Experimental overview of of Effective Field Theory

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Introduction

- Search for BSM in the experiment

Direct BSM searches

- Formulate a specific UV-complete model and searches for BSM signature directly
- Signals manifest as resonances or other non-SM signatures.
- Strength: concrete interpretation when the model is correct.

Effective Field Theory

- Develop a model-independent operator expansion and constrains it using SM measurements.
- New physics is characterized by a heavy scale Λ beyond direct reach.
- Effects appear in tails of distributions and in precision observables.
- Strength: broad and uniform language across many processes.

Standard Model Effective Field Theory (SMEFT)

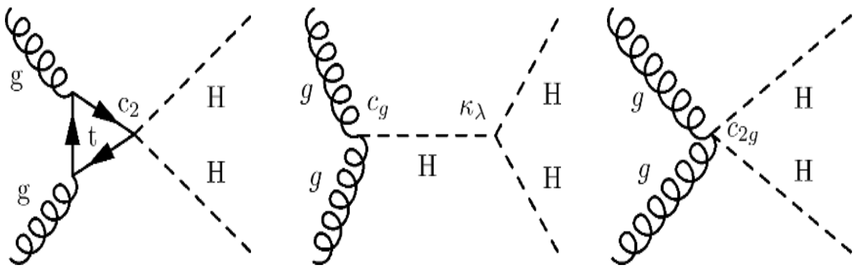
- **Higgs boson in EW doublet**
  - Exploit correlations among operators in combined fits
  - Expansion in mass dimension
- Start with fully-generic addition of all SU(3) × SU(2) × U(1) gauge-invariant effective operators composed of Standard Model fields
  - Dim-5 and 7 generate Majorana neutrino mass, violate lepton number → neglect
  - CP-odd operators need angular observables to constrain
  - 2499 dim-6 operators → reduced assuming full or top-restricted flavor symmetry
  - Often missing higher-dim operator amplitudes that interfere with SM

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

Higgs Effective Field Theory (HEFT)

- **Higgs boson is EW singlet**
  - Independent multi-Higgs contact interactions
  - Expansion in chiral dimension
  - Accommodates a broader class of UV models

- HH in the Higgs EFT (HEFT) scenario
  - linear variation of couplings ($k_\lambda, k_t, c_2, c_g, c_{2g}$)



$$|A|^2 = \kappa_\lambda^2 \cdot \kappa_t^2 \cdot |\triangle|^2 + \kappa_t^4 \cdot |\Box|^2 + c_2^2 \cdot |X|^2 + \kappa_\lambda \cdot \kappa_t \cdot c_2 \cdot |\triangle^* X + X^* \triangle| + \kappa_t^2 \cdot c_2 \cdot |\Box^* X + X^* \Box| + \kappa_t^3 \cdot \kappa_\lambda \cdot |\triangle^* \Box + \Box^* \triangle|$$

Two analysis approaches

- Complementary approaches to probing EFT and constrain Wilson coefficient (WC)
- Re-interpretation
  - From μ, σ, STXS, differential etc.
- Direct measurement
  - Inference from detector-level information

Interpretations: STXS, fid. diff XS, …

✓ Can constrain broad set of WC
✓ Flexibility to re-interpret
✗ Not optimized for EFT analysis
✗ No model of acceptance / migration effects

Fair sensitivity to wide set of operators

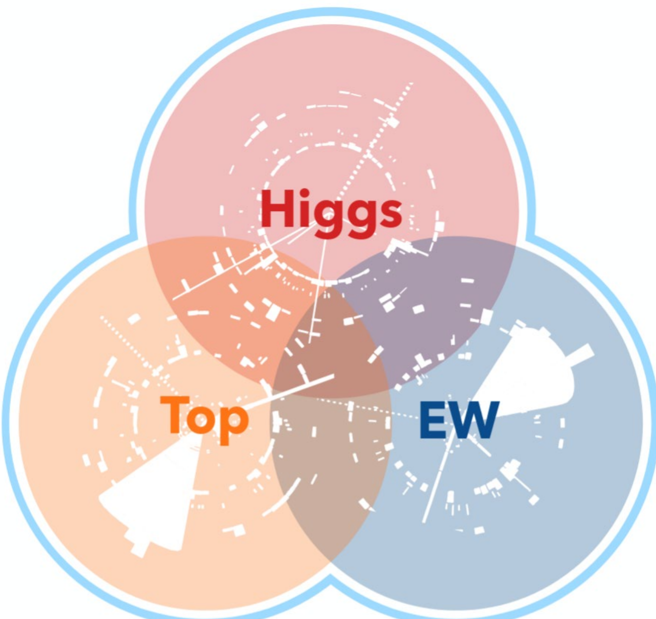
Direct: optimal observables

✓ Optimized for EFT analysis
✓ Fully model acceptance / migration effects
✗ Restrict to small set of WC
✗ Not easy to re-interpret

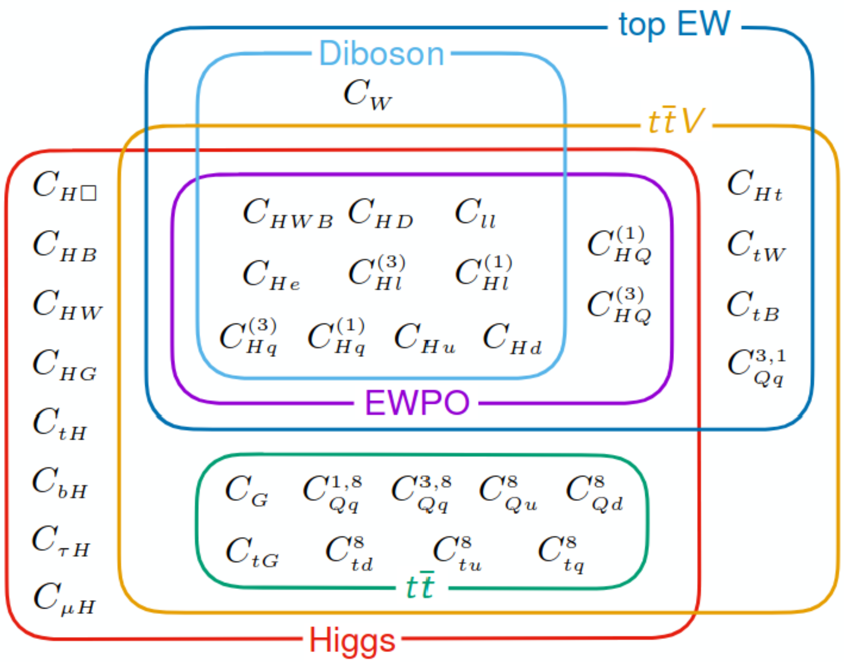
Great sensitivity to handful of operators

Global EFT

- A unified EFT picture overlaps the Higgs, top, and electroweak sectors.



By R. Balasubramanian



From JHEP 04 (2021) 279

Higgs-sector roadmap

- Three complementary Higgs EFT storylines
  - Single-Higgs direct EFT (optimal observables in $H\to4\ell$)
  - Single-Higgs reinterpretation (STXS/differential)
  - HH EFT/HEFT reinterpretation.

- Single-Higgs direct measurements are ideal when angular information and interference provide the main sensitivity.

- Single-Higgs reinterpretation gives the broadest operator coverage and is easiest to combine across decay channels.

- HH analyses are special because they add access to self-coupling and contact terms that are hard to constrain elsewhere.

H→4ℓ analysis with EFT

- H→4ℓ is the cleanest Higgs decay channel at the LHC
  - All final-state momenta are reconstructed, the mass peak is narrow, and the full angular structure is observable.
- Ideal for a direct detector-level EFT analysis
  - EFT effects in HVV tensor structures strongly distort angular distributions
- Could use matrix-element information through MELA to compress the most relevant kinematics into optimal observables.

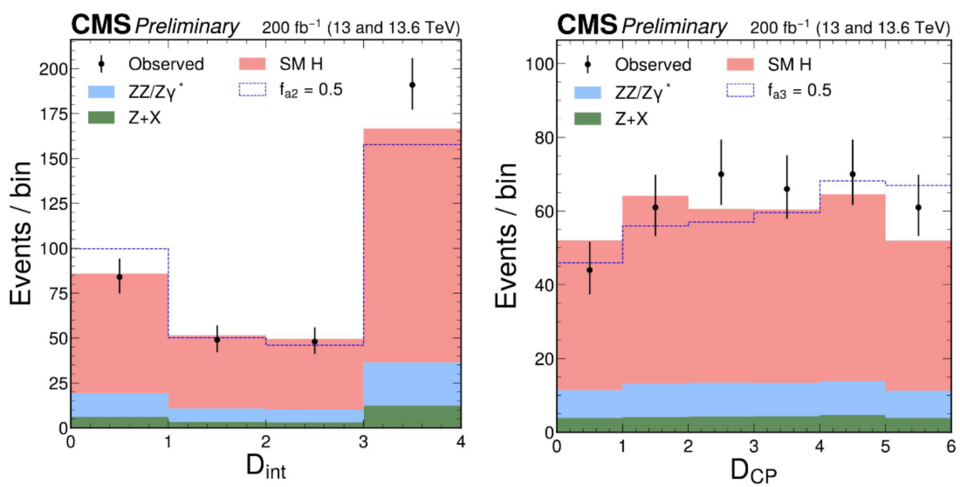
Probing HVV couplings in the four-lepton decay

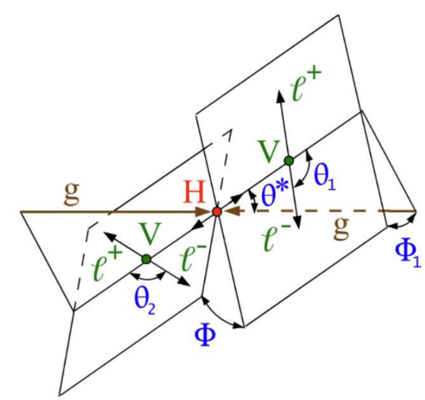
- Constrain tensor structure of HVV interactions using $H \rightarrow 4\ell$ decay kinematics.
- Datasets: Run 2 + 2022 + 2023, totaling about 200 fb^{-1}.
- D_bkg separates signal from background.
- Sensitive to seven independent anomalous couplings.
- The decay is described by $\Omega = \{\theta_1, \theta_2, \Phi, m_1, m_2, m_{4\ell}\}$.
- The MELA tool is used to build optimal observables for each coupling

CMS-PAS-HIG-25-011

$$\mathcal{D}_{\mathrm{interference}} = \frac{\mathcal{P}_{\mathrm{interference}}(\Omega)}{\mathcal{P}_{\mathrm{SM}}(\Omega)}$$

Optimal for EFT in the vicinity of the SM

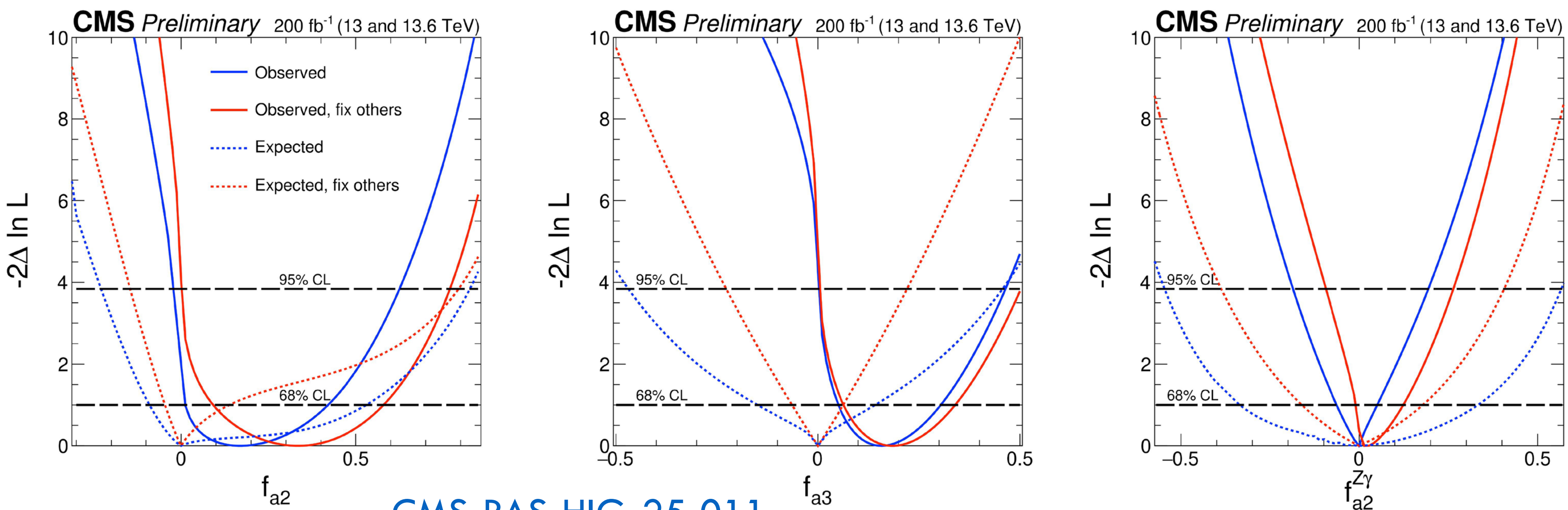




example discriminants D_int and D_CP

Probing HVV couplings in the four-lepton decay

- Seven EFT discriminants plus D_bkg define an 8-dimensional analysis space.
- A template fit is performed in 301 bins × 3 channels (4e, 2e2μ, 4μ).



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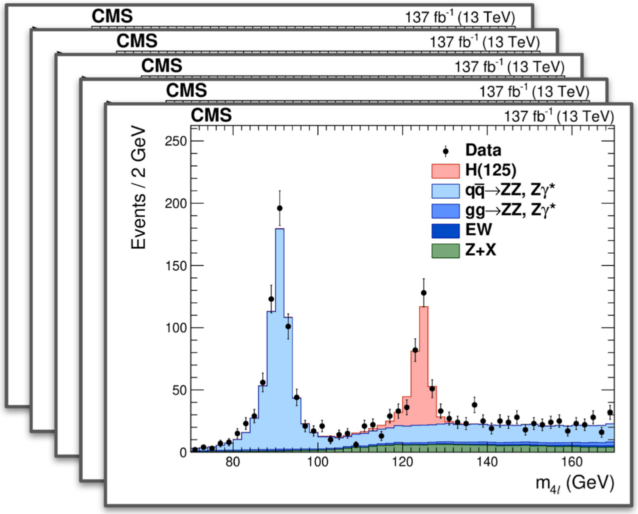
- Representative parameters such as f_{a2}, f_{a3}, and $f_{a2}^{Z\gamma}$ are shown with observed (solid) and expected (dashed) curves
  - Horizontal lines at Δ(−2lnL)=1 and 3.84 indicate approximate 68% and 95% CL thresholds.

This is a shape-dominated direct EFT measurement at detector level.

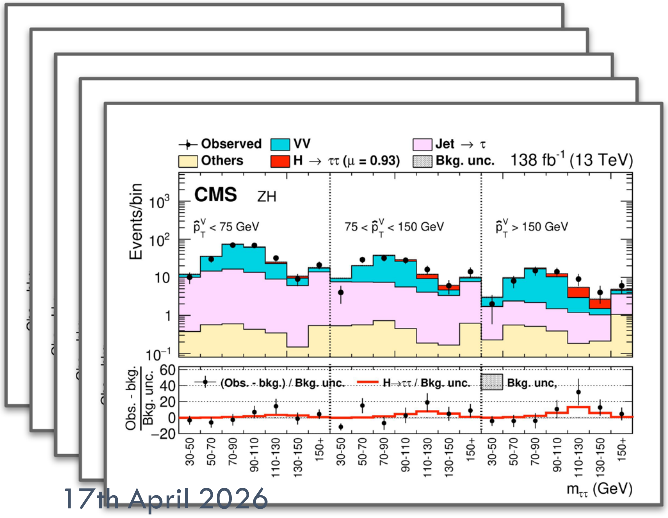
Run 2 STXS combination

[CMS-PAS-HIG-21-018]

- Ultimate precision via statistical combinations.
  - Includes H→γγ, H→ZZ→4ℓ, H→WW→ℓνℓν, H→ττ, H→bb, H→μμ, and H→Zγ using 138 fb^{-1}.
- Each decay mode targets multiple Higgs production processes.



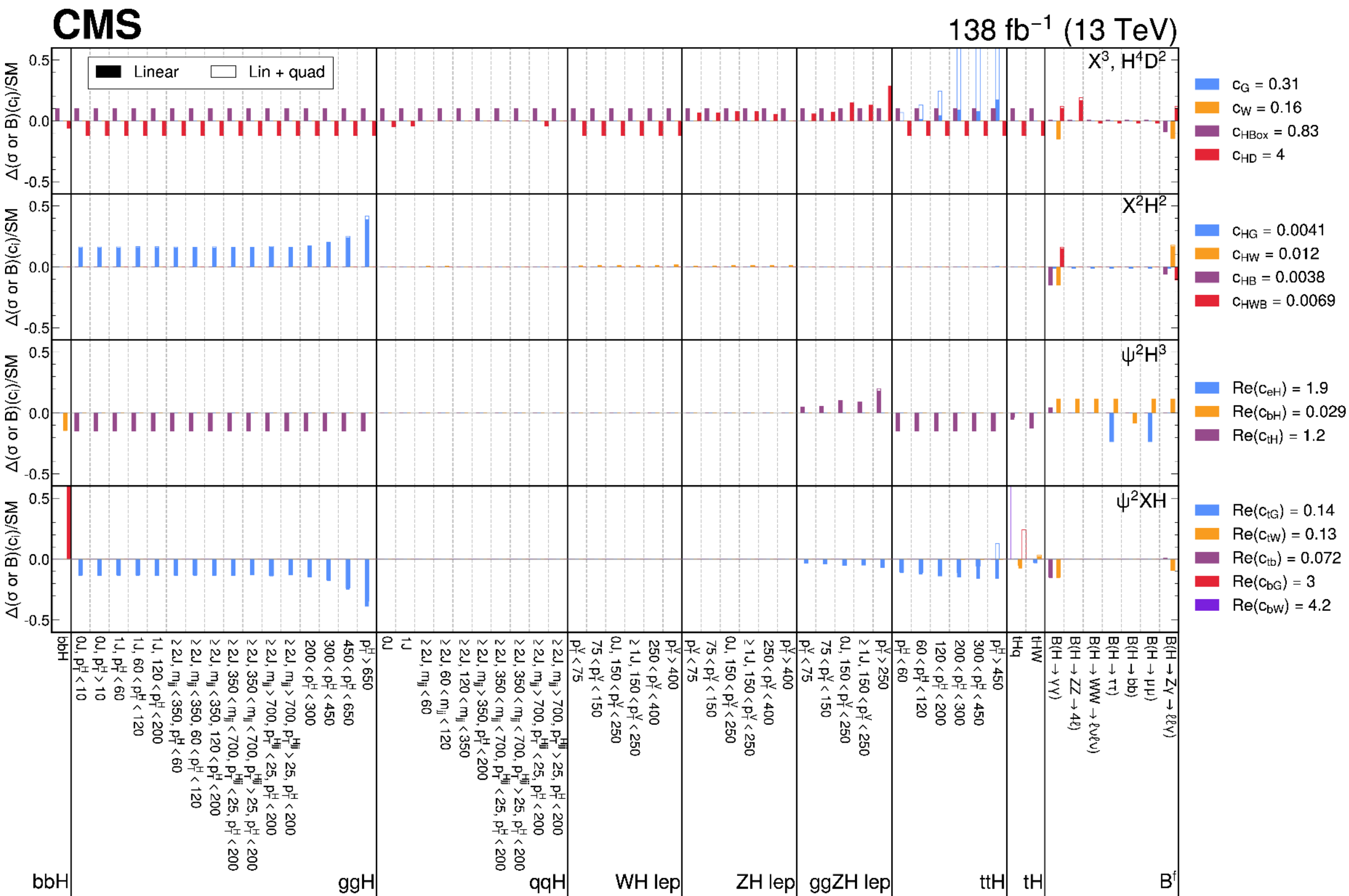
- Analysis regions: >1000 signal and control regions.
- Common nuisance sources correlated across channels: >10000.



- In each binned region, both the expected signal yield and the signal-shape information enter the likelihood in the final fit.

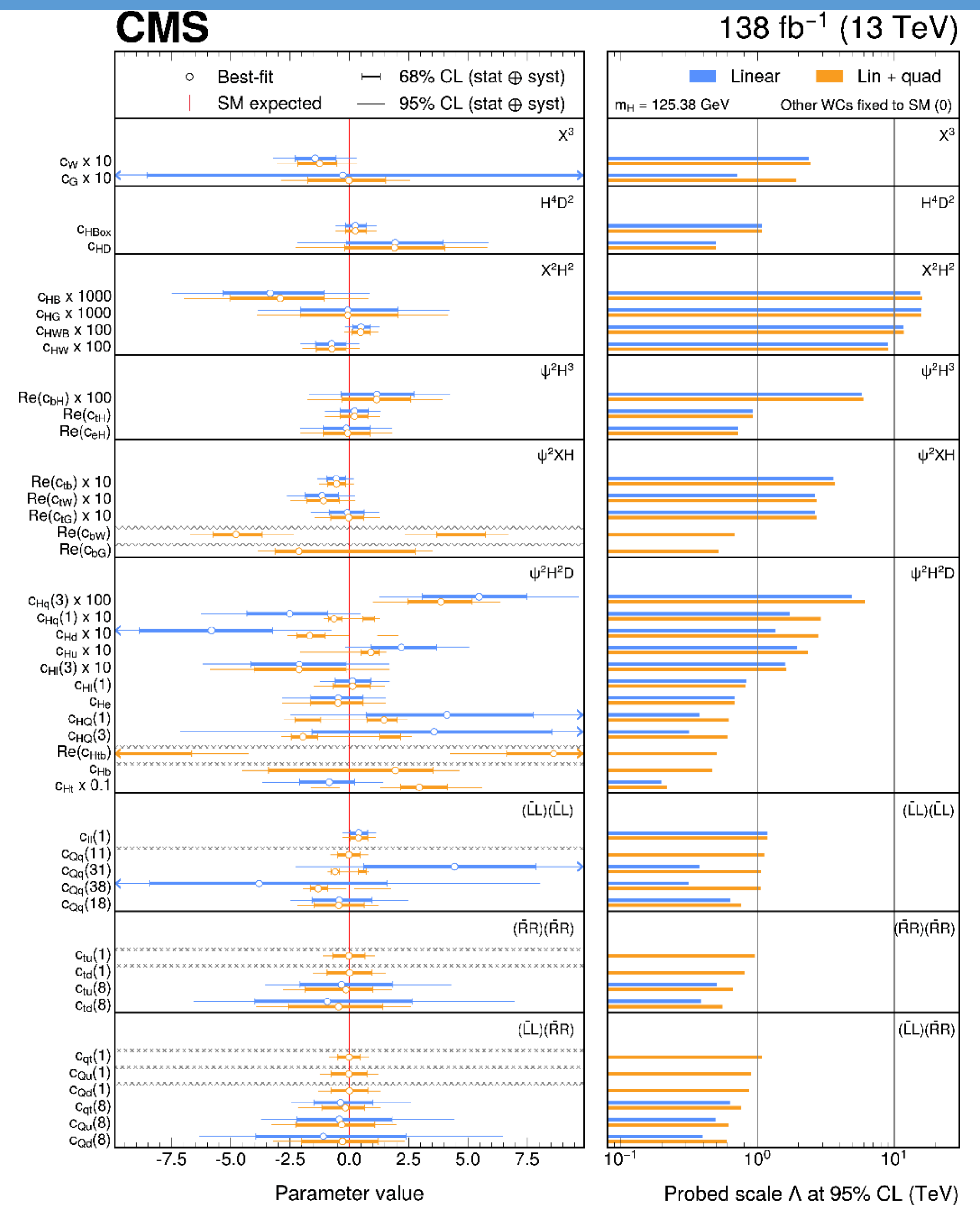
STXS EFT Interpretation

Impact of the SMEFT operators on the Higgs boson cross sections and branching fractions. CMS-PAS-HIG-21-018



STXS EFT Interpretation

- Likelihood scan over one Wilson coefficient while fixing the others to the SM.
- Good overall agreement with the Standard Model.
- CMS explicitly compares linear $O(\Lambda^{-2})$ and linear+quadratic $O(\Lambda^{-4})$ treatments

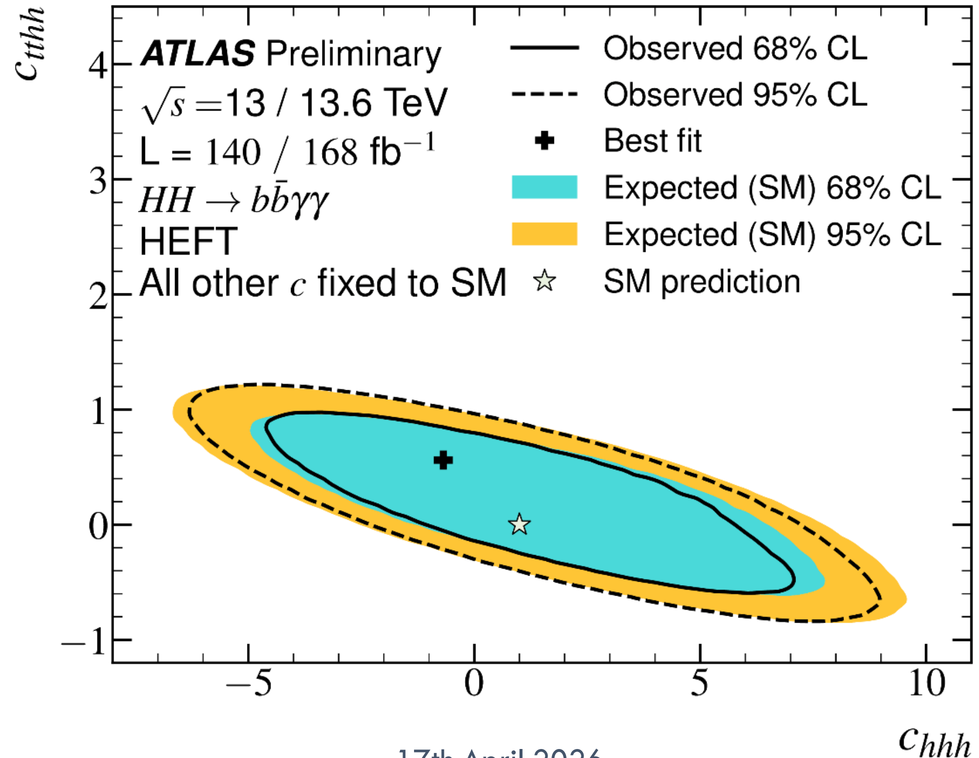


[CMS-PAS-HIG-21-018](CMS-PAS-HIG-21-018)

HH→bbγγ: HEFT result

- The bbγγ final state is statistically small but exceptionally clean
  - Good photon resolution and large bb decay branching ratio
- ATLAS uses categories based on multivariate discrimination
- EFT interpretation from the ATLAS experiment based on over 300 fb^{-1} of data.
  - 24%–45% improvement relative to the 140 fb^{-1} analysis.
  - A genuine 2D HEFT fit is performed

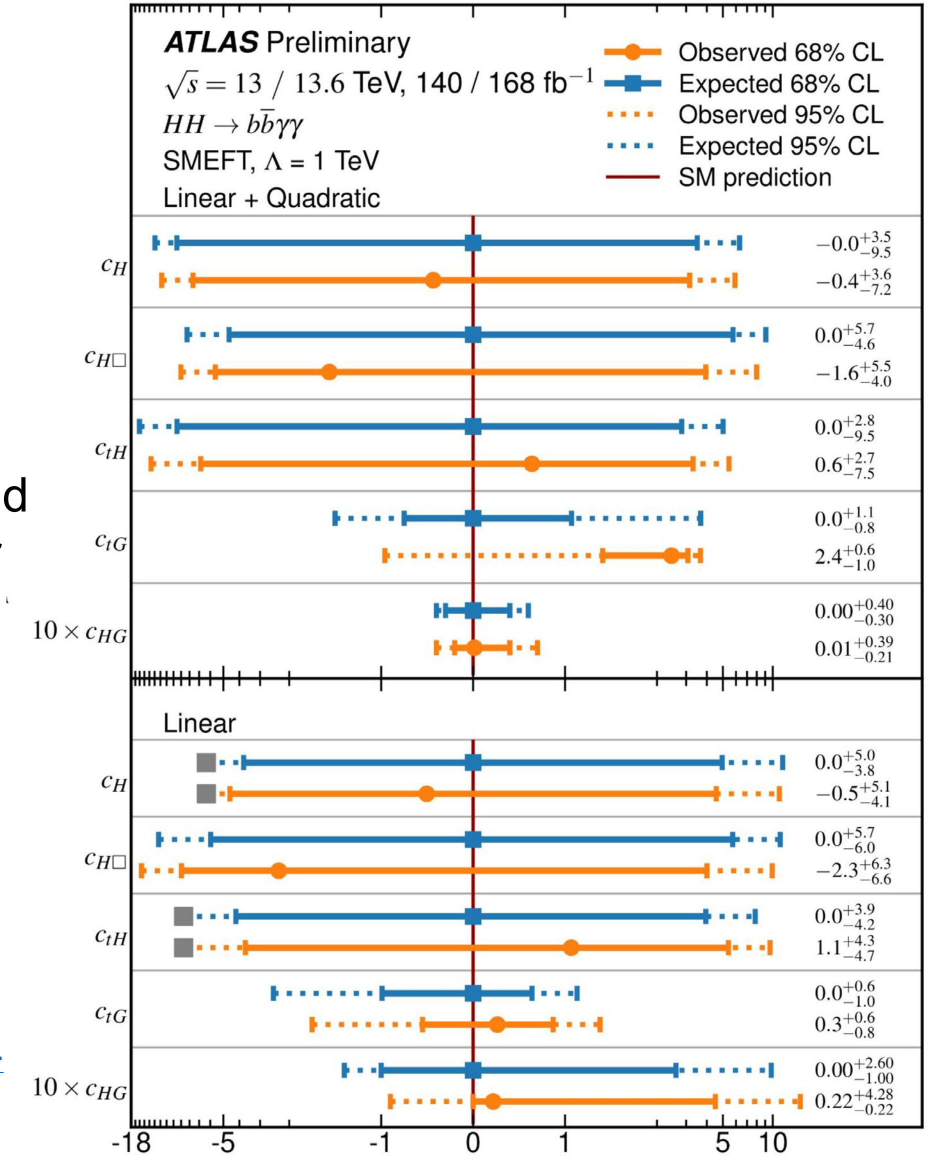
Observed and expected 68% / 95% CL contours are shown in the (c_{tthh}, c_{hhh}) plane.



ATL-PHYS-PUB-2025-034

HH→bbγγ: SMEFT result

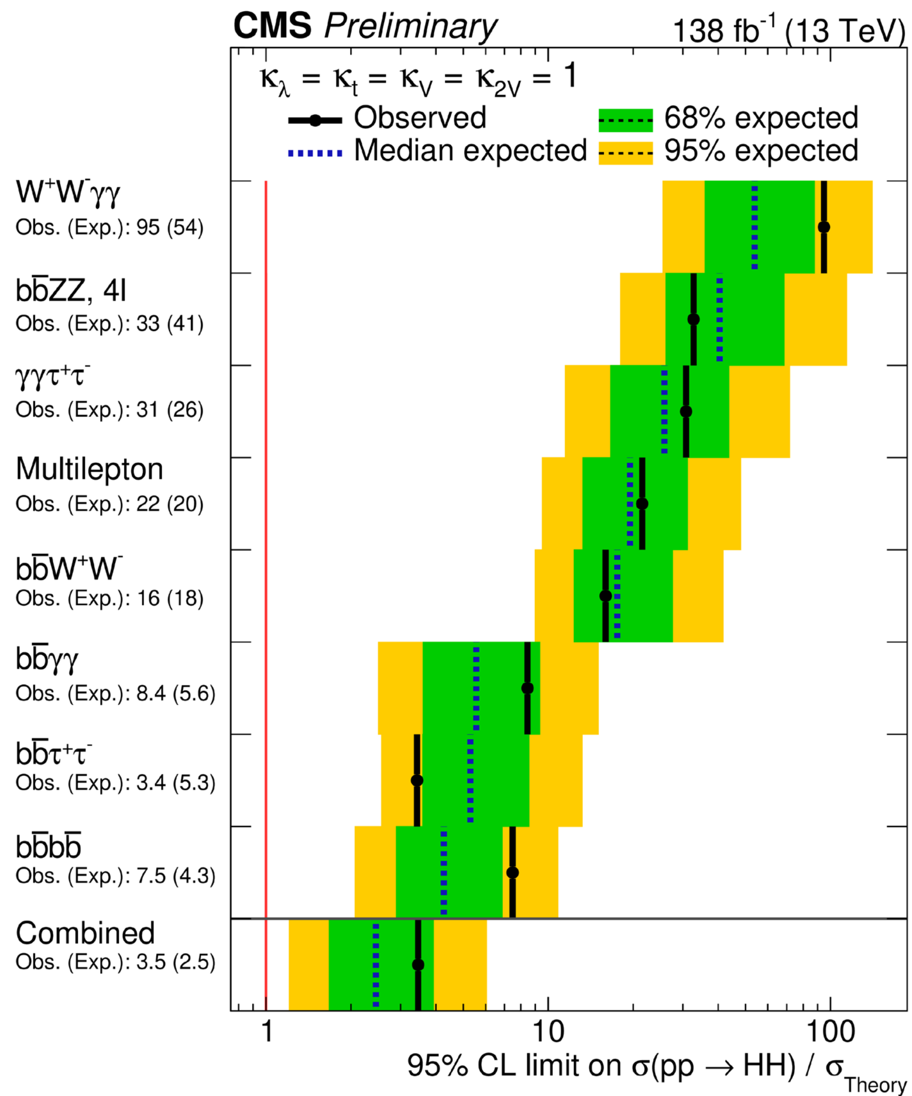
- Constraints on SMEFT c_H and $c_{H\Box}$ improve by 30%–50% relative to the previous 140 fb^{-1} result.
- The analysis is presented both in linear-only and linear+quadratic treatments.
- Observed 68% / 95% CL and expected 68% / 95% CL intervals are shown for each coefficient direction.
- Representative coefficient directions include c_H, $c_{H\Box}$, c_{tH}, c_{HG}, and normalized variants.



ATL-PHYS-PUB-2025-034

HH Run2 combination - CMS

- The most complete CMS combination to date
  - Using full Run 2 data with 138 fb^{-1}
  - All available channels in Run2
  - Updated uncertainties and signal cross section
  - New EFT interpretations
  - Updated Projections
- Expected and observed upper limits of HH production cross section
  - Observed (expected) 95% C.L. Upper limits on $\sigma_{HH}/\sigma_{Theory}$: 3.4 (2.5)

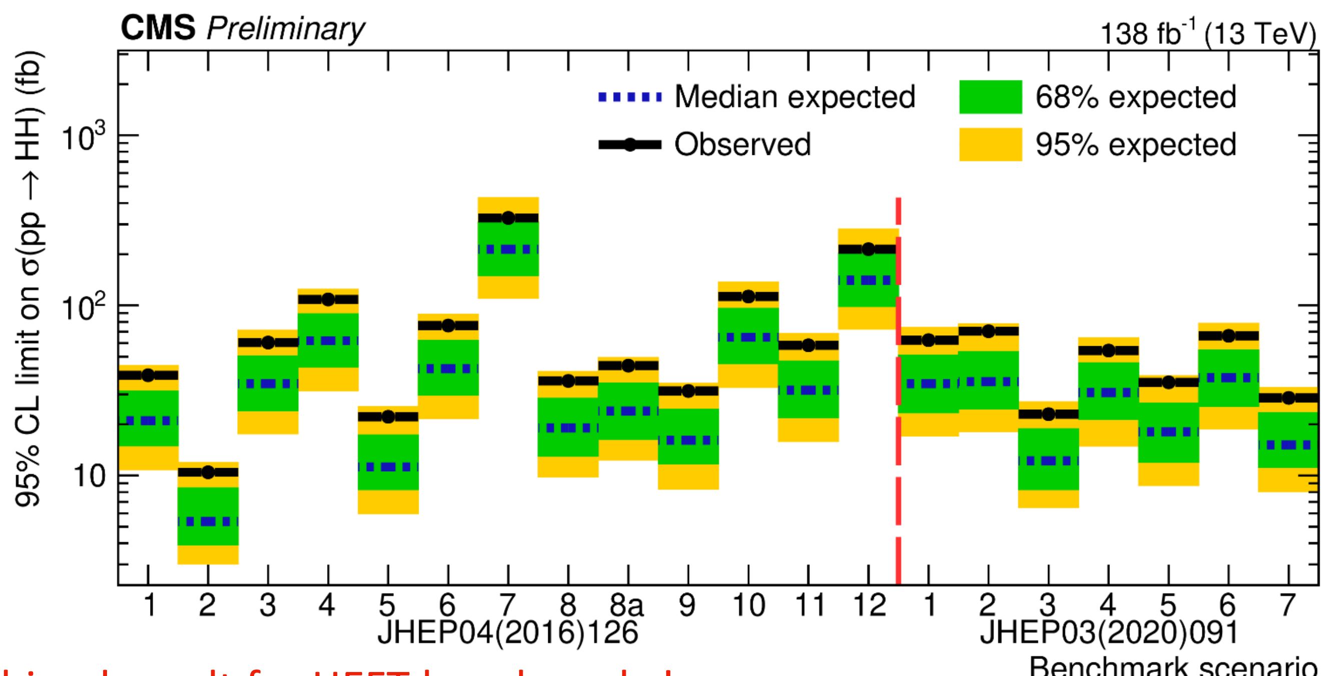


Limits extracted under the background-only hypothesis

CMS-PAS-HIG-20-011

Upper limits on HEFT benchmarks

- Upper limits in two representative HEFT benchmarks with different combinations of the coupling modifiers ($k_\lambda, k_t, c_2, c_g, c_{2g}$)
  - 1: Thirteen benchmark scenarios spanning a broad range of the coupling variations
  - 2: With NLO precision and considers direct and indirect constraints on couplings
- No significant deviations from expectations are observed
  - An overall small excess in all benchmarks, between 1σ and 2σ



First combined result for HEFT benchmarks!

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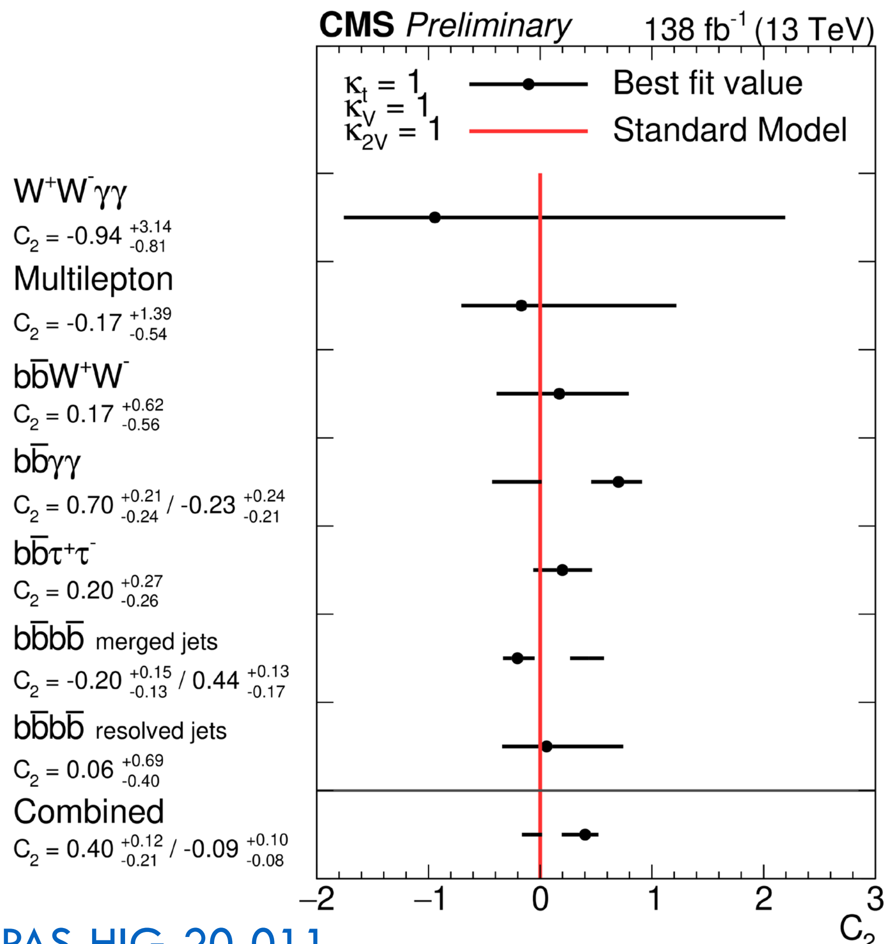
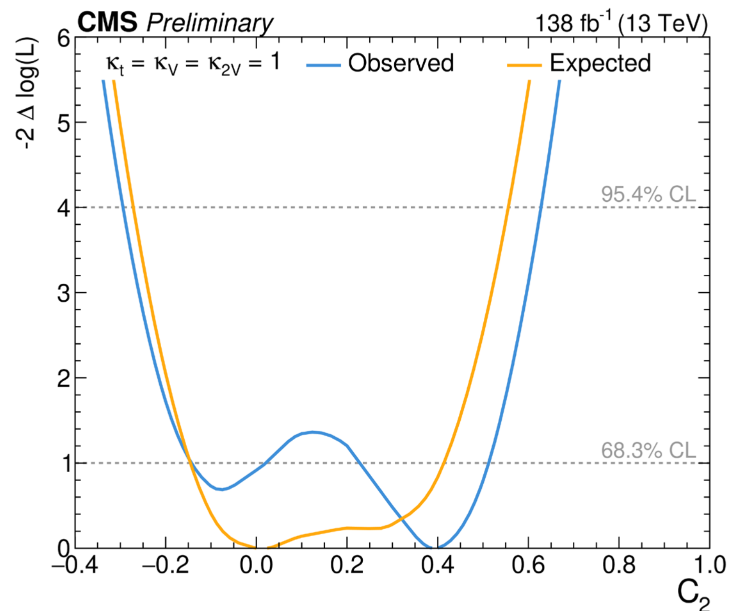
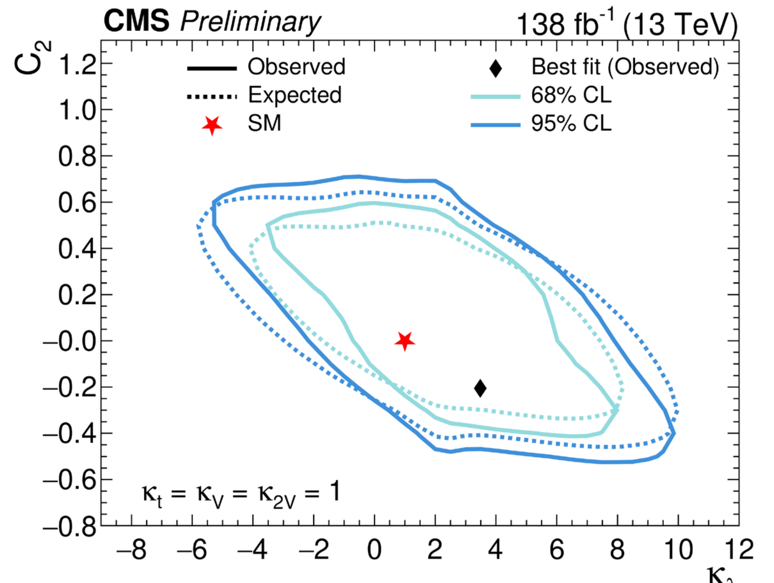
HEFT coupling scans

- Scan of C2 coupling modifier
  - In general compatible with the SM
  - The best fit slightly prefers $c_2 = 0.4$





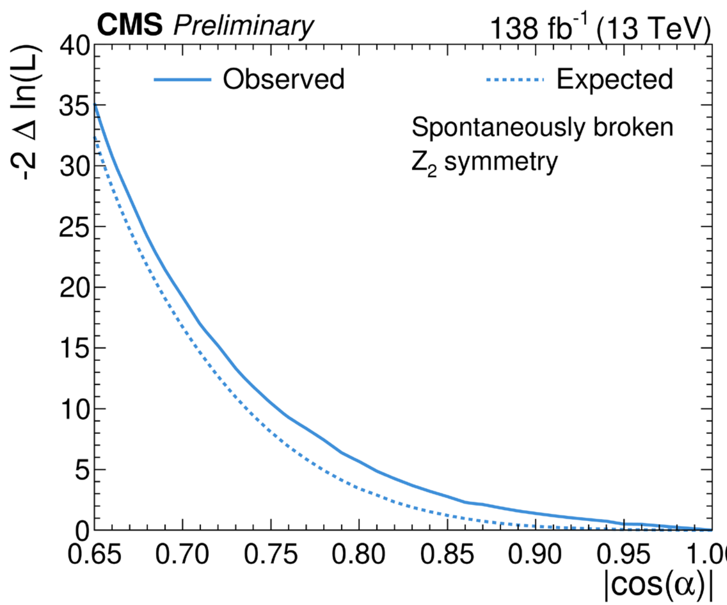


[CMS-PAS-HIG-20-011](CMS-PAS-HIG-20-011)

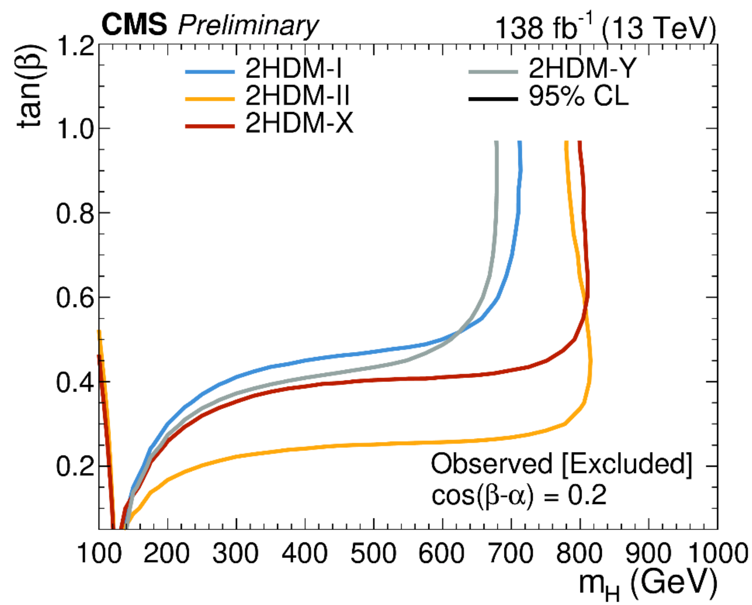
c

UV complete reinterpretations

- Probing UV complete models directly with available HH searches at CMS
  - Model dependent with more physical assumptions about interference, parameter values and correlations
  - A realistic testbed for assessing the reach and limitations of HH searches under explicit UV assumptions
  - Complementary to EFT interpretation and resonant searches
- Explored an example UV mappings for HH from [JHEP 02 (2021) 049]



Competitive singlet results



2HDM results: complementary coverage in the high-mass region

Electroweak and top EFT analysis

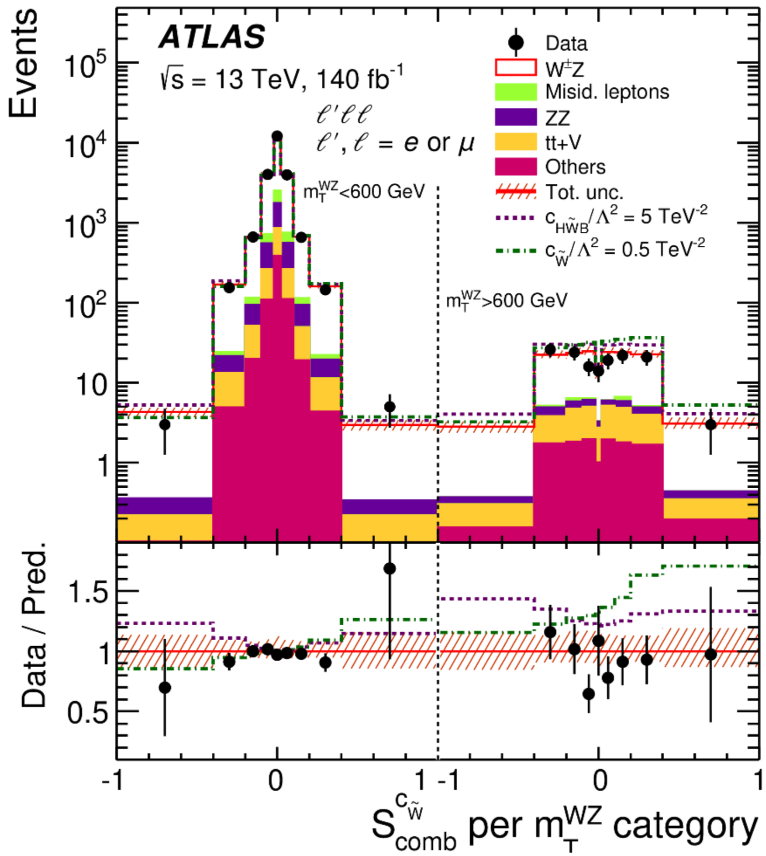
- In the electroweak sector, the role of the final state matters enormously
  - High-mass Drell–Yan probes currents
  - Diboson channels probe triple-gauge structures
  - VBS / triboson topologies sensitive to quartic and often dim-8 effects.
  - Sensitivity often from carefully modeled high-energy tails and CP-sensitive shapes.

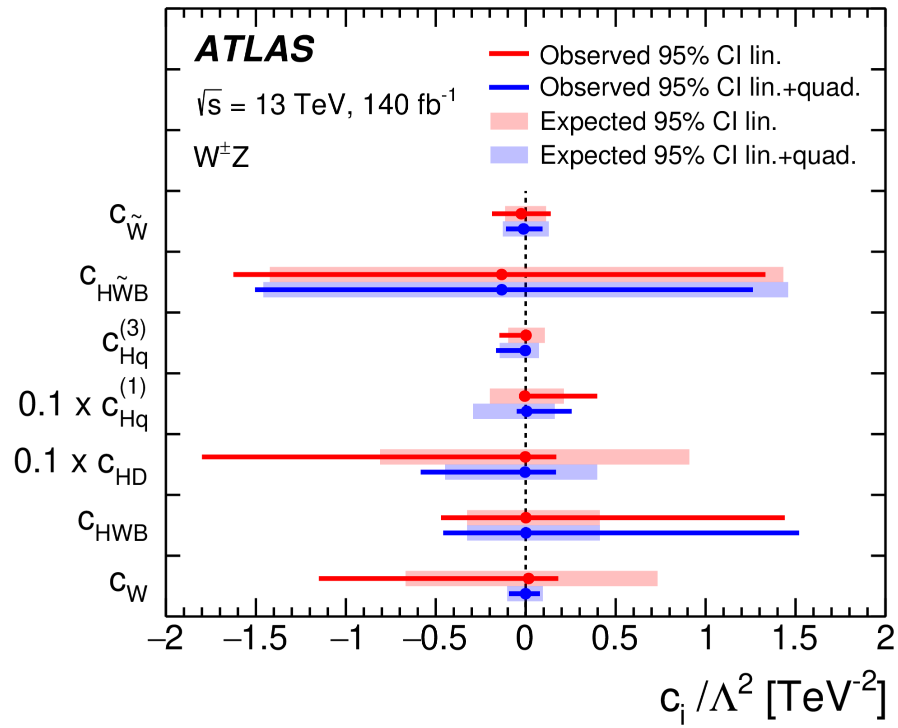
- Top EFT opens operator directions involving third-generation currents, dipoles, four-fermion structures, flavor, and CPV that are weakly constrained elsewhere.
  - Experimentally, single-top, ttV, ttZ+tZq, and high-multiplicity top final states each probe a different subset of those structures.
  - Top analyses increasingly use EFT-specific observable bases rather than standard inclusive distributions.

W±Z production: limits on CP-violating WCs

- Splitting the combined CP-sensitive observable by $m_T^{WZ} \gtrless 600\ GeV$ restores sensitivity to the quadratic term.

JHEP 11 (2025) 006

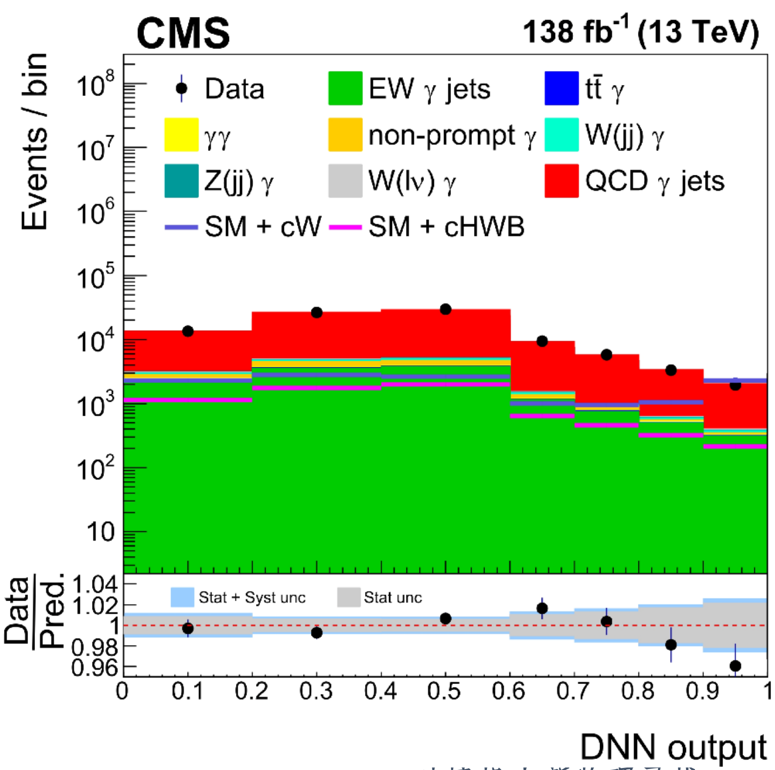


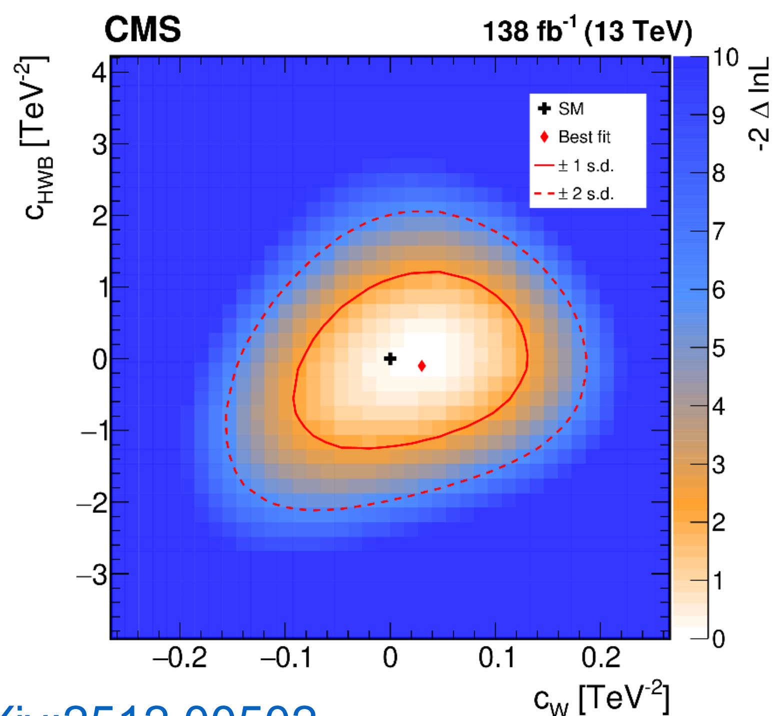


CP-odd limits competitive with current best ATLAS and CMS constraints

Vector Boson Scattering

- Vector boson fusion or electroweak production of one photon and two jets observed at 5 σ
- DNN trained to discriminate pure SM part from linear + quadratic EFT components
  - Trained with samples containing specific choices of Wilson Coefficients
- Crucial because quartic gauge vertices present already at leading order

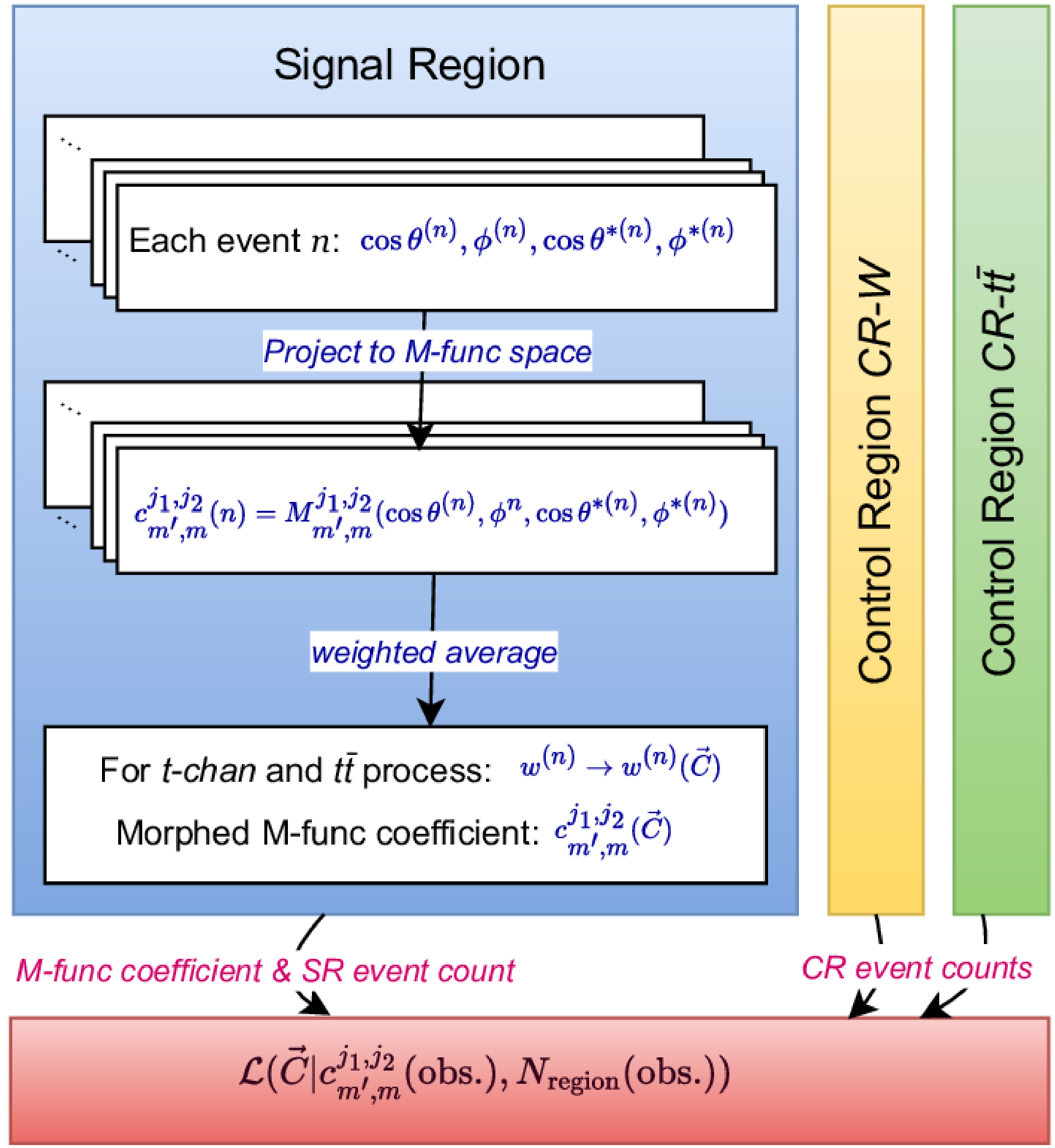




arXiv:2512.00502

Constraints on EFT via single top production

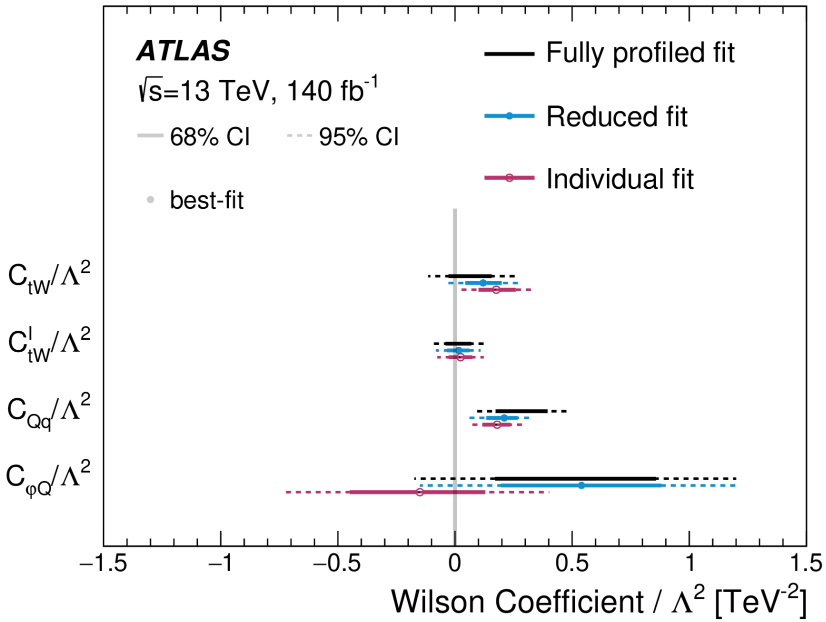
- Constraints on EFT via quadruple-differential angular decay rates from t-channel single-top-quark production
- Events from the signal region and control regions (CR-W and CR-$t\bar{t}$) are handled simultaneously.
- For t-channel and $t\bar{t}$ processes, morphed M-function coefficients are built event-by-event.
- Each distribution is decomposed into 23 Fourier coefficients.
- The fit is performed on these Fourier coefficients rather than directly on Δσ/Δx.

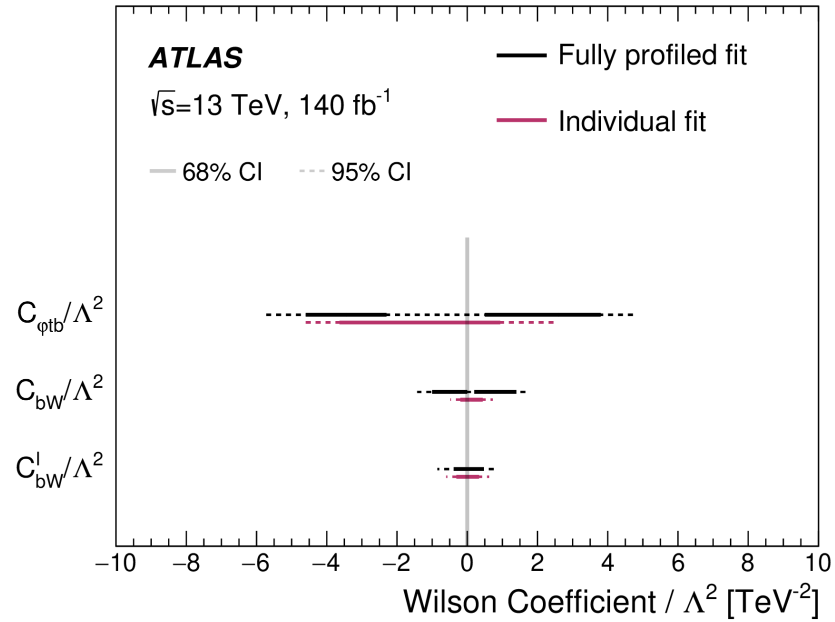


arXiv:2510.23372

Constraints on EFT via single top production

- Three different 1D fitting schemes are compared for seven Wilson coefficients.
  - Fully profiled fit: each POI scanned while profiling all others.
  - Reduced fit: coefficients dominated by quadratic dependencies are fixed to the SM.
  - Individual fit: all other POIs are fixed to the SM during the scan.





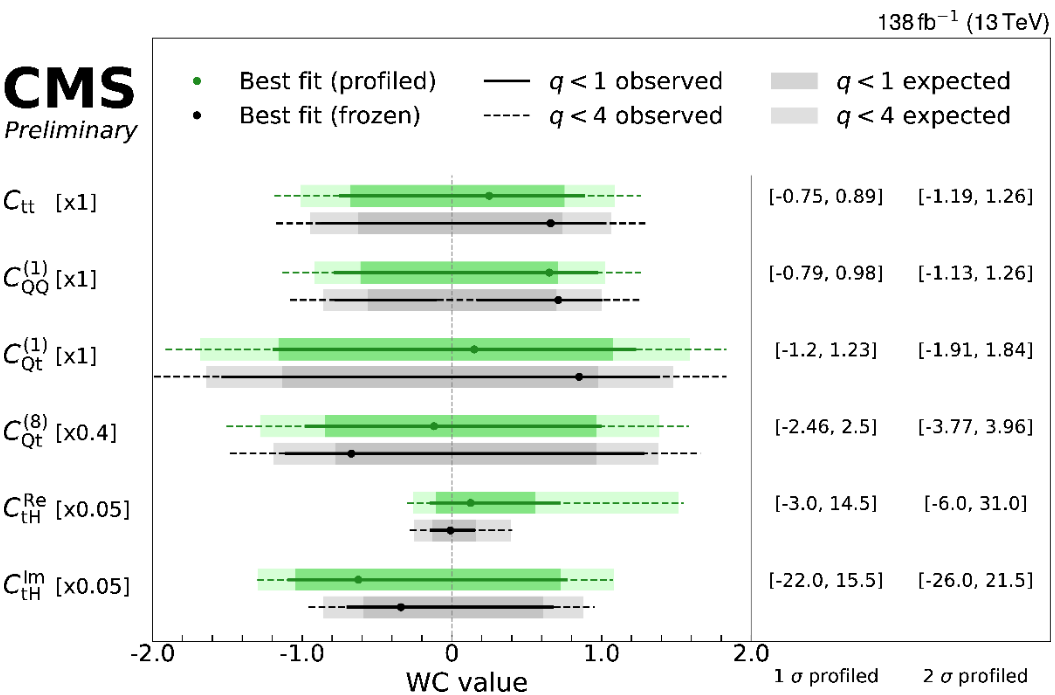
- Measurement systematics-dominated
- The best constraints to date on c_{tW} and $c_{\varphi Q}$.

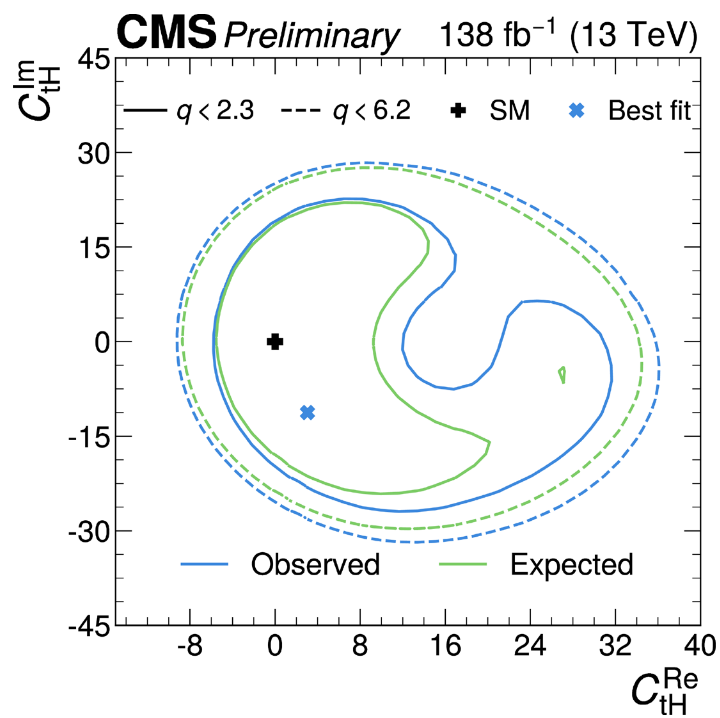
arXiv:2510.23372

New physics in three and four top processes

- Bounds on six Wilson coefficients include both linear and quadratic SMEFT contributions.
- The analysis gives the first constraints on c_{tH}^{lm} from a production measurement that includes both linear and quadratic terms.
- Yukawa modifiers are introduced and valid up to quadratic order.
  - Quoted bound on κ_t: $0.8 < |\kappa_t| < 1.3$.

CMS-PAS-TOP-24-008

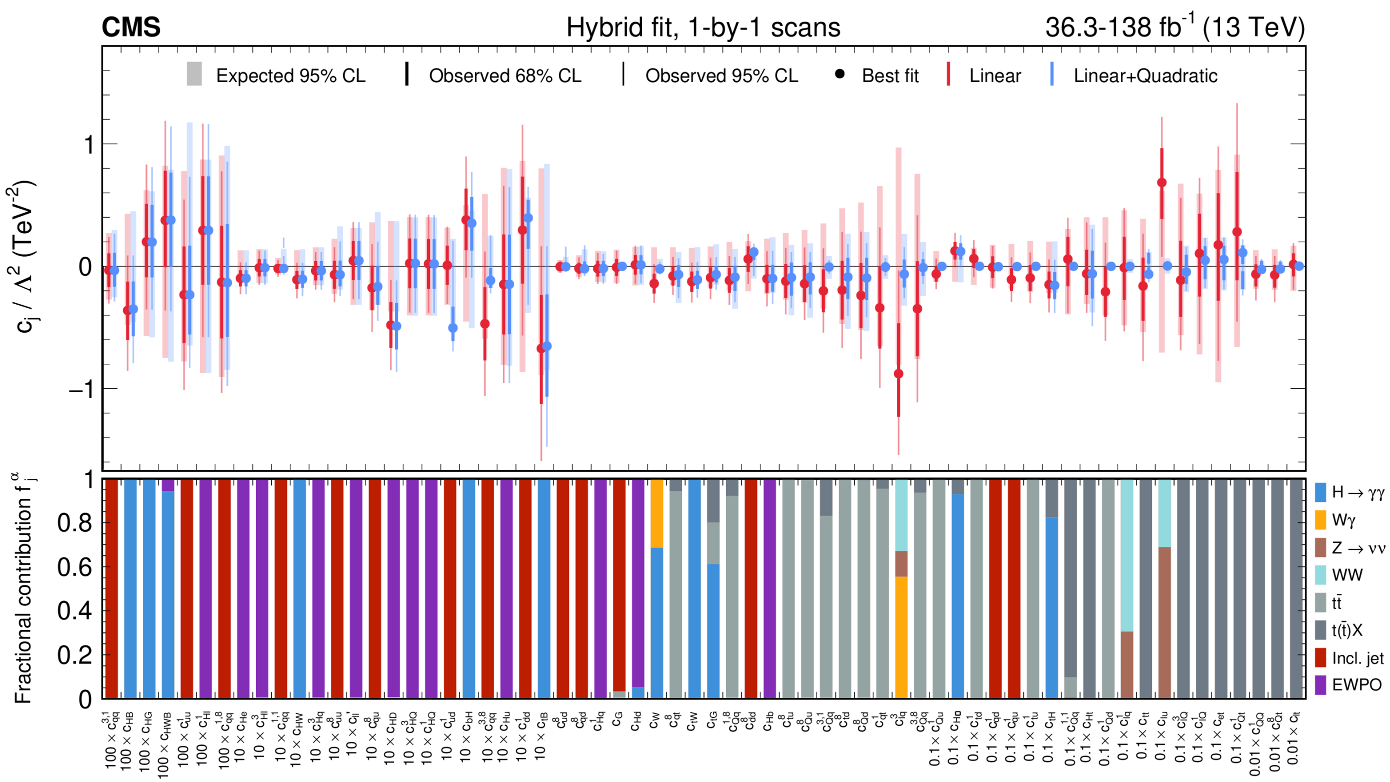




Global combination

- Global combinations are needed both to expose real degeneracies and to reveal where one sector genuinely breaks a flat direction left by another.
  - Common parameterizations, basis choices, and the linear-versus-quadratic truncation
- A simultaneous fit to measurements from the Higgs, EW, top, and multijet sectors.

SMP-24-003



Non-complete list of EFT papers in the past year

- Lots of new EFT results with Run2 and Run3 data in the past year

Data	Process	Type	Emphasis	Identifier
Run 2	ZZ→ℓℓνν; ZZjj→ℓℓννjj	Direct	aTGC/aQGC, dim-8, cutoff scale	arXiv:2511.15569
Run 2	t-channel single-top	Direct	Quadrupole differential analysis	arXiv:2510.23372
Run 2	ttWj	Direct	EW correction	arXiv:2509.19038
Run 2	W^+W^- cross section	Re-interp	Asymmetry, CP-odd observable, cutoff scale	arXiv:2505.11310
Run 2	H→WW→ℓνℓν, ggF+VBF	Re-interp	CP-odd STXS bins, PCA, detailed analysis	arXiv:2504.07686
Run 2+3	HH→bbγγ	Re-interp	ggHH, VBF HH	CDS 2942493
Run 3	H→ZZ→4ℓ	Re-interp	Cross sections	CDS 2929042
Run 2	VVZ	Re-interp	Observation, rate, clipping	arXiv:2412.15123
Run 2	EW VVjj→semi-lep	Direct	dim-8, modified SR	arXiv:2503.17461
Run 2	High-mass ττ	Re-interp	SM, tau-specific	arXiv:2503.19836
Run 2	WZ cross section	Direct	CP violation, optimal observable	arXiv:2507.03500
Run 2	HH combination	Indirect	HEFT	CMS-PAS-HIG-20-011

Non-complete list of EFT papers in the past year

Data	Process	Type	Emphasis	Identifier
Run 2	Triboson	Direct	Boosted topology	CDS 2946572
Run 2	HH combination	Re-interp	HEFT	arXiv:2510.07527
Run 2	Global combination	Re-interp	64 WC, 42 linear combinations, top+ QCD	arXiv:2504.02958
Run 2	ttZ+ VV flavor structure	Direct	Flavor separation, multi-lepton	arXiv:2507.17498
Run 2	$H \to WW \to \ell\nu\ell\nu$, ggF+ VBF	Direct	CP-odd, asymmetry	arXiv:2509.07958
Run 2	VBS $VV \to qq\ell\nu/\ell\ell$	Direct	aQGC	arXiv:2510.00118
Run 2	Nonresonant dilepton + b-jets	Direct	NP scale, 4-fermion flavor	arXiv:2506.13565
Run 2+ 3	ttZ+ tZq	Direct	CP-equivariant DNN for CP-odd observables	arXiv:2505.21206
Run 2	ggF $H \to \gamma\gamma$, ZZ, WW, $\tau\tau$	Re-interp	Differential, CP-odd, PCA	arXiv:2504.13081
Run 2	Search for yH production	Direct	Light Yukawas	arXiv:2502.05665

- Reinterpretation and direct EFT now coexist across Higgs, top, EW, and others.

Summary

- Rich landscape for EFT interpretations in Higgs/EW/Top physics and beyond

- Complementary approaches
  - Direct and re-interpretation in SMEFT/HEFT

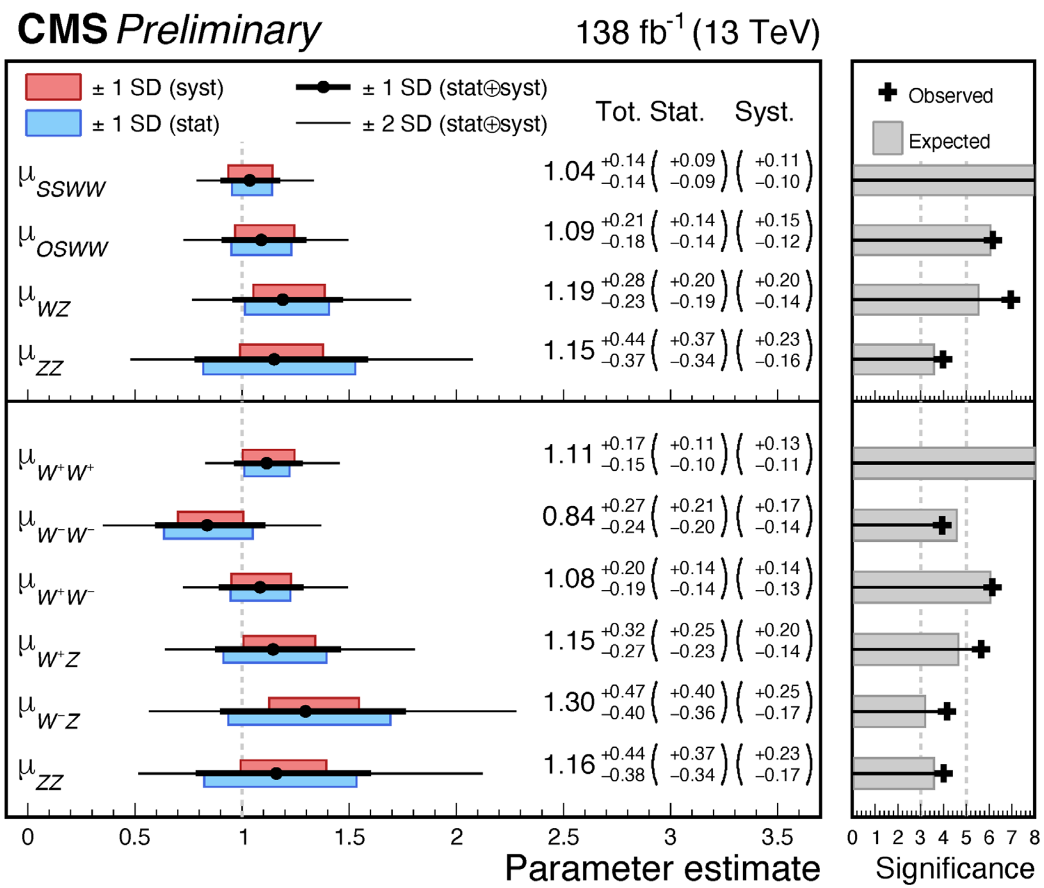
- Generally observe good agreement with SM, with some deviations to keep an eye on
  - Need to relax symmetry assumptions and explicitly test truncation validity
  - New statistical and ML methods entering both reinterpretations and direct EFT measurements

- Substantial room for new ideas and much stronger combinations with the large Run-3 dataset.

Backup

Vector Boson Scattering

- VBS measurements are crucial probes of new physics because quartic gauge vertices are present already at leading order.
- Many final states are now mature enough for EFT analyses.
- Combining several VBS final states is a promising avenue for new-physics searches.



[arXiv:2512.00502](https://arxiv.org/abs/2512.00502)

Non-complete list of EFT papers in the past year

Data	Process	Type	Emphasis	Identifier
Run 1+2	$B0 \to K^*0\ \mu+\mu-$	Direct	Angular analysis, C9, P′5, AFB	LHCb-PAPER-2025-041
13 TeV	$B0 \to K+\pi-\tau+\tau-$; $Bs0 \to K+K-\tau+\tau-$	Direct	$b \to s\tau\tau$, $C9\tau\tau/C10\tau\tau$	arXiv:2510.13716
Run 1+2	$B \to D^{**}\tau\nu$	Direct	FCCC, scalar/tensor sensitivity	PRL 135 (2025) 021802
2016–18	$\tau \to \mu\mu\mu$	Direct	LFV, dipole + 4ℓ ops	LHCb-PAPER-2025-052
Run 1+2	$Bs0 \to K-\pi+\gamma$	Direct	$b \to d\gamma$, radiative penguins	LHCb-PAPER-2025-056
2016–18	$\Lambda \to p\mu\nu$	Precision	LFU / CKM / semileptonic	arXiv:2511.15681