Results from global EFT fits from ATLAS + CMS

Andrew Levin

WIN 25

June 12, 2025

Introduction

- Bottom-up effective field theory (EFT) is a powerful tool to connect a known low-energy theory with an unknown high-energy theory
- The SM as the lowest order in an EFT is referred to as SMEFT
- Typical SMEFT studies in CMS and ATLAS focus on a subset of operators and their effect on a specific process
- However, deviations could be hidden in linear combinations of the operators and correlated effects across different processes
- Both CMS and ATLAS have recently released a “global” SMEFT fit
- “global” basically means “many operators” and “many analyses”

Outline

- Introduction
- Previous global SMEFT fits
- CMS and ATLAS global SMEFT fits
- Background topics
  - SMEFT
  - Simplified template cross sections
  - Simplified likelihood functions
  - Principal component analysis
- Operator effects
- Fit basis
- Fit results
- Conclusion

Previous SMEFT global fits

- 2019: "A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector" by Nathan P. Hartland, Fabio Maltoni, Emanuele R. Nocera, Juan Rojo, Emma Slade, Eleni Vryonidou, and Cen Zhang
- 2019: "The electro-weak couplings of the top and bottom quarks — Global fit and future prospects" by Gauthier Durieux, Adrian Irles, Víctor Miralles, Ana Peñuelas, Martín Perelló, Roman Pöschl, Marcel Vos
- 2020: "O new physics, where art thou? A global search in the top sector" by Ilaria Brivio, Sebastian Bruggisser, Fabio Maltoni, Rhea Moutafis, Tilman Plehn, Eleni Vryonidou, Susanne Westhoff, and Cen Zhang
- 2021: "Top, Higgs, diboson and electroweak fit to the Standard Model effective field theory" by John Ellis, Maeve Madigan, Ken Mimasu, Veronica Sanz, and Tevong You

CMS and ATLAS global SMEFT fits

- CMS-SMP-24-003 (submitted to the EPJC): “Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark, and multijet measurements”
- ATLAS-PHYS-PUB-2022-037: “Combined effective field theory interpretation of Higgs boson and weak boson production and decay with ATLAS data and electroweak precision observables”

Measurements included in CMS analysis

- H → $\gamma\gamma$ STXS measurement
- Wγ, Z→νν, WW, $t\bar{t}$, $t(\bar{t})X$ and inclusive jet differential cross section measurements
- Electroweak precision observables measured at LEP and the SLC Γ_Z, σ^0_{had}, R^0_l, $R^{0,l}_{\mathrm{FB}}$, R^0_b, R^0_c, $R^{0,b}_{\mathrm{FB}}$, $R^{0,c}_{\mathrm{FB}}$

Measurements included in ATLAS analysis

- H → $\gamma\gamma$, H → ZZ, H → WW, H → $\tau\tau$, H → $b\bar{b}$ STXS measurements
- WW leading lepton p_T, WZ transverse mass, ZZ mass of more-offshell Z boson, and electroweak Zjj $\Delta\phi_{jj}$
- Electroweak precision observables measured at LEP and the SLC Γ_Z, σ^0_{had}, R^0_l, $R^{0,l}_{\mathrm{FB}}$, R^0_b, R^0_c, $R^{0,b}_{\mathrm{FB}}$, $R^{0,c}_{\mathrm{FB}}$

Dimension 6 SMEFT

- Start at dimension 6 because at dimension 5 there is exactly one operator, the Weinberg operator, which violates lepton number conservation
- 2499 operators reduced to 129 by assuming CP is conserved and $U(2)^3$ symmetry for quark sector and $U(3)^2$ symmetry for lepton sector
- In general, the effect of the operator coefficients on an observable includes a linear component and a quadratic component:

$$\sum_i A_i c_i + \sum_i B_i c_i^2 + \sum_{i \neq j} C_{ij} c_i c_j$$

- The quadratic terms have same order in Λ as linear dim-8 SMEFT terms

SMEFT operator definitions

$$Q_G = f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$$
$$Q_W = \varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$

$$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$
$$Q_{HD} = (D^\mu H^\dagger H)\Box(H^\dagger D_\mu H)$$

$$Q_{tH} = \left(H^\dagger H\right)(\bar{Q} H b)$$
$$Q_{bH} = \left(H^\dagger H\right)\left(\bar{Q}\widetilde{H} t\right)$$

$$Q_{HG} = H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}$$
$$Q_{HW} = H^\dagger H W_{\mu\nu}^i B^{\mu\nu}$$
$$Q_{HB} = H^\dagger H W_{\mu\nu}^i W^{a\mu\nu}$$
$$Q_{HWB} = H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$Q_{tW} = (\bar{Q}\sigma^{\mu\nu} t)\sigma^i \widetilde{H} W_{\mu\nu}^i$$
$$Q_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\sigma^i \widetilde{H} B_{\mu\nu}$$
$$Q_{tG} = (\bar{Q}\sigma^{\mu\nu} T^a t)\widetilde{H} G_{\mu\nu}^a$$

SMEFT operator definitions

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

$Q_{lq}^{(1)}: (\bar{l}_p\gamma^\mu l_r)(\bar{q}\gamma^\mu q)$
$Q_{lQ}^{(3)}: (\bar{l}_p\sigma^i\gamma^\mu l_r)(\bar{Q}\sigma^i\gamma^\mu Q)$
$Q_{qq}^{(1,1)}: (\bar{q}\gamma^\mu q)(\bar{q}\gamma^\mu q)$
$Q_{qq}^{(3,8)}: (\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$
$Q_{Qq}^{(3,1)}: (\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
$Q_{lq}^{(3)}: (\bar{l}_p\sigma^i\gamma^\mu l_r)(\bar{q}\sigma^i\gamma^\mu q)$
$Q_{QQ}^{(1)}: (\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q)$
$Q_{qq}^{(1,8)}: (\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$
$Q_{Qq}^{(1,1)}: (\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$Q_{Qq}^{(3,8)}: (\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{Q}\sigma^i T^a\gamma^\mu Q)$
$Q_{lQ}^{(1)}: (\bar{l}_p\gamma^\mu l_r)(\bar{Q}\gamma^\mu Q)$
$Q_{ll}': (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)$
$Q_{qq}^{(3,1)}: (\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
$Q_{Qq}^{(1,8)}: (\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$

$Q_{et}: (e_p\gamma^\mu e_r)(\bar{t}\gamma^\mu t)$
$Q_{uu}^{(8)}: (\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$
$Q_{dd}^{(1)}: (\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$
$Q_{ud}^{(8)}: (\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$
$Q_{tt}: (\bar{t}\gamma_\mu t)(\bar{t}\gamma^\mu t)$
$Q_{tu}^{(8)}: (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
$Q_{dd}^{(8)}: (\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$
$Q_{td}^{(1)}: (\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$
$Q_{uu}^{(1)}: (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$
$Q_{tu}^{(8)}: (\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
$Q_{ud}^{(1)}: (\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$
$Q_{td}^{(8)}: (\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$

$Q_{Hl}^{(1)}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{Hq}^{(1)}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
$Q_{Hd}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$Q_{Ht}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$
$Q_{Hl}^{(3)}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_r)$
$Q_{Hq}^{(3)}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$
$Q_{HQ}^{(1)}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$Q_{Hb}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$
$Q_{He}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$Q_{Hu}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
$Q_{HQ}^{(3)}: (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$

Modeling of SMEFT

- At LO using SMEFTsim Feynrules model
- At NLO-QCD using SMEFTatNLO Feynrules model
- H → γγ based on analytic calculation for decay
- Propagator corrections using SMEFTsim

Simplified likelihood functions

- A likelihood function constructed from the covariance matrix V:

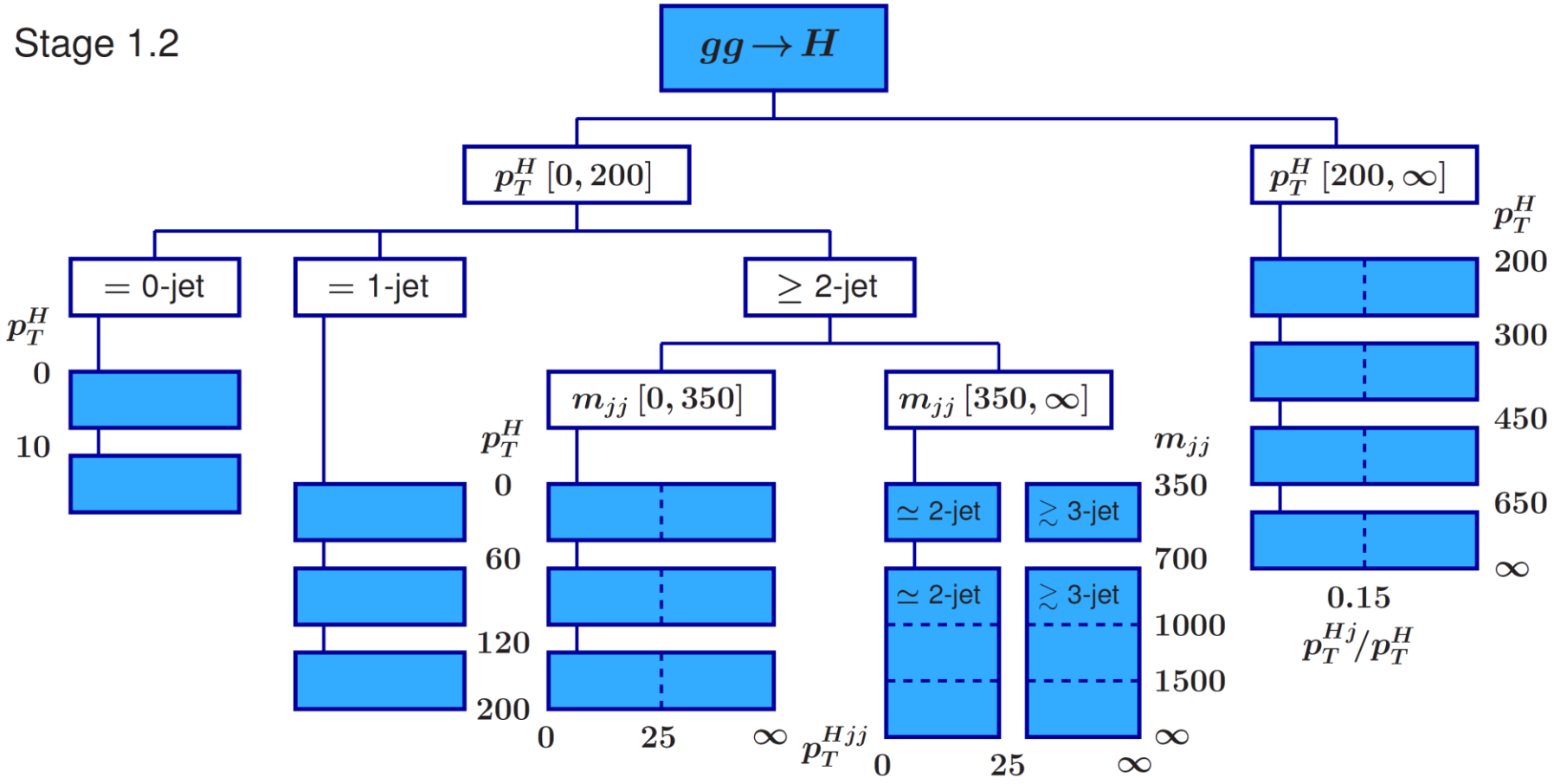
$$\mathcal{L}^{\mathrm{simpl}}(\vec{c}) = \frac{\exp\left(-\frac{1}{2}\Delta\vec{\mu}^T V^{-1}\Delta\vec{\mu}\right)}{\sqrt{(2\pi)^m \det(V)}}$$

- $\Delta\vec{\mu} = \vec{\mu} - \hat{\vec{\mu}}$, where $\hat{\vec{\mu}}$ is the best-fit values
- Much more convenient to share than full profile-likelihood functions, and much lower computational complexity
- Validated by comparing results based on the full versus simplified likelihood when both are available

Simplified template cross sections (STXS)

- A standardized definition of differential distributions for Higgs studies
- Defined based on the Higgs pre-decay and with a pseudo-rapidity cut of $|\eta| < 2.5$ and not other cuts on the Higgs boson
- Defined for ggH, qqH, VH, and ttH production modes
- The ggH bins are shown on the next slide

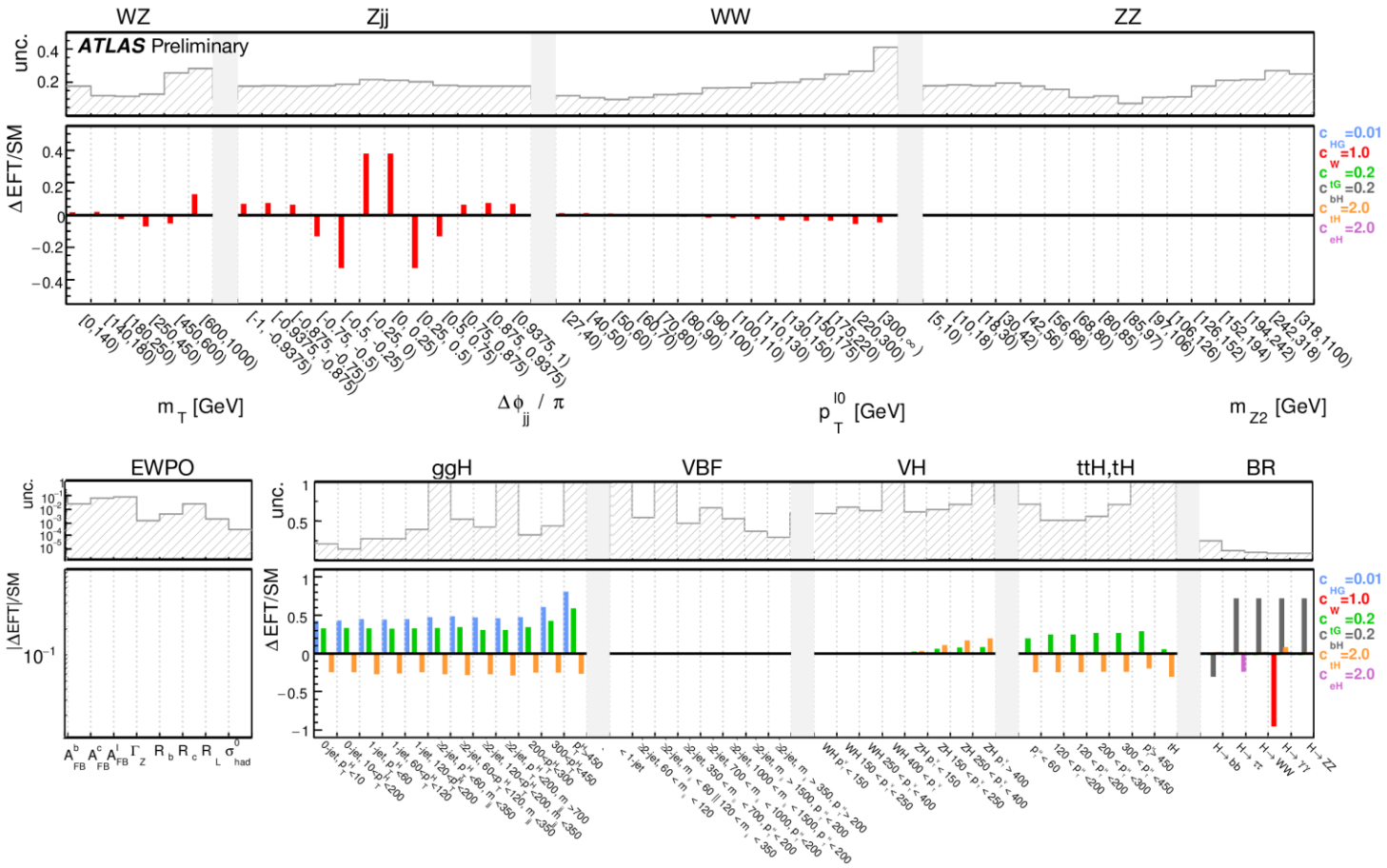
STXS stage 1.2 gg → H definitions



Principal component analysis

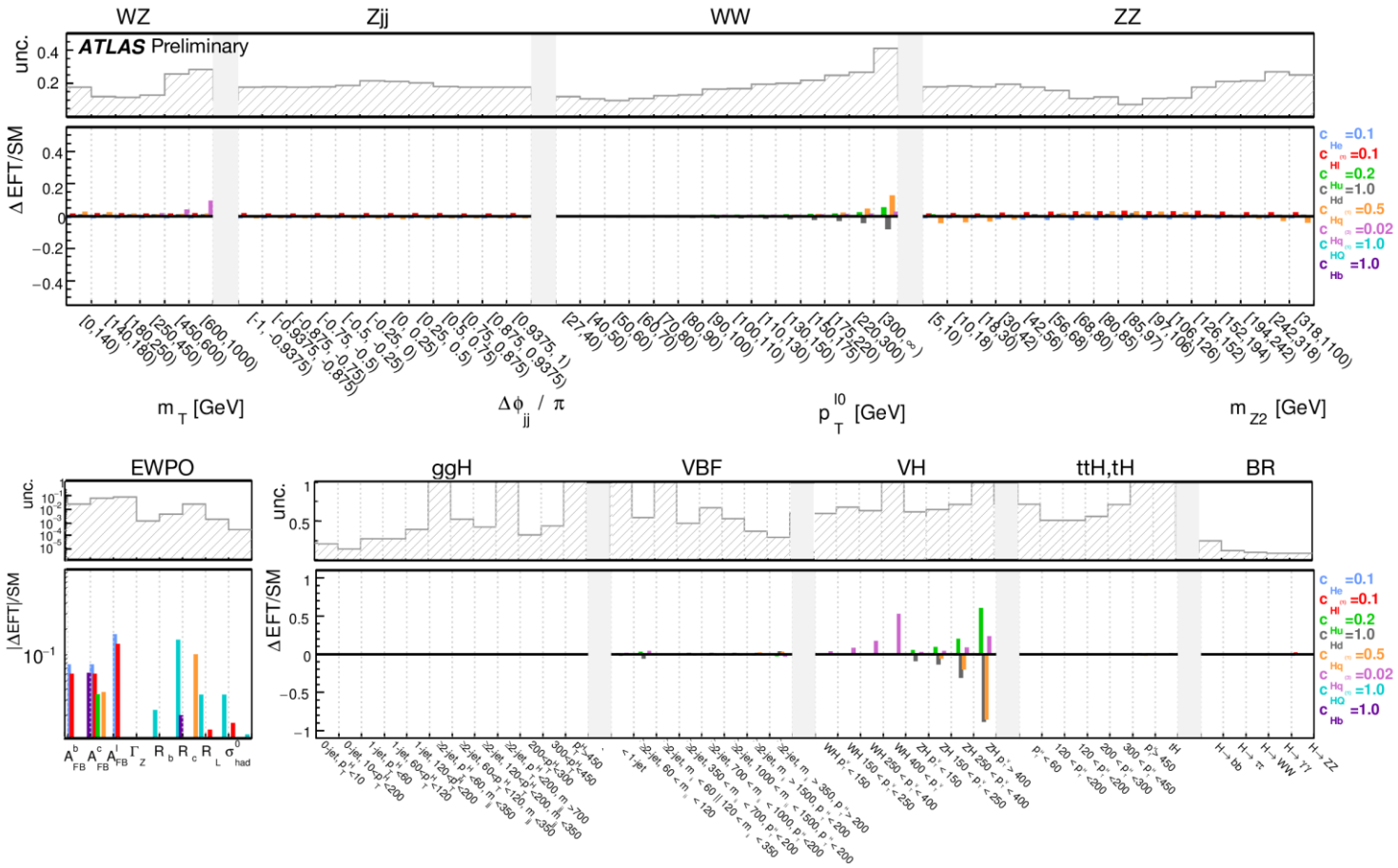
- Competing effects of different operators create flat or nearly flat directions in the parameter space of the likelihood function
- These flat directions correspond to eigenvectors of the Hessian matrix (evaluated at the minimum) with small eigenvalues
- The criteria for inclusion in the final fit is that $1/\sqrt{\text{eigenvalue}} < 5$
- CMS: perform PCA globally on all coefficients, so eigenvectors may not have a clear physics interpretation
- ATLAS: perform PCA on 8 subsets of operators, so eigenvectors have a more clear physics interpretation

ATLAS operator effects

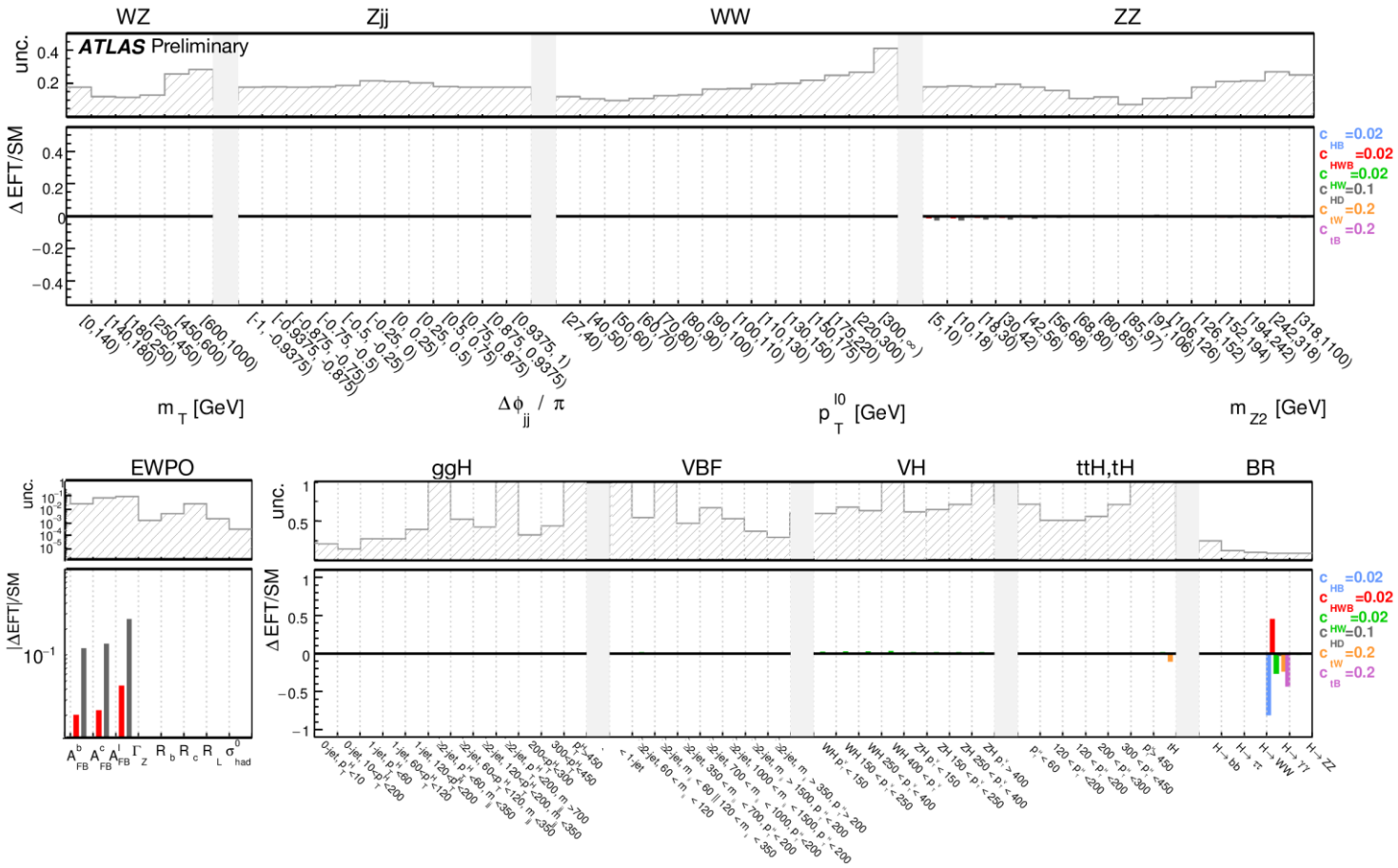


ATLAS style: all bins, subset of operators

ATLAS operator effects

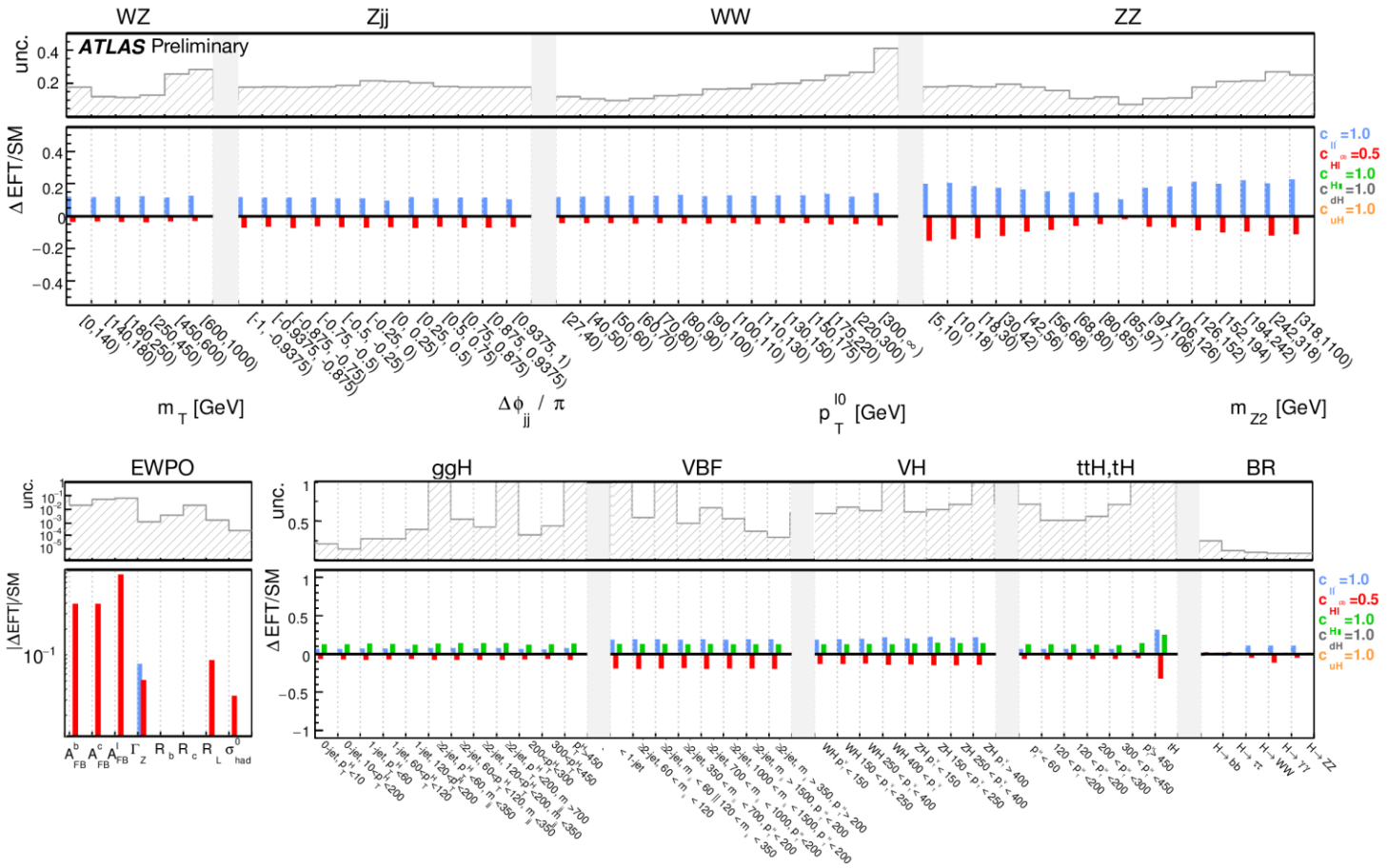


ATLAS operator effects



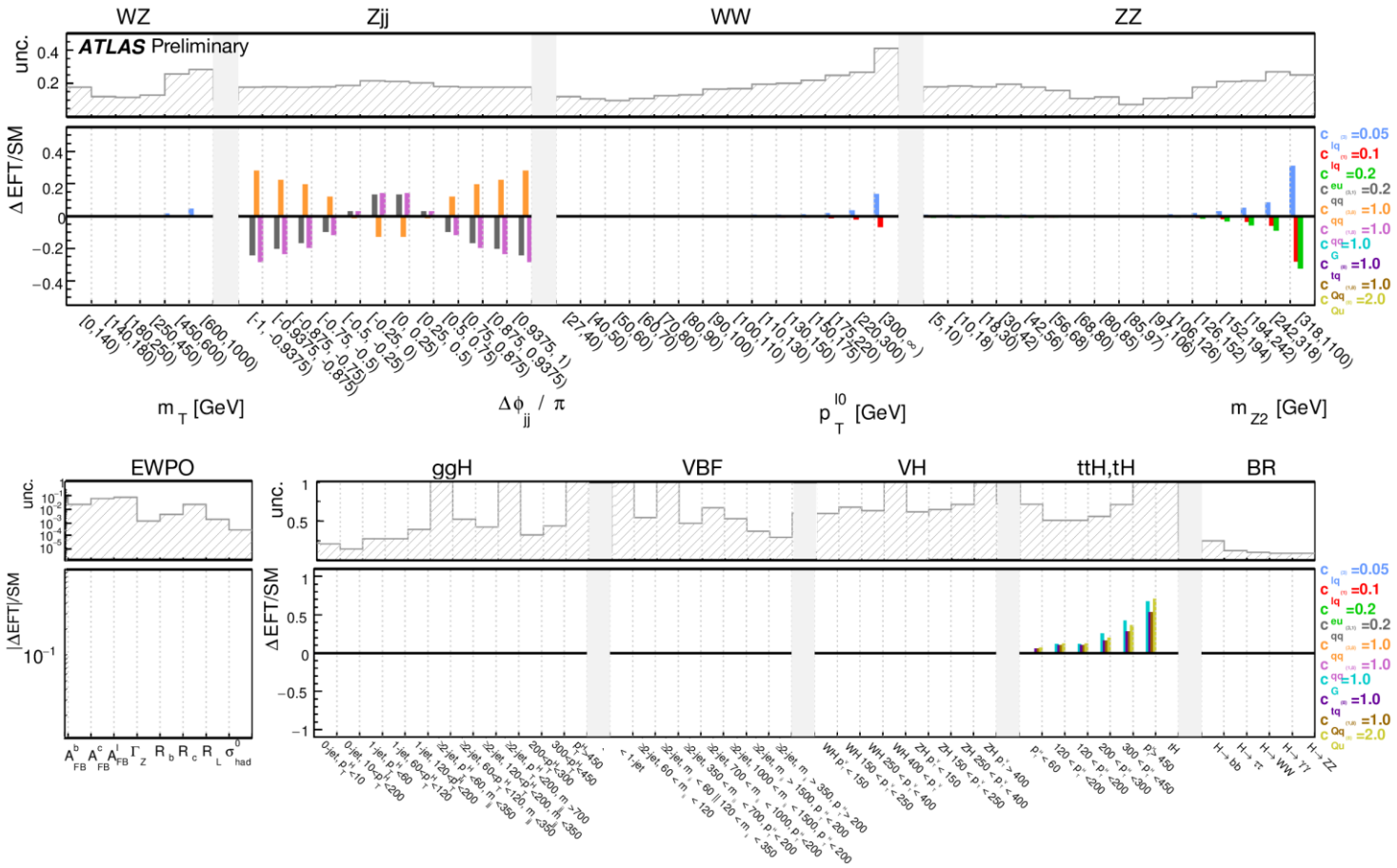
Unlike in the SM, H → γγ can occur at tree-level in SMEFT

ATLAS operator effects

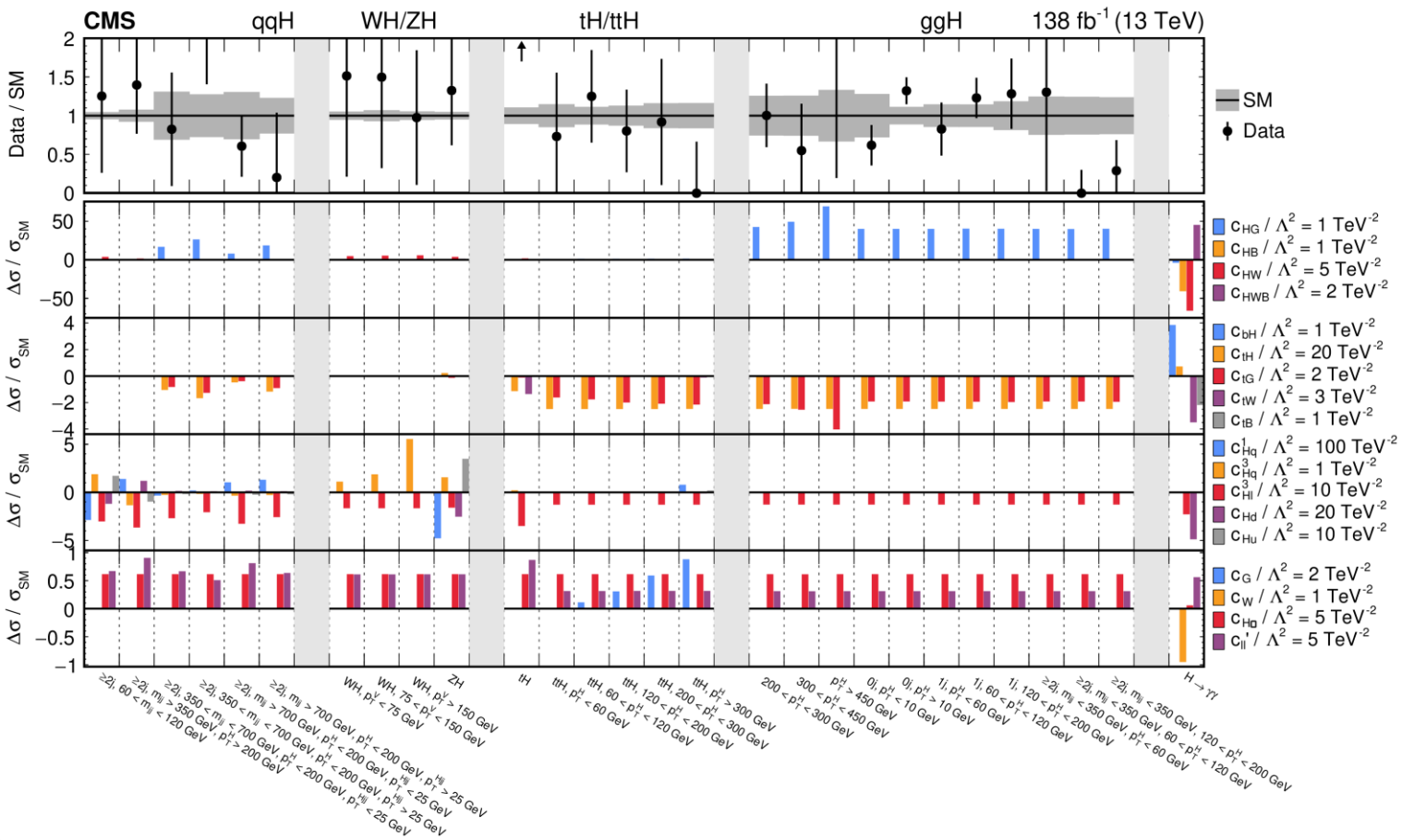


Can see interplay between EWPO and LHC measurements

ATLAS operator effects

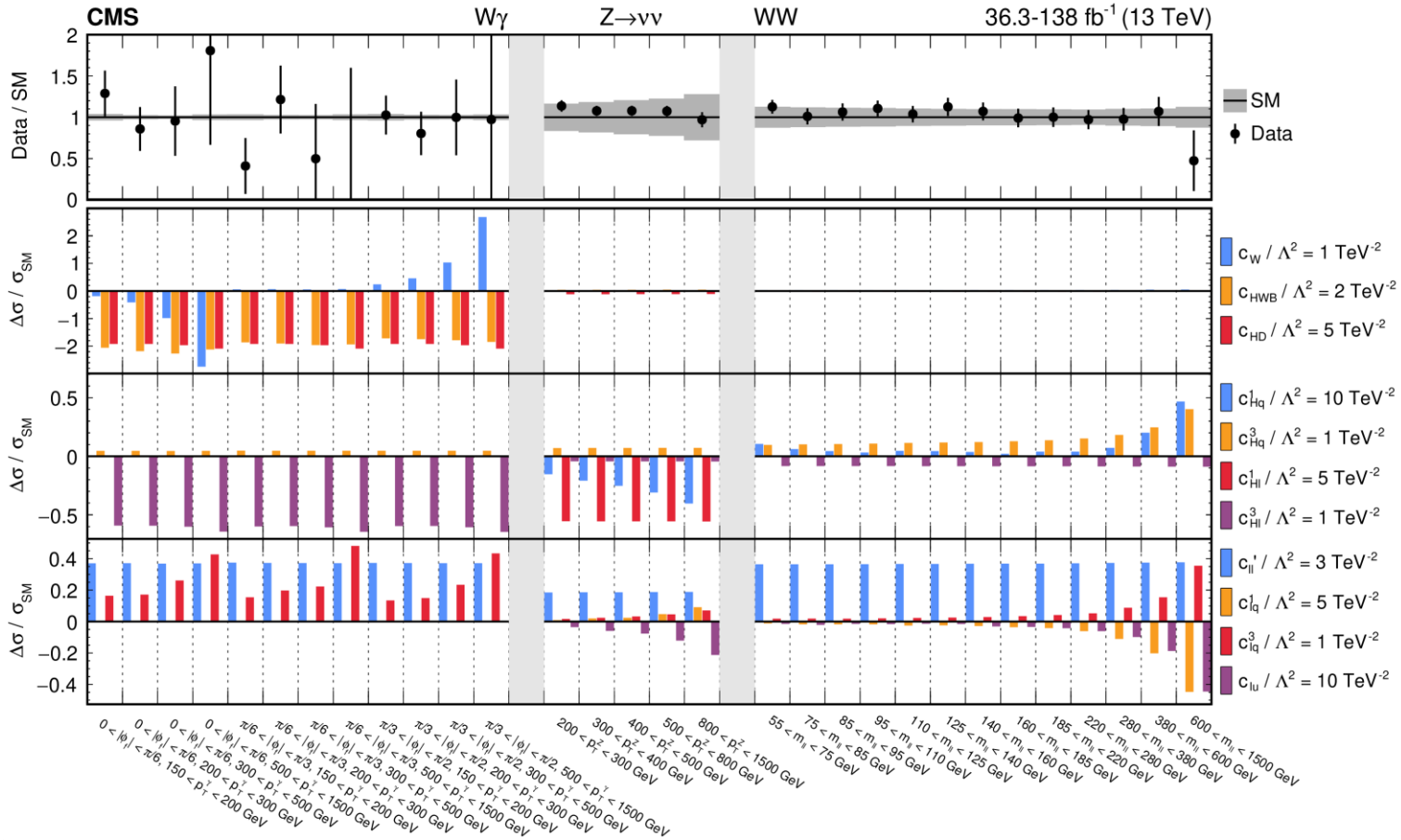


CMS operator effects

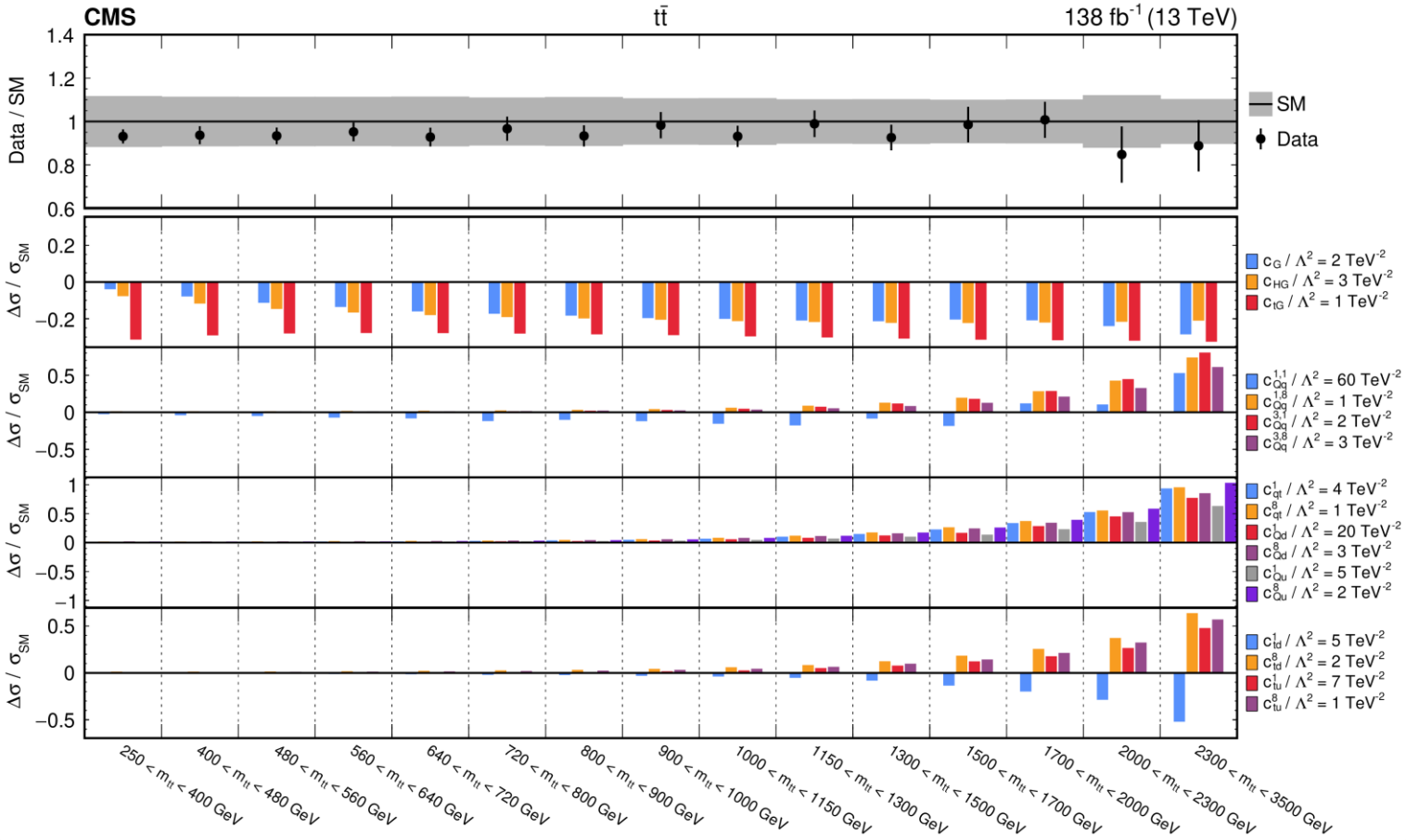


CMS style: all bins affected by subset of operators

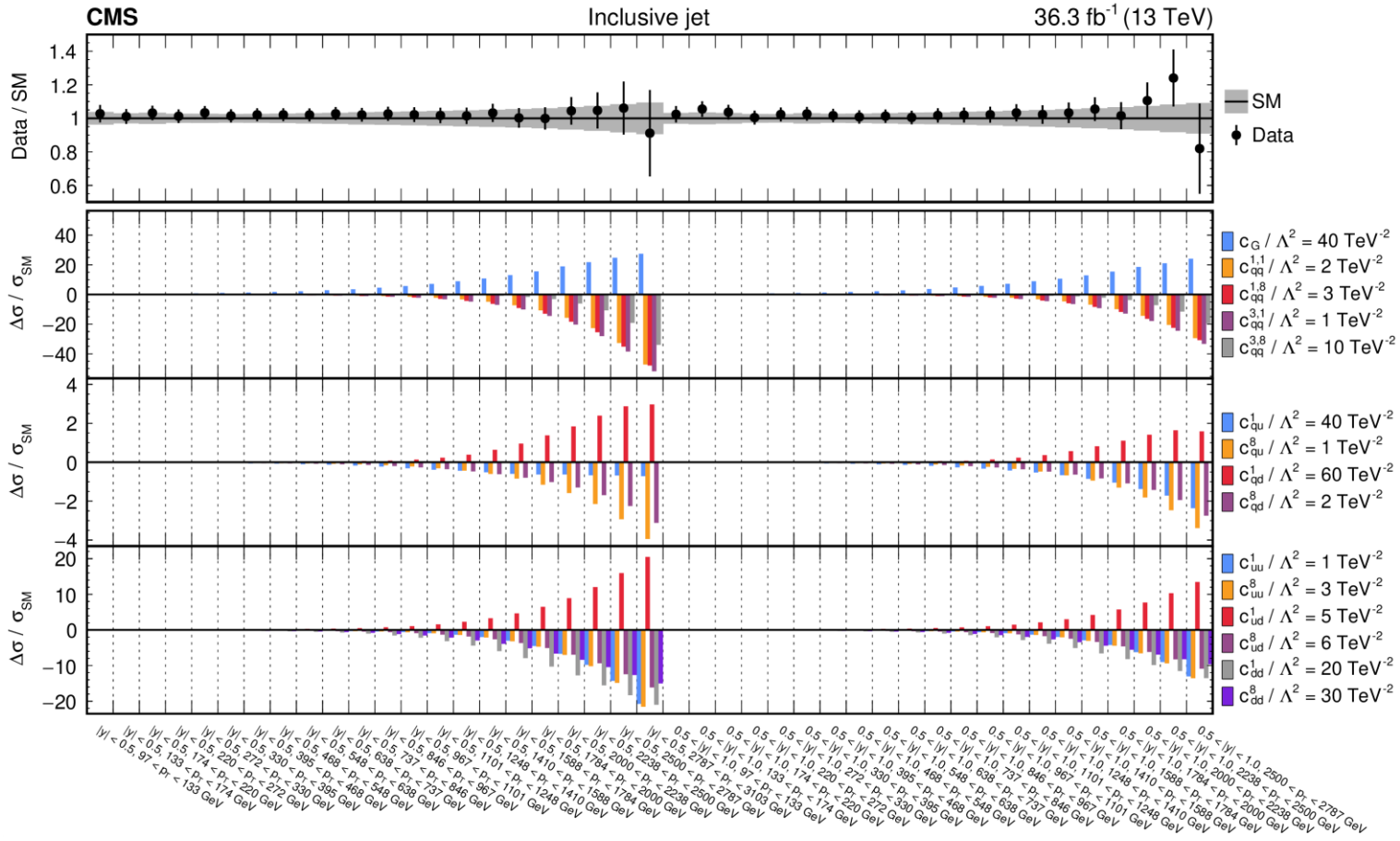
CMS operator effects



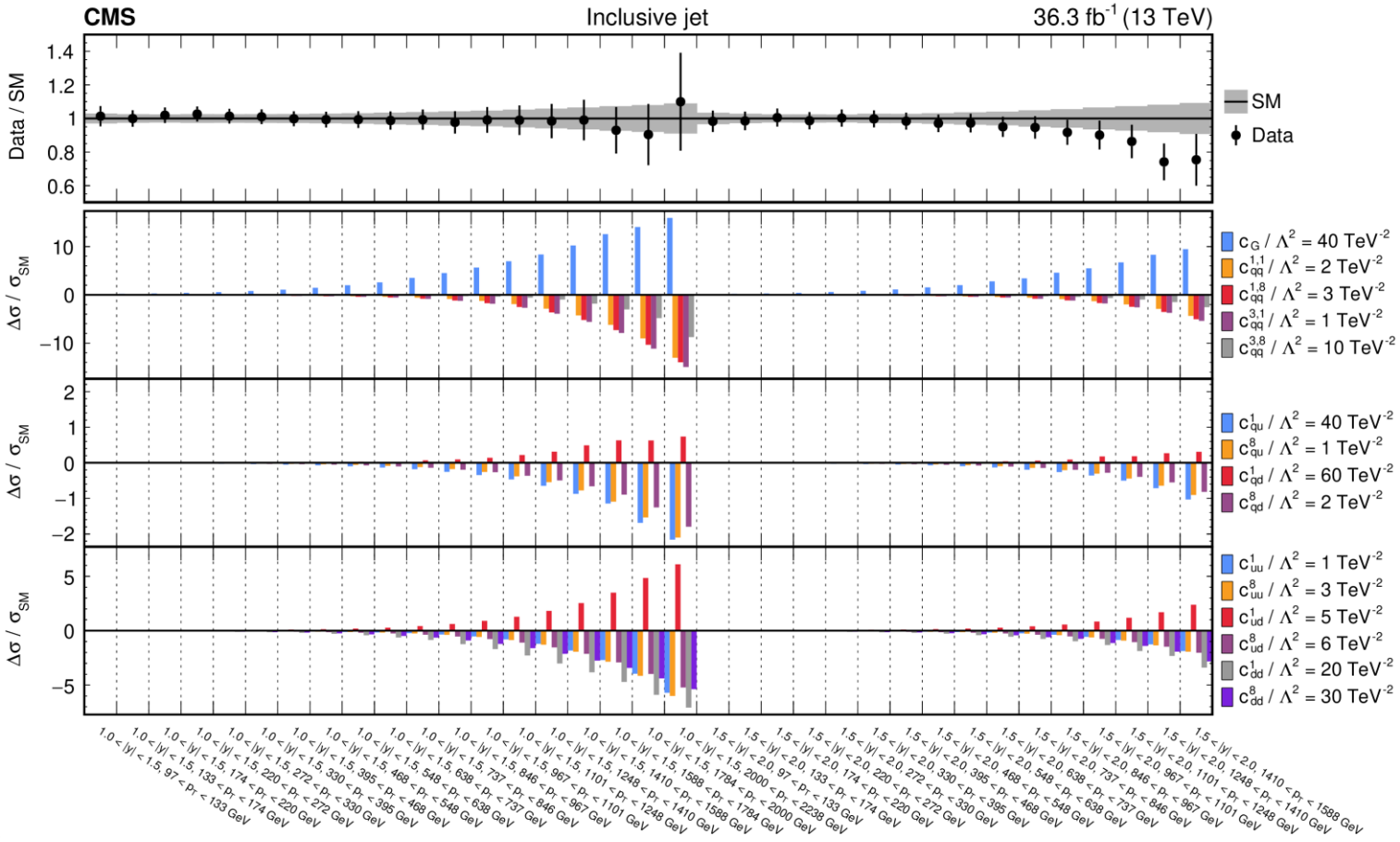
CMS operator effects



CMS operator effects

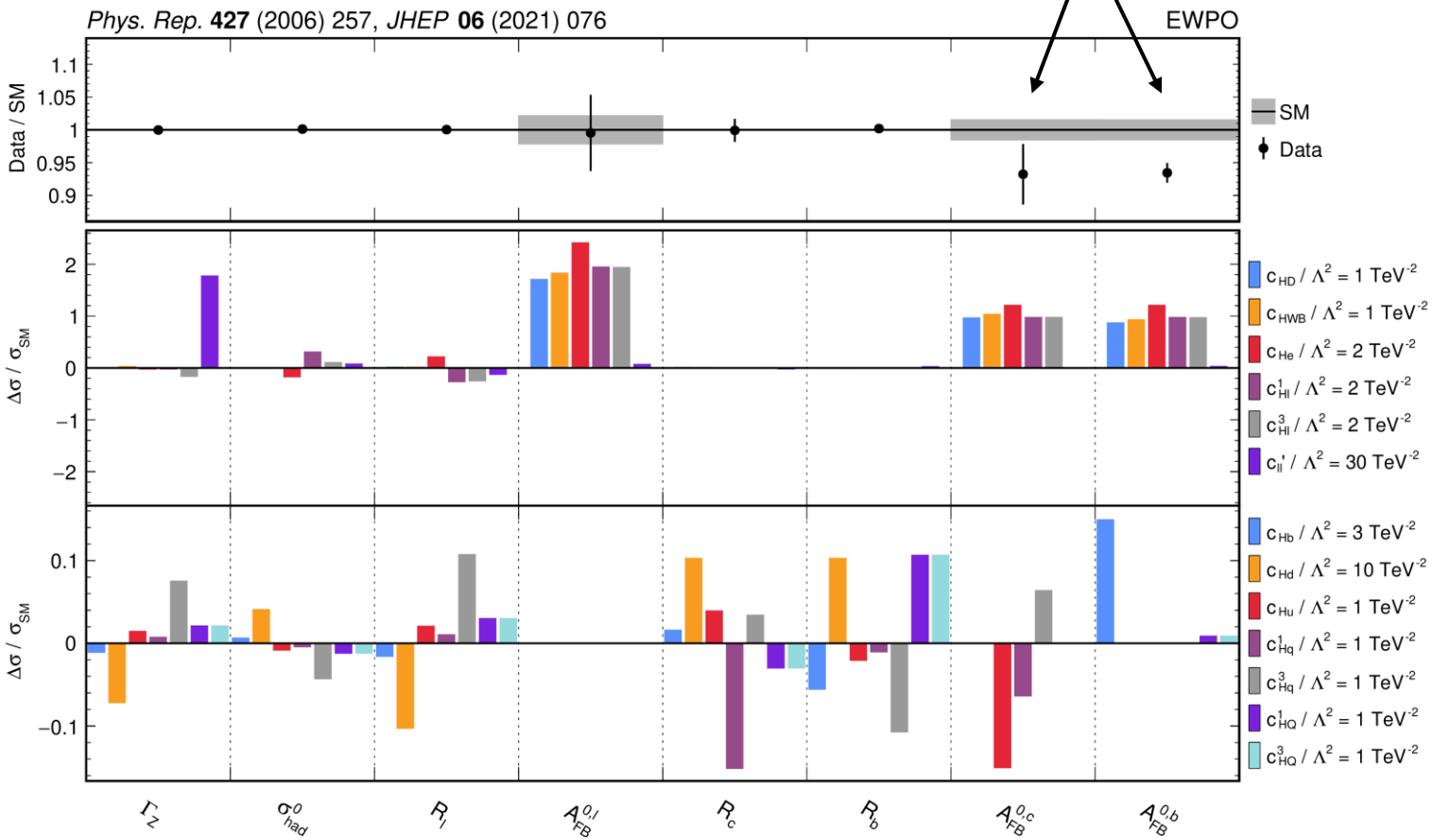


CMS operator effects

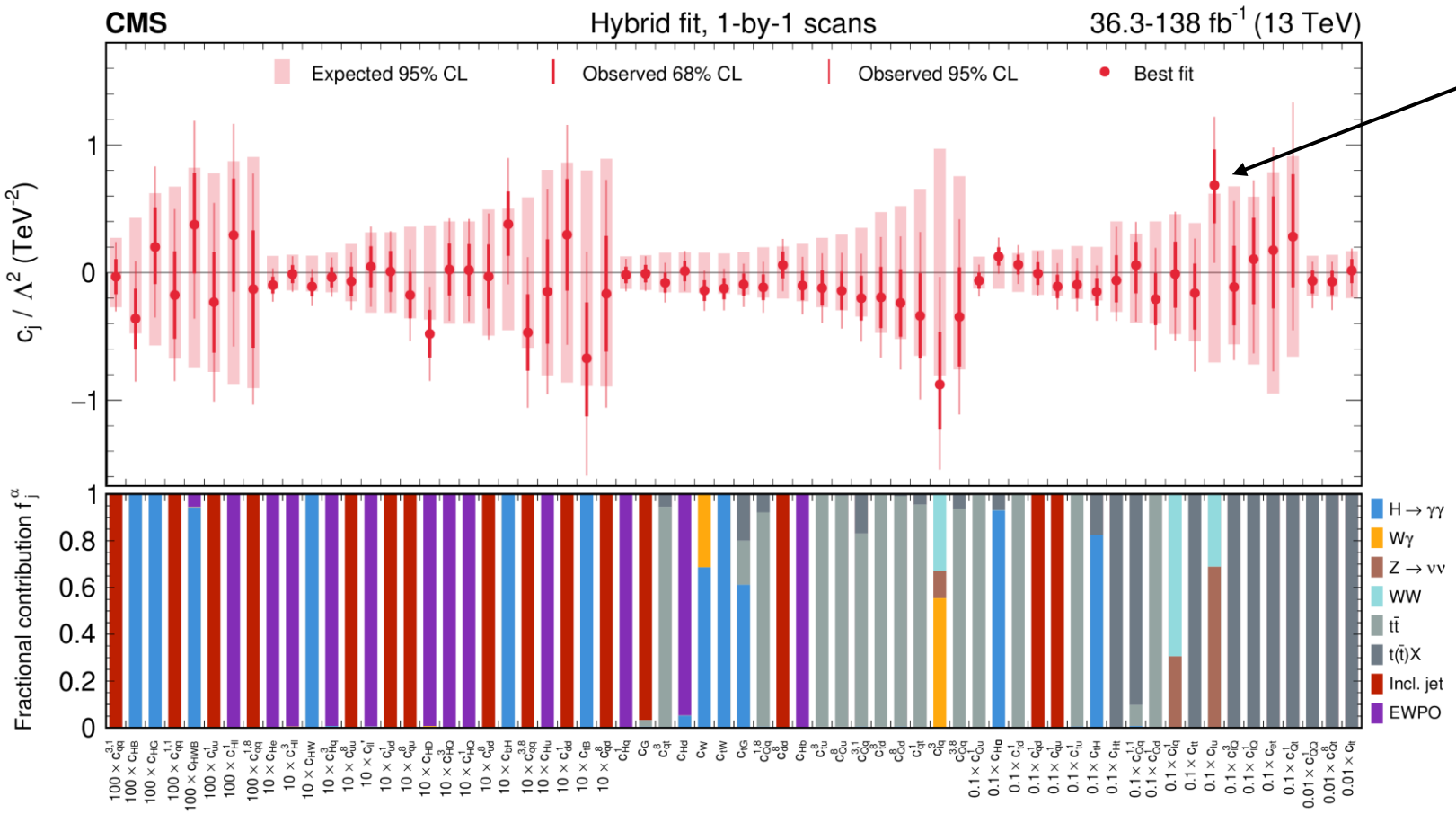


CMS operator effects

Well-known discrepancies in $A_{FB}^{0,b}$, $A_{FB}^{0,c}$ measurements

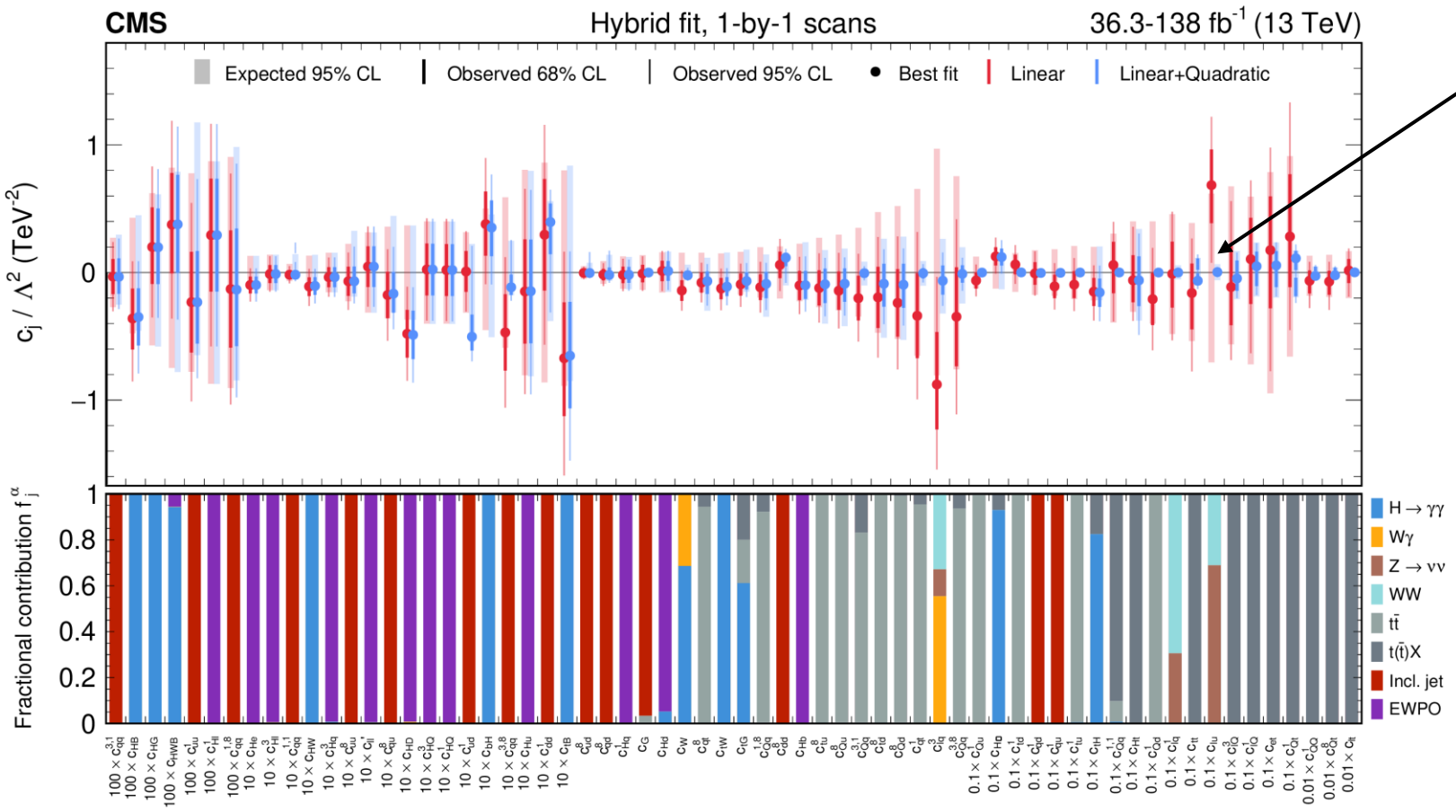


CMS constraints on individual coefficients



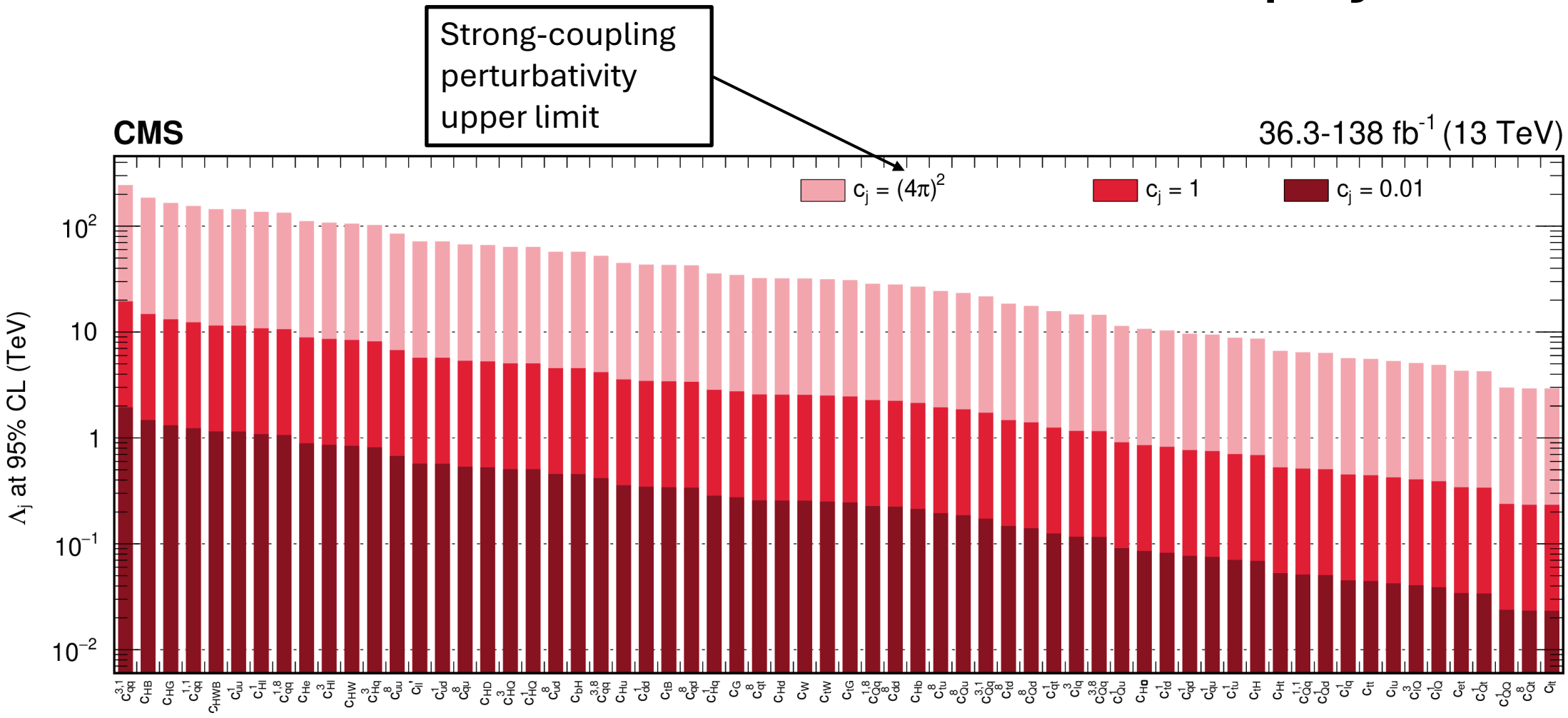
Would be more consistent in simultaneous fit of PDF + SMEFT

CMS linear vs. linear + quadratic constraints

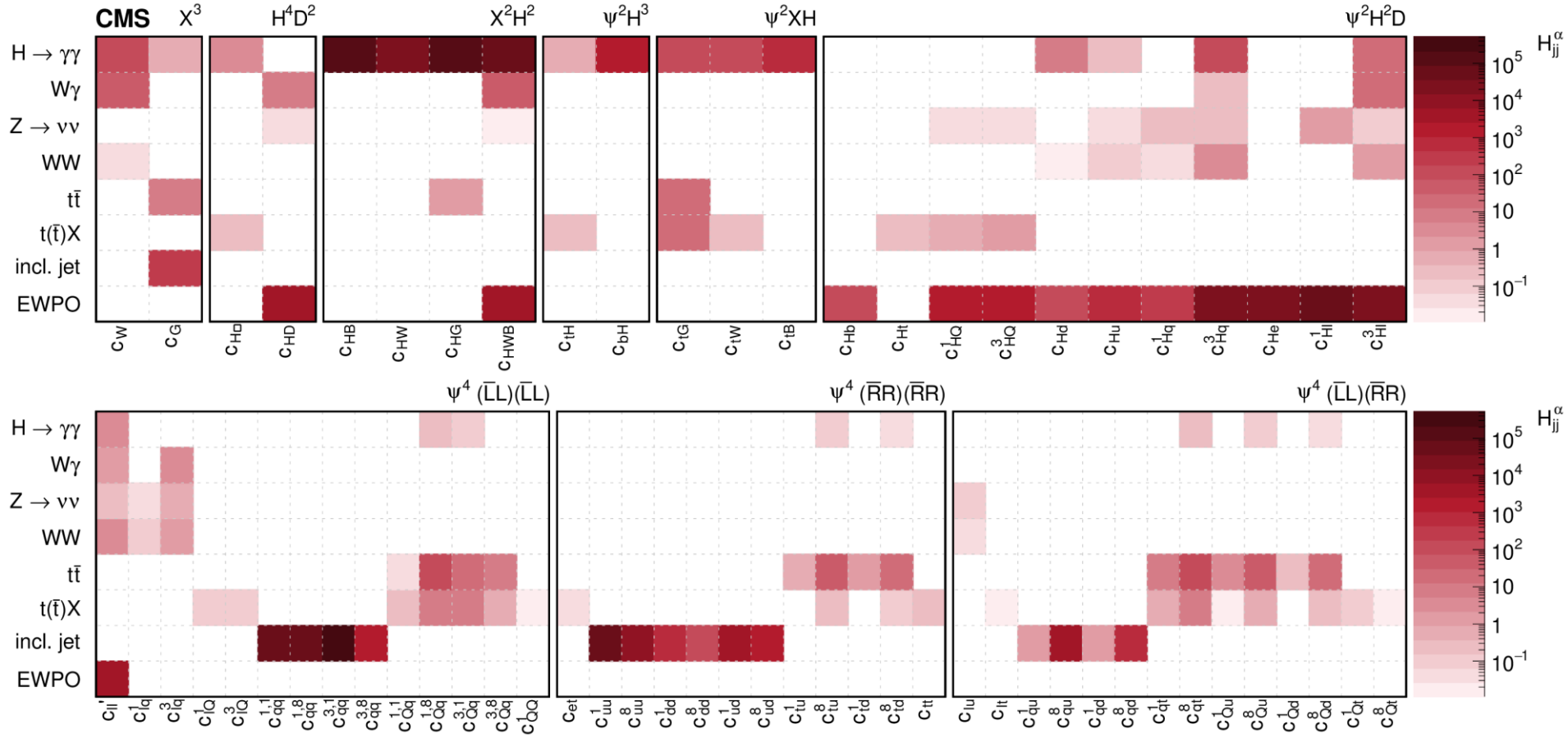


Quadratic terms lead to much tighter constraint in a few cases

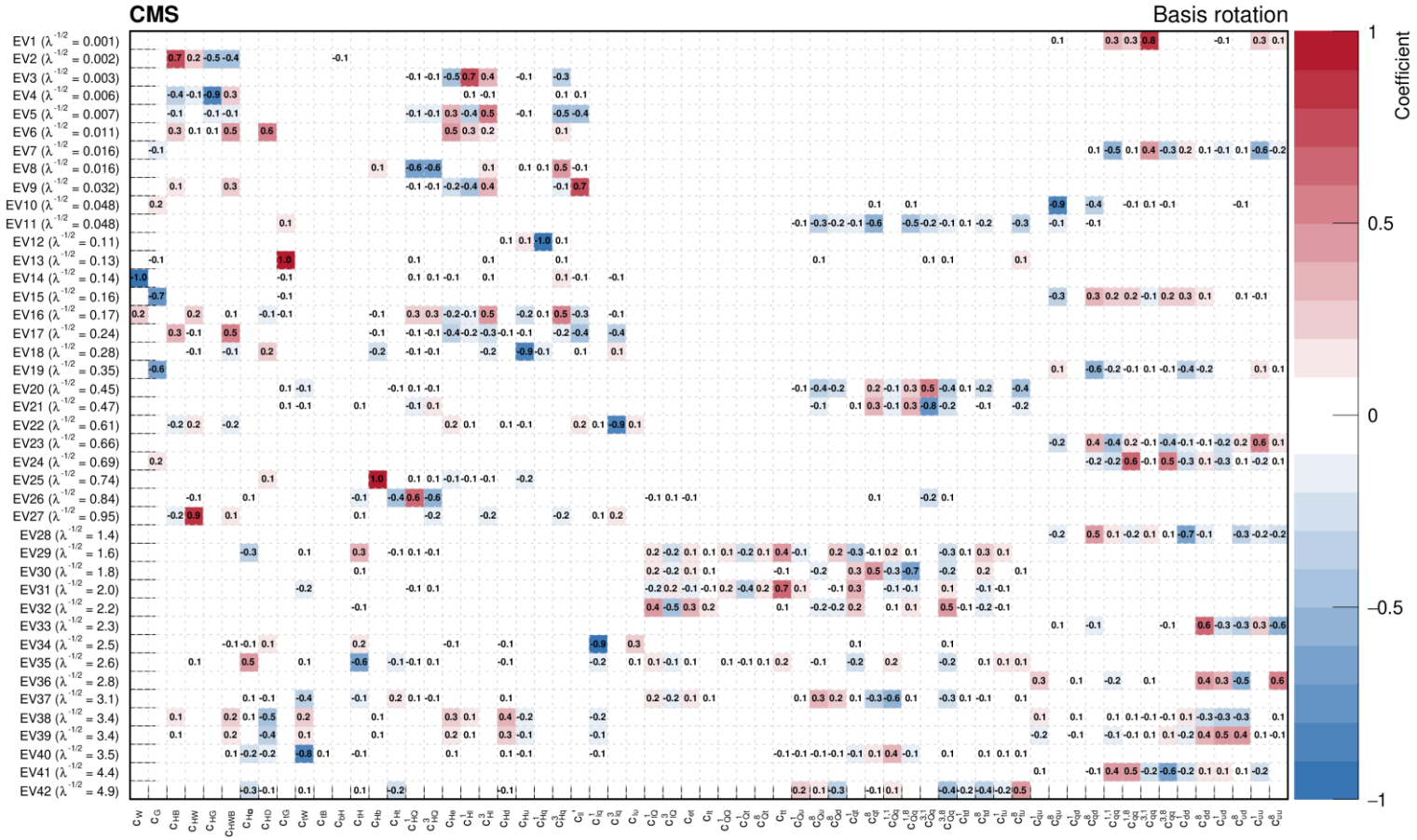
CMS constraints on the scale of new physics



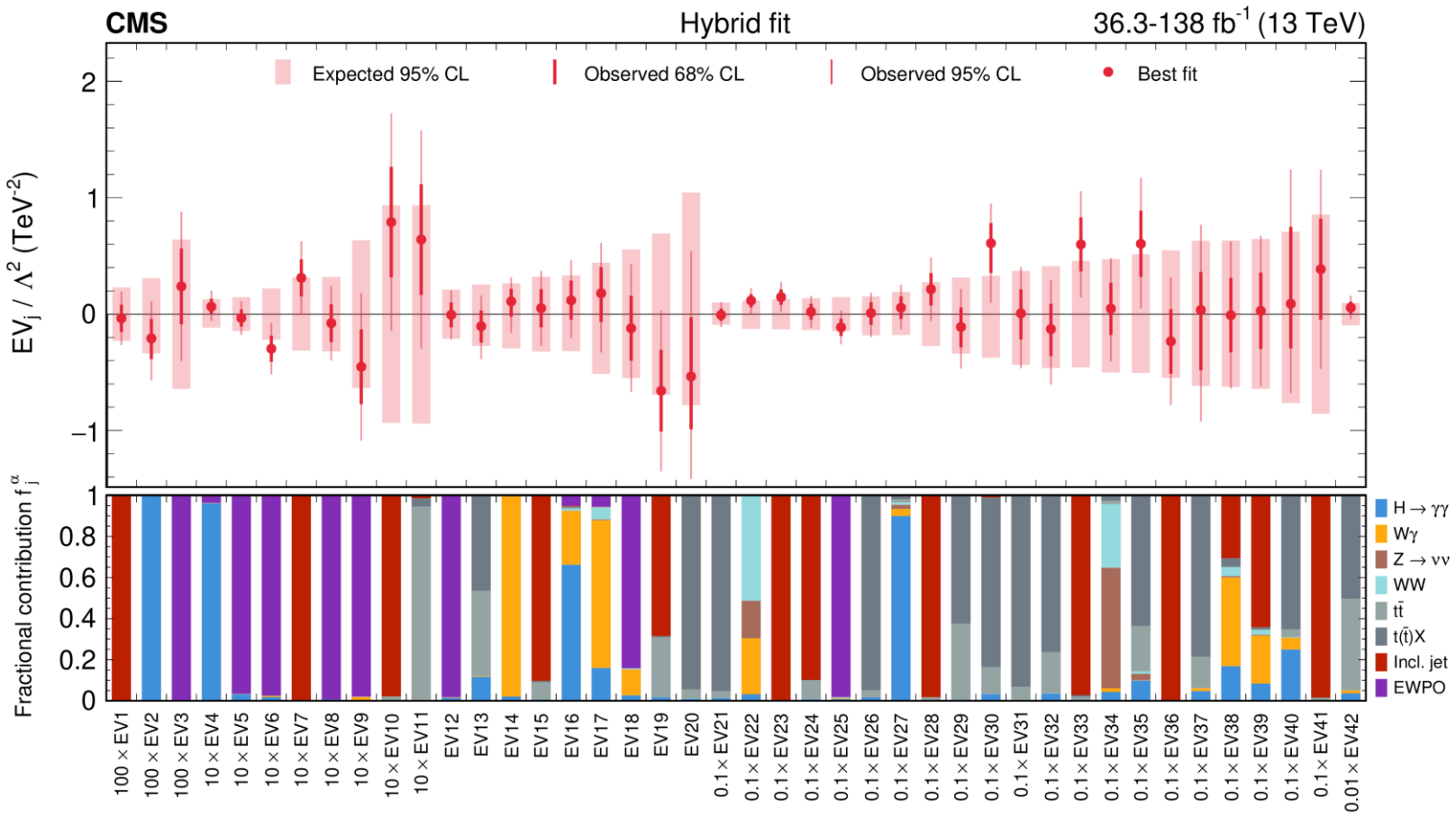
CMS Hessian diagonal entries



CMS PCA eigenvectors

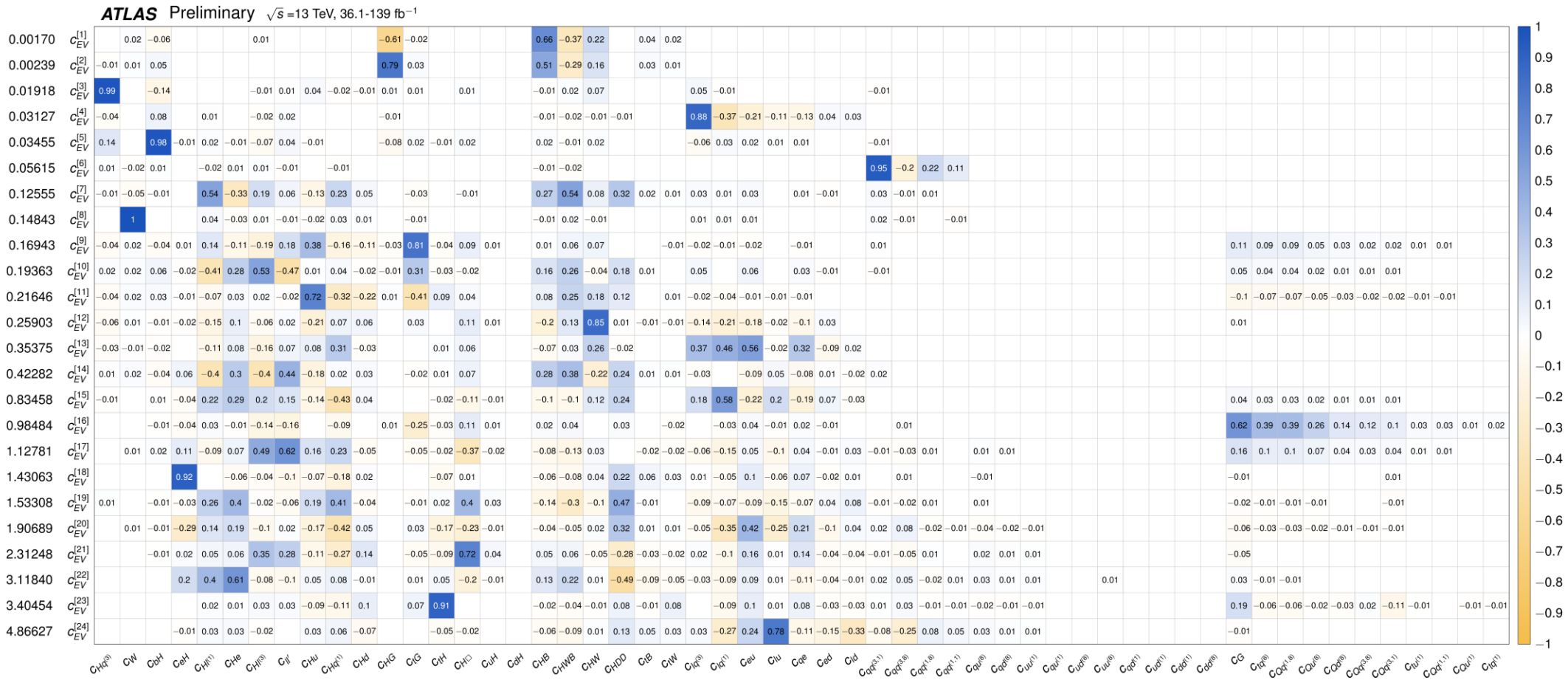


CMS PCA constraints

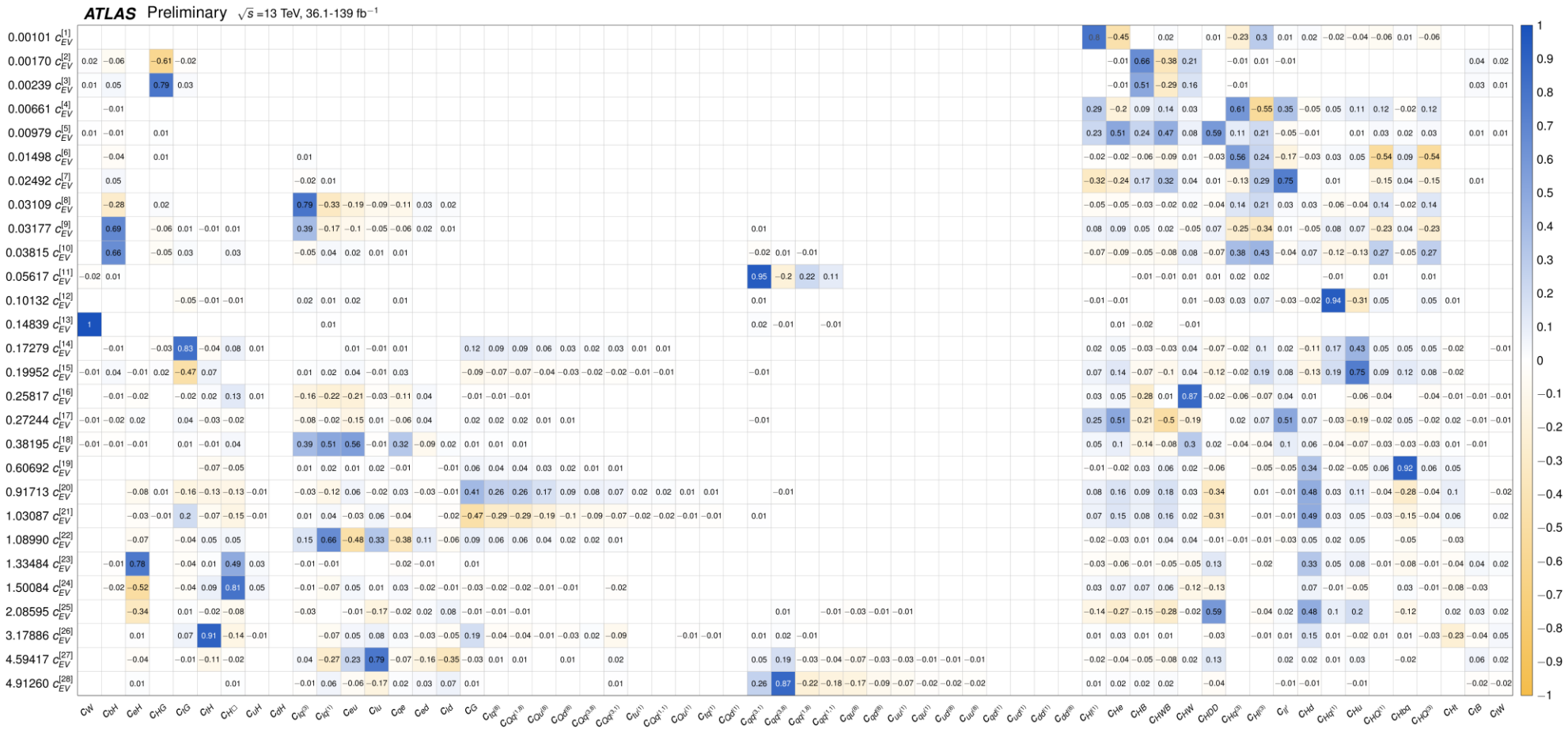


p-value = 1.7% (would be 26% w/o inclusive jet measurements)

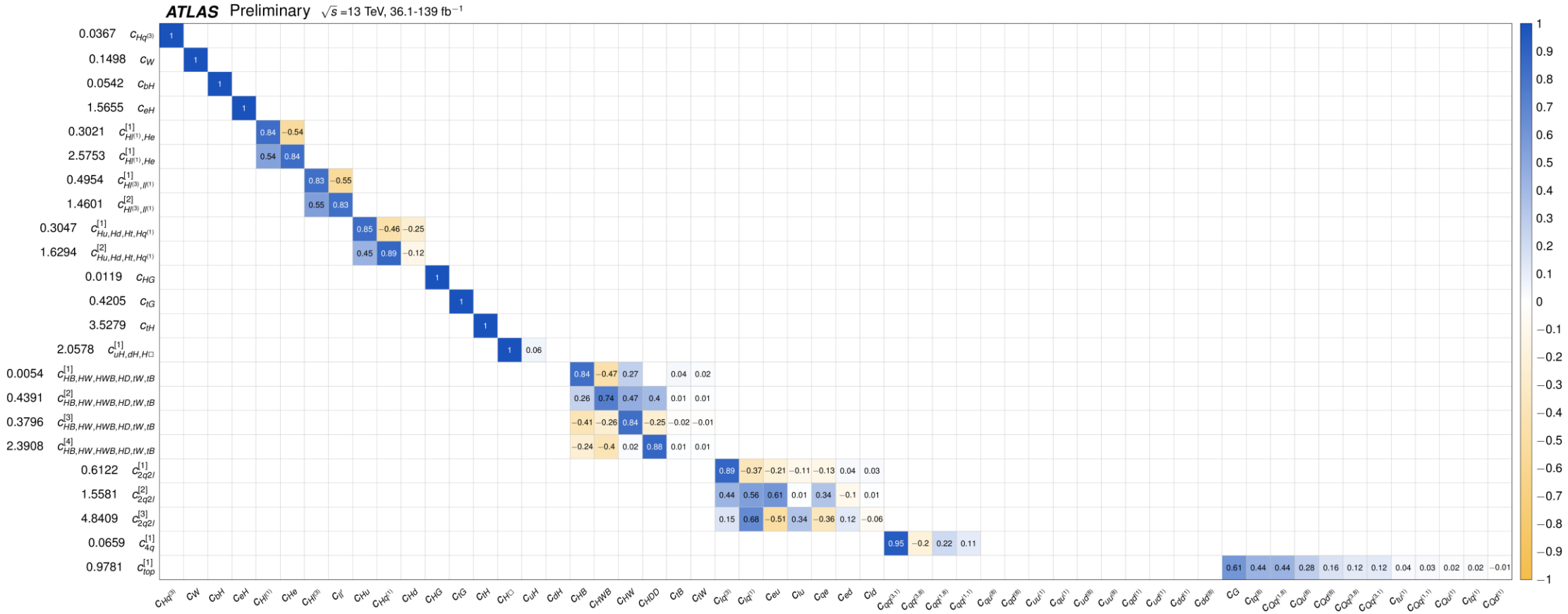
ATLAS PCA eigenvectors, ATLAS-only fit



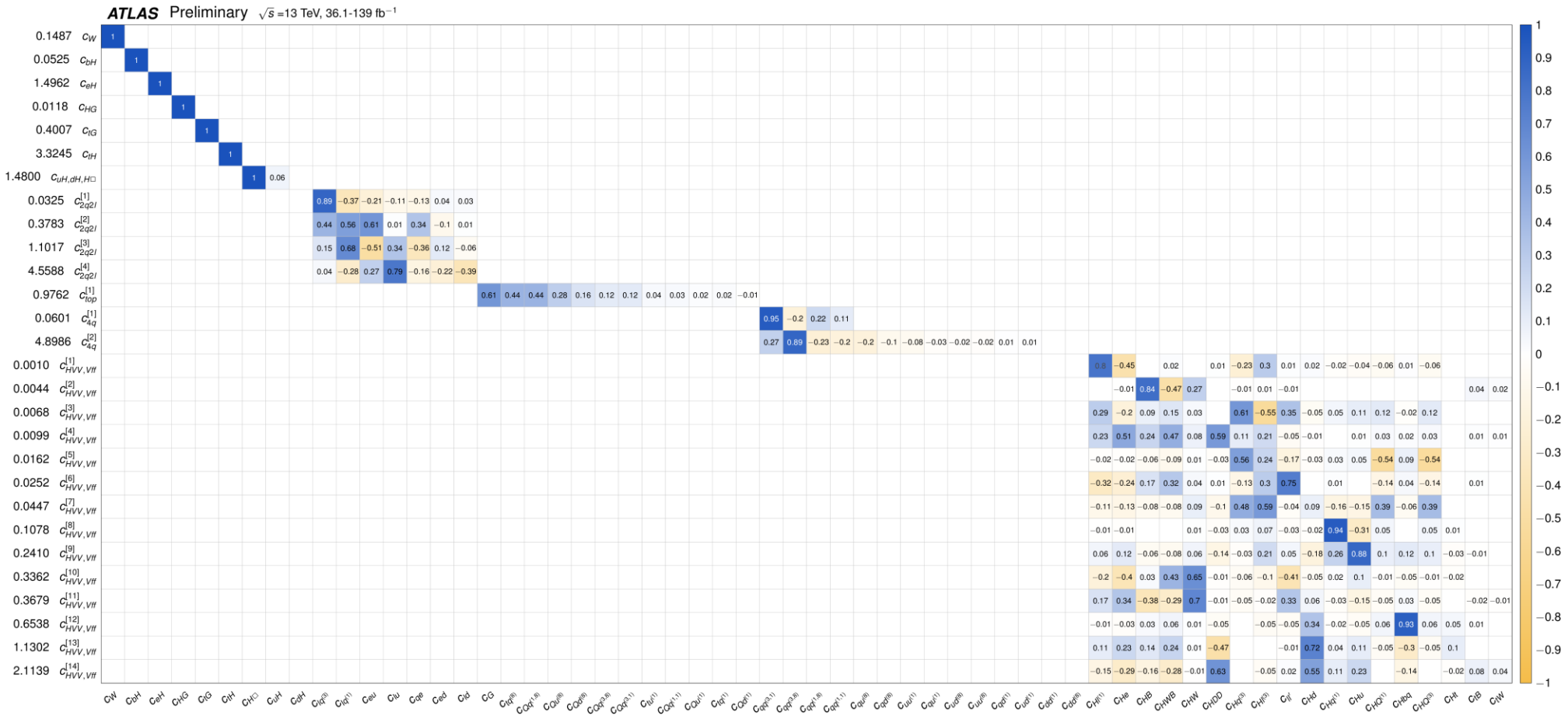
ATLAS PCA eigenvectors, combined fit



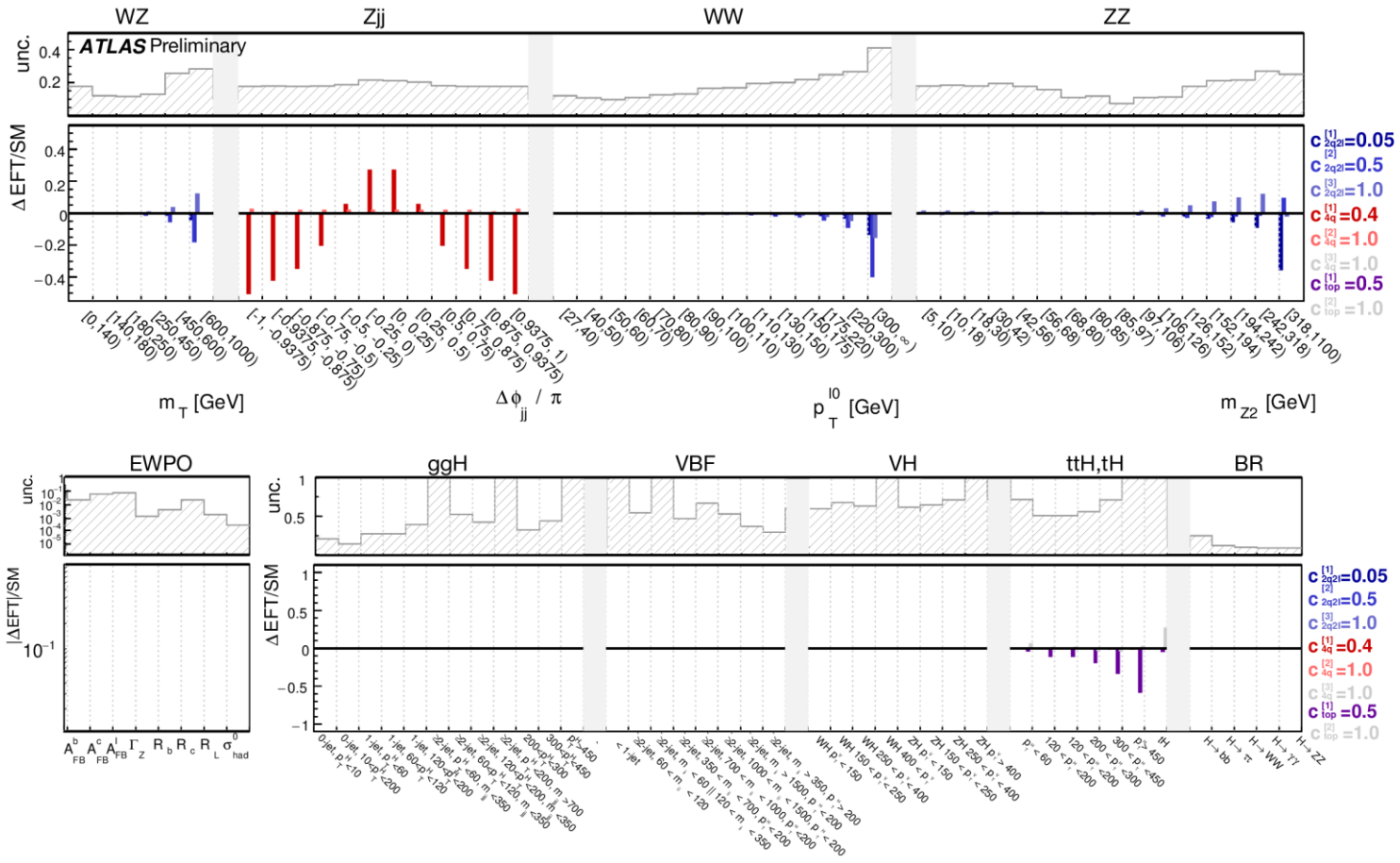
ATLAS fit basis, ATLAS-only fit



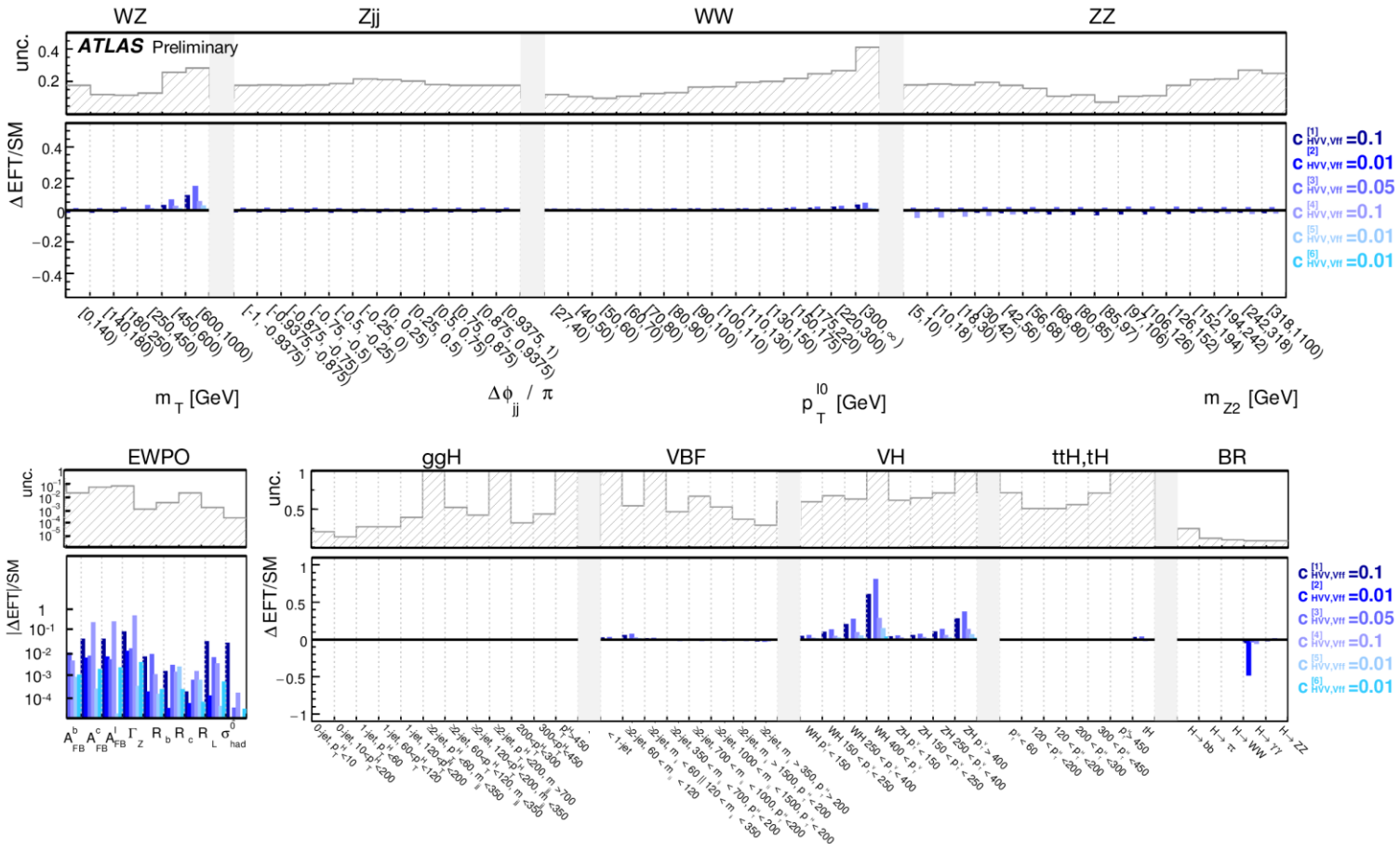
ATLAS fit basis, combined fit



ATLAS eigenvector effects

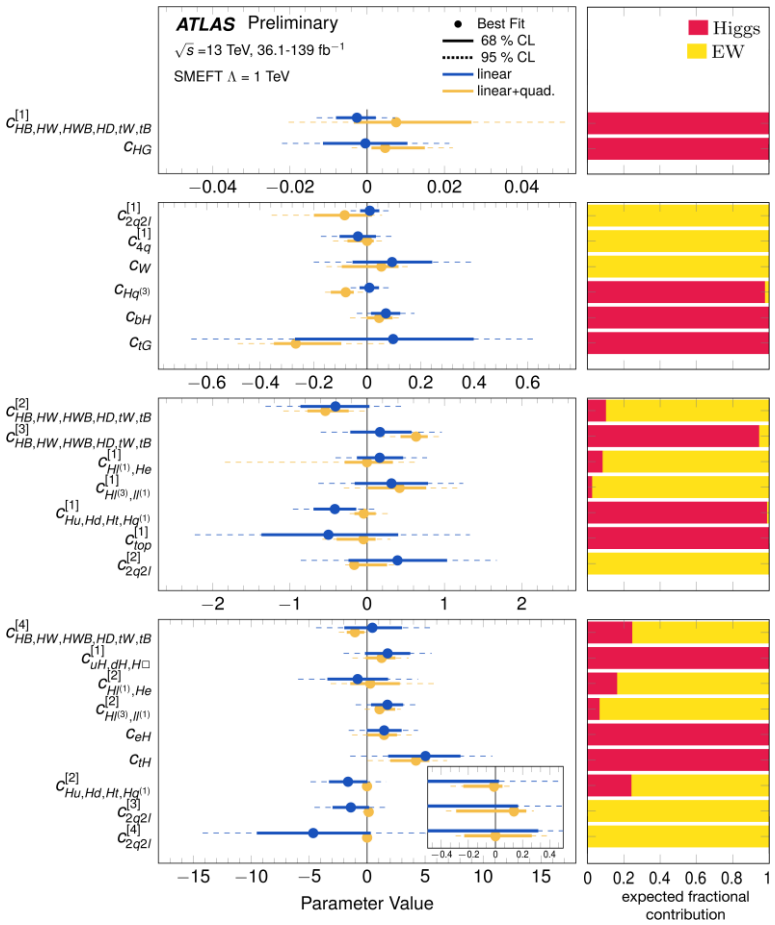


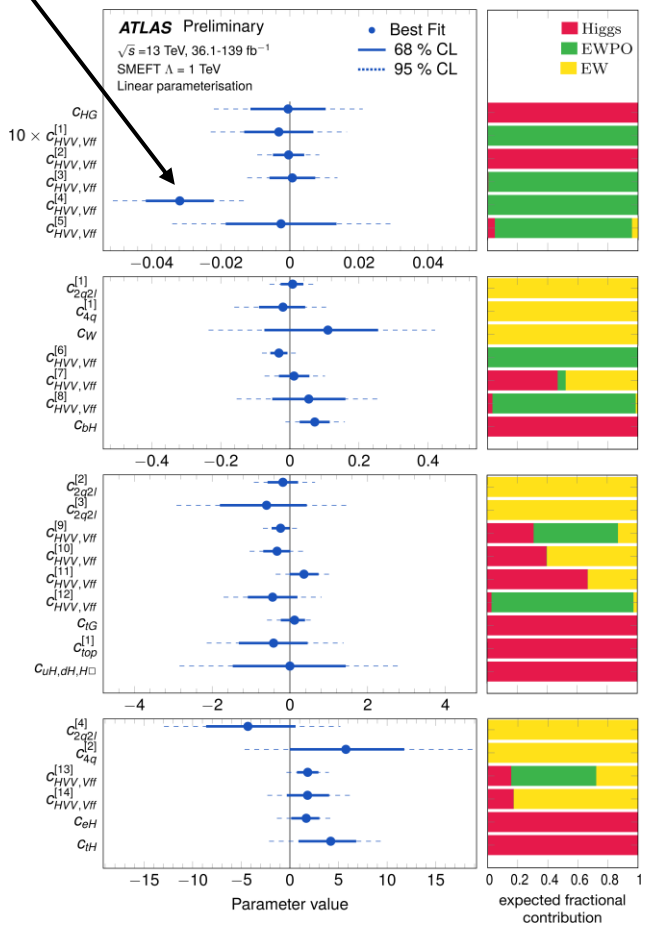
ATLAS eigenvector effects



ATLAS results

Due to known discrepancy in prior $A_{FB}^{0,b}$, $A_{FB}^{0,c}$ measurements





Conclusion

- Combinations of analyses can be very tedious, but very valuable for constraining full set of dimension 6 SMEFT operators
- Using simplified likelihood functions and simplified template cross sections greatly simplifies combination
- Principal component analysis necessary to remove flat directions
- Good agreement with SM for results not affected by two issues:
  - The PDF and SMEFT fits are not simultaneous
  - Well-known discrepancies in non-LHC forward-background asymmetries