Andrea Visibile,
on behalf of the ATLAS and CMS collaborations

GLOBAL EFT FITS IN ATLAS AND CMS

SM@LHC 2024, Rome

10 May 2024

This talk:

- Overview of ATLAS and CMS global EFT interpretations

ATLAS:
- Global EFT fits: ATL-PHYS-PUB-2022-037
- Higgs combination: 2402.05742

CMS:
- Top quark production in EFT: JHEP12(2023)068
- Higgs combination: CMS-PAS-HIG-19-005

Thanks to the many people in ATLAS and CMS that have helped preparing this talk!

Outline

EFT interpretations in ATLAS and CMS

- In the past years many efforts from the experimental community to interpret combined measurements in the EFT framework

- Multiple results including **EFT interpretations** have been produced within **ATLAS** and **CMS**, including different sets of measurements

  - ATLAS has published the **first global EFT fit** in 2022 (Higgs 139 fb^{-1} + EW 36-139 fb^{-1} + LEP) and since then updated the Higgs sector in 2024 with new channels

  - CMS has published in 2020 a partial Run2 Higgs combination and in 2023 a Top production interpretation (138fb^{-1})

ATLAS

ATL-PHYS-PUB-2022-037: global EFT combination including Higgs and electroweak data

Combined Higgs interpretation (2402.05742): including Higgs data from seven different channels

CMS

CMS-PAS-HIG-19-005: including Higgs data from five different channels

JHEP12(2023)068: top quark production processes interpretation ($t\bar{t}H, t\bar{t}W, t\bar{t}Z, tZq, tHq, t\bar{t}t\bar{t}$)

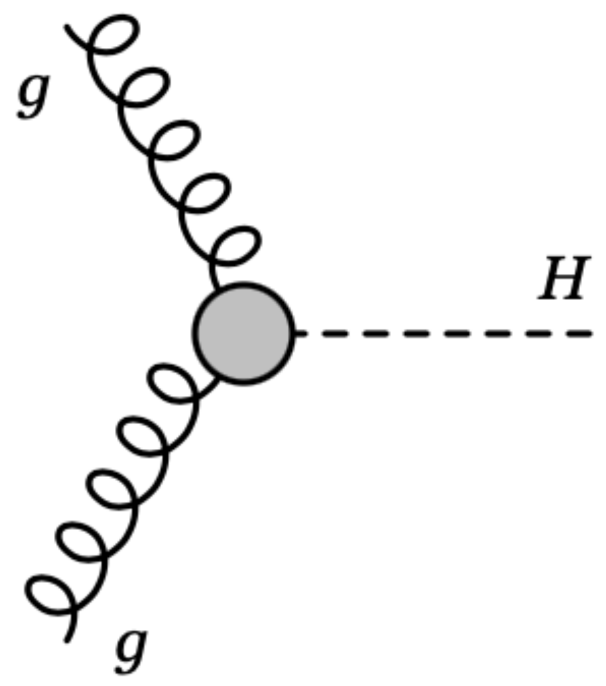
EFT predictions

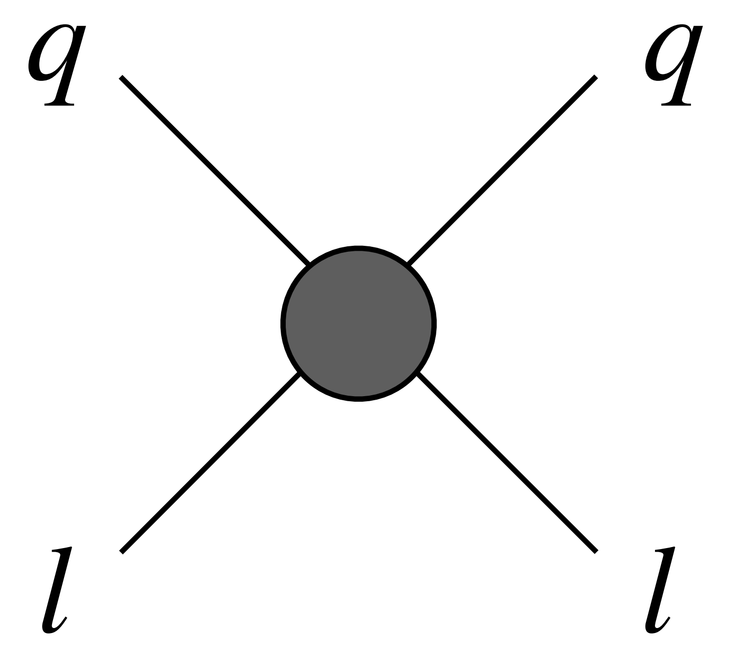
Current analyses **Future analyses**

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i^{N_5} \frac{c_i}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i^{N_6} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i^{N_7} \frac{c_i}{\Lambda^3} \mathcal{O}_i^{(7)} + \sum_i^{N_8} \frac{c_i}{\Lambda^4} \mathcal{O}_i^{(8)} + \dots$$

Violate Lepton and Baryon number!

- $\mathcal{O}_i^{(n)}$ → Operators - introduce new interaction vertices
- c_i → **Wilson coefficients** - free parameters of the model, strength of the interaction!
- **2499 operators at dimension six** - need to introduce some assumption to reduce their numbers → **Flavour symmetry!**

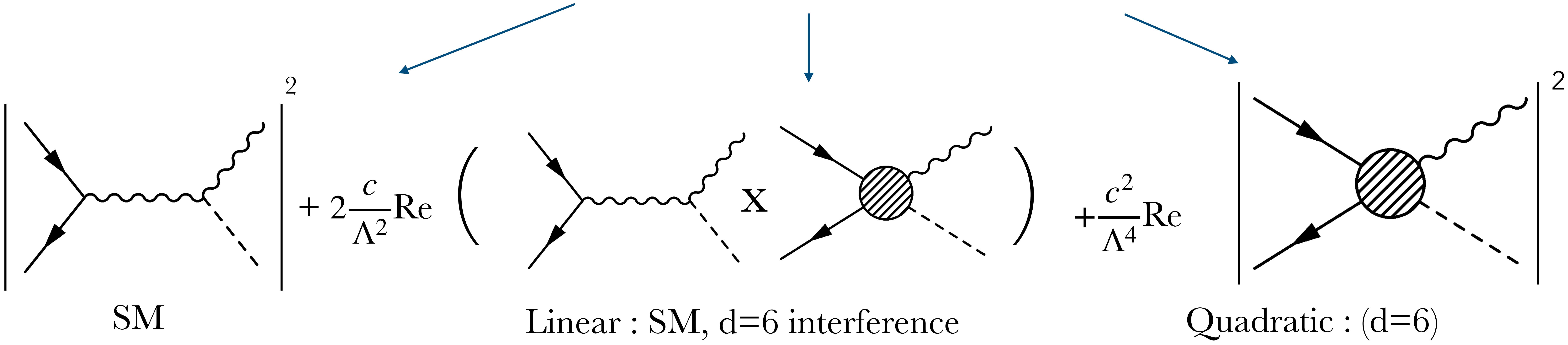




From measurements to EFT

- SMEFT dependence parameterised as **polynomials in Wilson coefficients:**

$$\sigma_{\text{SMEFT}} \sim |M_{SMEFT}|^2 = |M_{SM}|^2 + 2\text{Re}(M_{SM}M^*_{EFT}) + |M_{EFT}|^2 =$$



$$\mu_{SMEFT} = 1 + \sum_i A_i c_i + \sum_i B_i c_i^2 + \sum_{i,j} C_{ij} c_i c_j$$

- SMEFT effects on the SM predictions can be factored out in a **linear** and **quadratic** component
- Linear plus quadratic models are generally quoted to understand the impact of missing high order operators

Overview of EFT predictions in ATLAS and CMS

- EFT operators' impact on measurements is estimated in different ways between ATLAS and CMS and the various measurements included

- Both collaborations are working to produce a common SXTS SMEFT parameterisation

ATLAS

In both combinations:

- **MadGraph** plus **SMEFTsim** 3.0 is used for most of the measurements
- **Loop induced processed use instead SMEFTatNLO** ($gg \to H, gg \to ZH, H \to gg$) for NLO QCD corrections
- Analytical calculations are used for $H \to \gamma\gamma$ (from Dawson, Giardino, Phys. Rev. D 98, 095005 in global EFT fits) and $H \to Z\gamma$ (from Dawson, Giardino, Phys. Rev. D 97, 093003 in Higgs only comb)
- LEP EWPO from Corbett, Helset, Martin, Trott, JHEP06(2021)076

CMS

- Higgs combination (HEL):
  - Events generated with **MadGraph**
  - HEL model is defined using the **FEYNRULES** implementation
  - Decay channel parameterisation obtained from Hays, Sanz Gonzalez, Zemaityte
- Top production interpretation (SMEFT):
  - **MadGraph** plus **DIM6TOP** model to incorporate EFT effects

Sensitivity studies and choice of fit basis

- Not all Wilson coefficients (c_i) can be **simultaneously** constrained by data
- **Sensitivity studies:** in ATLAS a Principal Component Analysis (PCA) is generally performed on the information matrix to obtain the most sensitive directions in the space of EFT coefficients (other directions are fixed to SM)
- Definition of the different fit bases in back-up!

Information matrix

$$I_{\text{EFT}} = P^T C_{\text{meas}}^{-1} P$$

Parameterisation matrix, including all A_i

Covariance matrix

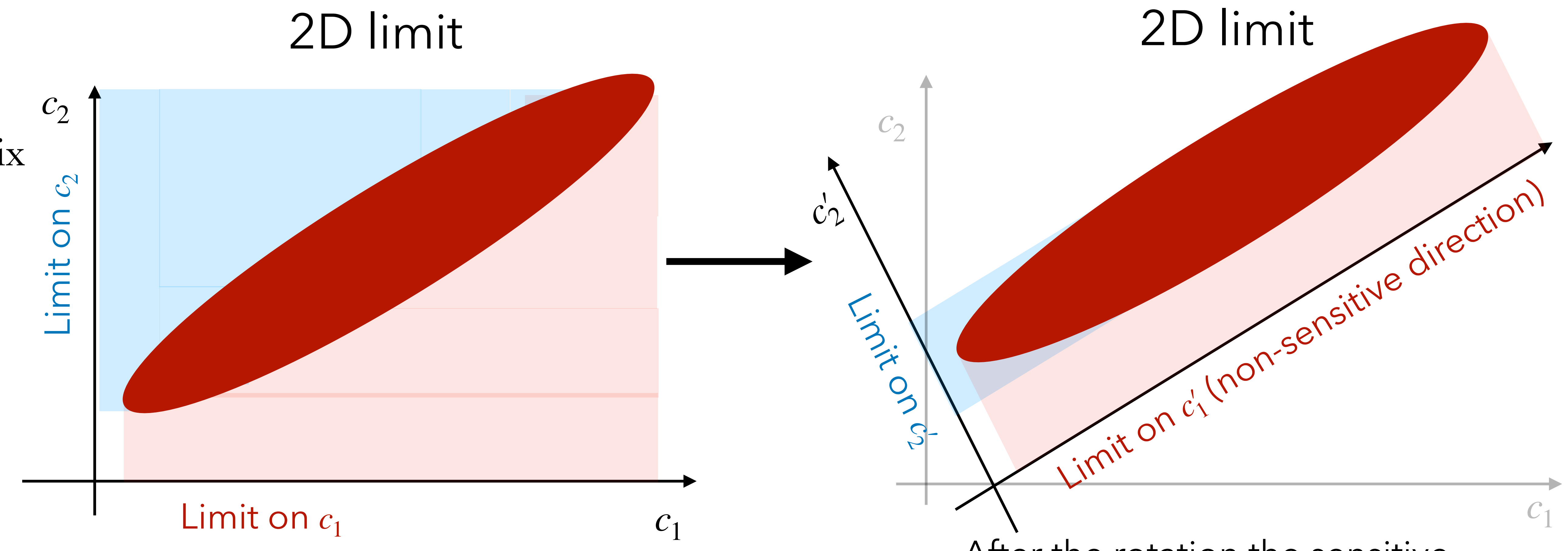
Principal component analysis on information matrix

↓

Eigenvector basis

↓

Fixing non-sensitive directions



Here both parameters are loosely constrained

After the rotation the sensitive direction is identified and the other one is fixed to SM

In this way the PCA allows us to identify flat directions and fix them to SM!

Input measurements

ATLAS

- **Global combination** (SMEFT) including:
  - Higgs data (Run2): STXS framework and five channels combination
  - Electroweak data (36-139 fb^{-1}): WW, WZ, ZZ and Z + jets processes
  - LEP & SLC data
  - 28 operators measured, largest combination in ATLAS until now
- **Updated Higgs combination** (SMEFT) to seven channels (adding $\mu\mu$ and $Z\gamma$) in 2024:
  - 19 operators measured
  - SMEFT to UV matching

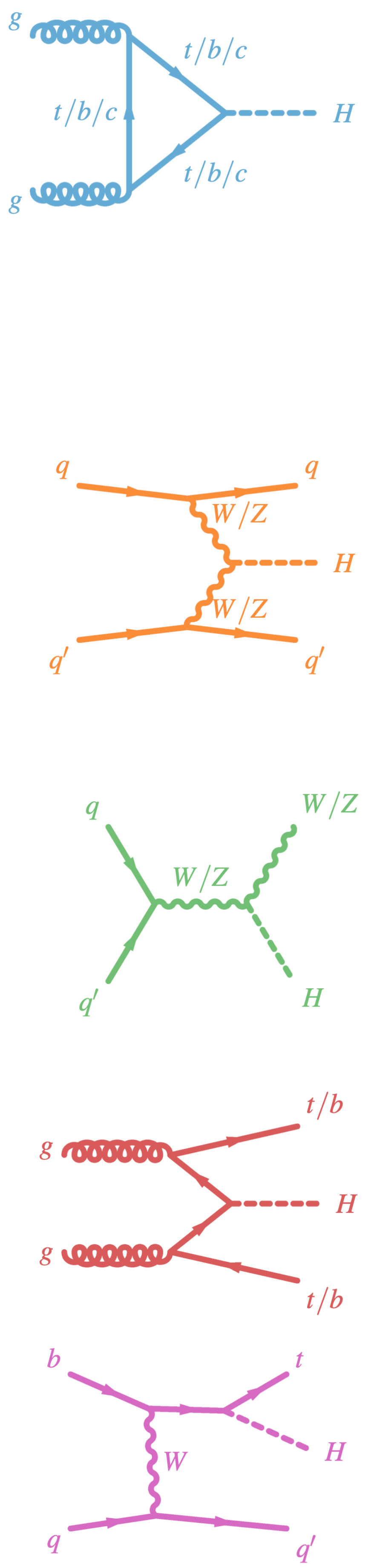
CMS

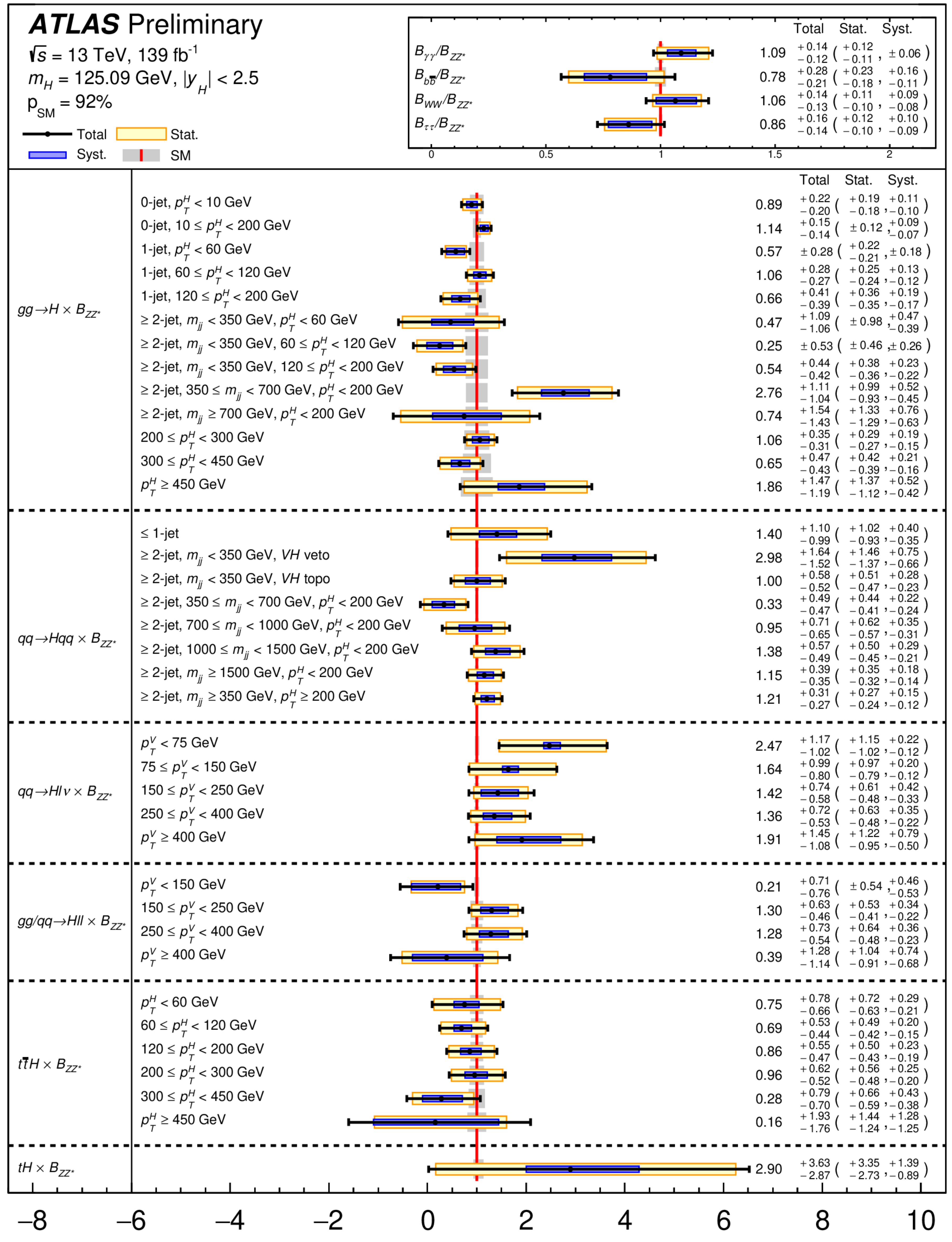
- **Higgs combination** (HEL):
  - Higgs data (partial Run2): STXS framework and 5 channels combination
  - 7 operators measured
- **Top processes interpretation** (SMEFT) :
  - SMEFT analysis using detector level categories and full Run2 data
  - $t\bar{t}H, t\bar{t}W, t\bar{t}Z, tZq, tHq, t\bar{t}t\bar{t}$ processes included
  - 26 operators measured

ATLAS: Higgs measurements

ATL-PHYS-PUB-2022-037

- STXS (**Simplified Template Cross-Section**) framework used as input for the Higgs sector in ATLAS:
  - Higgs cross sections measured differentially in production mode kinematic variables
  - **Five decay channels** (ZZ, WW, $\gamma\gamma$, bb, $\tau\tau$) included, spanning all production modes
    → **extended** in latest Higgs comb: **seven channels,** adding $\mu\mu$ and $Z\gamma$
  - Using STXS bins makes it easier to deal with most of the common issues in statistical combinations (overlap, correlation of systematics etc.)





CMS: Higgs measurements

CMS-PAS-HIG-19-005

- **STXS framework** also used as input for the CMS Higgs combination:
  - **5 decay channels** included (ZZ, WW, $\gamma\gamma$, bb, $\tau\tau$)
  - Partial Run2 dataset used
  - 2nd generation coupling measured with $\mu\mu$ but not included in EFT interpretation

Analysis	Decay tags	Production tags	Luminosity (fb^{-1})
$H \to \gamma\gamma$	$\gamma\gamma$	ggH, $p_T(H) \times$ N-jet bins VBF, $p_T(H\,jj)$ bins	77.4
		ttH	35.9, 41.5
$H \to ZZ^{(*)} \to 4\ell$	$4\mu, 2e2\mu/2\mu 2e, 4e$	ggH, $p_T(H) \times$ N-jet bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH	137
$H \to WW^{(*)} \to \ell\nu\ell\nu$	$e\mu/\mu e$ $ee+\mu\mu$ $e\mu$+jj 3ℓ 4ℓ	ggH $\leq$ 2-jets VBF ggH $\leq$ 1-jet VH hadronic WH leptonic ZH leptonic	35.9
$H \to \tau\tau$	$e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$	ggH, $p_T(H) \times$ N-jet bins VH hadronic VBF	77.4
		VH, high-$p_T(V)$	35.9
$H \to bb$	$W(\ell\nu)H(bb)$ $Z(\nu\nu)H(bb), Z(\ell\ell)H(bb)$	WH leptonic ZH leptonic	35.9, 41.5
	bb	ttH, $t\bar{t} \to 0, 1, 2\ell +$ jets	77.4
		ggH, high-$p_T(H)$ bins	35.9
ttH production with $H \to$ leptons	$2\ell ss, 3\ell, 4\ell$, $1\ell+2\tau_h, 2\ell ss+1\tau_h, 3\ell+1\tau_h$	ttH	35.9, 41.5
$H \to \mu\mu$	$\mu\mu$	ggH VBF	35.9

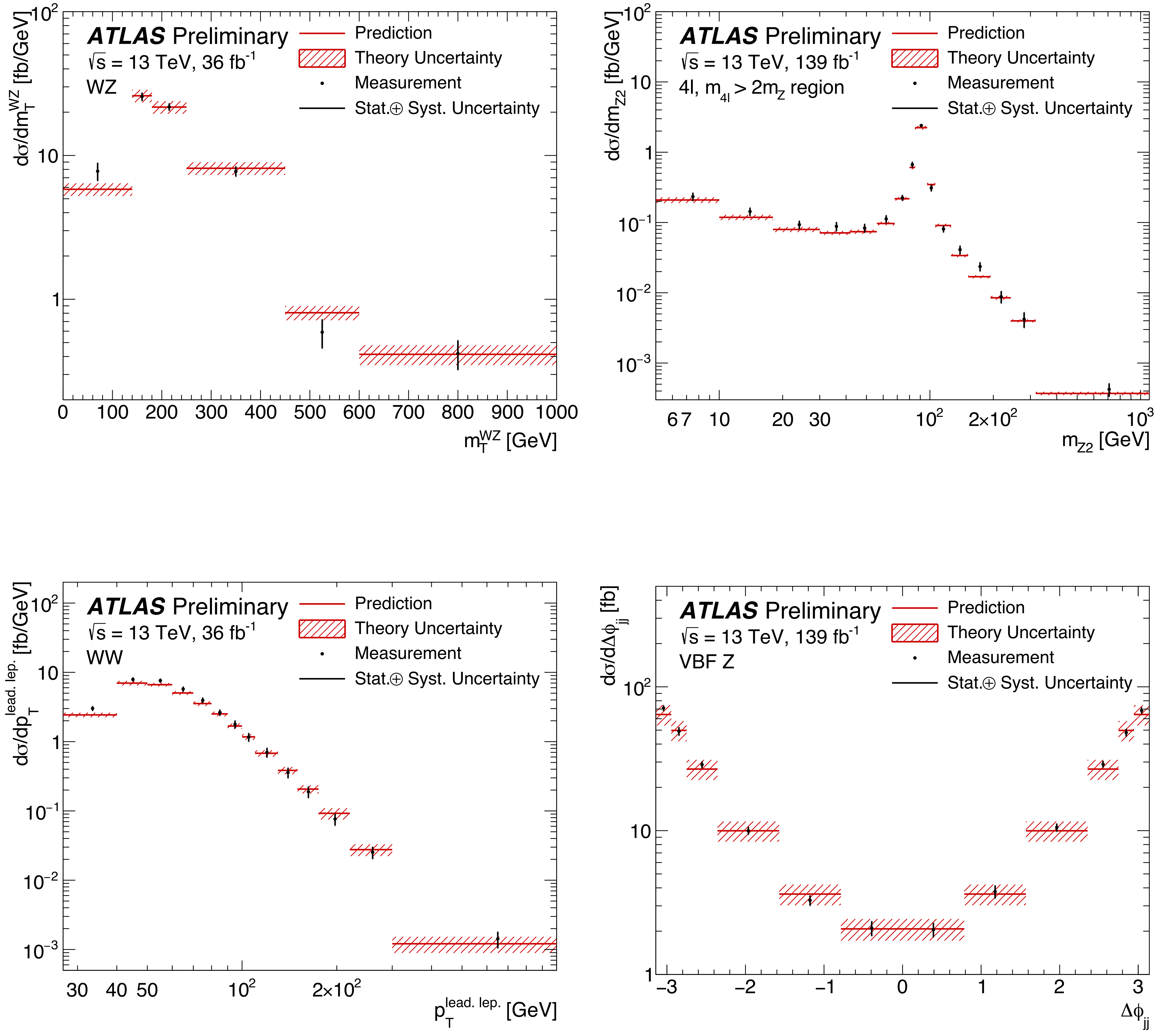
Adapted from reference

ATLAS: Electroweak measurements

ATL-PHYS-PUB-2022-037

- EW data included in ATLAS global EFT combination:
  - **WW, WZ, Z + jets, ZZ unfolded differential distributions** for complementary sensitivity to operators not probed in the Higgs sector
  - Differential cross-sections as function of different kinematic variables for each process

Process	Important phase space cuts	Observable	$\mathcal{L}$ [fb^{-1}]
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55$ GeV, $p_T^{\text{jet}} < 35$ GeV	$p_T^{\text{lead. lep.}}$	36
$pp \to \ell^+\ell^-\ell^{\pm}\nu$	$m_{\ell\ell} \in (81, 101)$ GeV	m_T^{WZ}	36
$pp \to \ell^+\ell^-\ell^+\ell^-$	$m_{4\ell} > 180$ GeV	m_{Z2}	139
$pp \to \ell^+\ell^- jj$	$m_{jj} > 1000$ GeV, $m_{\ell\ell} \in (81, 101)$ GeV	$\Delta\phi_{jj}$	139



LEP & SLC measurements

ATL-PHYS-PUB-2022-037

LEP **precision observables** added to ATLAS global EFT combination :

- LHC precision of EW data is around percent level, LEP & SLC around per mille
- ATLAS included these measurements in the latest global EFT fits: can give us insight into **what LHC can provide in terms of sensitivity to SMEFT**

Forward-backward asymmetry:

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}},$$

Ratio of partial decays widths:

$$R_\ell^0 \equiv \Gamma_{\mathrm{had}}/\Gamma_{\ell\ell},$$

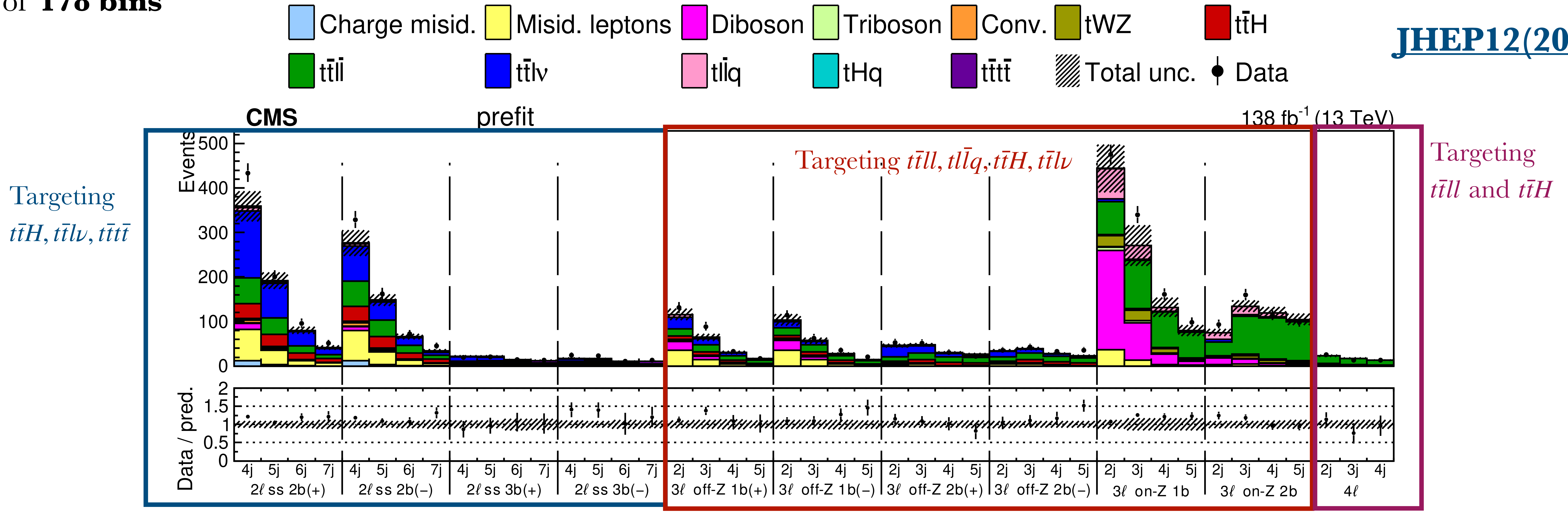
Hadronic pole cross-section:

$$\sigma_{\mathrm{had}}^0 \equiv \frac{12\pi}{m_Z^2}\frac{\Gamma_{\mathrm{ee}}\Gamma_{\mathrm{had}}}{\Gamma_Z^2}$$

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R_ℓ^0	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R_c^0	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R_b^0	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A_{\mathrm{FB}}^{0,\ell}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A_{\mathrm{FB}}^{0,c}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A_{\mathrm{FB}}^{0,b}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ_{had}^0 [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

- Not a combination of published results but standalone analysis!
- Events divided in two same-sign leptons (2*lss*), three leptons (3*l*) and four or more leptons (4*l*) categories
- 3*l* category divided further between on-shell and off-shell Z decays, 3*l* and 2*lss* categories subdivided also by the sign of the sum of the charges of the leptons and number of b-tagged jets
- Events in each of the **43 categories** binned according to a kinematic variable (e.g. p_T of the highest p_T pair of objects) for a total of **178 bins**

JHEP12(2023)068

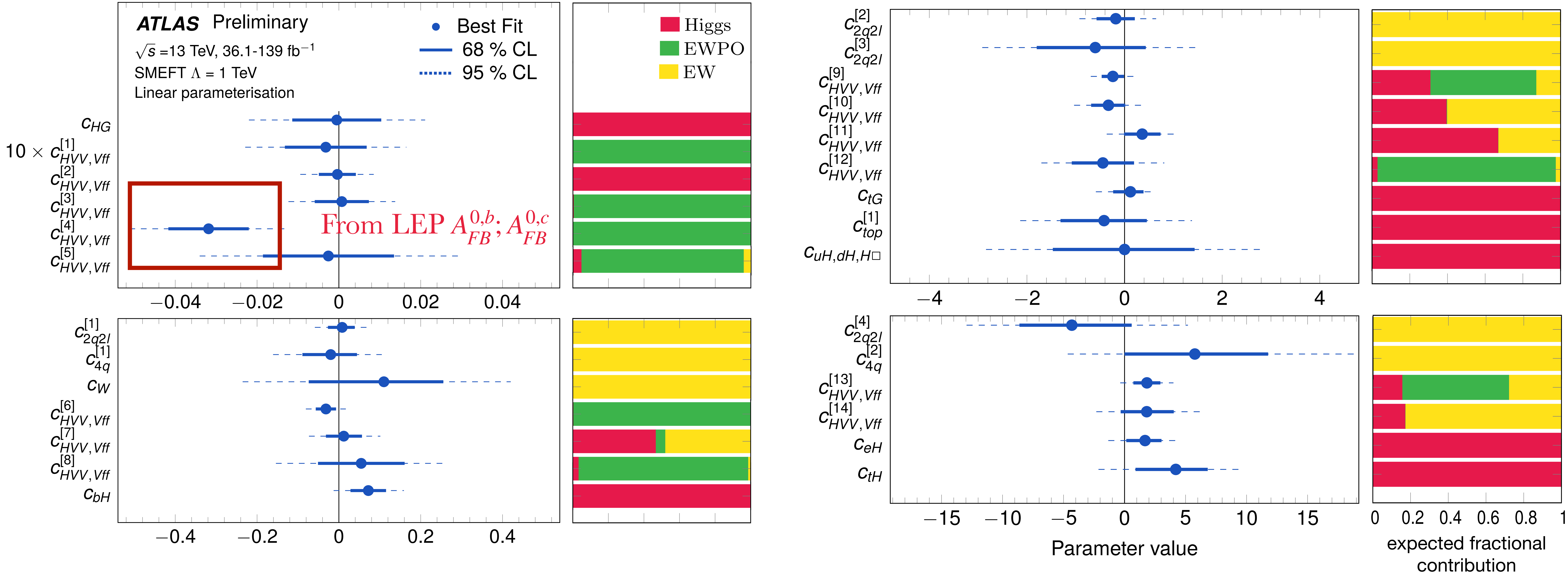


Results

ATLAS results: global EFT fits

- Results are expressed in terms of best fit values and 68% and 95% C.I., for both linear and linear plus quadratic models (linear here): **28 operators measured**
- **Source of sensitivity** to each operator is plotted alongside fit results

ATL-PHYS-PUB-2022-037



ATLAS results: Higgs only update

- Latest Higgs combination in ATLAS highlighted the importance of **connecting the sensitivity** to each operator to the set of measurements
- 19 operators measured, no significant deviations from the SM

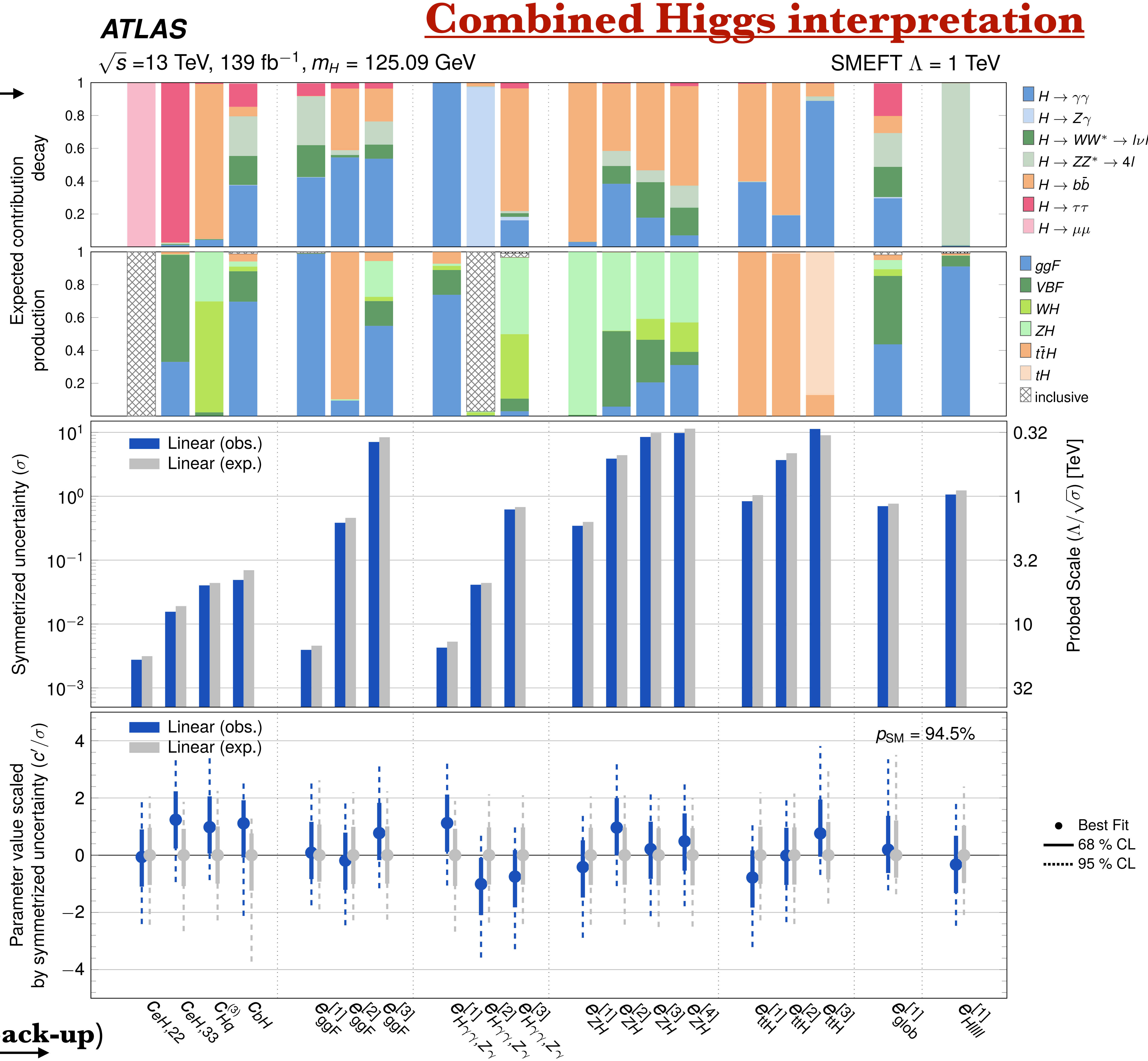
Sensitivity origin for each operator

Absolute uncertainty for each operator

Deviations from the SM

The operators measured (definition in back-up)

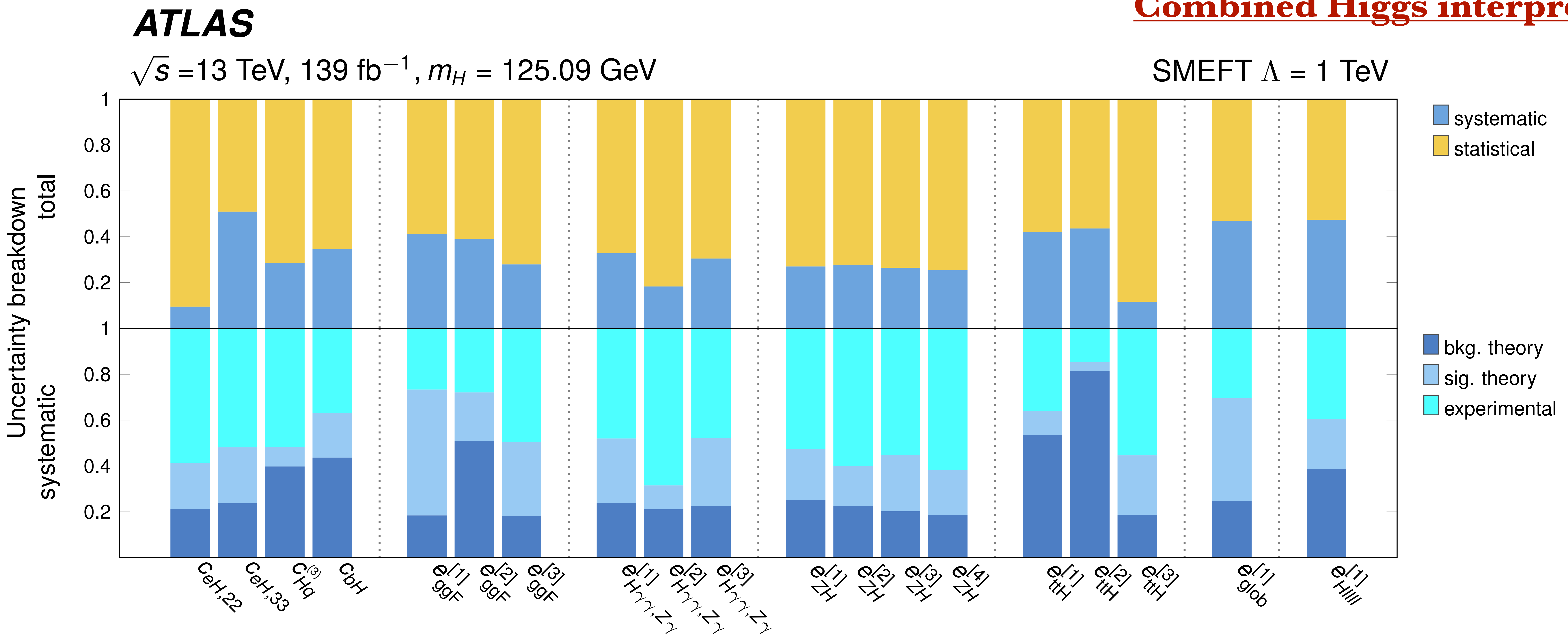
Combined Higgs interpretation



ATLAS results: uncertainties splitting

- Proper treatment of systematic uncertainties and their correlation between different measurements is of primary importance
- ATLAS combined Higgs results included a **breakdown of uncertainties**
- Most of the parameters are dominated by statistical uncertainty

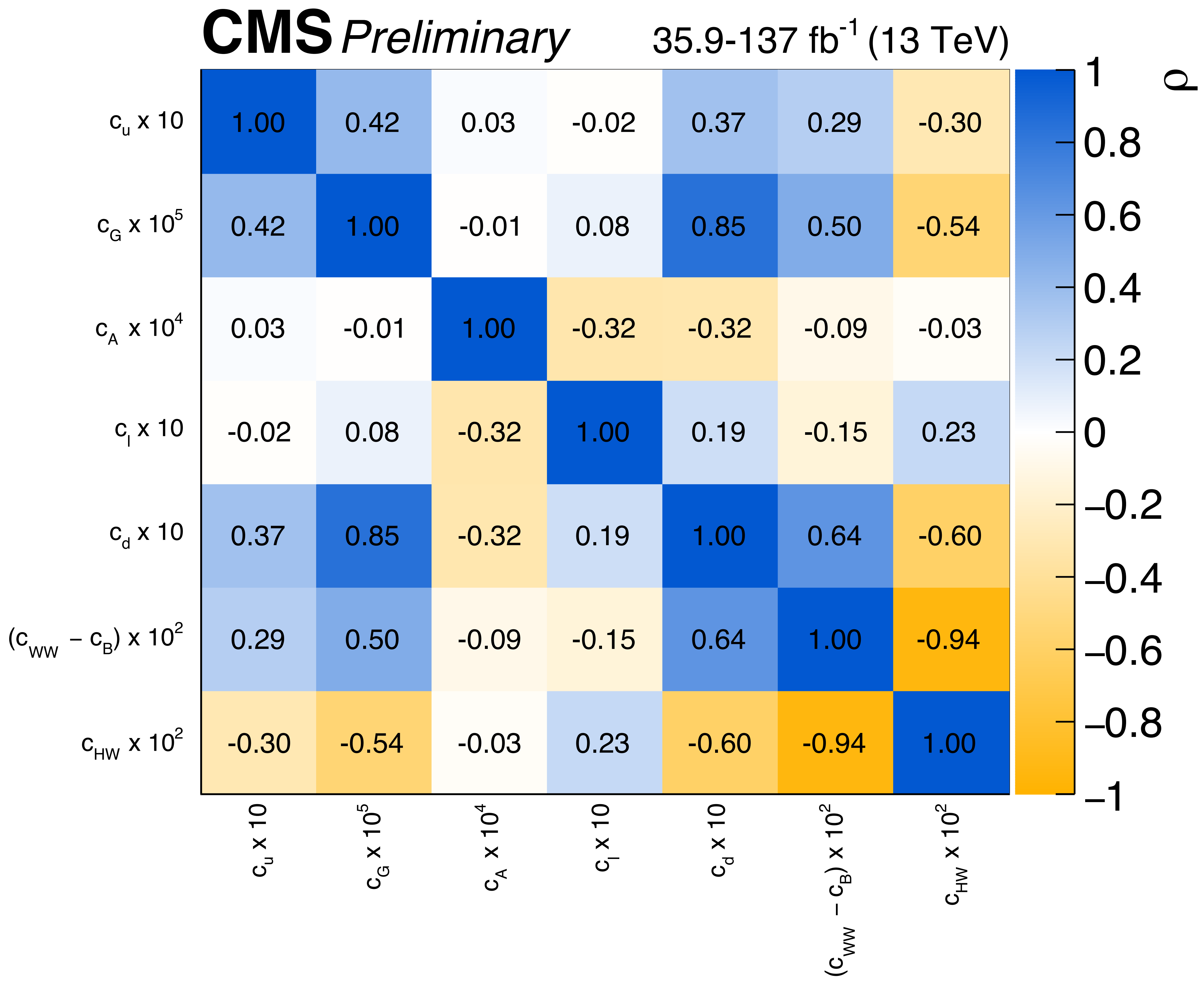
Combined Higgs interpretation



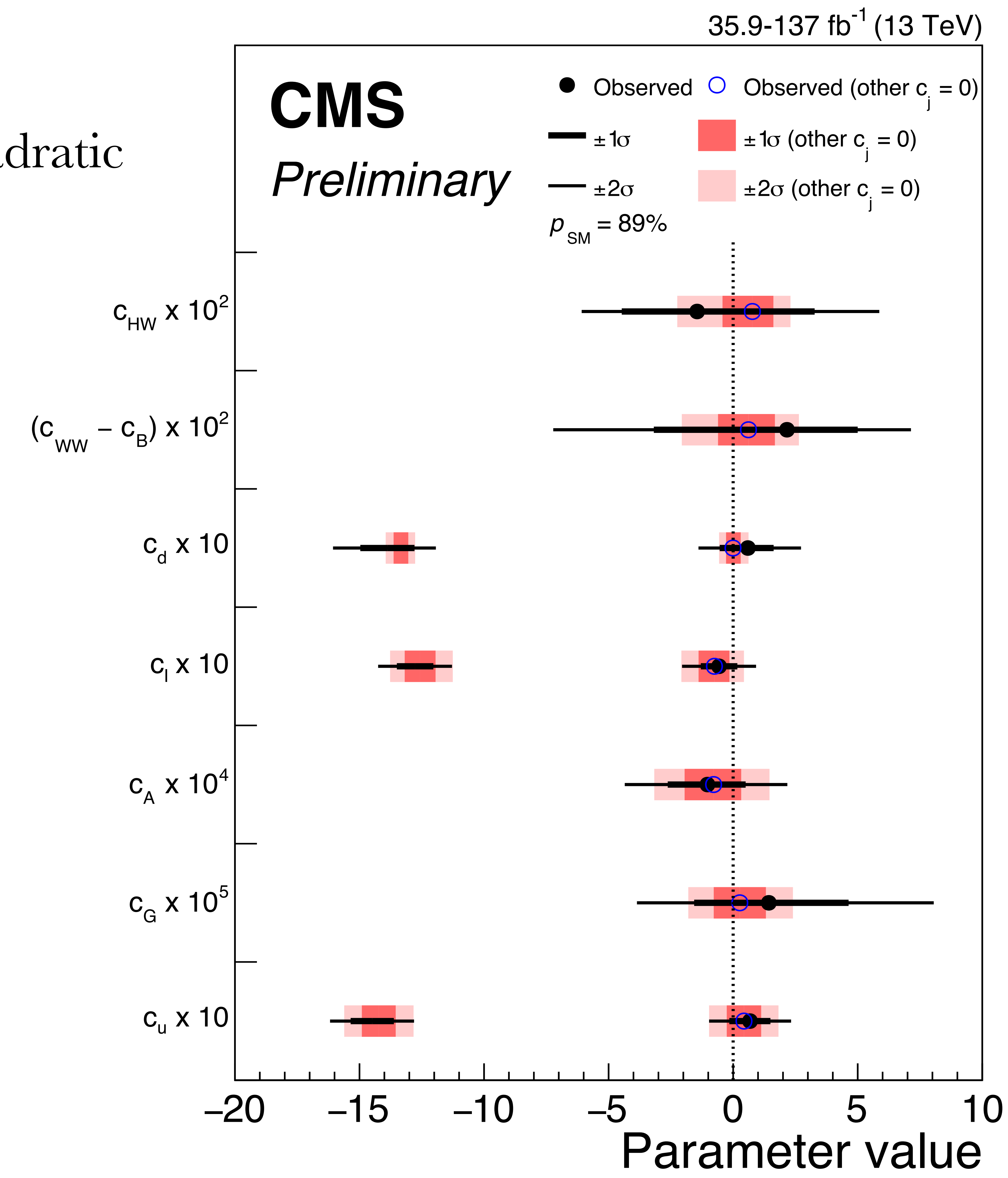
CMS results: Higgs

[CMS-PAS-HIG-19-005](CMS-PAS-HIG-19-005)

- **Simultaneous constraints** placed on **7 different HEL parameters** $(c_G, c_A, c_u, c_d, c_l, c_{HW}, c_{WW} - c_B)$
- Correlation matrix and best fit results are obtained for linear plus quadratic model



	c_u x 10	c_G x 10^5	c_A x 10^4	c_l x 10	c_d x 10	$(c_{WW} - c_B)$ x 10^2	c_{HW} x 10^2
c_u x 10	1.00	0.42	0.03	-0.02	0.37	0.29	-0.30
c_G x 10^5	0.42	1.00	-0.01	0.08	0.85	0.50	-0.54
c_A x 10^4	0.03	-0.01	1.00	-0.32	-0.32	-0.09	-0.03
c_l x 10	-0.02	0.08	-0.32	1.00	0.19	-0.15	0.23
c_d x 10	0.37	0.85	-0.32	0.19	1.00	0.64	-0.60
$(c_{WW} - c_B)$ x 10^2	0.29	0.50	-0.09	-0.15	0.64	1.00	-0.94
c_{HW} x 10^2	-0.30	-0.54	-0.03	0.23	-0.60	-0.94	1.00

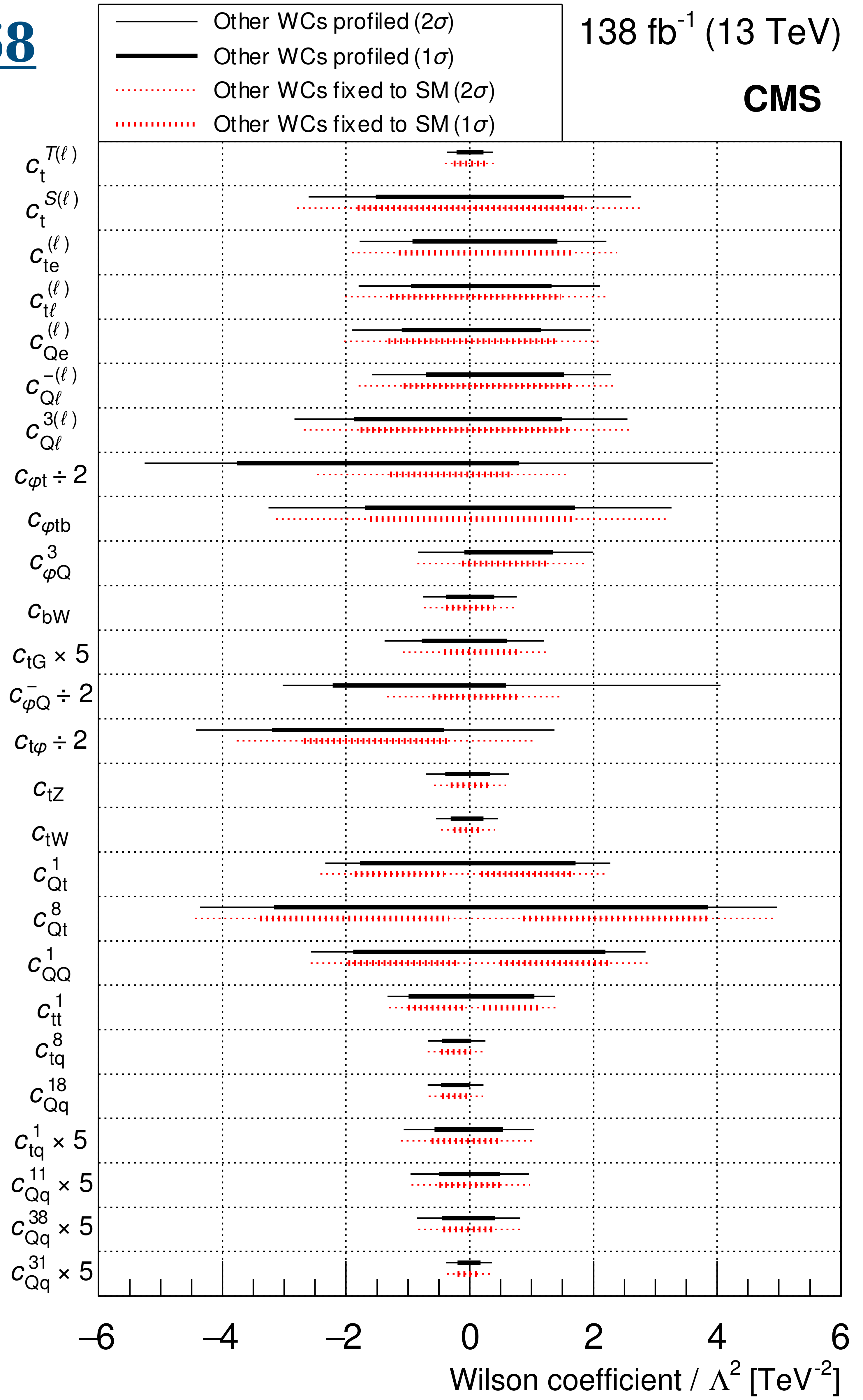


[JHEP12(2023)068](https://doi.org/10.1007/JHEP12(2023)068)

- Results are expressed in the Warsaw basis: **26 operators simultaneously constrained** (**most global EFT analysis to date in CMS**)

- Majority of the WCs dominated by statistical uncertainty

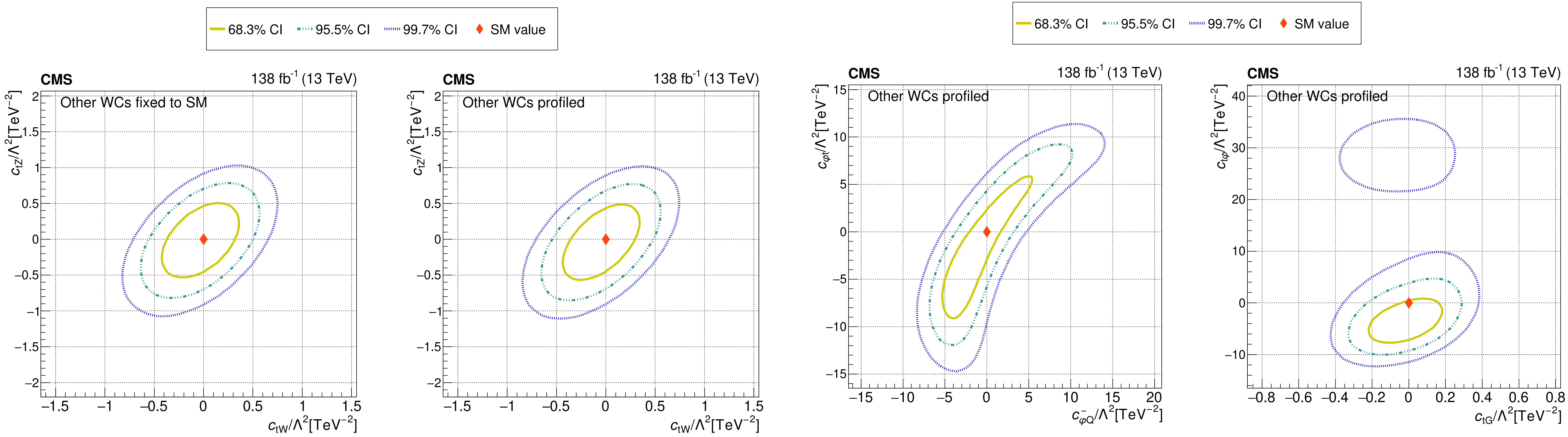
Systematic uncertainty	Average change in the yields
Integrated luminosity	1.6%
Jet energy scale and resolution	1%
b jet tagging scale factors	1%
Theoretical cross section	1–4% (QCD) 1% (PDF)
Renormalization and factorization scales	3%
Parton shower	1–2%
Additional radiation	7%
Electron and muon identification and isolation	2% (electron) 1% (muon)
Trigger efficiency	≤1%
Pileup	1%
L1 prefiring	1%
Misidentified-lepton rate	3%
Charge misreconstruction rate	1%
Jet mismodeling	7%



Nikhef

CMS results: Top

- Correlation between coefficients is explored with 2D scans of the likelihood
- In most cases, the 2D scans in which the other 24 WCs are profiled are very similar to the 2D scans in which the other WCs are fixed to zero
- Disjoint contours are also observed



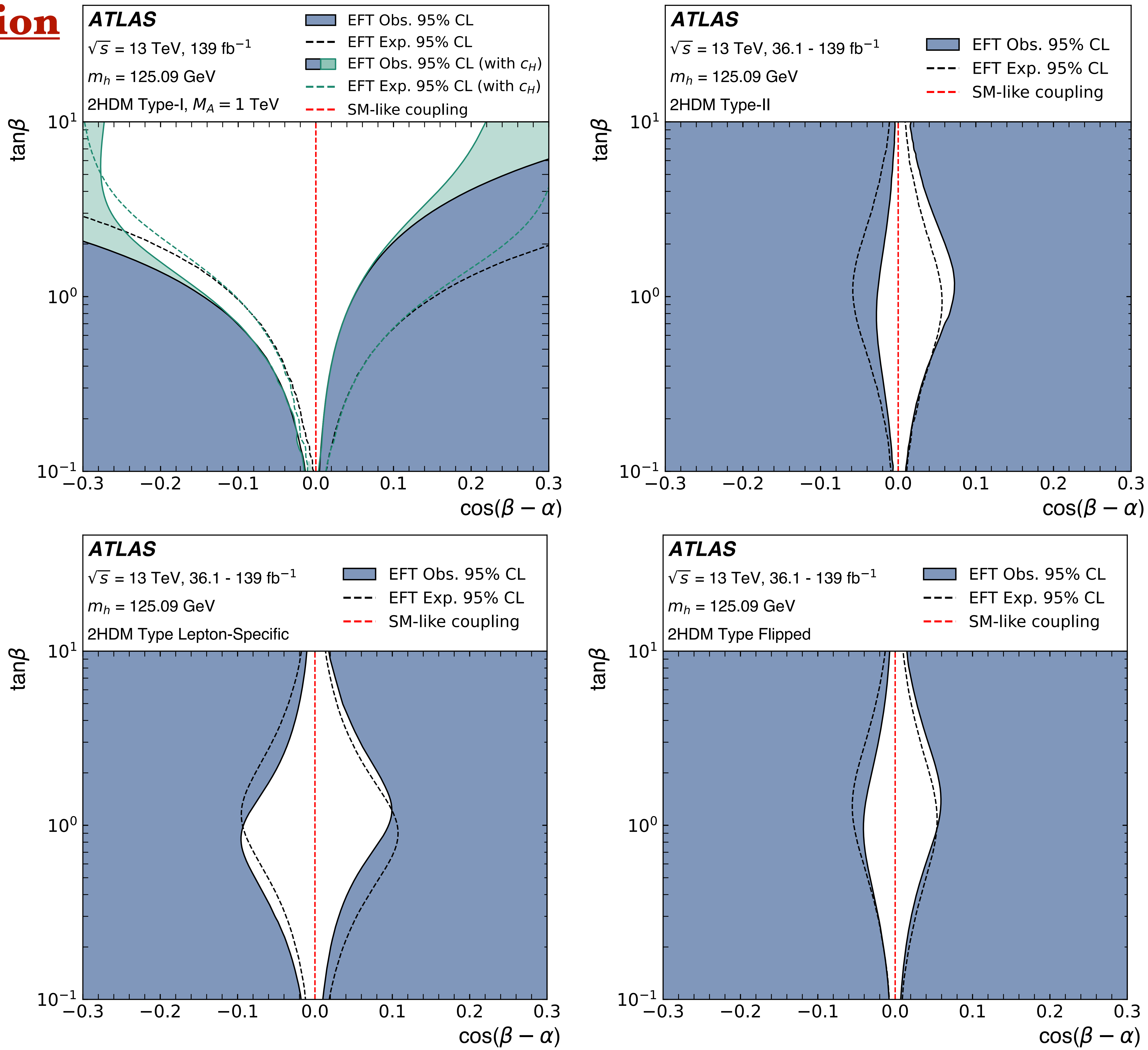
[JHEP12(2023)068]

Combined Higgs interpretation

- Constraints of SMEFT operators can be **re-interpreted into constraints in specific physics theories**

- E.g. **Two-Higgs doublet models (2HDM)** in latest ATLAS Higgs combination (using inputs from Phy. Rev. D 102, 055012 (2020) - S.Dawson, S.Homiller, & S.D. Lane)

- New particles modify the properties of the already discovered Higgs Boson → operators modifying those can be translated into constraints on 2HDM parameters



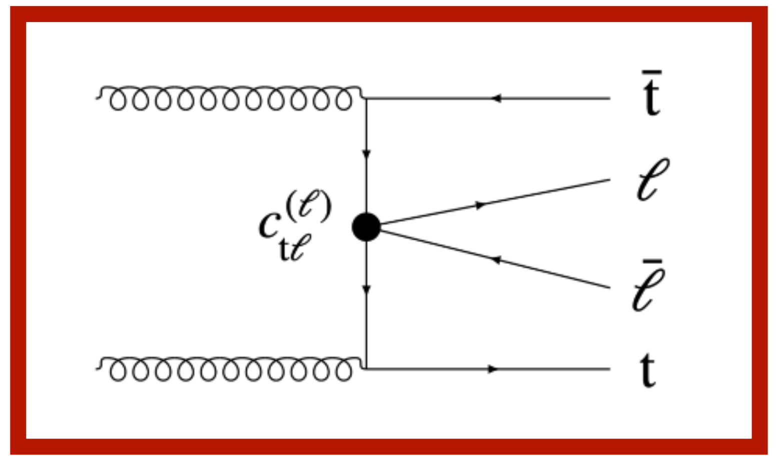
Conclusion

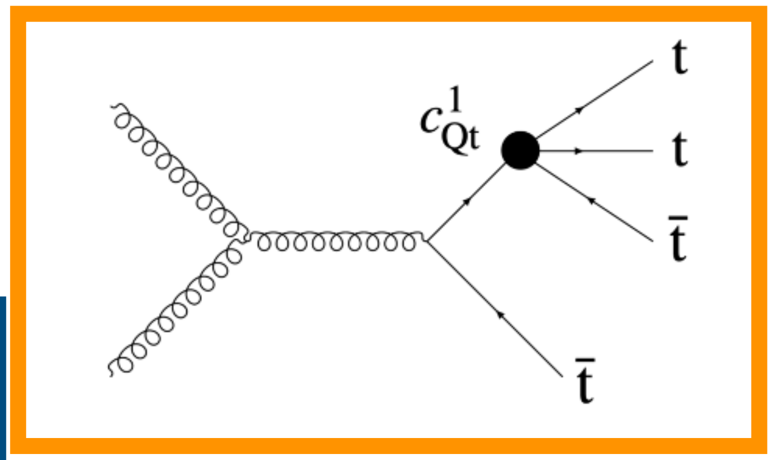
- Summary:
  - **ATLAS** has produced two interpretations of large combinations of measurements, mostly focusing on the **Higgs sector** and its combination with **electroweak measurements**
    - The collaboration is focusing on increasingly larger combinations trying to include measurements from all the sectors but for now the Top sector is not included
    - **SMEFT to UV matching**: first results with **2HDM** produced by ATLAS in latest Higgs combination
  - **CMS**: for now also no combinations of measurements from Higgs, EW and Top sectors together
    - **Higgs combination** done with partial Run2 data, constraining operators in HEL
    - **Top** quark production **analysis in EFT framework** includes processes that can simultaneously constrain many operators of different nature

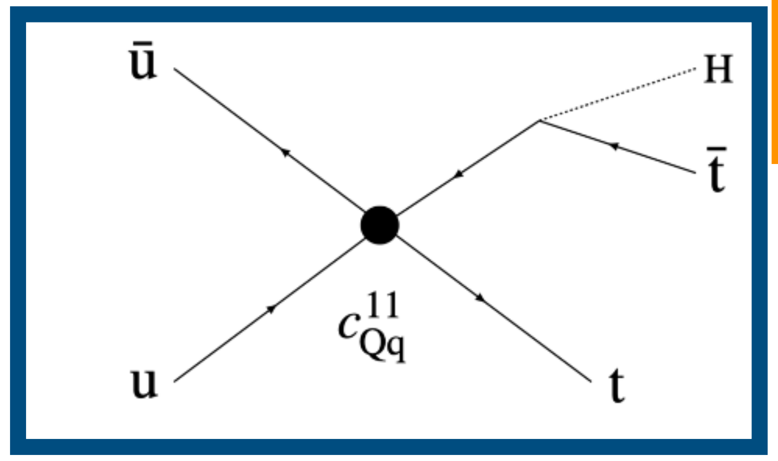
Thank you!

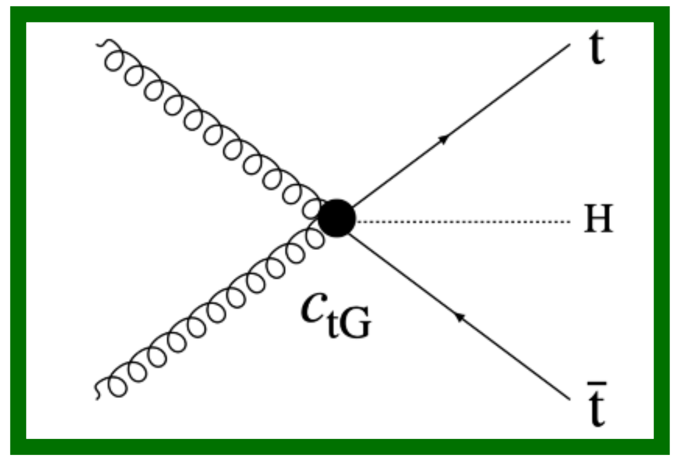
Back-up

CMS: Top quark production EFT sensitivity









Grouping of WCs	WCs	Lead categories
2hq2ℓ	$c_{Q\ell}^{3(\ell)}$, $c_{Q\ell}^{-(\ell)}$, $c_{Qe}^{(\ell)}$, $c_{t\ell}^{(\ell)}$, $c_{te}^{(\ell)}$, $c_{t}^{S(\ell)}$, $c_{t}^{T(\ell)}$	3ℓ off-Z
4hq	c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	2ℓss
2hq2lq "$t\bar{t}\ell\nu$-like"	c_{Qq}^{11}, c_{Qq}^{18}, c_{tq}^{1}, c_{tq}^{8}	2ℓss
2hq2lq "$t\ell\bar{\ell}q$-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
2hqV "$t\bar{t}\ell\bar{\ell}$-like"	c_{tZ}, $c_{\varphi t}$, $c_{\varphi Q}^{-}$	3ℓ on-Z and 2ℓss
2hqV "tXq-like"	$c_{\varphi Q}^{3}$, $c_{\varphi tb}$, c_{bW}	3ℓ on-Z
2hqV (significant impacts on many processes)	c_{tG}, $c_{t\varphi}$, c_{tW}	3ℓ and 2ℓss

Scaling down SMEFT: flavour symmetry

- Too many operators at dimension six, cannot be constrained by data included in the combinations
- **Flavour symmetry** used: choice based on data included

$U(3)^5$ scheme

All quark generations treated similarly

All lepton generations treated similarly

60 WCs (CP even)

Relax t,b →

topU3l scheme

First two quark generations treated similarly

All lepton generations treated similarly

129 WCs (CP even)

Relax leptons →

Top scheme

First two quark generations treated similarly

All leptons generations treated separately

204 WCs (CP even)

topU3l : top & bottom treated differently

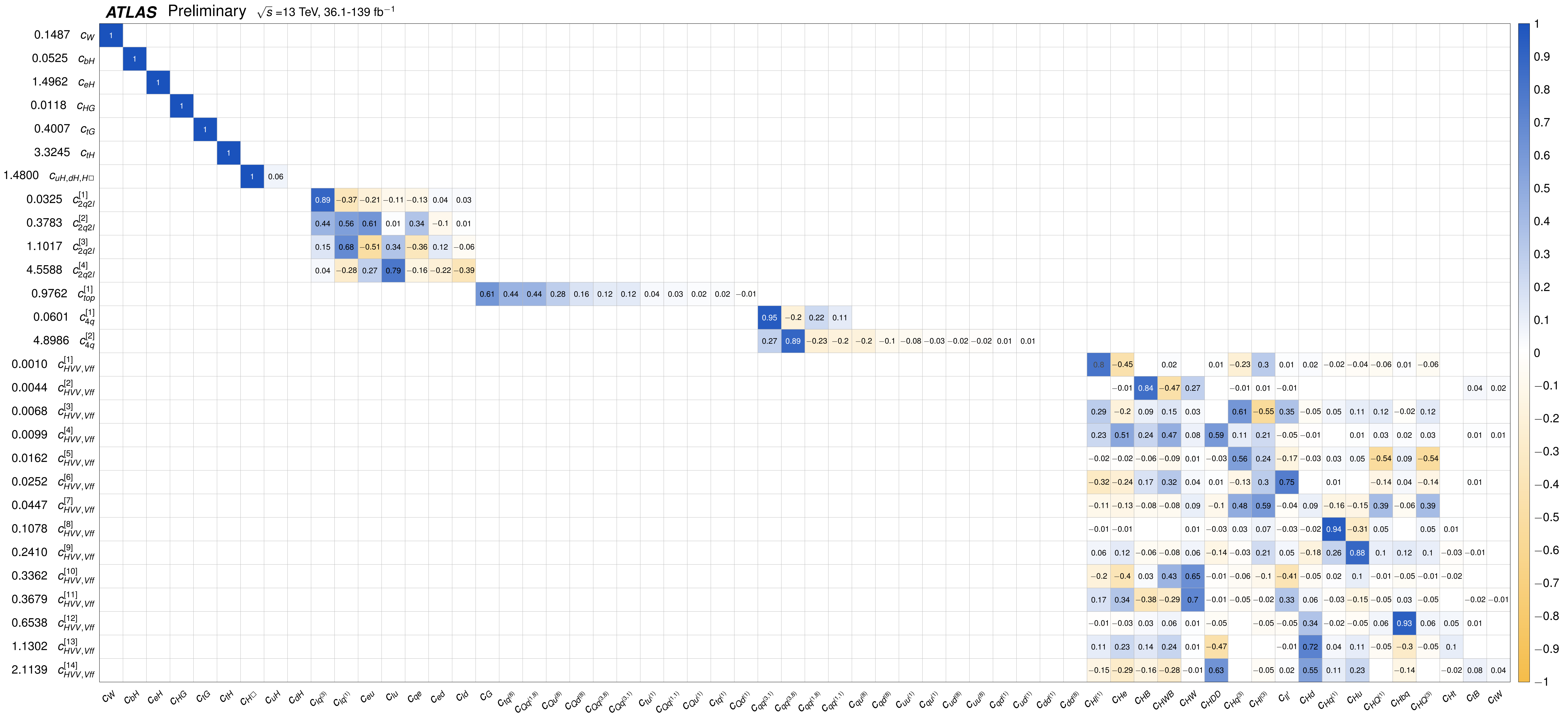
- ATLAS global EFT fits

Top: No lepton flavour universality

- ATLAS Higgs comb

Both CMS results assume lepton flavour universality!

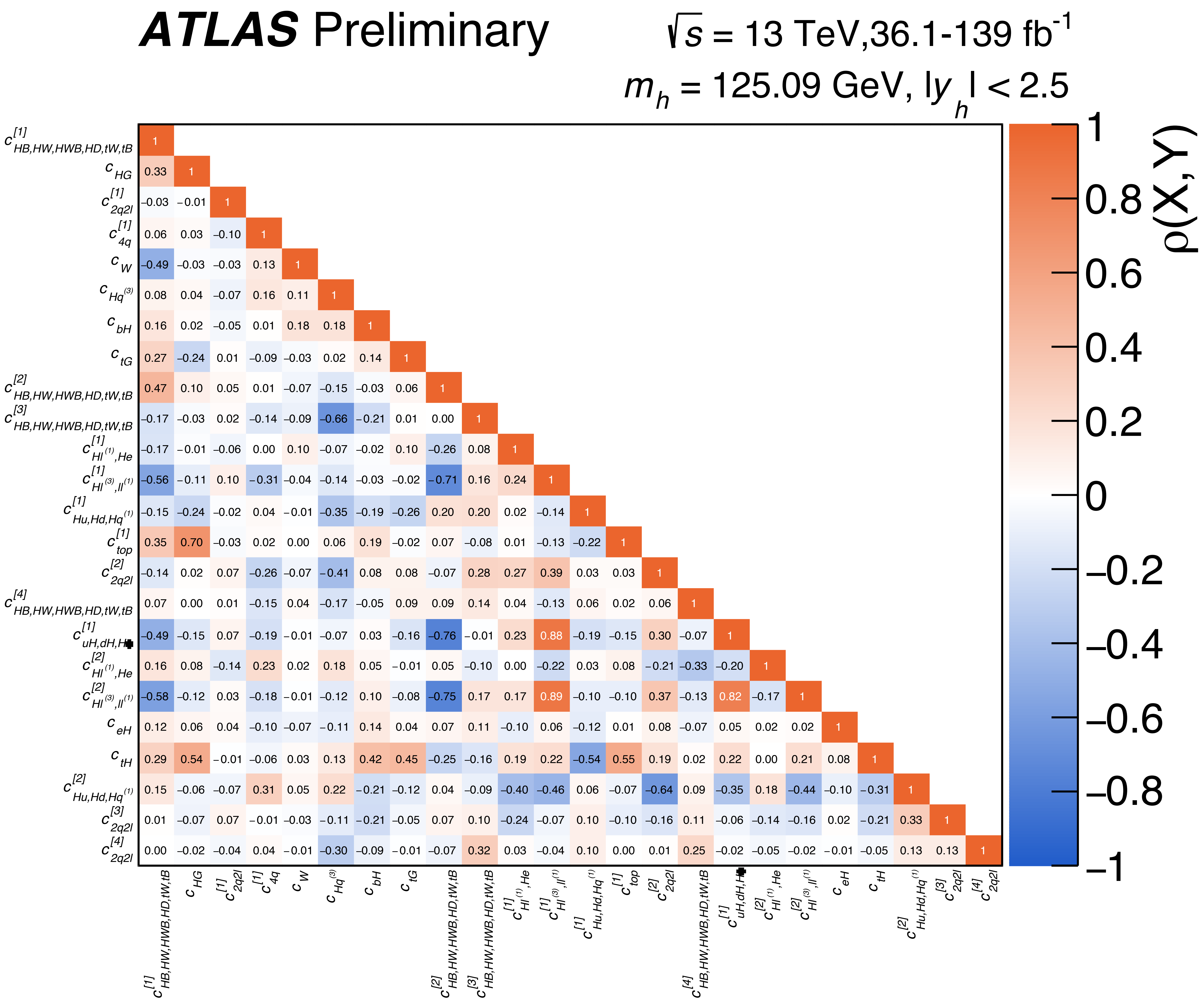
Fit basis: ATLAS global EFT fits definition



$$\text{e.g. } c^{[1]}_{2q2l} = 0.89c^{(3)}_{tq} - 0.37\ldots$$

Nikhef

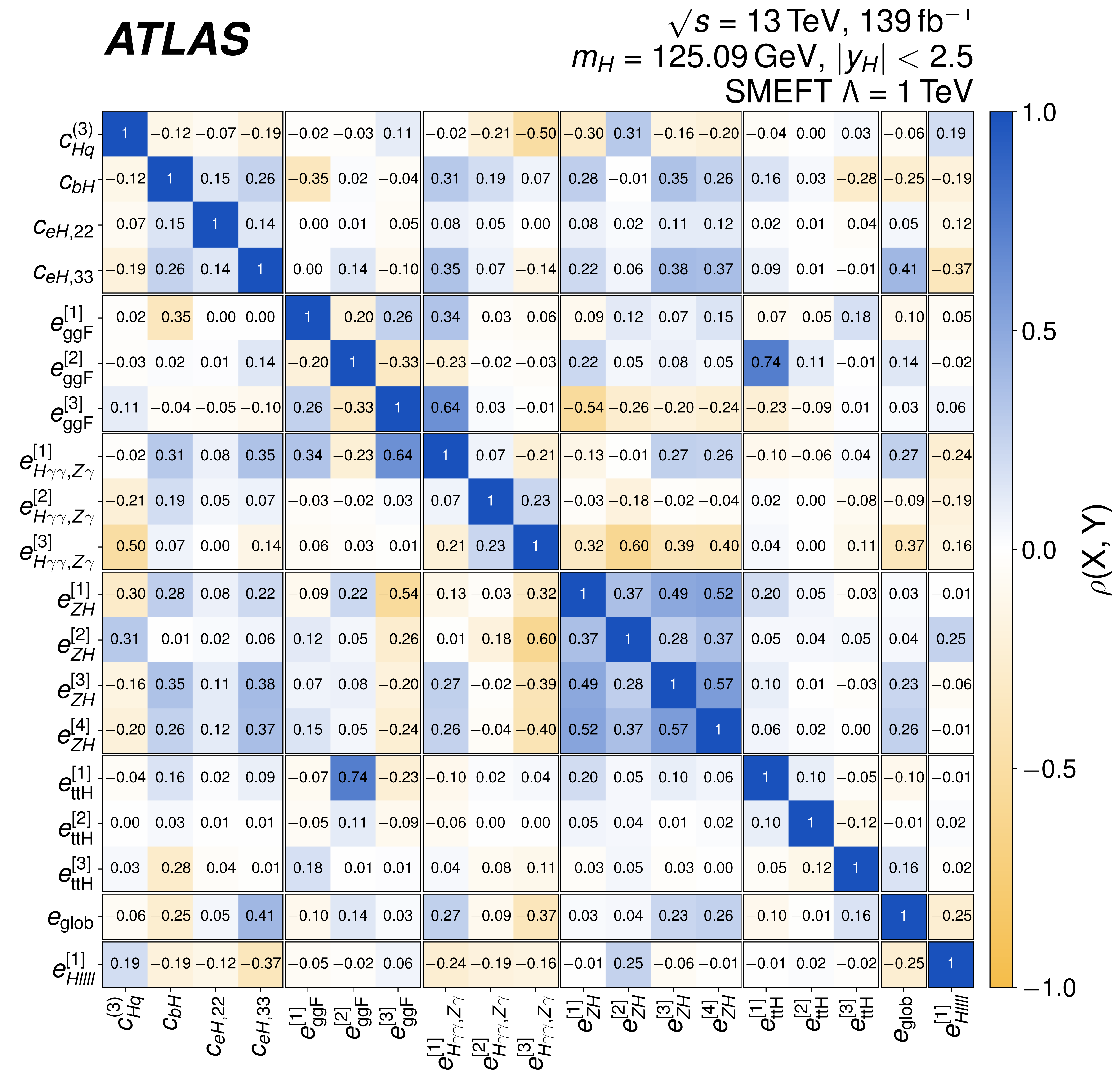
Fit basis: ATLAS global EFT fits correlation



Fit basis: ATLAS Higgs comb definition

e.g. $e^{[2]}_{ggF} = 0.03c_{HG} + 0.99c_{tG} + 0.11c_{tH}$

Fit basis: ATLAS Higgs comb correlation



Nikhef

Higgs Effective Lagrangian

- From Alloul, A., Fuks, B. & Sanz, V. ,JHEP04(2014)110

- Effective approach: higher dimensional operators to parametric the possible effects of non-observed states at higher energies

- The most general gauge-invariant Lagrangian at dimension six:

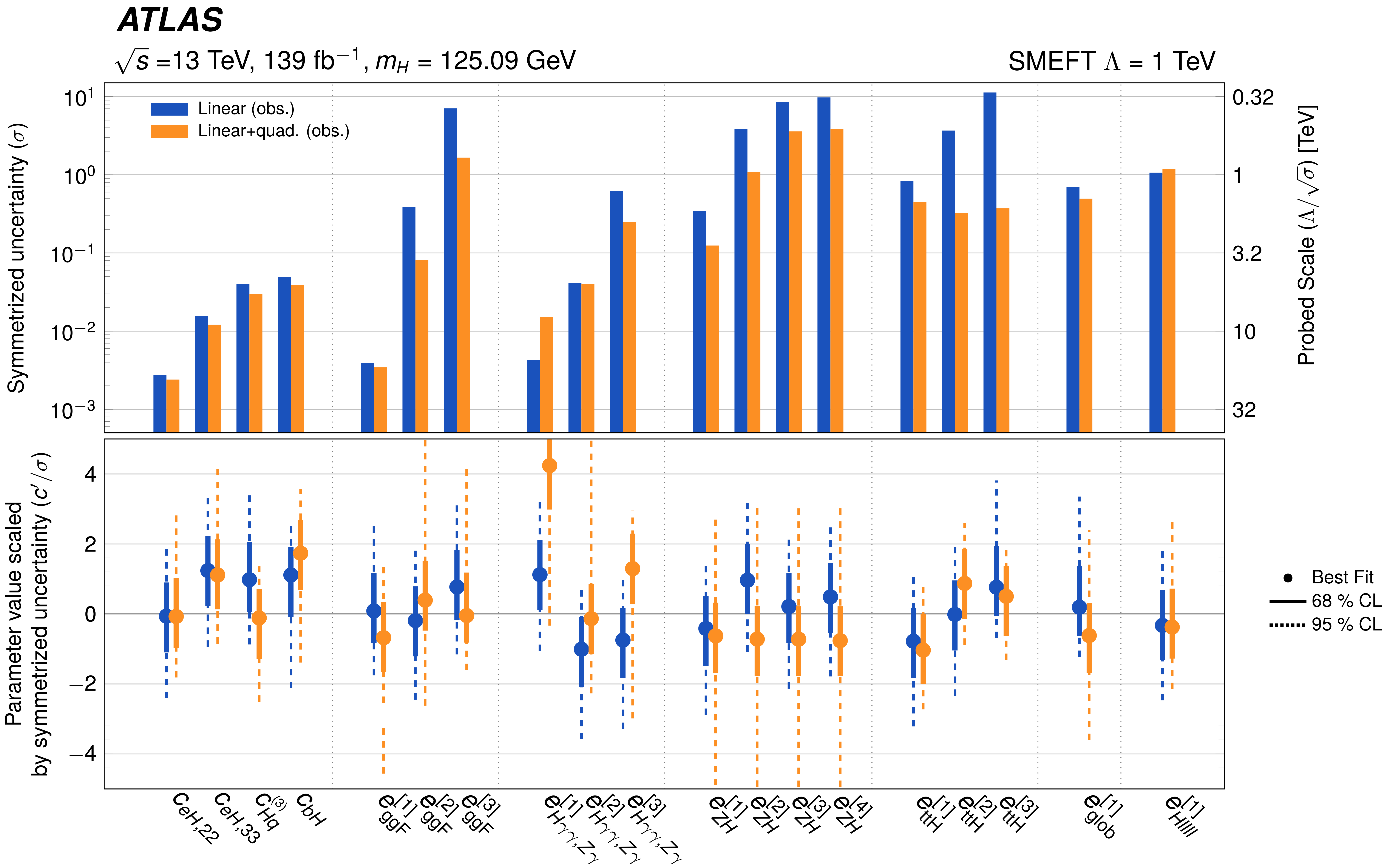
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \bar{c}_i \mathcal{O}_i = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SILH} + \mathcal{L}_{CP} + \mathcal{L}_{F_1} + \mathcal{L}_{F_2} + \mathcal{L}_G \,,$$

- Where

$$\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{\bar{c}_H}{2v^2}\partial^\mu\big[\Phi^\dagger\Phi\big]\partial_\mu\big[\Phi^\dagger\Phi\big] + \frac{\bar{c}_T}{2v^2}\big[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\big]\big[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\big] - \frac{\bar{c}_6\lambda}{v^2}\big[\Phi^\dagger\Phi\big]^3 \\
& - \Big[\frac{\bar{c}_u}{v^2} y_u \Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger\Phi\ \Phi\bar{Q}_L d_R + \frac{\bar{c}_l}{v^2} y_\ell\ \Phi^\dagger\Phi\ \Phi\bar{L}_L e_R + {\rm h.c.}\Big] \\
& + \frac{ig\ \bar{c}_W}{m_W^2}\big[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi\big] D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar{c}_B}{2m_W^2}\big[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\big]\partial^\nu B_{\mu\nu} \\
& + \frac{2ig\ \bar{c}_{HW}}{m_W^2}\big[D^\mu\Phi^\dagger T_{2k} D^\nu\Phi\big] W^k_{\mu\nu} + \frac{ig'\ \bar{c}_{HB}}{m_W^2}\big[D^\mu\Phi^\dagger D^\nu\Phi\big] B_{\mu\nu} \\
& + \frac{g'^2\ \bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu}\,,
\end{aligned}$$

ATLAS Higgs only: linear vs quadratic

Strongest improve with quadratic in $e^{[3]}_{ggF}$ (increased sensitivity in ggF, ZH and ttH production modes and $\gamma\gamma$ decay) and $e^{[2]}_{ttH}, e^{[3]}_{ttH}$ (high p_T bins sensitivity enhanced in ttH and tH)



Nikhef

Simplified likelihood fits

- Complexity of the model makes the fitting long and CPU expensive: a quick way of studying it is with **simplified likelihood fits**

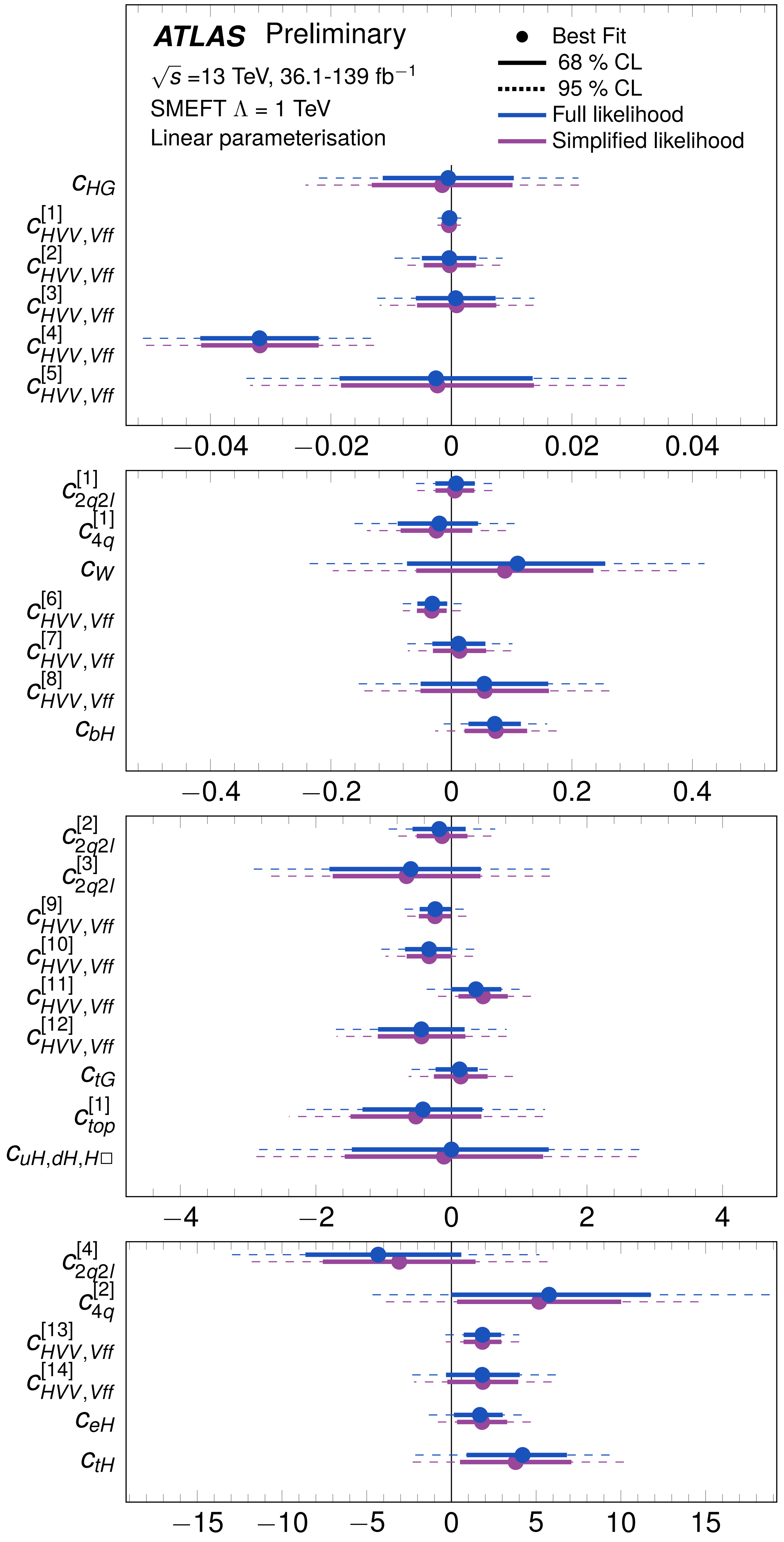
- MultiVariate Gaussian model (MVG) constructed as:

$$L(\mu) = \frac{1}{\sqrt{(2\pi)^{n_\mu} \det(C_\mu)}} \exp\left(-\frac{1}{2}\Delta\boldsymbol{\mu}^\intercal C_\mu^{-1} \Delta\boldsymbol{\mu}\right), \quad \Delta\boldsymbol{\mu} = \boldsymbol{\mu} - \hat{\boldsymbol{\mu}}.$$

where $\hat{\mu}$ are the POIs best fit results obtained over the full statistical model and C_μ is the covariance matrix at the best fit values, encoding information on statistical and systematic uncertainty

- Number of floating parameters is thus reduced from thousands to ~30

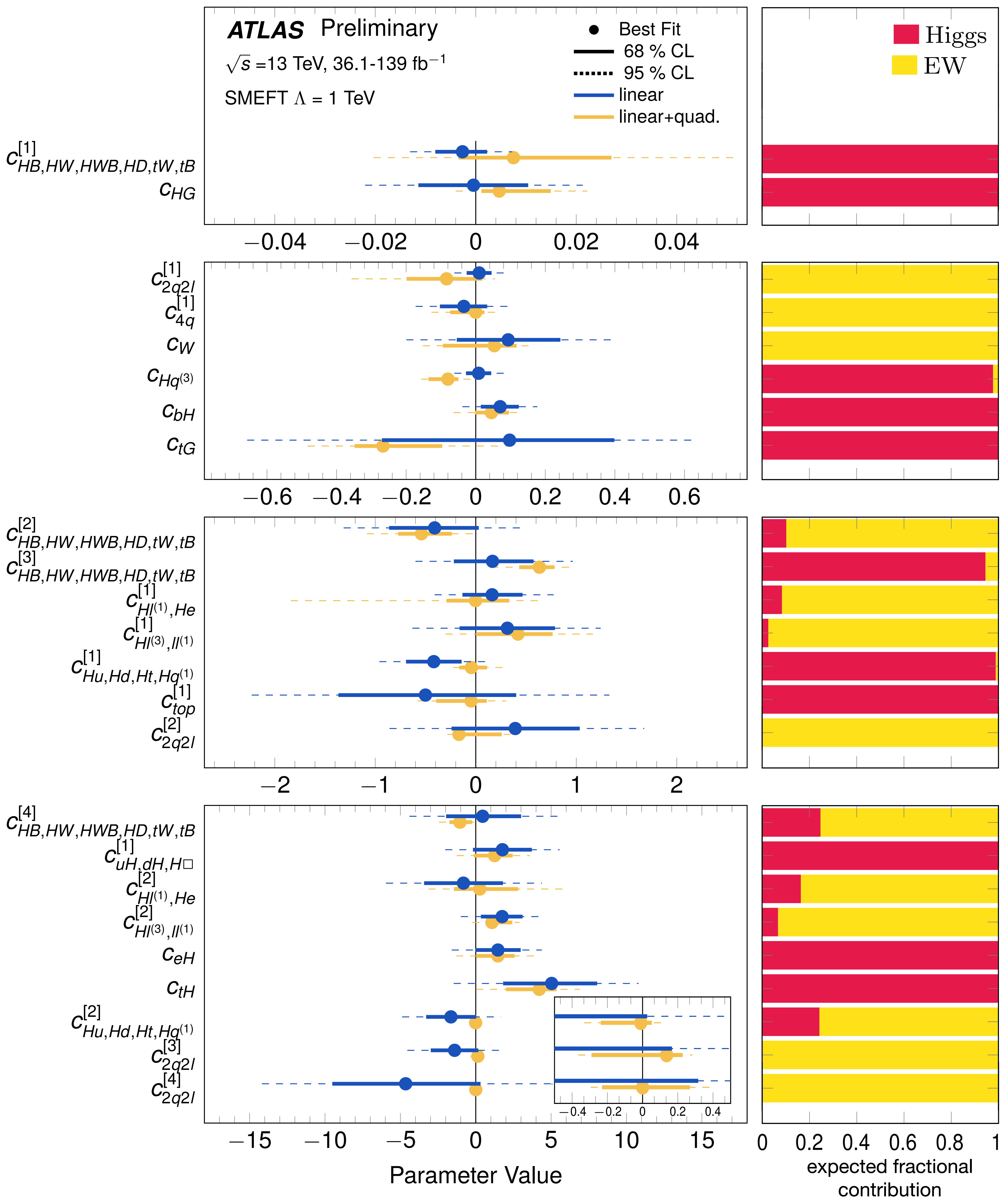
- Info to construct these models is publicly available



Comparison full -simplified likelihood from latest Higgs only comb

ATLAS global EFT: linear plus quadratic model

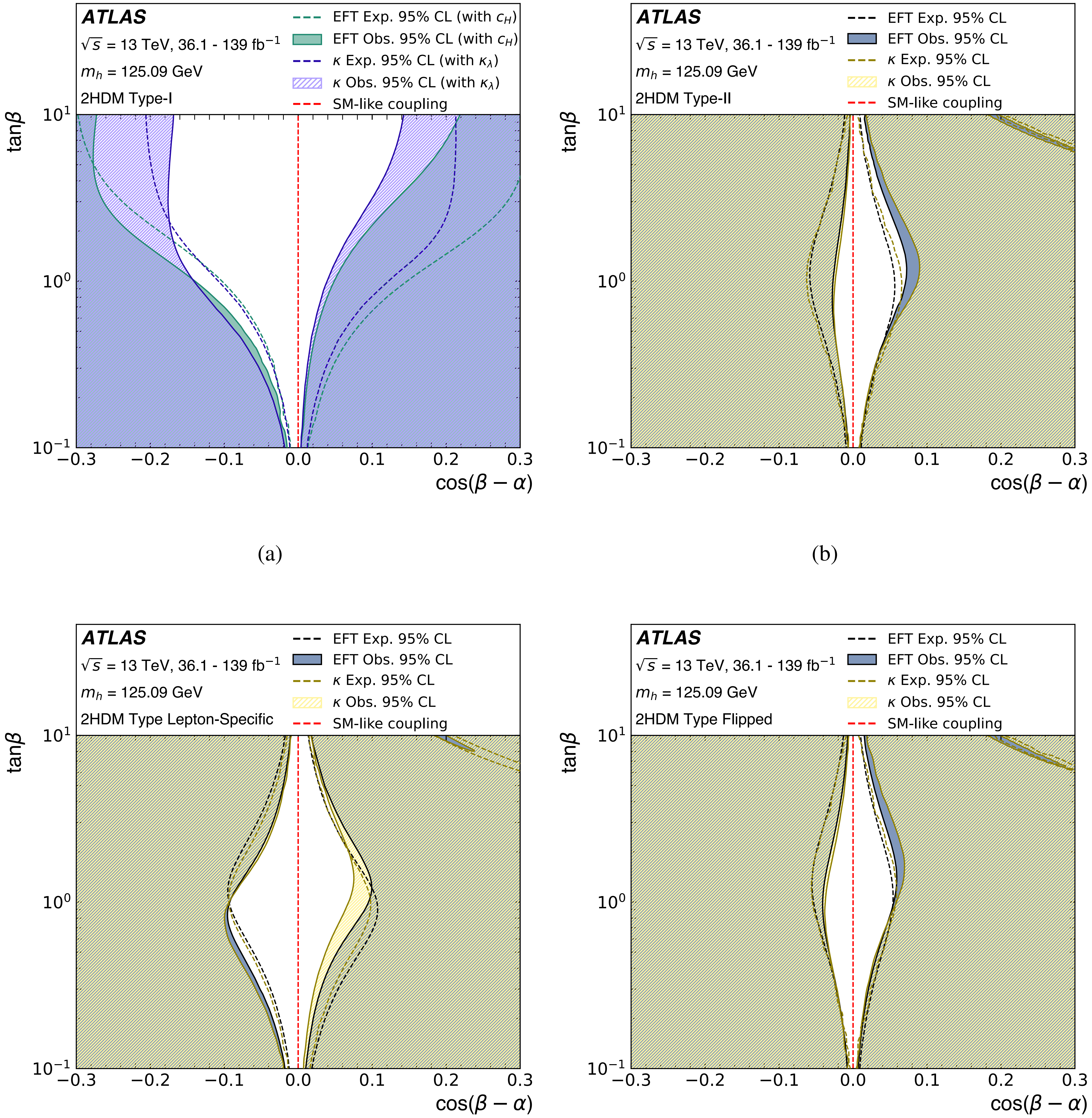
- ATLAS global EFT fits: no linear plus quadratic EFT predictions for LEP data, quadratic results only with LHC data
- Constraints on some parameters are weaker due to the introduction of additional correlation between parameters
- Constraints to $c_{4q}^{[1]}$ and c_W stronger due to contribution to VBF Z measurements and WW and WZ measurements



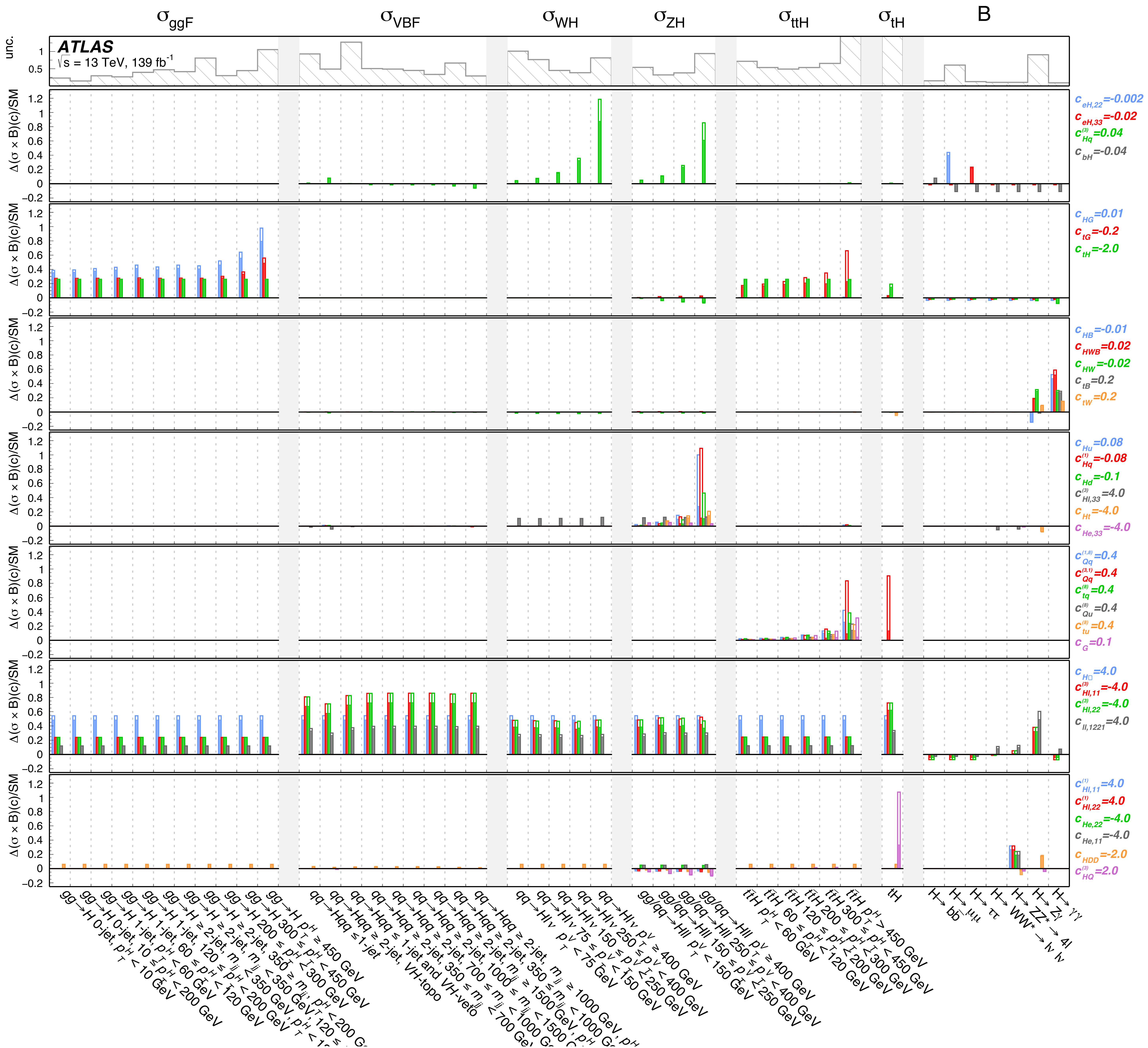
ATLAS Higgs only: EFT matching vs Kappa framework

Dimension six results are known not to reproduce full model results (PhysRevD.106.055012 - S.Dawson, D. Fontes, S. Homiller, M. Sullivan):

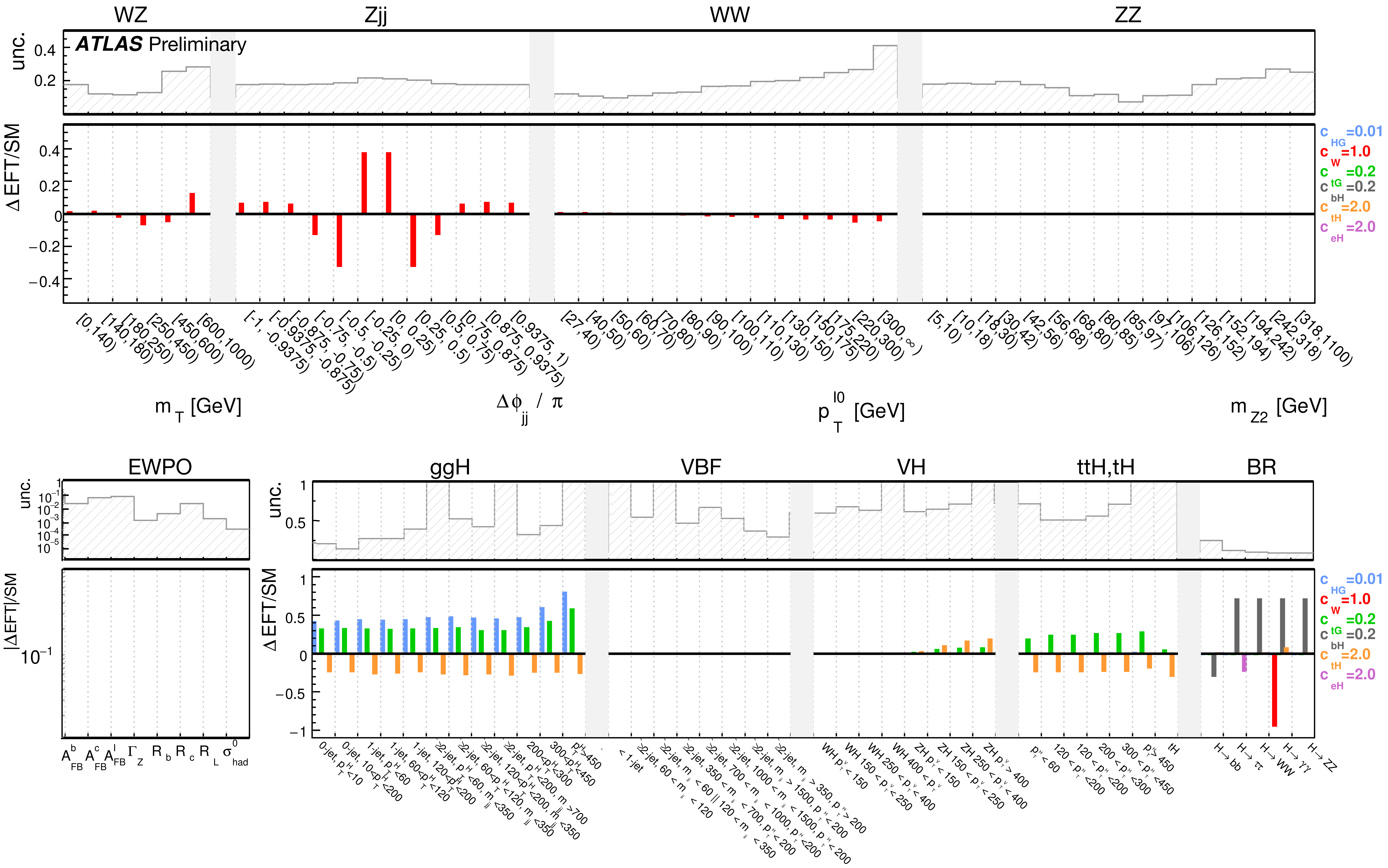
- Type I constraints are driven at high tan(β) by the effect of Higgs Boson couplings to vector bosons
- These effects are captured by EFT only at dimension eight
- For type L,F and II dimension six is unable to capture the "opposite sign" solution, i.e. the classical petal structure found in the full model is not present (only one minimum possible).
- Quadratic effects can capture this to a certain extent



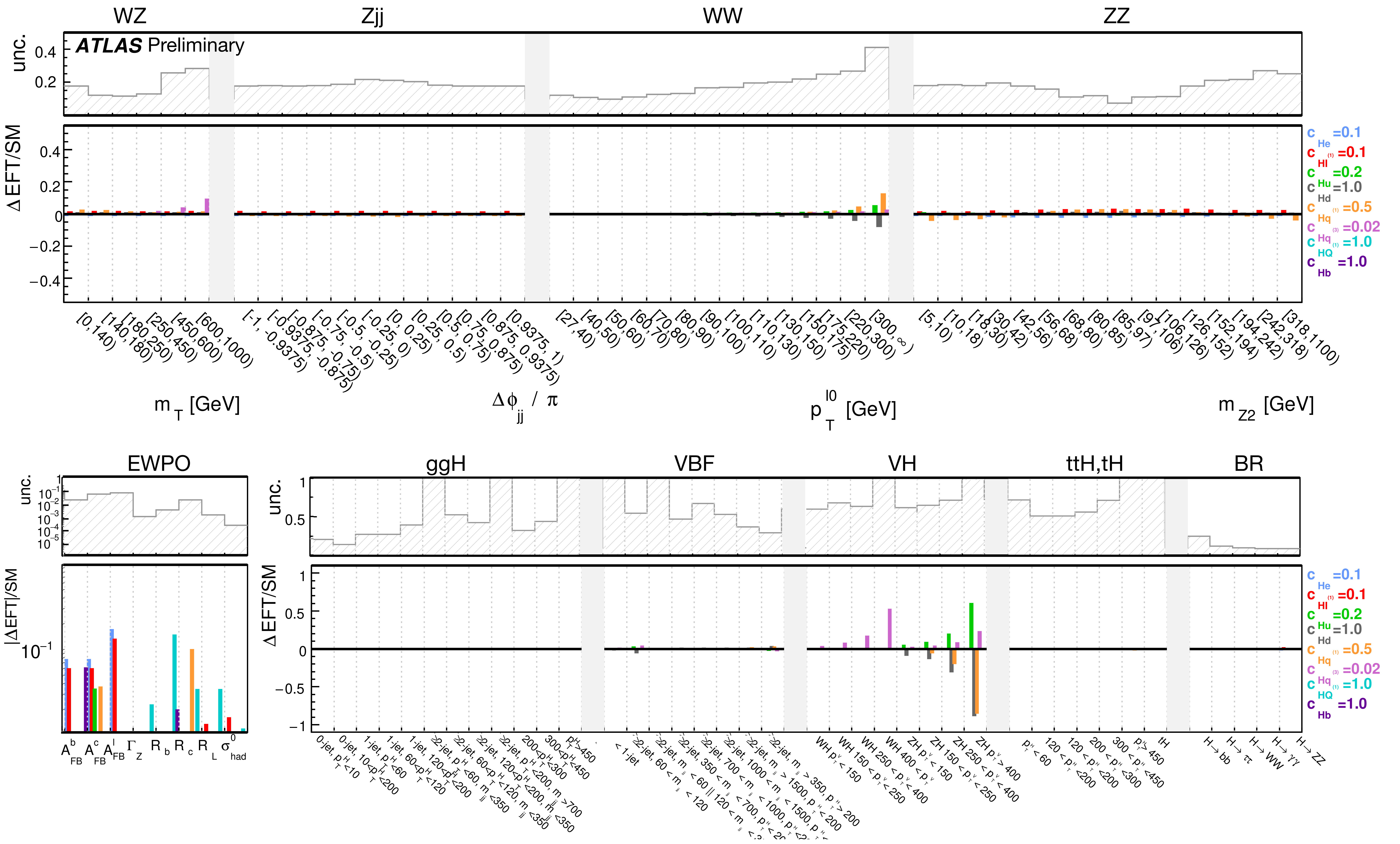
ATLAS Higgs only: visualising EFT impact on measurements



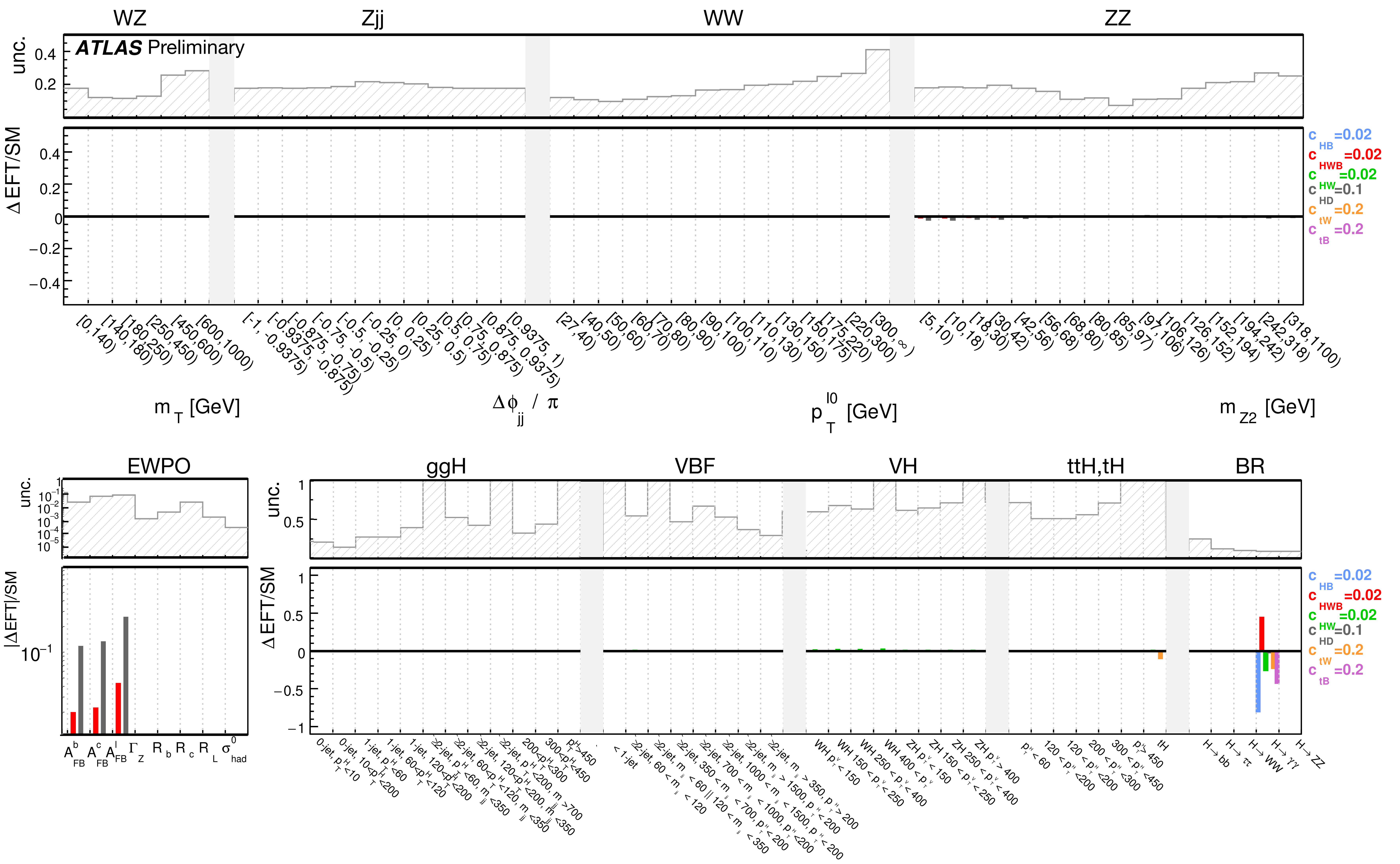
ATLAS global EFT: visualising EFT impact on measurements



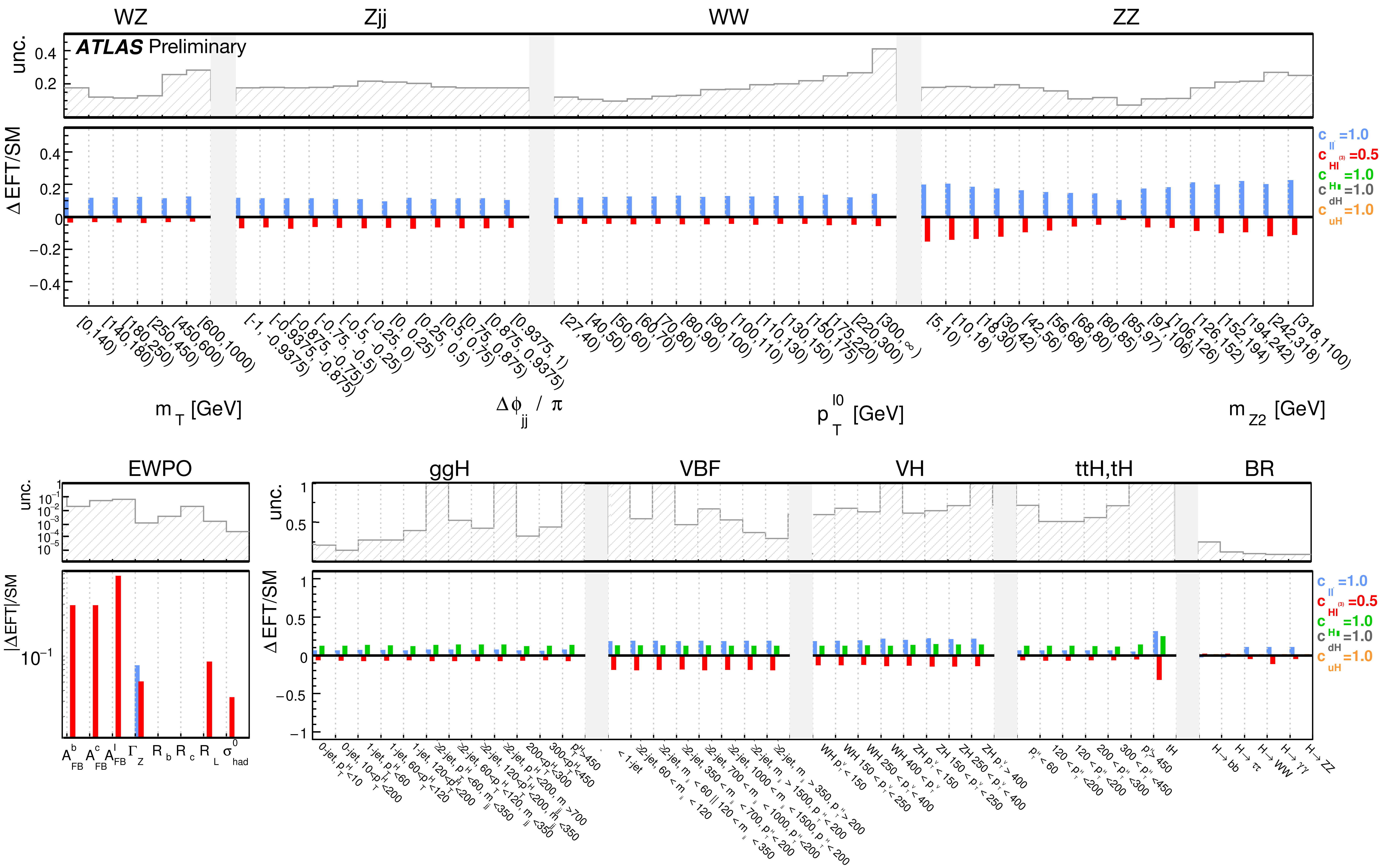
ATLAS global EFT: visualising EFT impact on measurements



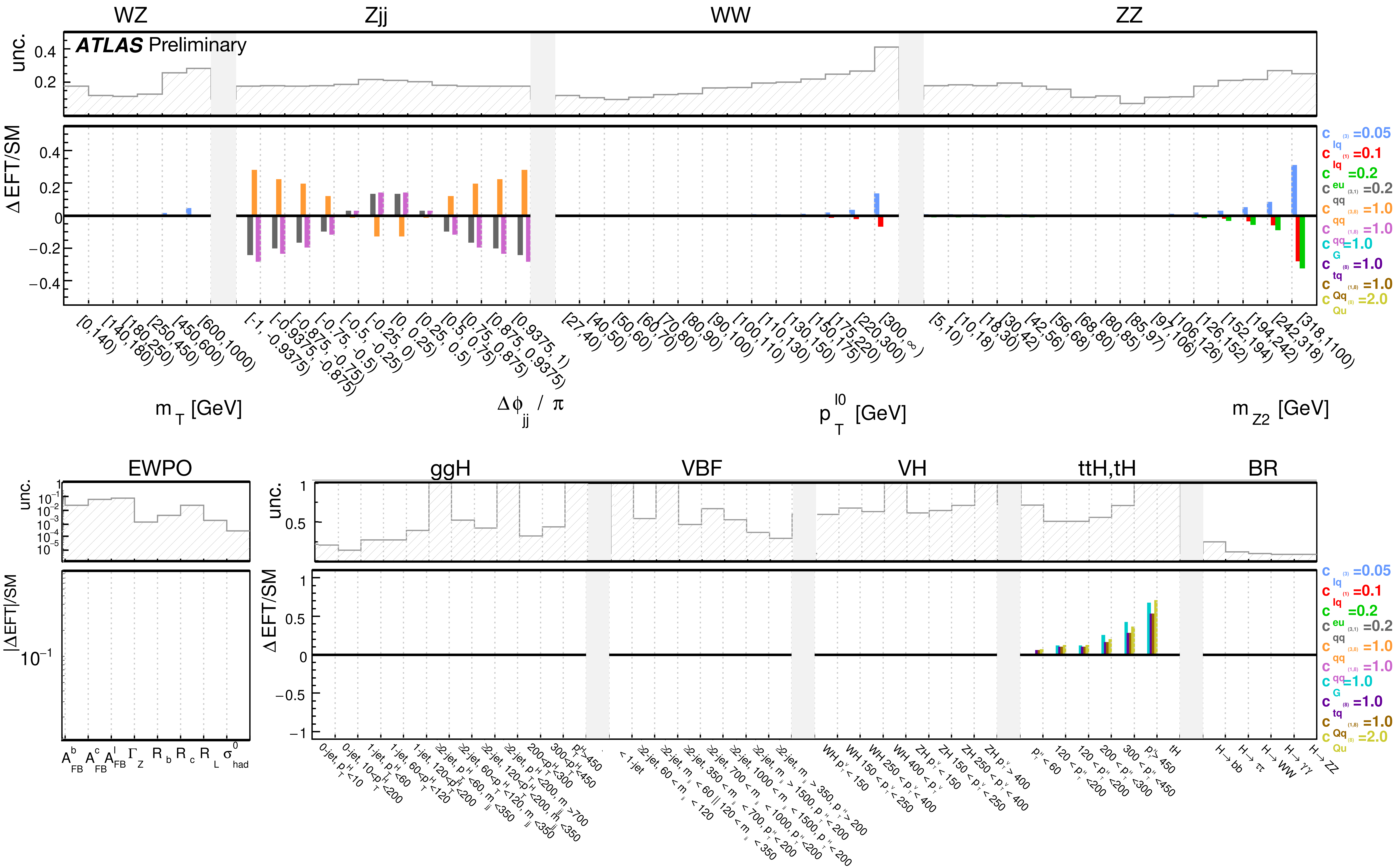
ATLAS global EFT: visualising EFT impact on measurements



ATLAS global EFT: visualising EFT impact on measurements



ATLAS global EFT: visualising EFT impact on measurements



SMEFT TO 2HDM PROCEDURE

- Relevant C_i (top flavour scheme) parametrised as function of the 2HDM parameters:

Phy. Rev. D 102, 055012 (2020) - S.Dawson, S.Homiller, & S.D. Lane

SMEFT parameters	Type I	Type II	Lepton-specific	Flipped
$\frac{v^2 c_{tH}}{\Lambda^2}$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{bH}}{\Lambda^2}$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$
$\frac{v^2 c_{eH,22}}{\Lambda^2}$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{eH,33}}{\Lambda^2}$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$	$-Y_\tau c_{\beta-\alpha}\tan\beta$	$Y_\tau c_{\beta-\alpha}\tan\beta$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_H}{\Lambda^2}$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$

with Λ the SMEFT energy scale , v the VEV, Y_i the Yukawa-couplings ($Y_i = \sqrt{2}m_i/v$) and η_i distinguishes the type of model, M is the common mass of the heavy decoupled scalars

Statistical model: likelihood

- Likelihood ratio used as a test statistic to perform statistical inference on SMEFT parameters, built from product of likelihood ratios of the different analyses

- Statistical model uses **likelihood built at the measurement level** (cross-sections or event counts) and only later rotated into the EFT space

Higgs

$$L(x\ \ \mu, \theta) = \prod_{c}^{N_{cat}} [\prod_{e}^{N_{bins}} \text{Poisson}(\Sigma_s N_s^c + \Sigma_b N_b^c), n_{obs,e}] \prod_{i}^{n_{syst}} (f_i(\theta_i)$$

LEP

$$L(\mu) = \exp(-\frac{1}{2}(\mu - \hat{\mu})^T C^{-1} (\mu - \hat{\mu}))$$

Total covariance

EW

$$L(\boldsymbol{x}|\boldsymbol{c}, \boldsymbol{\theta}) = \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}} \det(C)}} \exp\left(-\frac{1}{2} \Delta\boldsymbol{x}^{\mathsf{T}}(\boldsymbol{c}, \boldsymbol{\theta}) C^{-1} \Delta\boldsymbol{x}(\boldsymbol{c}, \boldsymbol{\theta})\right) \times \prod_{i}^{n_{\text{syst}}} f_i(\theta_i).$$

Stat-only covariance

Gaussian constraint terms

- Likelihood contains parameters of interests (POIs) μ and nuisance parameters (NPs) $\vec{\theta}$ to quantify the effect of systematic uncertainties in the measurement

- Systematic uncertainties are coming from theory predictions (over signal or backgrounds) and detector effects (e.g. luminosity uncertainty, objects reconstruction efficiencies etc): common NPs are correlated between sectors

Statistical model: nuisance parameters and systematics

- Impact of NPs in the **Higgs sector** is included per category c and generally parametrised as:

$$N^c(\theta) = N_0^c \exp(\log(1+\alpha)\theta) \approx N_0^c(1+\alpha\theta)$$

$$L(x \quad \mu, \theta) = \prod_c^{N_{cat}} [\prod_e^{N_{bins}} \text{Poisson}(\Sigma_s N_s^c + \Sigma_b N_b^c), n_{obs,e}] \prod_i^{n_{syst}} (f_i(\theta_i)$$

where N_c is the number of events in the category c, α is the relative impact of the systematic and θ is the nuisance parameter

- The **values of θ are constrained by** additional measurements called **auxiliary measurements** $f_i(\theta_i)$ which are always assumed to be expressible as independent Gaussians

- The number of NPs is in the thousands, but **a pruning procedure** (more in back- up) has usually been applied in the most recent combinations to skim their number

$$L(\boldsymbol{x}|\boldsymbol{c}, \boldsymbol{\theta}) = \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}} \det(C)}} \exp\left(-\frac{1}{2}\Delta\boldsymbol{x}^{\top}(\boldsymbol{c}, \boldsymbol{\theta})\, C^{-1} \Delta\boldsymbol{x}(\boldsymbol{c}, \boldsymbol{\theta})\right) \times \prod_i^{n_{\text{syst}}} f_i(\theta_i)$$

Stat-only covariance

- In the EW sector:

$$\Delta x(\theta) = x_{pred} - x_{meas}; \quad x_{pred}(\theta_{theo\ sys}) = x_{SM} \times \prod_j^{n_{theo\ syst}} (1+\alpha_j\theta_j); \quad x_{meas}(\theta_{exp\ sys}) = x \times \prod_i^{n_{exp\ syst}} (1+\alpha_i\theta_i)$$

$$n_{syst} = n_{theo\ syst} + n_{exp\ syst}$$

$$L(\mu) = \exp(-\frac{1}{2}(\mu - \hat{\mu})^T C^{-1} (\mu - \hat{\mu}))$$

- For LEP data, the effect of systematic uncertainties is **enclosed in the covariance matrix** used to construct the Gaussian model