Global EFT combinations in ATLAS and CMS

TOP2025

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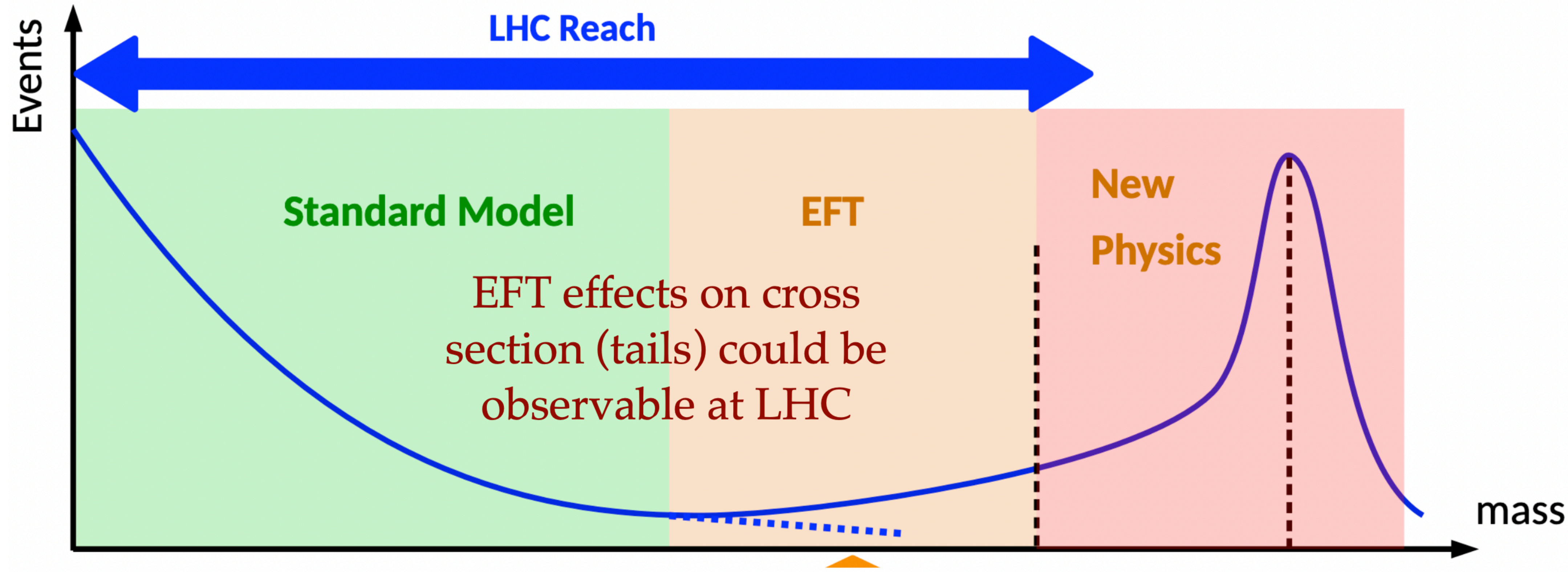
on behalf of the ATLAS and CMS collaborations

The (indirect) search for New Physics - EFT

- Despite its mature program, *no* new resonance observed at the LHC.
  - ➡ New particles may be at energy scales much higher then we can reach



- Effective Field Theories offer a (relatively) model-independent way to include the effects of unknown high-energy physics

Standard Model Effective Field Theory (SMEFT)

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i c_i^{(d)} \frac{1}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

$\mathcal{O}_i$: Higher dimensional **operators** which introduce new interaction vertices

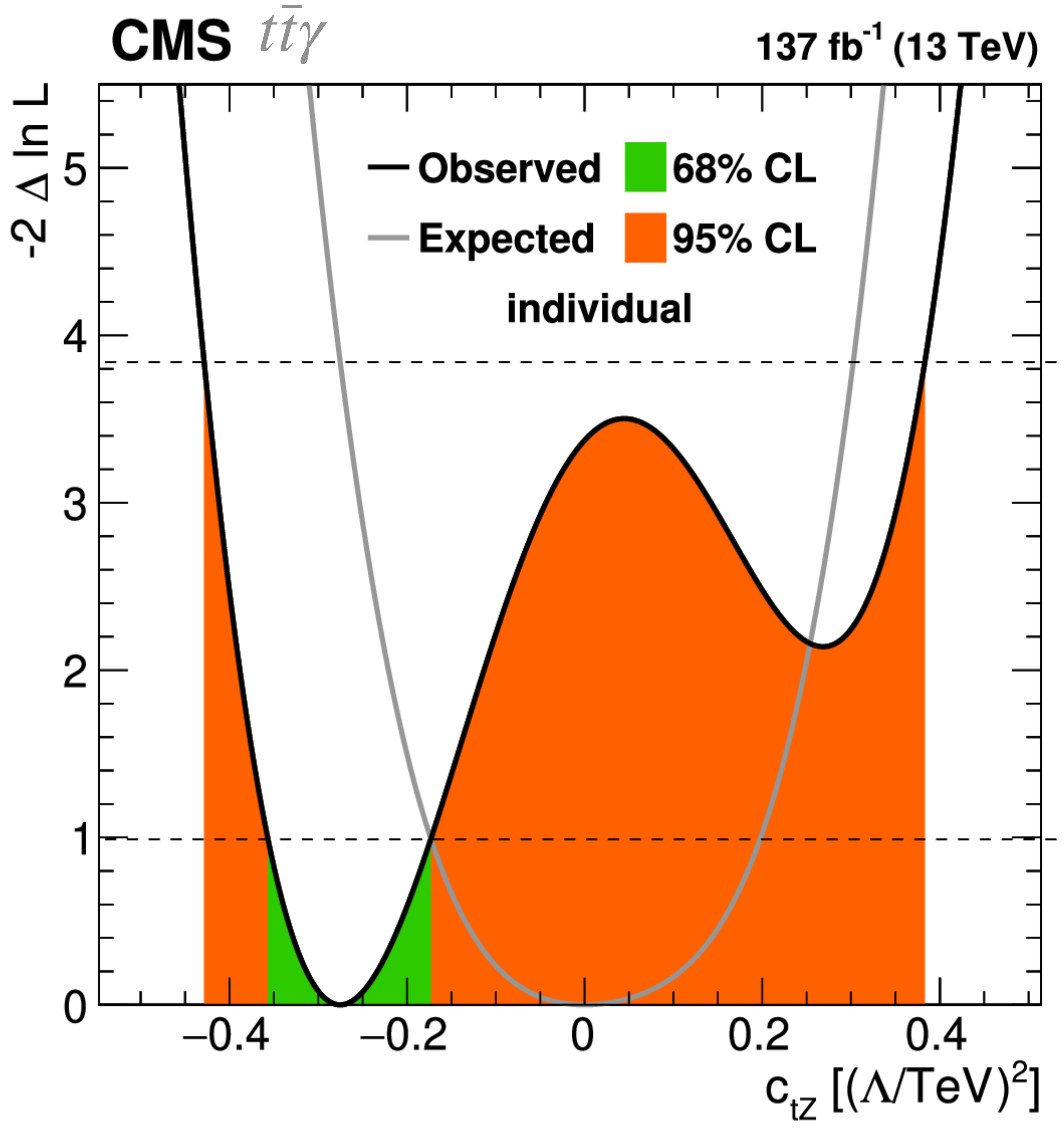
c_i : **Wilson coefficients (WC)** parameterize the strength of these operators

Λ : **Scale of new physics** - assumed to be 1 TeV

- From experimental data, one can set constraints on Wilson coefficients c_i, which can be matched to UV models.
  One can alternatively set limits on the energy scale Λ after fixing the WCs.

How we study SMEFT at LHC.

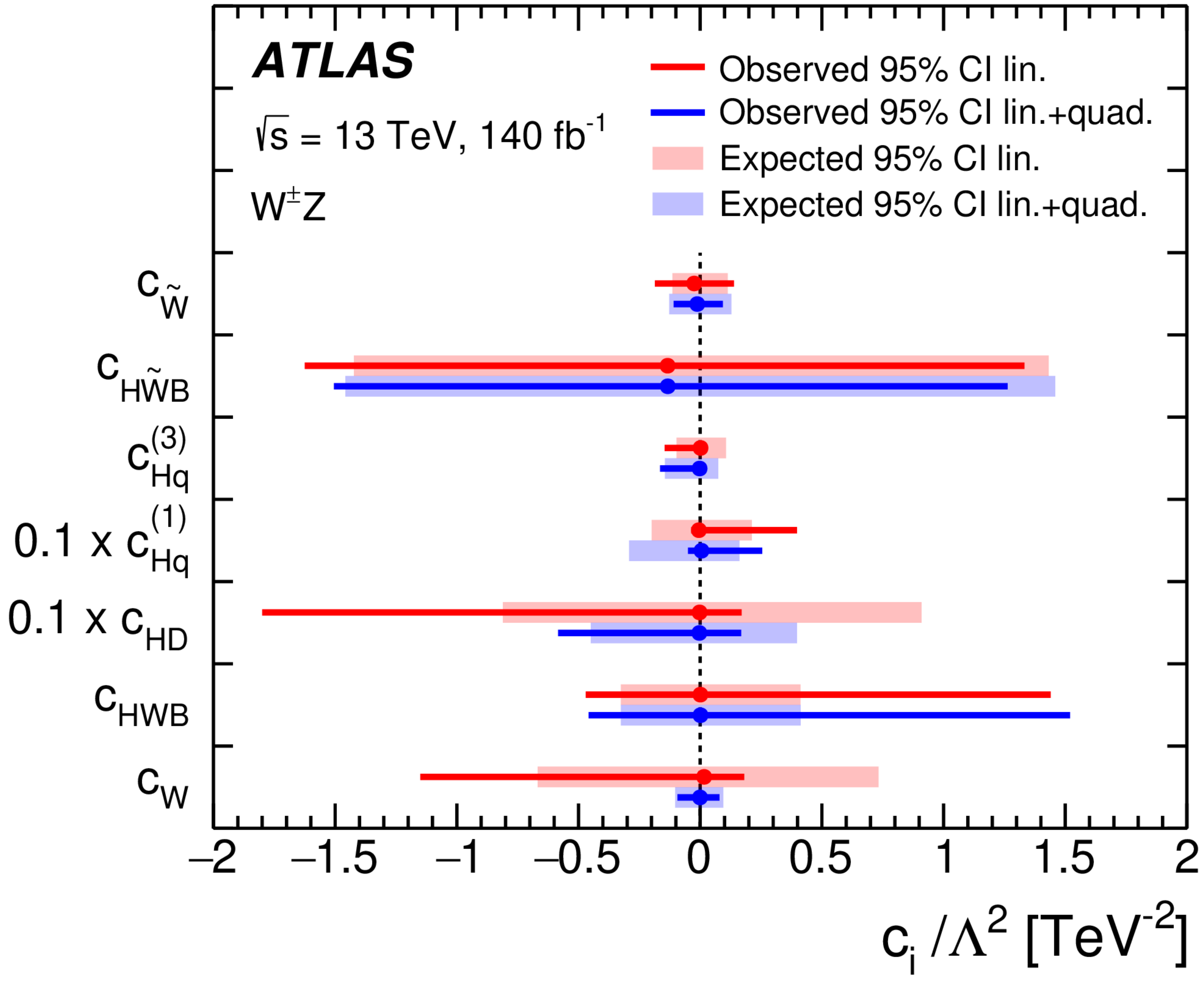
- Single physics process. One SMEFT operator at a time



[TOP-18-010]

How we study SMEFT at LHC.

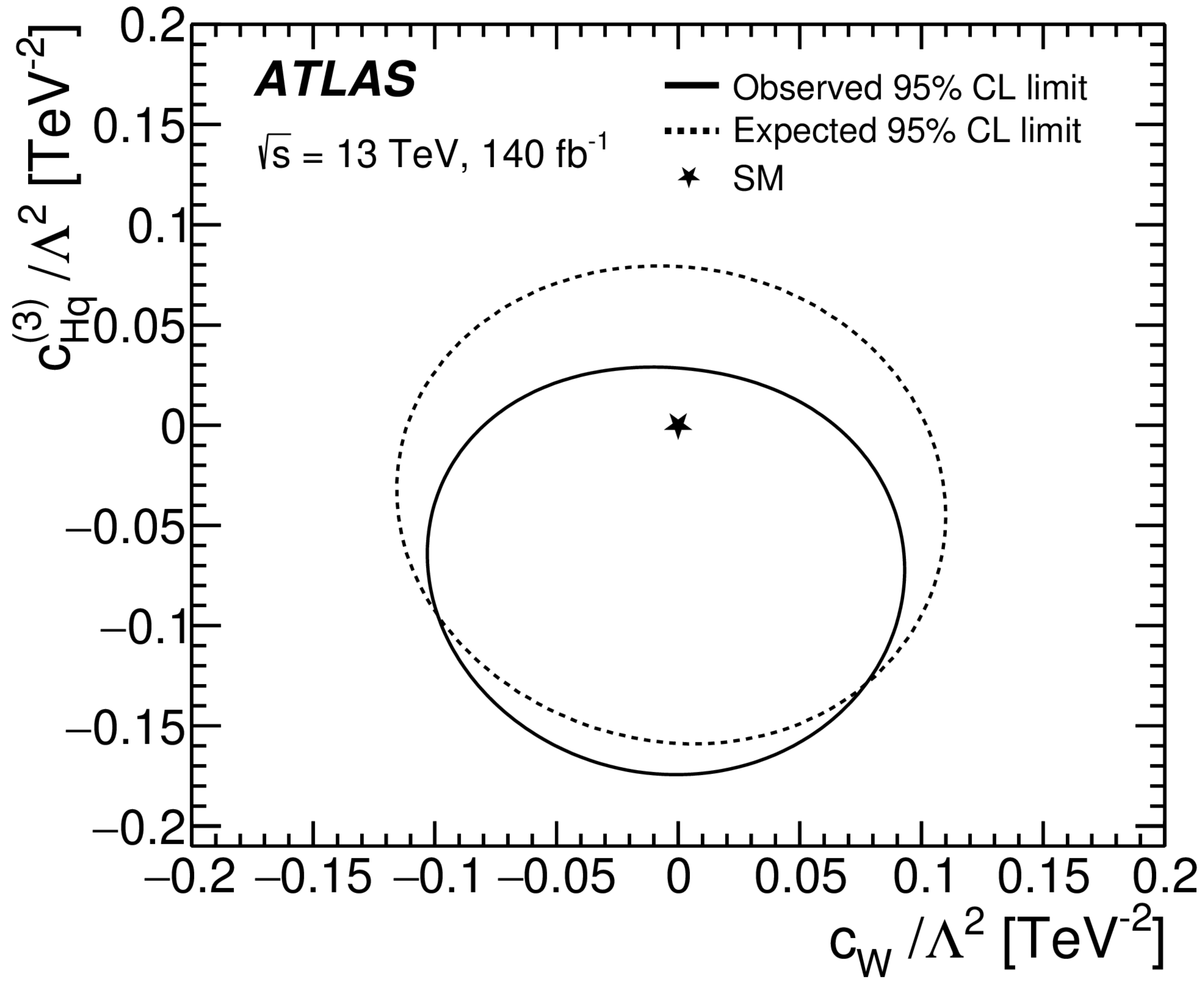
- Single physics process. One SMEFT operator at at time
- Single physics process. Several relevant SMEFT operators one at a time



[STDM-2019-26]

How we study SMEFT at LHC.

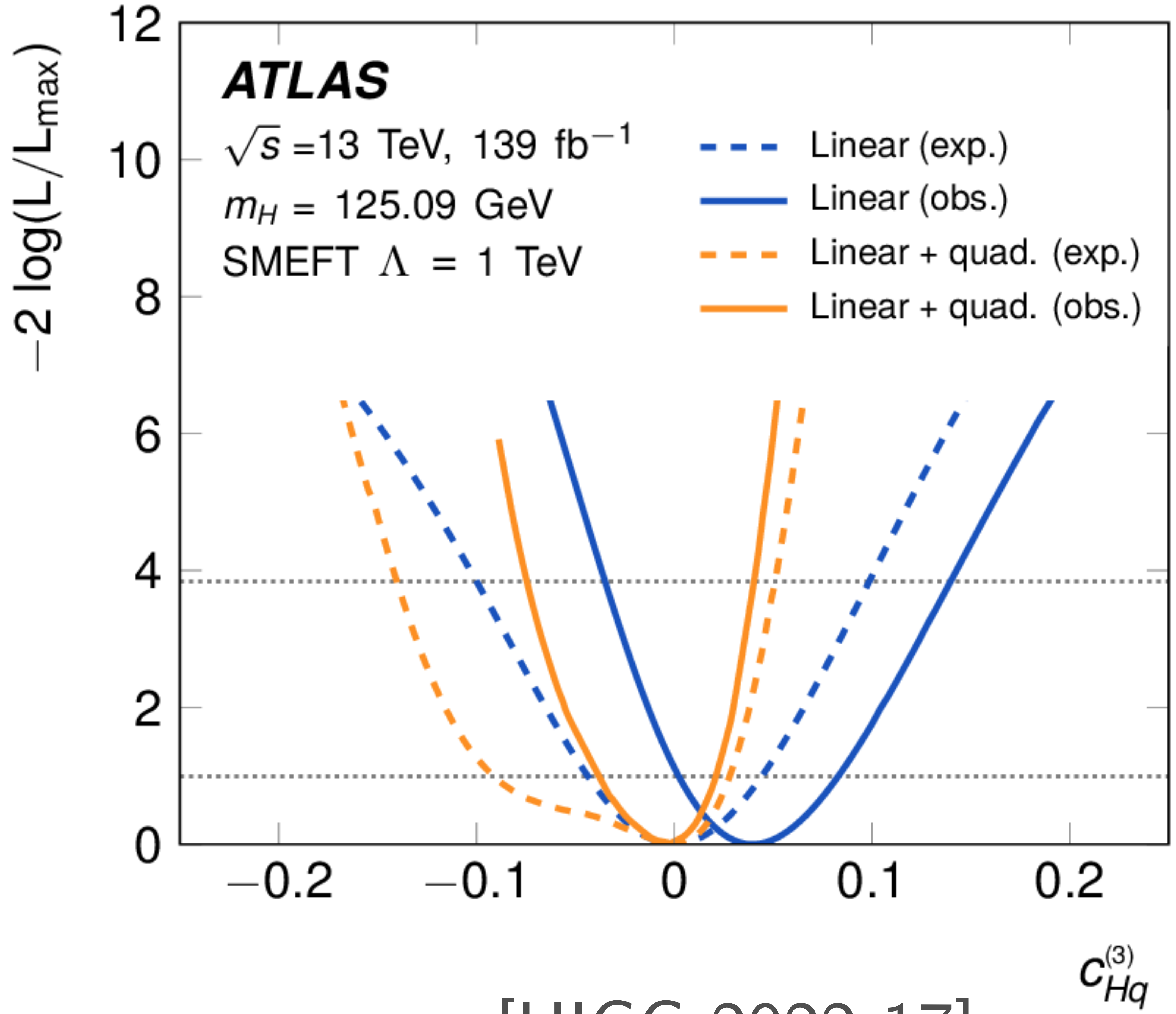
- Single physics process. One SMEFT operator at at time
- Single physics process. Several relevant SMEFT operators one at a time
- Single physics process. Several relevant SMEFT operators pairwise at a time



[STDM-2019-26]

How we study SMEFT at LHC.

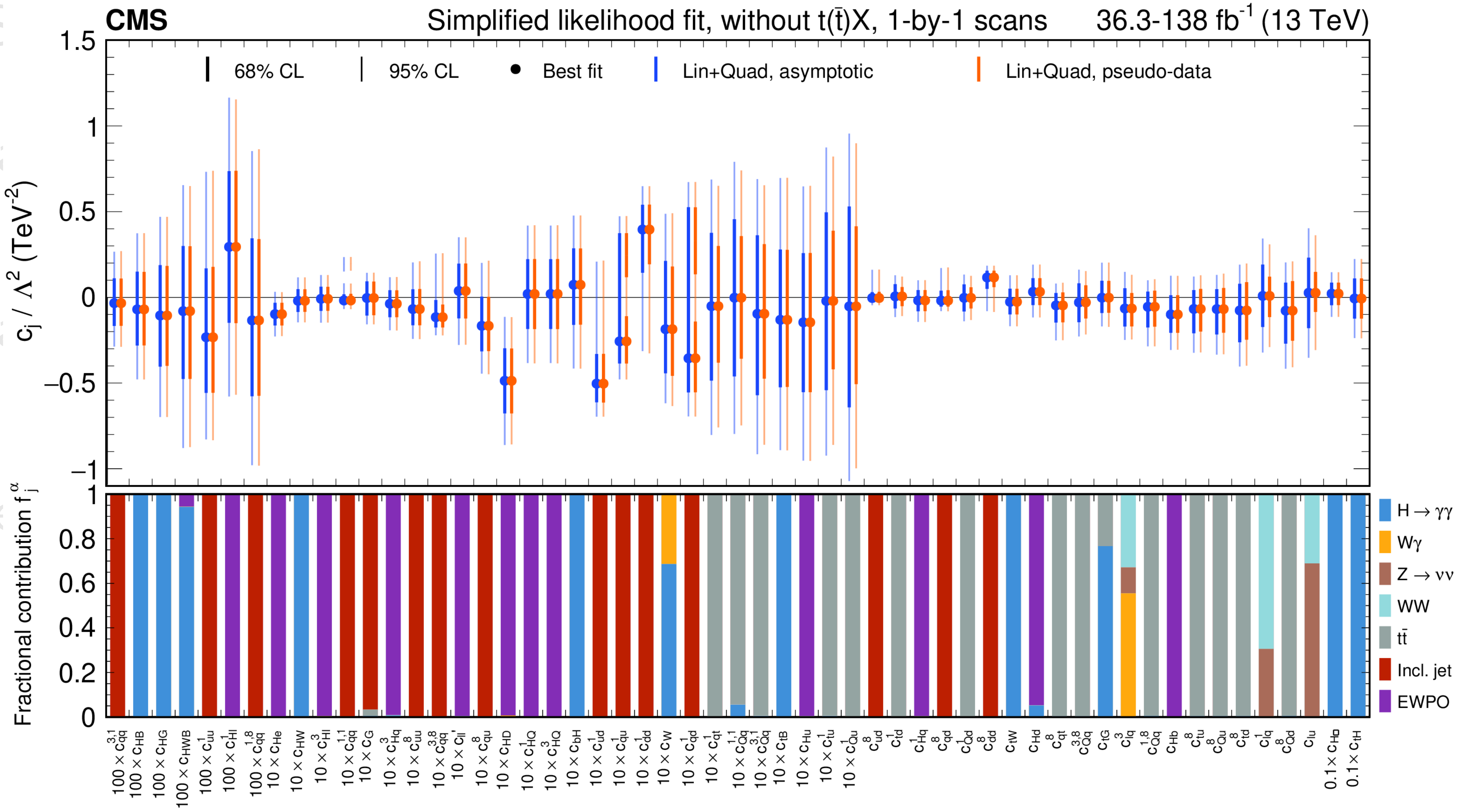
- Single physics process. One SMEFT operator at at time
- Single physics process. Several relevant SMEFT operators one at a time
- Single physics process. Several relevant SMEFT operators pairwise at a time
- Multiple physics process. One SMEFT operator



[HIGG-2022-17]

How we study SMEFT at LHC.

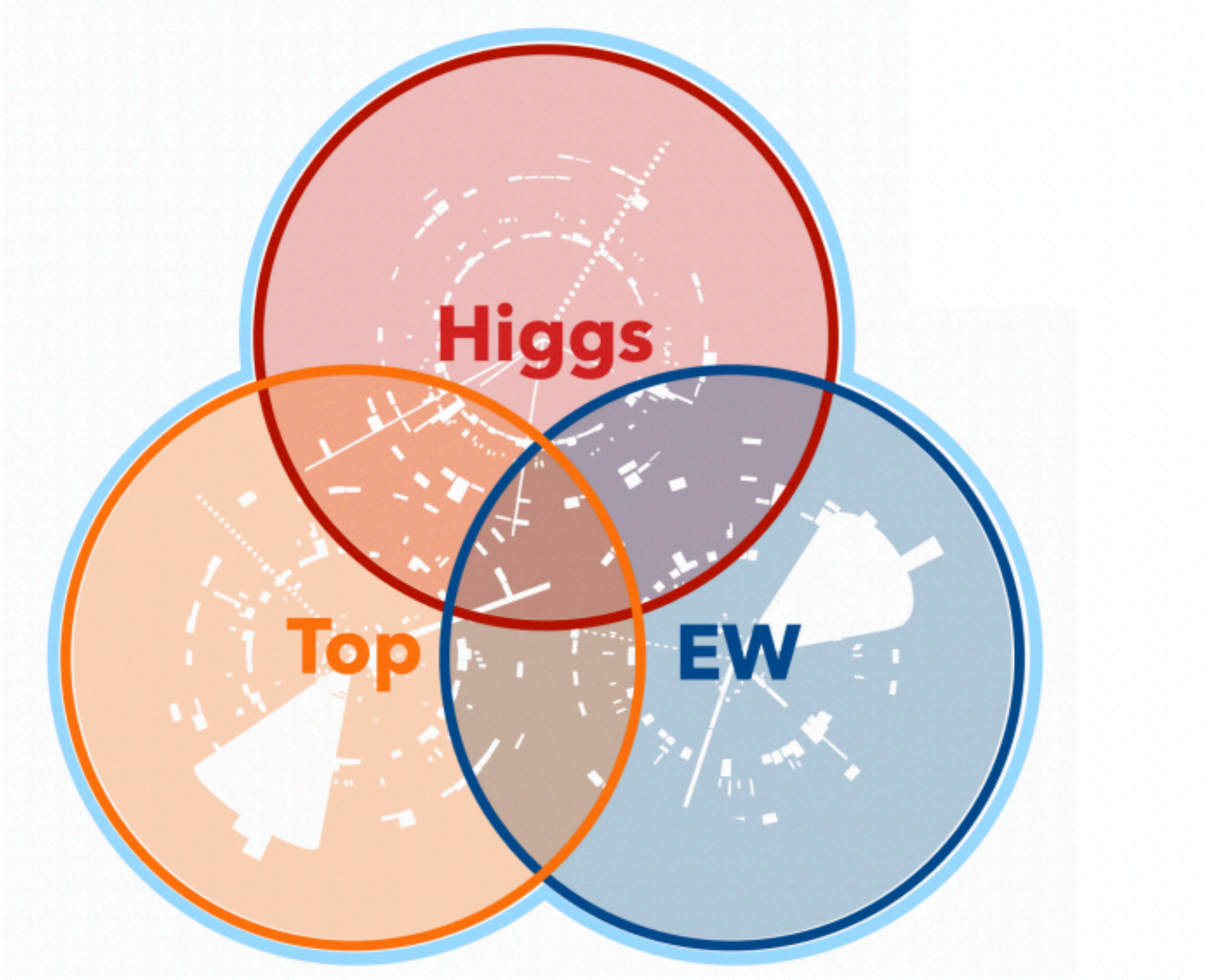
- Single physics process. One S
- Single physics process. Severa operators one at a time
- Single physics process. Severa operators pairwise at a time
- Multiple physics process. One
- Multiple physics process. Multiple SMEFT operators

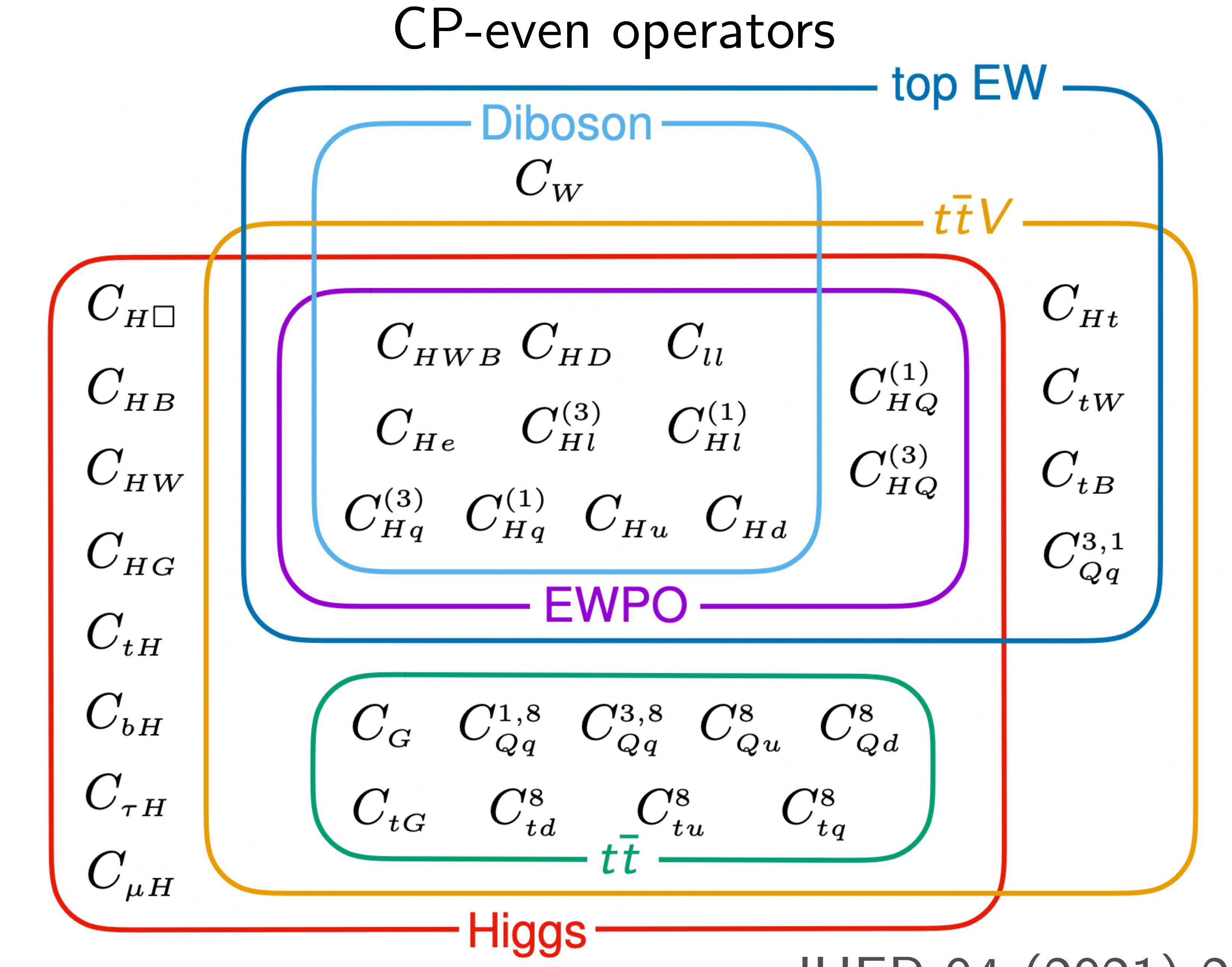


[SMP-24-003]

Getting Global 🌍

- Global Combinations give us a better understanding of the true Wilson coefficient value.
- Combine Higgs, Top, and Electroweak individual channel measurements
- Use data from multiple processes and experiments
- Constrain many SMEFT operators
- Complementarity across sectors improves sensitivity



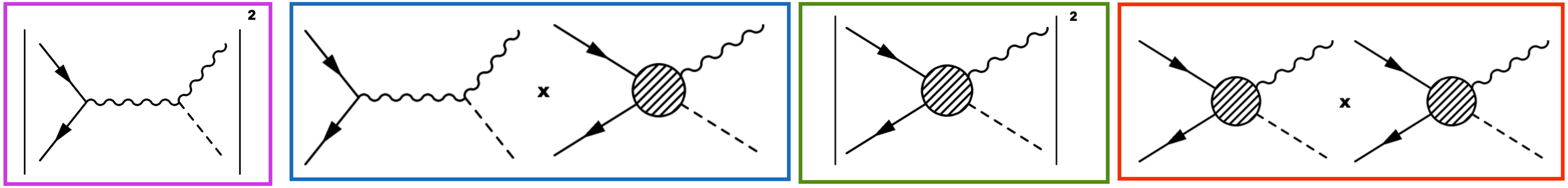


JHEP 04 (2021) 279

SMEFT Parameterisation

- A decomposition method is used where the EFT contribution is broken down:

$$\sigma \propto |M_{\text{SMEFT}}|^2$$
$$= |M_{\text{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\text{Re}\left(M_i^{(6)} M_{\text{SM}}^*\right) + \sum_i \frac{(c_i^{(6)})^2}{\Lambda^4} |M_i^{(6)}|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\text{Re}\left(M_i^{(6)} M_j^{(6)*}\right) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



interference of dim-6 operators with SM: **Linear term**

dim-6 operators squared: **Quadratic term**

interference of two different dim-6 operators: **Cross term**

- In this talk, we focus only on dimension-6 SMEFT operators.
- Nominally, the Warsaw basis offers a complete set of independent dim-6 operators
- An input parameter scheme of (m_W, m_Z, G_F) is used.

Analyses covered in this talk

Combinations in the TOP sector:

- **CMS Collaboration**, *Search for physics beyond the standard model in top quark production with additional leptons in the context of effective field theory* - **JHEP 12 (2023) 068**

Combinations in the HIGGS sector:

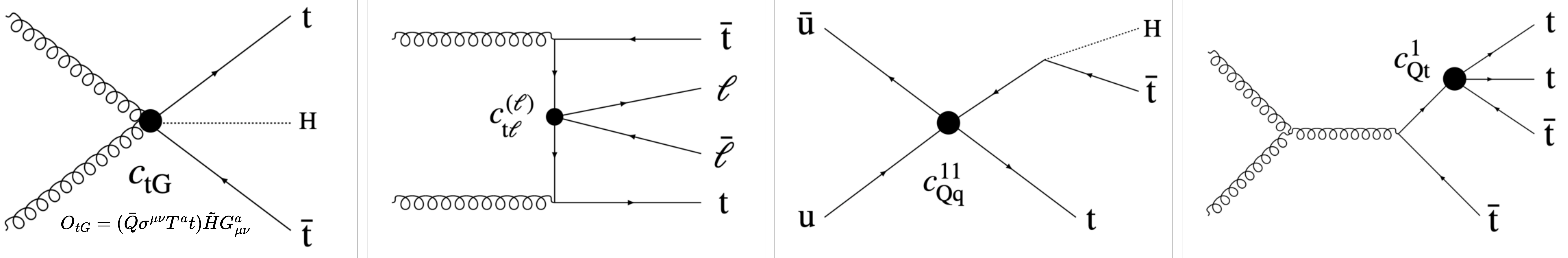
- **ATLAS Collaboration**, *Interpretations of the ATLAS measurements of Higgs boson production and decay rates and differential cross-sections in pp collisions at $\sqrt{s} = 13$ TeV* - **JHEP 11 (2024) 097**

Combinations across multiple sectors:

- **ATLAS Collaboration**, *Combined effective field theory interpretation of Higgs boson and weak boson production and decay with ATLAS data and electroweak precision observables* - **ATL-PHYS-PUB-2022-037**
- **CMS Collaboration**, *Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark, and multi-jet measurements* **arXiv:2504.02958**

CMS Collaboration, *Search for physics beyond the standard model in top quark production with additional leptons in the context of effective field theory* - **JHEP 12 (2023) 068**

- Detector-level EFT analysis of associated top quark production processes ($t\bar{t}H, t\bar{t}W, t\bar{t}Z, tZq, tHq, t\bar{t}t\bar{t}$)



- Each of these processes are irreducible backgrounds to each other
- Dataset is broken down into 43 unique event categories based on lepton multiplicity, jet multiplicity, b-tag multiplicity. Binning in a kinematical variable within each category

- Effects of dim-6 SMEFT operators are directly incorporated in the weights of simulated signal events
- Weight function for each simulated signal event β parameterized in the Wilson coefficients:

$$w^{\beta}(\vec{c},\vec{\theta}) = u_0^{\beta}(\vec{\theta}) + \sum_j \frac{c_j}{\Lambda^2} u_{1j}^{\beta}(\vec{\theta}) + \sum_{j,k} \frac{c_j c_k}{\Lambda^4} u_{2jk}^{\beta}(\vec{\theta})$$

- Predicted yield in bin i is calculated by summing the weight functions of each event that passes selection criteria of that bin: detector-level predictions are obtained
- Likelihood function is built:

$$L = \prod_{i=1}^{N_{bins}} \text{Poisson}\left(n_i \mid \nu_i(c,\theta)\right) \prod_{j=1}^{N_{NP}} p\left(\hat{\theta}_j \mid \theta_j\right)$$

Poisson$\left(n_i \mid \nu_i(c,\theta)\right)$: probability of observing n_i events in bin i

$p\left(\hat{\theta}_j \mid \theta_j\right)$: prior for nuisance parameter j evaluated at MLE $\hat{\theta}_j$

$\nu_i(c,\theta)$: expected event yield in bin i parametrized as quadratic functions of the Wilson coefficients

- Test statistic: $q(c_i) = -2 \ln \frac{L\left(c_i, \hat{\hat{\theta}}\right)}{L\left(\hat{c}_i, \hat{\theta}\right)}$

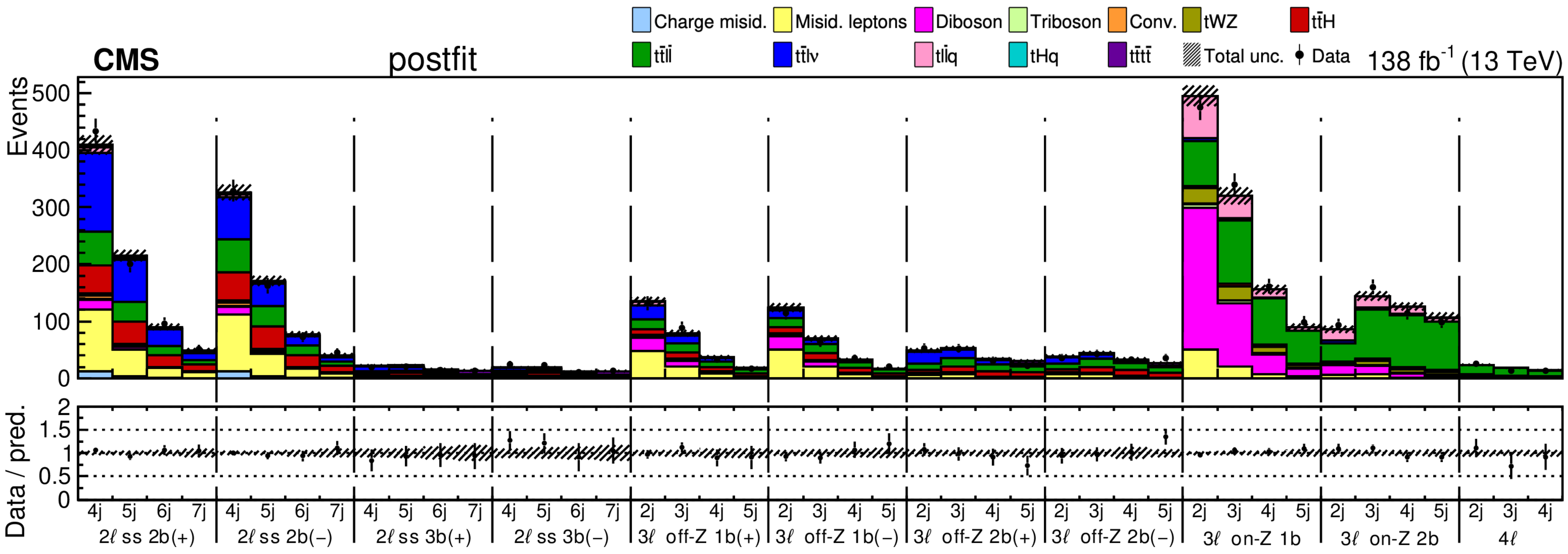
$\hat{\hat{\theta}}$: maximum likelihood estimate of the nuisance parameters for a fixed value of c_i

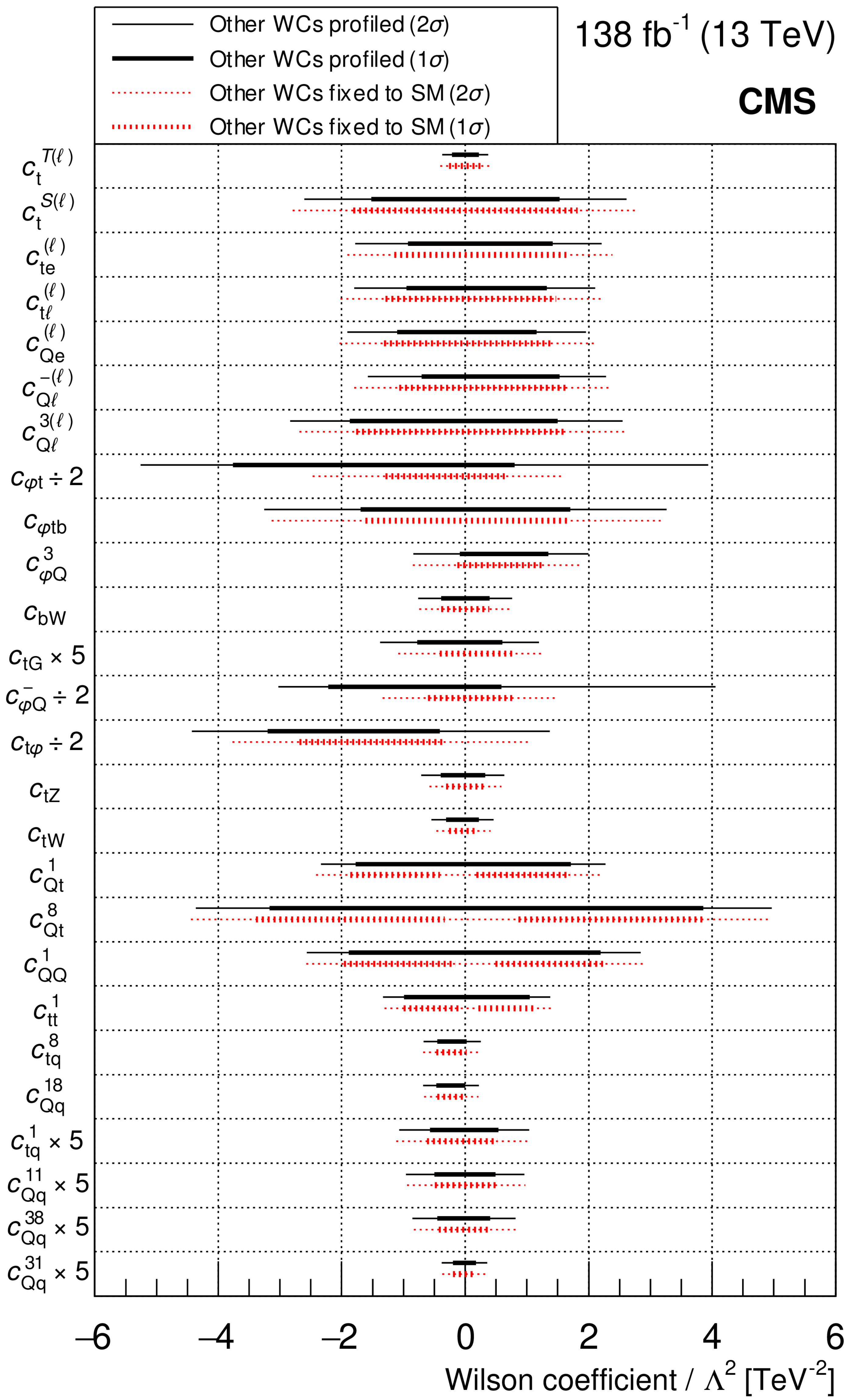
$\hat{c}_i, \hat{\theta}$ are unconditional maximum likelihood estimates of and the nuisance parameters, respectively

- Assuming Wilks' theorem is applicable, Confidence intervals are derived from the test statistic

$t\bar{t}X$ EFT combination: JHEP 12 (2023) 068

- Linear + Quadratic effects of 26 Wilson coefficients (dim-6) that affect top quarks studied and constrained in this analysis.
- Confidence intervals obtained from individual (red) and profiled fits (black) are similar → relatively small correlations between the effects of different operators





Higgs combination: JHEP 11 (2024) 097

ATLAS Collaboration, *Interpretations of the ATLAS measurements of Higgs boson production and decay rates and differential cross-sections in pp collisions at $\sqrt{s} = 13$ TeV* - **JHEP 11 (2024) 097**

- Simplified template cross sections (STXS) used for $H \to \gamma\gamma, ZZ, \tau\tau, WW, bb, Z\gamma, \mu\mu$
  STXS partitions the phase space into exclusive kinematic bins. Each bin is a physically measurable cross-section
- Further results obtained from differential $H \to \gamma\gamma, ZZ$ measurements
- Interpretation in SMEFT, 2HDM and MSSM models

Similar Higgs combination done by CMS collaboration: HIG-21-018

Higgs combination: JHEP 11 (2024) 097

- Number of cross-section measurements less than number of EFT parameters $\rightarrow$ not enough information to constrain all Wilson coefficients simultaneously $\rightarrow$ flat directions in the likelihood
- Principal component analysis (PCA) is a useful tool to identify linear combinations of WCs that can be constrained.
- Likelihood Hessian: encodes how well data constrain EFT parameters

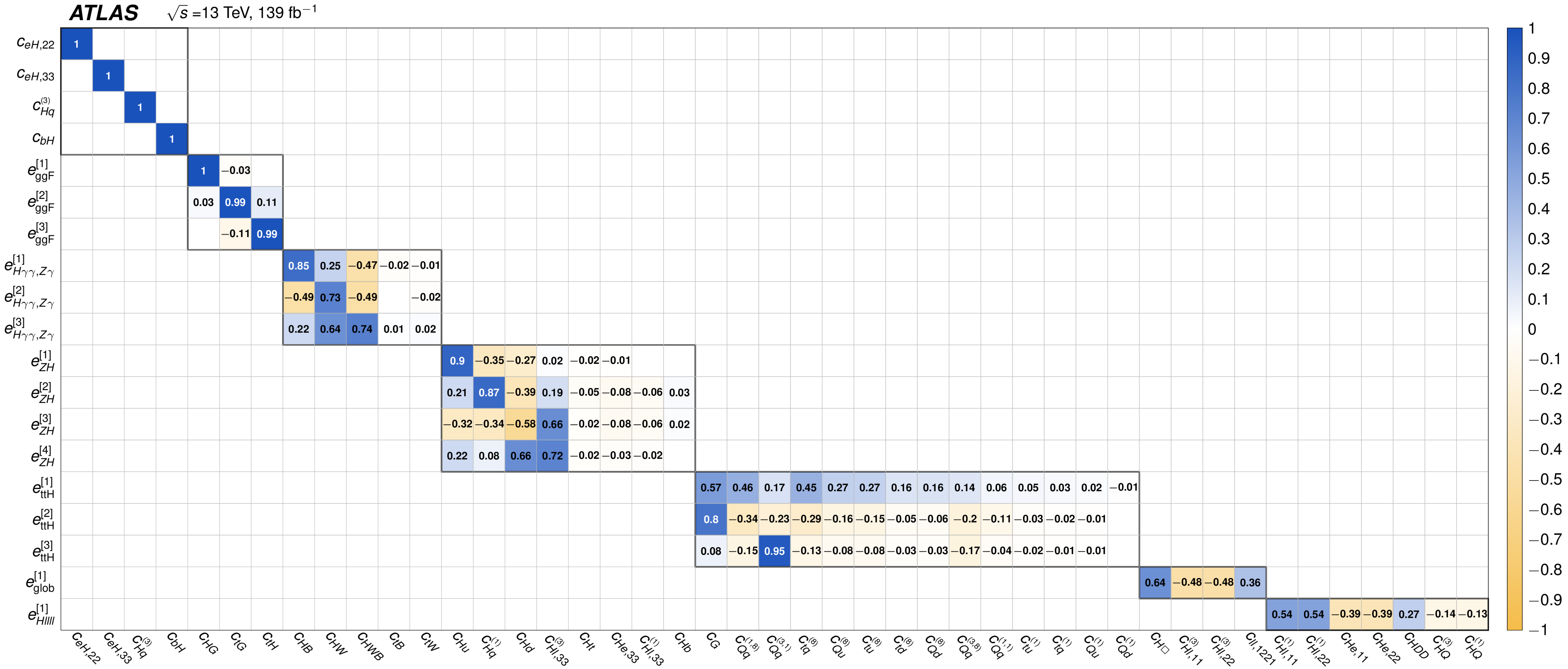
$$H \approx P^T C^{-1} P$$

C = covariance matrix of measurements,
P= SMEFT linear response matrix

- Eigendecomposition of H yields eigenvectors (linear combinations of WCs, EVi) and their corresponding sensitivity through the eigenvalues λ_i
- Large λ_i $\rightarrow$ well-constrained combinations
  Small λ_i $\rightarrow$ flat directions (unconstrained) and are fixed to SM value of 0.

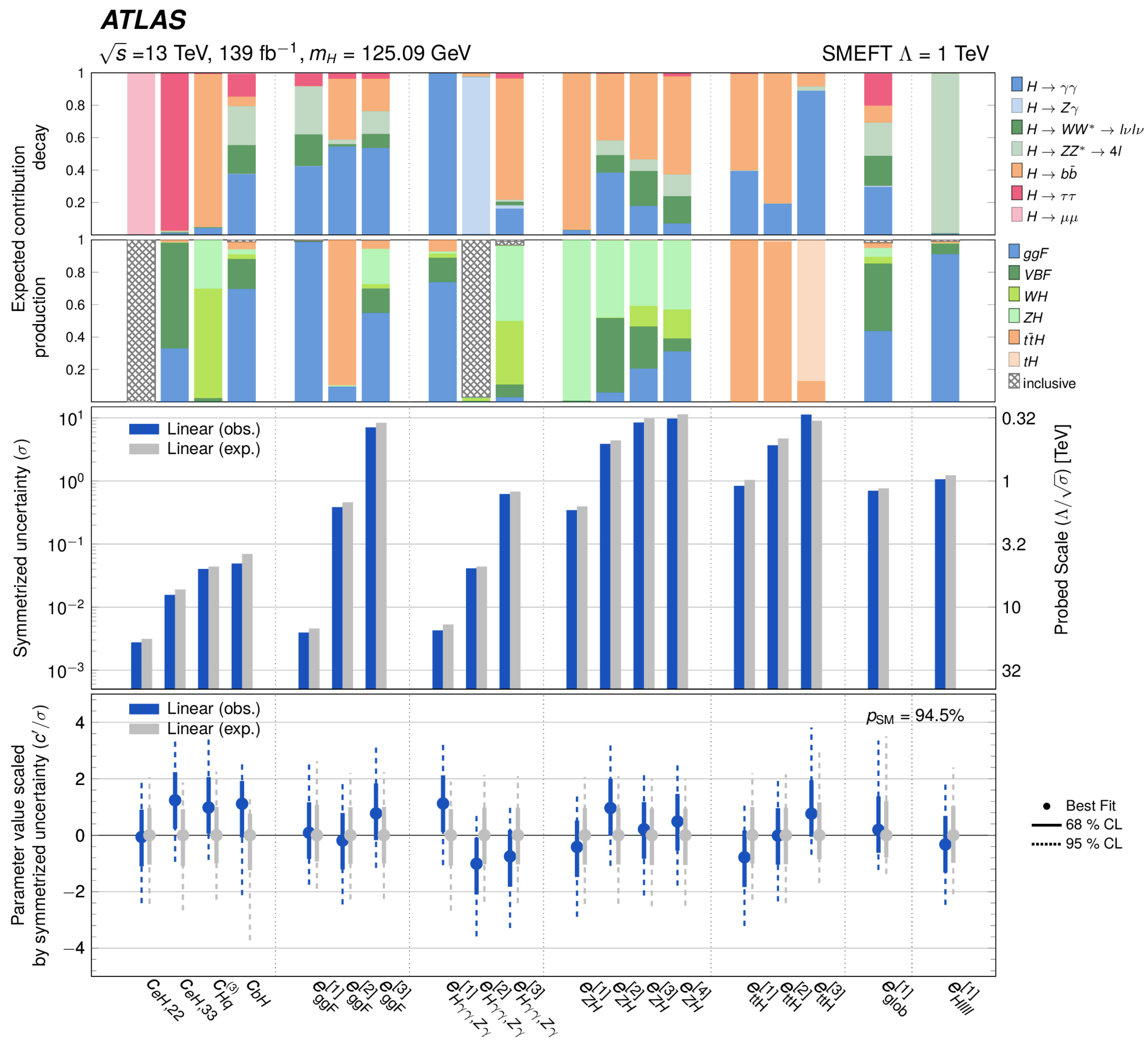
Higgs combination: JHEP 11 (2024) 097

- 46 dim-6 Wilson coefficients considered in total
  - ➡ 4 single Wilson coefficients
  - ➡ 15 linear combinations of 3-14 Wilson coefficients
    linear combinations obtained by PCA on 6 subgroups of Wilson coefficients



Higgs combination: JHEP 11 (2024) 097

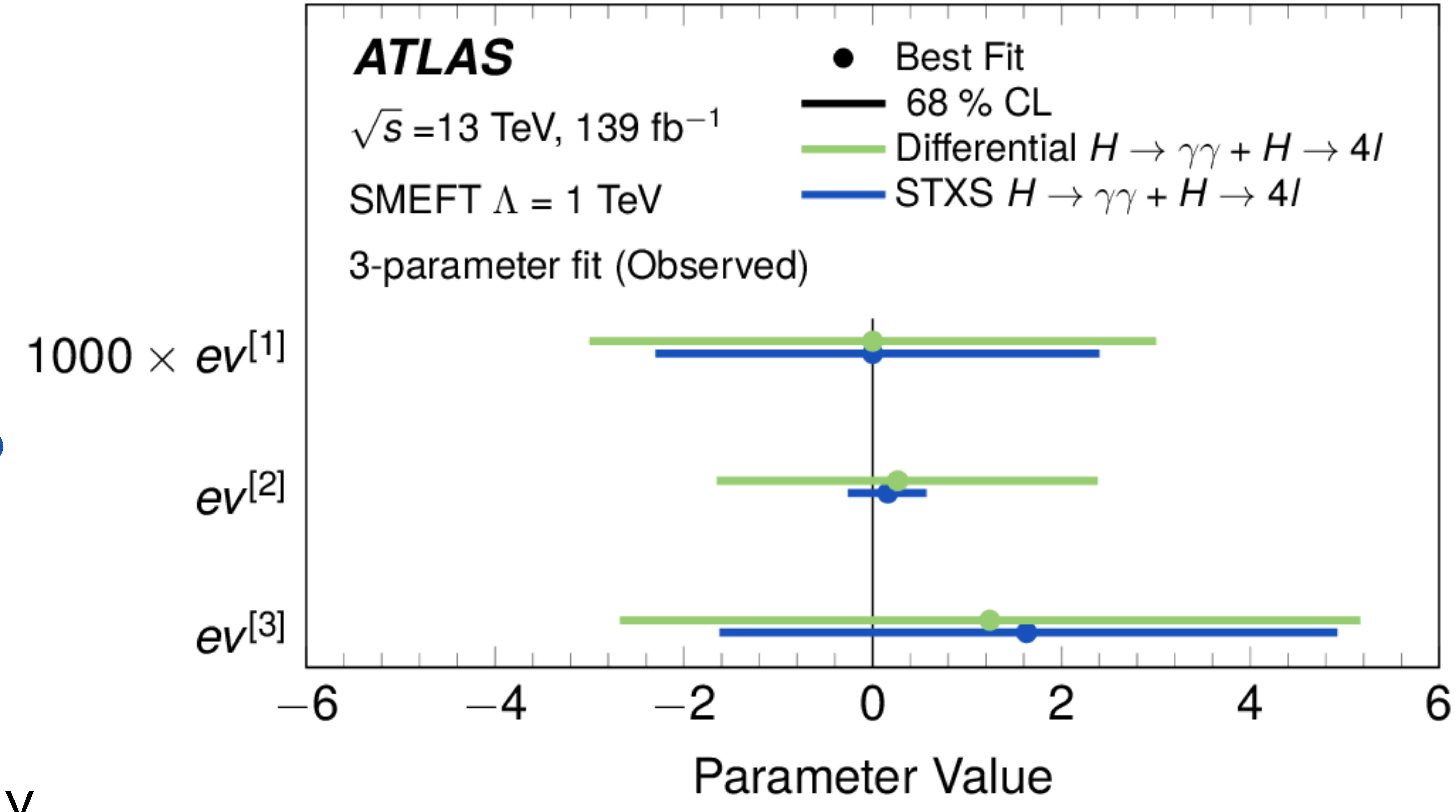
- Both linear only and linear+quad limits obtained. All consistent with SM.



- Differential cross-section results from $H \to \gamma\gamma, ZZ$ provides separate set of results for (linear combinations) Wilson coefficients:

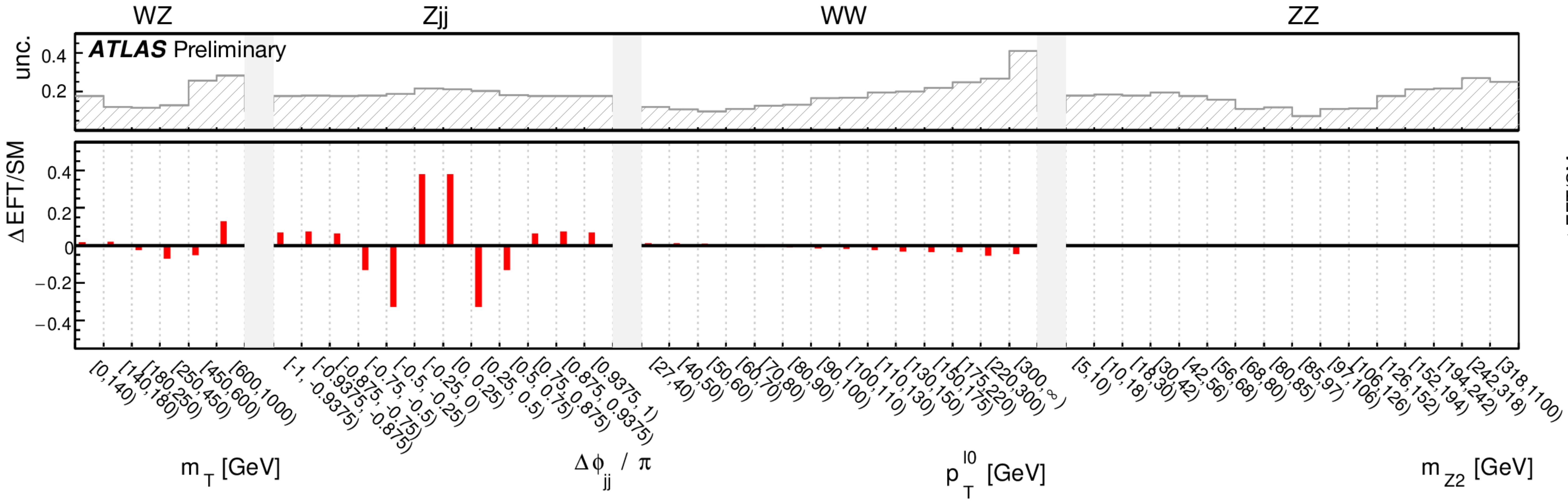
$$ev^{[1]} = 0.999c_{HG} - 0.035c_{tG} - 0.003c_{tH}$$
$$ev^{[2]} = 0.035c_{HG} + 0.978c_{tG} + 0.205c_{tH}$$
$$ev^{[3]} = -0.005c_{HG} - 0.205c_{tG} + 0.979c_{tH}$$

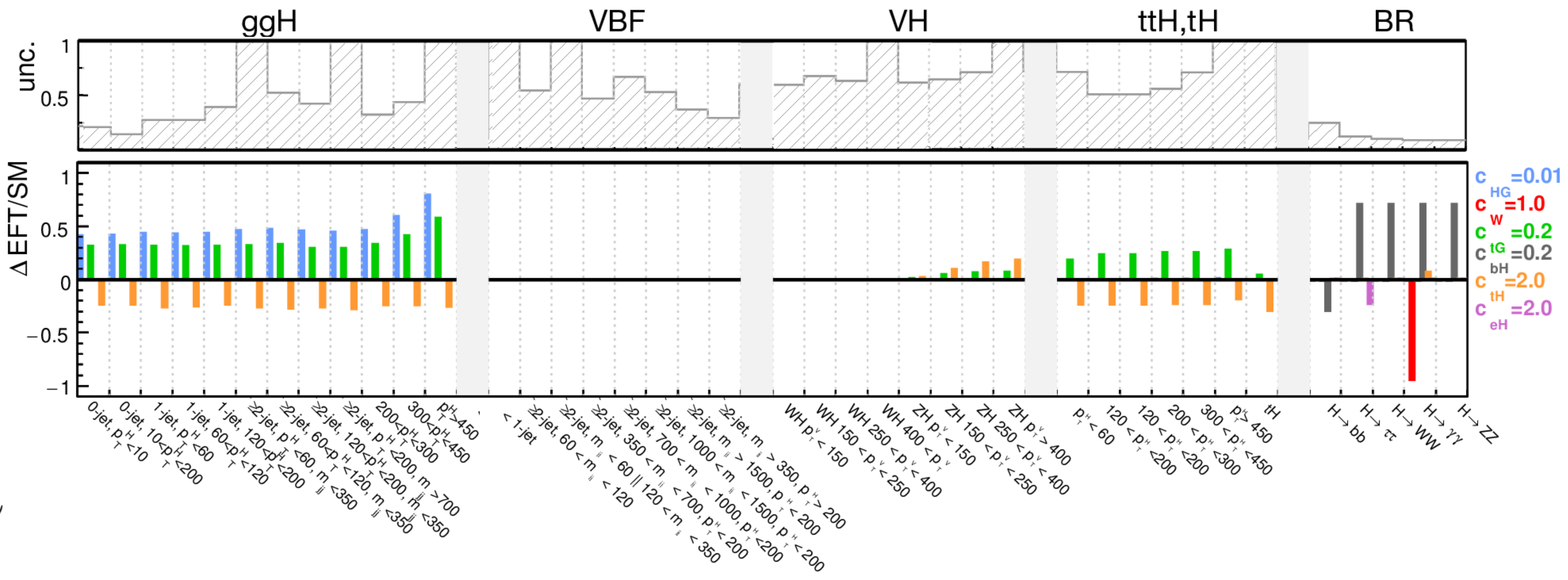
- Comparison of constraints on 3 linear combinations using diff. cross sections (green) or STXS (blue, with same two decay channels):
  STXS measurements provide stronger constraints as they separate Higgs production modes, which are differently affected by new physics operators.



ATLAS Collaboration, *Combined effective field theory interpretation of Higgs boson and weak boson production and decay with ATLAS data and electroweak precision observables* - **ATL-PHYS-PUB-2022-037**

- Combination of:
  - STXS Higgs $\rightarrow \gamma\gamma, ZZ, WW, \tau\tau, bb$ decay channels)
  - electroweak measurements from ATLAS (WW, WZ, ZZ, Z+jj)
  - electroweak precision observables measured at LEP & SLC
- A number of SMEFT operators can be constrained by different sectors
- Relative impact of linear SMEFT terms for each bin in each analysis studied



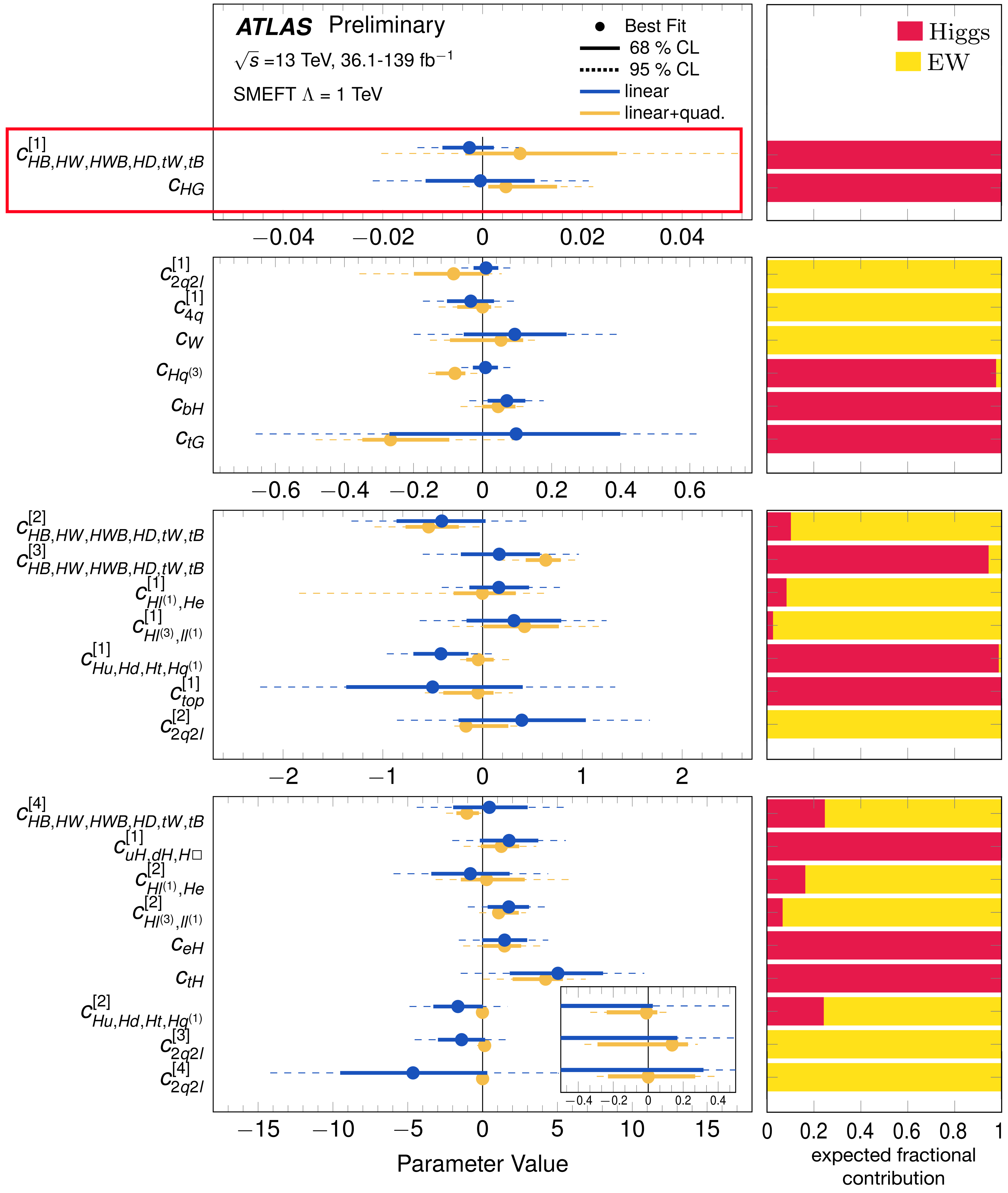


- Combinations of different sectors can provide complimentary information on Wilson coefficients.
- PCA on subgroups of Wilson coefficients: constraints on 6 single Wilson coefficients and 22 linear combinations of Wilson coefficients.

Higgs + EW (+ EWPO) combination: ATL-PHYS-PUB-2022-037

Higgs + EW (ATLAS only)

Most stringent constraints



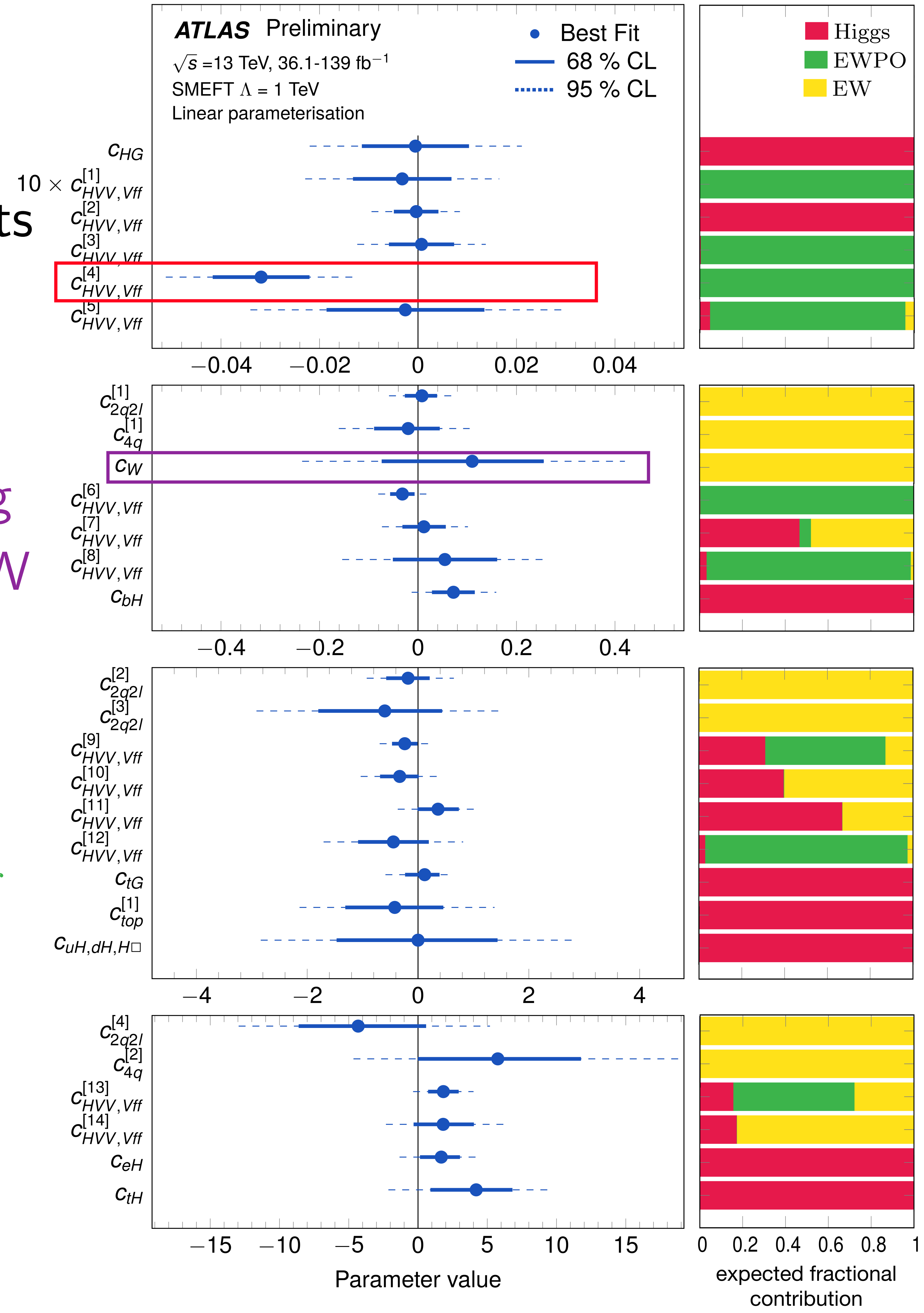
Large quadratic contributions; questions about neglected higher order corrections

Higgs + EW + EWPO (ATLAS + LEP/SLD)

Lack of quadratic parametrization of LEP data means no constraints can be derived in the linear+quadratic model

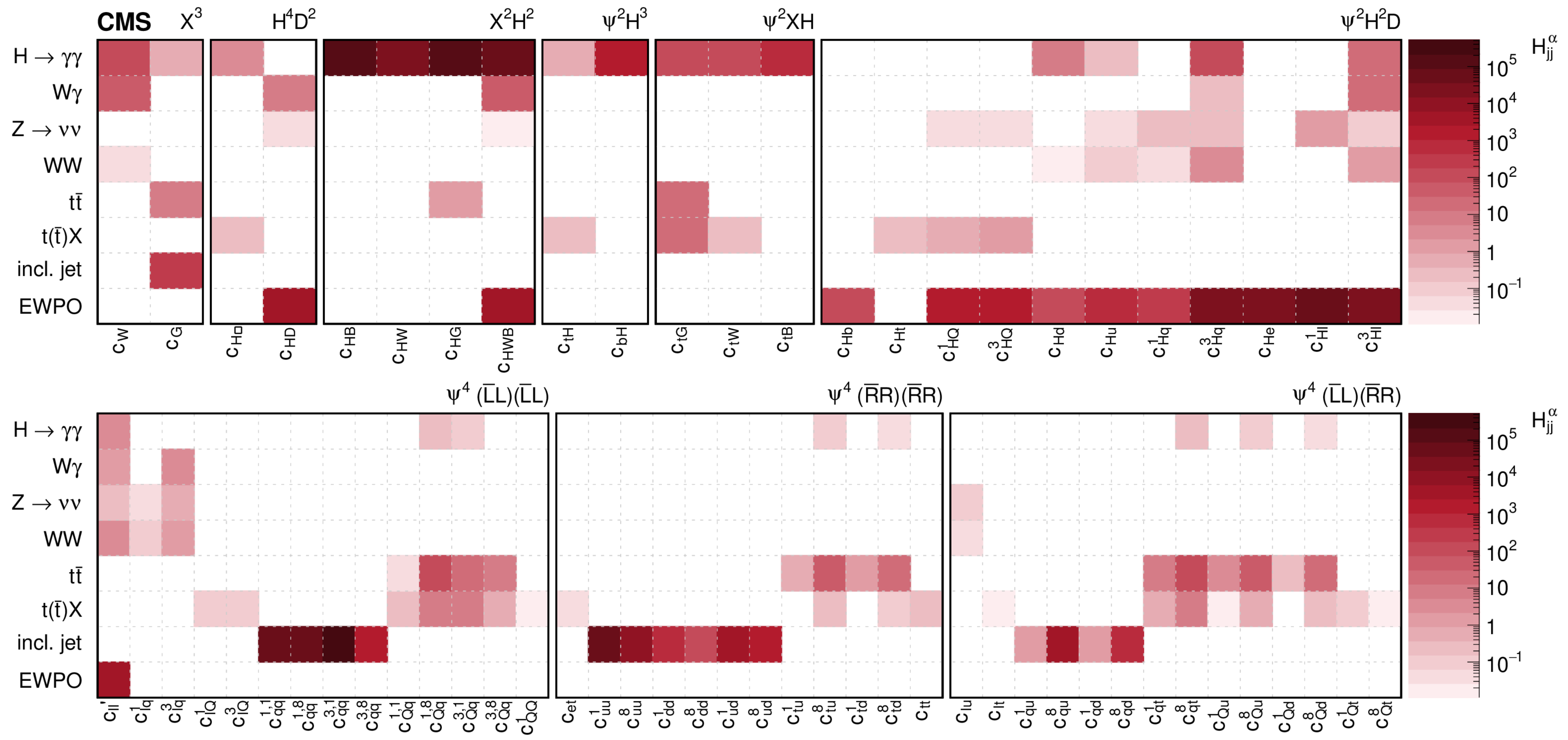
Weak boson self coupling c_W constrained by the EW sector

Only deviation in $c_{HVV,vff}^{[4]}$ whose excess is driven by known discrepancy between $A_{FB}^{0,c}$, $A_{FB}^{0,b}$ data and the SM expectation



CMS Collaboration, *Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark, and multijet measurements* - **arXiv:2504.02958**

- Combination of:
  - STXS $H \to \gamma\gamma$
  - electroweak measurements $WW, W\gamma, Z \to \nu\nu$
  - Top quark measurements $t\bar{t}, t(\bar{t})X$
  - Inclusive jet measurements
  - electroweak precision observables measured at LEP & SLC
- Event selections optimized for sensitivity to 64 dim-6 SMEFT operators, with negligible category overlap and backgrounds controlled from data.



- Diagonal entries H^{α}_{jj} of the Hessian Matrix show which input channels are most sensitive to each operator: higher values $\to$ stronger sensitivity.

METHODOLOGY

Likelihood Model:

- Combination of:

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

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

Used for $H \to \gamma\gamma, W\gamma, WW, Z \to \nu\nu, t(\bar{t})X$ measurements.

In $t(\bar{t})X$, signal yield is $\sum_j s_i^j(\vec{\nu}, \vec{c})$

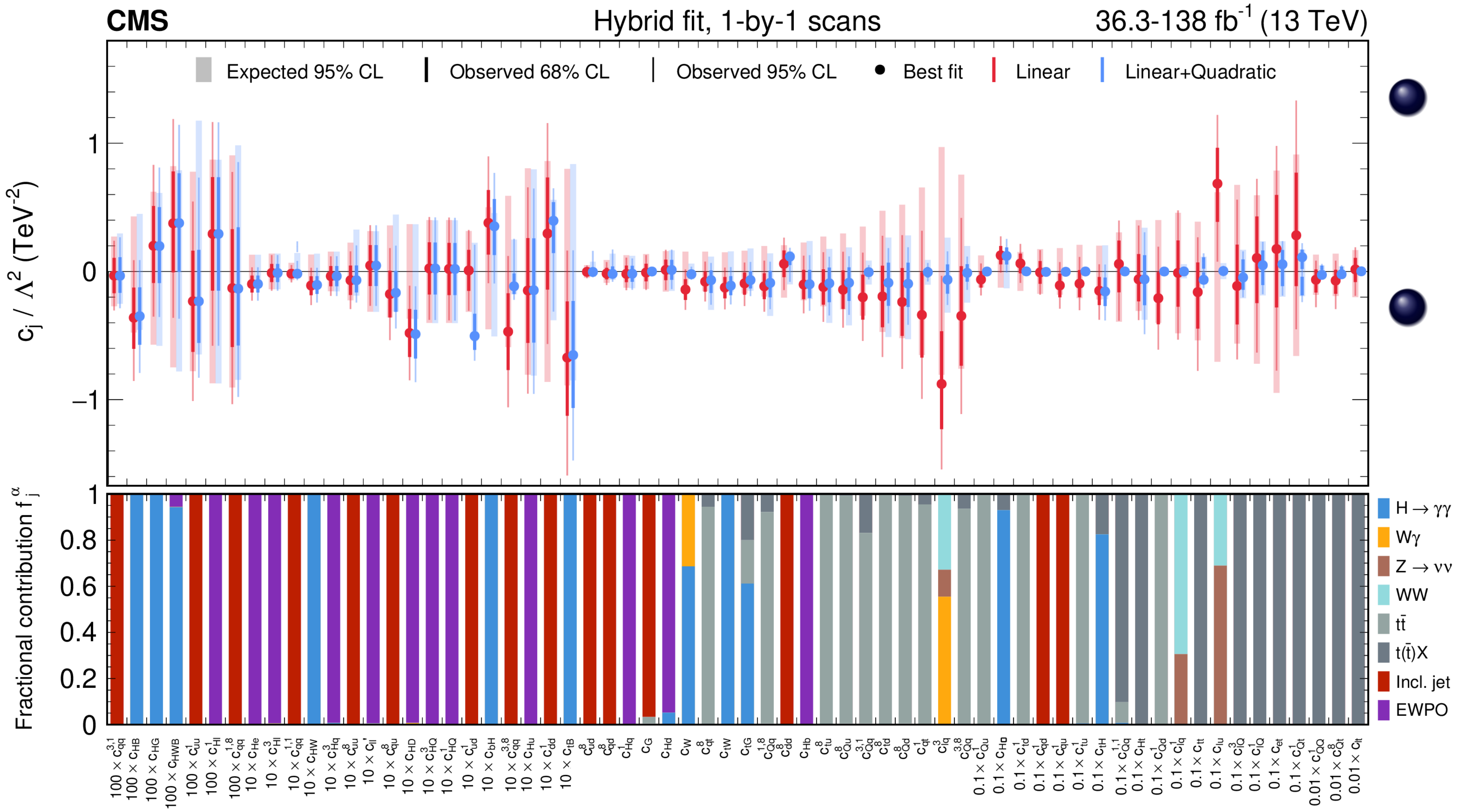
$$\mathscr{L}^{\text{simpl}}(\vec{c}) = \frac{\exp\left[-\frac{1}{2}\left(\vec{\mu}(\vec{c}) - \hat{\vec{\mu}}\right)^T V^{-1} \left(\vec{\mu}(\vec{c}) - \hat{\vec{\mu}}\right)\right]}{\sqrt{(2\pi)^m \det(V)}}$$

Used for $t\bar{t}$, inclusive jet and EWPO measurements

Covariance matrix:

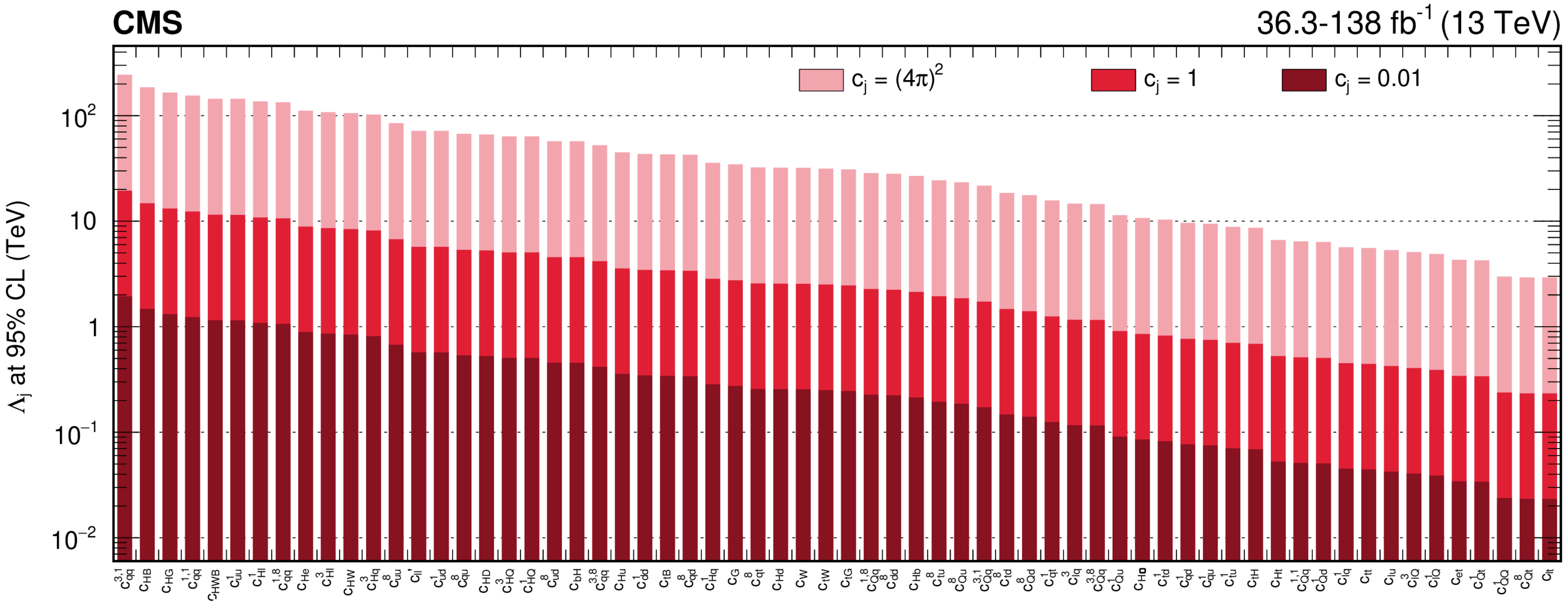
includes both theoretical and experimental uncertainties

Higgs + EW + Top + QCD + EWPO EFT combination: 2504.02958



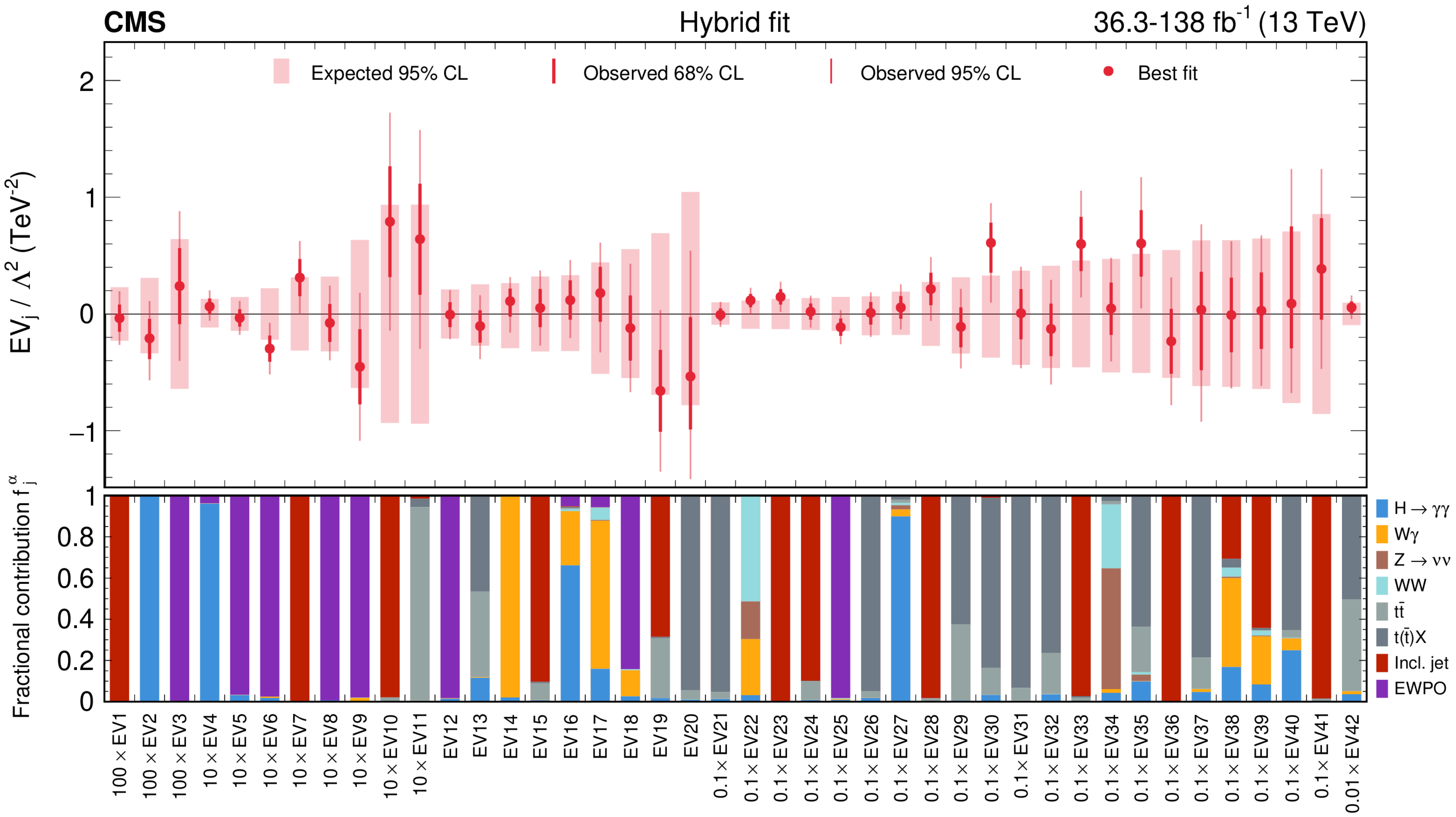
- Constraints on 64 individual Wilson coefficients (each obtained by fixing all others to 0)
- 95% confidence intervals for $\frac{c_i}{\Lambda^2}$ range from around ±20 to ±0.003

- 95% CL lower limits on the scale of new physics, Λ, can be obtained by setting c_j to specific values (of 0.01, 1, $(4\pi)^2$)



Higgs + EW + Top + QCD + EWPO EFT combination: 2504.02958

- Using PCA, constraints on 42 linear combinations of Wilson coefficients are obtained (each varied simultaneously)
- Many POIs receive significant contributions from multiple channels
  - ➡ 8 linear combinations constrained by inclusive jet
  - ➡ 8 by Higgs and electroweak
  - ➡ 7 by EWPO
  - ➡ 10 by top quark measurements
  - ➡ 9 by a mixture



- The SM compatibility p-value is 1.7%, driven mainly by the inclusive jet measurement (very sensitive to PDF), and increases to 26% when this input is excluded.

Summary and towards further Globalization

- SMEFT offers an effective framework for indirect searches at the current LHC energy scale
- To get the most general EFT results, it is a growing need to combine measurements of multiple observables
- Several combination analyses in ATLAS and CMS show no observed deviations from the SM expectation:

  ➡ Exception in known case of forward-backward discrepancy and multi jet PDF sensitivity

Next plans

- Efforts are on-going to pave the road for future ATLAS + CMS combinations!
- Several (rare) channels/data samples not yet included in current EFT combinations
- Background processes assumed to have no EFT effects. Need proper parameterisation
- Dimension-8 predictions need to be included in predictions from a theoretical perspective

Thank you!

감사합니다!

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YOUR COMMENTS ARE MOST APPRECIATED