EFT Interpretations using the Higgs boson in the ATLAS experiment

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On behalf of the ATLAS collaboration

Higgs Hunting 2024

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Introduction

- Interpretation of measurements of Higgs boson production and decay rates and differential cross sections with Run 2 data, arXiv:2402.05742.
  - STXS-0*: only distinguishes inclusive production processes.
  - STXS-1.2: partition production processes in kinematic regions.

Decay channel	Binning	SMEFT	Production mode	L [fb^{-1}]
$H \to \gamma\gamma$	**STXS-1.2**	√	***ggF, VBF, VH, ttH, tH***	**139**
	Differential p_T^H	√		
$H \to ZZ \to 4l$	**STXS-1.2**	√	***ZZ→4l: ggF, VBF, VH, ttH+tH***	**139**
	Differential p_T^H	√		
$H \to \tau\tau$	**STXS-1.2**	√	***ggF, VBF, VH, ttH, tH***	**139**
	differential	√		**139**
$H \to WW$	**STXS-1.2**	√	***ggF, VBF***	**139**
$H \to bb$	**STXS-1.2**	√	***VH, ttH+tH, VBF,* inclusive (boosted)**	**139, 126 (VBF)**
$H \to Z\gamma$	**STXS-0***	√	**inclusive**	**139**
$H \to \mu\mu$	**STXS-0***	√	***ggF+ttH+tH, VBF+VH***	**139**

* $H \to \tau\tau$ differential results from another stand-alone publication **arXiv:2407.16320.**

Interpretation based on SMEFT

- SMEFT Lagrangian: $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots$

operators with $d = 6$

operators with $d = 8$

  - c_i – Wilson coefficients
  - Only $d = 6$ operators are considered, impact of $d = 8$ operators might be non-negligible.

- SMEFT cross section relative to SM expectation:

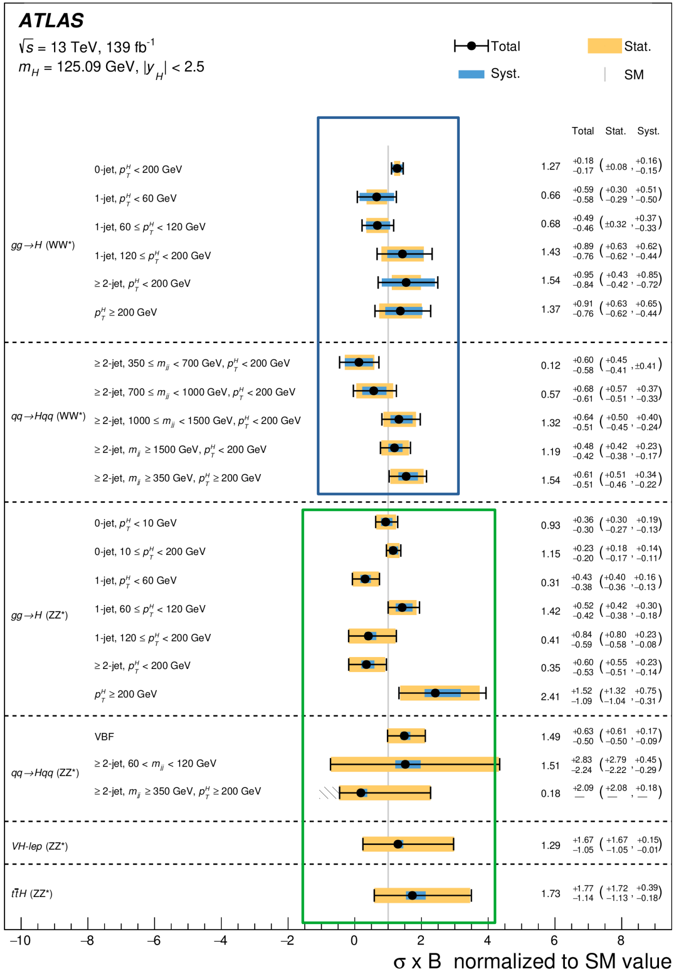
$$\frac{\sigma_{\text{EFT}}}{\sigma_{\text{SM}}} = 1 + \sum_{i} A_i c_i + \sum_{ij} B_{ij} c_i c_j$$

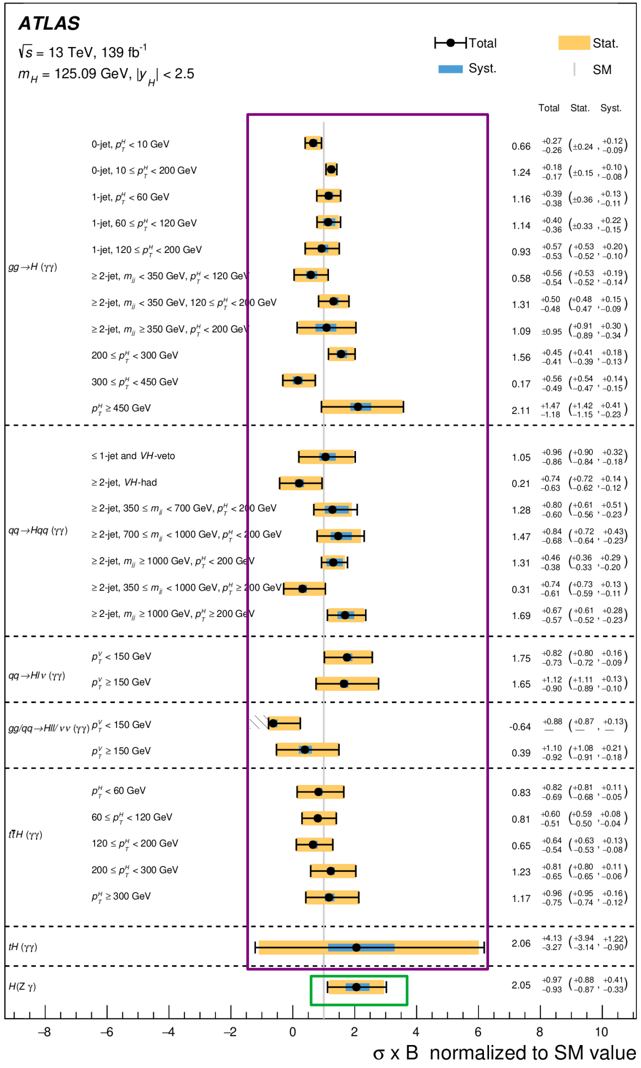
Arise from interference between the SM and the BSM processes, suppressed by Λ^{-2}

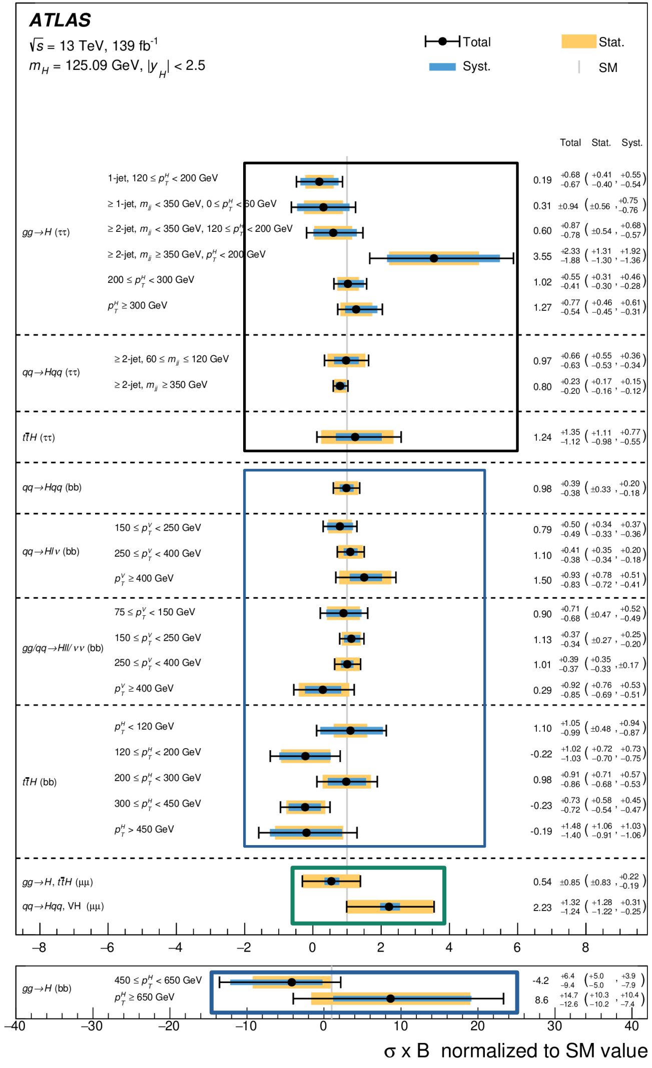
Arise from BSM processes, suppressed by Λ^{-4}

  - A_i, B_{ij}: calculated using MC.
  - STXS and differential measurements are reparameterised in terms of the impact of EFT operators.
  - Constraints measured on the corresponding Wilson coefficients (Warsaw basis).

STXS measurement







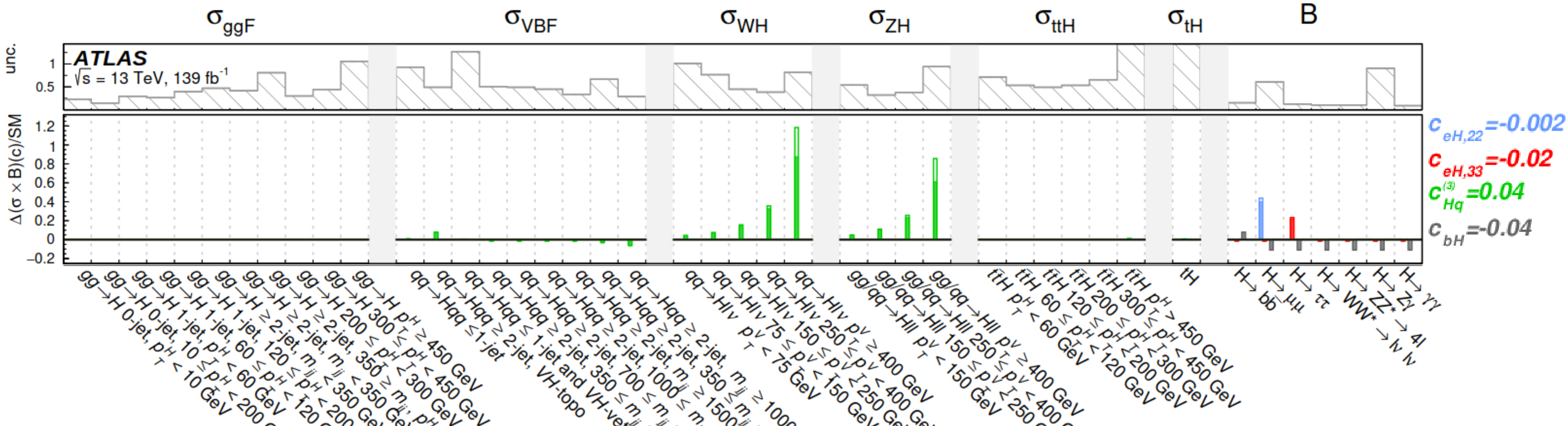
$H \to WW^*$, $H \to ZZ^*$

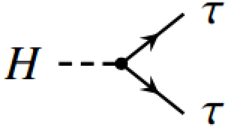
$H \to \gamma\gamma$, $H \to Z\gamma$

$H \to \tau\tau$, $H \to bb$, $H \to \mu\mu$

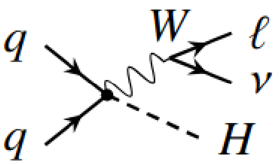
Expected impact of SMEFT operators

- Wilson coefficients $c_{eH,22}$, $c_{eH,33}$, c_{bH}: Yukawa coupling modifiers of $H \rightarrow \mu\mu$, $H \rightarrow \tau\tau$, $H \rightarrow bb$, c_{bH} also affects the total Higgs boson width.
- Coefficient $c_{Hq}^{(3)}$: mainly affects WH and ZH production, impact increase as a function of p_T^V.





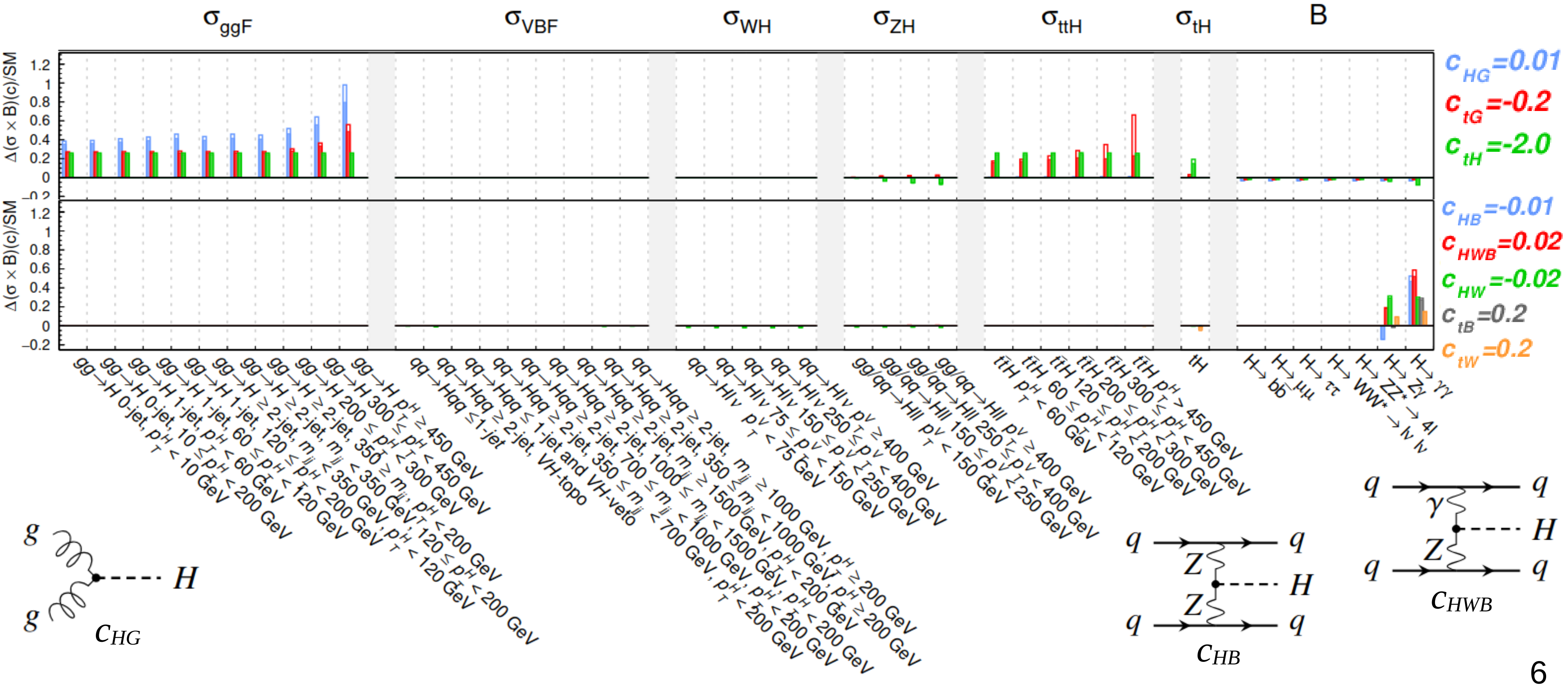
$c_{eH,33}$



$c_{Hq}^{(3)}$

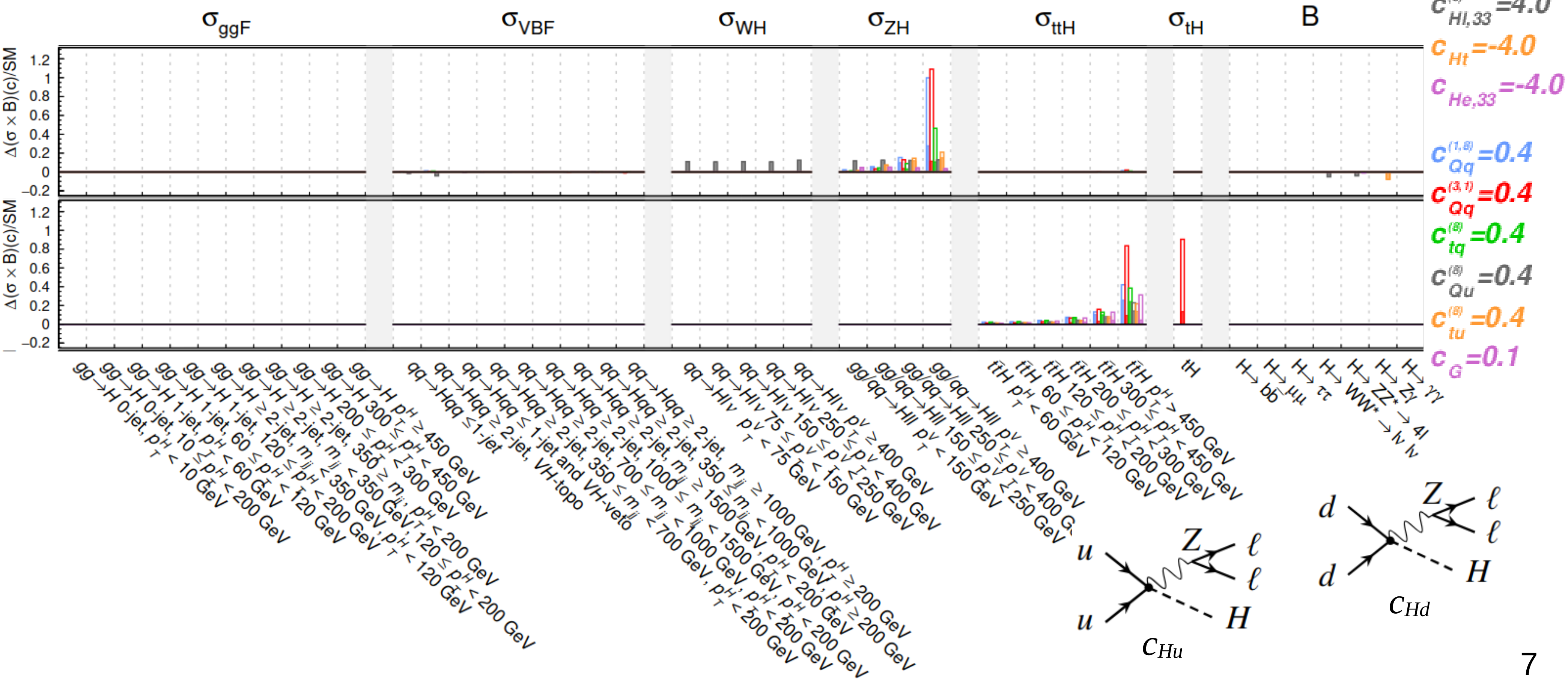
Expected impact of SMEFT operators

- Coefficients c_{HG}, c_{tG}, c_{tH}: mainly affect *ggF* and *ttH* production.
- Coefficients c_{HB}, c_{HWB}, c_{HW}, c_{tB}, c_{tW}: affect branching ratio of $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$.



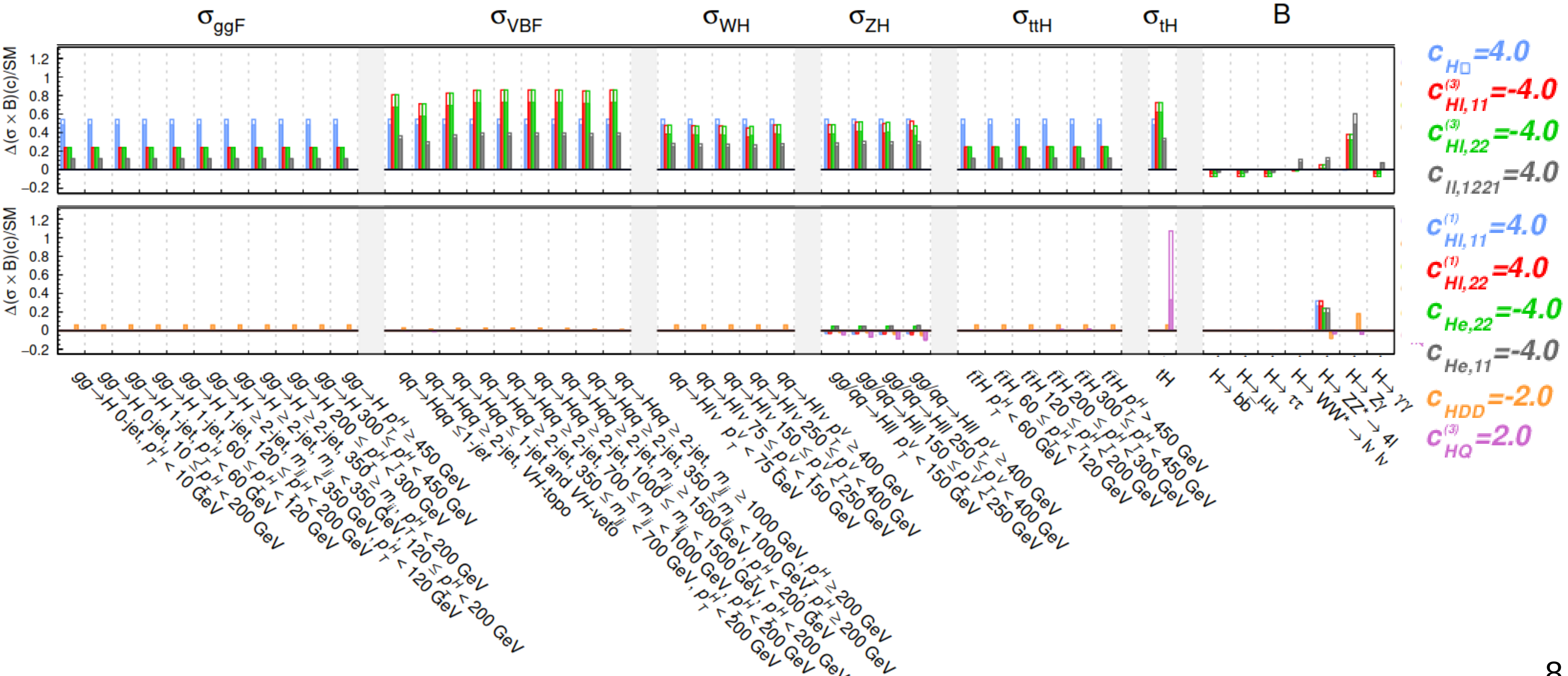
Expected impact of SMEFT operators

- Coefficients c_{Hu}, $c_{Hq}^{(1)}$, c_{Hd}, c_{Ht}, $c_{Hl,33}^{(3)}$, $c_{He,33}$: mainly constrained by $VH(H \to bb)$ decay channel.
- Coefficients $c_{Qq}^{(1,8)}$, $c_{Qq}^{(3,1)}$, $c_{tQ}^{(8)}$, $c_{Qu}^{(8)}$, $c_{tu}^{(8)}$, c_G: affect ttH and tH production modes.



Expected impact of SMEFT operators

- Coefficient $c_{Hl,11}^{(3)}$, $c_{Hl,22}^{(3)}$, $c_{ll,1221}$, $c_{H\square}$: overall scale factor across different production and decay modes.
- Coefficients $c_{Hl,11}^{(1)}$, $c_{Hl,22}^{(1)}$, $c_{He,22}$, $c_{He,11}$, c_{HDD}, $c_{HQ}^{(3)}$: mainly constrained by $H \rightarrow ZZ^* \rightarrow 4l$ decay.



Interpretation based on SMEFT

Interpretation based on EFT: obtain constraints on the Wilson coefficients c_i through a maximum likelihood analysis of the Higgs boson STXS measurements.

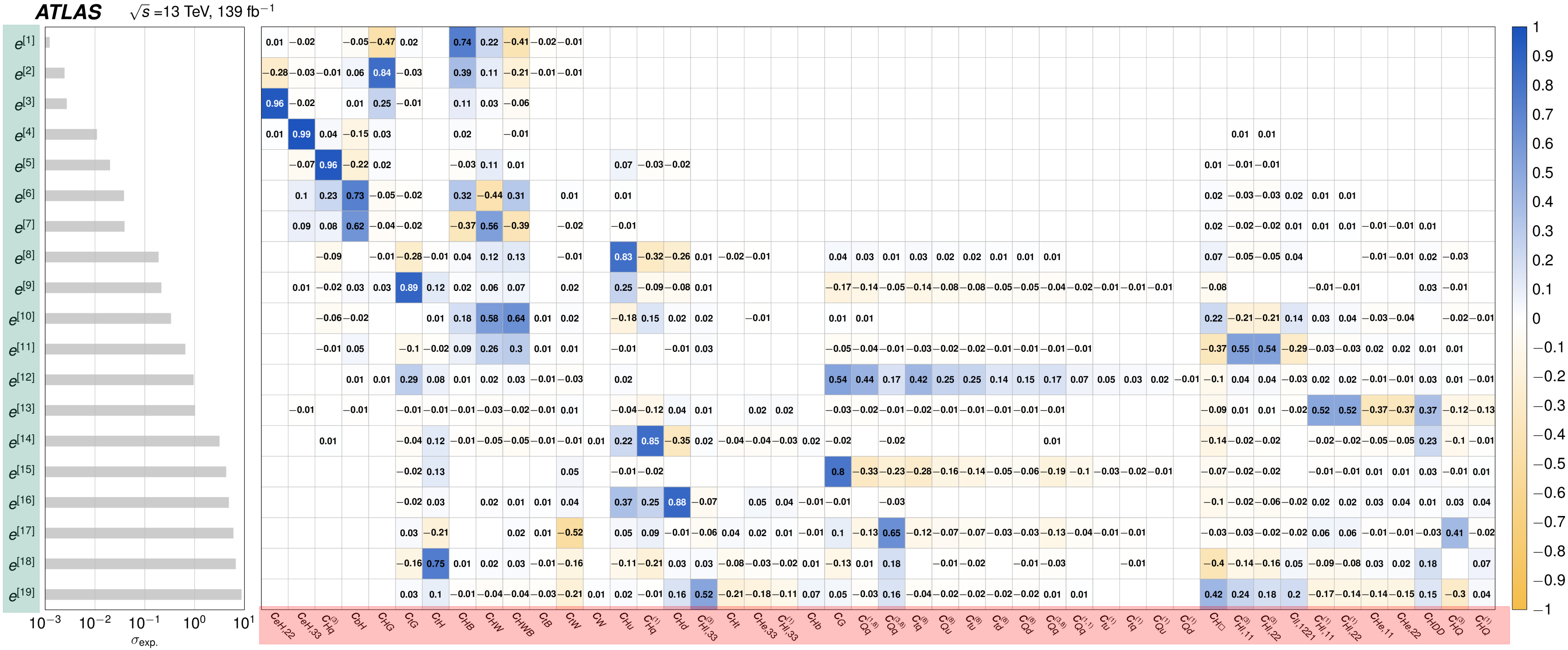
- Difficult to constrain all c_i simultaneously.
- Solution: a new fit basis expressed in terms of linear combinations of c_i (**eigenvector $\boldsymbol{e}^{[i]}$**).

- To determine this new basis (can be measured from data):
  - V_{STXS}: the SM-based expected covariance matrix from the STXS measurement of $\{\mu^{i,k',X}\}$.
  - $\mathrm{V}^{-1}_{\mathrm{STXS}}$ is obtained, rotated to SMEFT basis $\{c_j\}$

$$V^{-1}_{\mathrm{SMEFT}} = P^{T}_{(i,k',X)\to(j)}\, V^{-1}_{\mathrm{STXS}}\, P_{(i,k',X)\to(j)}$$

    expected Jacobian matrix $P_{(i,k',X)\to(j)}$ obtained from simulation, assuming Wilson coefficients not 0.
  - V^{-1}_{SMEFT}: the Fisher information matrix of its linearized SMEFT model re-parameterization.
    - The information matrix yields the eigenvectors $\boldsymbol{e}^{[i]}$.

Sensitivity estimate: information matrix



	$C_{eH,22}$	$C_{eH,33}$	$C_{Hq}^{(3)}$	C_{bH}	C_{HG}	C_{tG}	C_{tH}	C_{HB}	C_{HW}	C_{HWB}	C_{tB}	C_{tW}	C_{W}	C_{Hu}	$C_{Hq}^{(1)}$	C_{Hd}	$C_{Hl,33}^{(3)}$	C_{Ht}	$C_{He,33}$	$C_{Hl,33}^{(1)}$	C_{Hb}	C_{G}	$C_{Qq}^{(1,8)}$
$e^{[1]}$	0.01	−0.02		−0.05	−0.47	0.02		0.74	0.22	−0.41	−0.02	−0.01											
$e^{[2]}$	−0.28	−0.03	−0.01	0.06	0.84	−0.03		0.39	0.11	−0.21	−0.01	−0.01											
$e^{[3]}$	0.96	−0.02		0.01	0.25	−0.01		0.11	0.03	−0.06													
$e^{[4]}$	0.01	0.99	0.04	−0.15	0.03			0.02		−0.01													
$e^{[5]}$		−0.07	0.96	−0.22	0.02			−0.03	0.11	0.01				0.07	−0.03	−0.02							
$e^{[6]}$		0.1	0.23	0.73	−0.05	−0.02		0.32	−0.44	0.31		0.01		0.01									
$e^{[7]}$		0.09	0.08	0.62	−0.04	−0.02		−0.37	0.56	−0.39		−0.02		−0.01									
$e^{[8]}$			−0.09		−0.01	−0.28	−0.01	0.04	0.12	0.13		−0.01		0.83	−0.32	−0.26	0.01	−0.02	−0.01			0.04	0.03
$e^{[9]}$		0.01	−0.02	0.03	0.03	0.89	0.12	0.02	0.06	0.07		0.02		0.25	−0.09	−0.08	0.01					−0.17	−0.14
$e^{[10]}$			−0.06	−0.02			0.01	0.18	0.58	0.64	0.01	0.02		−0.18	0.15	0.02	0.02		−0.01			0.01	0.01
$e^{[11]}$			−0.01	0.05		−0.1	−0.02	0.09	0.26	0.3	0.01	0.01		−0.01		−0.01	0.03					−0.05	−0.04
$e^{[12]}$				0.01	0.01	0.29	0.08	0.01	0.02	0.03	−0.01	−0.03		0.02								0.54	0.44
$e^{[13]}$		−0.01		−0.01		−0.01	−0.01	−0.01	−0.03	−0.02	−0.01	0.01		−0.04	−0.12	0.04	0.01		0.02	0.02		−0.03	−0.02
$e^{[14]}$			0.01			−0.04	0.12	−0.01	−0.05	−0.05	−0.01	−0.01	0.01	0.22	0.85	−0.35	0.02	−0.04	−0.04	−0.03	0.02	−0.02	
$e^{[15]}$						−0.02	0.13					0.05		−0.01	−0.02							0.8	−0.33
$e^{[16]}$						−0.02	0.03		0.02	0.01	0.01	0.04		0.37	0.25	0.88	−0.07		0.05	0.04	−0.01	−0.01	
$e^{[17]}$						0.03	−0.21			0.02	0.01	−0.52		0.05	0.09	−0.01	−0.06	0.04	0.02	0.01	−0.01	0.1	−0.13
$e^{[18]}$						−0.16	0.75	0.01	0.02	0.03	−0.01	−0.16		−0.11	−0.21	0.03	0.03	−0.08	−0.03	−0.02	0.01	−0.13	0.01
$e^{[19]}$						0.03	0.1	−0.01	−0.04	−0.04	−0.03	−0.21	0.01	0.02	−0.01	0.16	0.52	−0.21	−0.18	−0.11	0.07	0.05	−0.03

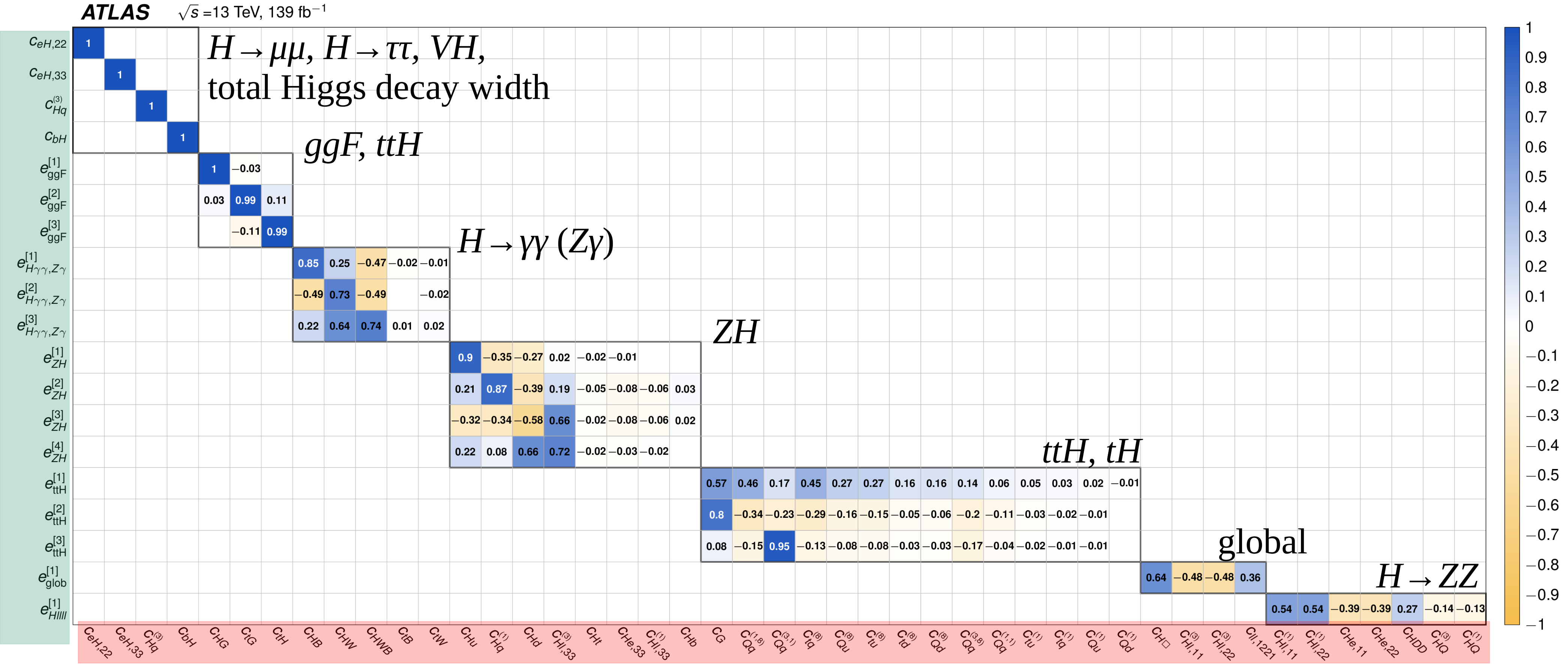
	$C_{Qq}^{(3,8)}$	$C_{tq}^{(8)}$	$C_{Qu}^{(8)}$	$C_{tu}^{(8)}$	$C_{td}^{(8)}$	$C_{Qd}^{(8)}$	$C_{Qq}^{(3,8)}$	$C_{Qq}^{(1,1)}$	$C_{tu}^{(1)}$	$C_{tq}^{(1)}$	$C_{Qu}^{(1)}$	$C_{Qd}^{(1)}$	$C_{H\Box}$	$C_{Hl,11}^{(3)}$	$C_{Hl,22}^{(3)}$	$C_{ll,1221}$	$C_{Hl,11}^{(1)}$	$C_{Hl,22}^{(1)}$	$C_{He,11}$	$C_{He,22}$	C_{HDD}	$C_{HQ}^{(3)}$	$C_{HQ}^{(1)}$
$e^{[1]}$																							
$e^{[2]}$																							
$e^{[3]}$																							
$e^{[4]}$														0.01	0.01								
$e^{[5]}$													0.01	−0.01	−0.01								
$e^{[6]}$													0.02	−0.03	−0.03	0.02	0.01	0.01					
$e^{[7]}$													0.02	−0.02	−0.02	0.01	0.01	0.01	−0.01	−0.01	0.01		
$e^{[8]}$	0.01	0.03	0.02	0.02	0.01	0.01	0.01						0.07	−0.05	−0.05	0.04			−0.01	−0.01	0.02	−0.03	
$e^{[9]}$	−0.05	−0.14	−0.08	−0.08	−0.05	−0.05	−0.04	−0.02	−0.01	−0.01	−0.01		−0.08				−0.01	−0.01			0.03	−0.01	
$e^{[10]}$													0.22	−0.21	−0.21	0.14	0.03	0.04	−0.03	−0.04		−0.02	−0.01
$e^{[11]}$	−0.01	−0.03	−0.02	−0.02	−0.01	−0.01	−0.01	−0.01					−0.37	0.55	0.54	−0.29	−0.03	−0.03	0.02	0.02	0.01	0.01	
$e^{[12]}$	0.17	0.42	0.25	0.25	0.14	0.15	0.17	0.07	0.05	0.03	0.02	−0.01	−0.1	0.04	0.04	−0.03	0.02	0.02	−0.01	−0.01	0.03	0.01	−0.01
$e^{[13]}$	−0.01	−0.02	−0.01	−0.01	−0.01	−0.01	−0.01						−0.09	0.01	0.01	−0.02	0.52	0.52	−0.37	−0.37	0.37	−0.12	−0.13
$e^{[14]}$	−0.02						0.01						−0.14	−0.02	−0.02		−0.02	−0.02	−0.05	−0.05	0.23	−0.1	−0.01
$e^{[15]}$	−0.23	−0.28	−0.16	−0.14	−0.05	−0.06	−0.19	−0.1	−0.03	−0.02	−0.01		−0.07	−0.02	−0.02		−0.01	−0.01	0.01	0.01	0.03	−0.01	0.01
$e^{[16]}$	−0.03												−0.1	−0.02	−0.06	−0.02	0.02	0.02	0.03	0.04	0.01	0.03	0.04
$e^{[17]}$	0.65	−0.12	−0.07	−0.07	−0.03	−0.03	−0.13	−0.04	−0.01	−0.01			−0.03	−0.03	−0.02	−0.02	0.06	0.06	−0.01	−0.01	−0.03	0.41	−0.02
$e^{[18]}$	0.18		−0.01	−0.02		−0.01	−0.03			−0.01			−0.4	−0.14	−0.16	0.05	−0.09	−0.08	0.03	0.02	0.18		0.07
$e^{[19]}$	0.16	−0.04	−0.02	−0.02	−0.02	−0.02	0.01	0.01					0.42	0.24	0.18	0.2	−0.17	−0.14	−0.14	−0.15	0.15	−0.3	0.04

Eigenvectors, obtained from expected measurements accounting for the observed values of NPs, ranked by eigenvalue λ, $\sigma_{\text{exp.}} = 1/\sqrt{\lambda}$.

Wilson coefficients

Definition of fit basis

- Definition of the fit basis coefficients in terms of the Warsaw basis Wilson coefficients.
  - Achieves both fit stability and fit-parameter interpretability.



	$c_{eH,22}$	$c_{eH,33}$	$c^{(3)}_{Hq}$	c_{bH}	c_{HG}	c_{tG}	c_{tH}	c_{HB}	c_{HW}	c_{HWB}	c_{tB}	c_{tW}	c_{Hu}	$c^{(1)}_{Hq}$	c_{Hd}	$c^{(3)}_{Hl,33}$	c_{Ht}	$c_{He,33}$	$c^{(1)}_{Hl,33}$	c_{Hb}	c_{G}	$c^{(1,8)}_{Qq}$	$c^{(3,1)}_{Qq}$	$c^{(8)}_{tq}$	$c^{(8)}_{Qu}$	$c^{(8)}_{tu}$	$c^{(8)}_{td}$	$c^{(8)}_{Qd}$	$c^{(3,8)}_{Qq}$	$c^{(1,1)}_{Qq}$	$c^{(1)}_{tu}$	$c^{(1)}_{tq}$	$c^{(1)}_{Qu}$	$c^{(1)}_{Qd}$	$c_{H\Box}$	$c^{(3)}_{Hl,11}$	$c^{(3)}_{Hl,22}$	$c_{ll,1221}$	$c^{(1)}_{Hl,11}$	$c^{(1)}_{Hl,22}$	$c_{He,11}$	$c_{He,22}$	c_{HDD}	$c^{(3)}_{HQ}$	$c^{(1)}_{HQ}$
$c_{eH,22}$	1																																												
$c_{eH,33}$		1																																											
$c^{(3)}_{Hq}$			1																																										
c_{bH}				1																																									
$e^{[1]}_{\mathrm{ggF}}$					1	−0.03																																							
$e^{[2]}_{\mathrm{ggF}}$					0.03	0.99	0.11																																						
$e^{[3]}_{\mathrm{ggF}}$						−0.11	0.99																																						
$e^{[1]}_{H\gamma\gamma,Z\gamma}$								0.85	0.25	−0.47	−0.02	−0.01																																	
$e^{[2]}_{H\gamma\gamma,Z\gamma}$								−0.49	0.73	−0.49		−0.02																																	
$e^{[3]}_{H\gamma\gamma,Z\gamma}$								0.22	0.64	0.74	0.01	0.02																																	
$e^{[1]}_{ZH}$													0.9	−0.35	−0.27	0.02	−0.02	−0.01																											
$e^{[2]}_{ZH}$													0.21	0.87	−0.39	0.19	−0.05	−0.08	−0.06	0.03																									
$e^{[3]}_{ZH}$													−0.32	−0.34	−0.58	0.66	−0.02	−0.08	−0.06	0.02																									
$e^{[4]}_{ZH}$													0.22	0.08	0.66	0.72	−0.02	−0.03	−0.02																										
$e^{[1]}_{\mathrm{ttH}}$																					0.57	0.46	0.17	0.45	0.27	0.27	0.16	0.16	0.14	0.06	0.05	0.03	0.02	−0.01											
$e^{[2]}_{\mathrm{ttH}}$																					0.8	−0.34	−0.23	−0.29	−0.16	−0.15	−0.05	−0.06	−0.2	−0.11	−0.03	−0.02	−0.01												
$e^{[3]}_{\mathrm{ttH}}$																					0.08	−0.15	0.95	−0.13	−0.08	−0.08	−0.03	−0.03	−0.17	−0.04	−0.02	−0.01	−0.01												
$e^{[1]}_{\mathrm{glob}}$																																			0.64	−0.48	−0.48	0.36							
$e^{[1]}_{Hllll}$																																							0.54	0.54	−0.39	−0.39	0.27	−0.14	−0.13

fit basis

Wilson coefficients

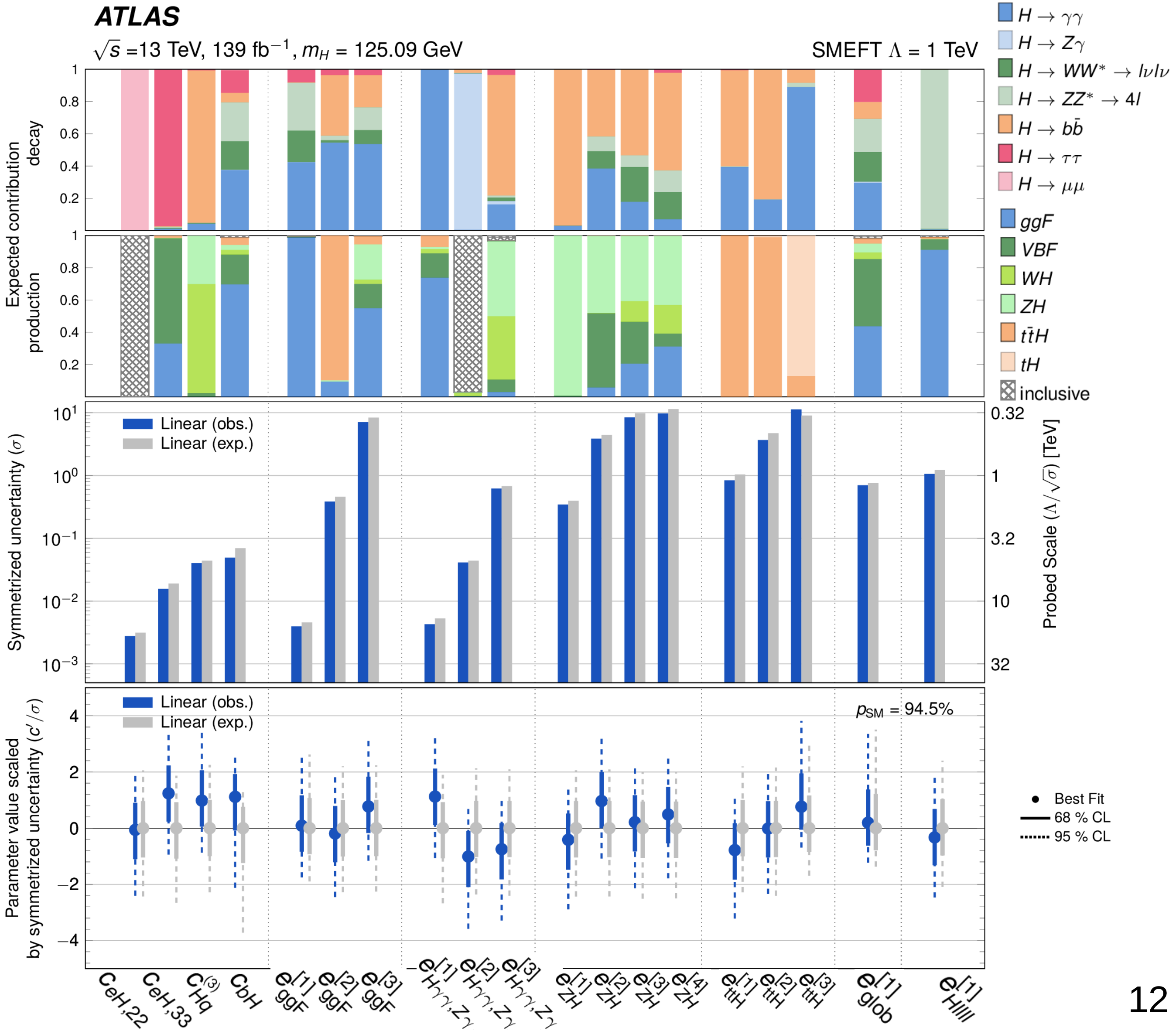
SMEFT result

SMEFT linear model: Λ^{-4} terms not included.

- *p*-value: corresponding to **94.5%**
- Statistical uncertainty dominates.

Symmetrised 68% CL uncertainty σ of each parameter measurement.

Measured parameter value (dot) and 68% and 95% CL intervals, divided by the symmetrised uncertainty shown above.



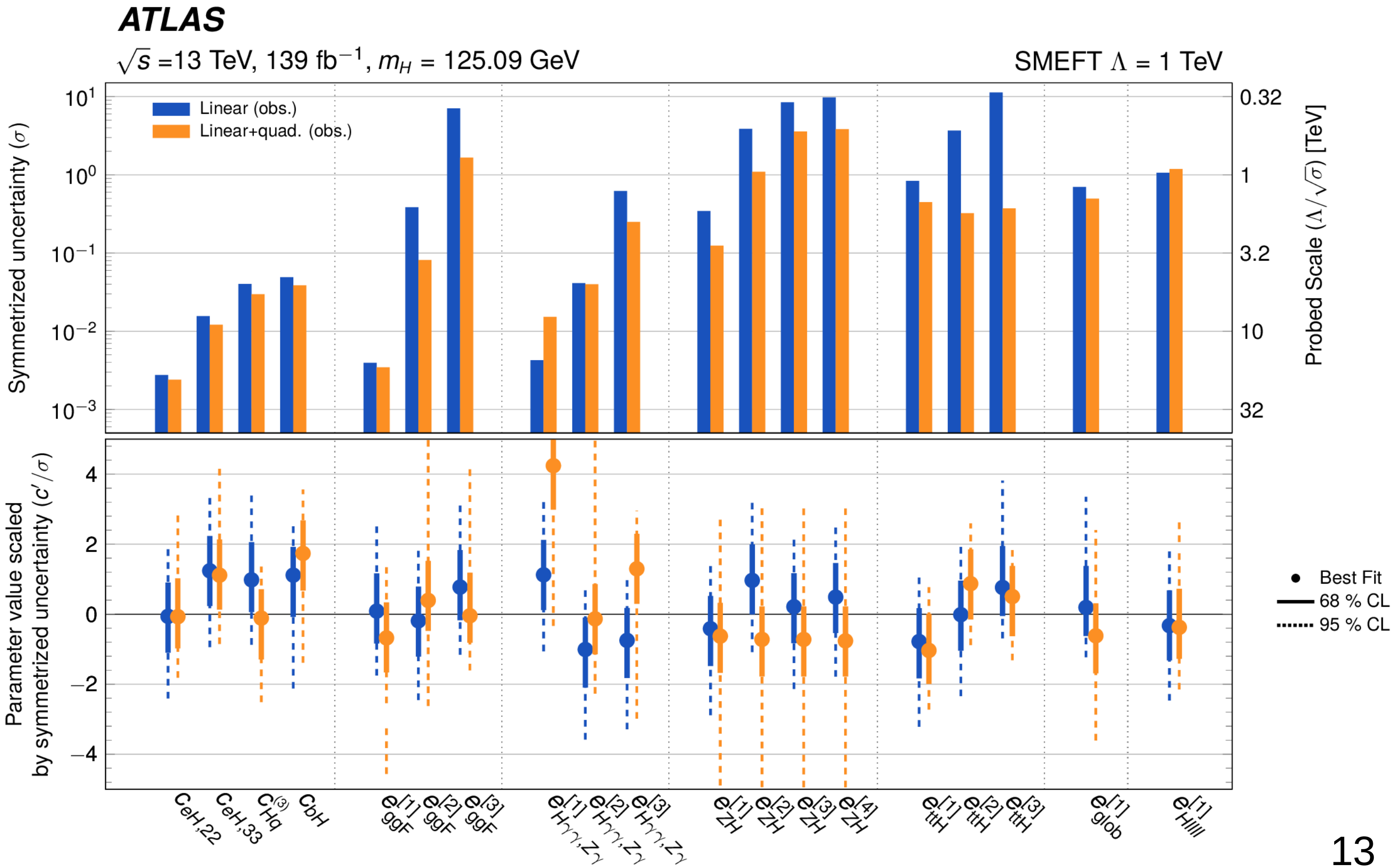
SMEFT result

SMEFT linear model: Λ^{-4} terms not included, SMEFT linear+quadratic: including Λ^{-4} terms.

- Linear+quadratic *p*-value: corresponding to **98.2%**, improvement compared to previous result (59%).
- Stronger constraints with linear+quad.

Symmetrised 68% CL uncertainty σ of each parameter measurement.

Measured parameter value (dot) and 68% and 95% CL intervals, divided by the symmetrised uncertainty shown above.



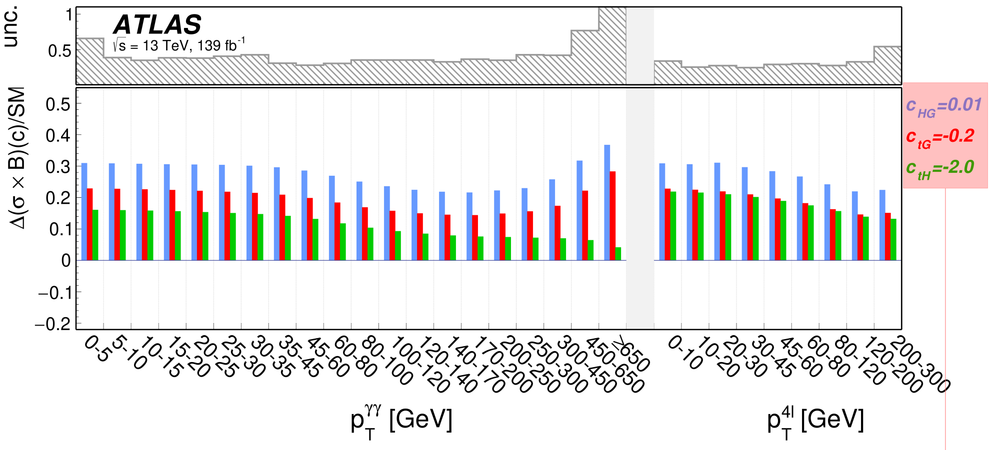
$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ differential cross section

Expected impact of the SMEFT operators on the fiducial differential distributions of $p_T^{\gamma\gamma}$ and p_T^{4l}, in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ decays respectively.

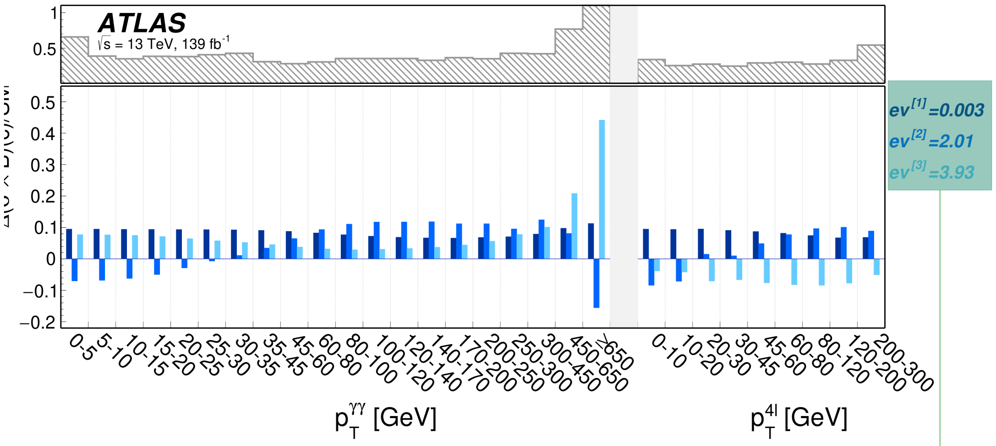
- Wilson coefficients of SMEFT operators sensitive to $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$: c_{HG}, c_{tG}, c_{tH}
- Impossible to constrain all three Wilson coefficients simultaneously, define a new fit basis:

$$\begin{aligned} ev^{[1]} &= 0.999c_{HG} - 0.035c_{tG} - 0.003c_{tH}, \\ ev^{[2]} &= 0.035c_{HG} + 0.978c_{tG} + 0.205c_{tH}, \\ ev^{[3]} &= -0.005c_{HG} - 0.205c_{tG} + 0.979c_{tH}. \end{aligned}$$

Expected impact of the SMEFT operators



Expected impact of rotated SMEFT operators



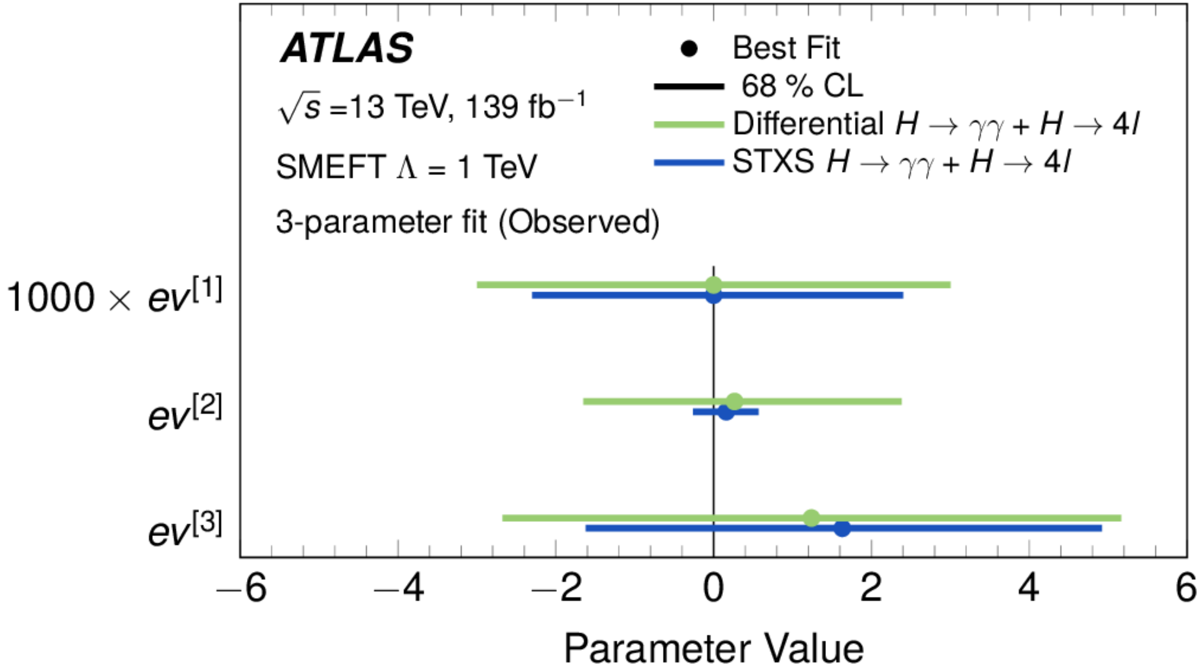
Wilson coefficients

fit basis

$H \to \gamma\gamma$ and $H \to ZZ$ results

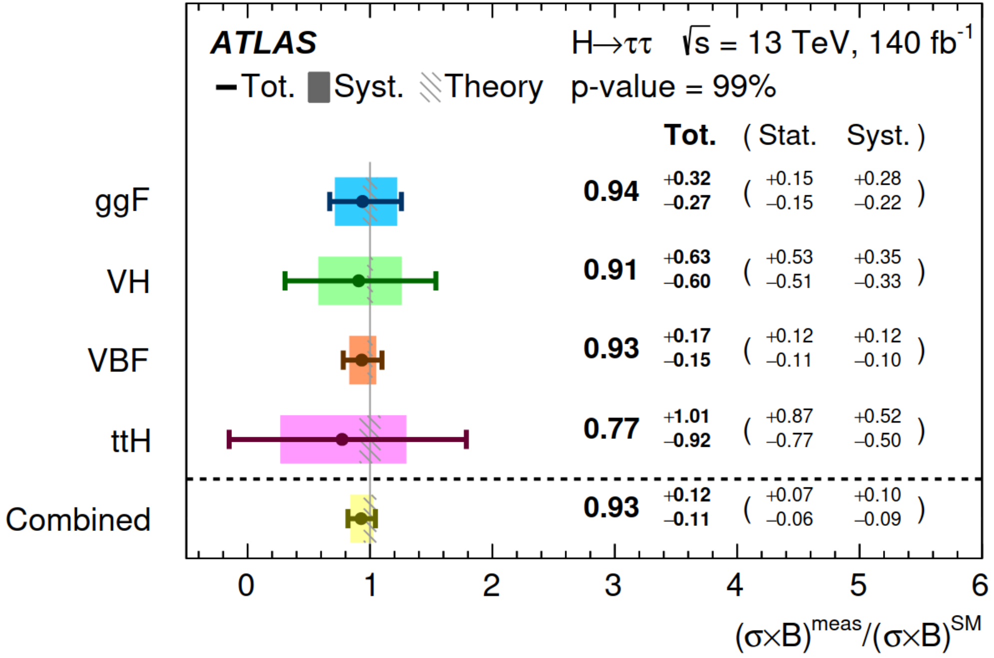
Observed 68% CL intervals on the fit basis $ev^{[i]}$.

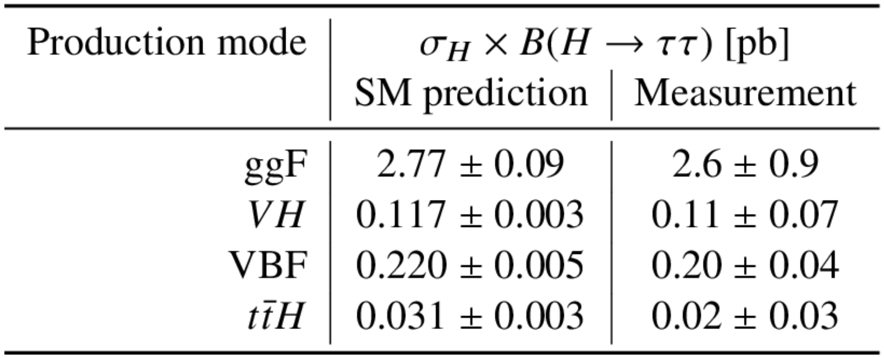
- $ev^{[1]}$: almost aligned c_{HG}; $ev^{[2]}$: close to c_{tG}; $ev^{[3]}$: close to c_{tH}.
- Result obtained using SMEFT linear model, with STXS (blue) or fiducial p_T differential cross-section measurements (green).
  - STXS: only $H \to \gamma\gamma$ and $H \to 4l$ included.



$H \to \tau\tau$ STXS measurement

- STXS and fiducial differential cross section measurement in $H \to \tau\tau$ decay, Run 2 data 140 fb^{-1}, arXiv:2407.16320.
  - Production modes: all modes were measured, particular focus on *VBF* (~ 83% signal events).



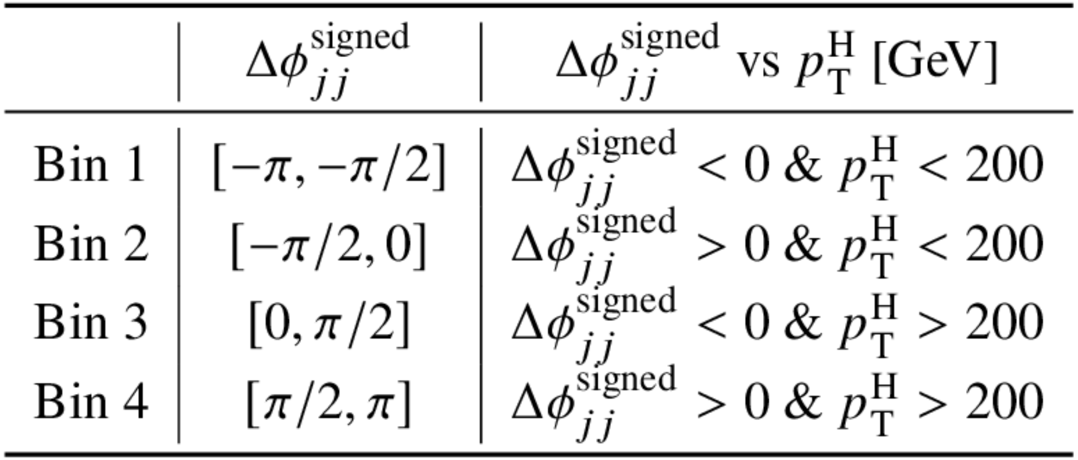


Production mode	$\sigma_H \times B(H \to \tau\tau)$ [pb] SM prediction	Measurement
ggF	2.77 ± 0.09	2.6 ± 0.9
VH	0.117 ± 0.003	0.11 ± 0.07
VBF	0.220 ± 0.005	0.20 ± 0.04
$t\bar{t}H$	0.031 ± 0.003	0.02 ± 0.03

measured values of σ_H×BR($H \to \tau\tau$) relative to the SM expectations

$H \to \tau\tau$ differential cross section

- Kinematic variables of *VBF* Higgs boson production sensitive to BSM effects:

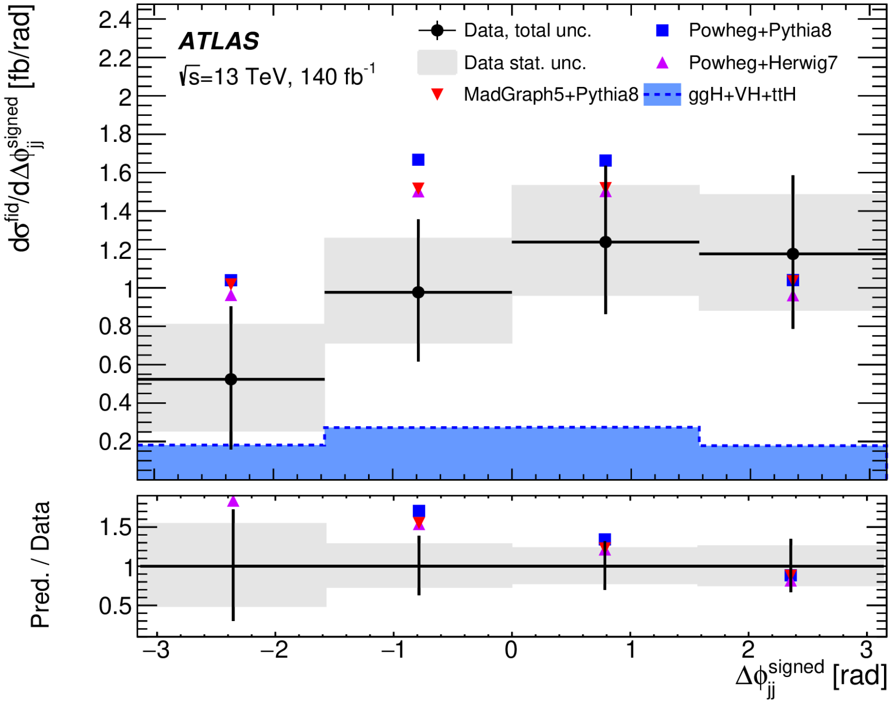


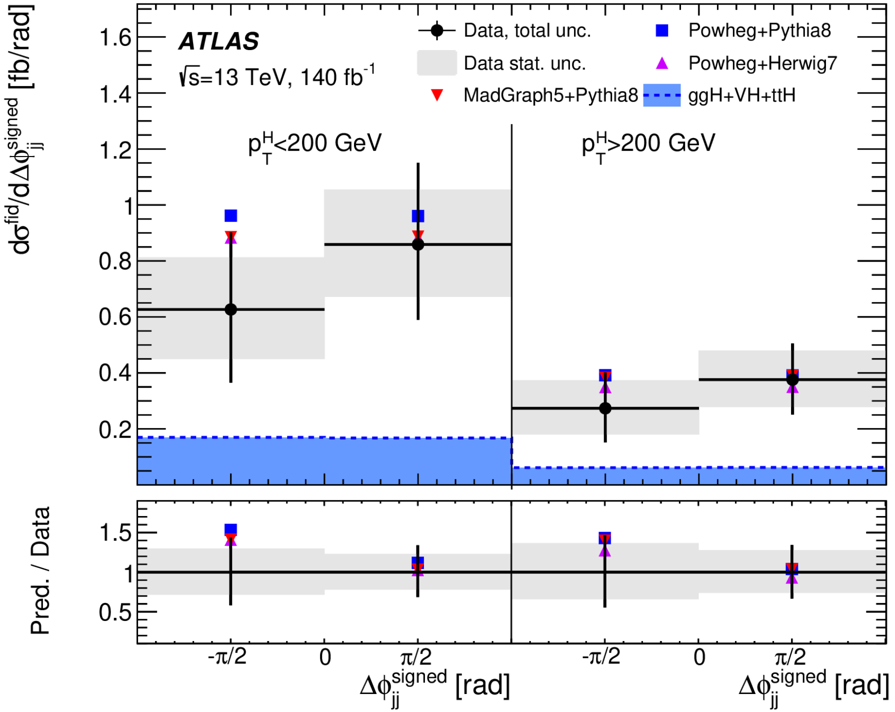
	$\Delta\phi_{jj}^{\text{signed}}$	$\Delta\phi_{jj}^{\text{signed}}$ vs p_{T}^{H} [GeV]
Bin 1	$[-\pi, -\pi/2]$	$\Delta\phi_{jj}^{\text{signed}} < 0$ & $p_{\text{T}}^{\text{H}} < 200$
Bin 2	$[-\pi/2, 0]$	$\Delta\phi_{jj}^{\text{signed}} > 0$ & $p_{\text{T}}^{\text{H}} < 200$
Bin 3	$[0, \pi/2]$	$\Delta\phi_{jj}^{\text{signed}} < 0$ & $p_{\text{T}}^{\text{H}} > 200$
Bin 4	$[\pi/2, \pi]$	$\Delta\phi_{jj}^{\text{signed}} > 0$ & $p_{\text{T}}^{\text{H}} > 200$

  - Signed angle of the two jets in transverse plane: $\Delta\phi_{jj}^{\text{signed}}$, provides sensitivity to the charge (C) and Parity (P) of the Higgs boson.
  - $\Delta\phi_{jj}^{\text{signed}}$ as a function of p_{T}^{H}.

$H \rightarrow \tau\tau$ differential cross section

- Measured differential cross sections for $\Delta\phi_{jj}^{\mathrm{signed}}$, $\Delta\phi_{jj}^{\mathrm{signed}}$ vs p_{T}^{H}.
  - Overall good agreement between measured cross sections and SM predictions. Per-bin precision is typically 25%-50%.
  - Experimental precision dominated by statistical uncertainties in most of the bins.

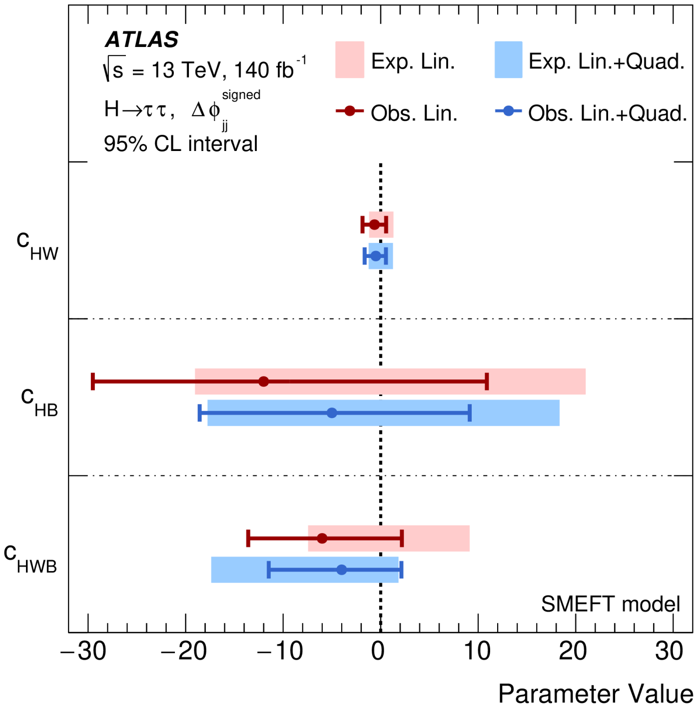




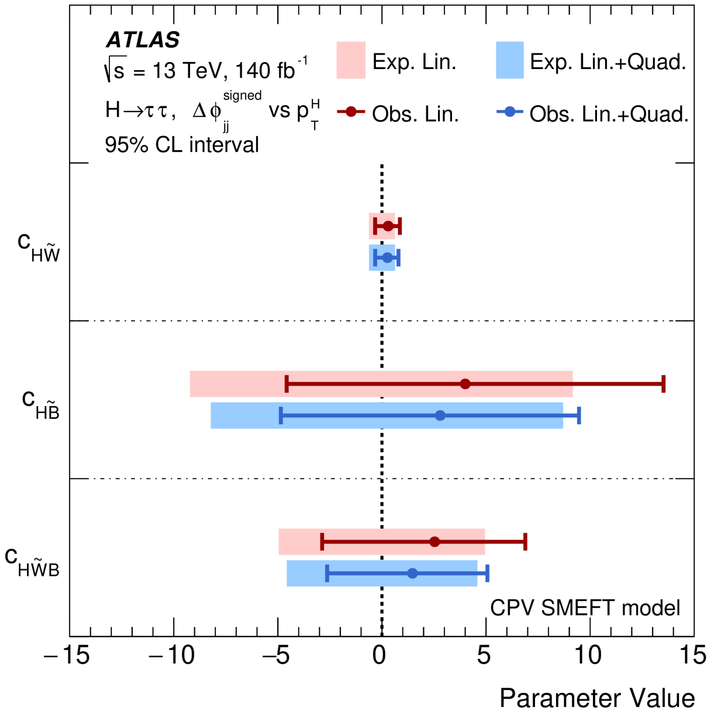
$H \to \tau\tau$ interpretation of diff. xs measurement in EFT

Expected and observed 95% CL intervals for each of the six considered Wilson coefficients.

- Wilson coefficients: c_{HW}, c_{HB}, c_{HWB}, $c_{H\widetilde{W}}$, $c_{H\widetilde{B}}$, $c_{H\widetilde{W}B}$. Each coefficient is fitted individually.
- both the linear and linear + quadratic models are considered.



Correspond to CP-even operators, $\Delta\phi_{jj}^{\text{signed}}$ distribution is used



Correspond to CP-odd operators, $\Delta\phi_{jj}^{\text{signed}}$ vs p_{T}^{H} distribution is used

Conclusion

- SMEFT interpretations of the combined ATLAS measurements of Higgs boson STXS.
  - Linear model and linear+quadratic model results provided.
    - The effects of operators suppressed by Λ^{-4} terms can significantly affect constraints on Wilson coefficients for a mass scale of $\Lambda = 1$ TeV.
- Fiducial differential cross-section measurements for $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ\rightarrow 4l$.
  - Significantly weaker constraints on top-gluon coupling compared to STXS measurement.
- Fiducial differential cross-section measurements for $VBF\ H\rightarrow\tau\tau$.
  - Provides also sensitivity to CP-odd EFT operators.
- No significant deviations from the SM are observed.

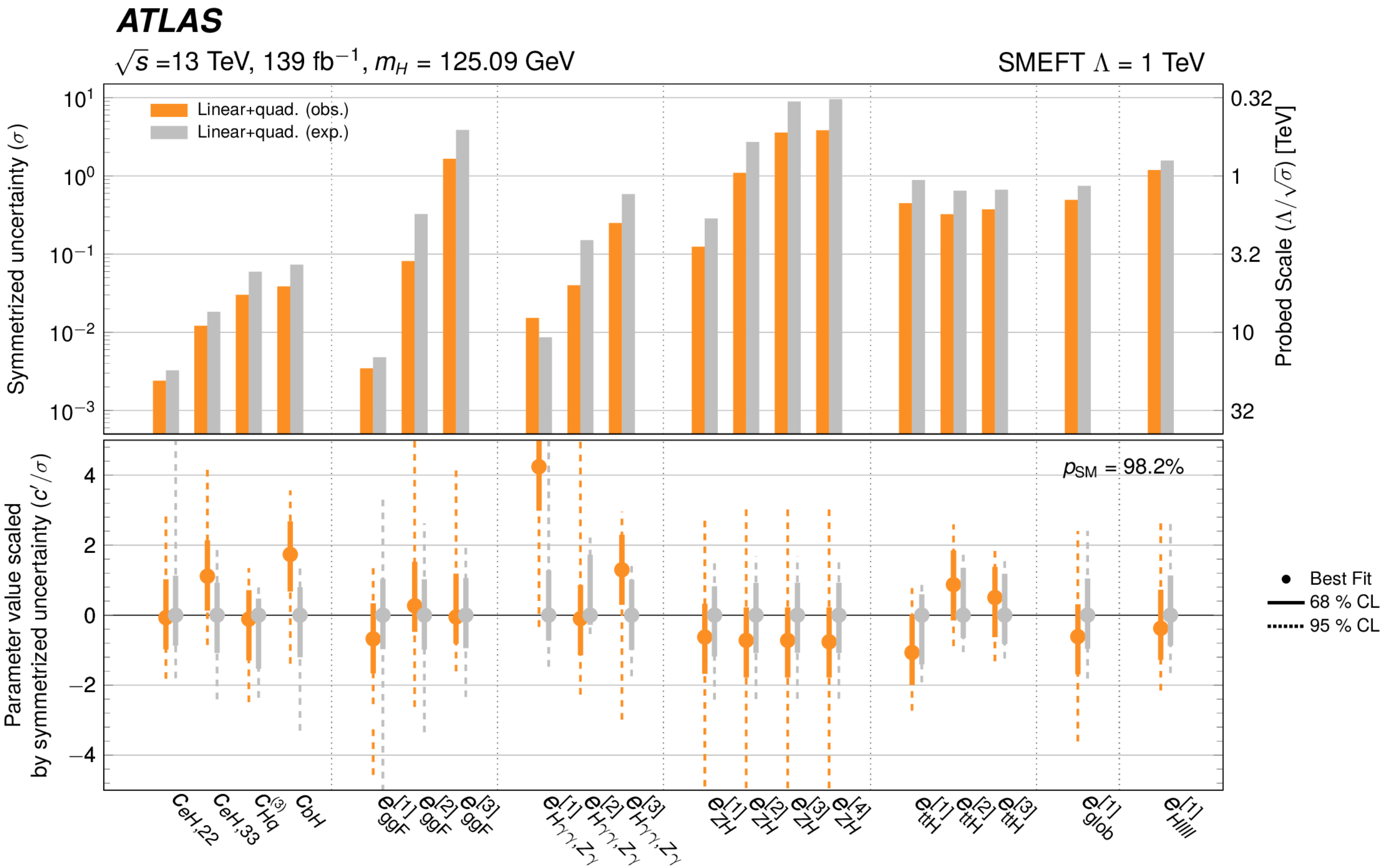
Backup

Rotate of fit basis.

$$
\begin{aligned}
\boldsymbol{c} = {} & \{c_{eH,22}\} \cup & & \boldsymbol{c}' = \{c_{eH,22}\} \cup \\
& \{c_{eH,33}\} \cup & & \qquad\; \{c_{eH,33}\} \cup \\
& \{c^{(3)}_{Hq}\} \cup & & \qquad\; \{c^{(3)}_{Hq}\} \cup \\
& \{c_{bH}\} \cup & & \qquad\; \{c_{bH}\} \cup \\
& \{c_{HG}, c_{tG}, c_{tH}\} \cup & \rightarrow & \qquad\; \{e^{[1]}_{\mathrm{ggF}}, e^{[2]}_{\mathrm{ggF}}, e^{[3]}_{\mathrm{ggF}}\} \cup \\
& \{c_{HB}, c_{HW}, c_{HWB}, c_{tB}, c_{tW}\} \cup & \rightarrow & \qquad\; \{e^{[1]}_{H\gamma\gamma,Z\gamma}, e^{[2]}_{H\gamma\gamma,Z\gamma}, e^{[3]}_{H\gamma\gamma,Z\gamma}\} \cup \\
& \{c_{Hu}, c^{(1)}_{Hq}, c_{Hd}, c^{(3)}_{Hl,33}, & & \\
& \qquad c_{Ht}, c_{He,33}, c^{(1)}_{Hl,33}, c_{Hb}\} \cup & \rightarrow & \qquad\; \{e^{[1]}_{ZH}, e^{[2]}_{ZH}, e^{[3]}_{ZH}, e^{[4]}_{ZH}\} \cup \\
& \{c_{G}, c^{(1,8)}_{Qq}, c^{(3,1)}_{Qq}, c^{(8)}_{tq}, c^{(8)}_{Qu}, c^{(8)}_{tu}, c^{(8)}_{td}, & & \\
& \qquad c^{(8)}_{Qd}, c^{(3,8)}_{Qq}, c^{(1,1)}_{Qq}, c^{(1)}_{tu}, c^{(1)}_{tq}, c^{(1)}_{Qu}, c^{(1)}_{Qd}\} \cup & \rightarrow & \qquad\; \{e^{[1]}_{\mathrm{ttH}}, e^{[2]}_{\mathrm{ttH}}, e^{[3]}_{\mathrm{ttH}}\} \cup \\
& \{c_{H\Box}, c^{(3)}_{Hl,11}, c^{(3)}_{Hl,22}, c_{ll,1221}\} \cup & \rightarrow & \qquad\; \{e^{[1]}_{\mathrm{glob}}\} \cup \\
& \{c^{(1)}_{Hl,11}, c^{(1)}_{Hl,22}, c_{He,11}, c_{He,22}, c_{HDD}, c^{(3)}_{HQ}, c^{(1)}_{HQ}\} & \rightarrow & \qquad\; \{e^{[1]}_{Hllll}\}.
\end{aligned}
$$

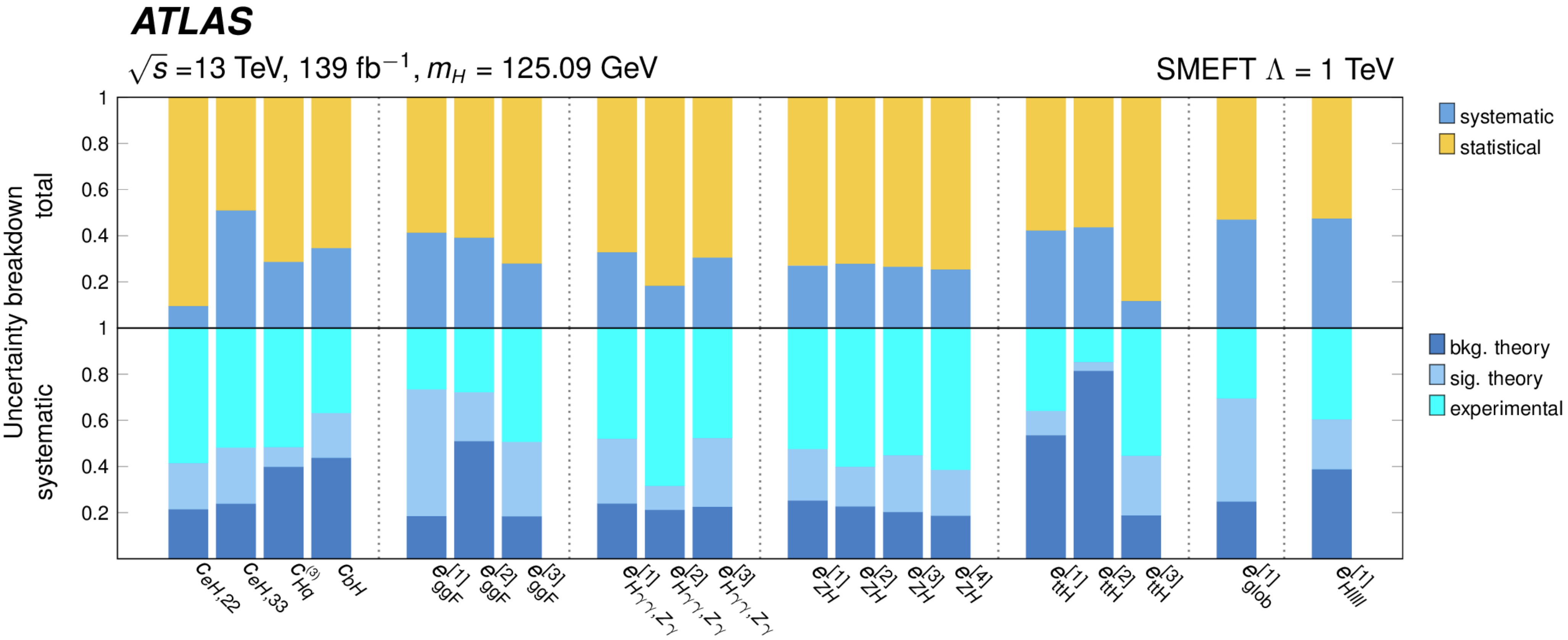
Backup

SMEFT linear+quadratic model result.



Backup

Uncertainty breakdown of SMEFT linear model result.

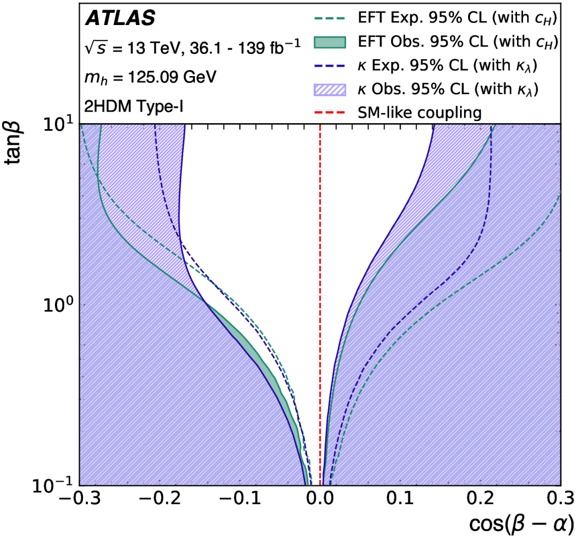


Backup

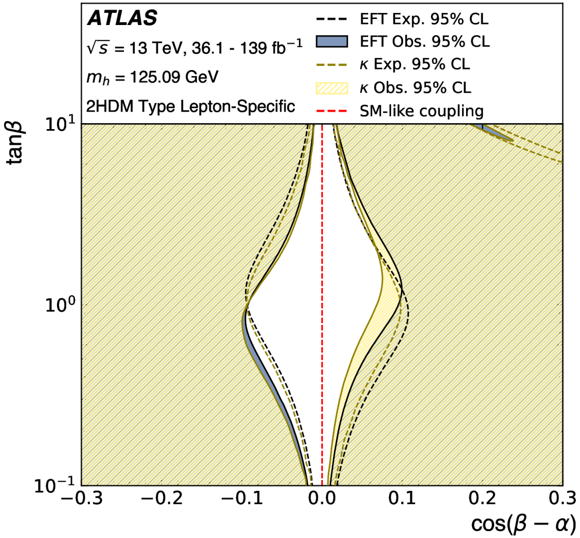
Comparison of EFT approach and UV-complete approach.

- Comparison of the constraints from the approaches based on the κ- and EFT-frameworks in the tanβ, cos(β-α) plane.
- The κ_λ constraint is included in the Type-I model interpretation.

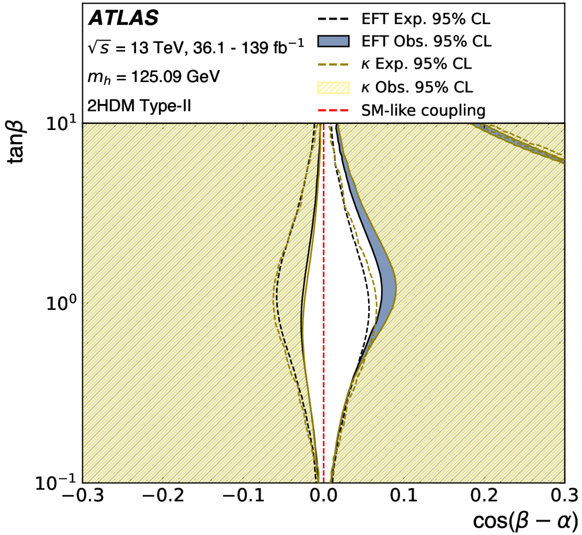
Type-I model



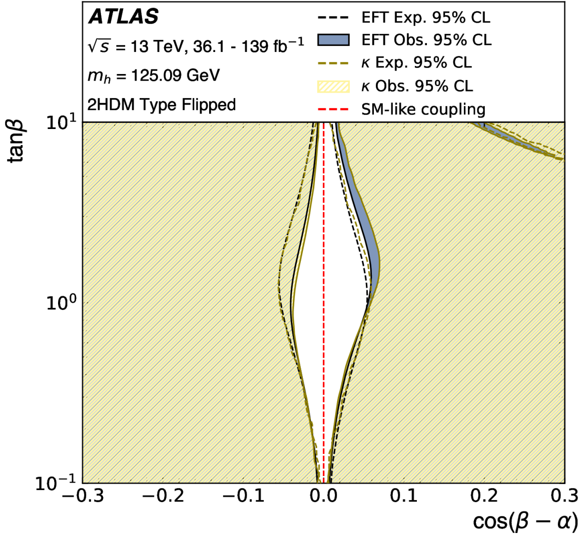
Lepton-specific model



Type-II model

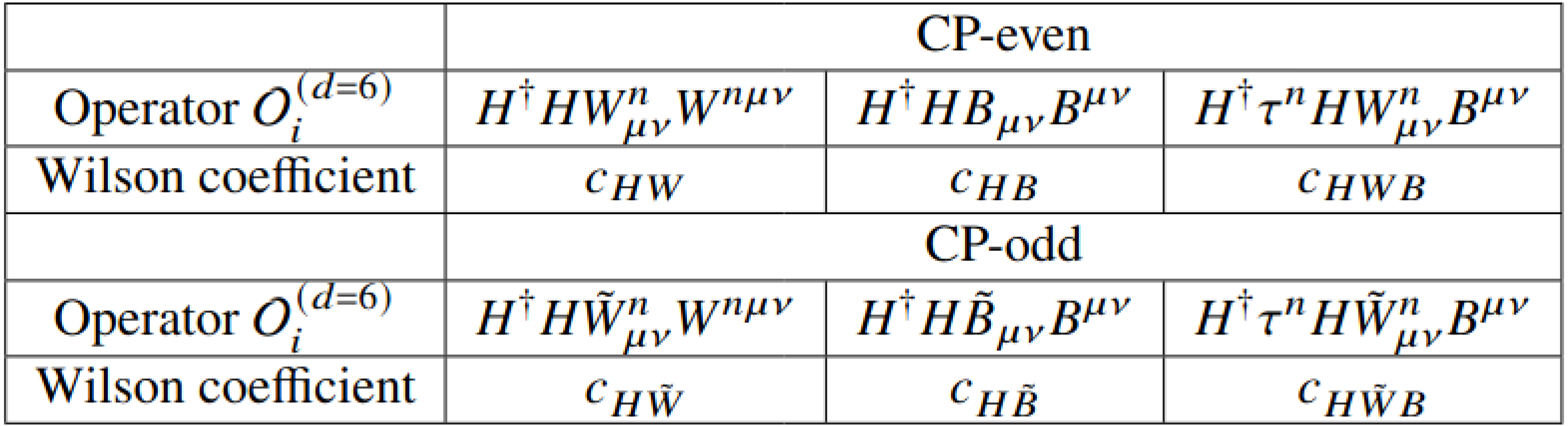


Flipped model



Backup

$H \rightarrow \tau\tau$ Wilson coefficients and EFT operators.

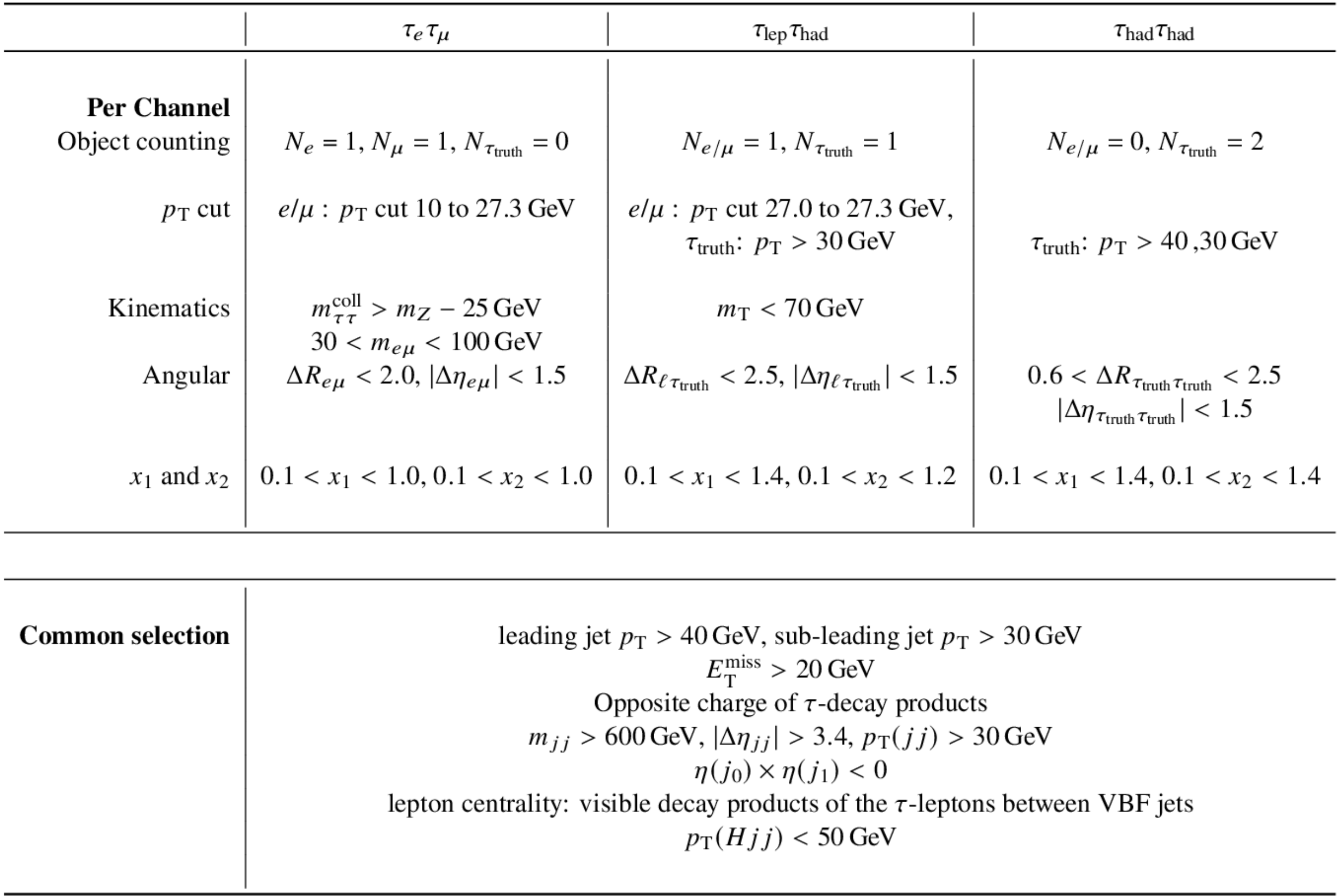


	CP-even		
Operator $O_i^{(d=6)}$	$H^\dagger H W^n_{\mu\nu} W^{n\mu\nu}$	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$H^\dagger \tau^n H W^n_{\mu\nu} B^{\mu\nu}$
Wilson coefficient	c_{HW}	c_{HB}	c_{HWB}
	CP-odd		
Operator $O_i^{(d=6)}$	$H^\dagger H \tilde{W}^n_{\mu\nu} W^{n\mu\nu}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$H^\dagger \tau^n H \tilde{W}^n_{\mu\nu} B^{\mu\nu}$
Wilson coefficient	$c_{H\tilde{W}}$	$c_{H\tilde{B}}$	$c_{H\tilde{W}B}$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2022-07/

Backup

$H \rightarrow \tau\tau$ fiducial differential cross section particle level event selection.



	$\tau_e\tau_\mu$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
Per Channel			
Object counting	$N_e = 1, N_\mu = 1, N_{\tau_{\text{truth}}} = 0$	$N_{e/\mu} = 1, N_{\tau_{\text{truth}}} = 1$	$N_{e/\mu} = 0, N_{\tau_{\text{truth}}} = 2$
p_T cut	e/μ : p_T cut 10 to 27.3 GeV	e/μ : p_T cut 27.0 to 27.3 GeV, τ_{truth}: $p_T > 30$ GeV	τ_{truth}: $p_T > 40$,30 GeV
Kinematics	$m_{\tau\tau}^{\text{coll}} > m_Z - 25$ GeV $30 < m_{e\mu} < 100$ GeV	$m_T < 70$ GeV	
Angular	$\Delta R_{e\mu} < 2.0, \lvert\Delta\eta_{e\mu}\rvert < 1.5$	$\Delta R_{\ell\tau_{\text{truth}}} < 2.5, \lvert\Delta\eta_{\ell\tau_{\text{truth}}}\rvert < 1.5$	$0.6 < \Delta R_{\tau_{\text{truth}}\tau_{\text{truth}}} < 2.5$ $\lvert\Delta\eta_{\tau_{\text{truth}}\tau_{\text{truth}}}\rvert < 1.5$
x_1 and x_2	$0.1 < x_1 < 1.0, 0.1 < x_2 < 1.0$	$0.1 < x_1 < 1.4, 0.1 < x_2 < 1.2$	$0.1 < x_1 < 1.4, 0.1 < x_2 < 1.4$

Common selection	leading jet $p_T > 40$ GeV, sub-leading jet $p_T > 30$ GeV $E_T^{\text{miss}} > 20$ GeV Opposite charge of τ-decay products $m_{jj} > 600$ GeV, $\lvert\Delta\eta_{jj}\rvert > 3.4$, $p_T(jj) > 30$ GeV $\eta(j_0) \times \eta(j_1) < 0$ lepton centrality: visible decay products of the τ-leptons between VBF jets $p_T(Hjj) < 50$ GeV