(Some) Challenges in constraining SMEFT with experimental data

1. Large number of (dim-6) Wilson coefficients, many of which could be correlated between each other.

- **1D fit** with one parameter at a time ignores the possibility of such correlations, resulting in too strong limits.
- **Global fit** of all parameters simultaneously requires a combination of many complementary observables.

X^3		H^6 and H^4D^2		$\psi^2 H^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
X^2H^2		$\psi^2 X H$		$\psi^2 H^2 D$	
$\mathcal{O}_{HG}$	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$				

2. Each measurement affected by a large number of systematic uncertainties, with non-trivial uncertainty correlations between measurements.

- **Marginalized likelihoods**
  (phenomenology approach: computing-efficient, but not exact)
  Nuisance parameters in a measurement are integrated out, correlation of uncertainties between measurements treated through covariance matrices.
- **Profiled likelihoods**
  (experimental approach: computing intensive, but more accurate)
  Separate treatment of each uncertainty in a measurement & detailed treatment of correlations between measurements.

3. EFT validity/truncation:

Quadratic dim-6 terms (c_i^2/Λ^4) could be of same size as unknown dim-8 terms → need to minimize their impact.

ATLAS & CMS SMEFT interpretations of combined Higgs data

Simultaneous profiled likelihood fit of Wilson coefficients grouped into PCA-based eigenvectors.
Eigenvector definitions are measurement-dependent, making direct comparisons difficult.
→ comparing eigenvectors that have the strongest relation to a given Warsaw-basis Wilson coefficient.

CMS $EV1 : (0.94c_{HG},\ 0.26c_{HB},\ -0.15c_{HWB},\ 0.08c_{HW},\ 0.14c_{bH},\ -0.03c_{tG},\ 0.01c_{tB})$

ATLAS $E^{[1]}_{ggF} : (1.00c_{HG},\ -0.03c_{tG})$

ATLAS Higgs STXS-1.2, arXiv:2402.05742:
$(ggH, VBF, WH, ZH, ttH, tH)$ x $(p_T^H, N_{jets}, m_{jj})$
combining $\gamma\gamma, Z\gamma, WW, ZZ, bb, \tau\tau$ & $\mu\mu$ decays
* *lin-only & lin+quad parametrization*

CMS differential p_T^H, CMS-PAS-HIG-23-013:
inclusive Higgs production,
combining $\gamma\gamma, WW, ZZ,$ & $\tau\tau$ decay channels
* *lin+quad parametrization*

- STXS-based eigenvectors more strongly related to a single WC.
- Comparable sensitivity from STXS & differential measurements, but STXS adds some more sensitivity to Hqq, Hll and HVqq vertices.
- Significant dependence on quadratic terms for $c_{HB}, c_{tG}, c_{tH}, c_{Hq}^{(1)}$ (4 - 10 times stronger limits).

EV dominated by a **single WC**

EV with a **strong contribution** from a given WC

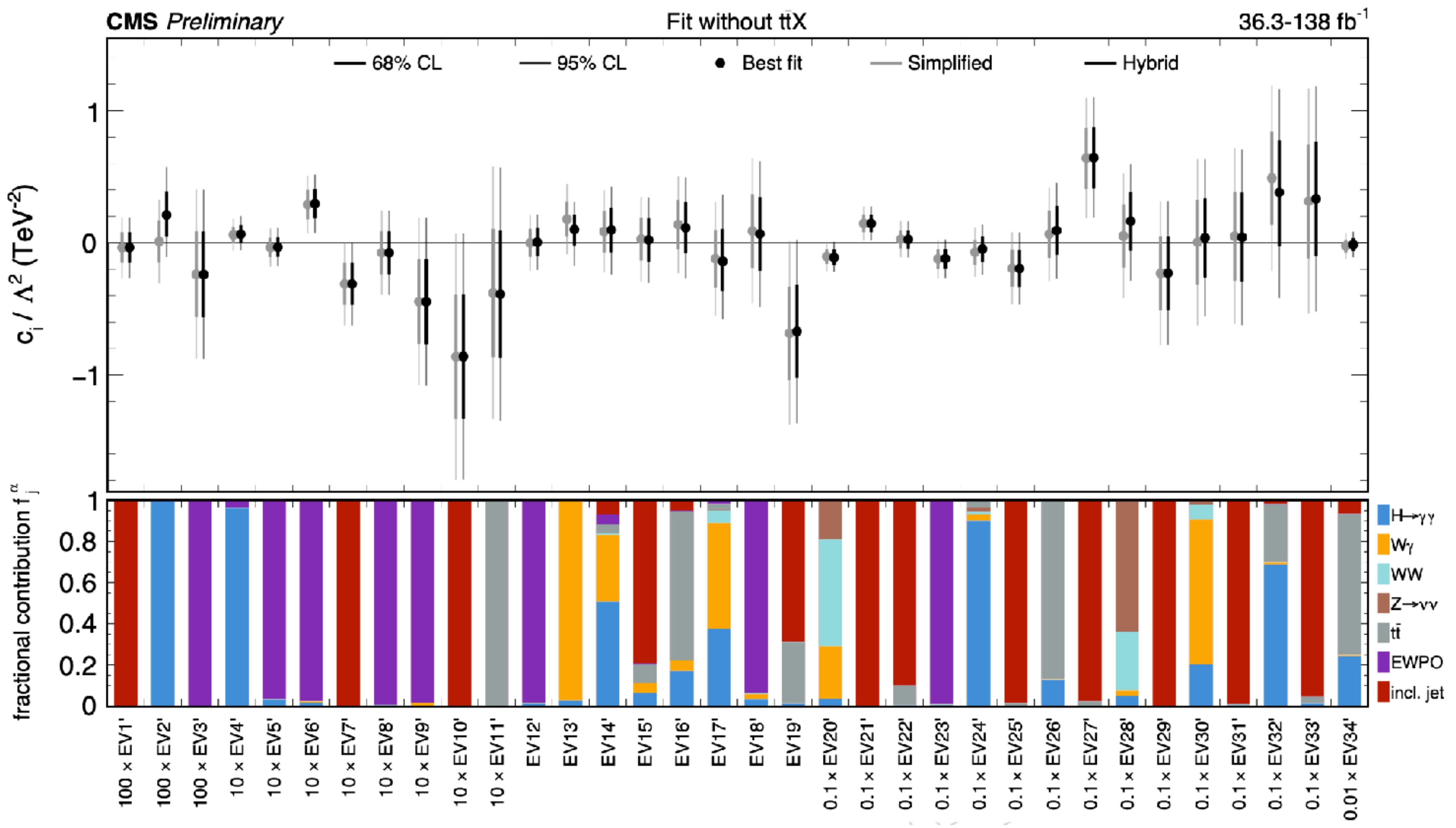
EV with **moderate/small contribution** from a given WC

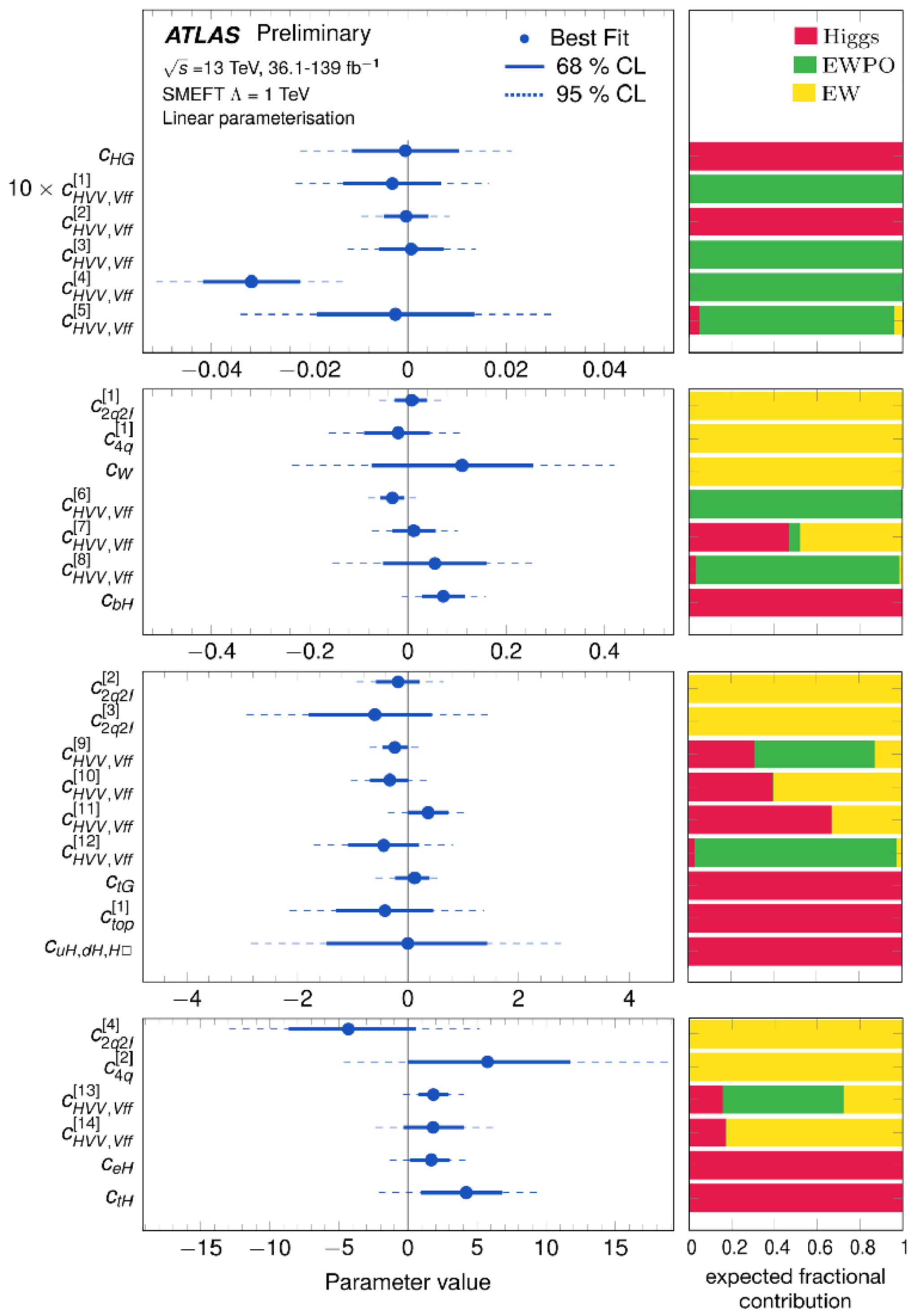
Warsaw-basis Wilson coeff.	$\mathcal{O}$(Uncertainty on c_i/Λ^2) ATLAS STXS	$\mathcal{O}$(Uncertainty on c_i/Λ^2) CMS differential p_T^H	Vertex	Most sensitive observables
C_{HW}, C_{HB}, C_{HWB}	0.001 - 0.1	0.001 - 1	HVV	STXS (yy, Zy) & diff
C_{HG}	0.001	0.001	Hgg	STXS (ggH) & diff
C_{tG}	0.1	0.1	Hgtt	STXS (ggH) & diff
C_{tH}	10	-	Hqq	STXS (ttH)
C_{bH}	0.01	0.1		STXS (Higgs width)
$C_{eH,22}$	0.001	1	Hll	STXS (mumu)
$C_{eH,33}$	0.01			STXS (tautau)
C_{Hq3}	0.01	0.1	HVqq	STXS (VHbb)
C_{Hu}	0.1	10		STXS (ZHbb)
C_{Hq1}	1	1		STXS (VHbb)
C_{Hd}	10	10		STXS (VHbb)

Global SMEFT interpretations (Higgs+EW+Top/QCD+EWPO)

CMS-PAS-SMP-24-003:
Higgs: differential p_T^H in $H \to \gamma\gamma$,
EW: $WW(m_{\ell\ell})$, $W\gamma(p_T^\gamma x|\phi_f|)$, $Z \to \nu\nu(p_T^Z)$
Top/QCD: tt, ttX, incl. jets
EWPO

ATL-PHYS-PUB-2022:
Higgs: STXS-1.2,
EW: $WW(p_T^{\text{lead. lep.}})$, $WZ(m_T^{WZ})$, $ZZ(m_{Z2})$, $Zjj(\Delta\Phi_{jj})$
EWPO





Comparable sensitivities in ATLAS and CMS.

Additional sensitivity to Higgs-related Wilson coefficients:
c_{tH} from **Top**; c_{Hu}, $c_{Hq}^{(1)}$, $c_{Hq}^{(3)}$ from **EWPO**;
(up to an order of magnitude better limits)

Sensitivity to further Wilson coefficients (not probed by the Higgs data):
EW: many operators affecting *2l2q* vertices
Top/QCD: c_G, c_{Ht}, and many operators affecting *4q* vertices
EWPO: many operators affecting *Vll, Vqq, Hll, Hqq, HVll, HVqq, 4l* vertices

What's next? An open list:

- Updates of combined Higgs interpretations:

  - individual measurements with improved analysis techniques
  - additional Higgs observables
    ($\Delta\Phi_{jj}$, matrix-elements, $H + \gamma$ or other new channels, Higgs decay kinematics …)

- Additional EW/Top/Di-Higgs observables in the global EFT fit

- ATLAS+CMS global EFT interpretation

- Inclusion of CP-odd parameters in the global fit?

- Improvements in th. predictions, better treatment of EFT truncation uncertainties …

- Complementary approaches:
  matching of UV models to SMEFT, linear SM extensions in SMEFT…