intervals so readers can see whether sensitivity is driven by interference or by quadratic terms. Second, when quoting quadratic-driven limits, accompany them with information about the kinematic scales that dominate the sensitivity, since the same $\mathcal{O}(1/\Lambda^4)$ order also receives contributions from dimension-eight operators. Where the sensitivity is driven by extreme tails, coverage studies or alternative interval constructions can be useful, especially if asymptotic assumptions are questionable.

These considerations have become a standard component of SMEFT interpretations in collider measurements and are discussed extensively in the EFT literature [3, 11].

6.4. Practical Mitigations and Reporting Strategies

Several pragmatic strategies can improve the transparency of EFT interpretations in the presence of truncation ambiguities. One approach is to report both linear-only and quadratic-inclusive constraints (when meaningful), thereby making explicit the role of $\mathcal{O}(1/\Lambda^4)$ terms. Another is to provide constraints in restricted phase-space regions with an explicit maximum probed scale, or to present results in bins of a characteristic energy variable. These practices help readers assess whether the inferred constraints plausibly correspond to Λ values above the energies that dominate the sensitivity.

A related point concerns positivity and parameter-space boundaries. Quadratic terms ensure positive-definite yields, but they can also introduce likelihood minima away from the SM point and lead to bounded confidence regions. In such situations, asymptotic approximations can be less reliable, and coverage studies or alternative interval constructions may be warranted. Importantly, these features reflect the non-linear EFT dependence rather than an experimental artifact.

Overall, a balanced interpretation strategy treats quadratic constraints as sensitivity benchmarks, while emphasizing interference-dominated observables—notably CP-odd measurements—as providing the most theoretically robust information within a dimension-six truncation.

6.5. Connecting Constraints to UV Scales

A complementary way to communicate EFT consistency is to translate confidence intervals on Wilson coefficients into indicative lower bounds on a UV scale under simple coupling assumptions, e.g. $c_i \sim g_*^2$ or $c_i \sim 1$. While such translations are model dependent, presenting them alongside the nominal SMEFT intervals can help readers gauge whether the inferred Λ is plausibly above the characteristic energy scale of the selected events, and it makes explicit the assumptions under which quadratic-inclusive limits can be interpreted as robust constraints on new physics.

6.6. Cross-Checks and Interpretation Robustness

A recurring practical question in SMEFT fits is how sensitive the reported intervals are to modeling assumptions and to the choice of observables used in the likelihood. A useful validation is to repeat the fits using alternative binnings or reduced observable sets, verifying that constraints are not driven by a single extreme bin. Another is to compare linear-only and quadratic-inclusive interpretations in the same phase space, highlighting directions where interference dominates versus those where quadratic terms provide most of the sensitivity.

For the CP-odd measurement, the use of antisymmetric observables provides an intrinsic robustness check: residual detector-induced asymmetries can be constrained using control samples and by verifying the symmetry of background contributions. For CP-even measurements, analogous robustness comes from multi-region fits in which control regions constrain backgrounds and nuisance parameters. These practices will become increasingly important at the HL-LHC, where statistical uncertainties shrink and systematic modeling becomes the limiting factor.

7. Outlook for the High-Luminosity LHC

At the HL-LHC, a natural extension of current practice is to report SMEFT constraints together with information about the kinematic scales that dominate the sensitivity. Presenting intervals as a function of a maximum probed scale, or providing fits in bins of an energy proxy, makes EFT-validity assumptions explicit and improves the portability of results into global combinations that span different processes and phase-space selections.

The High-Luminosity LHC will substantially increase the reach of indirect searches in the top-quark sector. Improved statistical precision will enable more granular differential measurements and more comprehensive multi-parameter fits, while demanding tighter control of experimental and theoretical systematic uncertainties. In this environment, the interplay between sensitivity and theoretical consistency will increasingly shape interpretation choices.

Interference-sensitive observables, multi-channel combinations, and explicit validity assessments together define a robust path forward for the SMEFT program in the top sector. In particular, CP-odd measurements that isolate interference effects will remain essential to ensure that global interpretations retain both sensitivity and theoretical robustness as datasets and analysis sophistication grow.

Projected HL-LHC sensitivity for selected SMEFT directions is shown in Figure 5.

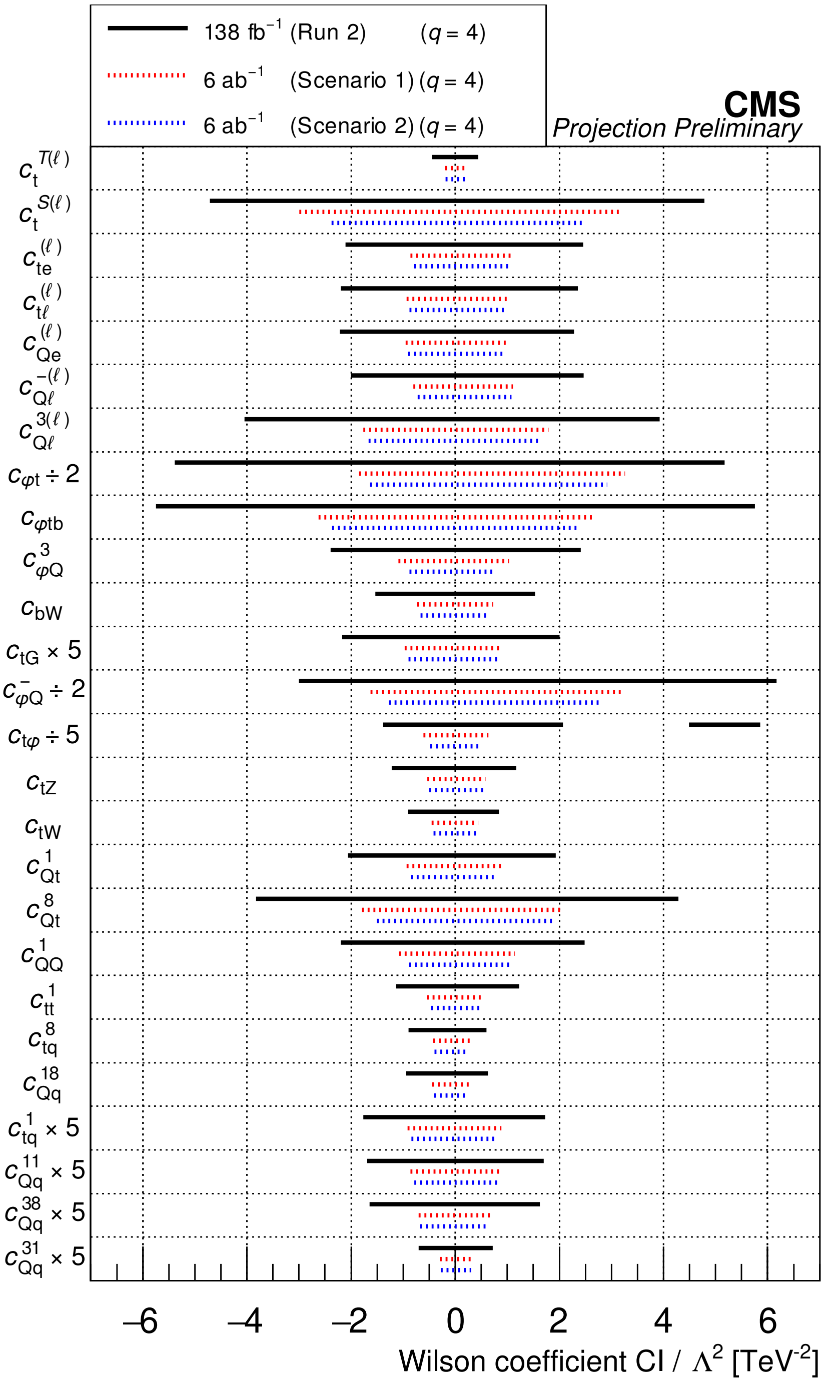

Figure 5. Projected sensitivity at the HL-LHC for selected SMEFT directions. Together with Figures 3 and 4, this plot illustrates the interplay between current constraints and future HL-LHC projections (from Ref. [13]).

8. Conclusions

The aim of this article is to synthesize the common message of these recent CMS results and to contextualize their interpretation within a broader SMEFT framework. CP-odd observables in $t\bar{t}Z$ and tZq production provide direct access to interference effects and preserve sign sensitivity for CP-odd dipole couplings. Multilepton analyses combining $t\bar{t}Z$ with diboson production demonstrate how flavor-resolved interpretations can be achieved within a single fit. Multi-channel Run 2 combinations highlight the role of complementary final states in reducing degeneracies and improving robustness in higher-dimensional parameter spaces.

Looking ahead, HL-LHC measurements will increasingly require explicit attention to EFT consistency. Reporting strategies that clarify the role of quadratic terms and the kinematic scales probed, together with interference-sensitive observables and combined likelihood interpretations, provide a clear path toward both sensitive and theoretically robust global SMEFT programs in the top sector.

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Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used ChatGPT (OpenAI) to assist with language editing. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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