Highlights from ATLAS

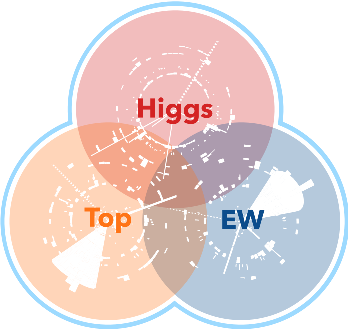
Eleonora Rossi

8th General Meeting of the LHC EFT Working Group

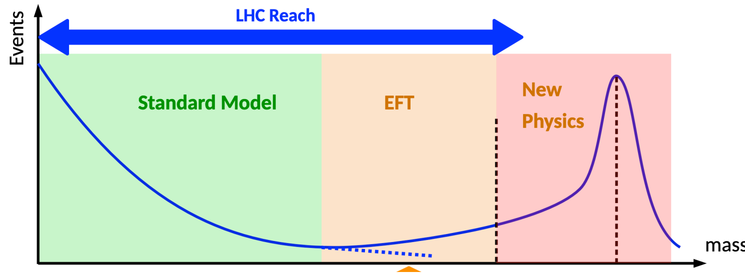
02/12/2024

ATLAS EXPERIMENT

UNIVERSITY OF OXFORD



Introduction



Sketch from Nicolas

The LHC has not yet found any evidence of New Physics.

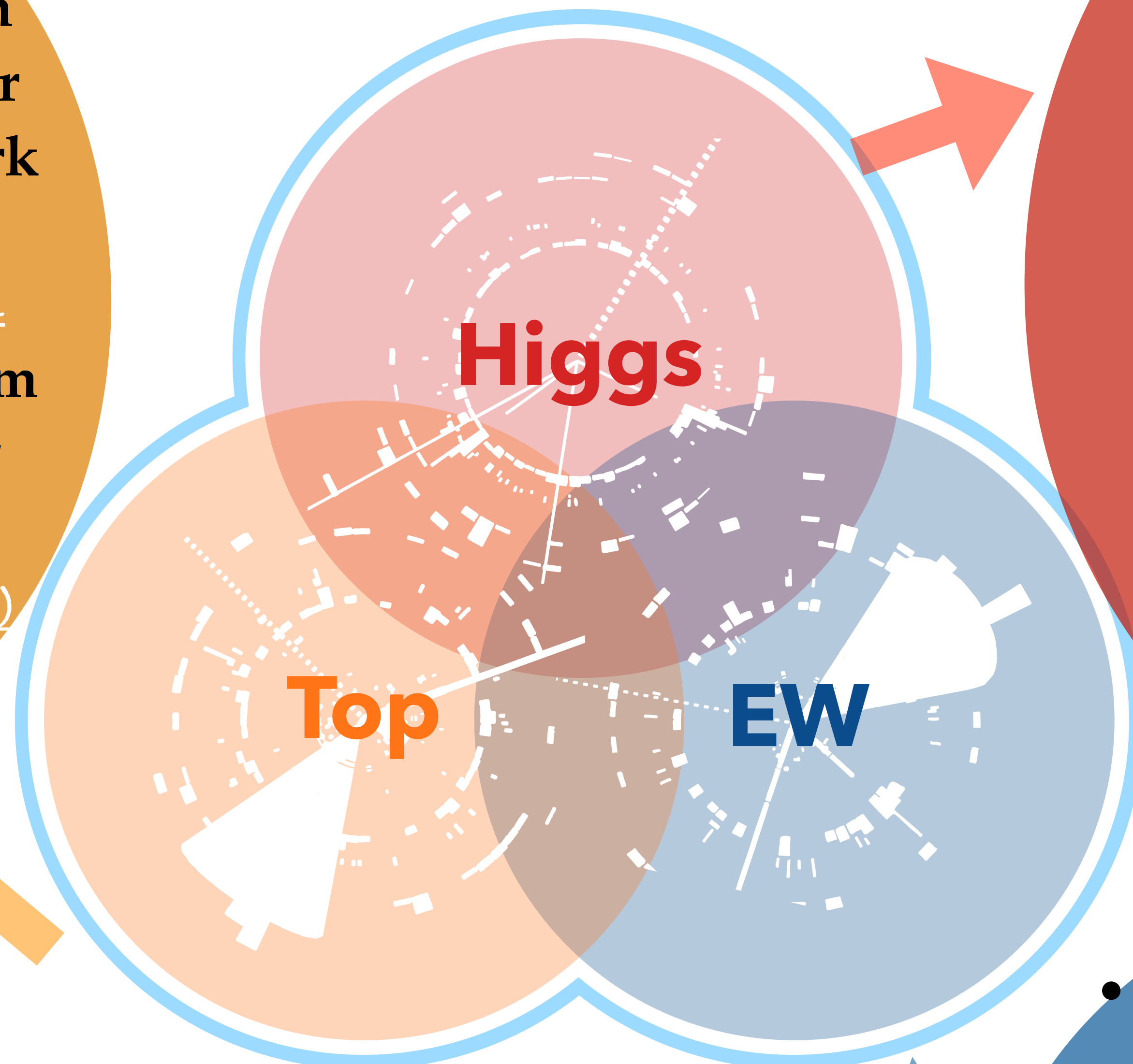
- Direct searches for SUSY or exotics continue, but the focus on indirect exploration is increasing…
- Increasing number of **Effective Field Theory (EFT)** measurements and reinterpretations in ATLAS and CMS:
  - STXS (Simplified template cross section)-based interpretations in all main decay modes ($H \rightarrow \gamma\gamma, 4\ell, WW^*, b\bar{b}, \tau^+\tau^-$) and combination; dedicated analyses for CP & Anomalous Couplings; differential and inclusive cross sections.

- Input observables: angles, p_T, mass…
- Interpretation in the context of EFT complementing (or superseding) other interpretations.

- EFT results interpret **unfolded spectrum** (reinterpretation - indirect) or measure coefficients with the **primary likelihood** (reparameterisation - direct).
- Constrain EFT coefficients -> constrain large classes of UV theories.

Latest results

- EFT interpretation from the search for same-sign top quark pairs
  arXiv:2409.14982
- Interpretations from the search for *tHq* FCNC
  Eur. Phys. J. C 84 (2024) 757



Sketch from R.Balasubramanian
inspired by Ken Mimasu

- EFT interpretations from HH combination,
  PhysRevLett.133.101801
- Interpretations of Higgs combination
  JHEP11(2024)097
- Differential cross-section of $H \to \tau^+\tau^-$,
  arxiv:2407.16320

- Electroweak WZ boson pair production in association with two jets,
  JHEP 06 (2024) 192
- Same-sign W boson pair production in association with two jets
  JHEP 04 (2024) 026

- **EFT interpretation from the search for same-sign top quark pairs**
  arXiv:2409.14982
- **Interpretations from the search for *tHq* FCNC**
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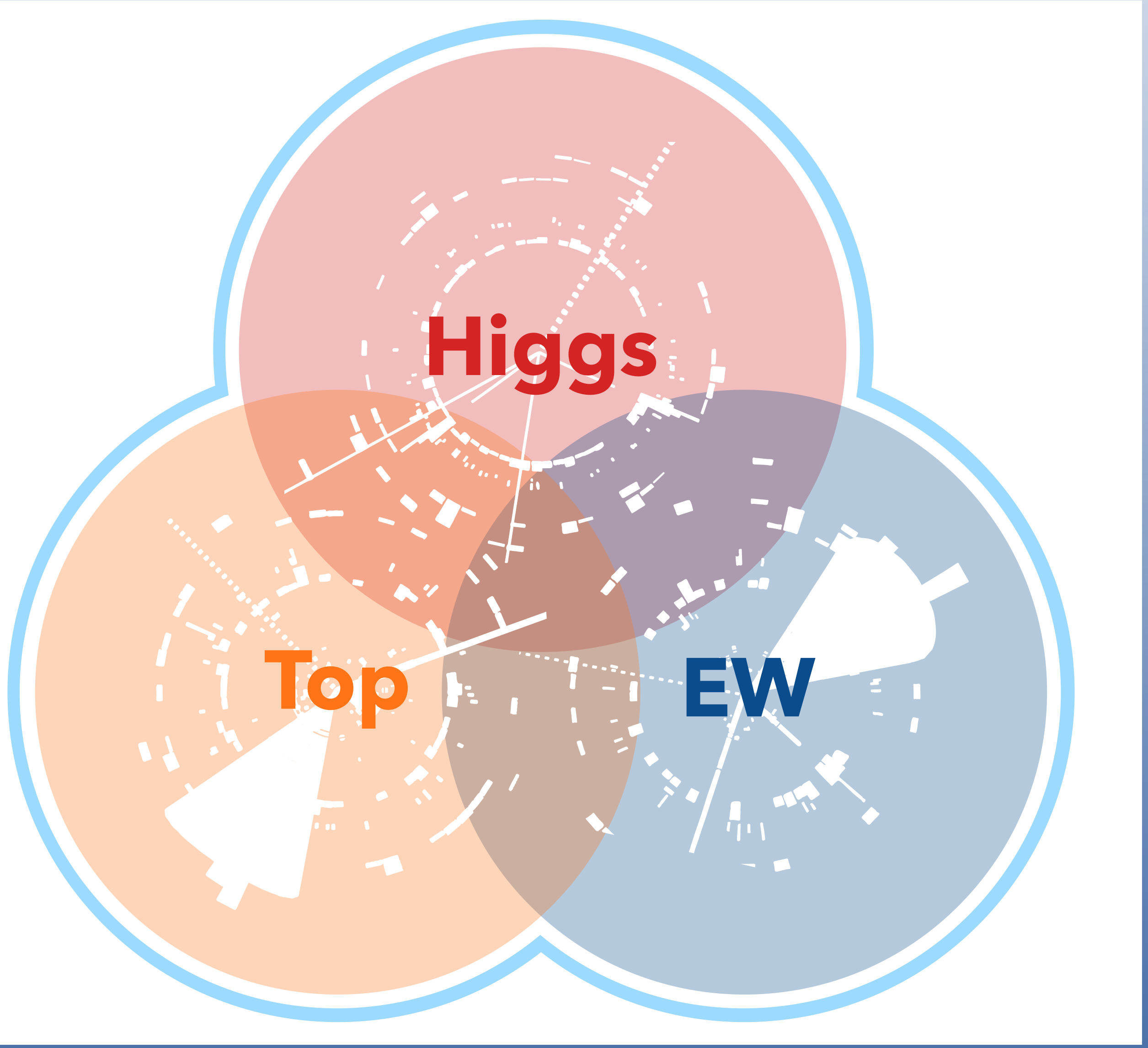


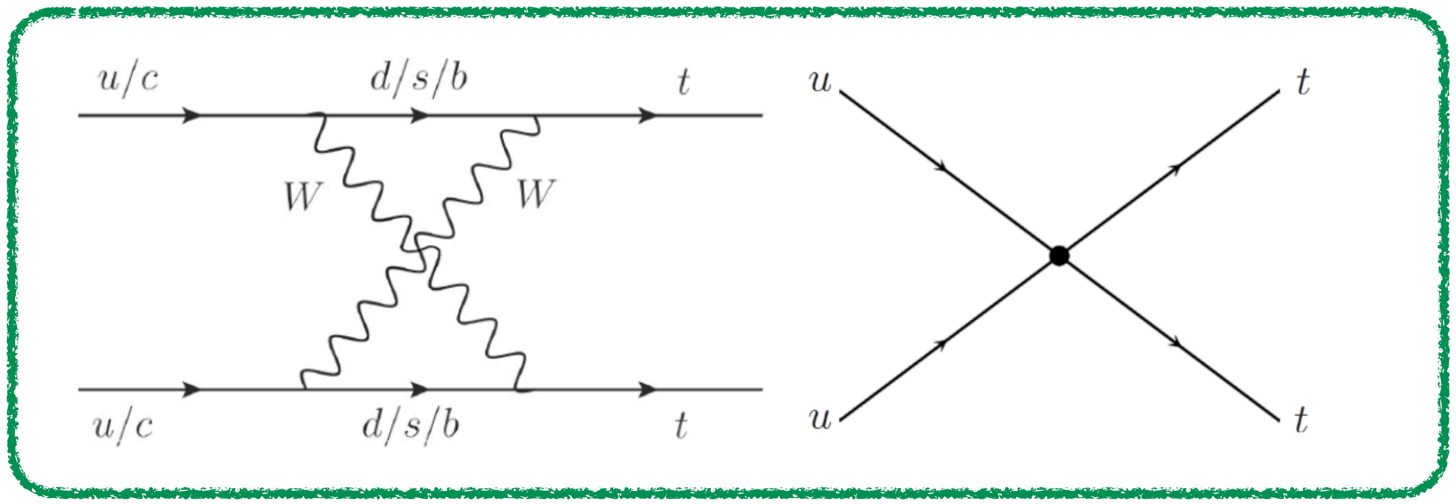
Sketch from R.Balasubramanian
inspired by Ken Mimasu

Observables	NN distributions
EFT framework	SMEFT + FCNC
Operators	CP-even
Results	one-at-a-time and simultaneous limits on EFT parameters.

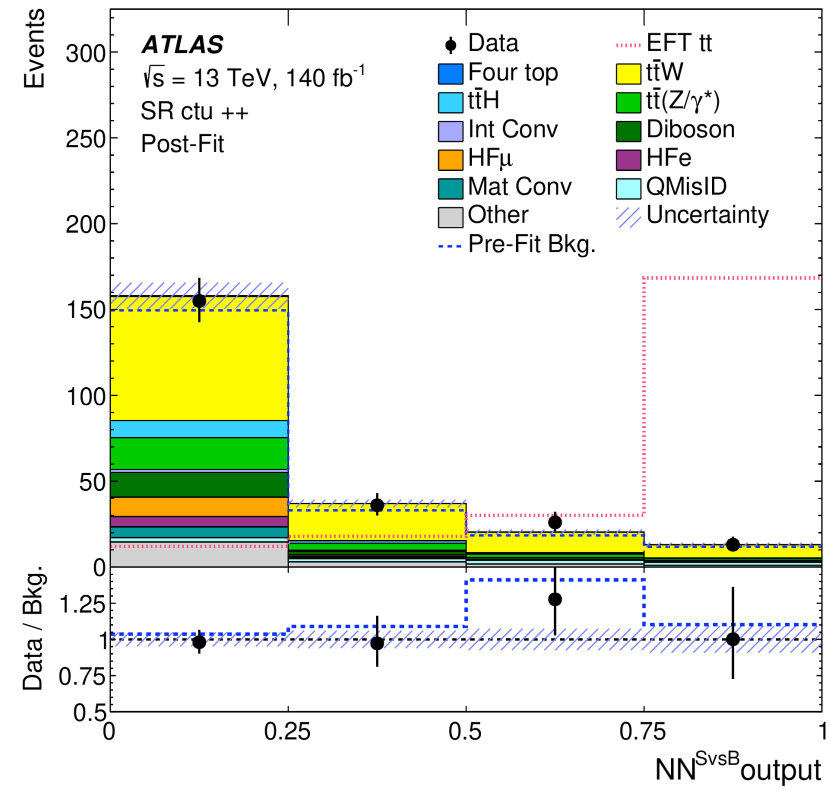
EFT interpretation from the search for same-sign top quark pairs

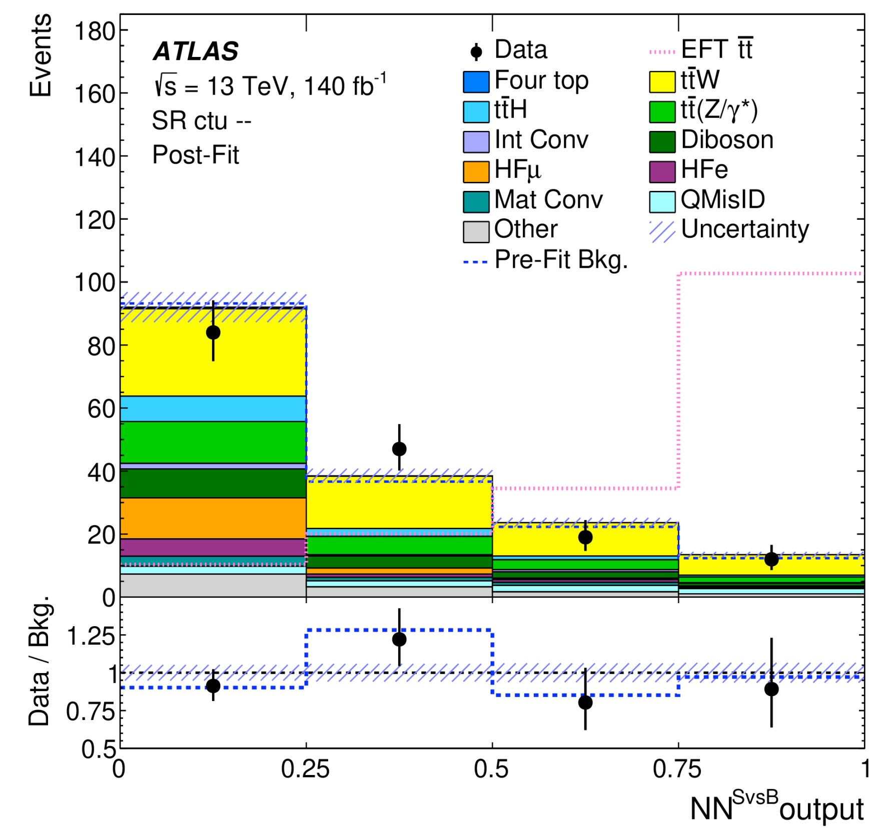
arXiv:2409.14982

- Search for the production of top-quark pairs with the same electric charge (tt or $\bar{t}\bar{t}$); events with two same-charge leptons and at least two b-tagged jets are selected.



- **Neural networks** (NN) are employed to define signal regions sensitive to the EFT operators.
- NNs are trained to discriminate between SS top-quark pairs generated by the different EFT operators.
- Only the **four-fermion operators** $c_{tu}^{(1)}, c_{Qu}^{(1)}, c_{Qu}^{(8)}$ are considered
- The results are in agreement with the SM, with no significant signal detected.

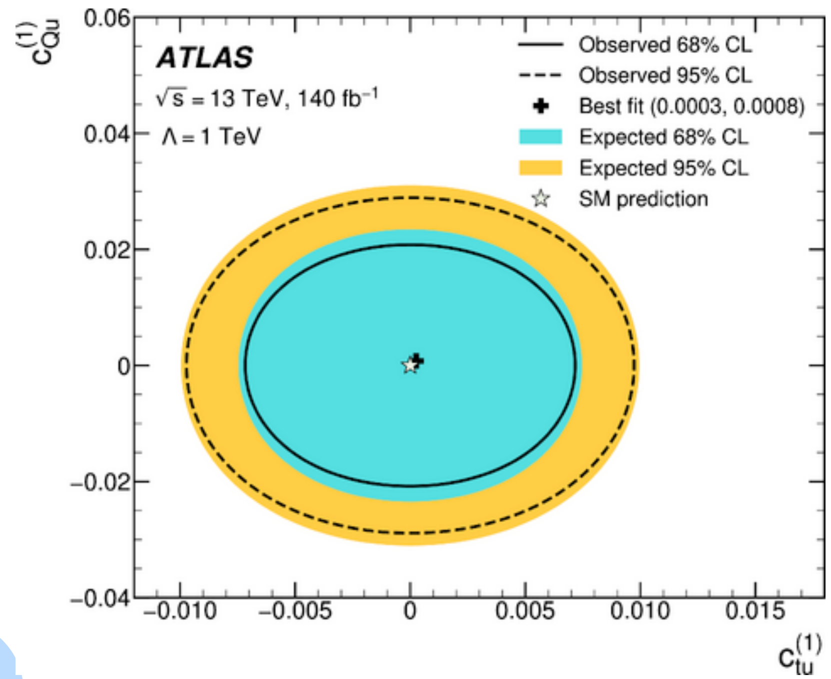


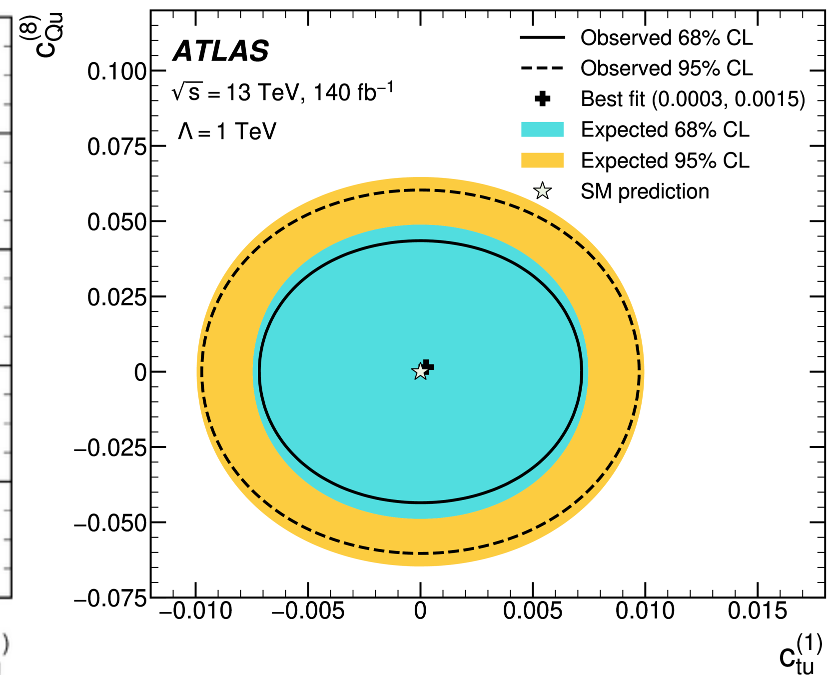


EFT interpretation from the search for same-sign top quark pairs

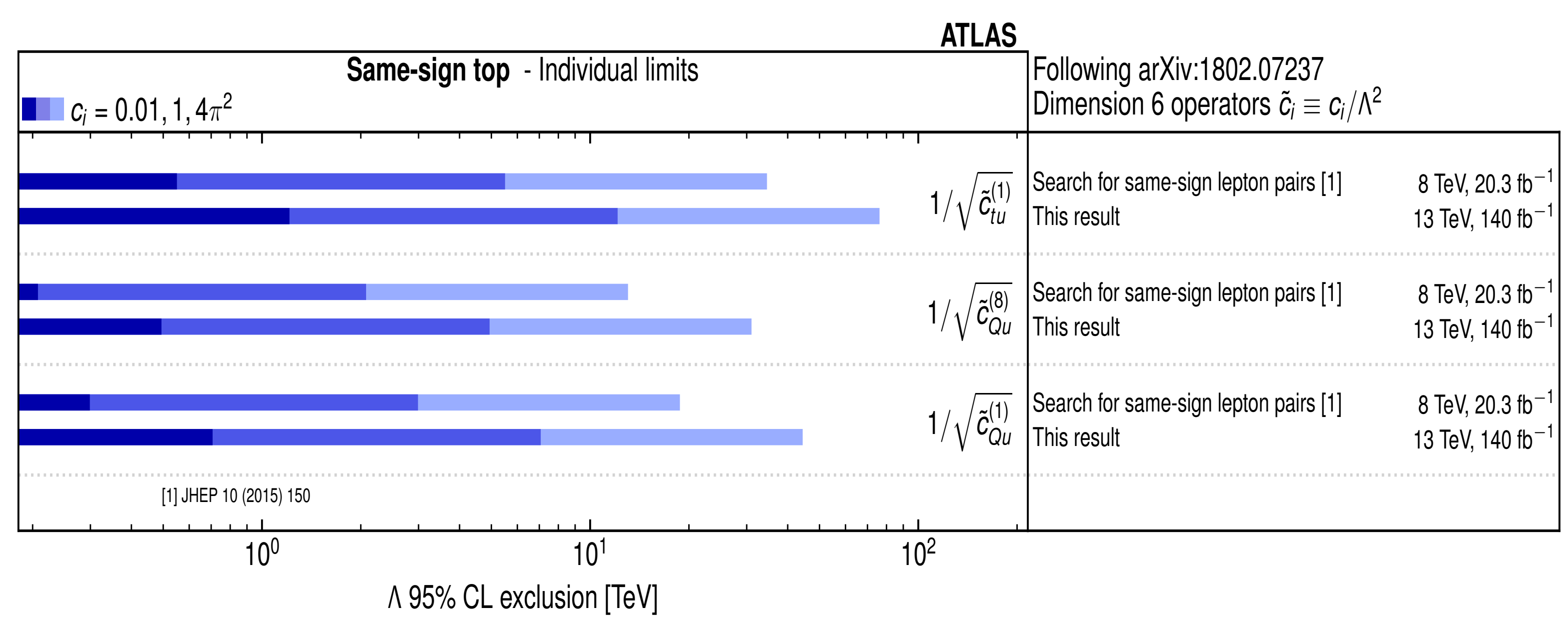
- Upper limits on the three WCs are determined by running **1D- and 2D-likelihood scans.**
- The sensitivity of the analysis is limited by the **statistical uncertainties.**
- Most stringent limits on the WCs $c_{tu}^{(1)}, c_{Qu}^{(1)}, c_{Qu}^{(8)}$ to date, improving previous limits by approximately a factor of 10.

Uncertainties	Wilson Coefficient CIs at 95% CL ($\times 10^{-2}$) $c_{tu}^{(1)}$	$c_{Qu}^{(1)}$	$c_{Qu}^{(8)}$
Statistical uncertainty only	[-0.65, 0.65]	[-1.9, 1.9]	[-3.9, 3.9]
Statistical + modeling uncertainties	[-0.67, 0.67]	[-1.9, 1.9]	[-4.0, 4.0]
Total uncertainty	[-0.68, 0.68]	[-2.0, 2.0]	[-4.1, 4.1]





- Observed lower limits at 95% confidence level on the scale of new physics Λ for different values of WCs



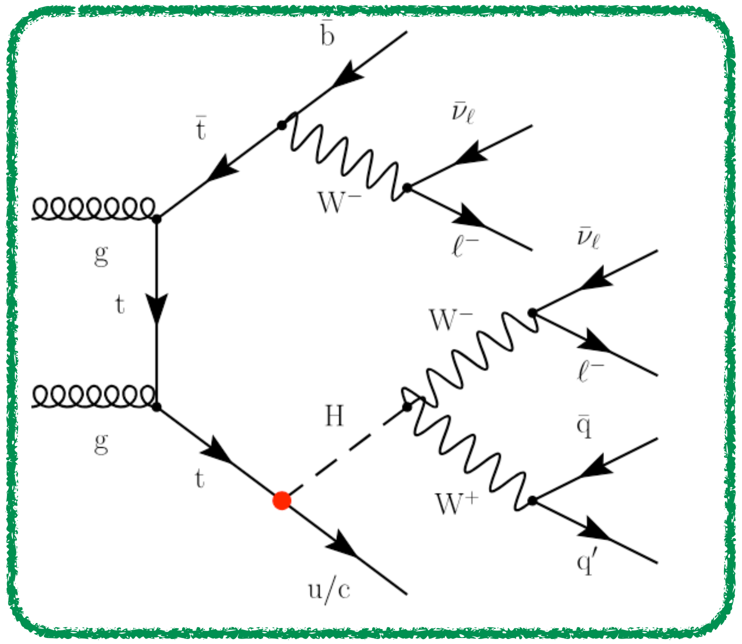
Interpretations from the search for *tHq* FCNC

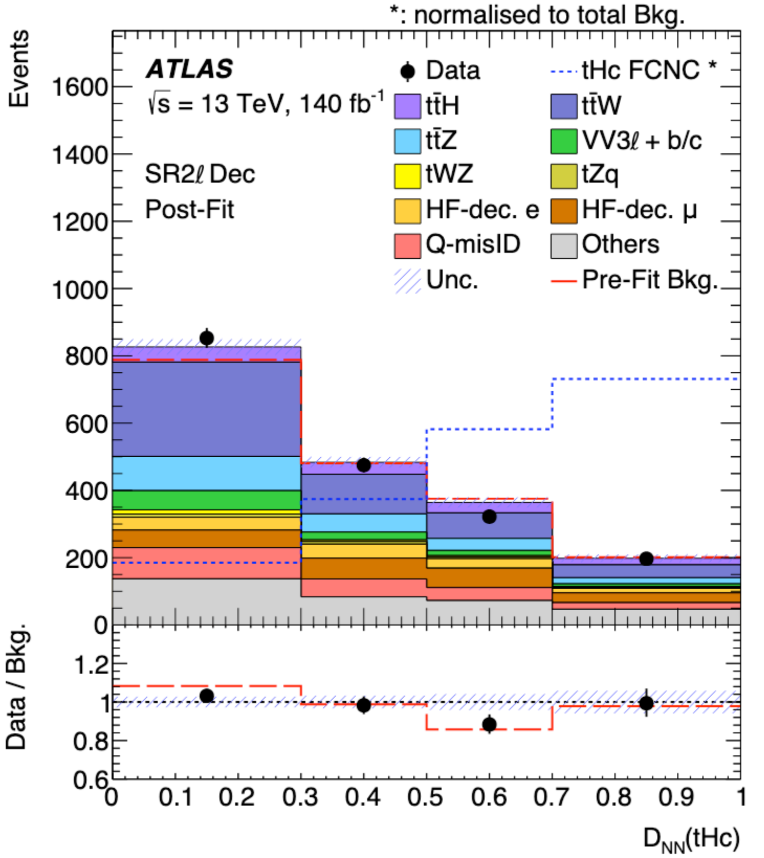
Eur. Phys. J. C 84 (2024) 757

- Search for **flavour-changing neutral-current** (FCNC) couplings between the top quark, the Higgs boson and a second up-type quark with **leptonic decays** of the top quark along with Higgs boson decays into two **W bosons, two Z bosons or a τ +τ − pair.**
- FCNC vertices are tested both in both top-quark production and top-quark decay.
- Coupling parametrized via an effective field theory:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{q=u,c}\left[\frac{C_{u\phi}^{qt}}{\Lambda^2}O_{u\phi}^{qt} + \frac{C_{u\phi}^{tq}}{\Lambda^2}O_{u\phi}^{tq}\right].$$

- No differences between $c_{u\phi}^{qt}$ and $c_{u\phi}^{tq}$: the top quarks are produced unpolarised and the Higgs boson is a scalar particle-> limits on $C_{u\phi}^{qt,tq} = \frac{C_{u\phi}^{qt}+C_{u\phi}^{tq}}{2}$
- The signal vs background neural network distributions are used as discriminant. The distribution of the neural network output is used as input to a maximum-likelihood fit:
  - upper limits are set on the FCNC BRs and the Wilson coefficients of the EFT dimension-6 operators.
- The results are compatible with the SM and no evidence of FCNC couplings is observed.





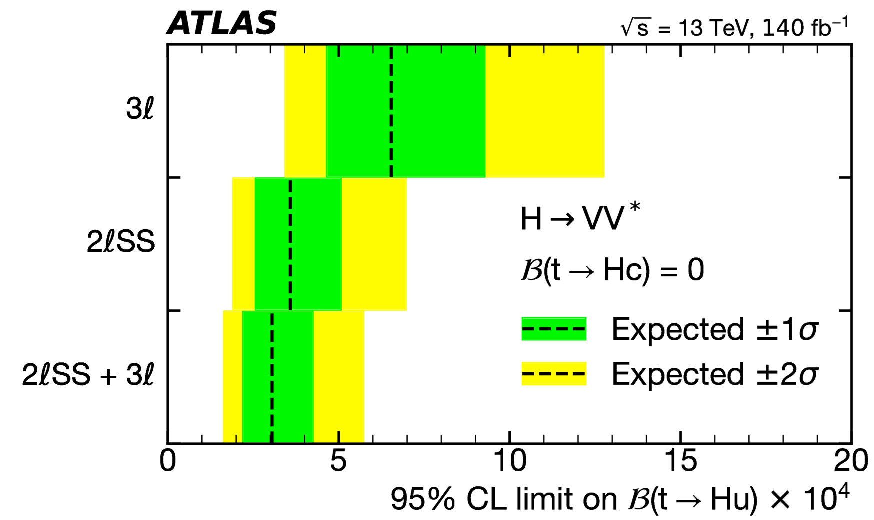
Interpretations from the search for *tHq* FCNC

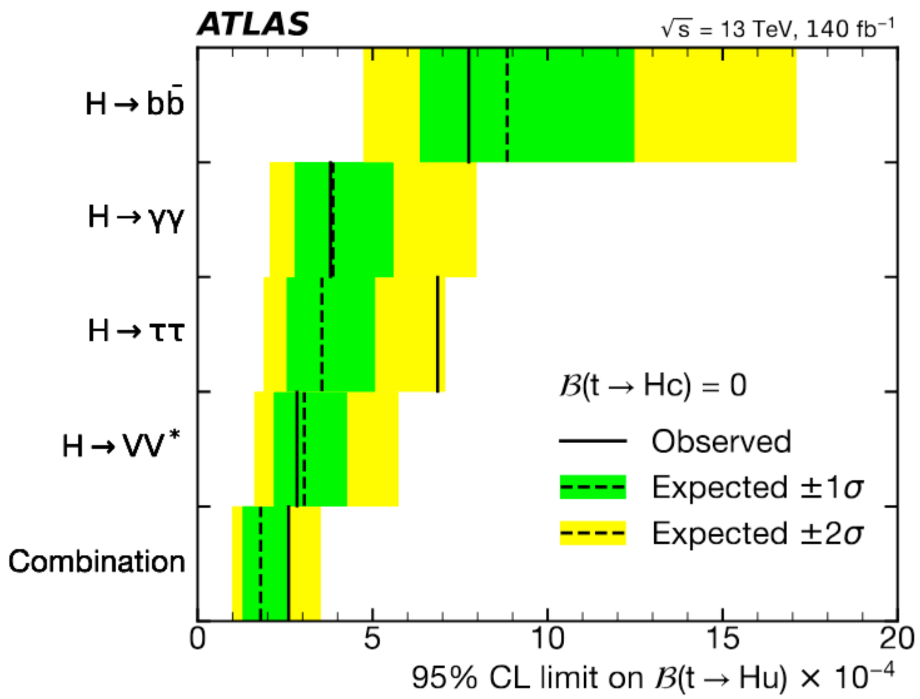
Eur. Phys. J. C 84 (2024) 757

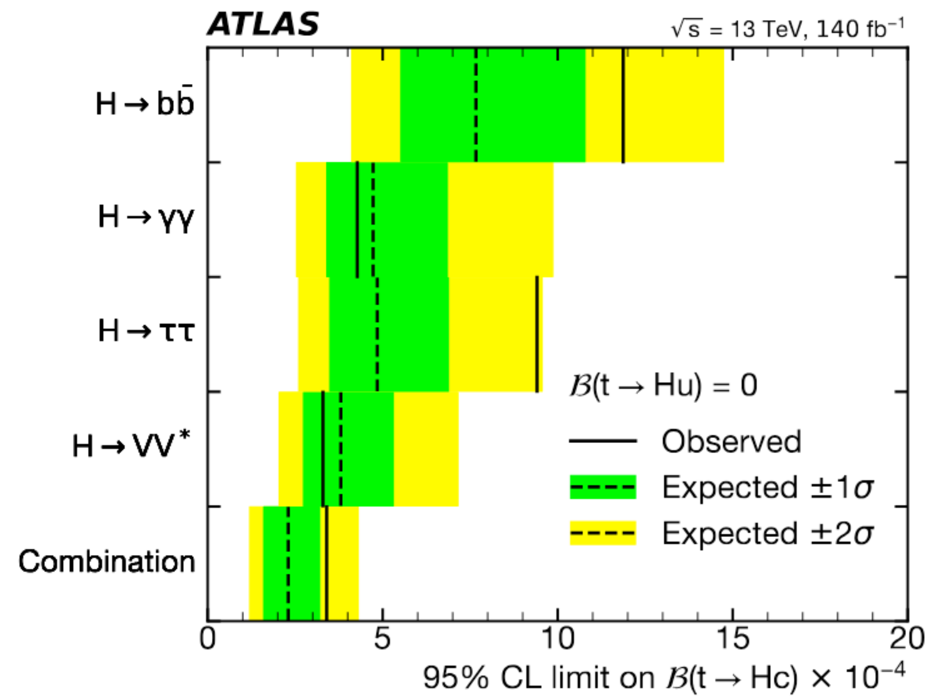
- Upper limits at 95 % CL are set on the branching ratio B(t → Hq).
- The branching ratios are reinterpreted as limits on the average of the Wilson coefficients for the left-handed and the right-handed dimension-6 operators modelling the effective tHq couplings (Λ = 1 TeV).
- These are the most stringent upper limits reported for H to VV*.

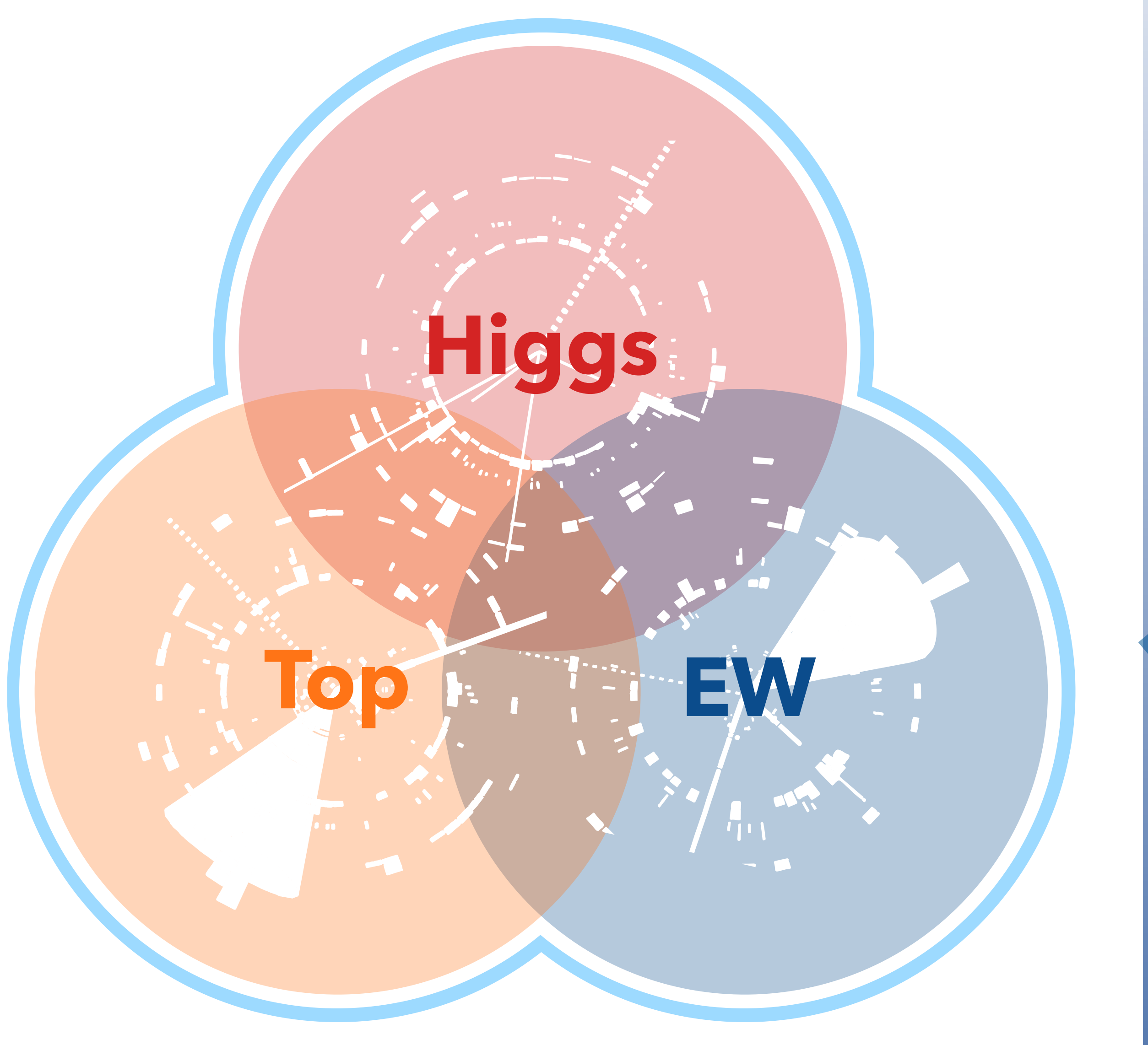
- Results are statistically combined with those from other ATLAS searches for *tHq* FCNC interactions in different final states.

Signal	Observed (expected) 95% CL upper limits $\mathcal{B}(t \to Hq)$	$\lvert C_{u\phi}^{qt,tq} \rvert$
tHu	$2.8\ (3.0) \times 10^{-4}$	0.71 (0.73)
tHc	$3.3\ (3.8) \times 10^{-4}$	0.76 (0.82)









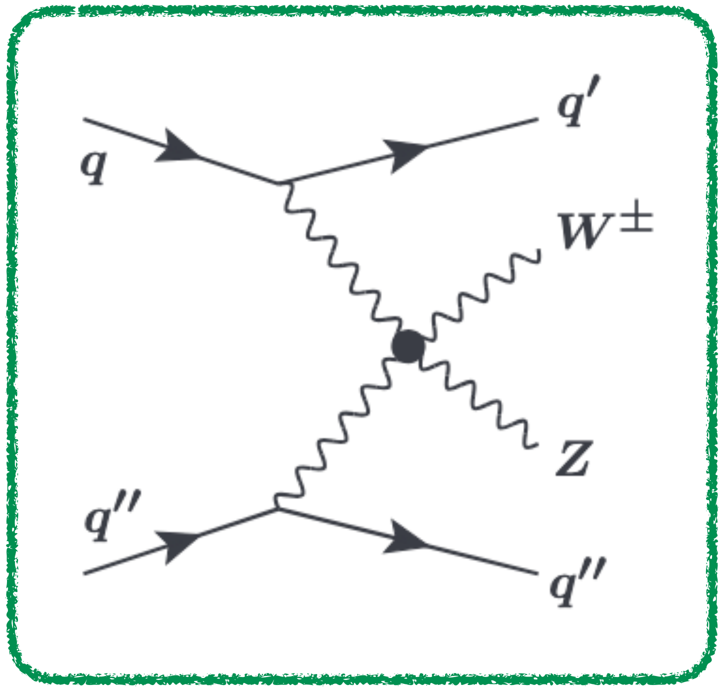
- **Electroweak WZ boson pair production in association with two jets,** [JHEP 06 (2024) 192]
- **Same-sign W boson pair production in association with two jets** [JHEP 04 (2024) 026]

Observables	Differential
EFT framework	Dim8 EFT
Operators	M,S, T operators
Results	one-at-a-time and 2D limits

Electroweak WZ boson pair production in association with two jets

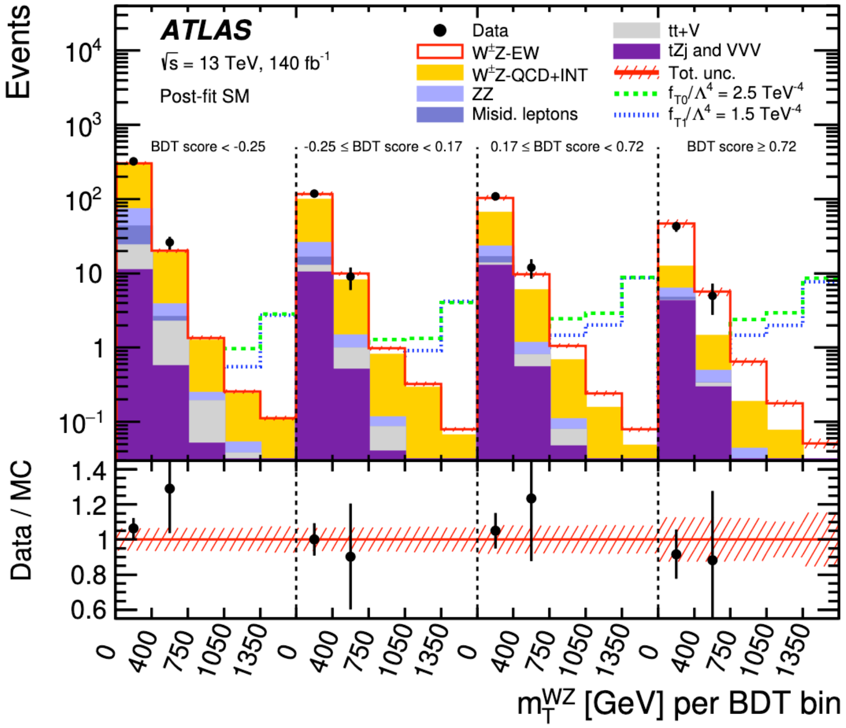
JHEP 06 (2024) 192

- Measurements of integrated and differential cross-sections for electroweak $W^{\pm}Z$ production in association with two jets (three identified leptons, either electrons or muons, and two jets are selected).
- Unfolded cross sections used to search for signatures of anomalous weak-boson quartic interactions using the framework of **dimension-8 EFT**
  - all dimension-6 couplings, affecting triple gauge boson couplings, are assumed to be equal to zero.



- This analysis almost completes the Run2 program of VBS measurements in ATLAS, with WW (SS and OS), WZ, Wγ, ZZ, Zγ observed and studied

- A two-dimensional combination of the BDT score, separating **WZjj–EW** from **WZjj–QCD** events, and m_T^{WZ} observables is used to look for dimension-8 EFT contributions.
- The bin boundaries are optimised to obtain the best expected limits when no unitarisation cut-off are applied.



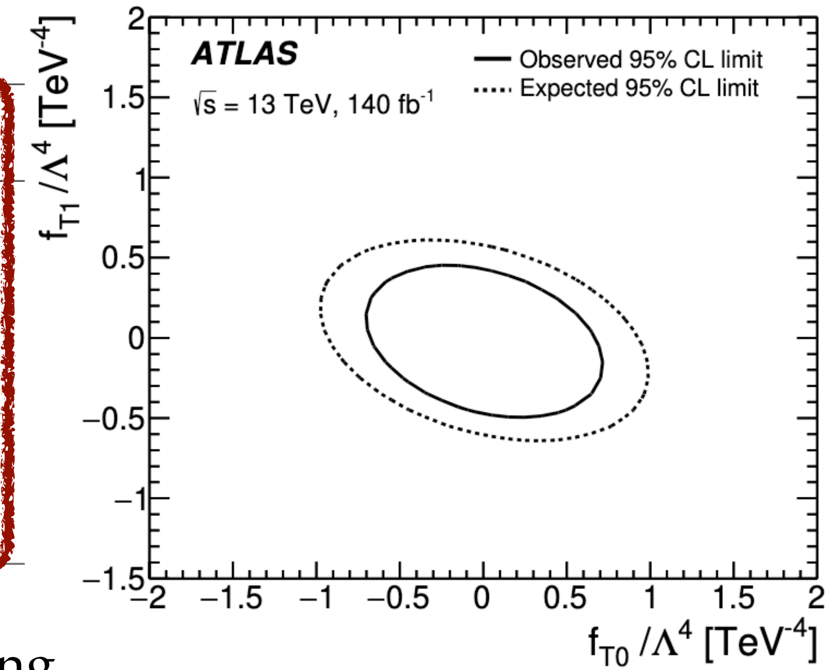
Electroweak WZ boson pair production in association with two jets

JHEP 06 (2024) 192

- f_{T0}/Λ^4 and f_{T1}/Λ^4 are the most tightly constrained.
- Non-zero dimension-8 operators violate tree-level unitarity at sufficiently high energy.
- More physical limits are obtained by **removing the EFT contribution** above the **unitarity limit** and keeping the SM prediction even above the unitarity limit

no unitarisation procedure

	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
f_{T0}/Λ^4	[-0.80, 0.80]	[-0.57, 0.56]
f_{T1}/Λ^4	[-0.52, 0.49]	[-0.39, 0.35]
f_{T2}/Λ^4	[-1.6, 1.4]	[-1.2, 1.0]
f_{M0}/Λ^4	[-8.3, 8.3]	[-5.8, 5.6]
f_{M1}/Λ^4	[-12.3, 12.2]	[-8.6, 8.5]
f_{M7}/Λ^4	[-16.2, 16.2]	[-11.3, 11.3]
f_{S02}/Λ^4	[-14.2, 14.2]	[-10.4, 10.4]
f_{S1}/Λ^4	[-42, 41]	[-30, 30]



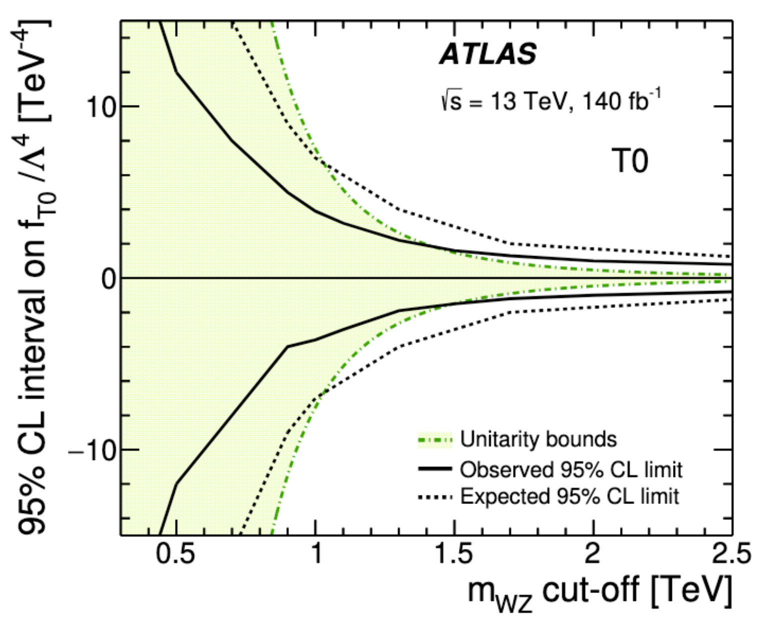
- Individual 95% CL intervals of each Wilson coefficients obtained when applying a unitarisation cut-off at the unitarity bound are reported.
- The constraints are similar to those obtained by the CMS Collaboration using the W±Zjj final state

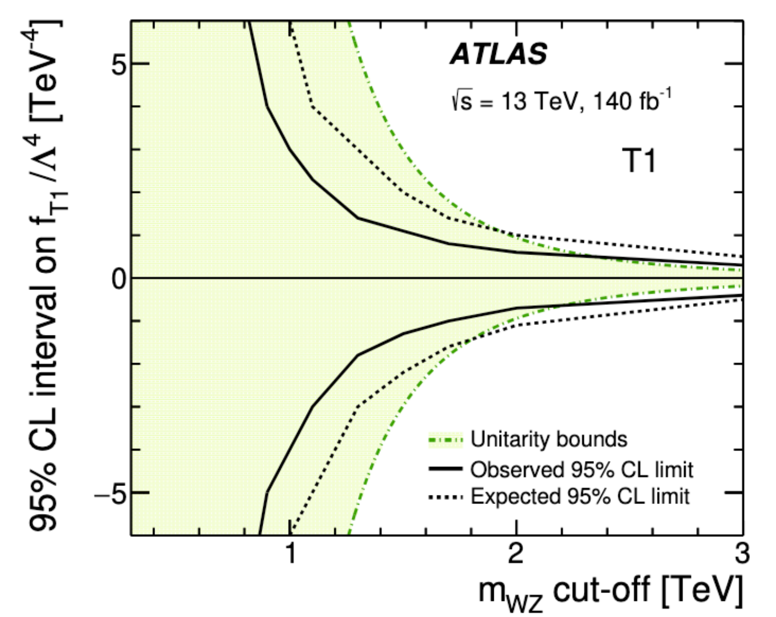
unitarisation cut-off set at the unitary bound

		Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
field strength tensors	f_{T0}/Λ^4	[-7.0, 7.0]	[-1.5, 1.6]
	f_{T1}/Λ^4	[-1.1, 1.0]	[-0.7, 0.6]
	f_{T2}/Λ^4	[-12, 6]	[-2.4, 1.8]
covariant derivative+field strength tensors	f_{M0}/Λ^4	[-60, 60]	[-12, 12]
	f_{M1}/Λ^4	[-32, 32]	[-15, 15]
	f_{M7}/Λ^4	[-30, 30]	[-15, 15]
covariant derivative	f_{S02}/Λ^4	[-41, 41]	[-18, 18]
	f_{S1}/Λ^4	—	—

OS1 operator: no crossing with the unitarity bound was found in the scanned region above 600 GeV

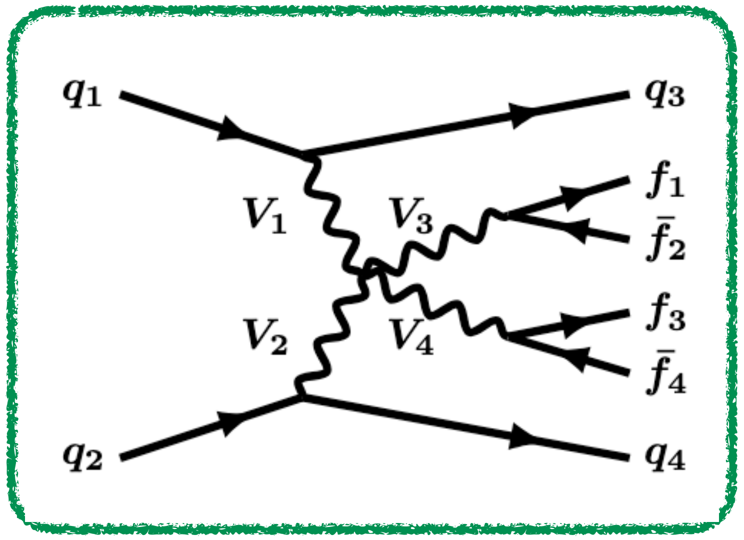
- Evolution of the expected and observed 95% CL intervals as a function of the cut-off scale m_{WZ} used in the unitarisation procedure



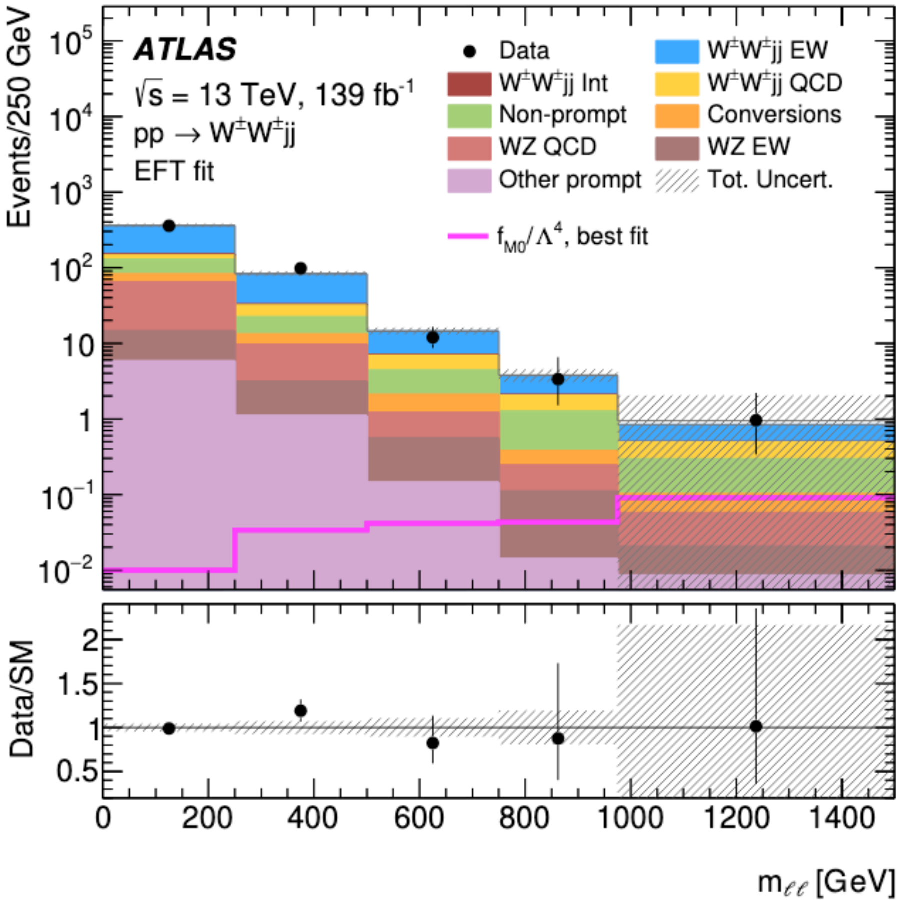


Same-sign W boson pair production in association with two jets

JHEP 04 (2024) 026



- Fiducial and differential cross sections for the electroweak and inclusive production of a same-sign W boson pair in association with two jets ($W\pm W\pm\ j\ j$).
- Two same-charge leptons, electron or muon, and at least two jets with large invariant mass and a large rapidity difference are selected.

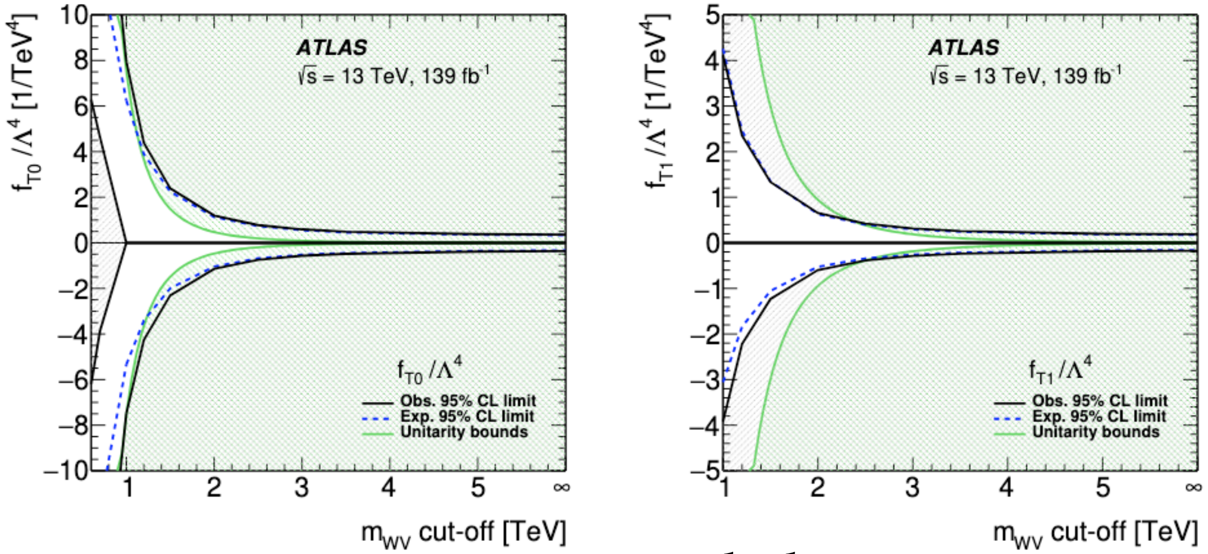


- Differential $m_{\ell\ell}$ distribution with optimised binning is used to set limits on independent charge-conjugate and parity conserving Dim-8 effective operators:

$$f_{S02}/\Lambda^4, f_{S1}/\Lambda^4, f_{M0}/\Lambda^4, f_{M1}/\Lambda^4, f_{M7}/\Lambda^4, f_{T0}/\Lambda^4, f_{T1}/\Lambda^4, \text{ and } f_{T2}/\Lambda^4.$$

- More physical limits are obtained by removing the EFT contributions above the unitarity limit and keeping the SM predictions for all VV invariant masses, even above the unitarity limit (clipping).

Same-sign W boson pair production in association with two jets



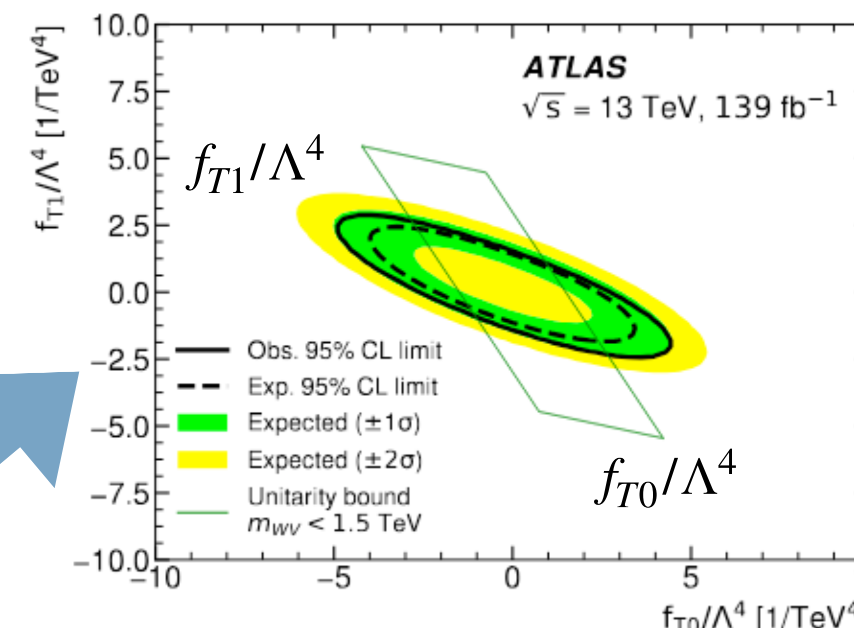
- For clipping scales below approximately 1 TeV , zero values of the coefficients f_{M0}, f_{S1}, f_{S02}, and f_{T0} are excluded at 95% CL.

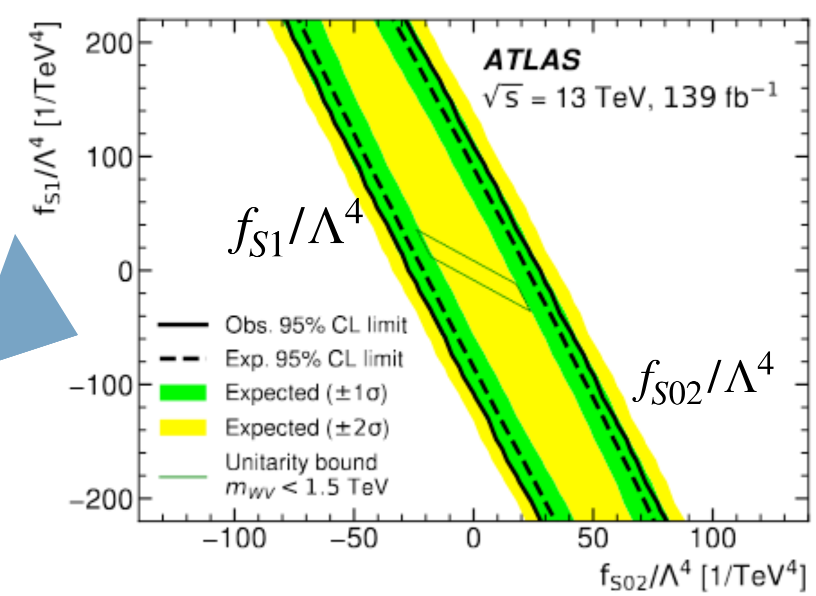
- Constraints competitive with those previously obtained by the CMS Collaboration using the same final state.

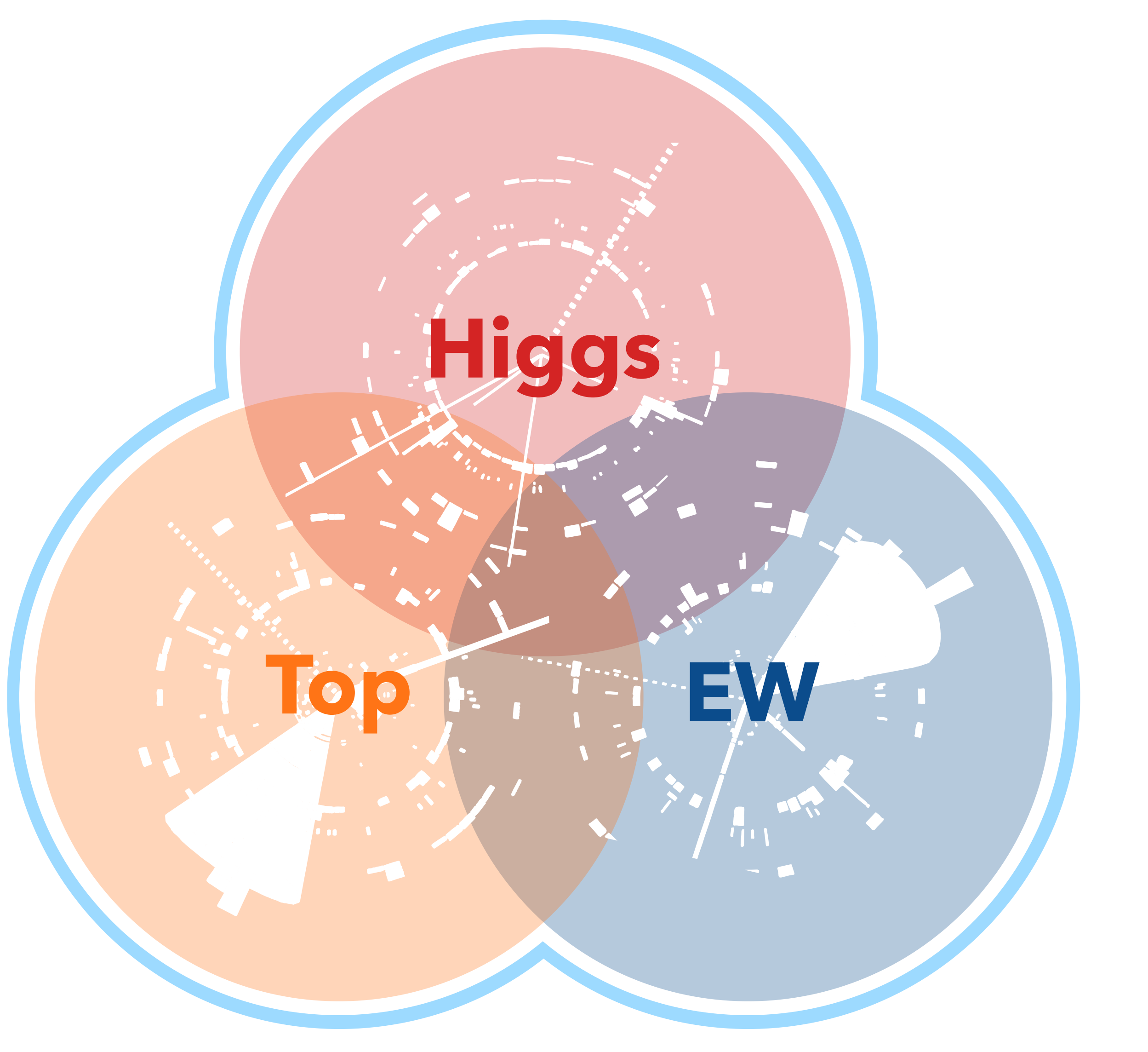
Three families of operators (M, S - covariant derivative, T)

Coefficient	Type	No unitarisation cut-off [TeV^{-4}]	Lower, upper limit at the respective unitarity bound [TeV^{-4}]
f_{M0}/Λ^4	Exp.	[-3.9, 3.8]	-64 at 0.9 TeV, 40 at 1.0 TeV
	Obs.	[-4.1, 4.1]	-140 at 0.7 TeV, 117 at 0.8 TeV
f_{M1}/Λ^4	Exp.	[-6.3, 6.6]	-25.5 at 1.6 TeV, 31 at 1.5 TeV
	Obs.	[-6.8, 7.0]	-45 at 1.4 TeV, 54 at 1.3 TeV
f_{M7}/Λ^4	Exp.	[-9.3, 8.8]	-33 at 1.8 TeV, 29.1 at 1.8 TeV
	Obs.	[-9.8, 9.5]	-39 at 1.7 TeV, 42 at 1.7 TeV
f_{S02}/Λ^4	Exp.	[-5.5, 5.7]	-94 at 0.8 TeV, 122 at 0.7 TeV
	Obs.	[-5.9, 5.9]	–
f_{S1}/Λ^4	Exp.	[-22.0, 22.5]	–
	Obs.	[-23.5, 23.6]	–
f_{T0}/Λ^4	Exp.	[-0.34, 0.34]	-3.2 at 1.2 TeV, 4.9 at 1.1 TeV
	Obs.	[-0.36, 0.36]	-7.4 at 1.0 TeV, 12.4 at 0.9 TeV
f_{T1}/Λ^4	Exp.	[-0.158, 0.174]	-0.32 at 2.6 TeV, 0.44 at 2.4 TeV
	Obs.	[-0.174, 0.186]	-0.38 at 2.5 TeV, 0.49 at 2.4 TeV
f_{T2}/Λ^4	Exp.	[-0.56, 0.70]	-2.60 at 1.7 TeV, 10.3 at 1.2 TeV
	Obs.	[-0.63, 0.74]	–

2D limits at 95% CL obtained with a unitarisation cut-off scale of 1.5 TeV







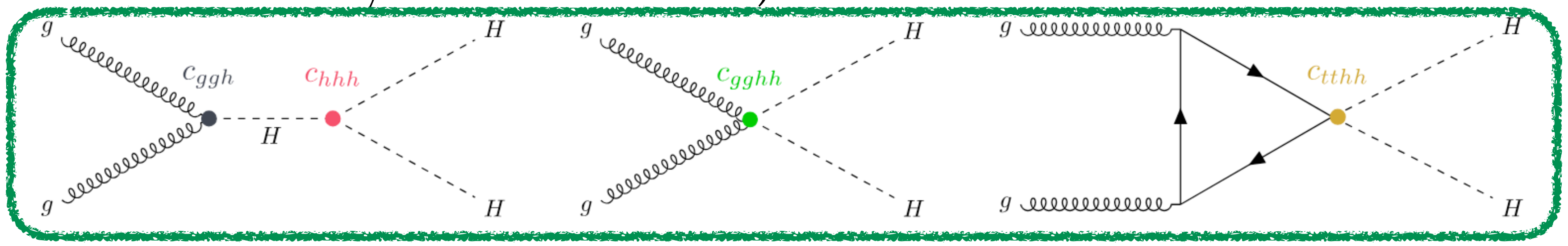
- **EFT interpretations from HH combination,** PhysRevLett.133.101801
- **Interpretations of Higgs combination** JHEP11(2024)097
- **Differential cross-section of $H \to \tau^+\tau^-$,** arxiv:2407.16320

Observables	HH production cross-section, differential, STXS
EFT framework	HEFT, SMEFT - SMEFTsim + SMEFTatNLO
Operators	CP-even + CP-odd
Results	one-at-a-time and simultaneous limits on EFT parameters.

EFT interpretations from HH combination

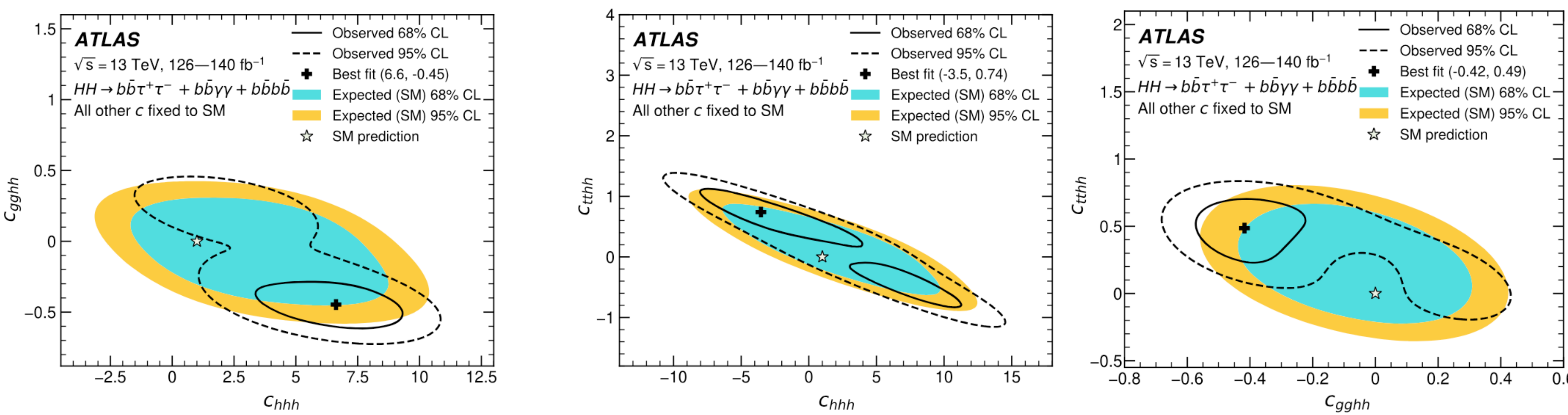
PhysRevLett.133.101801

- The three most sensitive HH decay channels, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, and $b\bar{b}b\bar{b}$, are combined.
- Advantage of HEFT: anomalous single-Higgs-boson and HH couplings defined separately.
- In the HEFT Lagrangian, ggF HH production is described at LO by the Wilson coefficients (WC): c_{hhh}, c_{tth}, c_{ggh}, c_{gghh}, c_{tthh} .
  - c_{hhh} and c_{tth}: coupling modifiers for the Higgs boson self-coupling and top-quark Yukawa coupling.
  - c_{ggh}, c_{gghh}, c_{tthh} affect respectively the ggH, $ggHH$ and $ttHH$ vertex interactions.
- Reweighing methods are used to estimate the particle-level m_{HH} distributions for alternative values of the WCs.
- The most stringent constraints to date on c_{gghh} and c_{tthh} are set (not enough sensitivity for simultaneous constraints of all WCs the analyses are sensitive to).



$-0.38 < c_{gghh} < 0.49(-0.36 < c_{gghh} < 0.36)$

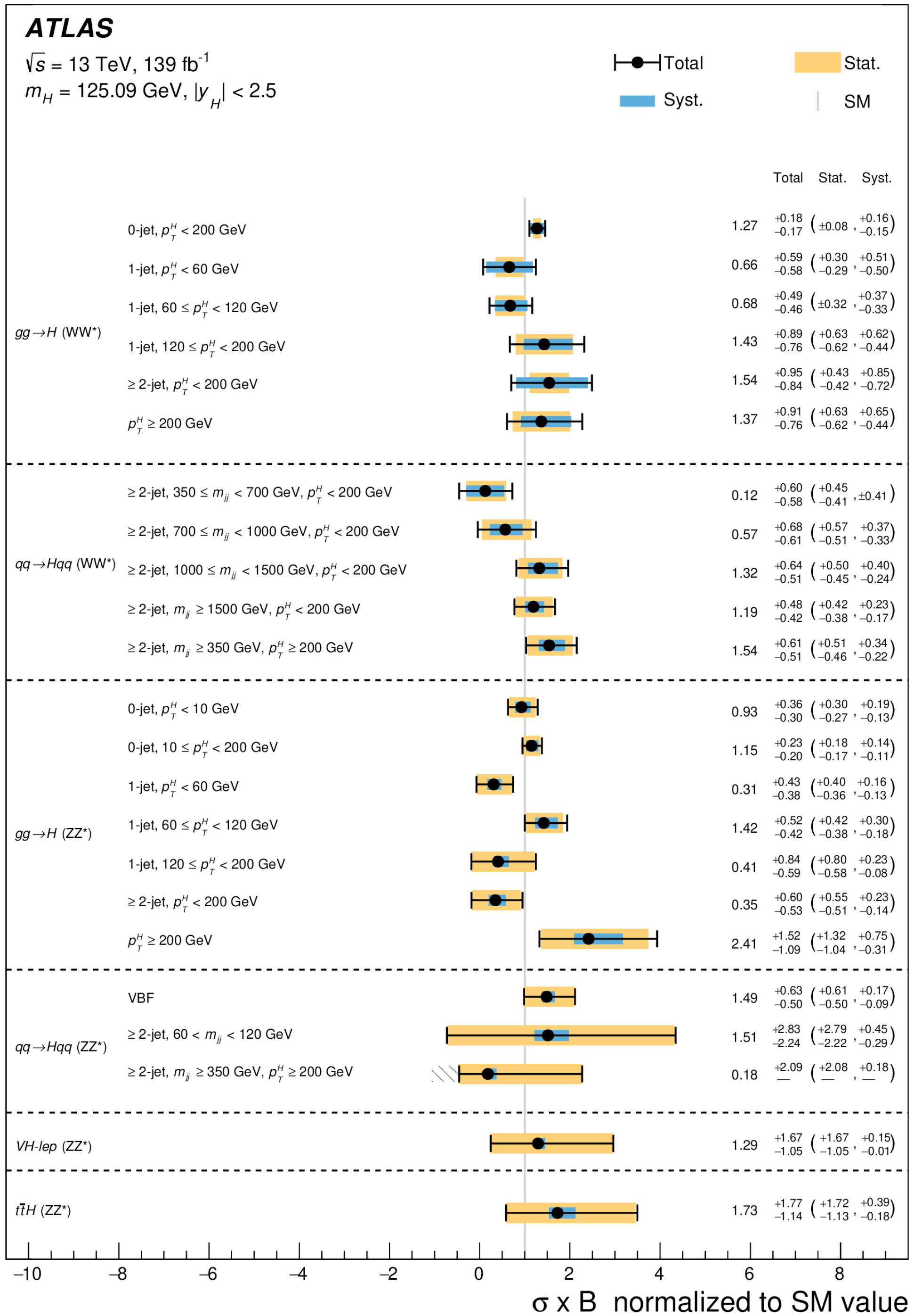
$-0.19 < c_{tthh} < 0.70(-0.27 < c_{tthh} < 0.66)$

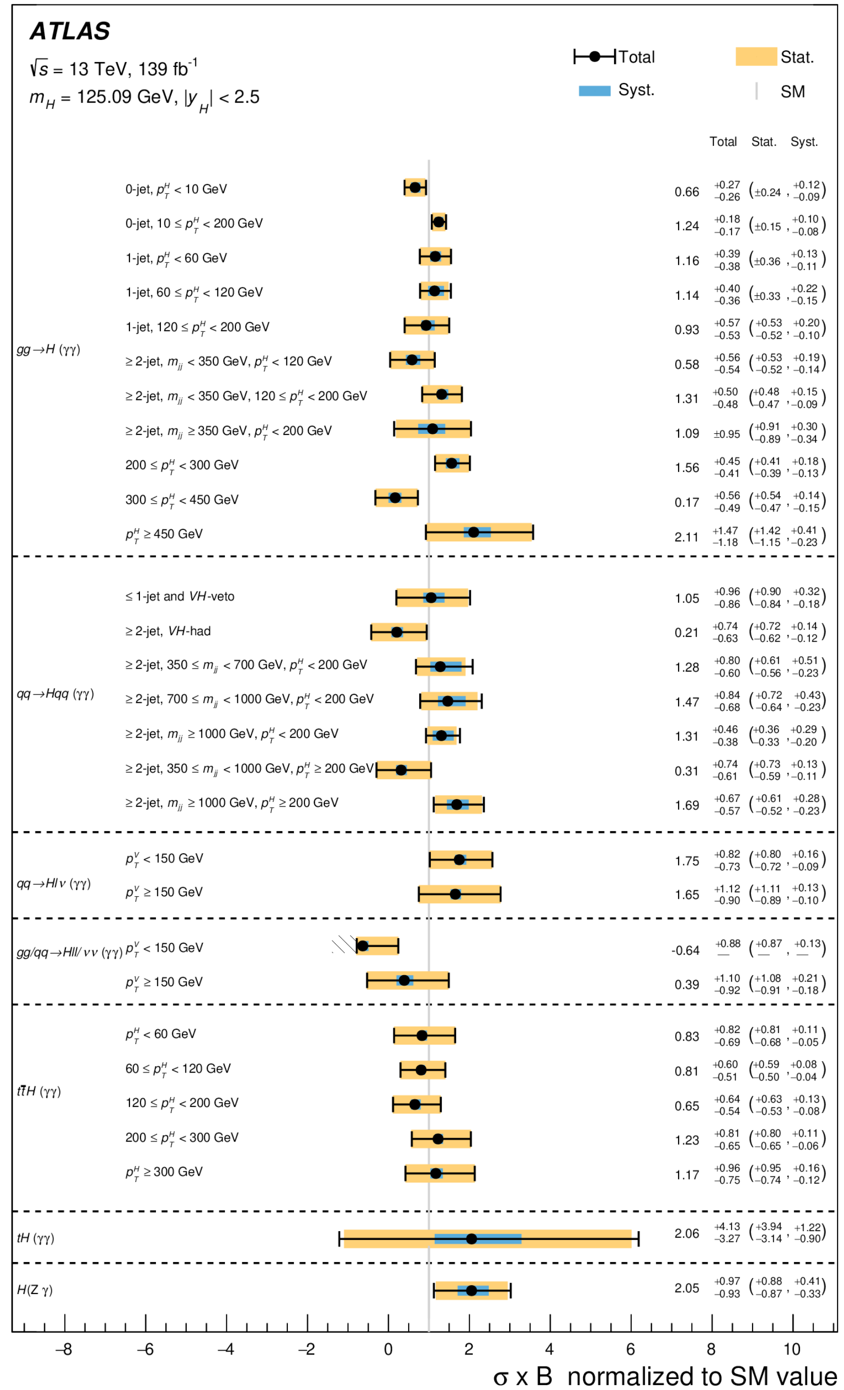


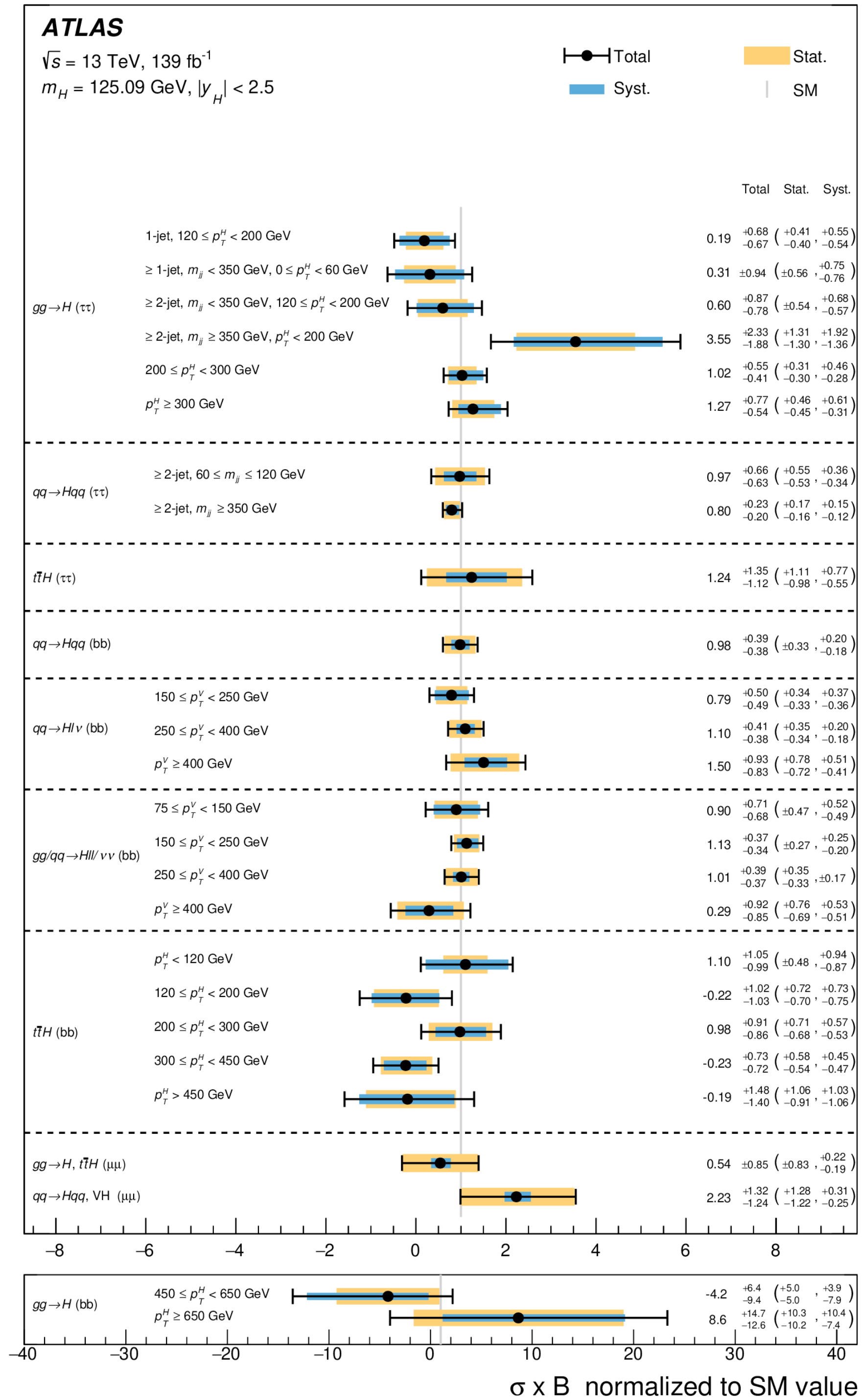
Interpretations of Higgs combination- STXS inputs

Link to Tae's talk on Wednesday

JHEP11(2024)097



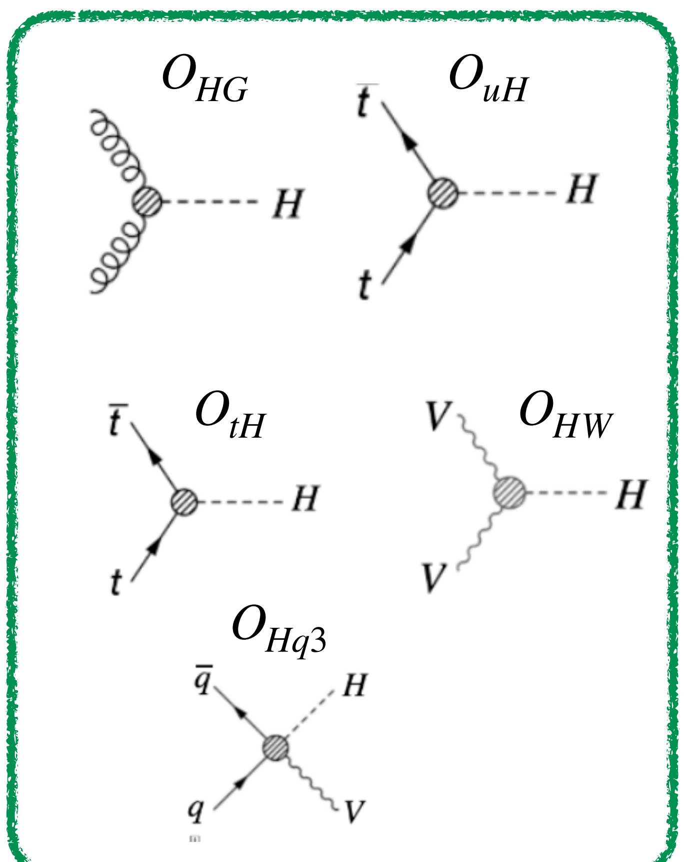


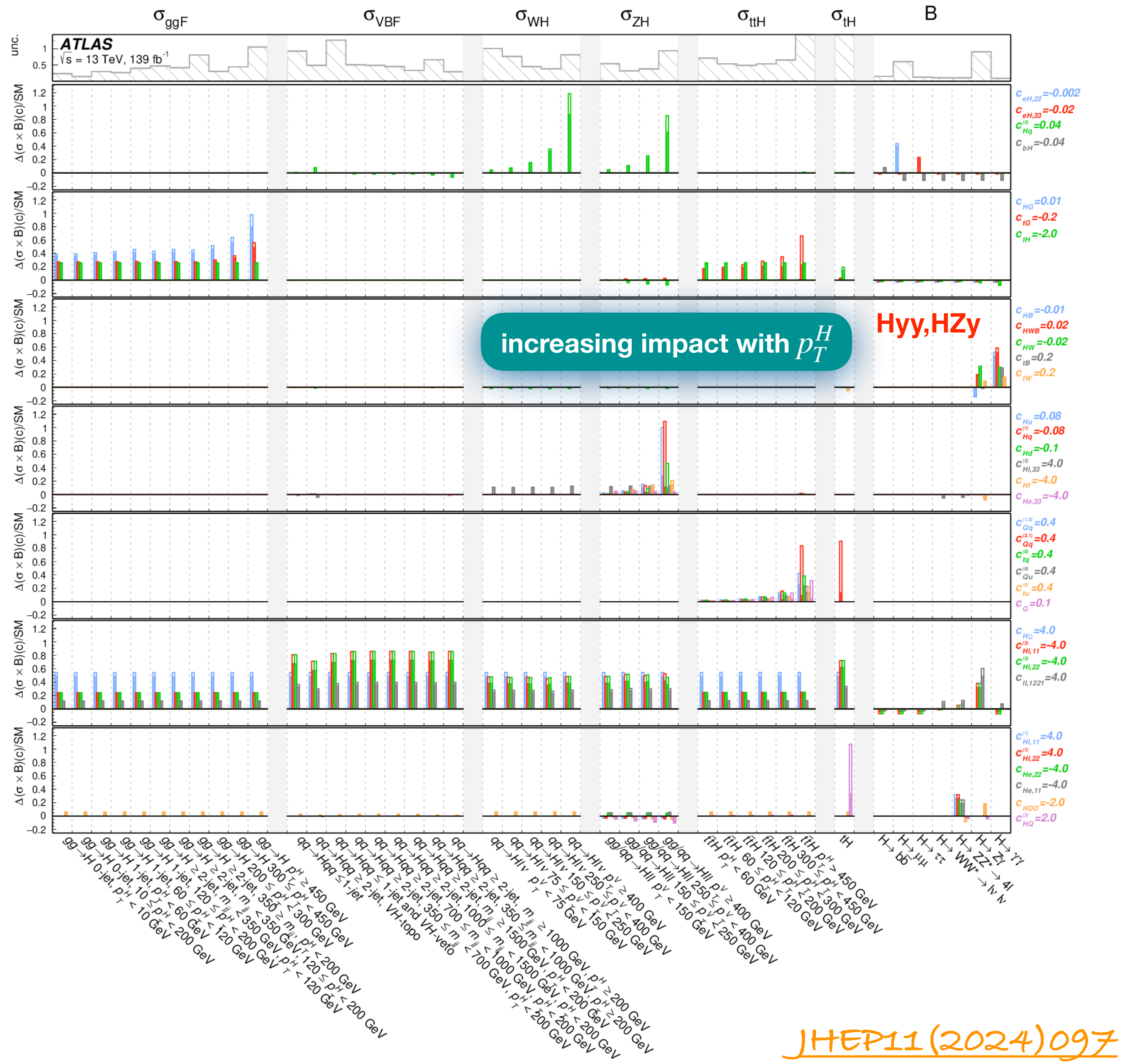


WW, ZZ $\gamma\gamma, Z\gamma$ $\tau\tau, \mu\mu, b\bar{b}$

SMEFT impact on STXS bins and decay

- Impact of Wilson coefficients can be visualised-> Value of ci scaled appropriately for plotting.
- 33 WCs plotted, remaining are subleading.
- Impact of quadratic terms significant for WH,ZH and tH.





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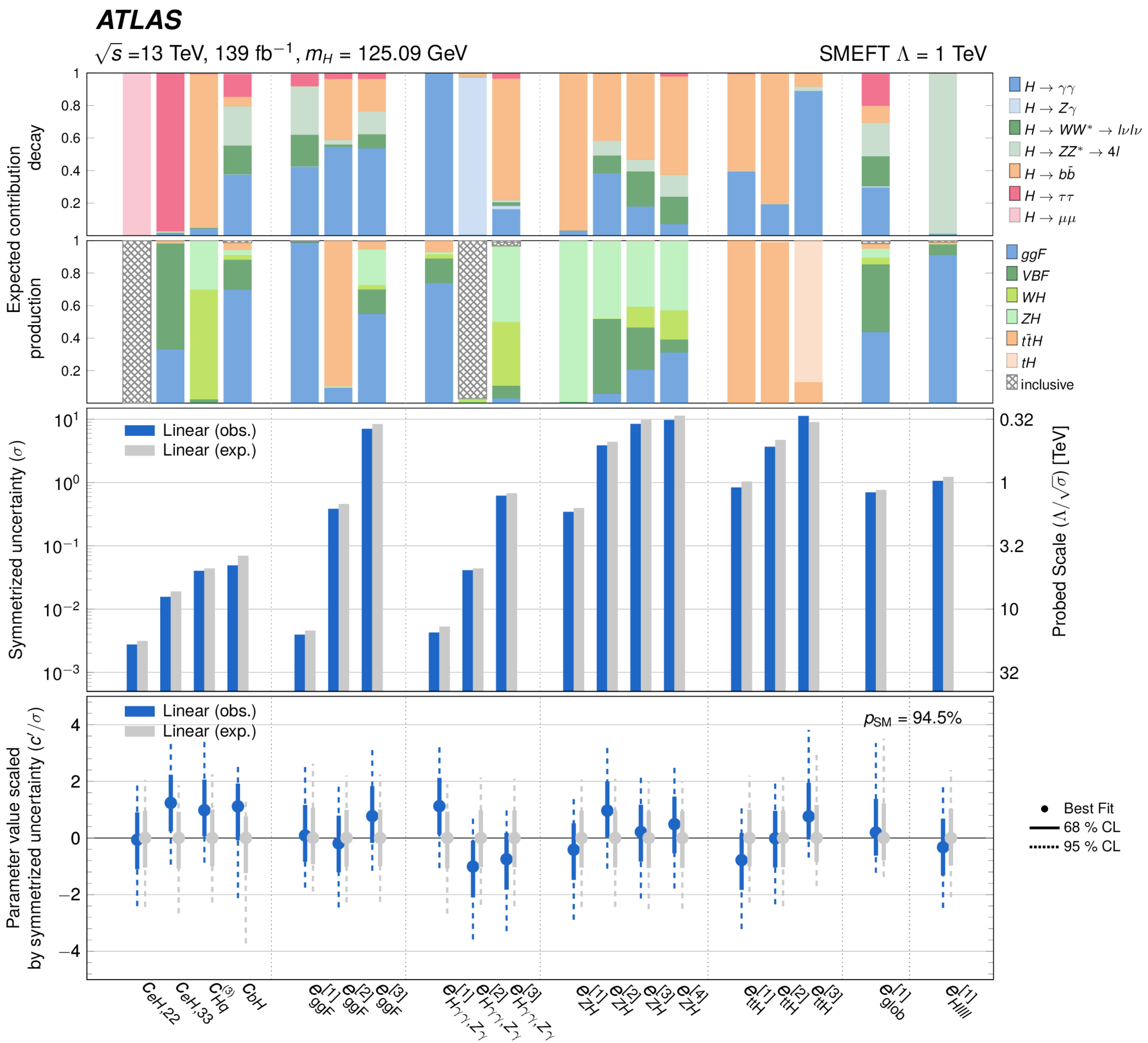
Linear STXS SMEFT results

JHEP11(2024)097

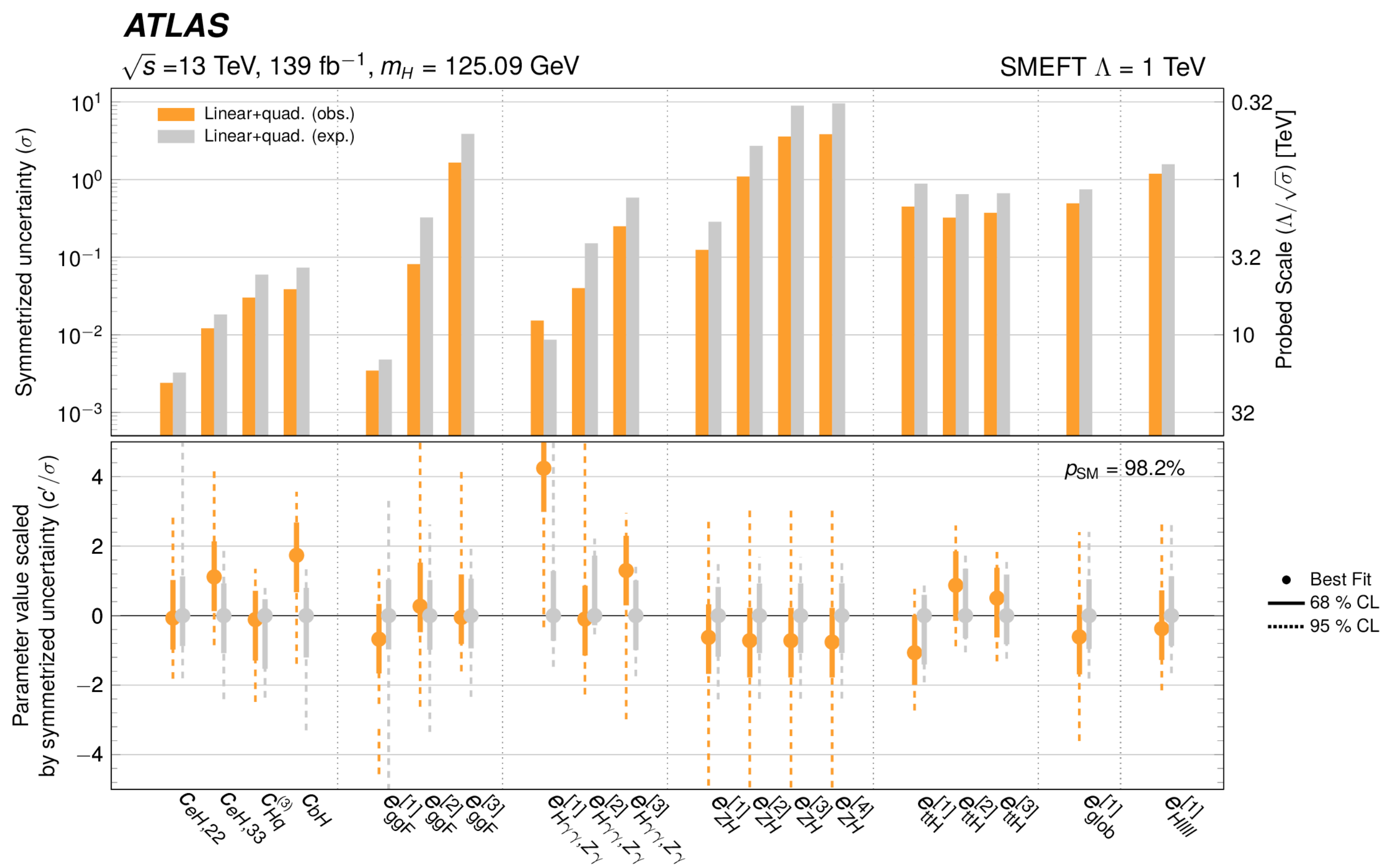


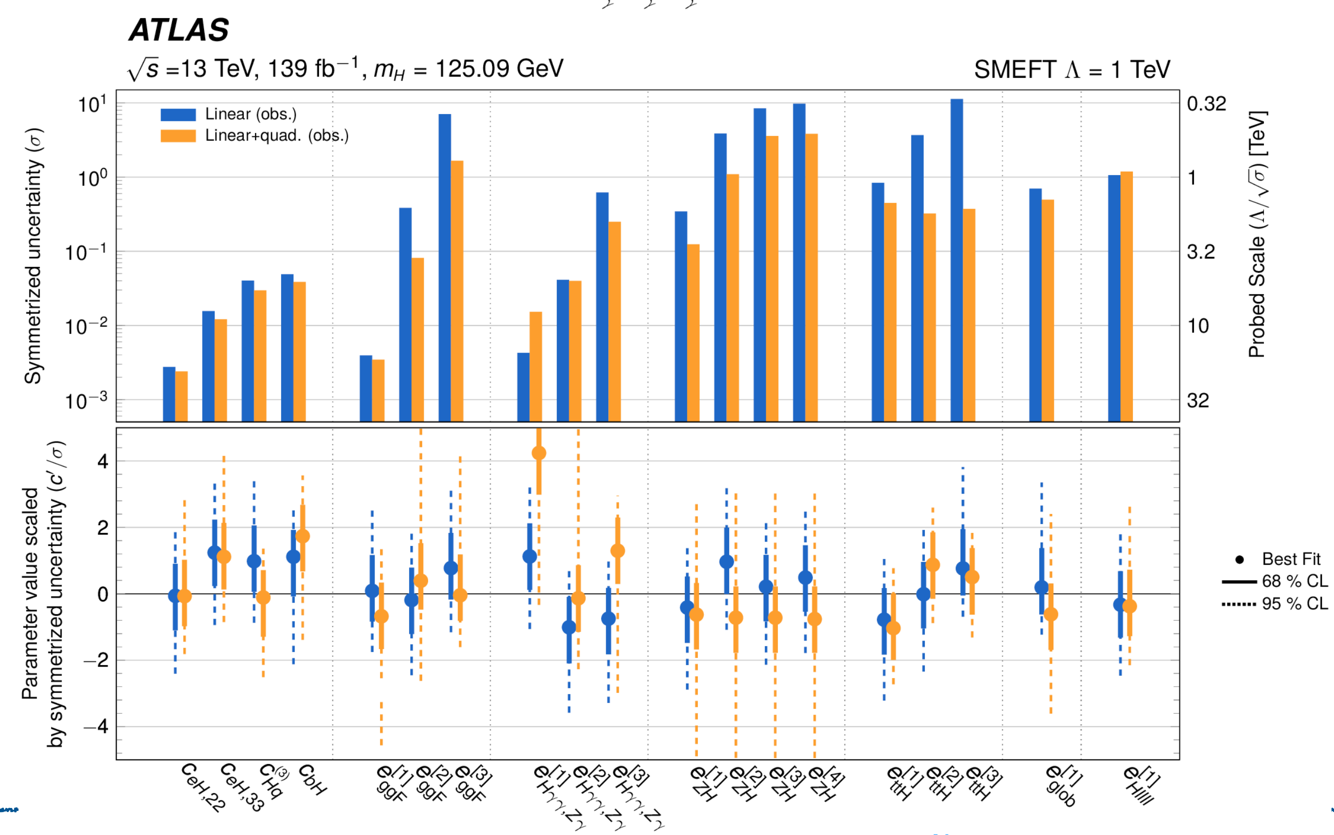
- $c_{eH_{33}}$, $c_{eH_{22}}$ can be individually measured from the corresponding Higgs channels that enter the combination.
- c_{HG}, c_{tG} and c_{tH} are constrained by *ggF* and *ttH* production.
- c_{HW}, c_{HWB}, c_{HB}, impact on branching ratios of the $H \to \gamma\gamma$ and $H \to Z\gamma$ decay.
- *H→WW* contributes only in minor ways, despite being one of the best measured channels
- High-stats regions in channels may not be the most powerful for SMEFT constraints -> design of the analysis

inc: breakdown into production modes is not available ($H \to \mu^+\mu^-$ and $H \to Z\gamma$).

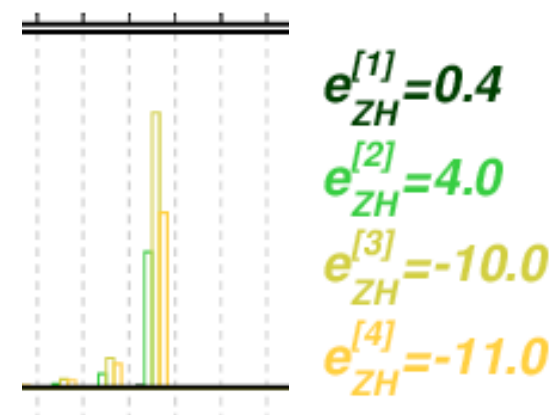
Linear+quadratic STXS SMEFT results

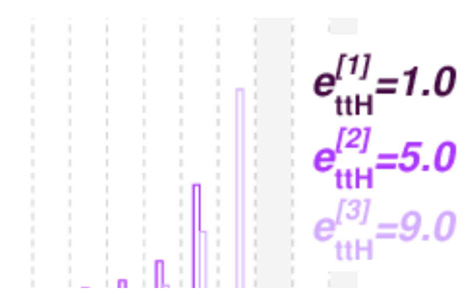
JHEP11(2024)097





- Significant impact of quadratic terms for different parameters:
  - ZH directions significantly affected + tH ($e^{[3]}_{ttH}$)





- Double minima structure observed for several parameters.

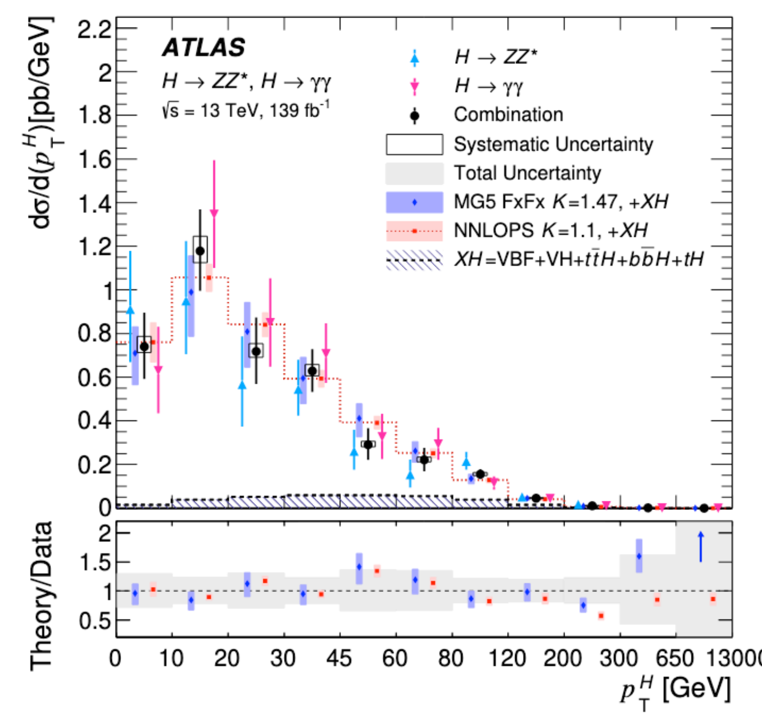
- For now treating difference between $1/\Lambda^2$ and $1/\Lambda^4$ as magnitude indicator of effect missing SM-Dim8 interference.

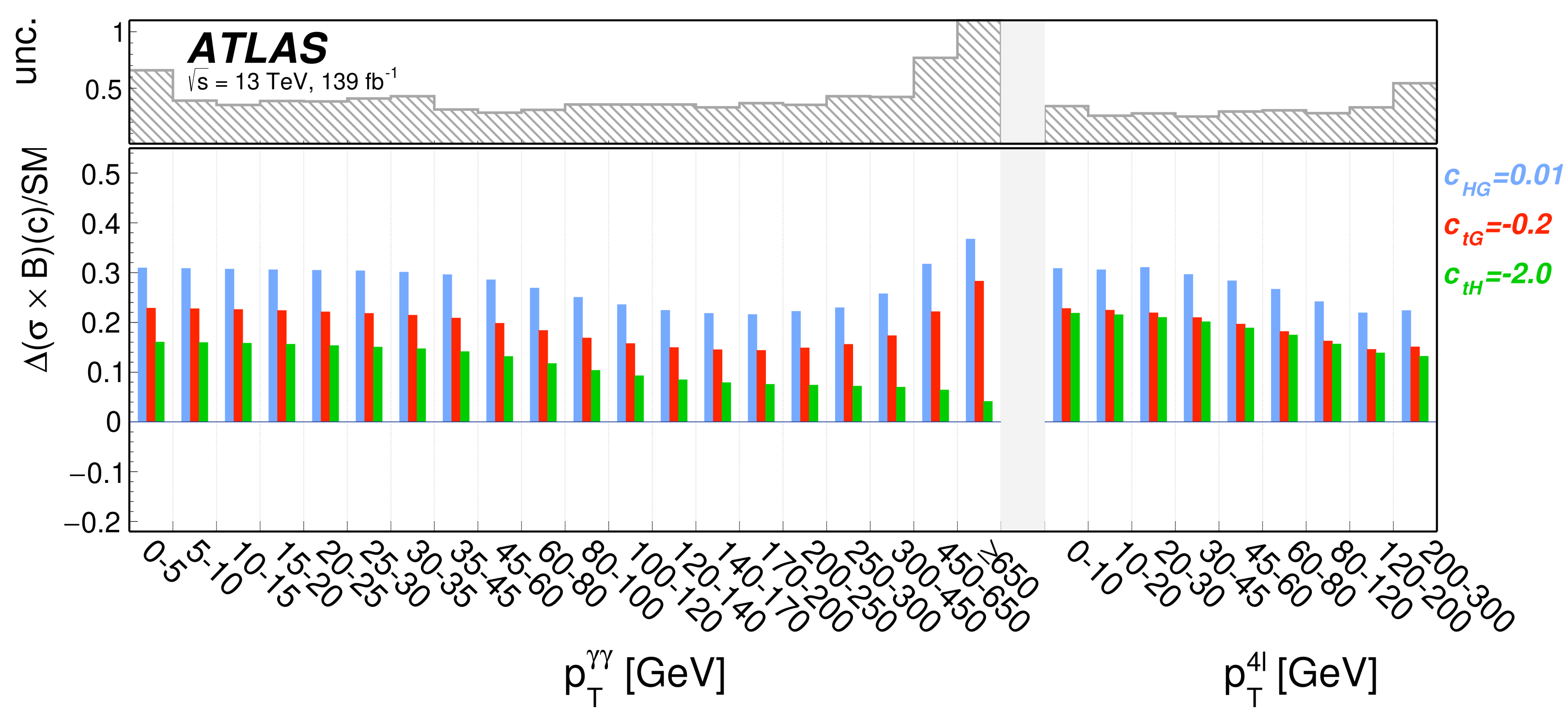
Differential SMEFT interpretation

- Combination of p_T^H measurements from the $H \to \gamma\gamma$ and $H \to ZZ^*$ channels.
- Some operators are expected to have high impact in the tails of p_T^H distribution:
  - ★ c_{tG}: top-gluon interaction (additional amplitudes for ggH or tt$H$ Higgs boson production + $H \to gg$).
  - ★ c_{HG}: Higgs gluon interaction (Hgg vertex that modifies the ggH production cross-section as well as the $H \to gg$).
  - ★ c_{tH}: Yukawa modifier for top quark (top-quark-loop mediated ggF, ttH, top-quark-loop amplitude contributing to the $H \to \gamma\gamma$ partial width + $H \to gg$).

Fiducial unfolded p_T^H from $H \to \gamma\gamma$ & $H \to 4l$

JHEP 05 (2023) 028

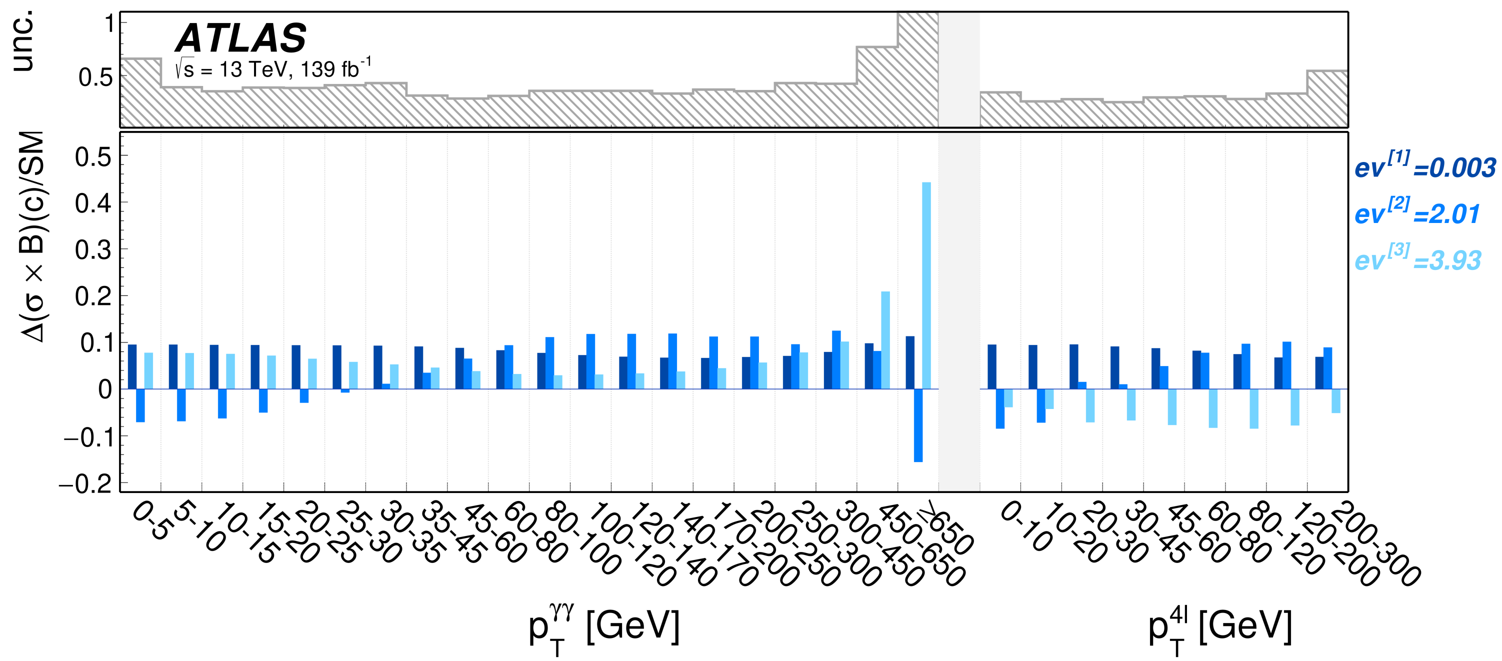




Differential SMEFT interpretation

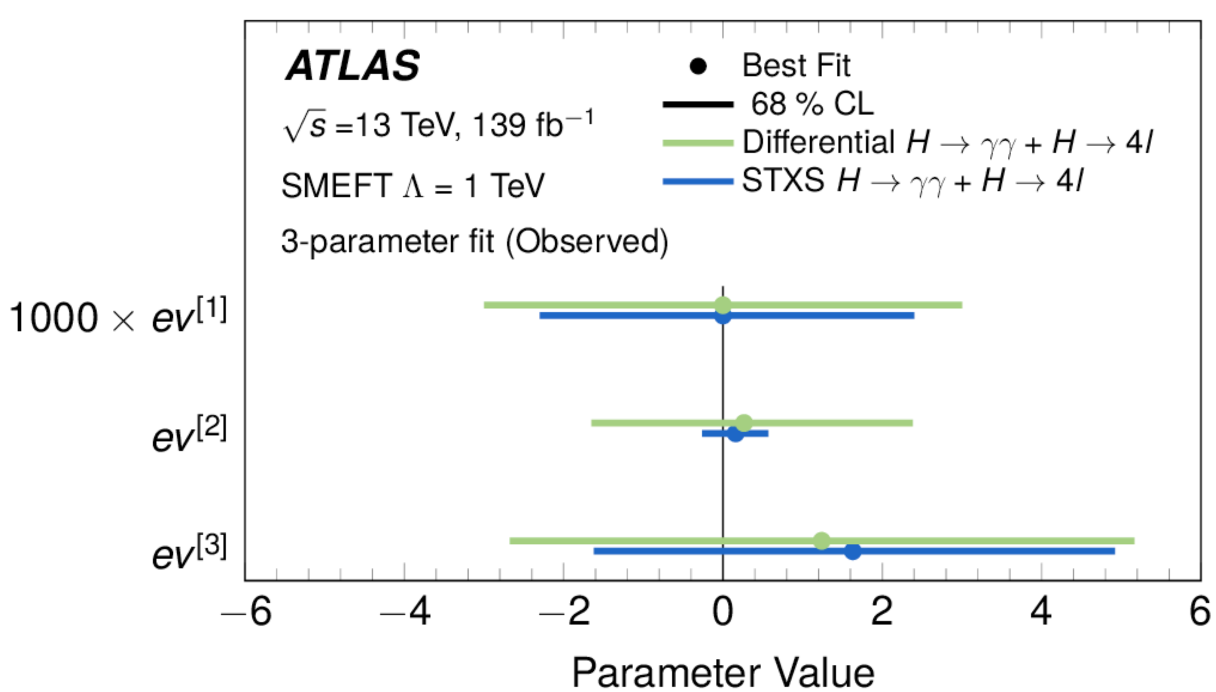
JHEP11(2024)097

- High correlation-> new basis and most sensitive directions can be obtained with an eigenvector decomposition.



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

STXS - differential comparison



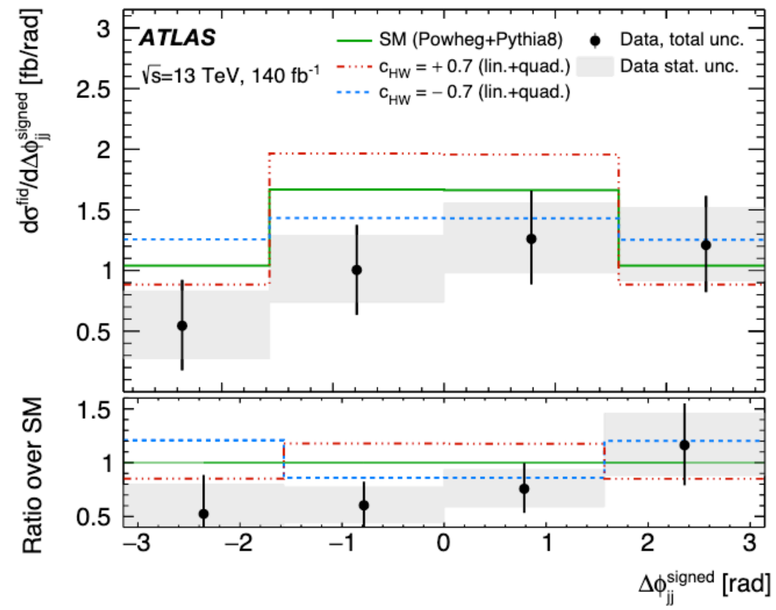
- $ev^{[1]}$ is mainly constrained by ggH - slight degradation in differential expected since the measurements are inclusive in production mode.
- $ev^{[2]}$ and $ev^{[3]}$ constraints come from the remaining production modes which can be probed separately in the STXS framework.

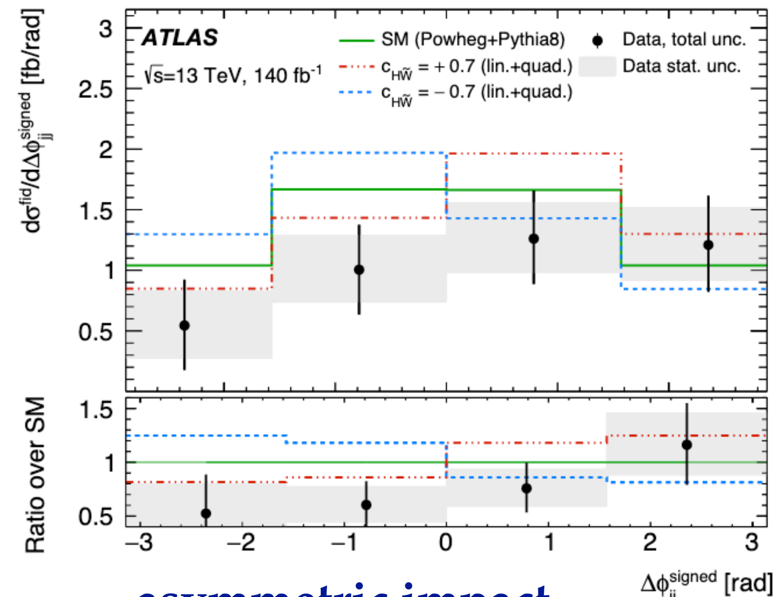
- Differential cross-section measurements have less constraining power than STXS ones:
  - finer granularity + inclusive in production modes vs separation of the different production modes.

Differential cross-section of $H \to \tau^+\tau^-$

arxiv:2407.16320

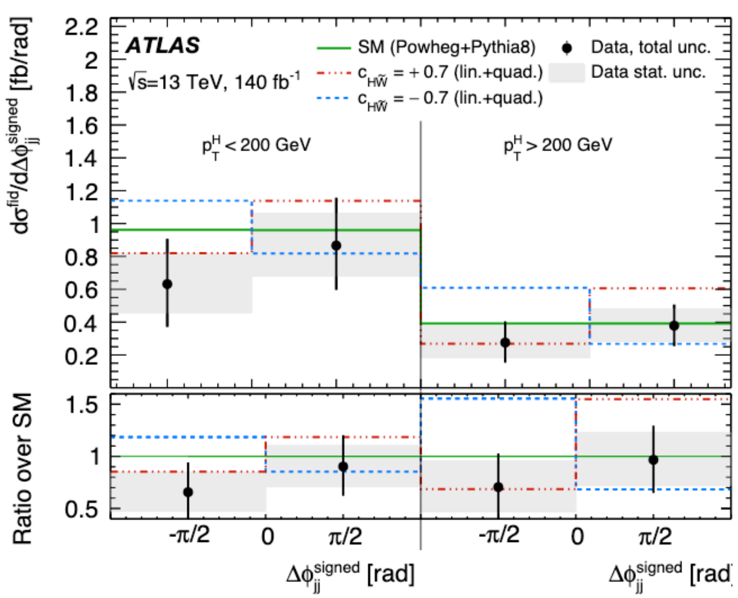
- Differential measurements of Higgs boson production in the τ-lepton-pair decay channel are performed as functions of variables characterizing the **VBF topology**, such as the signed $\Delta\phi_{jj}$ between the two leading jets.
- The fiducial measurement approach does not distinguish between the different Higgs boson production modes-> a phase-space region enriched in VBF events is defined to ensure optimal measurement sensitivity.
- This results in a less model-dependent approach than the STXS framework, although still relying on simulated SM samples to derive response matrices.

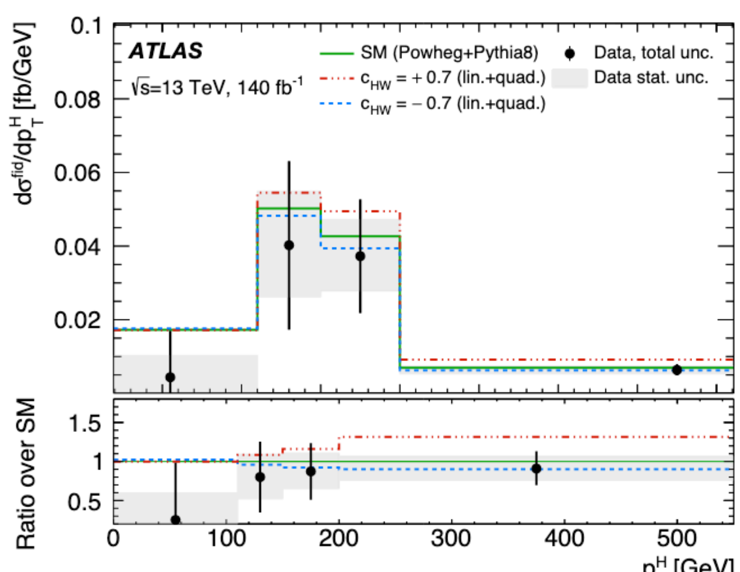




relative magnitude of the effect is enhanced by the cut on p_T^H in the two-dimensional distribution

asymmetric impact



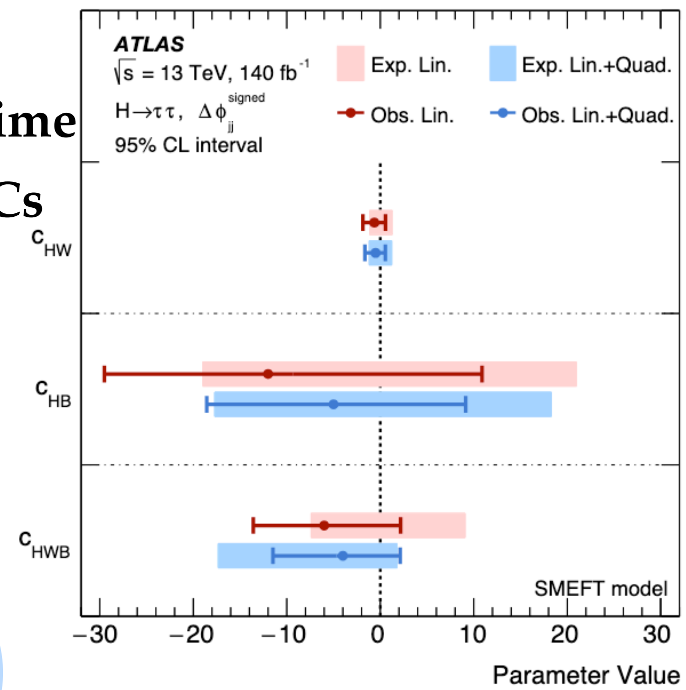


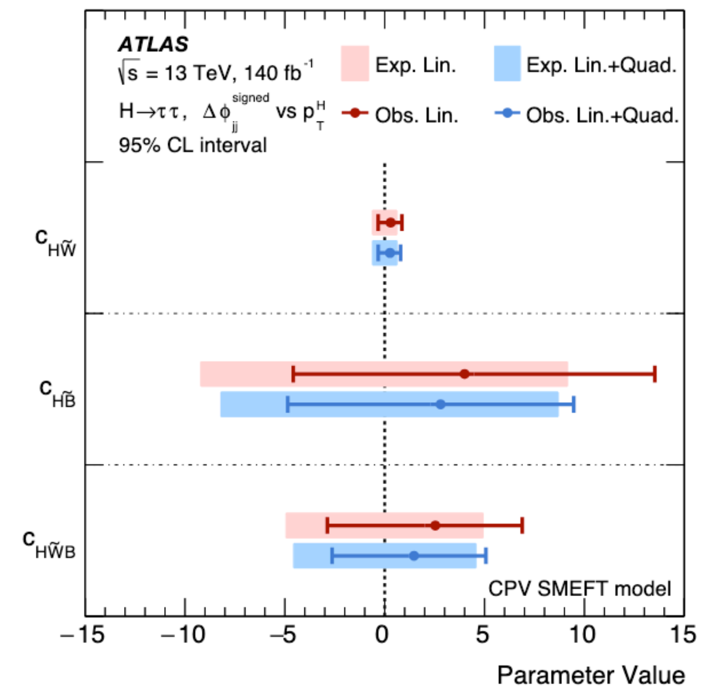
- The **unfolded data** are used along with the **theoretical dependence** of the cross-section on the Wilson coefficients to extract the best-fit value of each of the **six considered WCs**.
- The measurements have a precision of 30%–50% and agree well with the Standard Model predictions.

Differential cross-section of $H \to \tau^+\tau^-$

arxiv:2407.16320

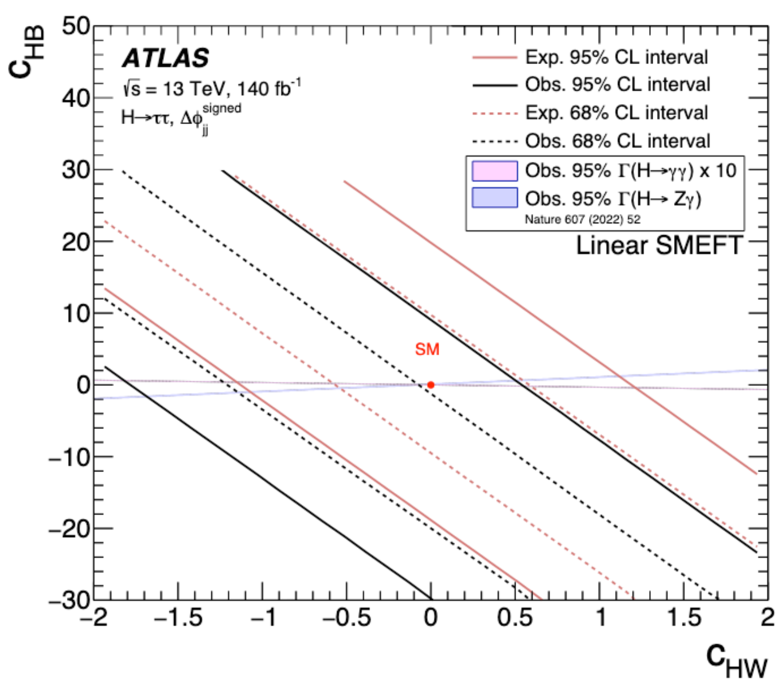
- For **CP-even** operators the **signed** $\Delta\phi_{jj}$ distribution is used to extract the confidence interval, while for the **CP-odd** operators the **signed** $\Delta\phi_{jj}$ **vs** p_T^H distribution is used.
- Results are provided for the 6 WCs profiled **one-at-a-time** (linear + linear - quadratic terms) and profiling **two WCs** simultaneously.
- The intervals considering only the linear term are very similar to the one when both the linear and quadratic terms are considered
- The constraints on the CP-odd Wilson coefficient $c_{H\tilde{W}}$ [−0.31, +0.88], are among the **most stringent to date** from any channel.

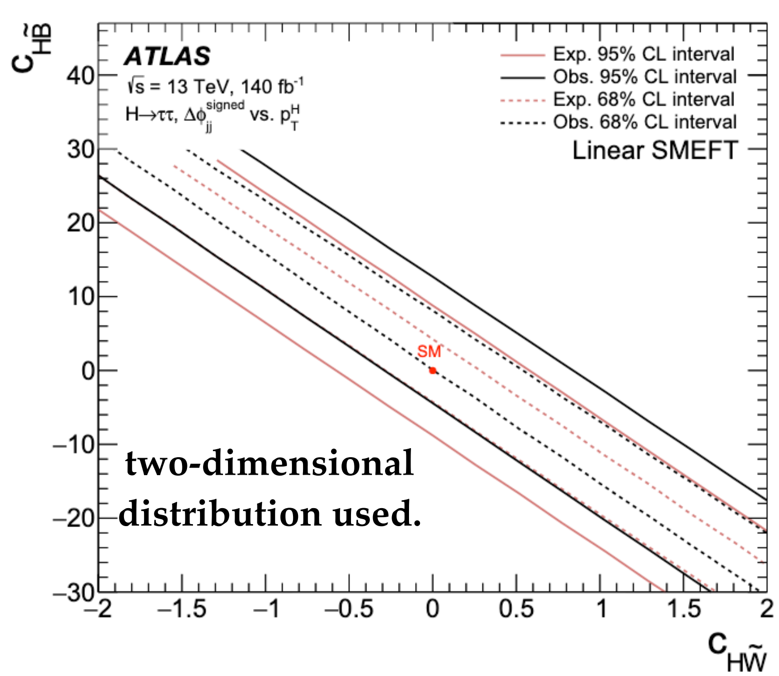




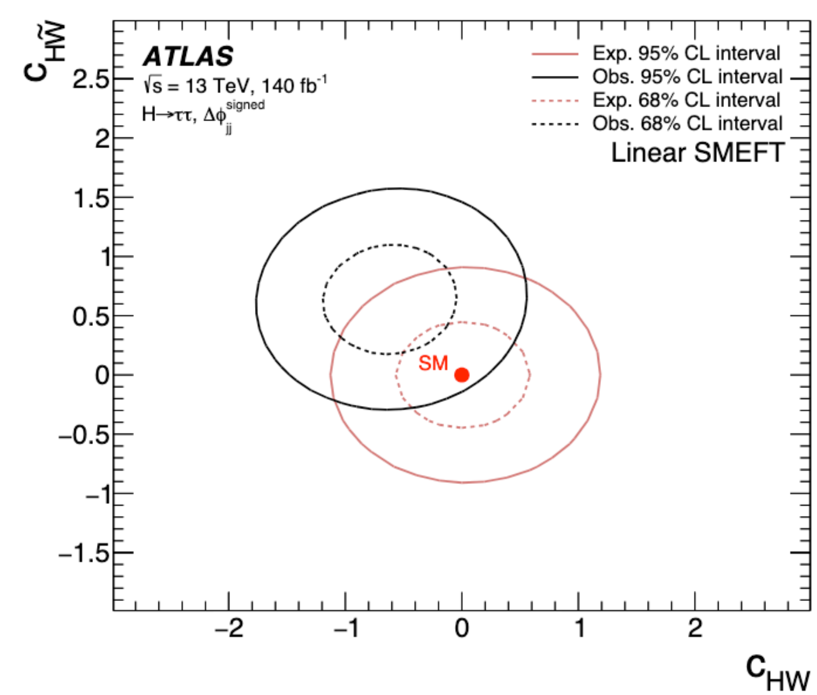
flat directions where the effects of the two Wilson coefficients cancel each other out and there is no sensitivity

distinct shape differences to the distribution no 'flat directions'





two-dimensional distribution used.



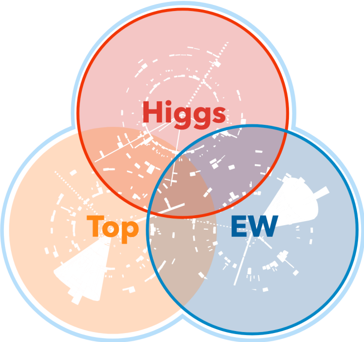
Road towards future Combination(s)

Several channels/data samples not yet included in current ATLAS EFT combination

- Within different physics groups
  - 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)
  - Final combination of aQGC measurements and top channels
- Higgs pair production
  - Unique sensitivity to self-coupling - opportunity to start exploiting these channels!
- Many opportunities for combinations
  - Full Run2 analyses in the process of being finalised
  - multi sector combinations: higgs, dibosons, top-quarks
  - Further constraints from LEP/SLC/ATLAS precision data

- Many potential challenges (besides harmonisations of SMEFT assumptions/tools)
  - $t\bar{t}$ signal = Higgs background-> coherent modelling of $t\bar{t}$ in Higgs?
  - experimental systematics across physics groups?
- Combination with CMS

Stay tuned!!!



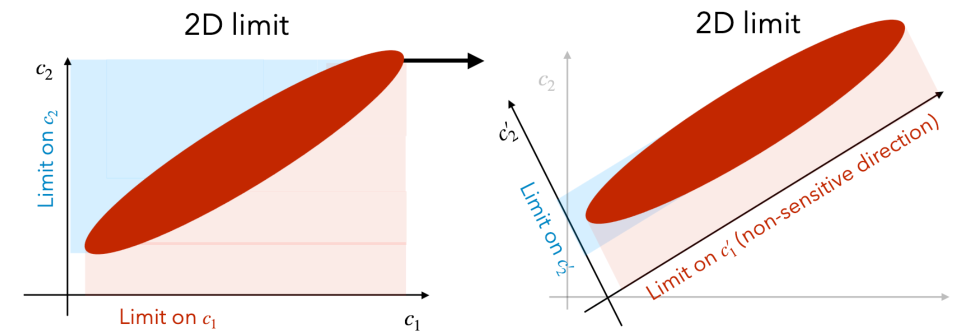
Thank you!!

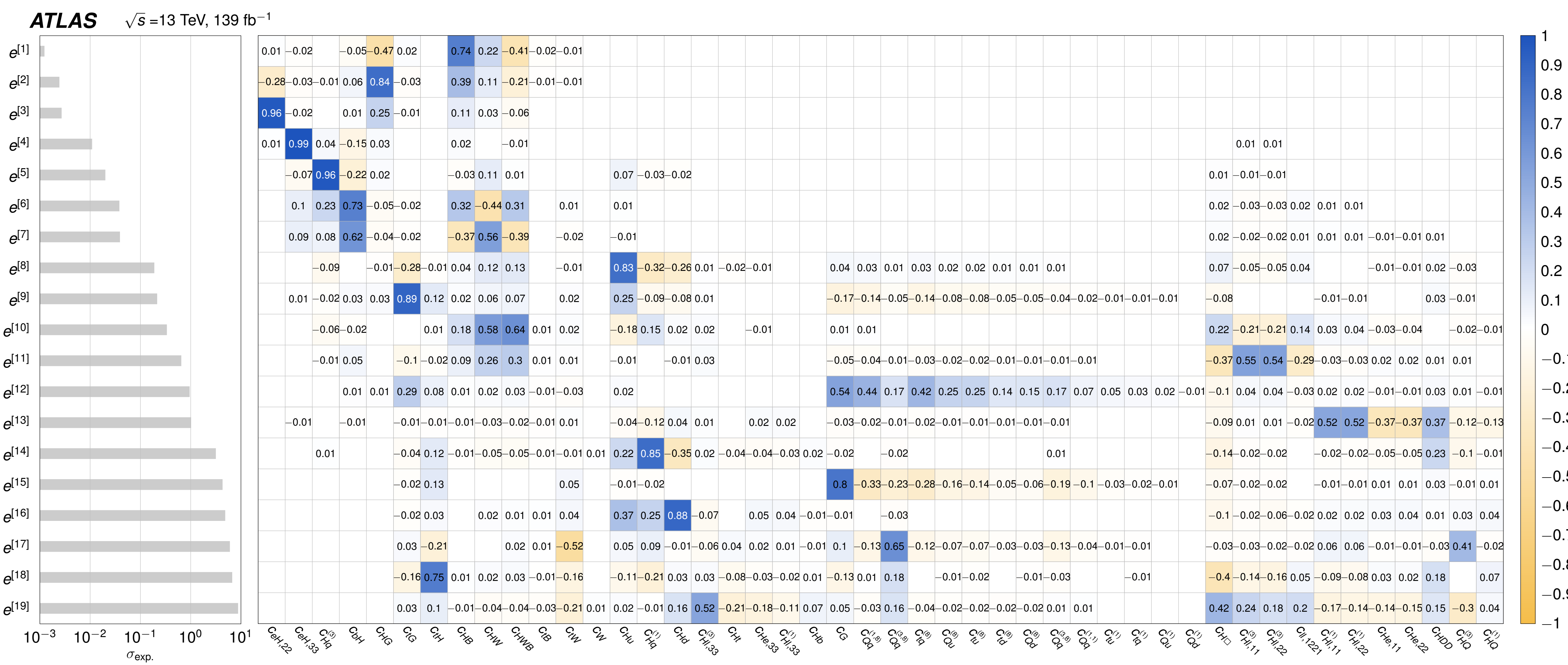
STXS sensitivity study

- 50 Wilson coefficients have a non-negligible impact on STXS bins.
- Not all the parameters can be constrained directly in the Warsaw basis, need to identify sensitive directions that can be reasonably constrained.
- Principal component analysis on information matrix:

$$H_{SMEFT} = P^T H_\mu P$$

  - H_{SMEFT}: in the limit of Gaussian STXS measurements: Fisher information matrix
  - Eigenvalue decomposition





STXS sensitivity study

- 50 Wilson coefficients have a non-negligible impact on STXS bins.
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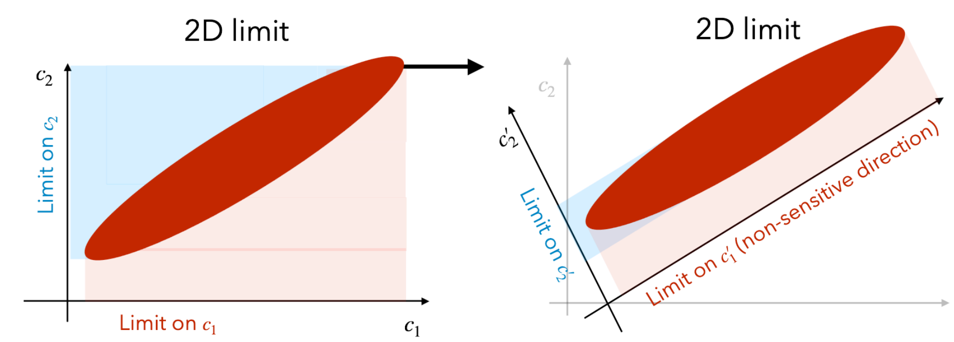
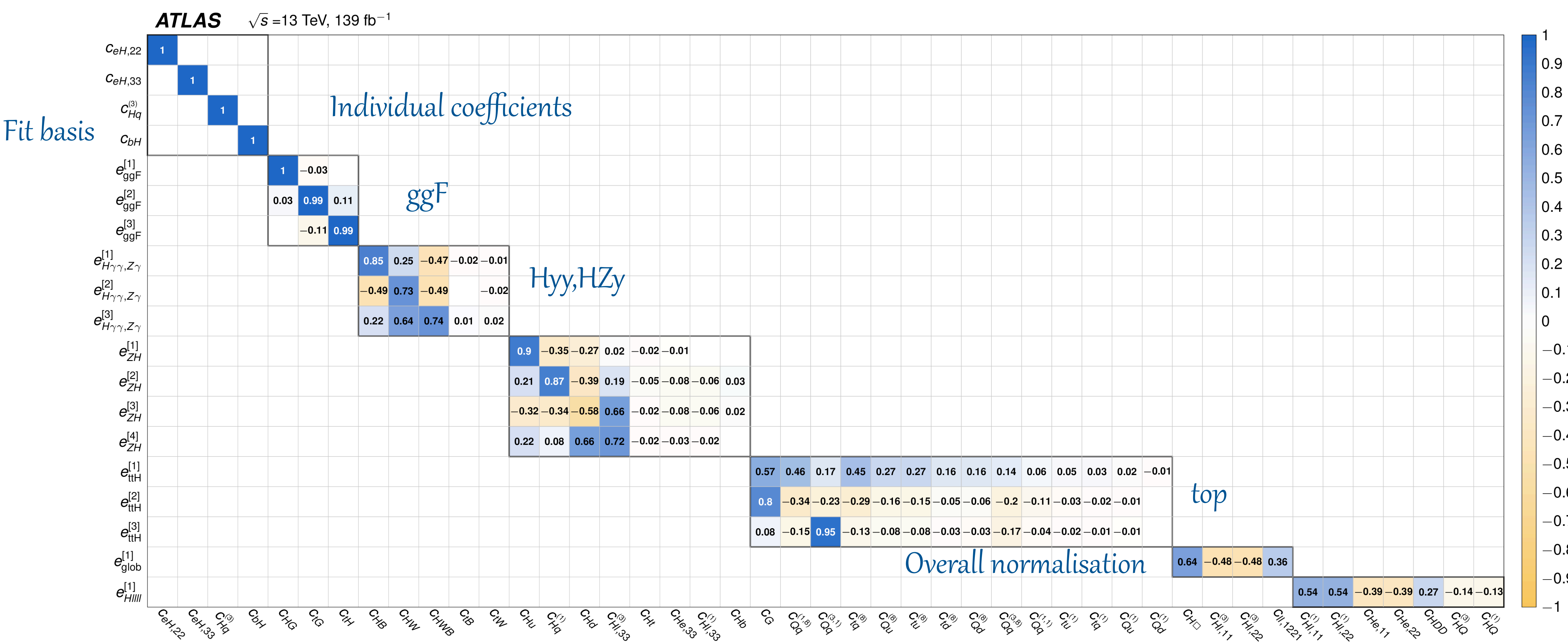
$$H_{SMEFT} = P^T H_\mu P$$

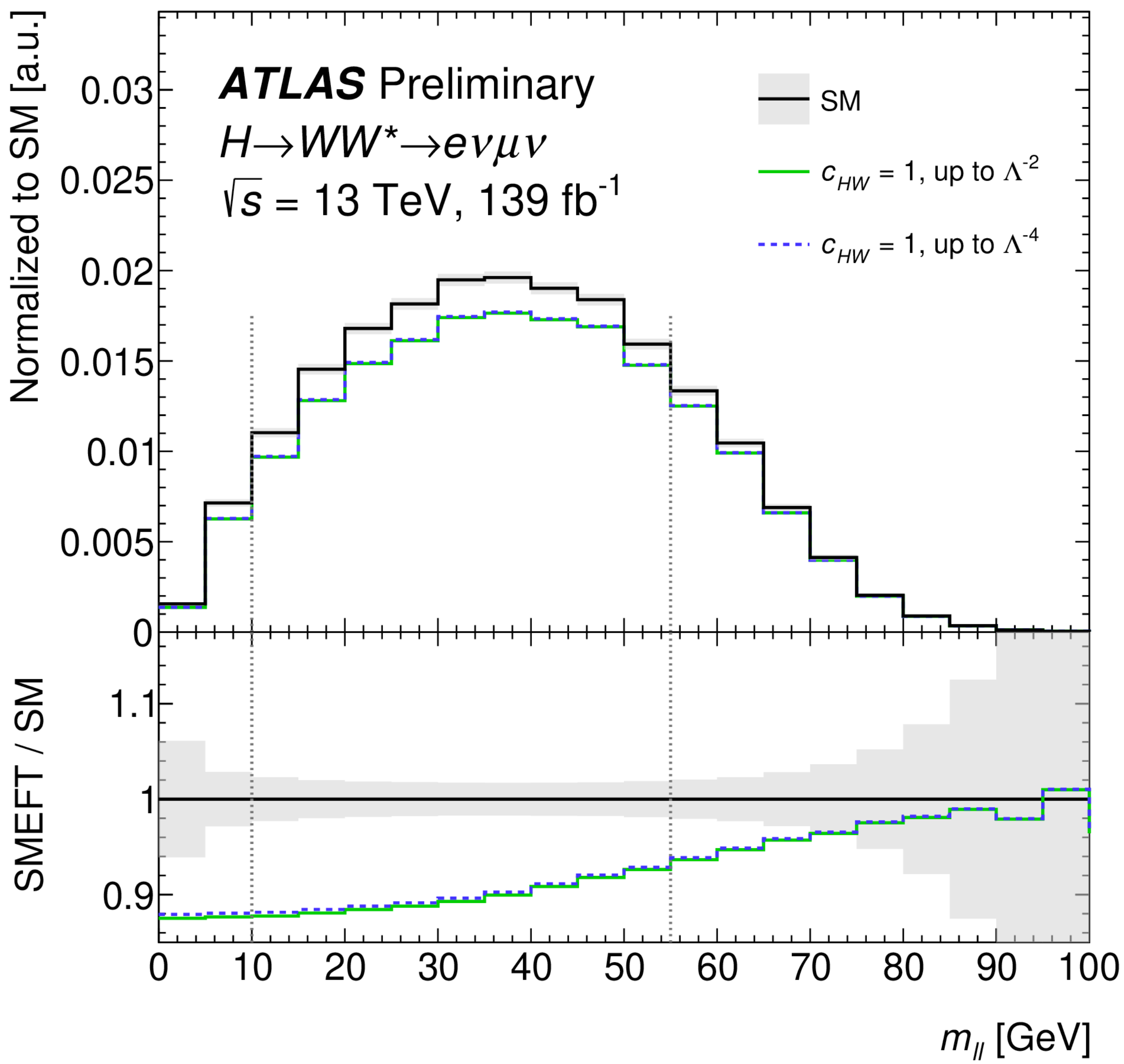
  - Full eigenvector basis-> Negligible correlation, hard to interpret.
  - Fit basis-> Higher correlation, easy to interpret.

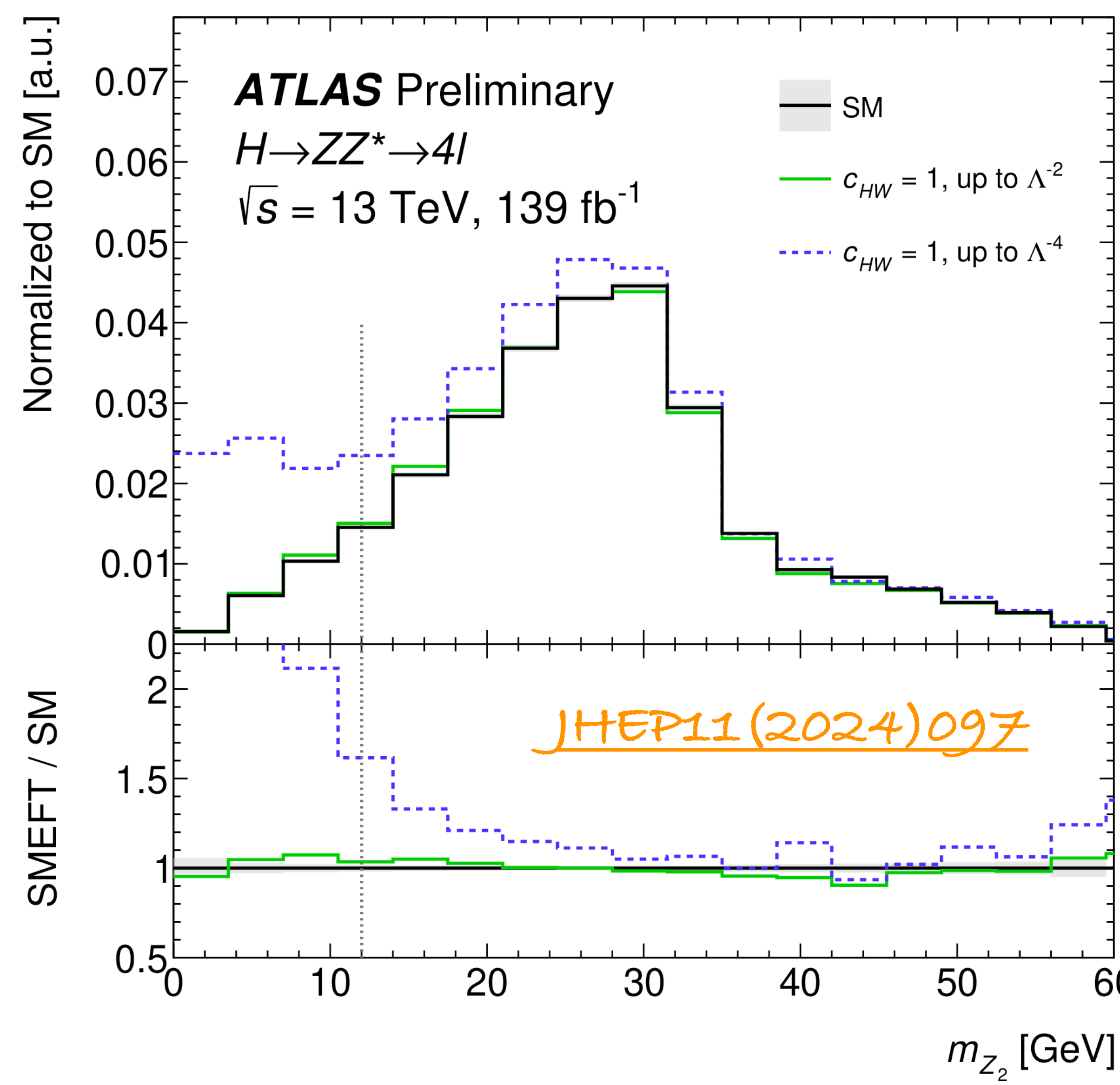




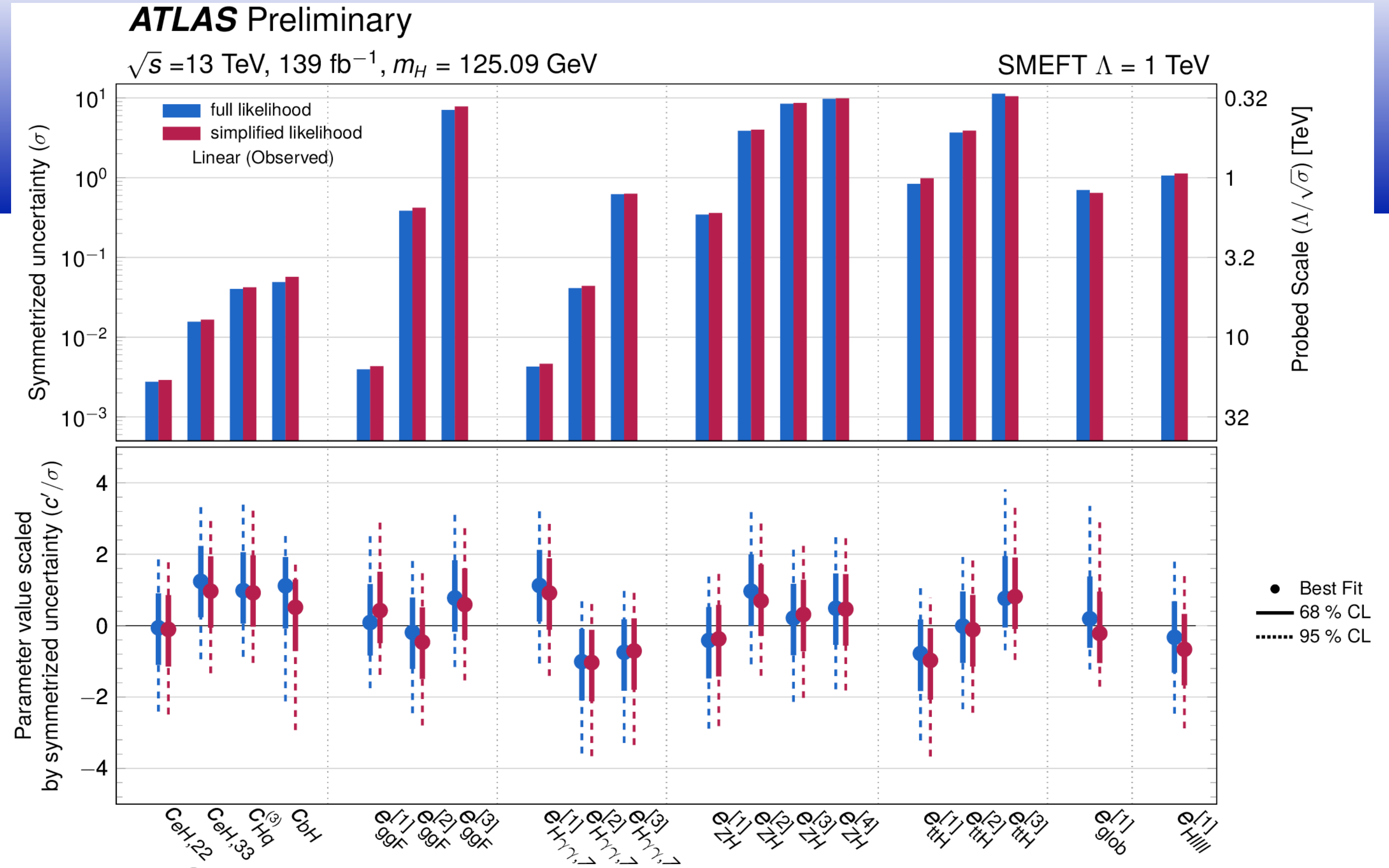
STXS: acceptance corrections for HWW/H4l decays

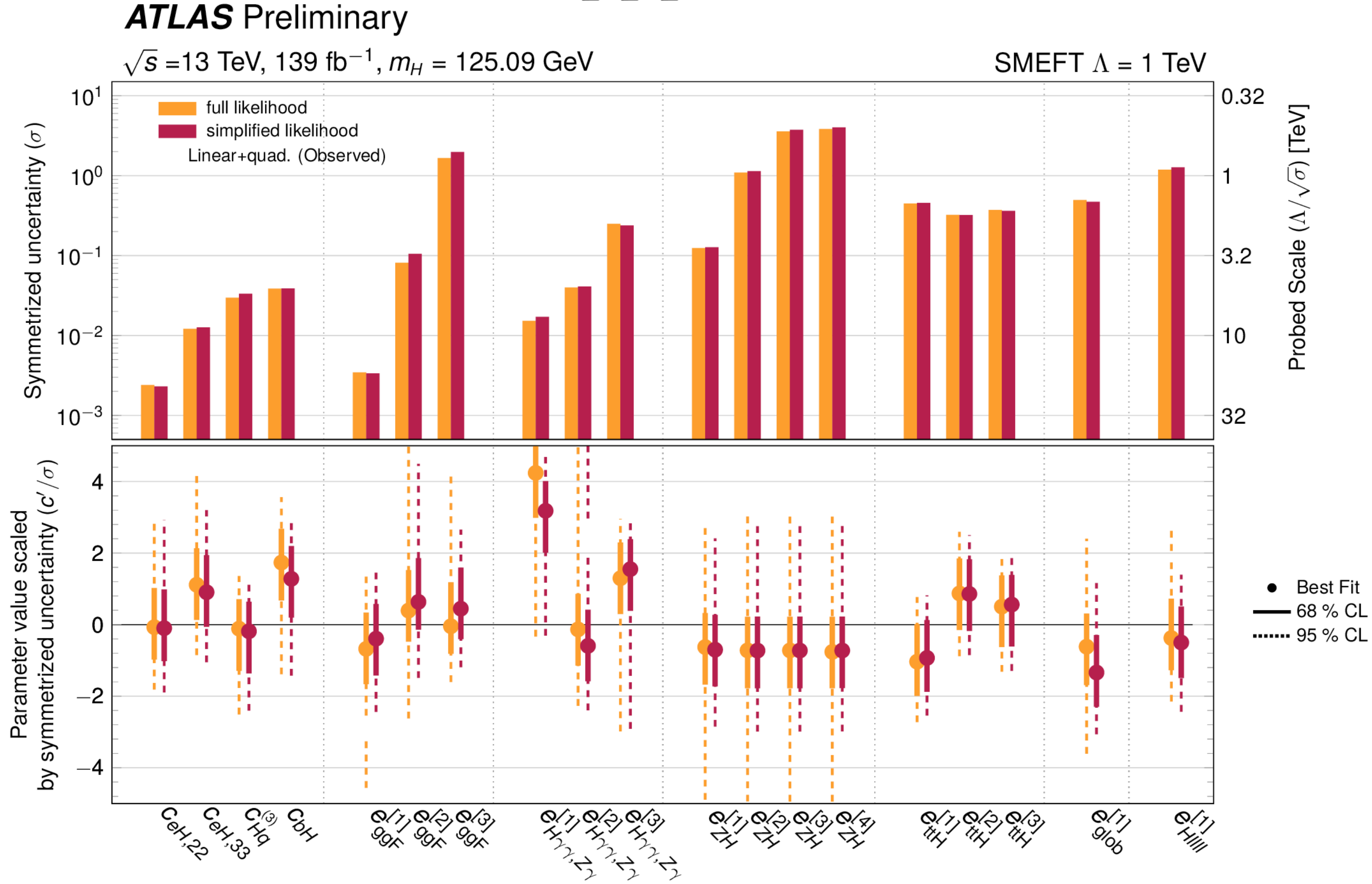
- SMEFT operators can alter the kinematics of the Higgs boson decay products: acceptance differences between SM and SMEFT.
- For decay side, the acceptance effect is predominant in four-body decays but studies show effect also pronounced in some 2-body decays e.g. effect in boosted $H \to bb$ up to 20%!
- Acceptance corrections for STXS interpretation have been included for H → WW* and H → 4l channels, linear and linear+quadratic results.
- Future: harmonised approach to acceptance possible in Run-3 with introduction of decay-side STXS definition.





Validity of Gaussian approximation





- Alternative likelihood function, based on a multivariate Gaussian approximation of the STXS measurements instead of the full measurement, built from the information provided in the paper.
- Make available digitally all information needed to reproduce
- It represents reasonably good approximation of the full likelihood.

2HDM

- The most popular extension of Higgs Sector: two-Higgs doublet model
- Additional scalar doublet Φ_2 with VEV ν_2
  - After symmetry breaking, four new bosons are predicted: **1 neutral CP-even Higgs bosons** H, **1 neutral CP-odd Higgs boson** A and **2 charged bosons** $H^{\pm}$.
  - Observed Higgs assumed to be h
  - In order to avoid flavour changing neutral currents (FCNC) at tree level, an additional symmetry is imposed: one fermion couples with only one Higgs doublet → Four types of 2HDMs
  - **Free parameters:**
    - $m_h, m_H, m_A, m_{H^{\pm}}$ and m_{12}^2 , the softly breaking term of Z2 symmetry
    - Angles α (mixing angle between the two neutral CP-even Higgs state) and β ($tan\beta = \frac{\nu_2}{\nu_1}$)
      - α and β determine the couplings to vector bosons and fermions;
      - *decoupling limit* assumed-> $m_H \gg v$ -> implies the alignment limit $|cos(\beta - \alpha)| \ll 1$, h has SM-like couplings.

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
$\frac{v^2 c_{tH}}{\Lambda^2}$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{bH}}{\Lambda^2}$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$
$\frac{v^2 c_{eH,22}}{\Lambda^2}$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{eH,33}}{\Lambda^2}$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$	$-Y_\tau c_{\beta-\alpha}\tan\beta$	$Y_\tau c_{\beta-\alpha}\tan\beta$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_H}{\Lambda^2}$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$	$c^2_{\beta-\alpha}M^2_A/v^2$

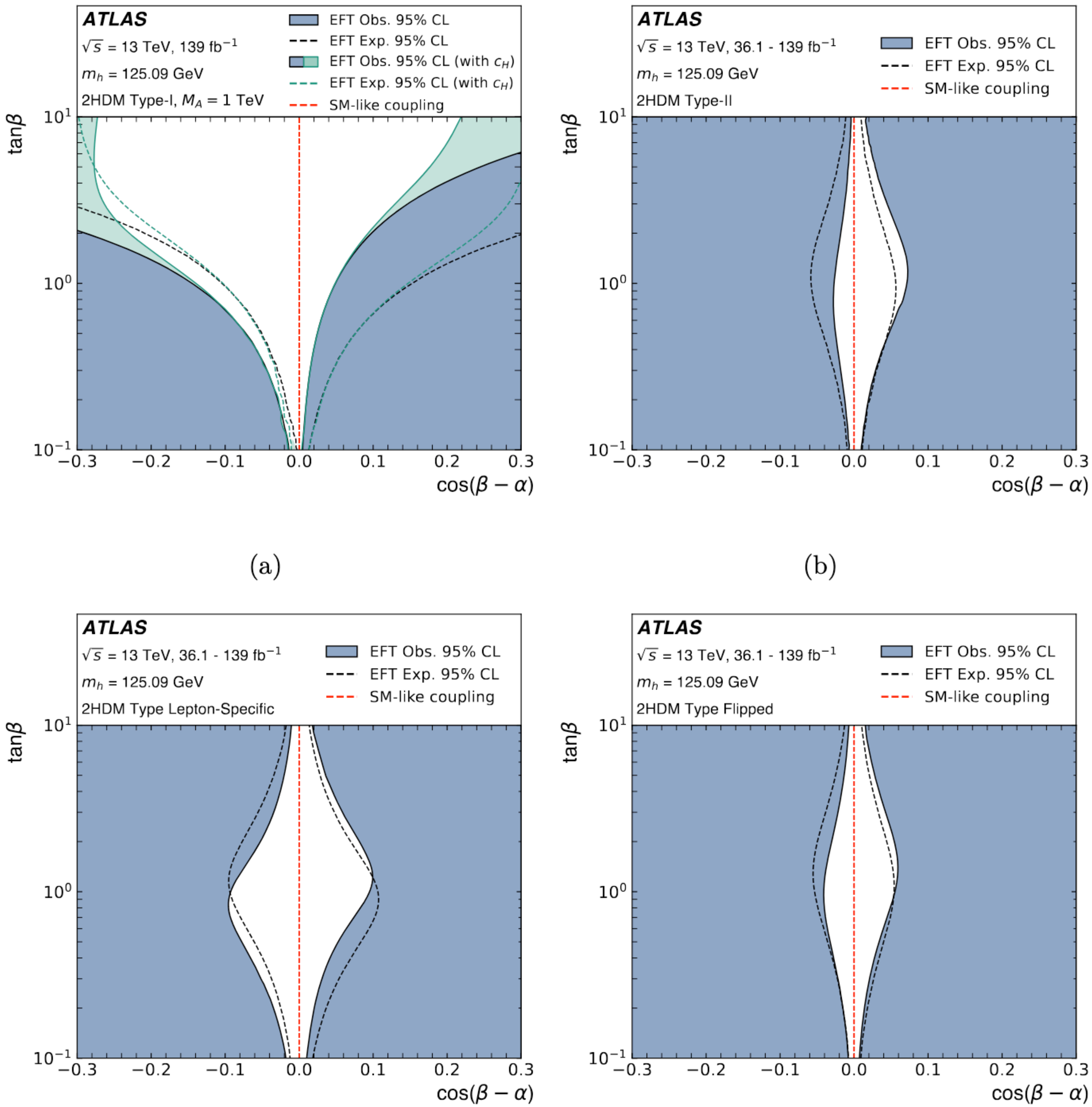
with Λ the SMEFT energy scale , v the VEV, Y_i the Yukawa-couplings ($Y_i = \sqrt{2}m_i/v$), η_i distinguishes the type of model, M is the common mass of the heavy decoupled scalars

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

EFT to 2HDM

JHEP11(2024)097

- Relevant coefficients parametrised as function of the 2HDM parameters.
- Type I: no constraints from vector boson couplings in SMEFT model (would occur in dim-8).
- Others: the region with flipped coupling sign does not appear (petal region)-> likelihood function in the EFT-based approach is approximately Gaussian and has a single maximum.
- Linear expansion is performed.



Mapping is affected by missing SMEFT dimension-8 operators:

- constraints from SMEFT parameters weaker than from k-parameters

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, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	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, $p_{\text{T}}^{\text{jet}} < 35$ GeV	$p_{\text{T}}^{\text{lead. lep.}}$	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
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A_{\text{FB}}^{0,b}$	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.

ATLAS Global combination

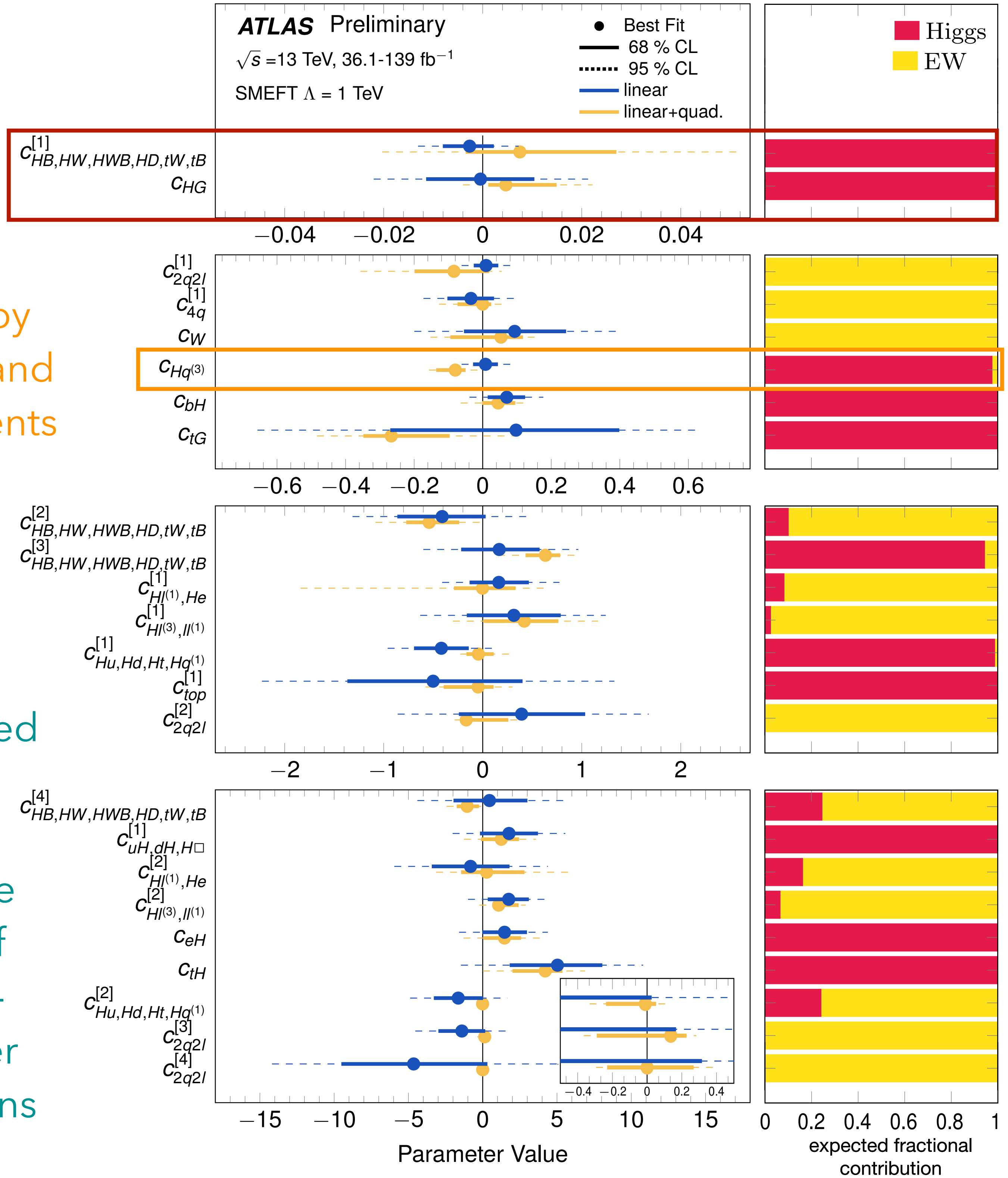
HIGGS+EW

- Previous round of Higgs combination used in the context of the ATLAS Global combination
- Principal component analysis to identify sensitive directions-> a modified basis of linear combinations of WCs is defined (**7+17 coefficients**)
- Sensitivity eigenvectors instead of original Wilson Coefficient.
- 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



ATL-PHYS-PUB-2022-037

ATLAS Global combination

HIGGS+EW+EWPO

- Constraining **6** individual and **22** linear combinations of Wilson coefficients - 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.