Experimental EFT Combinations

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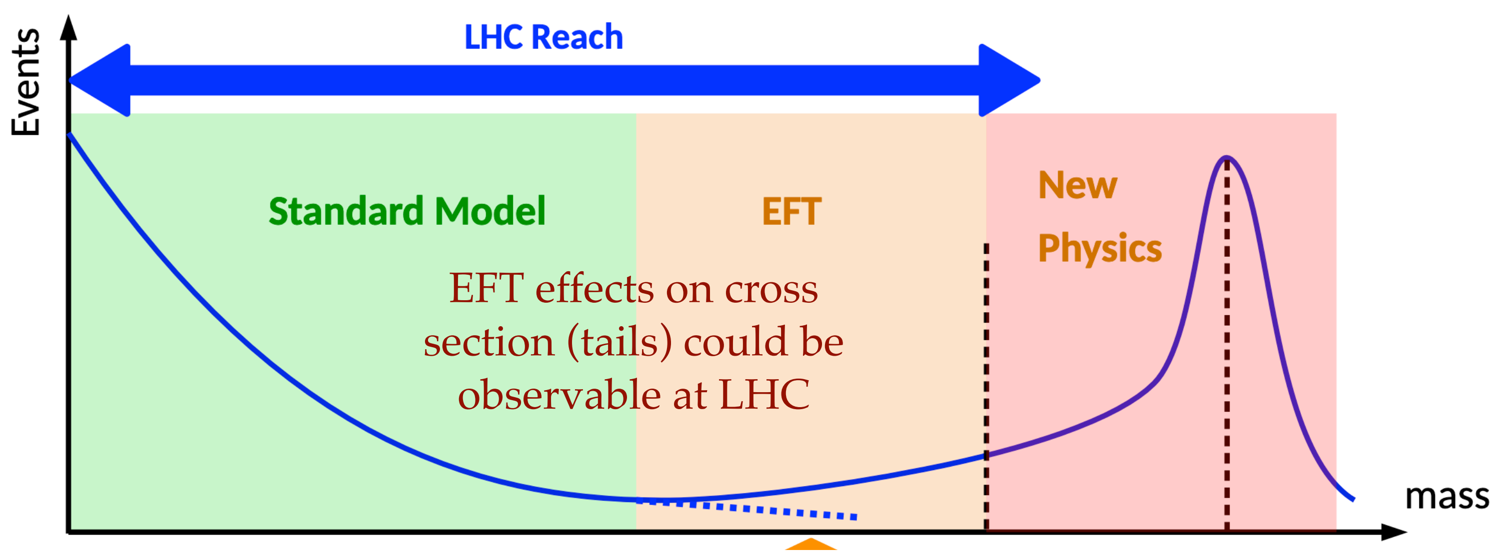
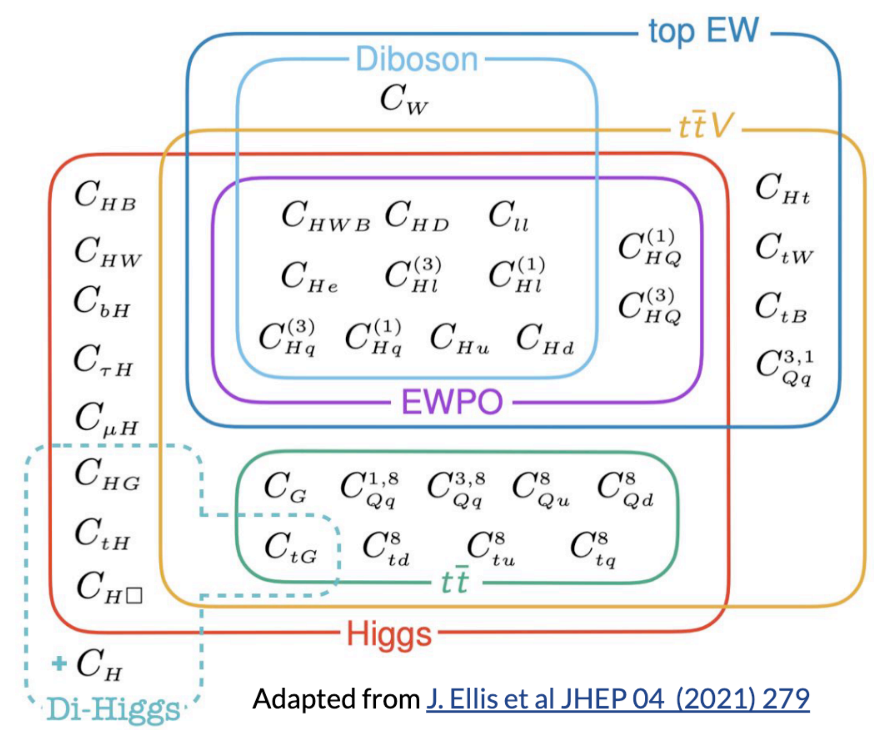
Introduction

- Increasing number of **Effective Field Theory (EFT)** measurements and reinterpretations in ATLAS and CMS which are complementing (or superseding) other interpretations.
- An EFT approach is a **very powerful tool** used in different fields of physics; allows one to combine different types of measurements (Higgs, top, EW physics,…).
- Constrain EFT coefficients -> constrain large classes of UV theories.
- A popular EFT model is the SMEFT (standard for dim6 interpretations): complete QFT compatible with higher-order calculations.

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

Wilson coefficients





Adapted from J. Ellis et al JHEP 04 (2021) 279

Global combinations: inputs + parameterisation

Going "Global": inputs

- Focus on **global combinations**, **public results** + **challenges & open points**
  - interesting talks on results by individual sectors (Higgs, Vector Bosons, Fermions)
- Focus on **dimension6 results**; interesting talk on dimension8 (Link).

ATLAS Global combination 2022 (Higgs+EW+EWPO):

ATL-PHYS-PUB-2022-037 (SMEFTsim + SMEFT@NLO)

Observable
Γ_Z [MeV]
R^0_ℓ
R^0_c
R^0_b
$A^{0,\ell}_{FB}$
$A^{0,c}_{FB}$
$A^{0,b}_{FB}$
σ^0_{had} [pb]

Decay channel	Target Production Modes
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$
$H \to WW^*$	ggF, VBF
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{had}\tau_{had})$
$H \to b\bar{b}$	WH, ZH
	VBF
	$t\bar{t}H$

Process
$pp \to e^{\pm}\nu\mu^{\mp}\nu$
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$
$pp \to \ell^{+}\ell^{-}jj$

CMS Global combination 2024 (Higgs+SM+EWPO+TOP):

CMS PAS SMP-24-003 (SMEFTsim + SMEFT@NLO)

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, $A^{0,\ell}_{FB}$, $A^{0,c}_{FB}$, $A^{0,b}_{FB}$	×
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	✓

ATLAS Global combination

ATL-PHYS-PUB-2022-037

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139
$H \to WW^*$	ggF, VBF	139
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{had}\tau_{had})$	139
	WH, ZH	139
$H \to b\bar{b}$	VBF	126
	$t\bar{t}H$	139

- **ATLAS Higgs boson data (2021 combination)**
- **Higgs boson production and decay combined measurements in STXS bins**

Higgs Combination

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55$ GeV, $p_T^{jet} < 35$ GeV	$p_T^{lead. lep.}$	36
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)$ 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

WW,WZ,4l, Z+2jets combination

- **ATLAS electroweak data**
- Differential cross-section measurements for diboson and Z production via VBF

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
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A_{FB}^{0,c}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A_{FB}^{0,b}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ_{had}^0 [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

Precision Electroweak Measurements on the Z Resonance

- **Electroweak precision observables measured at LEP and SLC**
- Eight pseudo observables describing the physics at the Z-pole are interpreted.

CMS Global combination

CMS PAS SMP-24-003

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$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]

JHEP 07 (2021) 027

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WW	Fid. diff. cross sections	$m_{\ell\ell}$
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^Z
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$

- Wγ, Phys. Rev. D 105 (2022) 052003
- WW, Phys. Rev. D 102, 092001 (2020)
- ZW, JHEP 05 (2021) 205
- Inclusive Jet, JHEP 02 (2022) 142

Analysis	Type of measurement	Observables used
$t\bar{t}X$	Direct EFT	Yields in regions of interest
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$

- $t\bar{t}\chi$, JHEP 12 (2023) 068
- $t\bar{t}$, Phys. Rev. D 104 (2021) 092013

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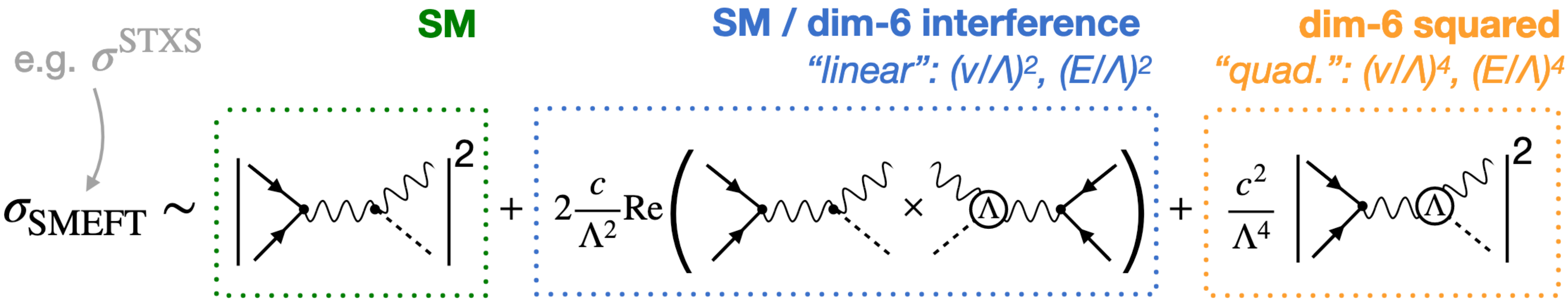
Going "Global": parameterisation

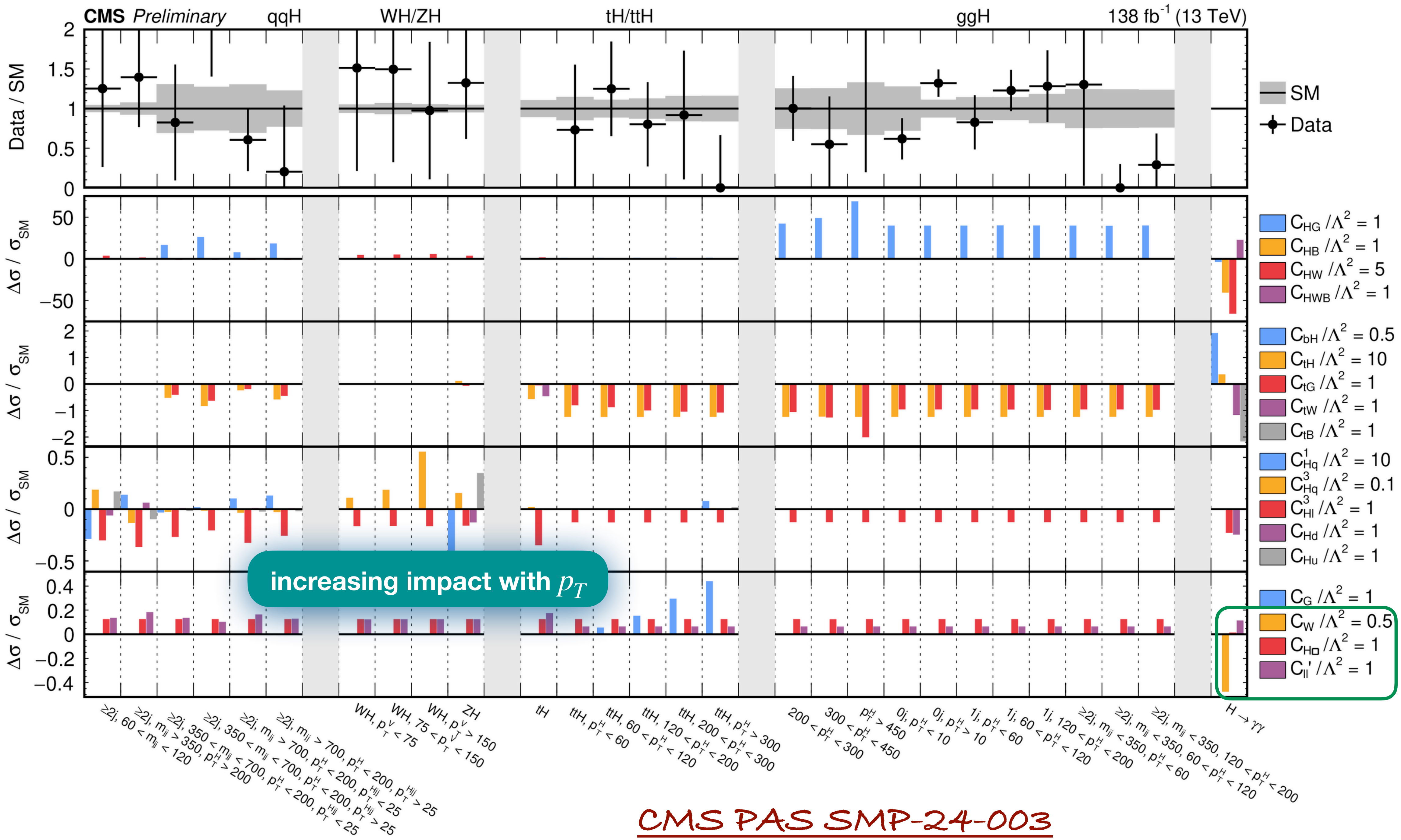


- The **Warsaw basis**, which provides a complete set of independent operators allowed by the SM gauge symmetries, is used; a value of **Λ = 1 TeV** is assumed.
- Only **dim-6** operators are considered (dim-5 and dim-7 violate Lepton and Baryon number).
- Input parameter scheme: (m_W, m_Z, G_F).
- **TopU31** flavour scheme used: $\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d \times \mathrm{U}(3)_l \times \mathrm{U}(3)_e$ $\xrightarrow{\text{Relax leptons}}$
  - First two quark generations treated similarly ($\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$)
  - All lepton generations treated similarly ($\mathrm{U}(3)_l \times \mathrm{U}(3)_e$)
- SMEFT dependence parameterised as polynomials in Wilson coefficients: SMEFT effects on the SM predictions can be factored out in a linear and quadratic component.

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

Going “Global”: parameterisation

- Impact of Wilson coefficients can be visualised (linear here)-> Value of c_i scaled appropriately for plotting.
- Large class of operators can be constrained by different sectors: $H \to \gamma\gamma$ from CMS shown.



CMS PAS SMP-24-003

Going "Global": parameterisation

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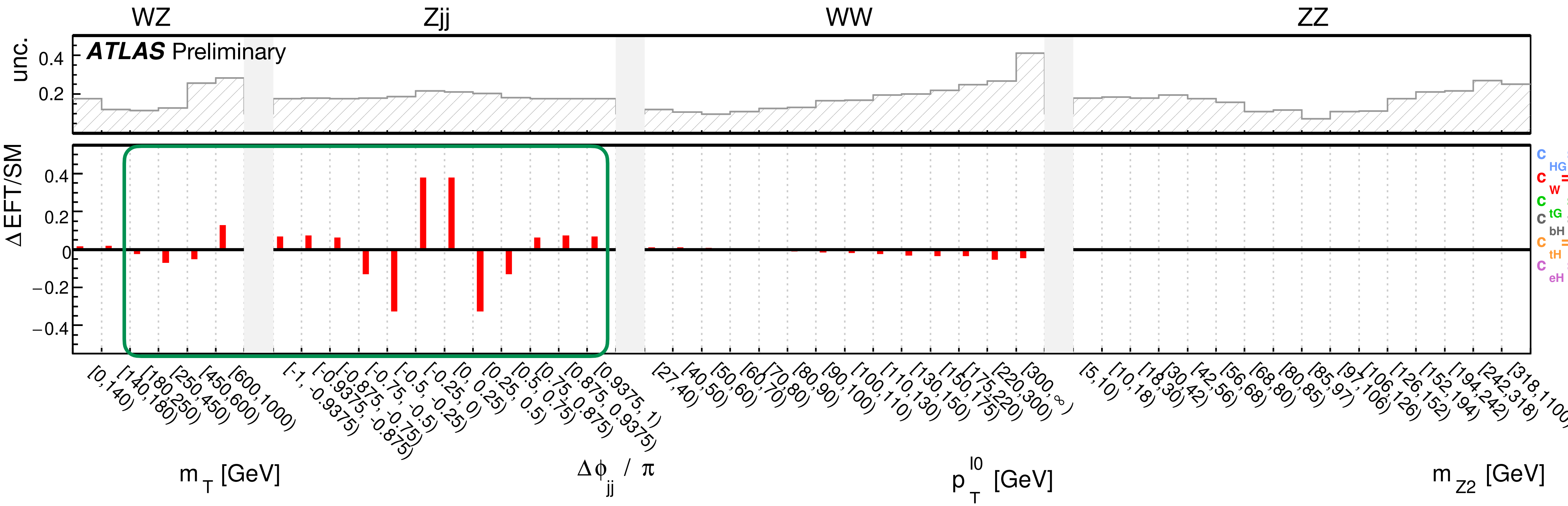
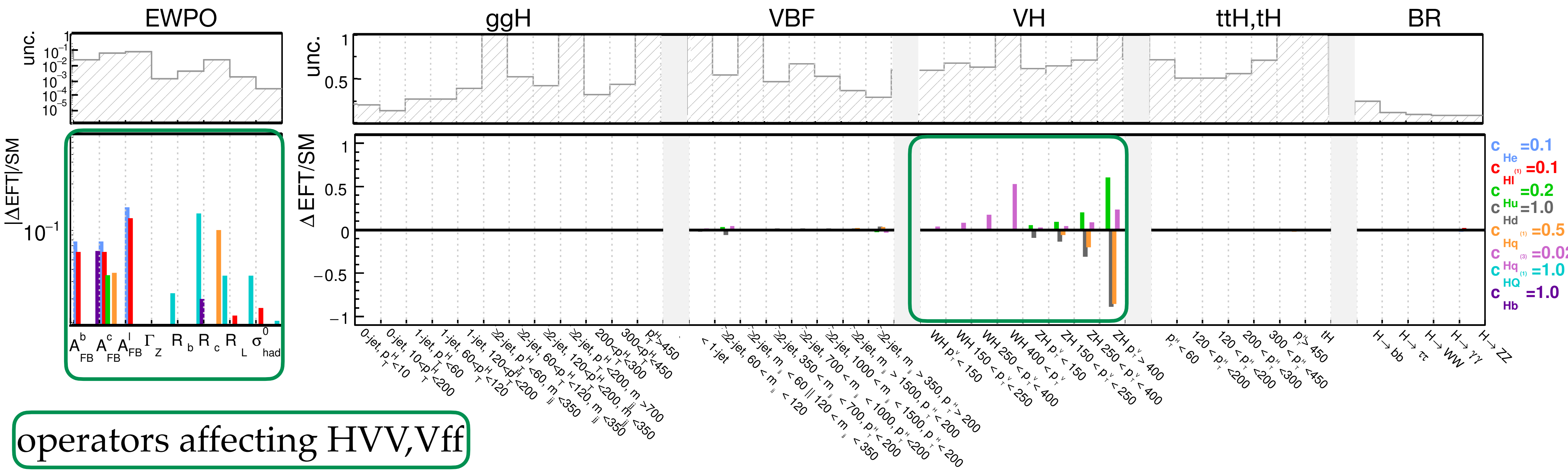
- Additional sensitivity coming from EW measurements and EWPO, e.g. cW that cannot be disentangled using just $H \rightarrow \gamma\gamma$ decay -> ATLAS parameterisation shown





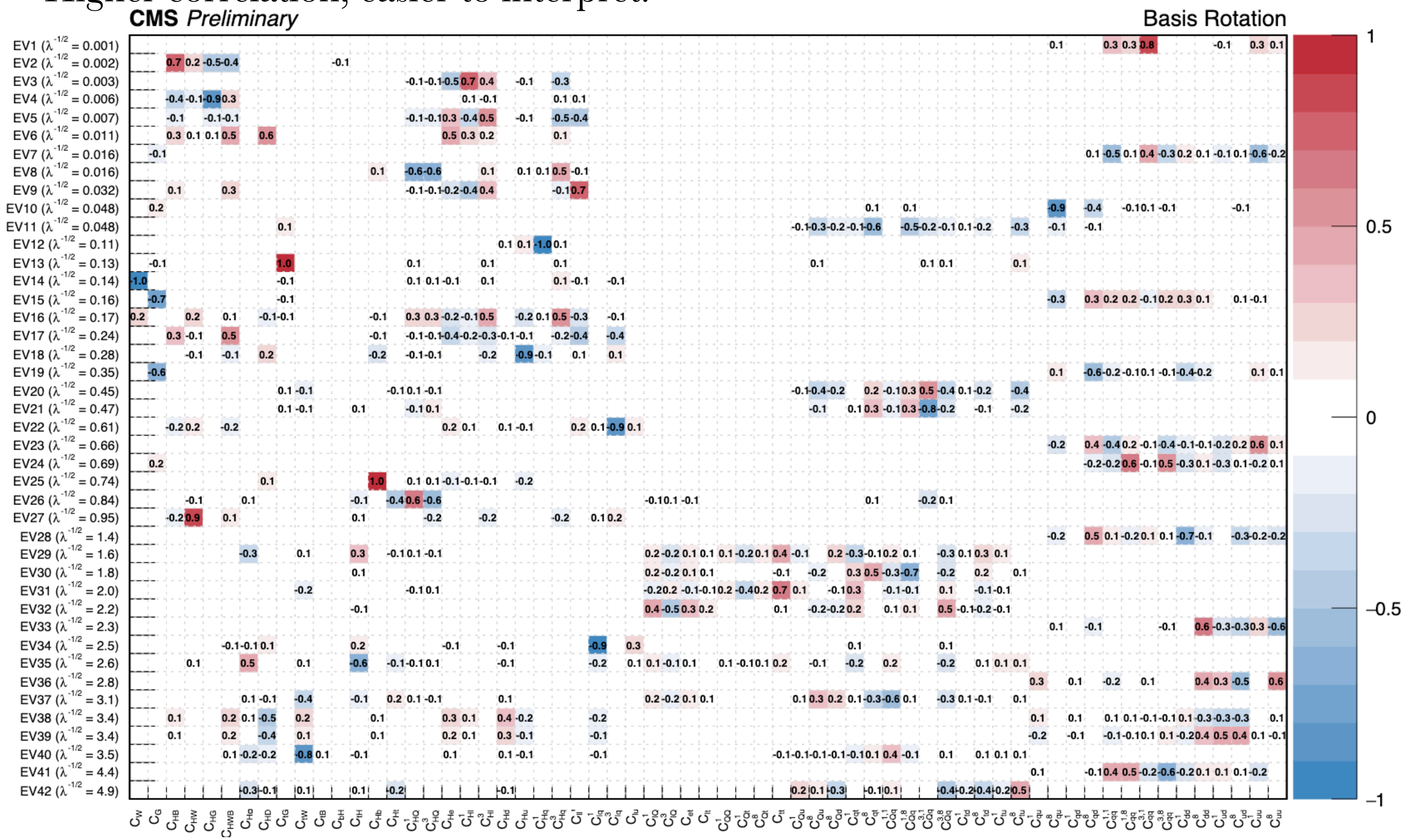
operators affecting HVV,Vff

Going "Global": sensitivity

CMS PAS SMP-24-003

- While SMEFT parameters define a complete basis, measurable subset is small:
  - not sensitive to all the Wilson coefficients (~180 in TopU3l scheme); need to identify sensitive directions that can be reasonably constrained (non sensitive ones will be fixed)
- Principal component analysis on information matrix: $H_{SMEFT} = P^T H_\mu P$
  - Full eigenvector basis-> Negligible correlation, harder to interpret.
  - Fit basis-> Higher correlation, easier to interpret.

- H_μ: covariance matrix of the input measurements
- P: matrix that gives the parametrisation



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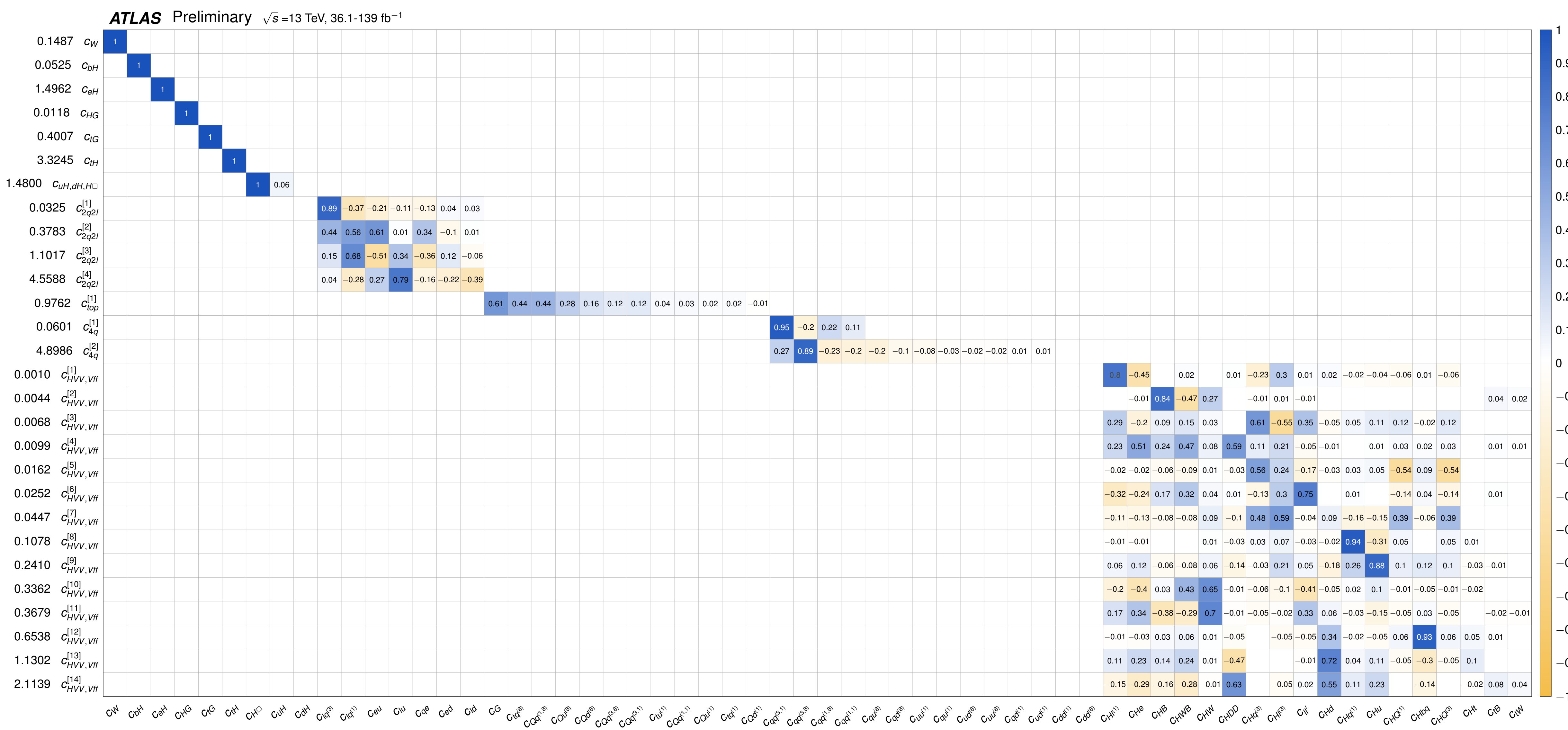


Global combinations: results

ATLAS Global combination

ATL-PHYS-PUB-2022-037

HIGGS+EW

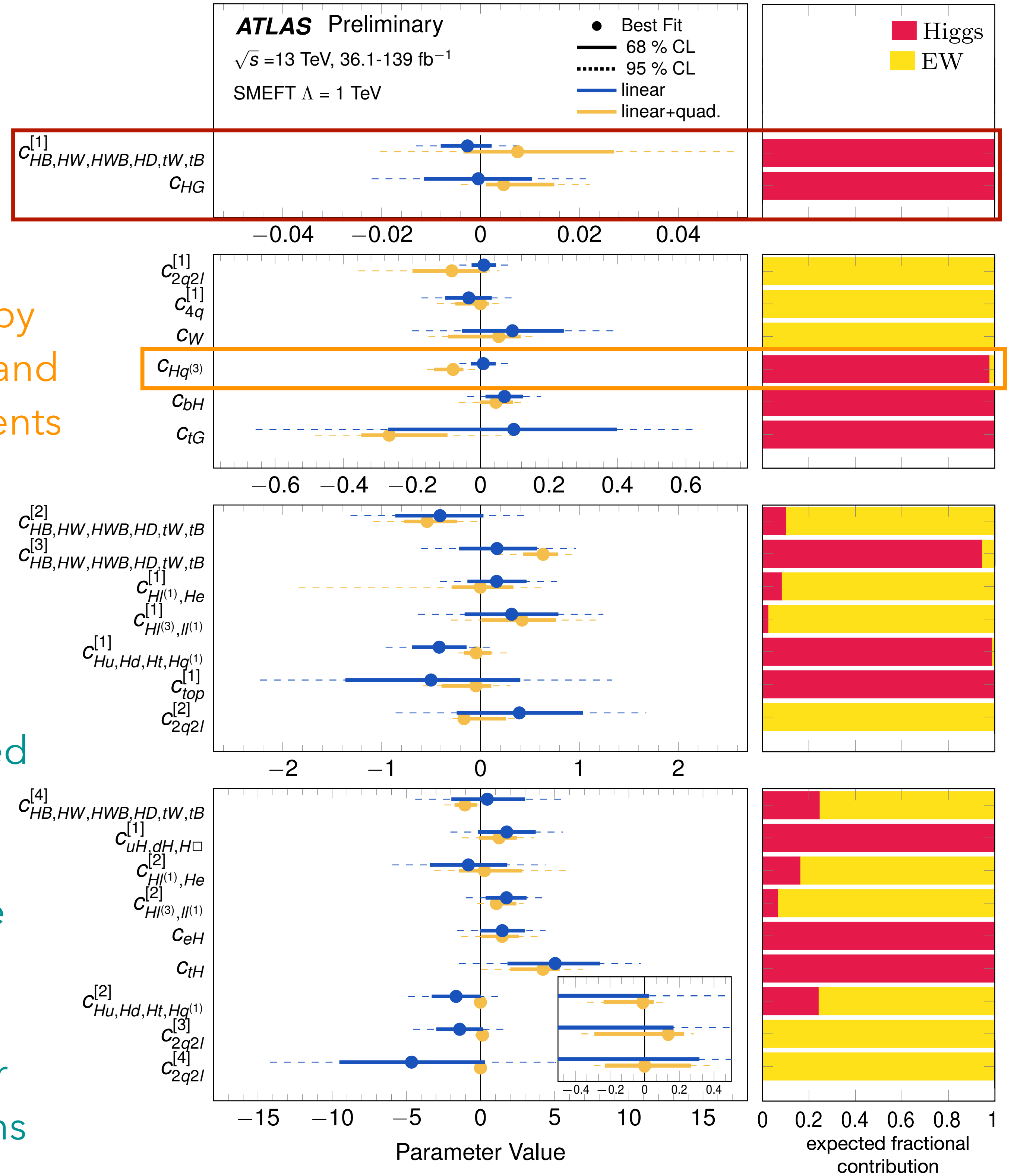
- Principal component analysis to identify sensitive directions-> a modified basis of linear combinations of WCs is defined. Constraining **7** individual and **17** linear combinations of WCs

- Linear and linear+quadratic results.
- Complementary information.

Most stringent constraints

Constrained by both diboson and VH measurements

Weakly constrained fit directions-> quadratic contributions are large; validity of the constraints - neglected higher order contributions



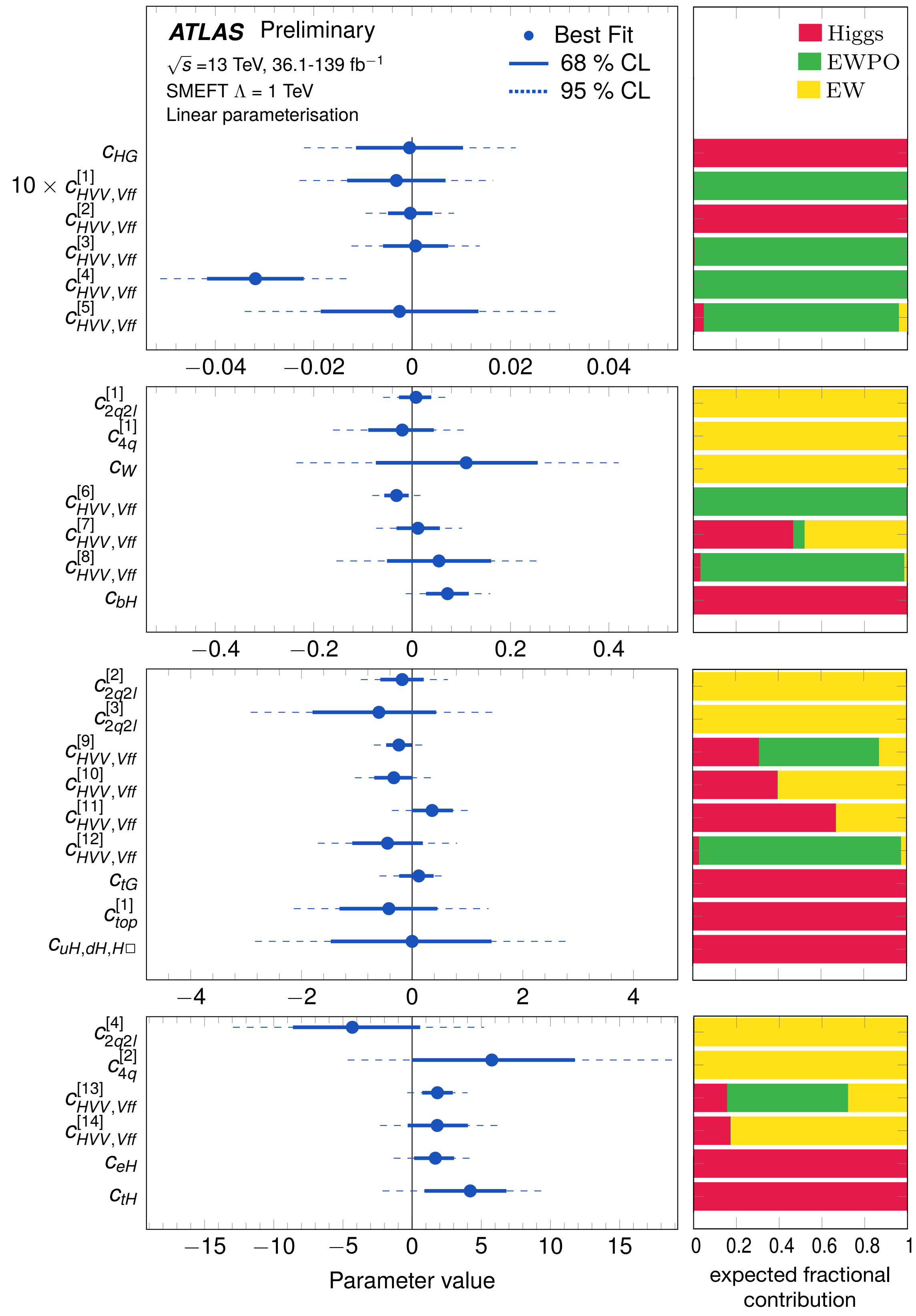
ATLAS Global combination

ATL-PHYS-PUB-2022-037

HIGGS+EW+EWPO

- Constraining **6+22** directions - linear only results.
- Several constraints driven by both ATLAS and LEP/SLD.

- Complementary information.
- Linear fits agree with the SM expectation for most fitted parameters, except for:
  - $c^{[4]}_{HVV,Vff}$ → excess driven by a well-known discrepancy in $A^{0,b}_{FB}$ from the SM expectation.



CMS Global combination

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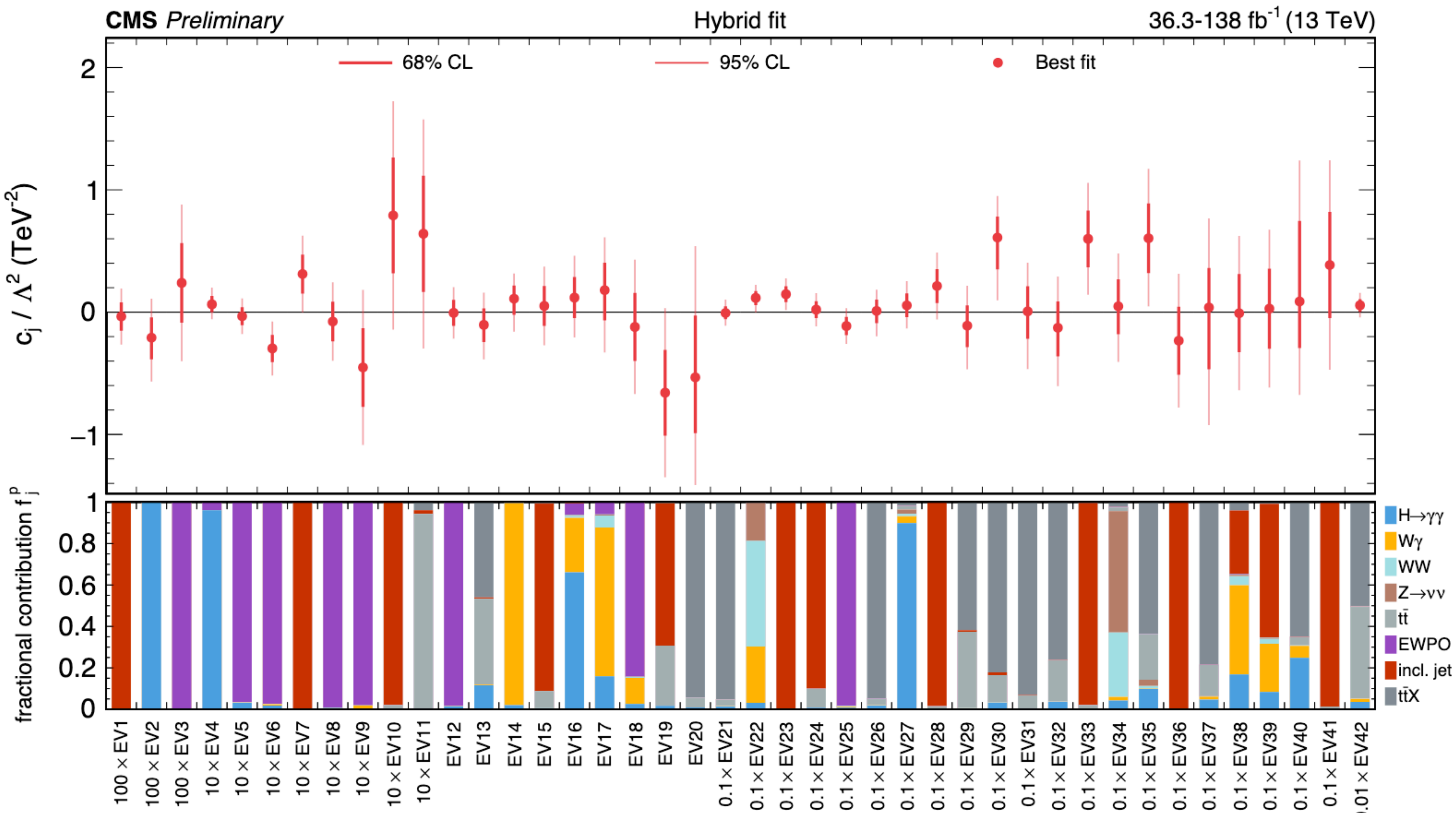
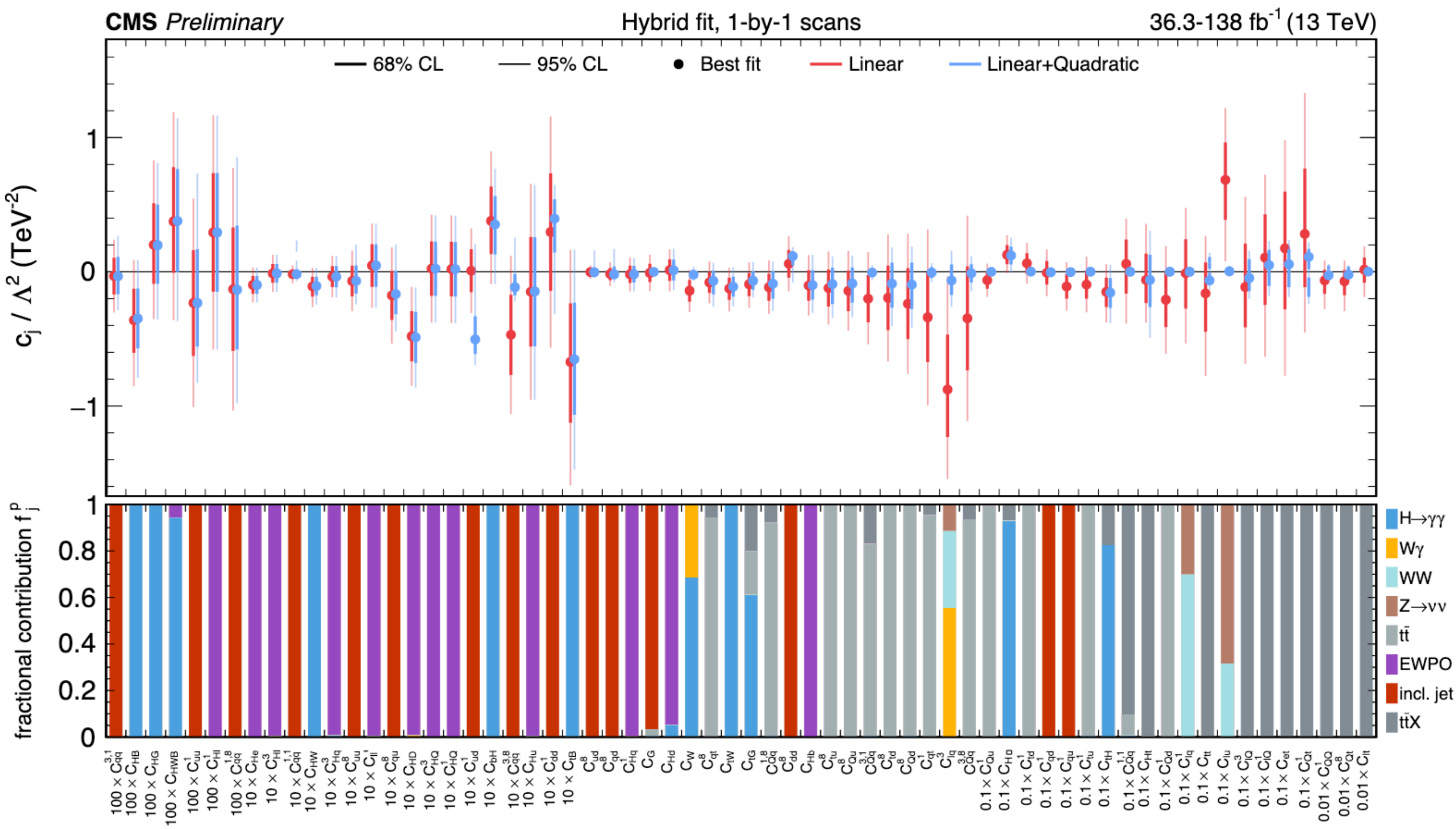
- All linear combinations of WCs are varied simultaneously: **42 eigenvector directions.**
- The 95% confidence intervals on the 42 eigenvector directions are in the range ±10 to ±0.002.
- The p-value for the compatibility with the SM (all Wilson coefficients equal to 0) is 1.7%.
- The deviation from the SM is mostly driven by the inclusive jet measurement; when excluding it from the combination, the p-value is found to be 26%.

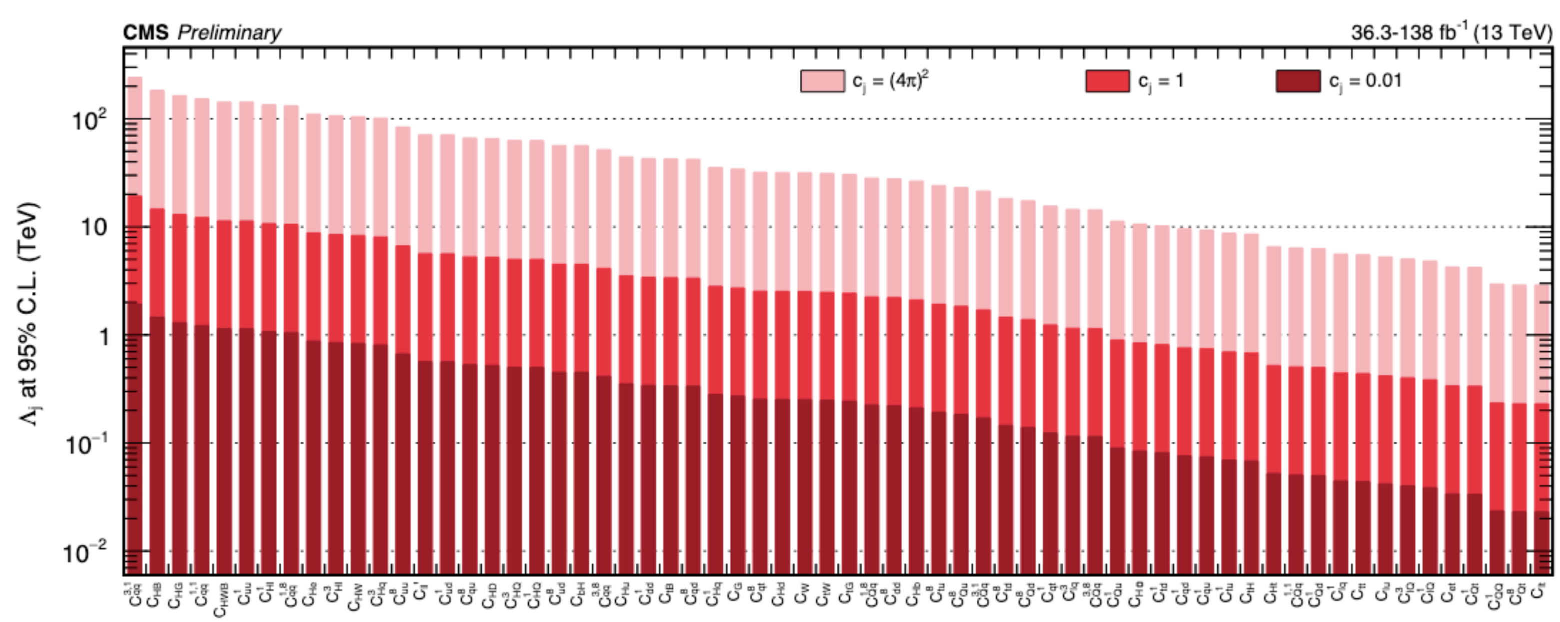


CMS Global combination

CMS PAS SMP-24-003



- Constraints on **64 individual WCs**, obtained when fixing all other WCs to 0.
- The 95% confidence interval on the individual WCs c_j/Λ^2 ranges from around ±20 to ±0.003.



- By setting c_j to specific values, obtained constraints on WCs are translated into 95% CL lower limits on the scale of new physics Λ.

Lessons learned
(personal selection)

Open points and challenges

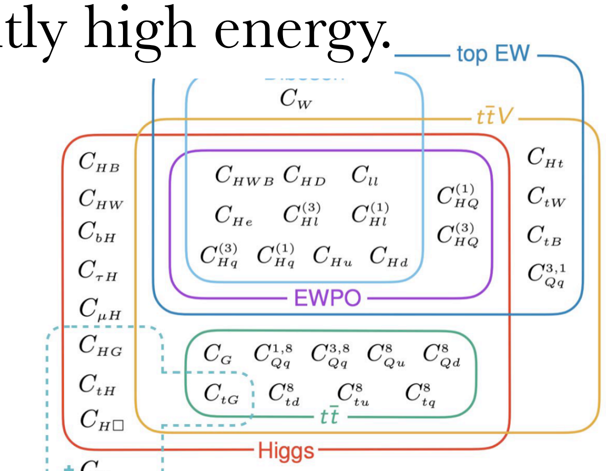
- **Many potential challenges and open points** (that will not be fully addressed by the short-term future EFT combinations, but should be taken into account for Run3 interpretations).

- **Challenges at the level of combinations**
  - overlap between input analyses;
  - harmonisation of systematics & phase-space across groups;
  - harmonisation of SMEFT assumptions/tools.

- **Challenges at conceptual level (more for future combinations)**
  - parameterisation of background: e.g. $t\bar{t}$ signal = Higgs background-> coherent modelling of $t\bar{t}$ in Higgs?
  - inclusion of dimension8 contributions - **interplay between linear and quadratic;**
  - **matching to UV models** (ATLAS Higgs combination has done it for the first time);
  - moving towards higher and higher pT bins-> unitarity violation at sufficiently high energy.

Interaction with **theory community** is really important (LHCEFTWG)

  - **reproducibility of the results.**



Adapted from J. Ellis et al JHEP 04 (2021) 279

Interplay between linear and quadratic results

Linear vs linear +quadratic

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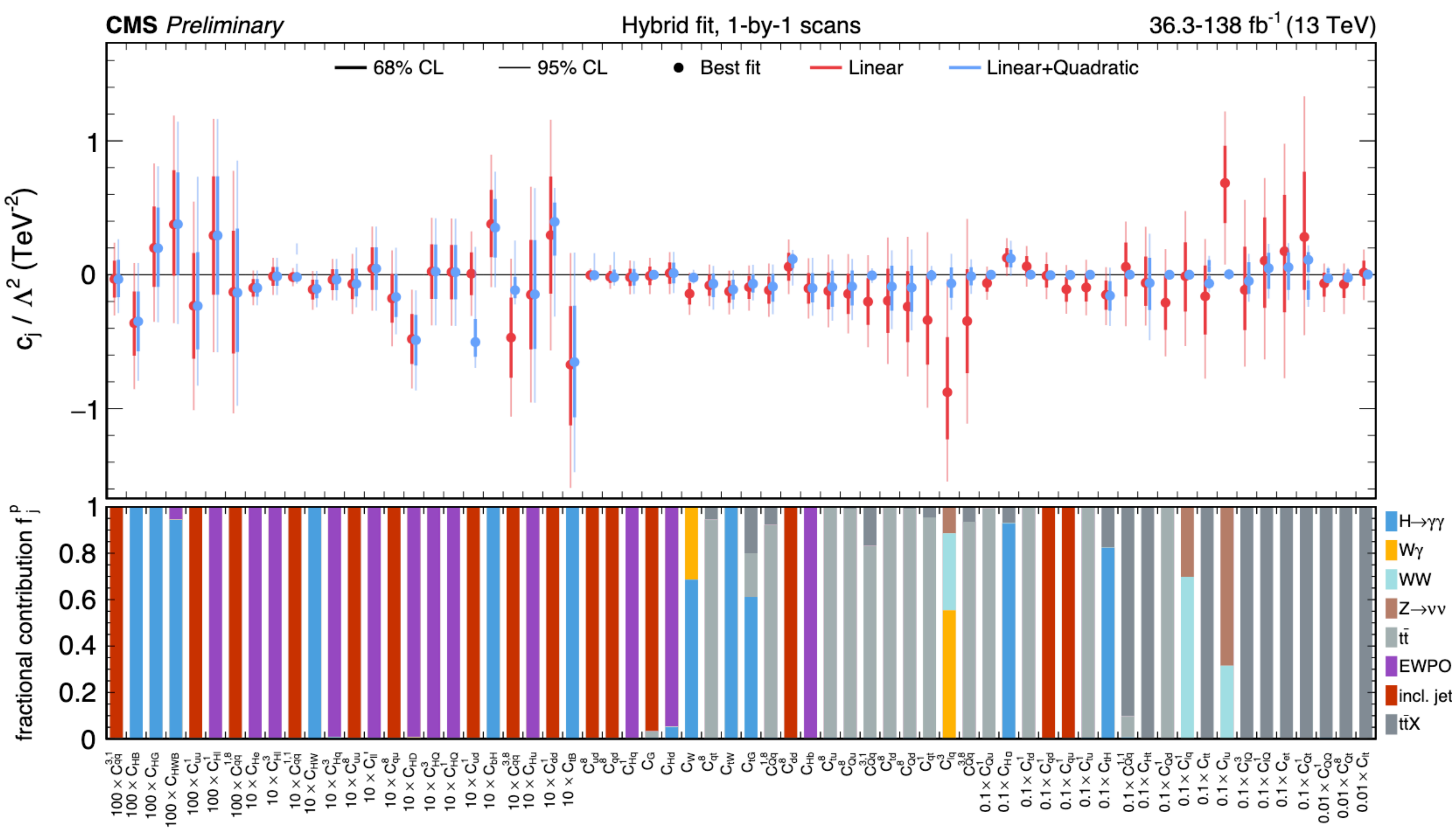
- Constraints on the WCs when using **linear contributions** ($\propto \Lambda^{-2}$) vs **quadratic order** ($\propto \Lambda^{-4}$).
- WCs with the loosest constraints: **BSM contributions dominate**.
- WCs more tightly constrained: **SM-BSM interference terms** dominate the sensitivity.

- For now treating difference between Λ^{-2} and Λ^{-4} as **magnitude indicator of effect missing SM-Dim8** interference.

- Next steps:

1. Collect & implement **available** dim-8 calculations (=incomplete but growing set).

2. Develop a more sophisticated strategy to quote **truncation uncertainty** using partial calculations.



Matching to UV models

EFT to 2HDM

- Premise of EFT is that measurements can be mapped *a posteriori* to put constraints on UV-complete models
- SMEFT constraints can be rotated into 2HDM models using inputs from the theory community

Paper

- Relevant Wilson coefficients (free parameters of SMEFT Lagrangian) can be expressed in terms of 2HDM parameters:

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} .$$

→ **Wilson coefficients**

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

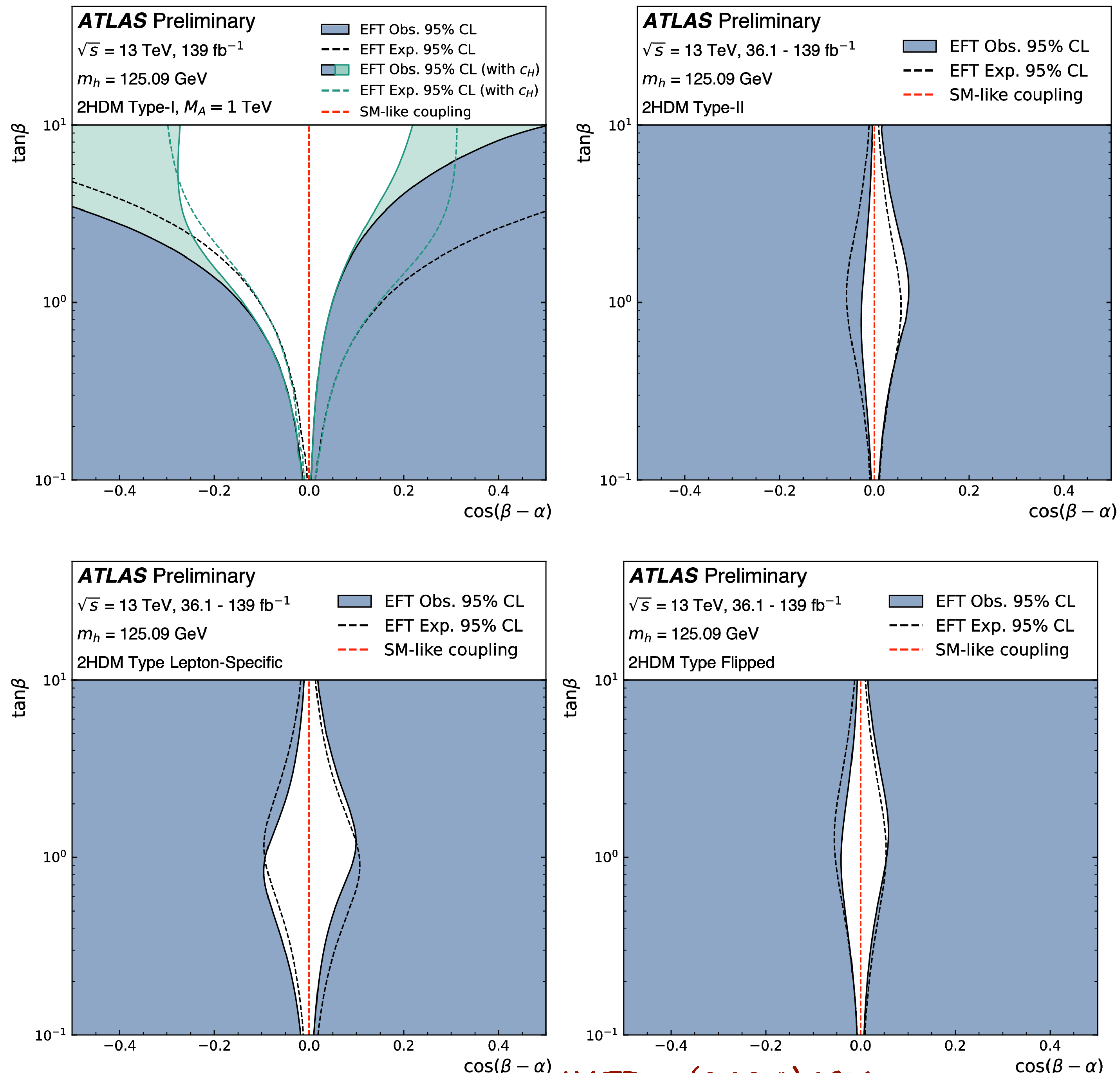
with Λ the SMEFT energy scale , ν the VEV, Y_i the Yukawa-couplings ($Y_i = \sqrt{2}m_i/\nu$), M_A is the common mass of the heavy decoupled scalars.
Angles α (mixing angle between the two neutral CP-even Higgs state) and β ($tan\beta = \frac{\nu_2}{\nu_1}$)

- Formulas valid in the limit of $cos(\beta - \alpha) \to 0$ (alignment limit), in agreement with EFT assumptions.

EFT to 2HDM

- Results obtained in 2023 ATLAS Higgs combination (STXS, seven decay channels) for all types of models.
- Relevant coefficients parametrised as function of the 2HDM parameters.
- self-coupling role studied separately for type I: adds a vertical constraint in the 2D space of cos(β − α) − tan β (negligible for other types)

- Mapping is affected by missing SMEFT dimension-8 operators:
    - constraints from SMEFT parameters weaker than from k-parameters



JHEP11(2024)097

Reproducibility of the results

Simplified likelihood

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:

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

where $\hat{\boldsymbol{\mu}}$ 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

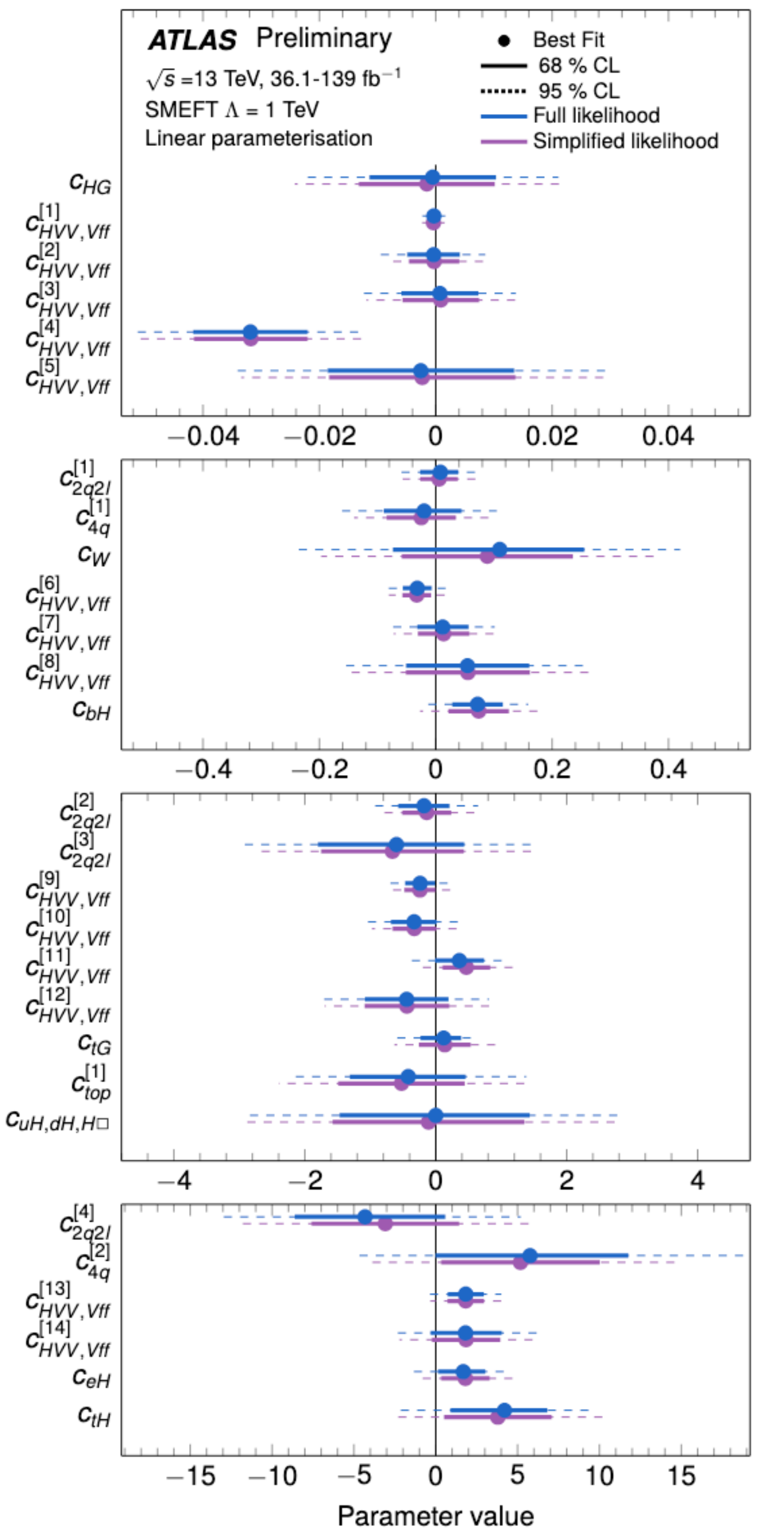
Simplified likelihood model:

- format to deliver results for re-interpretation;
- make available digitally all information needed to reproduce Gaussian version of measurement and SMEFT interpretation
  - signal strength modifier + correlation matrix + parameterisation.

Simplified likelihood

Results from the full likelihood fit compared to those using a simplified likelihood following a multi-variate Gaussian approach:

- minimal differences between the two methods;
- the simplified model is nuisance parameter free, as the effect of all uncertainties is encoded in the covariance matrix-> computationally inexpensive.



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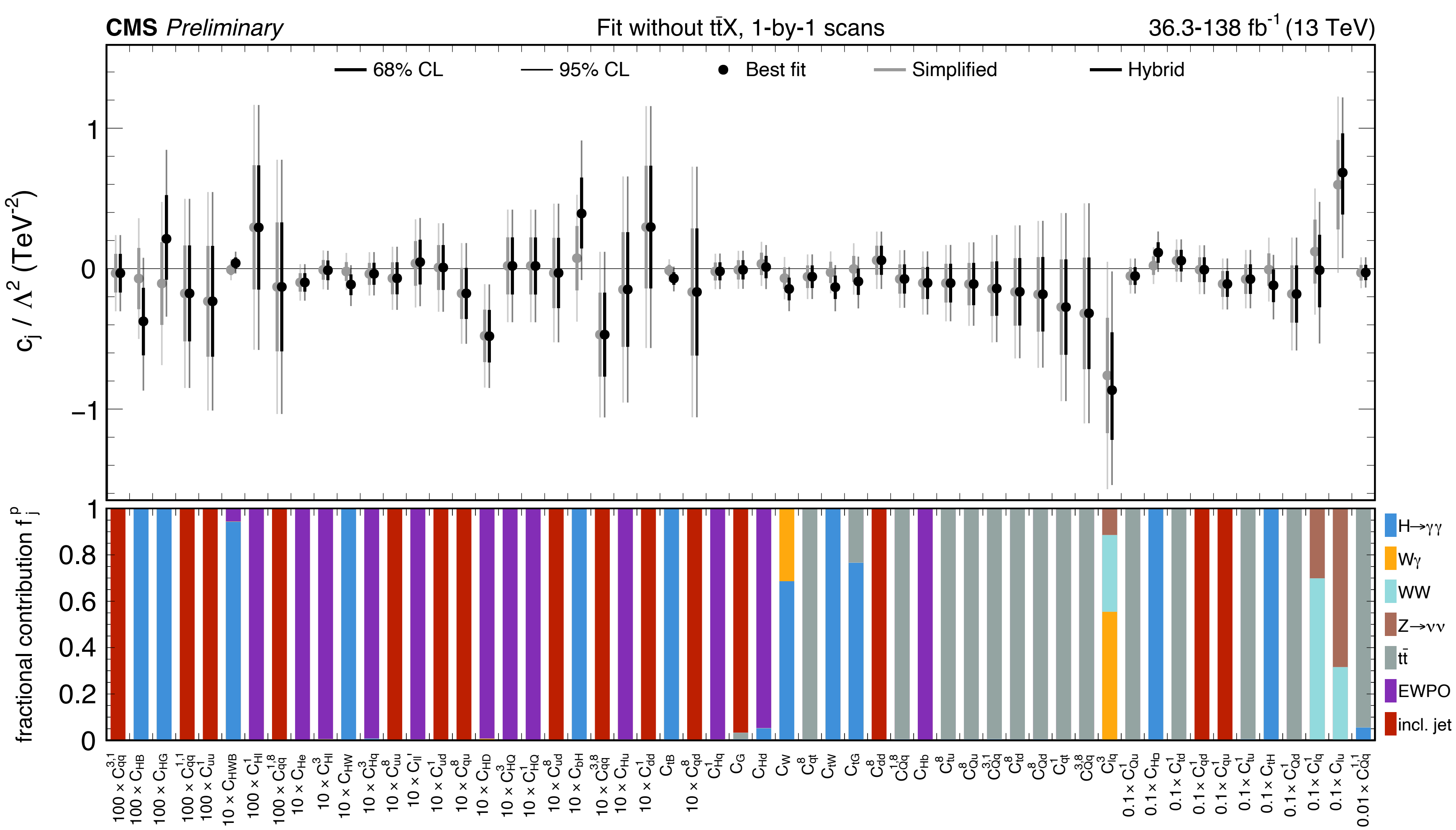


CMS PAS SMP-24-003

What's next?

Current and future plans

Several channels/data samples not yet included in current ATLAS +CMS EFT combinations

- Higgs
  - Rare processes $H \to cc$, $VBF \to H\gamma$
  - Off-shell regions of $H \to WW$ and $H \to ZZ$
  - Angular observables sensitive to CP-odd operators (in both production & decay)
  - full STXS results for both ATLAS and CMS
  - Run3 developments (like new STXS scheme) will offer nice opportunities to further improve our limits
- Higgs pair production
  - increasing number of SMEFT interpretation: preparing for future combinations
- Many opportunities for combinations
  - dibosons, Drell-Yan, top-quarks

- ATLAS + CMS combination
  - Efforts are on-going to pave the road for future combinations (e.g. shared STXS parameterisation)

Several open points we can try to address while working on Run3, e.g.:

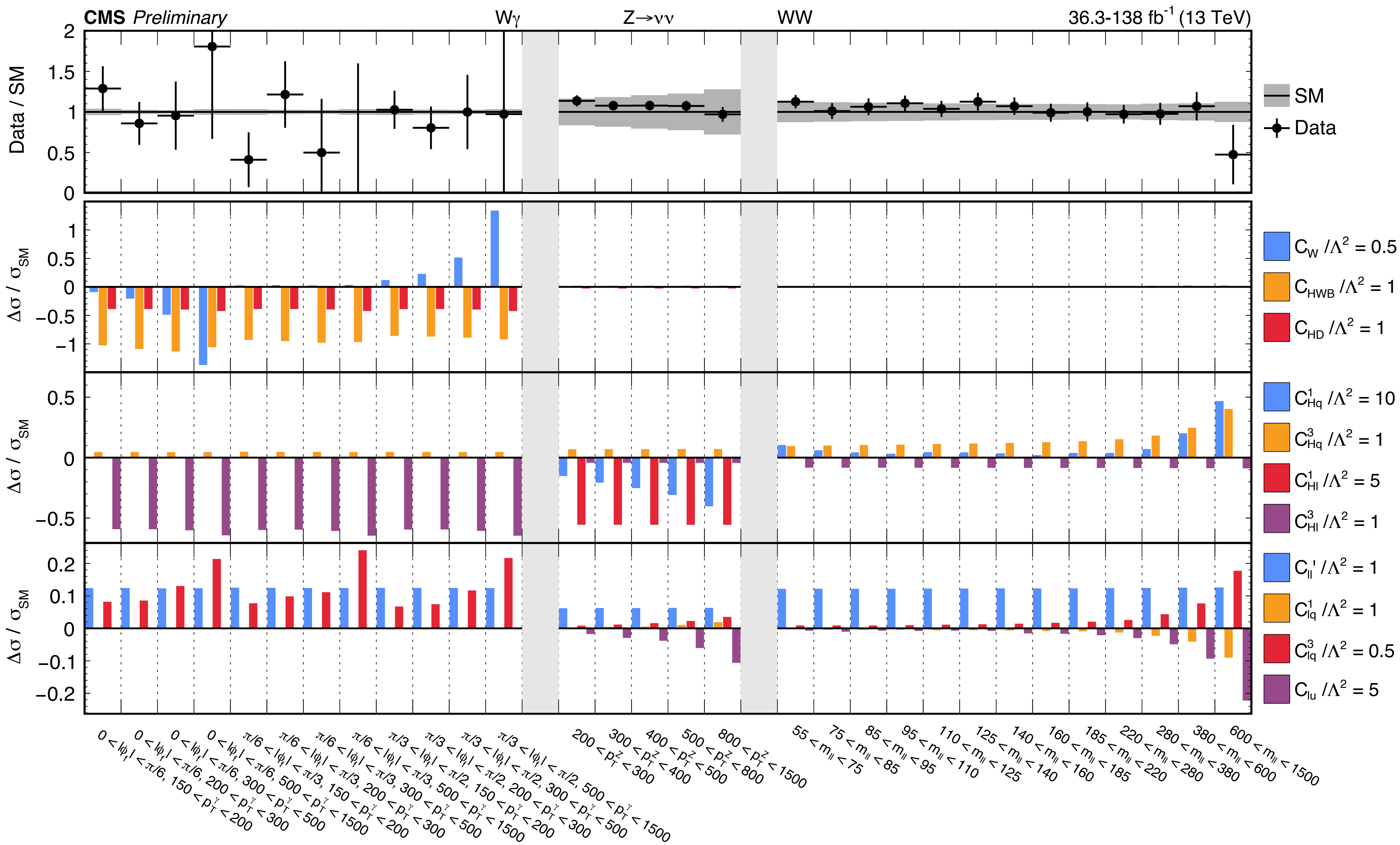
- experimental side: background parameterisation
- theoretical side: dimension8 contributions

Stay tuned!!!

Thanks a lot!!

Going "Global": parameterisation

- Impact of Wilson coefficients can be visualised (linear here)-> Value of c_i scaled appropriately for plotting.
- Large class of operators can be constrained by different sectors: $H \rightarrow \gamma\gamma$ from CMS shown.



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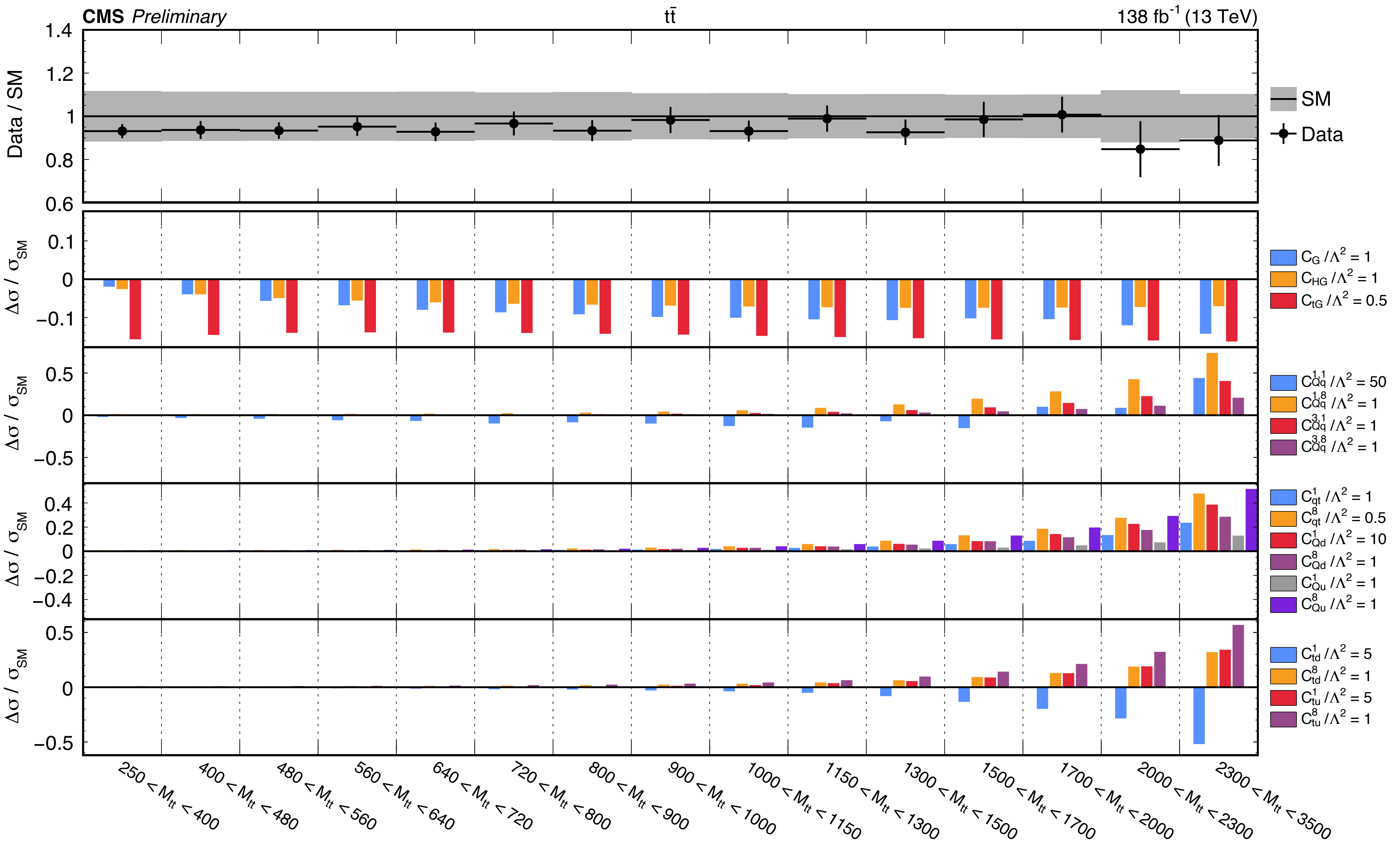

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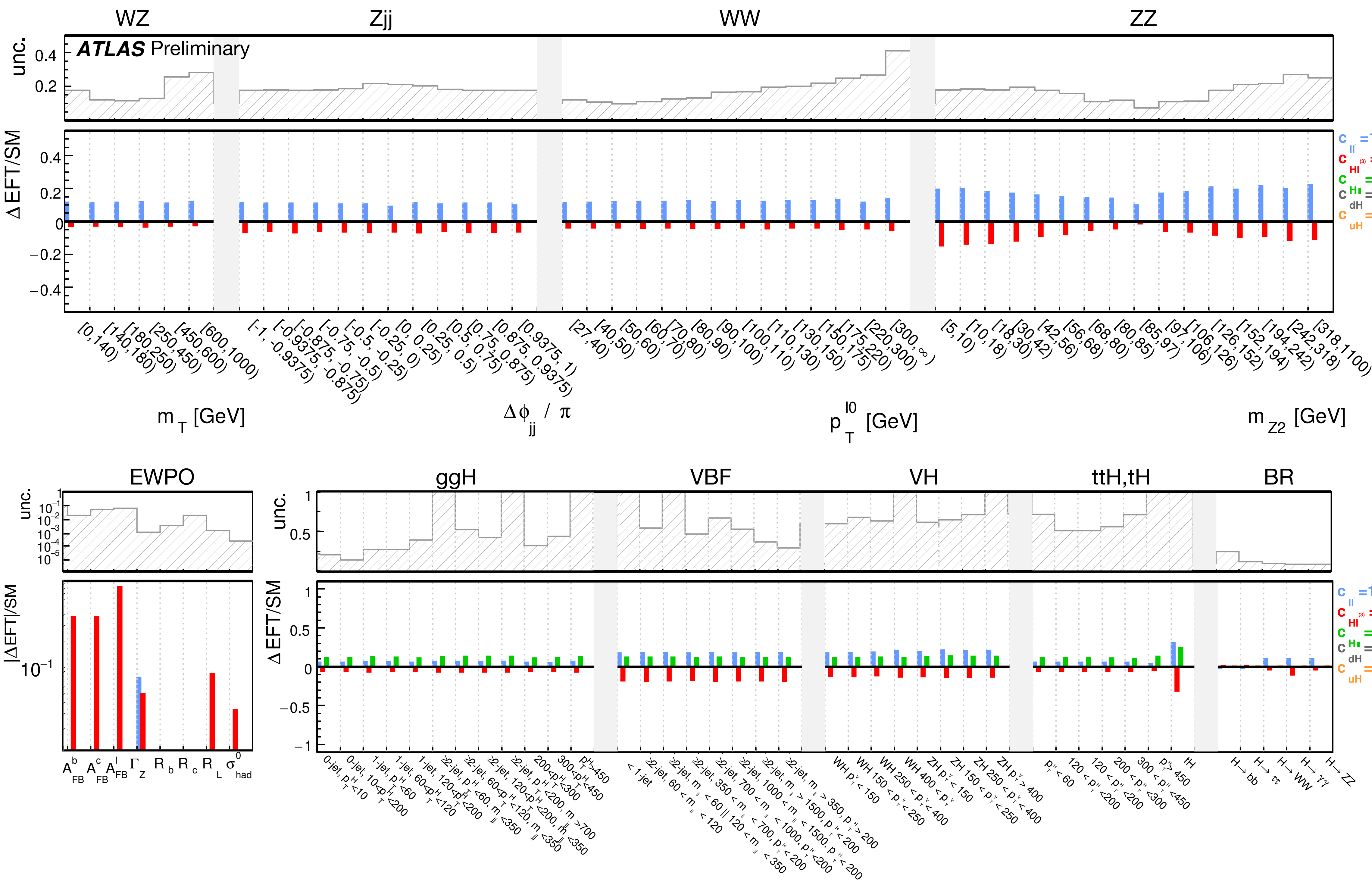
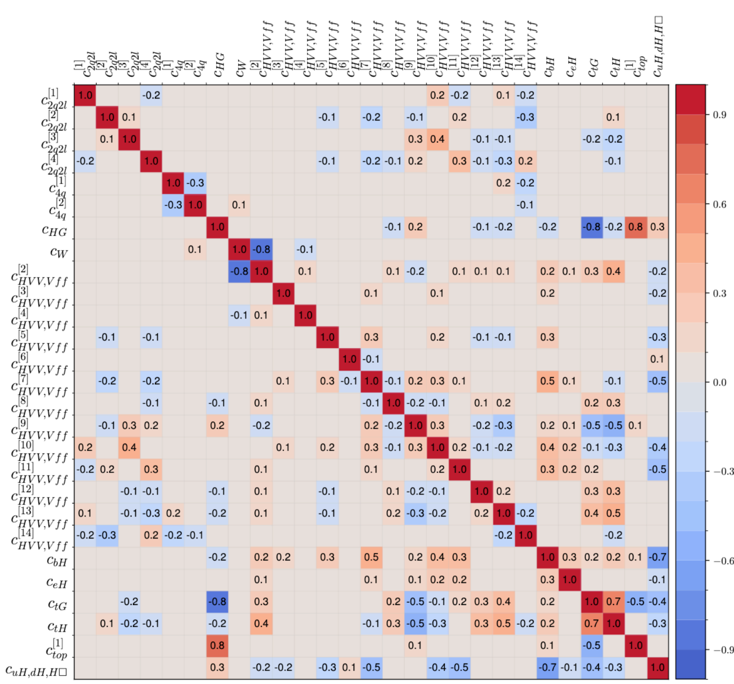
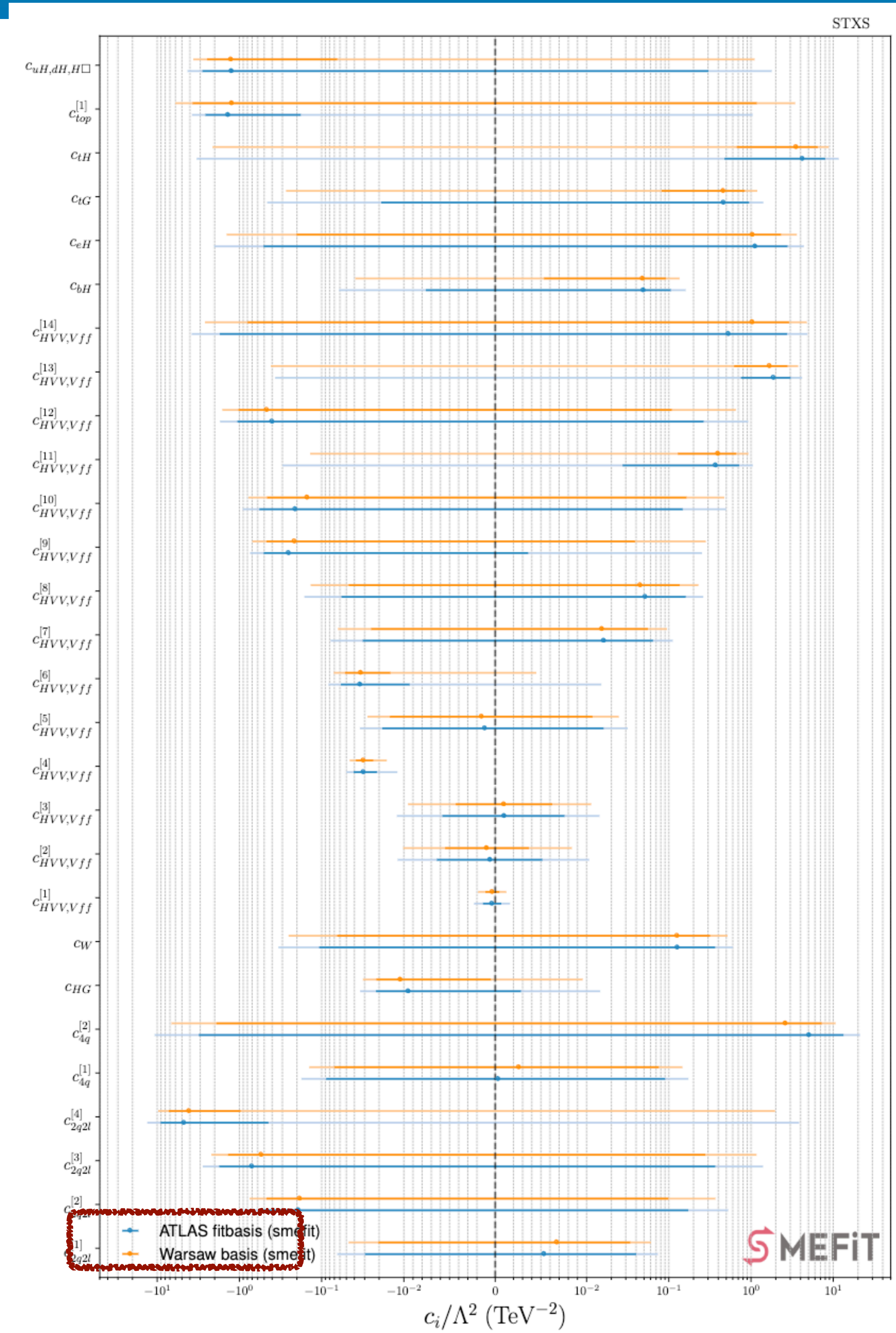


Simplified likelihood: reinterpretation

arXiv:2302.06660

- The open source **SMEFiT** has been used to reproduce the ATLAS EFT interpretation of LHC and LEP data.
- The SM and linear EFT cross-sections from the ATLAS measurement are taken and parse into the SMEFiT format adopting the same flavour assumptions for the fitting basis.
- Good agreement is obtained both in terms of central values and of the uncertainties of the fitted Wilson coefficients.
- Furthermore, similar agreement is obtained for the correlations between EFT coefficients.





Statistical model

1. Poisson distributions multiplied with constraint terms f for each nuisance parameters

Higgs

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

2. The likelihood $L(\boldsymbol{x} \,|\, \boldsymbol{c}, \boldsymbol{\theta})$ for an individual measurement is modelled as a multivariate Gaussian

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

Stat-only covariance

Gaussian constraint terms

Include impact of NP of expt. and theory unc

Common nuisance parameters ($\vec{\theta}$) are correlated (later in more details)

3. No nuisance parameters and both theoretical and experimental uncertainties are included in the covariance matrix.

LEP

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

Total covariance

EFT to 2HDM

- Type I: one Higgs doublet couples to vector bosons, the other to fermions.
- Type II: one Higgs doublet couples to up-type quarks, the other to down-type quarks + charged leptons.
- Lepton-specific: coupling to quarks as in as in Type I, coupling to charged leptons as in Type II
- Flipped: coupling to quarks as in as in Type II, coupling to charged leptons as in Type I

Coupling scale factor	Type I	Type II
κ_V	$s_{\beta-\alpha}$	
κ_u	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$
κ_d	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - \tan\beta\, c_{\beta-\alpha}$
κ_l	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - \tan\beta\, c_{\beta-\alpha}$

Coupling scale factor	Lepton-specific	Flipped
κ_V	$s_{\beta-\alpha}$	
κ_u	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$
κ_d	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - \tan\beta\, c_{\beta-\alpha}$
κ_l	$s_{\beta-\alpha} - \tan\beta\, c_{\beta-\alpha}$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$

The Higgs self-coupling can also be re-parametrised as Paper

$$\kappa_\lambda = \sin^3(\beta-\alpha) + \left(3 - 2\frac{\bar{m}^2}{m_h^2}\right)\cos^2(\beta-\alpha)\sin(\beta-\alpha) + 2\cot 2\beta\left(1 - \frac{\bar{m}^2}{m_h^2}\right) * \cos^3(\beta-\alpha)$$

with

$$\bar{m}^2 = \frac{m_{12}^2}{\sin\beta\cos\beta} = m_A^2 + \lambda_5 v^2$$

alignment limit: $\bar{m}$ close to m_A->

$\bar{m} = m_A = 1$ TeV

EFT to 2HDM

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