EFT Highlights from CMS

8th General Meeting of the LHC EFT Working Group

Fabian Stäger on behalf of the CMS Collaboration

University of Zurich UZH

CMS

2 December 2024

Analyses covered in this talk

Differential Higgs Combination

- CMS-PAS-HIG-23-013: «Combination and interpretation of fiducial differential Higgs boson production cross sections at $\sqrt{s} = 13$ TeV»

Combination across multiple sectors

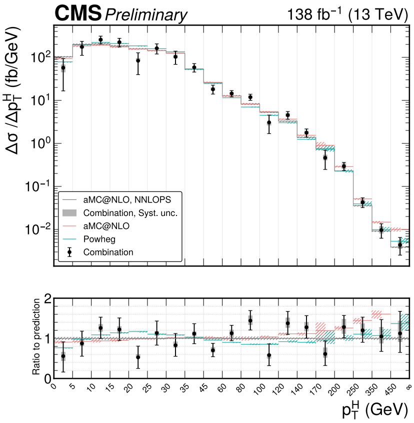
- CMS-PAS-SMP-24-003: «Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark, and multi-jet measurements»

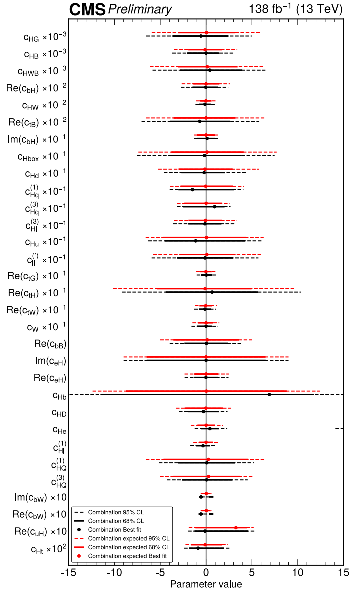
Differential Higgs Combination

CMS-PAS-HIG-23-013: «Combination and interpretation of fiducial differential Higgs boson production cross sections at $\sqrt{s} = 13$ TeV»

Differential Higgs combination

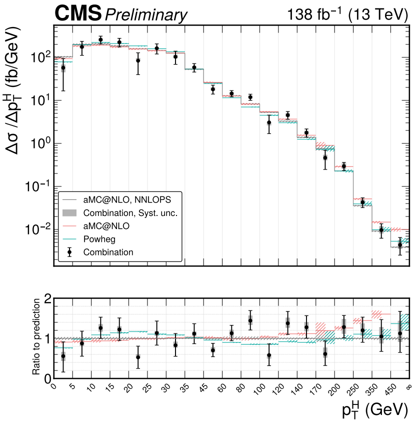
- Combination of fiducial differential Higgs measurements using the $H \to \gamma\gamma$, ZZ, WW, $\tau\tau$ channels
- 31 dim-6 operators considered (CP-even and CP-odd)
- 1-dimensional scans
- 2-d scans of CP-even and CP-odd pairs

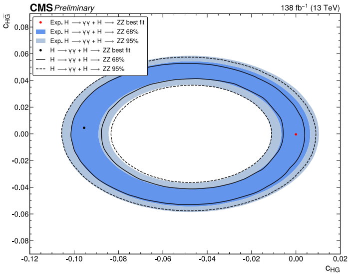


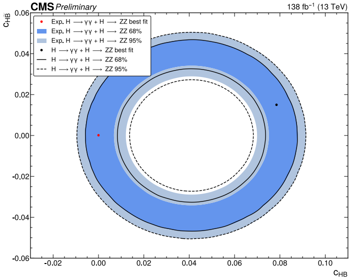


Differential Higgs combination

- Combination of fiducial differential Higgs measurements using the H $\rightarrow \gamma\gamma$, ZZ, WW, $\tau\tau$ channels
- 31 dim-6 operators considered (CP-even and CP-odd)
- 1-dimensional scans
- 2-d scans of CP-even and CP-odd pairs

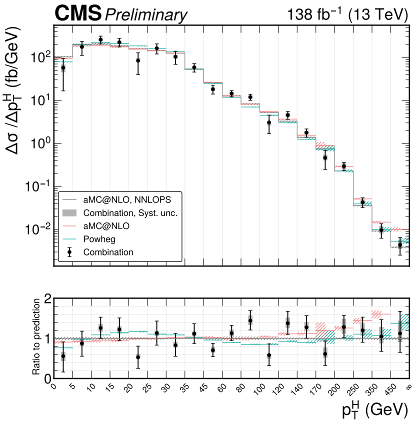


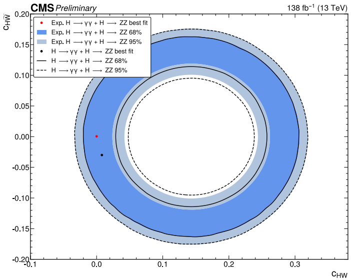


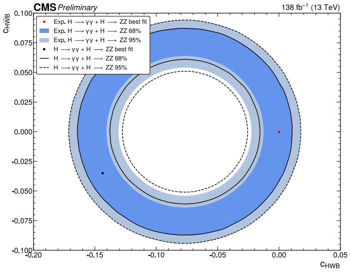


Differential Higgs combination

- Combination of fiducial differential Higgs measurements using the H $\rightarrow \gamma\gamma$, ZZ, WW, $\tau\tau$ channels
- 31 dim-6 operators considered (CP-even and CP-odd)
- 1-dimensional scans
- 2-d scans of CP-even and CP-odd pairs







Principal Component Analysis

- The available data do not contain enough information to constrain all Wilson coefficients in a simultaneous fit; unconstrained degrees of freedom (flat directions in the likelihood)
- Principal component analysis (PCA) is a useful tool to identify linear combinations of WCs that can be constrained:
  - Obtain the Hessian matrix of the likelihood parametrized in terms of the Wilson coefficients,

    $$\mathcal{H} \approx C_{\text{SMEFT}}^{-1} = P^T C^{-1} P\,,$$

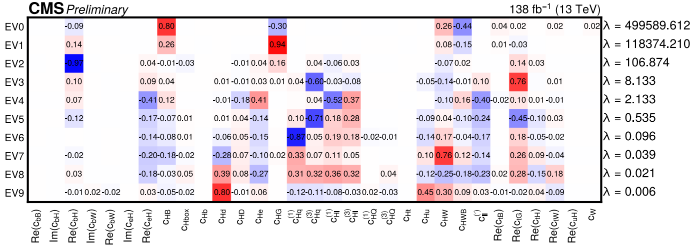
    where C is the covariance matrix between the measurement bins, and P is the matrix of the linear SMEFT parameterization

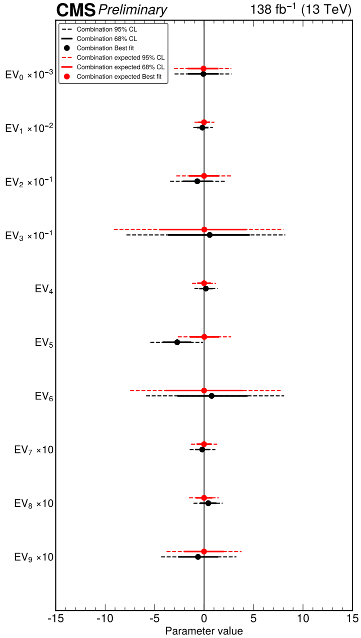
    $$P_{ij} = A^i_j\,, \quad \text{where } (\sigma \times \mathcal{B})^i_{\text{SMEFT}} = (\sigma \times \mathcal{B})^i_{\text{SM}}\Big(1 + \sum_j A^i_j c_j + \sum_{j,k} B^i_{jk} c_j c_k\Big)$$

  - Eigendecomposition of C_{SMEFT}^{-1} yields the eigenvectors (which are used to write linear combinations of Wilson coefficients, EVi), the corresponding eigenvalues λ_i and variances $1/\lambda_i$
  - Linear combinations with small eigenvalue $\lambda_i \to 0$ correspond to flat directions and are fixed to their SM value of 0

Fitting linear combinations

- Set constraints on 10 linear combinations of Wilson coefficients





Combination across multiple sectors

CMS-PAS-SMP-24-003: «Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark, and multi-jet measurements»

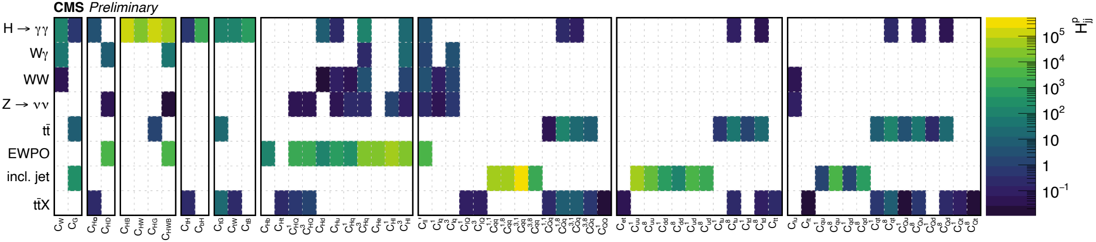
Inputs to the combination

- **Combined SMEFT interpretation of data from four sectors of the SM (Higgs, Top, Electroweak, QCD):** Seven CMS measurements + EWPO from LEP and SLC
- Inputs chosen to provide sensitivity to broad set of dim-6 SMEFT operators (64 in total), negligible overlap in event selections, small backgrounds (or estimated from data)

Analysis	Type of measurement	Observables used	Experimental likelihood
$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]	✓
$W\gamma$	Fid. diff. cross sections	$p_T^{\gamma} \times \lvert\phi_f\rvert$	✓
WW	Fid. diff. cross sections	$m_{\ell\ell}$	✓
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^{Z}	✓
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$	×
EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A_{FB}^{0,\ell}$, $A_{FB}^{0,c}$, $A_{FB}^{0,b}$	×
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$	×
$t\bar{t}X$	Direct EFT	Yields in regions of interest	✓

Inputs to the combination

- **Combined SMEFT interpretation of data from four sectors of the SM (Higgs, Top, Electroweak, QCD):** Seven CMS measurements + EWPO from LEP and SLC
- Inputs chosen to provide sensitivity to broad set of dim-6 SMEFT operators (64 in total), negligible overlap in event selections, small backgrounds (or estimated from data)
- Which input channel is sensitive to which operators?



- plot shows diagonal entries of the Hessian matrix, $H_{jk} = \frac{\partial^2 \ln \mathcal{L}}{\partial c_j \partial c_k}$
  - $(H^p_{jj})^{-1/2}$: estimate of half the expected 68% confidence interval on Wilson coefficient c_j/Λ^2, evaluated with input channel p)

SMEFT parameterization

- Scattering cross section is proportional to matrix element squared

$$\sigma = |\mathcal{M}_{\mathrm{SM}} + \sum_j \frac{c_j}{\Lambda^2}\mathcal{M}_j|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\sum_j \frac{c_j}{\Lambda^2}\mathrm{Re}\left(\mathcal{M}_j\mathcal{M}^*_{\mathrm{SM}}\right) + \sum_{j,k}\frac{c_j c_k}{\Lambda^4}\mathrm{Re}\left(\mathcal{M}_j\mathcal{M}^*_k\right)$$

- This means that cross section of process p in kinematic bin i can be written as

$$\sigma^{i,p}_{\mathrm{SMEFT}} = \sigma^{i,p}_{\mathrm{SM}} + \sigma^{i,p}_{\mathrm{int.}}(\vec{c}) + \sigma^{i,p}_{\mathrm{BSM}}(\vec{c}) = \sigma^{i,p}_{\mathrm{SM}}\left(1 + \sum_j A^{i,p}_j \frac{c_j}{\Lambda^2} + \sum_{j,k} B^{i,p}_{jk}\frac{c_j c_k}{\Lambda^4}\right)$$

  - Majority of results we report use parameterizations truncated at $\mathcal{O}(c/\Lambda^2)$ (linear terms)

- $A^{i,p}_j$, $B^{i,p}_{jk}$ computed using `MG5_aMC@NLO`+`Pythia`+`SMEFTsim3` (`SMEFT@NLO` for gg $\rightarrow$ H, ZH)
- SMEFT modifications of masses and decay widths also taken into account
- For H $\rightarrow \gamma\gamma$ decay and EWPO, analytic calculations are used

Modifications to input analyses and likelihood model

Likelihood model:

- Combined likelihood model:

$$\mathcal{L}\left(\text{data}\,;\,\vec{c},\vec{\nu}\right)=\mathcal{L}^{\text{expt}}\left(\vec{c},\vec{\nu}\right)\mathcal{L}^{\text{simpl}}\left(\vec{c}\right)$$

- «experimental likelihood»:

$$\mathcal{L}^{\text{expt}}\left(\vec{c},\vec{\nu}\right)=\prod_{i}\text{Poisson}\Big(n_i\,\Big|\,\sum_j \mu'^{j}(\vec{c})s_i^j(\vec{\nu})+b_i(\vec{\nu})\Big)\prod_k p_k\left(y_k\,\middle|\,\nu_k\right)$$

  - covers the $\mathrm{H}\to\gamma\gamma$, $\mathrm{W}\gamma$, WW, and $\mathrm{Z}\to\nu\nu$ measurements
  - in the $\mathrm{t\bar{t}X}$ measurement, instead of $\sum_j \mu'^{j}(\vec{c})s_i^j(\vec{\nu})$, signal yield takes the form $\sum_j s_i^j(\vec{\nu},\vec{c})$

- «simplified likelihood»:

$$\mathcal{L}^{\text{simpl}}\left(\vec{c}\right)=\frac{\exp\Big(-\frac{1}{2}\big(\vec{\mu}(\vec{c})-\hat{\vec{\mu}}\big)^T V^{-1}\big(\vec{\mu}(\vec{c})-\hat{\vec{\mu}}\big)\Big)}{\sqrt{(2\pi)^m\det(V)}}$$

  - covers the EWPO, $\mathrm{t\bar{t}}$, and inclusive jet measurements

Modifications to input analyses and likelihood model

Likelihood model:

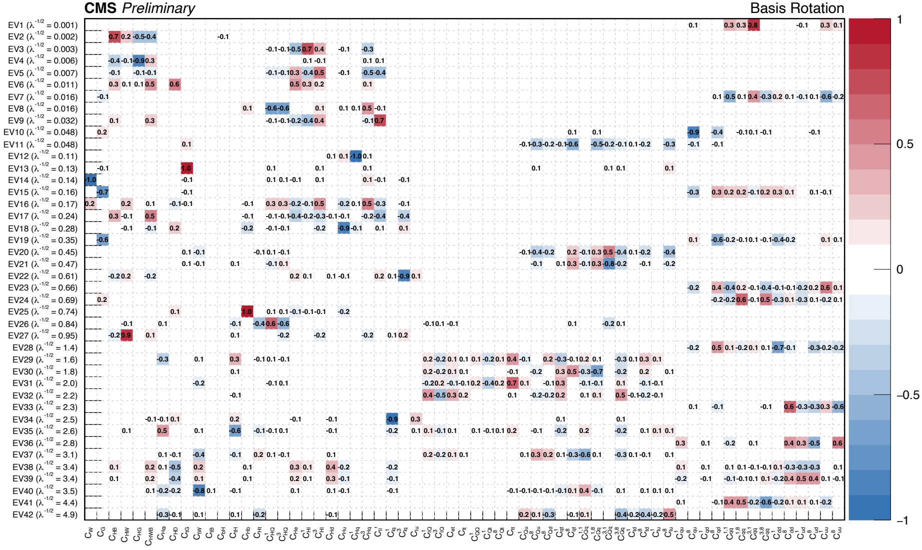
- Combined likelihood model: $\mathcal{L}\,(\text{data}\,;\,\vec{c},\vec{\nu}) = \mathcal{L}^{\text{expt}}\,(\vec{c},\vec{\nu})\,\mathcal{L}^{\text{simpl}}\,(\vec{c})$
- $\mathcal{L}^{\text{expt}}(\vec{c},\vec{\nu}) = \prod_i \text{Poisson}\Big(n_i \,\Big|\, \sum_j \mu'^j(\vec{c}) s_i^j(\vec{\nu}) + b_i(\vec{\nu})\Big) \prod_k p_k\,\big(y_k \,\big|\, \nu_k\big)$ (H, Wγ, WW, Z, t$\bar{\text{t}}$X)
- $\mathcal{L}^{\text{simpl}}\,(\vec{c}) = \exp\Big(-\frac{1}{2}\big(\vec{\mu}(\vec{c}) - \hat{\vec{\mu}}\big)^T V^{-1}\big(\vec{\mu}(\vec{c}) - \hat{\vec{\mu}}\big)\Big) \Big/ \sqrt{(2\pi)^m \det(V)}$ (t$\bar{\text{t}}$, inclusive jet, EWPO)

Modifications to input measurements:

- SM predictions for inclusive jet measurement rederived with up-to-date PDF set
- For all (CMS) measurements, derived theoretical uncertainties on SM predictions (PDF, factorization and renormalization scale uncertainties)
- PDF and luminosity uncertainties (partially) correlated between the input measurements
- SMEFT parameterizations derived up to $\mathcal{O}(c^2/\Lambda^4)$ in a consistent way for all input measurements
    - For the «direct» EFT measurement t$\bar{\text{t}}$X:
        - basis rotation from `dim6top` to SMEFT `topU3l` as implemented in SMEFTsim3
        - added operators that were not considered in original analysis: $\mathcal{Q}_{\text{H}\Box}$ and 2-heavy-2-light-quark

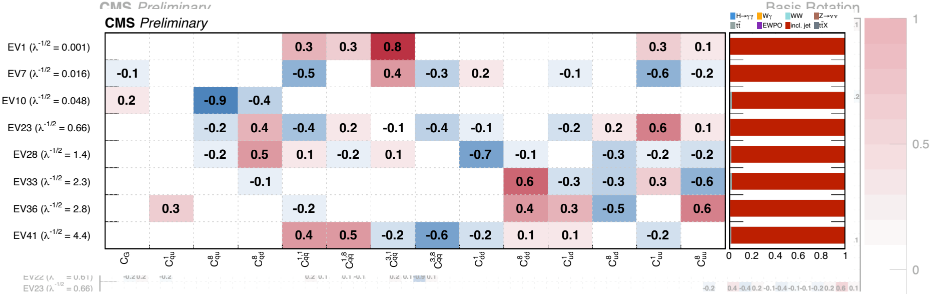
Basis rotation

- Perform PCA to identify 42 linear combinations of Wilson coefficients that can be constrained simultaneously
- 22 «flat directions» ($\lambda < 0.04$) fixed to zero

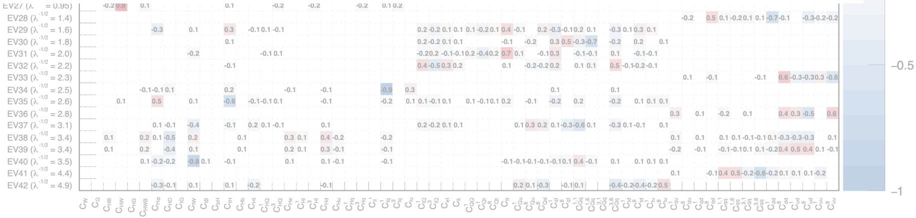


Basis rotation

- Perform PCA to identify 42 linear combinations of Wilson coefficients that can be constrained simultaneously
- 22 «flat directions» ($\lambda < 0.04$) fixed to zero

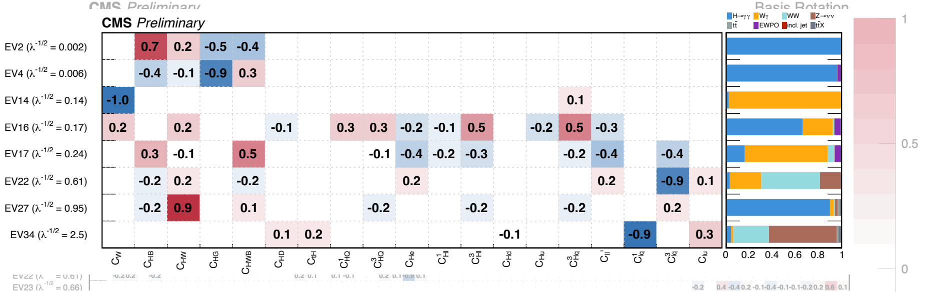


- 8 linear combinations constrained by inclusive jet measurement ($\mathcal{Q}_G$, ψ^4 (4-light-quark) operators)

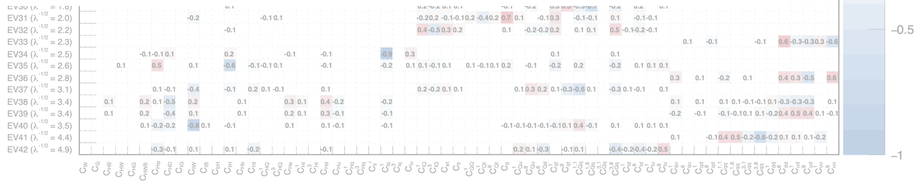


Basis rotation

- Perform PCA to identify 42 linear combinations of Wilson coefficients that can be constrained simultaneously
- 22 «flat directions» ($\lambda < 0.04$) fixed to zero

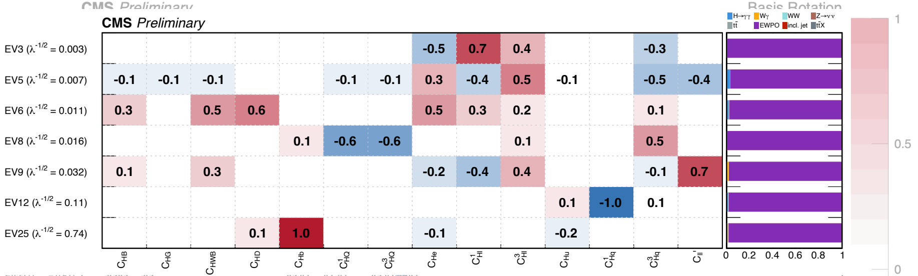


- 8 linear combinations constrained by inclusive jet measurement ($\mathcal{Q}_{\mathrm{G}}$, ψ^4 (4-light-quark) operators)
- 8 by Higgs and electroweak measurements ($\mathcal{Q}_{\mathrm{W}}$, $\mathcal{Q}_{\mathrm{HD}}$, H+V, H+$\psi$, ψ^4 (2ℓ or 4ℓ) operators)



Basis rotation

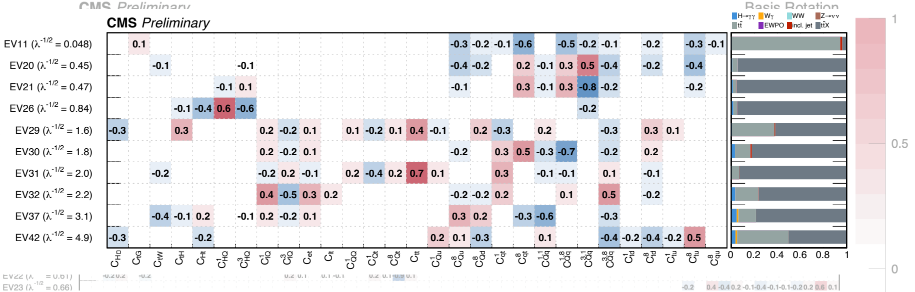
- Perform PCA to identify 42 linear combinations of Wilson coefficients that can be constrained simultaneously
- 22 «flat directions» ($\lambda < 0.04$) fixed to zero



- 8 linear combinations constrained by inclusive jet measurement ($\mathcal{Q}_G$, ψ^4 (4-light-quark) operators)
- 8 by Higgs and electroweak measurements ($\mathcal{Q}_W$, $\mathcal{Q}_{HD}$, H+V, H+ψ, ψ^4 (2ℓ or 4ℓ) operators)
- 7 by EWPO ($\mathcal{Q}_{HD}$, $\mathcal{Q}_{ll}$, H+V, H+ψ operators)

Basis rotation

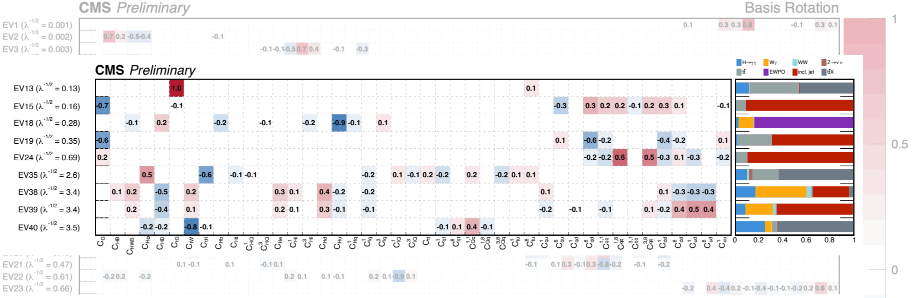
- Perform PCA to identify 42 linear combinations of Wilson coefficients that can be constrained simultaneously
- 22 «flat directions» ($\lambda < 0.04$) fixed to zero



- 8 linear combinations constrained by inclusive jet measurement ($\mathcal{Q}_{\mathrm{G}}$, ψ^4 (4-light-quark) operators)
- 8 by Higgs and electroweak measurements ($\mathcal{Q}_{\mathrm{W}}$, $\mathcal{Q}_{\mathrm{HD}}$, H+V, H+$\psi$, ψ^4 (2ℓ or 4ℓ) operators)
- 7 by EWPO ($\mathcal{Q}_{\mathrm{HD}}$, $\mathcal{Q}_{\mathrm{ll}}$, H+V, H+$\psi$ operators)
- 10 by top quark measurements ($\mathcal{Q}_{\mathrm{H}\Box}$, V+$\psi$, H+$\psi$, ψ^4 (2- or 4-heavy-quark) operators)

Basis rotation

- Perform PCA to identify 42 linear combinations of Wilson coefficients that can be constrained simultaneously
- 22 «flat directions» ($\lambda < 0.04$) fixed to zero



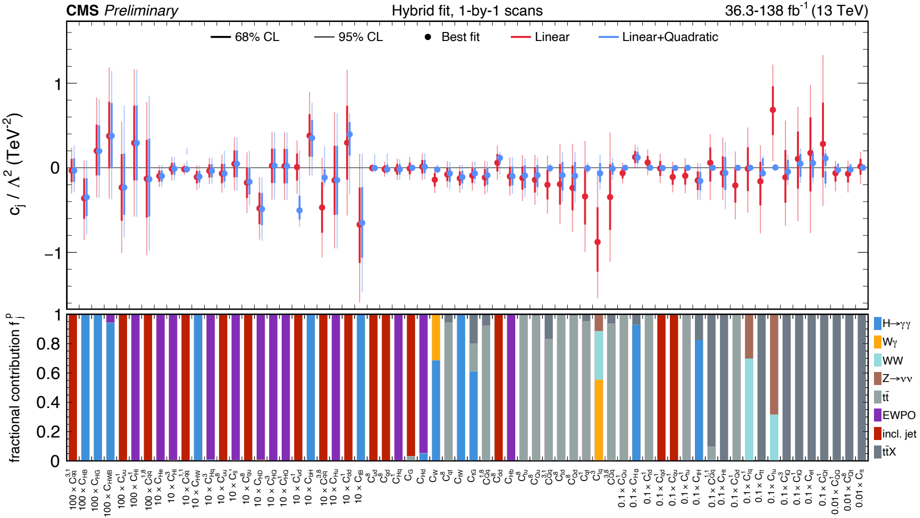
- 8 linear combinations constrained by inclusive jet measurement ($\mathcal{Q}_{\mathrm{G}}$, ψ^4 (4-light-quark) operators)
- 8 by Higgs and electroweak measurements ($\mathcal{Q}_{\mathrm{W}}$, $\mathcal{Q}_{\mathrm{HD}}$, H+V, H+$\psi$, ψ^4 (2ℓ or 4ℓ) operators)
- 7 by EWPO ($\mathcal{Q}_{\mathrm{HD}}$, $\mathcal{Q}_{\mathrm{ll}}$, H+V, H+$\psi$ operators)
- 10 by top quark measurements ($\mathcal{Q}_{\mathrm{H}\Box}$, V+$\psi$, H+$\psi$, ψ^4 (2- or 4-heavy-quark) operators)
- 9 by a mixture
  - Higgs+Top (EV13, EV35, EV40), multi-jet+Top (EV15, EV19, EV24)
  - CMS EWK+EWPO (EV18), Higgs+EWK+multi-jet (EV38, EV39)

Individual constraints on Wilson coefficients

- Setting constraints on 64 individual Wilson coefficients (each obtained by fixing all others to 0)
- 95% confidence intervals range from around ±20 to ±0.003
- Breakdown of contributions of each measurement p, calculated as

$$f_j^p = \frac{H_{jj}^p}{H_{jj}^{\text{comb.}}}$$

- Several operators constrained by multiple analyses

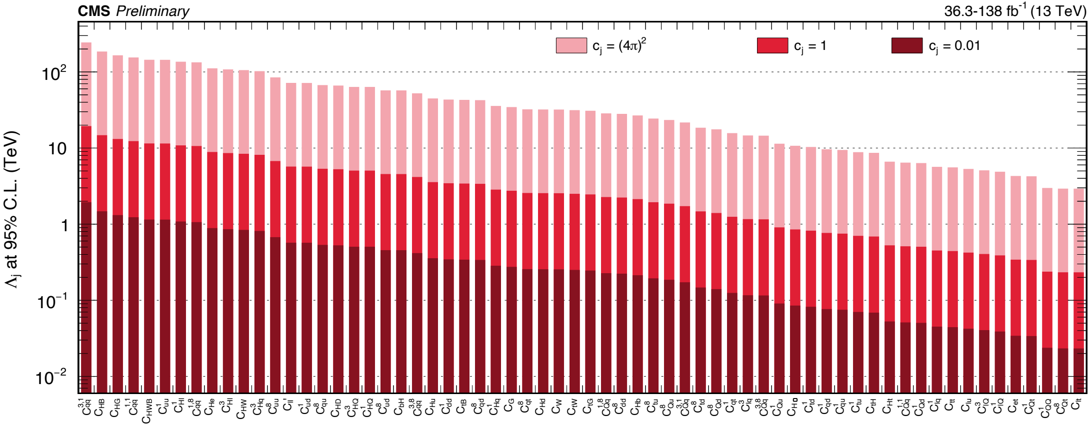


Individual constraints on Wilson coefficients

- Several Wilson coefficients receive significant constraints from multiple measurements, e.g.
  - Through combination of **$\mathrm{t\bar{t}}$ cross section measurements and the $\mathrm{t\bar{t}X}$ EFT analysis**, we obtain stronger constraints on the **2-heavy-2-light quark operators**
  - Combination of **$\mathrm{W}\gamma$ and $\mathrm{H} \to \gamma\gamma$** yields an improved constraint on $\boldsymbol{c_W}$ with respect to any single-analysis result (linear-only sensitivity ∼45% higher than CMS Wγ result)
  - **2-(light)quark-2-lepton operators** constrained by combination of **EW vector boson** measurements
  - Interplay of Higgs- and Top-sectors (c_{tG}, c_{tH}, $c_{H\Box}$)
- Comparison of results with linear-only ($\mathcal{O}(c/\Lambda^2)$) and linear+quadratic parameterization ($\mathcal{O}(c^2/\Lambda^4)$) gives an indication of how much the inclusion of orders $1/\Lambda^4$ could change the sensitivity of the results

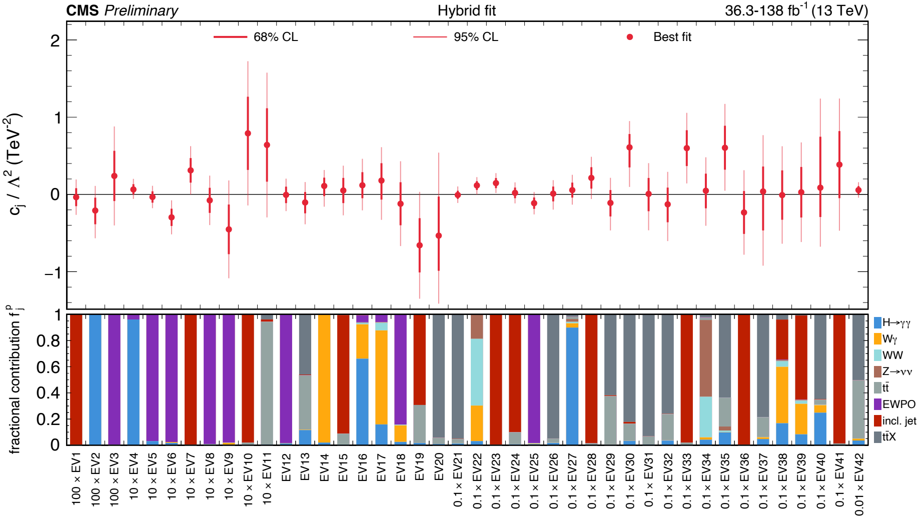
Lower limits on energy scales of new physics

- Translate constraints on c_j/Λ^2 into 95% CL lower limits on the scale of new physics Λ_j, by setting c_j to specific values (of 0.01, 1 and $(4\pi)^2$)



Constraints on linear combinations of Wilson coefficients

- Setting constraints on 42 linear combinations of Wilson coefficients (each varied simultanoeusly)
- Majority of POI receives significant contributions from multiple channels
- 8 linear combinations constrained by inclusive jet measurement
- 8 by Higgs and electroweak measurements
- 7 by EWPO
- 10 by top quark measurements
- 9 by a mixture



Constraints on linear combinations of Wilson coefficients

- Setting constraints on 42 linear combinations of Wilson coefficients (varied simultanoeusly)
- 95% confidence intervals range from around ± 10 to ± 0.002
- Majority of POI receives significant contributions from multiple channels
  - 8 linear combinations constrained by inclusive jet measurement
  - 8 by Higgs and electroweak measurements
  - 7 by EWPO
  - 10 by top quark measurements
  - 9 by a mixture
- The p-value for the compatibility with the SM is 1.7%
  - Deviation from SM is mostly driven by inclusive jet measurement
  - When excluding it from the combination, the p-value is found to be 26%

Summary

- Differential Higgs combination ($H \to \gamma\gamma$, ZZ, WW, $\tau\tau$) setting constraints on 28 CP-even and 3 CP-odd dimension-6 operators individually / 10 linear combinations simultaneously
  - no deviations from SM expectation observed
- Combination of measurements from Higgs, Top, Electroweak, and QCD sectors constraining 64 dimension-6 operators individually / 42 linear combination simultaneously
  - some deviation from SM (p-value 1.7%), mostly driven by multijet production
- Developments for future global combinations: Combine and (re-)interpret different types of measurements (differential cross sections and direct EFT measurements) in a consistent way

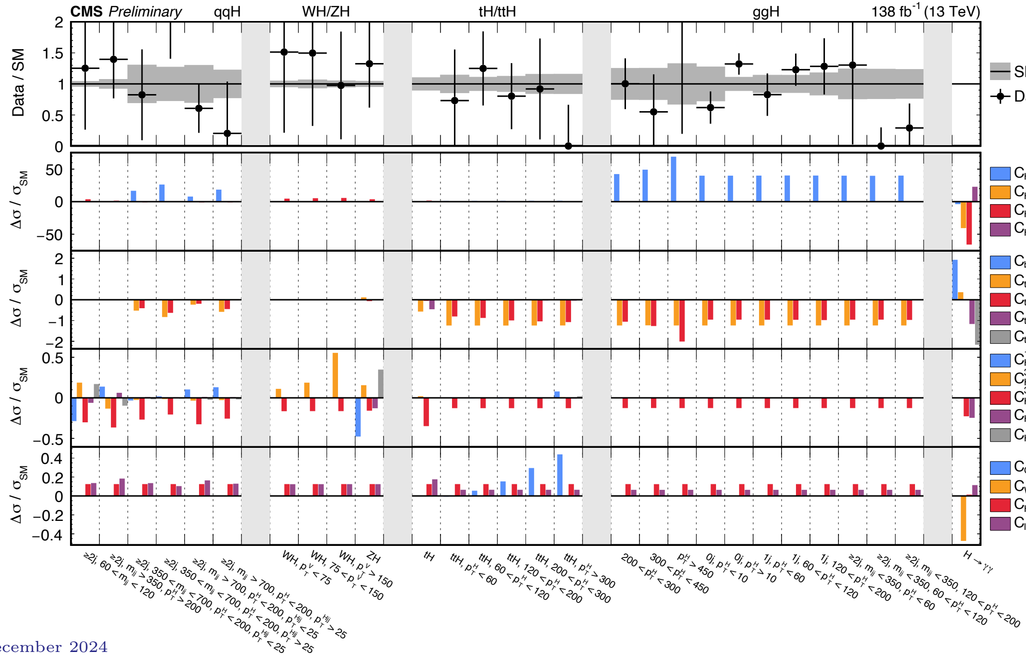
BACKUP

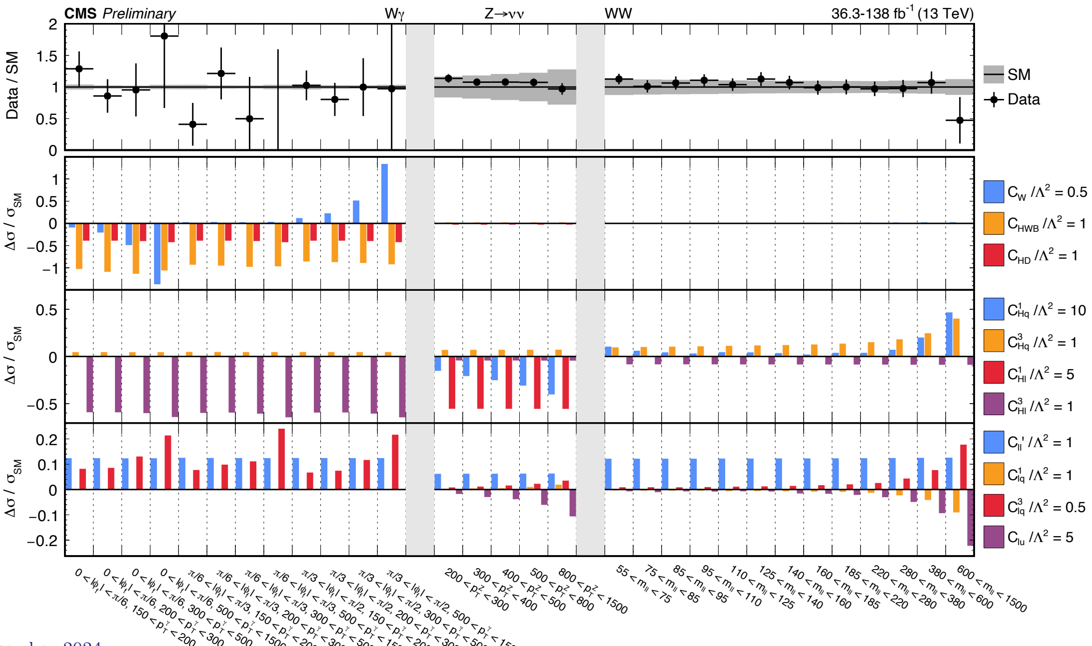
Linear combination	expected linear	observed linear	Wilson coefficient	expected linear	observed linear
$EV1/\Lambda^2$	$[-0.002, 0.002]$	$[-0.003, 0.002]$	$EV2/\Lambda^2$	$[-0.003, 0.003]$	$[-0.006, 0.001]$
$EV3/\Lambda^2$	$[-0.006, 0.006]$	$[-0.004, 0.009]$	$EV4/\Lambda^2$	$[-0.012, 0.013]$	$[-0.006, 0.020]$
$EV5/\Lambda^2$	$[-0.014, 0.014]$	$[-0.018, 0.011]$	$EV6/\Lambda^2$	$[-0.022, 0.022]$	$[-0.052, -0.008]$
$EV7/\Lambda^2$	$[-0.031, 0.031]$	$[-0.000, 0.062]$	$EV8/\Lambda^2$	$[-0.032, 0.032]$	$[-0.040, 0.024]$
$EV9/\Lambda^2$	$[-0.063, 0.063]$	$[-0.11, 0.018]$	$EV10/\Lambda^2$	$[-0.093, 0.093]$	$[-0.014, 0.17]$
$EV11/\Lambda^2$	$[-0.094, 0.094]$	$[-0.030, 0.16]$	$EV12/\Lambda^2$	$[-0.21, 0.21]$	$[-0.22, 0.20]$
$EV13/\Lambda^2$	$[-0.27, 0.25]$	$[-0.39, 0.16]$	$EV14/\Lambda^2$	$[-0.29, 0.26]$	$[-0.16, 0.32]$
$EV15/\Lambda^2$	$[-0.32, 0.32]$	$[-0.27, 0.37]$	$EV16/\Lambda^2$	$[-0.32, 0.33]$	$[-0.21, 0.46]$
$EV17/\Lambda^2$	$[-0.51, 0.44]$	$[-0.33, 0.61]$	$EV18/\Lambda^2$	$[-0.55, 0.55]$	$[-0.67, 0.43]$
$EV19/\Lambda^2$	$[-0.69, 0.69]$	$[-1.4, 0.033]$	$EV20/\Lambda^2$	$[-0.78, 1.0]$	$[-1.4, 0.54]$
$EV21/\Lambda^2$	$[-0.91, 0.99]$	$[-1.1, 1.0]$	$EV22/\Lambda^2$	$[-1.3, 1.1]$	$[-0.015, 2.2]$
$EV23/\Lambda^2$	$[-1.3, 1.3]$	$[0.18, 2.8]$	$EV24/\Lambda^2$	$[-1.4, 1.4]$	$[-1.2, 1.6]$
$EV25/\Lambda^2$	$[-1.5, 1.5]$	$[-2.6, 0.32]$	$EV26/\Lambda^2$	$[-1.8, 1.5]$	$[-2.0, 1.8]$
$EV27/\Lambda^2$	$[-1.8, 1.9]$	$[-1.3, 2.5]$	$EV28/\Lambda^2$	$[-2.7, 2.7]$	$[-0.60, 4.9]$
$EV29/\Lambda^2$	$[-3.4, 3.1]$	$[-4.7, 2.1]$	$EV30/\Lambda^2$	$[-3.7, 3.3]$	$[0.97, 9.5]$
$EV31/\Lambda^2$	$[-4.4, 3.7]$	$[-4.6, 4.0]$	$EV32/\Lambda^2$	$[-4.6, 4.1]$	$[-6.0, 2.9]$
$EV33/\Lambda^2$	$[-4.6, 4.6]$	$[1.4, 11]$	$EV34/\Lambda^2$	$[-5.0, 4.7]$	$[-4.1, 4.8]$
$EV35/\Lambda^2$	$[-5.0, 5.1]$	$[0.48, 12]$	$EV36/\Lambda^2$	$[-5.5, 5.5]$	$[-7.8, 3.1]$
$EV37/\Lambda^2$	$[-6.2, 6.3]$	$[-9.2, 7.7]$	$EV38/\Lambda^2$	$[-6.2, 6.3]$	$[-6.4, 6.2]$
$EV39/\Lambda^2$	$[-6.4, 6.5]$	$[-6.2, 6.7]$	$EV40/\Lambda^2$	$[-7.6, 7.1]$	$[-6.8, 12]$
$EV41/\Lambda^2$	$[-8.6, 8.6]$	$[-4.7, 12]$	$EV42/\Lambda^2$	$[-9.5, 9.6]$	$[-4.2, 16]$

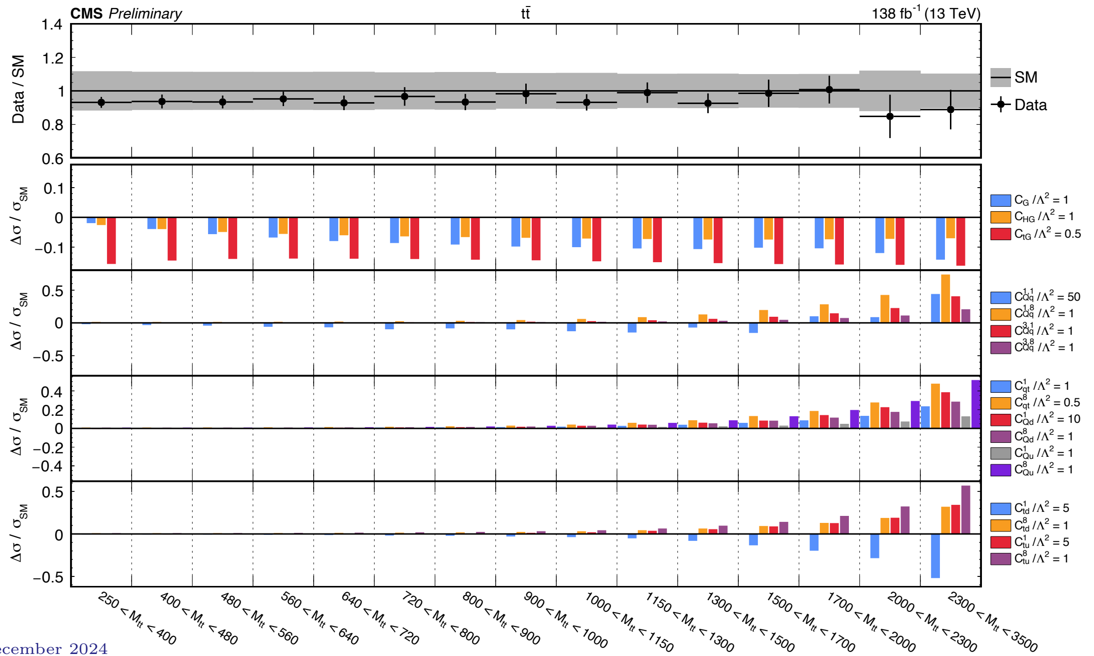
Wilson coefficient	expected linear	observed linear	expected linear+quadratic	observed linear+quadratic
$c_{qq}^{(3,1)}/\Lambda^2$	$[-0.003, 0.003]$	$[-0.003, 0.002]$	$[-0.003, 0.003]$	$[-0.003, 0.003]$
c_{HB}/Λ^2	$[-0.005, 0.004]$	$[-0.009, 0.001]$	$[-0.005, 0.004]$	$[-0.008, 0.001]$
c_{HG}/Λ^2	$[-0.006, 0.006]$	$[-0.004, 0.008]$	$[-0.006, 0.006]$	$[-0.004, 0.008]$
$c_{qq}^{(1,1)}/\Lambda^2$	$[-0.007, 0.007]$	$[-0.008, 0.005]$	$[-0.005, 0.014]$	$[-0.007, 0.008]$
$c_{uu}^{(1)}/\Lambda^2$	$[-0.008, 0.008]$	$[-0.010, 0.005]$	$[-0.006, 0.012]$	$[-0.008, 0.007]$
c_{HWB}/Λ^2	$[-0.007, 0.008]$	$[-0.004, 0.012]$	$[-0.008, 0.008]$	$[-0.004, 0.011]$
$c_{Hl}^{(1)}/\Lambda^2$	$[-0.009, 0.009]$	$[-0.006, 0.012]$	$[-0.009, 0.009]$	$[-0.006, 0.012]$
$c_{qq}^{(1,8)}/\Lambda^2$	$[-0.009, 0.009]$	$[-0.010, 0.008]$	$[-0.008, 0.010]$	$[-0.010, 0.009]$
c_{He}/Λ^2	$[-0.013, 0.013]$	$[-0.023, 0.003]$	$[-0.013, 0.013]$	$[-0.023, 0.003]$
$c_{Hl}^{(3)}/\Lambda^2$	$[-0.014, 0.014]$	$[-0.015, 0.013]$	$[-0.014, 0.014]$	$[-0.015, 0.013]$
c_{HW}/Λ^2	$[-0.015, 0.013]$	$[-0.026, 0.003]$	$[-0.014, 0.014]$	$[-0.024, 0.003]$
$c_{Hq}^{(3)}/\Lambda^2$	$[-0.015, 0.015]$	$[-0.019, 0.012]$	$[-0.015, 0.015]$	$[-0.019, 0.012]$
$c_{uu}^{(8)}/\Lambda^2$	$[-0.022, 0.022]$	$[-0.029, 0.016]$	$[-0.019, 0.033]$	$[-0.024, 0.020]$
c'_{ll}/Λ^2	$[-0.031, 0.031]$	$[-0.027, 0.036]$	$[-0.031, 0.031]$	$[-0.027, 0.036]$
$c_{ud}^{(1)}/\Lambda^2$	$[-0.032, 0.032]$	$[-0.031, 0.032]$	$[-0.054, 0.022]$	$[-0.070, 0.021]$
$c_{qu}^{(8)}/\Lambda^2$	$[-0.036, 0.036]$	$[-0.054, 0.018]$	$[-0.031, 0.044]$	$[-0.045, 0.020]$
c_{HD}/Λ^2	$[-0.037, 0.037]$	$[-0.085, -0.011]$	$[-0.037, 0.037]$	$[-0.086, -0.012]$
$c_{HQ}^{(3)}/\Lambda^2$	$[-0.040, 0.040]$	$[-0.038, 0.042]$	$[-0.040, 0.040]$	$[-0.038, 0.042]$
$c_{HQ}^{(1)}/\Lambda^2$	$[-0.040, 0.040]$	$[-0.038, 0.042]$	$[-0.040, 0.040]$	$[-0.038, 0.042]$
$\mathrm{Re}(c_{bH})/\Lambda^2$	$[-0.045, 0.050]$	$[-0.009, 0.090]$	$[-0.051, 0.046]$	$[-0.009, 0.077]$
$c_{ud}^{(8)}/\Lambda^2$	$[-0.049, 0.049]$	$[-0.052, 0.046]$	$[-0.041, 0.075]$	$[-0.045, 0.16]$
$c_{qq}^{(3,8)}/\Lambda^2$	$[-0.059, 0.059]$	$[-0.11, 0.012]$	$[-0.018, 0.025]$	$[-0.022, 0.025]$

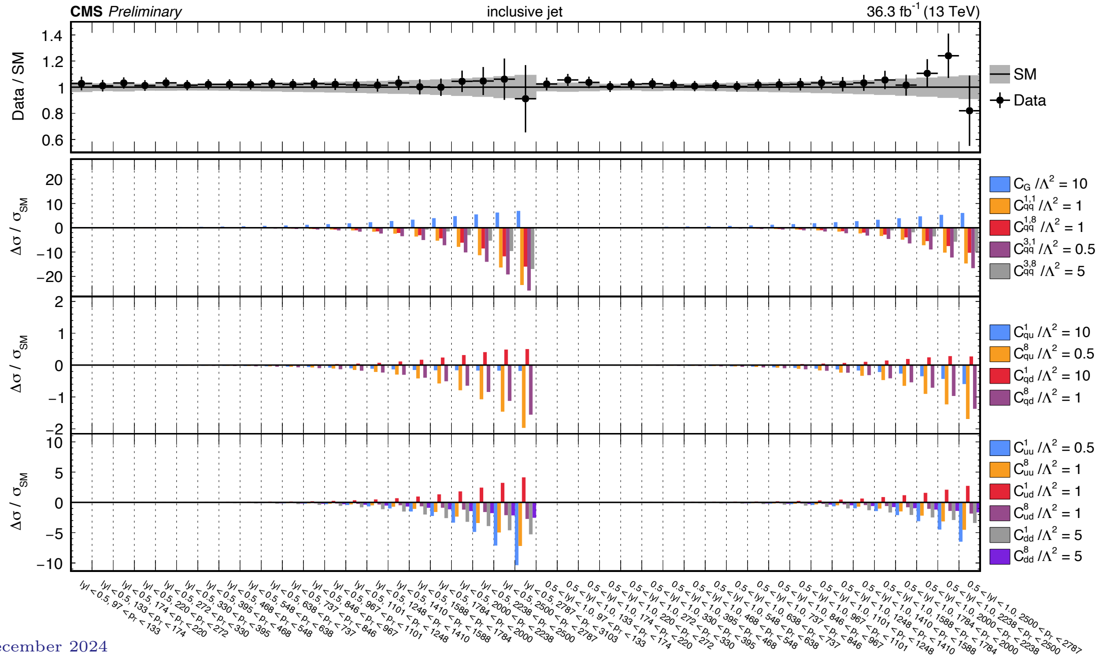
c_{Hu}/Λ^2	$[-0.081, 0.080]$	$[-0.095, 0.066]$	$[-0.081, 0.080]$	$[-0.095, 0.065]$
$\mathrm{Re}(c_{tB})/\Lambda^2$	$[-0.089, 0.080]$	$[-0.16, 0.016]$	$[-0.085, 0.084]$	$[-0.15, 0.016]$
$c_{dd}^{(1)}/\Lambda^2$	$[-0.086, 0.086]$	$[-0.057, 0.12]$	$[-0.038, 0.056]$	$[-0.031, 0.065]$
$c_{qd}^{(8)}/\Lambda^2$	$[-0.089, 0.089]$	$[-0.11, 0.073]$	$[-0.066, 0.14]$	$[-0.080, 0.17]$
$c_{Hq}^{(1)}/\Lambda^2$	$[-0.13, 0.13]$	$[-0.15, 0.11]$	$[-0.13, 0.12]$	$[-0.14, 0.10]$
c_{G}/Λ^2	$[-0.14, 0.14]$	$[-0.14, 0.13]$	$[-0.017, 0.015]$	$[-0.016, 0.014]$
$c_{qt}^{(8)}/\Lambda^2$	$[-0.15, 0.15]$	$[-0.23, 0.076]$	$[-0.30, 0.12]$	$[-0.26, 0.066]$
$\mathrm{Re}(c_{tW})/\Lambda^2$	$[-0.17, 0.15]$	$[-0.30, 0.031]$	$[-0.16, 0.16]$	$[-0.26, 0.034]$
c_{Hd}/Λ^2	$[-0.16, 0.16]$	$[-0.14, 0.17]$	$[-0.15, 0.16]$	$[-0.14, 0.17]$
c_{W}/Λ^2	$[-0.16, 0.15]$	$[-0.30, 0.015]$	$[-0.061, 0.061]$	$[-0.065, 0.037]$
$\mathrm{Re}(c_{tG})/\Lambda^2$	$[-0.17, 0.16]$	$[-0.27, 0.070]$	$[-0.15, 0.18]$	$[-0.19, 0.074]$
$c_{Qq}^{(1,8)}/\Lambda^2$	$[-0.20, 0.20]$	$[-0.31, 0.084]$	$[-0.35, 0.14]$	$[-0.29, 0.075]$
$c_{dd}^{(8)}/\Lambda^2$	$[-0.20, 0.20]$	$[-0.14, 0.26]$	$[-0.10, 0.16]$	$[-0.081, 0.18]$
c_{Hb}/Λ^2	$[-0.22, 0.22]$	$[-0.33, 0.12]$	$[-0.22, 0.24]$	$[-0.31, 0.13]$
$c_{tu}^{(8)}/\Lambda^2$	$[-0.27, 0.27]$	$[-0.39, 0.15]$	$[-0.40, 0.18]$	$[-0.34, 0.11]$
$c_{Qu}^{(8)}/\Lambda^2$	$[-0.30, 0.30]$	$[-0.44, 0.15]$	$[-0.42, 0.19]$	$[-0.34, 0.12]$
$c_{Qq}^{(3,1)}/\Lambda^2$	$[-0.35, 0.35]$	$[-0.54, 0.15]$	$[-0.10, 0.084]$	$[-0.062, 0.049]$
$c_{td}^{(8)}/\Lambda^2$	$[-0.47, 0.47]$	$[-0.67, 0.28]$	$[-0.51, 0.26]$	$[-0.41, 0.18]$
$c_{Qd}^{(8)}/\Lambda^2$	$[-0.52, 0.52]$	$[-0.76, 0.28]$	$[-0.53, 0.28]$	$[-0.42, 0.19]$
$c_{qt}^{(1)}/\Lambda^2$	$[-0.65, 0.65]$	$[-0.99, 0.32]$	$[-0.10, 0.090]$	$[-0.078, 0.066]$
$c_{Qq}^{(3,8)}/\Lambda^2$	$[-0.76, 0.76]$	$[-1.1, 0.42]$	$[-0.24, 0.20]$	$[-0.14, 0.12]$

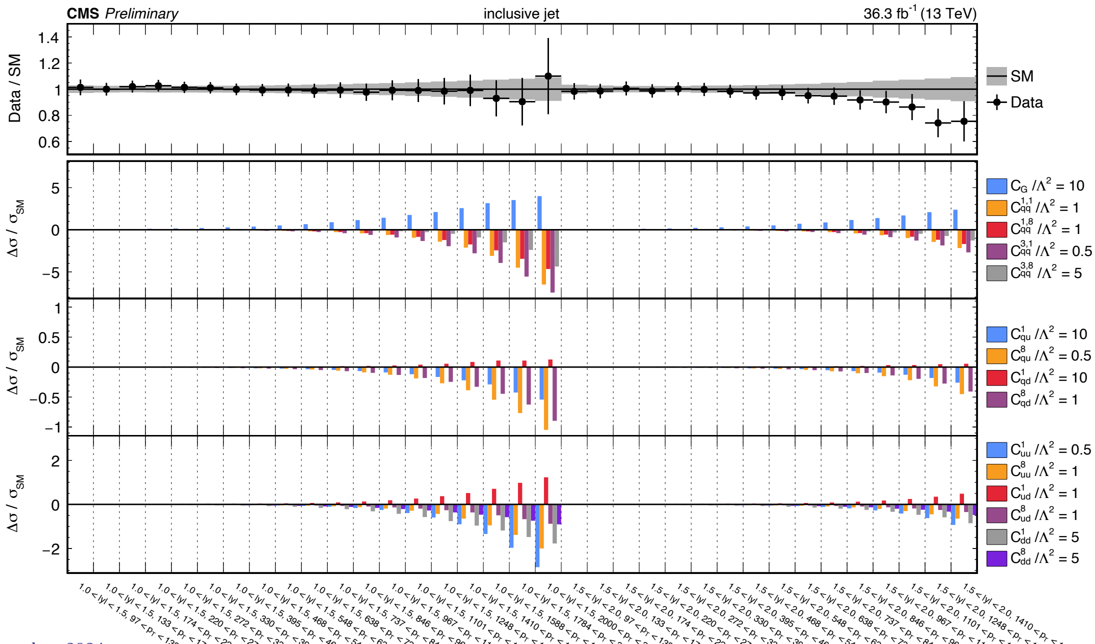
$c^{(3)}_{lq}/\Lambda^2$	$[-0.81, 0.97]$	$[-1.5, -0.034]$	$[-0.32, 0.26]$	$[-0.26, 0.16]$
$c^{(1)}_{Qu}/\Lambda^2$	$[-1.2, 1.2]$	$[-1.9, 0.62]$	$[-0.14, 0.13]$	$[-0.10, 0.093]$
$c_{H\Box}/\Lambda^2$	$[-1.3, 1.4]$	$[-0.085, 2.7]$	$[-1.3, 1.3]$	$[-0.086, 2.5]$
$c^{(1)}_{td}/\Lambda^2$	$[-1.5, 1.5]$	$[-0.89, 2.1]$	$[-0.15, 0.17]$	$[-0.11, 0.13]$
$c^{(1)}_{qd}/\Lambda^2$	$[-1.7, 1.7]$	$[-1.8, 1.7]$	$[-0.060, 0.059]$	$[-0.069, 0.067]$
$c^{(1)}_{qu}/\Lambda^2$	$[-1.8, 1.8]$	$[-2.9, 0.72]$	$[-0.040, 0.040]$	$[-0.048, 0.047]$
$c^{(1)}_{tu}/\Lambda^2$	$[-2.1, 2.1]$	$[-3.0, 1.1]$	$[-0.12, 0.11]$	$[-0.091, 0.086]$
$\mathrm{Re}(c_{tH})/\Lambda^2$	$[-2.2, 2.0]$	$[-3.8, 0.56]$	$[-2.2, 2.0]$	$[-3.8, 0.54]$
$c^{(1,1)}_{Qq}/\Lambda^2$	$[-3.9, 3.0]$	$[-3.8, 4.0]$	$[-0.10, 0.10]$	$[-0.075, 0.075]$
c_{Ht}/Λ^2	$[-3.1, 4.0]$	$[-3.8, 3.6]$	$[-3.8, 3.4]$	$[-4.9, 3.1]$
$c^{(1)}_{Qd}/\Lambda^2$	$[-4.0, 4.0]$	$[-6.1, 1.9]$	$[-0.18, 0.17]$	$[-0.14, 0.13]$
c_{tt}/Λ^2	$[-5.4, 3.9]$	$[-7.8, 2.7]$	$[-1.0, 1.1]$	$[-1.3, 1.4]$
$c^{(1)}_{lq}/\Lambda^2$	$[-4.8, 4.6]$	$[-5.3, 4.8]$	$[-0.54, 0.56]$	$[-0.36, 0.36]$
$c^{(3)}_{lQ}/\Lambda^2$	$[-5.6, 6.7]$	$[-6.9, 5.6]$	$[-2.1, 1.7]$	$[-2.0, 1.6]$
$c^{(1)}_{lQ}/\Lambda^2$	$[-7.2, 5.9]$	$[-6.3, 7.2]$	$[-1.9, 2.3]$	$[-1.8, 2.3]$
c_{lu}/Λ^2	$[-7.0, 6.2]$	$[0.76, 12]$	$[-0.60, 0.65]$	$[-0.37, 0.44]$
$c^{(1)}_{Qt}/\Lambda^2$	$[-6.6, 9.1]$	$[-4.5, 13]$	$[-1.9, 1.7]$	$[-2.4, 2.2]$
c_{et}/Λ^2	$[-9.5, 7.9]$	$[-7.7, 9.8]$	$[-2.0, 2.4]$	$[-1.9, 2.4]$
$c^{(1)}_{QQ}/\Lambda^2$	$[-18, 13]$	$[-28, 8.4]$	$[-3.9, 4.6]$	$[-5.2, 5.8]$
$c^{(8)}_{Qt}/\Lambda^2$	$[-19, 14]$	$[-29, 8.4]$	$[-3.4, 4.0]$	$[-4.4, 4.9]$
c_{lt}/Λ^2	$[-20, 17]$	$[-19, 19]$	$[-2.1, 2.2]$	$[-2.0, 2.2]$


CMS Preliminary
qqH
WH/ZH
tH/ttH
ggH
138 fb^{-1} (13 TeV)
Data / SM
SM
Data
$\Delta\sigma / \sigma_{SM}$
$C_{HG}/\Lambda^2 = 1$
$C_{HB}/\Lambda^2 = 1$
$C_{HW}/\Lambda^2 = 5$
$C_{HWB}/\Lambda^2 = 1$
$C_{bH}/\Lambda^2 = 0.5$
$C_{tH}/\Lambda^2 = 10$
$C_{tG}/\Lambda^2 = 1$
$C_{tW}/\Lambda^2 = 1$
$C_{tB}/\Lambda^2 = 1$
$C^1_{Hq}/\Lambda^2 = 10$
$C^3_{Hq}/\Lambda^2 = 0.1$
$C^3_{Hl}/\Lambda^2 = 1$
$C_{Hd}/\Lambda^2 = 1$
$C_{Hu}/\Lambda^2 = 1$
$C_G/\Lambda^2 = 1$
$C_W/\Lambda^2 = 0.5$
$C_{H\Box}/\Lambda^2 = 1$
$C_{ll}'/\Lambda^2 = 1$
≥2j, 60 < m_{jj} < 120
≥2j, m_{jj} > 350, p_T^H > 200
≥2j, 350 < m_{jj} < 700, p_T^H < 200, p_T^{Hjj} < 25
≥2j, 350 < m_{jj} < 700, p_T^H < 200, p_T^{Hjj} > 25
≥2j, m_{jj} > 700, p_T^H < 200, p_T^{Hjj} < 25
≥2j, m_{jj} > 700, p_T^H < 200, p_T^{Hjj} > 25
WH, p_T^V < 75
WH, 75 < p_T^V < 150
WH, p_T^V > 150
ZH
tH
ttH, p_T^H < 60
ttH, 60 < p_T^H < 120
ttH, 120 < p_T^H < 200
ttH, 200 < p_T^H < 300
ttH, p_T^H > 300
200 < p_T^H < 300
300 < p_T^H < 450
p_T^H > 450
0j, p_T^H < 10
0j, p_T^H > 10
1j, p_T^H < 60
1j, 60 < p_T^H < 120
1j, 120 < p_T^H < 200
≥2j, m_{jj} < 350, p_T^H < 60
≥2j, m_{jj} < 350, 60 < p_T^H < 120
≥2j, m_{jj} < 350, 120 < p_T^H < 200
H → γγ


CMS Preliminary
Wγ
Z→νν
WW
36.3-138 fb-1 (13 TeV)
Data / SM
Δσ / σSM
SM
Data
CW /Λ2 = 0.5
CHWB /Λ2 = 1
CHD /Λ2 = 1
C1Hq /Λ2 = 10
C3Hq /Λ2 = 1
C1Hl /Λ2 = 5
C3Hl /Λ2 = 1
Cll' /Λ2 = 1
C1lq /Λ2 = 1
C3lq /Λ2 = 0.5
Clu /Λ2 = 5
200 < pTZ < 300
300 < pTZ < 400
400 < pTZ < 500
500 < pTZ < 800
800 < pTZ < 1500
55 < mll < 75
75 < mll < 85
85 < mll < 95
95 < mll < 110
110 < mll < 125
125 < mll < 140
140 < mll < 160
160 < mll < 185
185 < mll < 220
220 < mll < 280
280 < mll < 380
380 < mll < 600
600 < mll < 1500

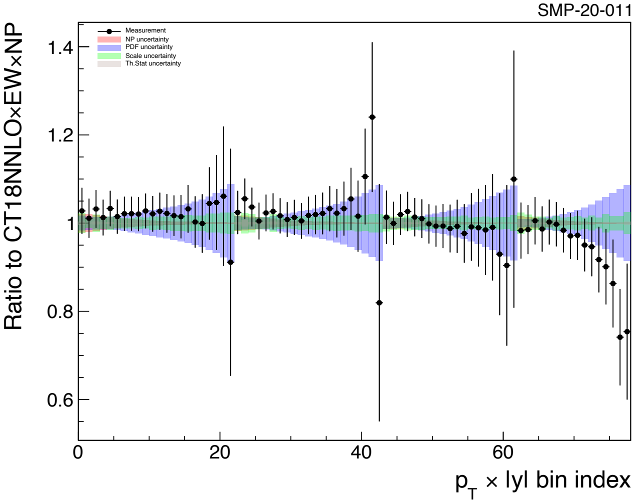

CMS Preliminary
$t\bar{t}$
138 fb^{-1} (13 TeV)
Data / SM
SM
Data
$\Delta\sigma / \sigma_{SM}$
$C_G / \Lambda^2 = 1$
$C_{HG} / \Lambda^2 = 1$
$C_{tG} / \Lambda^2 = 0.5$
$C_{Qq}^{1,1} / \Lambda^2 = 50$
$C_{Qq}^{1,8} / \Lambda^2 = 1$
$C_{Qq}^{3,1} / \Lambda^2 = 1$
$C_{Qq}^{3,8} / \Lambda^2 = 1$
$C_{qt}^{1} / \Lambda^2 = 1$
$C_{qt}^{8} / \Lambda^2 = 0.5$
$C_{Qd}^{1} / \Lambda^2 = 10$
$C_{Qd}^{8} / \Lambda^2 = 1$
$C_{Qu}^{1} / \Lambda^2 = 1$
$C_{Qu}^{8} / \Lambda^2 = 1$
$C_{td}^{1} / \Lambda^2 = 5$
$C_{td}^{8} / \Lambda^2 = 1$
$C_{tu}^{1} / \Lambda^2 = 5$
$C_{tu}^{8} / \Lambda^2 = 1$
$250 < M_{tt} < 400$
$400 < M_{tt} < 480$
$480 < M_{tt} < 560$
$560 < M_{tt} < 640$
$640 < M_{tt} < 720$
$720 < M_{tt} < 800$
$800 < M_{tt} < 900$
$900 < M_{tt} < 1000$
$1000 < M_{tt} < 1150$
$1150 < M_{tt} < 1300$
$1300 < M_{tt} < 1500$
$1500 < M_{tt} < 1700$
$1700 < M_{tt} < 2000$
$2000 < M_{tt} < 2300$
$2300 < M_{tt} < 3500$


CMS Preliminary
inclusive jet
36.3 fb-1 (13 TeV)
Data / SM
1.4
1.2
1
0.8
0.6
SM
Data
Δσ / σSM
20
10
0
−10
−20
CG /Λ2 = 10
Cqq1,1 /Λ2 = 1
Cqq1,8 /Λ2 = 1
Cqq3,1 /Λ2 = 0.5
Cqq3,8 /Λ2 = 5
Δσ / σSM
2
1
0
−1
−2
Cqu1 /Λ2 = 10
Cqu8 /Λ2 = 0.5
Cqd1 /Λ2 = 10
Cqd8 /Λ2 = 1
Δσ / σSM
10
5
0
−5
−10
Cuu1 /Λ2 = 0.5
Cuu8 /Λ2 = 1
Cud1 /Λ2 = 1
Cud8 /Λ2 = 1
Cdd1 /Λ2 = 5
Cdd8 /Λ2 = 5
|y| < 0.5, 97 < pT < 133
|y| < 0.5, 133 < pT < 174
|y| < 0.5, 174 < pT < 220
|y| < 0.5, 220 < pT < 272
|y| < 0.5, 272 < pT < 330
|y| < 0.5, 330 < pT < 395
|y| < 0.5, 395 < pT < 468
|y| < 0.5, 468 < pT < 548
|y| < 0.5, 548 < pT < 638
|y| < 0.5, 638 < pT < 737
|y| < 0.5, 737 < pT < 846
|y| < 0.5, 846 < pT < 967
|y| < 0.5, 967 < pT < 1101
|y| < 0.5, 1101 < pT < 1248
|y| < 0.5, 1248 < pT < 1410
|y| < 0.5, 1410 < pT < 1588
|y| < 0.5, 1588 < pT < 1784
|y| < 0.5, 1784 < pT < 2000
|y| < 0.5, 2000 < pT < 2238
|y| < 0.5, 2238 < pT < 2500
|y| < 0.5, 2500 < pT < 2787
|y| < 0.5, 2787 < pT < 3103
0.5 < |y| < 1.0, 97 < pT < 133
0.5 < |y| < 1.0, 133 < pT < 174
0.5 < |y| < 1.0, 174 < pT < 220
0.5 < |y| < 1.0, 220 < pT < 272
0.5 < |y| < 1.0, 272 < pT < 330
0.5 < |y| < 1.0, 330 < pT < 395
0.5 < |y| < 1.0, 395 < pT < 468
0.5 < |y| < 1.0, 468 < pT < 548
0.5 < |y| < 1.0, 548 < pT < 638
0.5 < |y| < 1.0, 638 < pT < 737
0.5 < |y| < 1.0, 737 < pT < 846
0.5 < |y| < 1.0, 846 < pT < 967
0.5 < |y| < 1.0, 967 < pT < 1101
0.5 < |y| < 1.0, 1101 < pT < 1248
0.5 < |y| < 1.0, 1248 < pT < 1410
0.5 < |y| < 1.0, 1410 < pT < 1588
0.5 < |y| < 1.0, 1588 < pT < 1784
0.5 < |y| < 1.0, 1784 < pT < 2000
0.5 < |y| < 1.0, 2000 < pT < 2238
0.5 < |y| < 1.0, 2238 < pT < 2500
0.5 < |y| < 1.0, 2500 < pT < 2787



CMS Preliminary
inclusive jet
36.3 fb^{-1} (13 TeV)
Data / SM
SM
Data
$\Delta\sigma / \sigma_{SM}$
$C_G / \Lambda^2 = 10$
$C_{qq}^{1,1} / \Lambda^2 = 1$
$C_{qq}^{1,8} / \Lambda^2 = 1$
$C_{qq}^{3,1} / \Lambda^2 = 0.5$
$C_{qq}^{3,8} / \Lambda^2 = 5$
$C_{qu}^{1} / \Lambda^2 = 10$
$C_{qu}^{8} / \Lambda^2 = 0.5$
$C_{qd}^{1} / \Lambda^2 = 10$
$C_{qd}^{8} / \Lambda^2 = 1$
$C_{uu}^{1} / \Lambda^2 = 0.5$
$C_{uu}^{8} / \Lambda^2 = 1$
$C_{ud}^{1} / \Lambda^2 = 1$
$C_{ud}^{8} / \Lambda^2 = 1$
$C_{dd}^{1} / \Lambda^2 = 5$
$C_{dd}^{8} / \Lambda^2 = 5$
$1.0 < |y| < 1.5, 97 < p_T < 133$
$1.0 < |y| < 1.5, 133 < p_T < 174$
$1.0 < |y| < 1.5, 174 < p_T < 220$
$1.0 < |y| < 1.5, 220 < p_T < 272$
$1.0 < |y| < 1.5, 272 < p_T < 330$
$1.0 < |y| < 1.5, 330 < p_T < 395$
$1.0 < |y| < 1.5, 395 < p_T < 468$
$1.0 < |y| < 1.5, 468 < p_T < 548$
$1.0 < |y| < 1.5, 548 < p_T < 638$
$1.0 < |y| < 1.5, 638 < p_T < 737$
$1.0 < |y| < 1.5, 737 < p_T < 846$
$1.0 < |y| < 1.5, 846 < p_T < 967$
$1.0 < |y| < 1.5, 967 < p_T < 1101$
$1.0 < |y| < 1.5, 1101 < p_T < 1248$
$1.0 < |y| < 1.5, 1248 < p_T < 1410$
$1.0 < |y| < 1.5, 1410 < p_T < 1588$
$1.0 < |y| < 1.5, 1588 < p_T < 1784$
$1.0 < |y| < 1.5, 1784 < p_T < 2000$
$1.0 < |y| < 1.5, 2000 < p_T < 2238$
$1.5 < |y| < 2.0, 97 < p_T < 133$
$1.5 < |y| < 2.0, 133 < p_T < 174$
$1.5 < |y| < 2.0, 174 < p_T < 220$
$1.5 < |y| < 2.0, 220 < p_T < 272$
$1.5 < |y| < 2.0, 272 < p_T < 330$
$1.5 < |y| < 2.0, 330 < p_T < 395$
$1.5 < |y| < 2.0, 395 < p_T < 468$
$1.5 < |y| < 2.0, 468 < p_T < 548$
$1.5 < |y| < 2.0, 548 < p_T < 638$
$1.5 < |y| < 2.0, 638 < p_T < 737$
$1.5 < |y| < 2.0, 737 < p_T < 846$
$1.5 < |y| < 2.0, 846 < p_T < 967$
$1.5 < |y| < 2.0, 967 < p_T < 1101$
$1.5 < |y| < 2.0, 1101 < p_T < 1248$
$1.5 < |y| < 2.0, 1248 < p_T < 1410$
$1.5 < |y| < 2.0, 1410 < p_T < 1588$

Modifications to input analyses: Inclusive jets predictions



- Rederived both nominal NNLO QCD predictions and uncertainties with CT18 NNLO PDF set
- PDF uncertainties: 28 eigenvector variations, symmetrized and taken as fully correlated between bins
- Renormalization and factorization scale: correlated between p_T bins of a given $|y|$ bin
- Theory statistical: obtained from fastNLO, treated as uncorrelated between bins
- Electroweak corrections and uncertainties from non-perturbative effects taken from HEPData

Electroweak precision observables from LEP & SLC

The measurement of eight pseudo-observables measured at LEP and SLC [35, 36] is incorporated in the interpretation presented here. These observables are the Z boson total width, Γ_Z; the hadronic pole cross section, σ^0_{had}, defined as

$$\sigma^0_{\text{had}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{\text{ee}}\Gamma_{\text{had}}}{\Gamma_Z^2}\,, \tag{2}$$

where Γ_{ee} is the partial decay width of the Z boson to an electron-positron pair and $\Gamma_{\text{had}} = \Gamma_{\text{uu}} + \Gamma_{\text{dd}} + \Gamma_{\text{cc}} + \Gamma_{\text{ss}} + \Gamma_{\text{bb}}$ is the hadronic Z boson decay width; three ratios of partial decay widths, R_ℓ, R_c, R_b, defined as

$$R_\ell = \frac{\Gamma_{\text{had}}}{\Gamma_{\ell\ell}}\,, \quad R_{c,b} = \frac{\Gamma_{\text{cc,bb}}}{\Gamma_{\text{had}}}\,; \tag{3}$$

and three forward-backward asymmetries, $A^{0,\ell}_{FB}$, $A^{0,\text{c}}_{FB}$, $A^{0,\text{b}}_{FB}$, defined as

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}\,. \tag{4}$$

In this expression, N_F (N_B) is the number of events where the charged lepton, c quark, or b quark is produced in the direction of the electron beam (anti-electron beam). SMEFT corrections on these pseudo-observables were evaluated analytically in Ref. [36].

SMEFT parameterization (details on event generation)

$$\sigma^i_{p,\mathrm{SMEFT}} = \sigma^i_{p,\mathrm{SM}} \left(1 + \sum_j A^i_{p,j} \frac{c_j}{\Lambda^2} + \sum_{j,k} B^i_{p,jk} \frac{c_j c_k}{\Lambda^4} \right)$$

- ○ $A^i_{p,j} \frac{c_j}{\Lambda^2}$: *linear terms* or *interference terms*, from interference of SM and BSM
- ○ $B^i_{p,jk} \frac{c_j c_k}{\Lambda^4}$: *quadratic terms* or *cross terms* (when $j \neq k$)

- Constants $A^i_{p,j}$, $B^i_{p,jk}$ are computed by generating events at LO with `MADGRAPH5_AMC@NLO` + `PYTHIA 8.3`. SMEFT effects are modelled using `SMEFTsim3` (and `SMEFT@NLO` for loop-induced processes gg → H and gg → ZH)
- Phase space selections for each kinematic bin are reproduced using `RIVET 3.1.9`
- NNPDF 3.1 is used when computing the parameterizations
- All parameterizations use $\{m_W, m_Z, G_\mathrm{F}\}$ input scheme and `topU3l` flavour symmetry

SMEFT operators (1/2)

	X^3	
$\mathcal{Q}_{\mathrm{G}} = f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	$\mathcal{Q}_{\mathrm{W}} = \varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	
	$H^4 D^2$	
$\mathcal{Q}_{\mathrm{H}\Box} = (H^\dagger H)\Box(H^\dagger H)$	$\mathcal{Q}_{\mathrm{HD}} = (D^\mu H^\dagger H)(H^\dagger D_\mu H)$	
	$X^2 H^2$	
$\mathcal{Q}_{\mathrm{HG}} = H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}$ $\mathcal{Q}_{\mathrm{HWB}} = H^\dagger H W_{\mu\nu}^i B^{\mu\nu}$	$\mathcal{Q}_{\mathrm{HW}} = H^\dagger H W_{\mu\nu}^i W^{i\mu\nu}$	$\mathcal{Q}_{\mathrm{HB}} = H^\dagger H B_{\mu\nu} B^{\mu\nu}$
	$\psi^2 H^3$	
$\mathcal{Q}_{\mathrm{tH}} = (H^\dagger H)(\bar{Q}\tilde{H}t)$	$\mathcal{Q}_{\mathrm{bH}} = (H^\dagger H)(\bar{Q}Hb)$	
	$\psi^2 X H$	
$\mathcal{Q}_{\mathrm{tW}} = (\bar{Q}\sigma^{\mu\nu}t)\sigma^i \tilde{H} W_{\mu\nu}^i$	$\mathcal{Q}_{\mathrm{tB}} = (\bar{Q}\sigma^{\mu\nu}t)\tilde{H} B_{\mu\nu}$	$\mathcal{Q}_{\mathrm{tG}} = (\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{H} G_{\mu\nu}^a$
	$\psi^2 H^2 D$	
$\mathcal{Q}_{\mathrm{Hl}}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$ $\mathcal{Q}_{\mathrm{Hq}}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$ $\mathcal{Q}_{\mathrm{Hd}} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$ $\mathcal{Q}_{\mathrm{Ht}} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{\mathrm{Hl}}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$ $\mathcal{Q}_{\mathrm{Hq}}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{q}\sigma^i \gamma^\mu q)$ $\mathcal{Q}_{\mathrm{HQ}}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$ $\mathcal{Q}_{\mathrm{Hb}} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	$\mathcal{Q}_{\mathrm{He}} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$ $\mathcal{Q}_{\mathrm{Hu}} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$ $\mathcal{Q}_{\mathrm{HQ}}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{Q}\sigma^i \gamma^\mu Q)$

SMEFT operators (2/2)

ψ^4, $(\bar{L}L)(\bar{L}L)$

$\mathcal{Q}_{lq}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{q}\gamma^\mu q)$	$\mathcal{Q}_{lq}^{(3)} = (\bar{l}_p\sigma^i\gamma_\mu l_r)(\bar{q}\sigma^i\gamma^\mu q)$	$\mathcal{Q}_{lQ}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{Q}\gamma^\mu Q)$
$\mathcal{Q}_{lQ}^{(3)} = (\bar{l}_p\sigma^i\gamma_\mu l_r)(\bar{Q}\sigma^i\gamma^\mu Q)$	$\mathcal{Q}_{QQ}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q)$	$\mathcal{Q}_{ll} = (\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$\mathcal{Q}_{qq}^{(1,1)} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$	$\mathcal{Q}_{qq}^{(1,8)} = (\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$	$\mathcal{Q}_{qq}^{(3,1)} = (\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
$\mathcal{Q}_{qq}^{(3,8)} = (\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$	$\mathcal{Q}_{Qq}^{(1,1)} = (\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$	$\mathcal{Q}_{Qq}^{(1,8)} = (\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
$\mathcal{Q}_{Qq}^{(3,1)} = (\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$	$\mathcal{Q}_{Qq}^{(3,8)} = (\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$	

ψ^4, $(\bar{R}R)(\bar{R}R)$

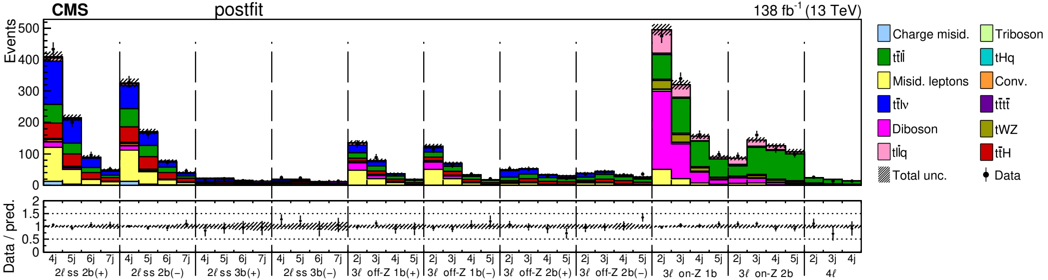
$\mathcal{Q}_{et} = (\bar{e}_p\gamma_\mu e_r)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{tt} = (\bar{t}\gamma_\mu t)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{uu}^{(1)} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$
$\mathcal{Q}_{uu}^{(8)} = (\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$	$\mathcal{Q}_{tu}^{(1)} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$	$\mathcal{Q}_{tu}^{(8)} = (\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
$\mathcal{Q}_{dd}^{(1)} = (\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$	$\mathcal{Q}_{dd}^{(8)} = (\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$	$\mathcal{Q}_{ud}^{(1)} = (\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$
$\mathcal{Q}_{ud}^{(8)} = (\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$	$\mathcal{Q}_{td}^{(1)} = (\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$	$\mathcal{Q}_{td}^{(8)} = (\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$

ψ^4, $(\bar{L}L)(\bar{R}R)$

$\mathcal{Q}_{lu} = (\bar{l}_p\gamma_\mu l_r)(\bar{u}\gamma^\mu u)$	$\mathcal{Q}_{lt} = (\bar{l}_p\gamma_\mu l_r)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{qu}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$
$\mathcal{Q}_{qu}^{(8)} = (\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$	$\mathcal{Q}_{Qu}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$	$\mathcal{Q}_{Qu}^{(8)} = (\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$\mathcal{Q}_{qt}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{qt}^{(8)} = (\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$	$\mathcal{Q}_{Qt}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{t}\gamma^\mu t)$
$\mathcal{Q}_{Qt}^{(8)} = (\bar{Q}T^a\gamma_\mu Q)(\bar{t}T^a\gamma^\mu t)$	$\mathcal{Q}_{qd}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$	$\mathcal{Q}_{qd}^{(8)} = (\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$
$\mathcal{Q}_{Qd}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$	$\mathcal{Q}_{Qd}^{(8)} = (\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$	

Input Measurements: CMS-TOP-22-006, $t\bar{t}X$ EFT

- CMS-TOP-22-006 (JHEP 12 (2023) 068):
  EFT in associated top quark production ($t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, tZq, tHq, and $t\bar{t}t\bar{t}$ processes)
- Each process can be studied individually, but they are irreducible backgrounds to each other
- Event selection based on number of leptons, jets, and b-tagged jets
  - 43 categories, binning in a kinematical variable within each category
- Total predicted event yield in each observable bin parameterized as a quadratic function of 26 WCs
  - Detector-level predictions accounting for all relevant EFT effects on each of the signal processes simultaneously



Input Measurements: CMS-TOP-22-006, $t\bar{t}X$ EFT

- Original analysis sets constraints on 26 Wilson coefficients in the `dim6top` basis
- In the combination we use `topU31` SMEFT basis as implemented in SMEFTsim3, and consider additional operators that may affect the $t\bar{t}X$ processes
- To include $t\bar{t}X$ analysis in the combination in a consistent way, we therefore had to
  - rotate from `dim6top` to SMEFT `topU31`
  - study the effect of missing operators on $t\bar{t}X$ processes
- $\mathcal{Q}_{H\Box}$ uniformly scales all SM Higgs boson couplings
  - added to $t\bar{t}X$ analysis as **rescaling** of $t\bar{t}H$ and tHq signals
- **2-heavy-2-light quark operators** enhance $t\bar{t}Z$ and $t\bar{t}H$ production rates (effect on shape and normalization)
  - added to $t\bar{t}X$ analysis by **reweighting the signal samples** using standalone reweighting modules produced by MadGraph («post-mortem reweighting»)
- Effect of other operators found to be negligible