SMEFT in ATLAS

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on behalf of ATLAS

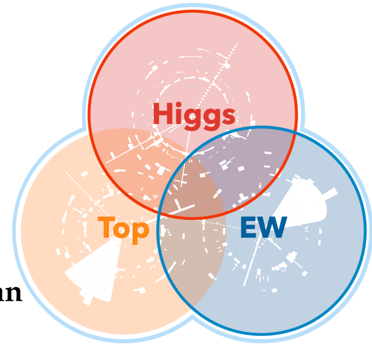
20th Workshop of LHC Higgs WG
13-15 November 2023

Outline

- Off-shell HZZ SMEFT interpretation
- Latest interpretation of the Nature Higgs combination: consolidate EFT and BSM interpretations including new channels w.r.t. the 2021 combination + differential interpretation (ConfNote) **- new inputs: boosted-Hbb, $H \to Z\gamma$, $H \to \mu\mu$ + differential**

Analysis Decay channel	Production mode	$\mathcal{L}$ [fb^{-1}]	Reference	Binning	SMEFT	Dedicated BSM
$H \to \gamma\gamma$	(all production modes)	139	[23]	STXS-1.2	✓	✓
			[20]	differential	✓(subset)	
$H \to ZZ^* \to 4\ell$	(all production modes)	139	[22]	STXS-1.2	✓	✓
			[19]	differential	✓(subset)	
	($t\bar{t}H$ multileptons)	36.1	[34]	STXS-0		✓
$H \to \tau\tau$	(all production modes)	139	[29]	STXS-1.2	✓	✓
	($t\bar{t}H$ multileptons)	36.1	[34]	STXS-0		✓
$H \to WW^*$	(ggF, VBF)	139	[30]	STXS-1.2	✓	✓
	(VH)	36.1	[45]	STXS-0		✓
	($t\bar{t}H$ multileptons)	36.1	[34]	STXS-0		✓
$H \to b\bar{b}$	(VH)	139	[24, 25]	STXS-1.2	✓	✓
	(VBF)	126	[26]	STXS-1.2	✓	✓
	($t\bar{t}H$)	139	[28]	STXS-1.2	✓	✓
	(all production modes, boosted)	139	[27]	STXS-1.2	✓	✓
$H \to Z\gamma$	(all production modes)	139	[31]	STXS-0	✓	✓
$H \to \mu\mu$	(all production modes)	139	[32]	STXS-0	✓	✓

- Preparing the way towards a new ATLAS Global Combination!!



Sketch from R.Balasubramanian inspired by Ken Mimasu

EFT interpretation

The LHC has not found any evidence of New Physics.

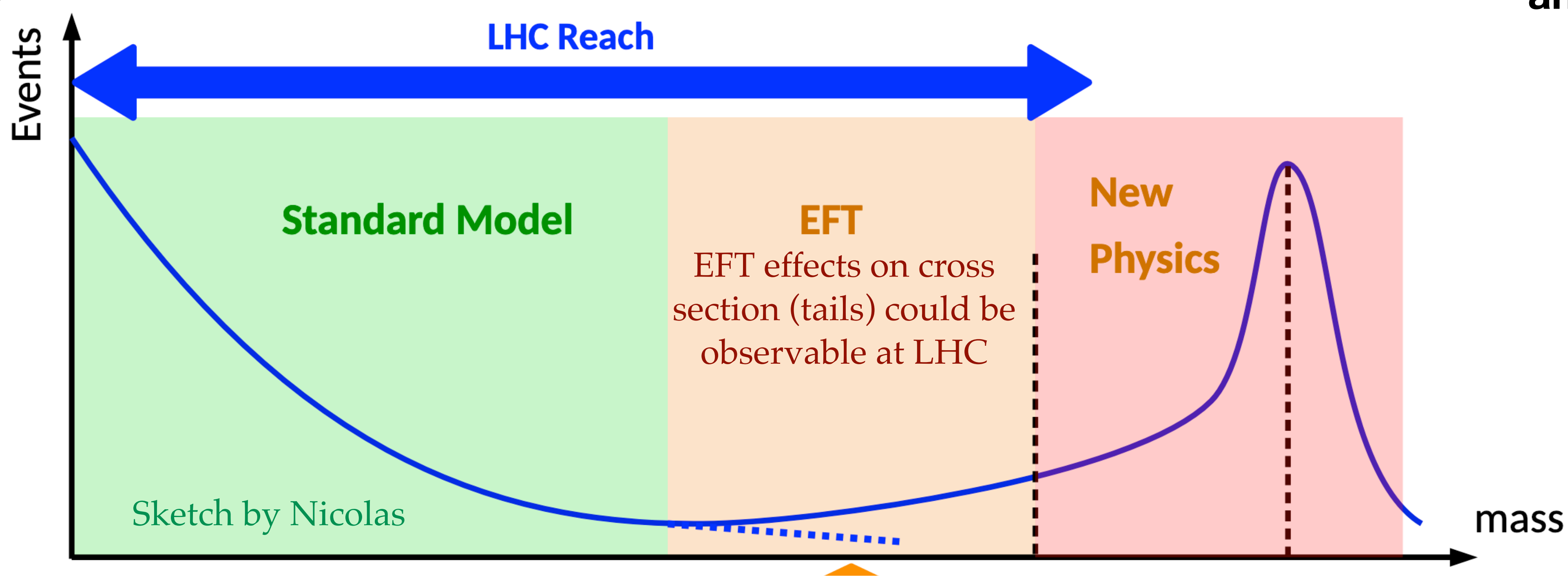
- Direct searches for SUSY or exotics continue, but the focus on indirect exploration is increasing…
- An Effective Field Theory (EFT) approach can be used to set **model-independent constraints** on BSM physics and perform indirect searches for BSM physics that is not within the direct reach of the LHC.
  - It is a very powerful tool used in different fields of physics; allows one to combine different types of measurements (Higgs, top, EW physics,…).
  - Constrain EFT coefficients -> constrain large classes of UV theories.
  - A popular EFT model is the SMEFT
  - SMEFT is a complete QFT compatible with higher-order calculations.

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

SM Lagrangian

Wilson coefficients

complete set of operators of mass-dimensions d = 6 and d = 8



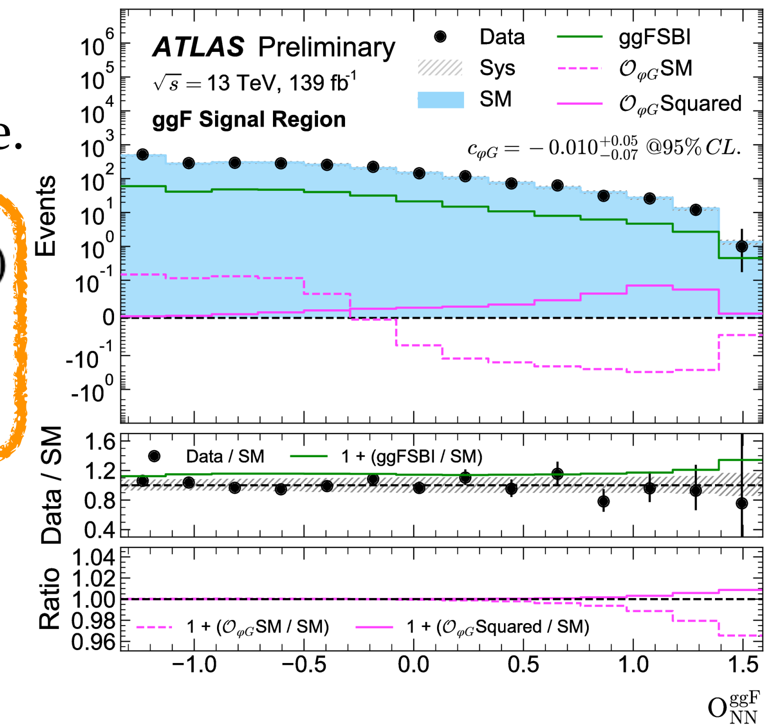
Off-shell interpretation

SMEFT interpretation of off-shell H->ZZ

- Higgs boson decays to $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ final states.
- Off-shell Higgs boson events offer the opportunity to probe a higher energy scale.

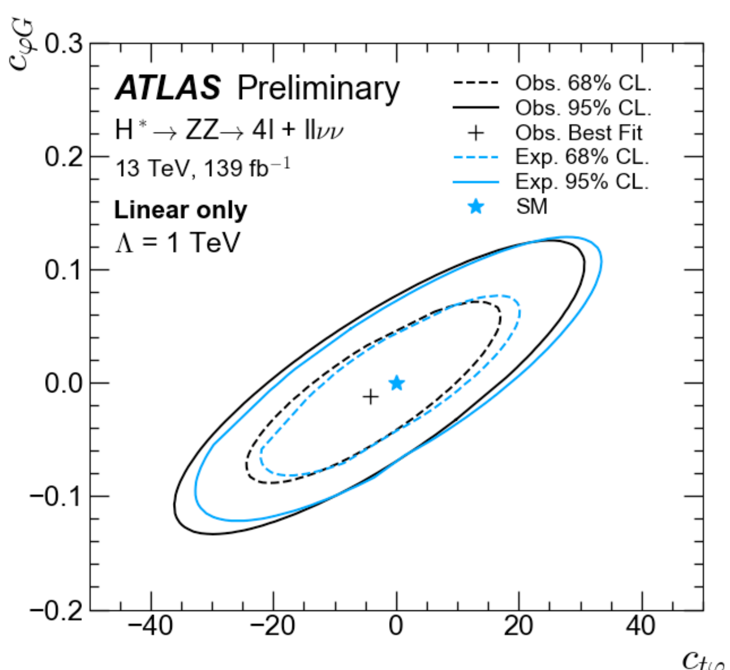
$$\frac{\sigma^{\rm SMEFT}(c_t, c_g)}{\sigma^{\rm SM}} \simeq (c_t + c_g)^2 \left(1 - \frac{7}{15}\frac{c_g}{c_t + c_g}\frac{m_H^2}{4m_t^2}\right)$$

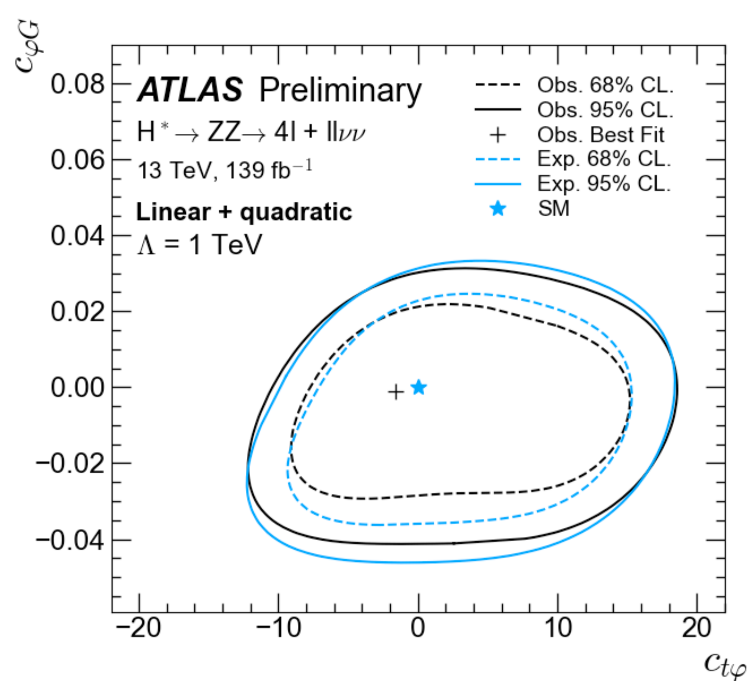
$$c_{t\varphi} = -\frac{y_t \Lambda^2}{v^2}(c_t - 1) \qquad c_{\varphi G} = \frac{g_s^2 \Lambda^2}{48\pi^2 v^2} c_g$$

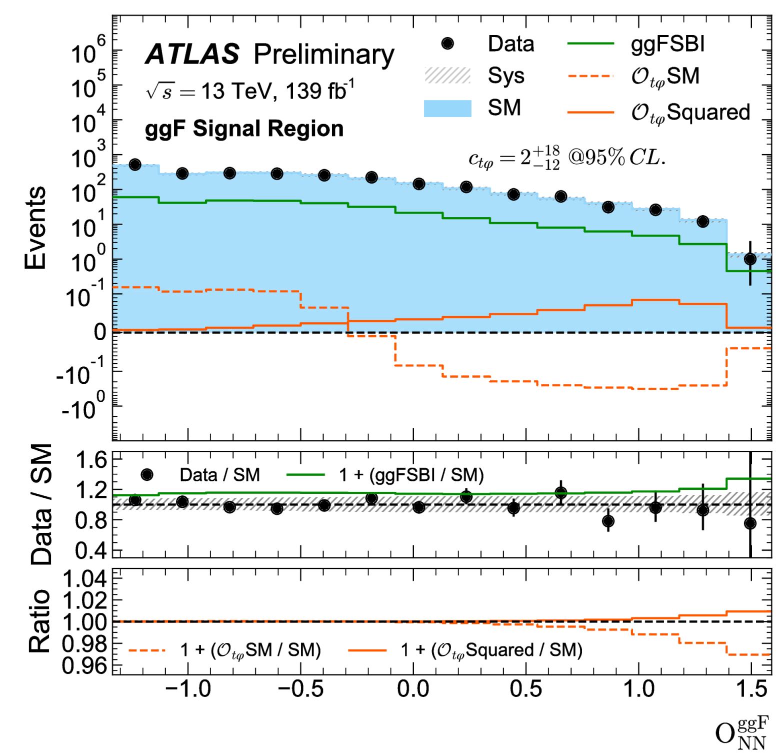


- Off-shell: mass-dependent term cannot be neglected-> degeneracy of the Higgs-top quark and effective Higgs-gluon couplings broken, enabling separate measurements of the coupling modifiers.

- The 95% CL limits on the single WCs (lin+quad) are:
  - $c\varphi G$ (Higgs-gluon coupling modifier): observed & expected **[-0.04, 0.03].**
  - $c_{t\phi}$ (Higgs-top coupling modifier): observed (expected) **[-9, 18] ([-9, 17]).**







More details in Rafael's talk

Results comparable to the boosted ttH analysis by CMS

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STXS interpretation

STXS inputs

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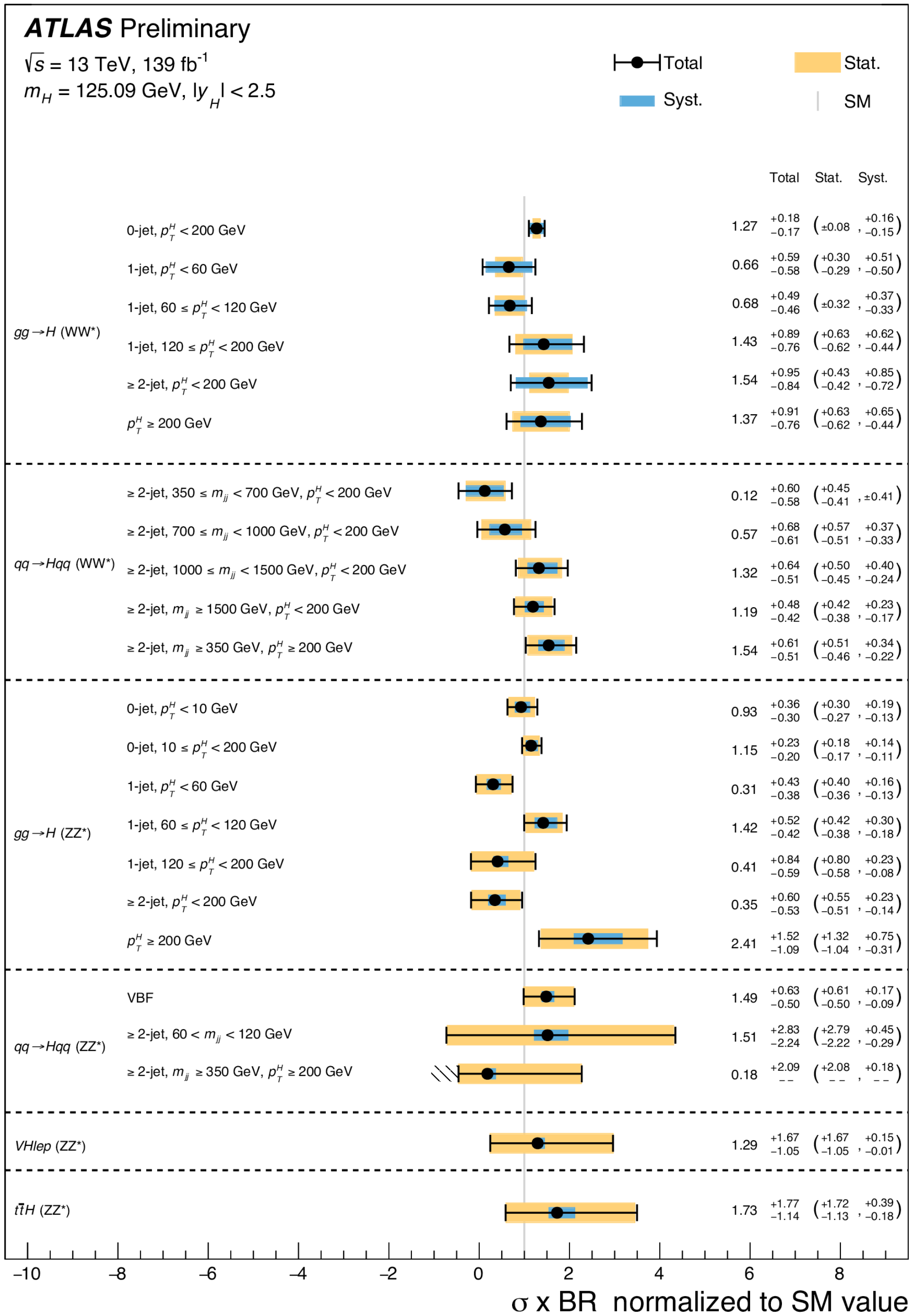
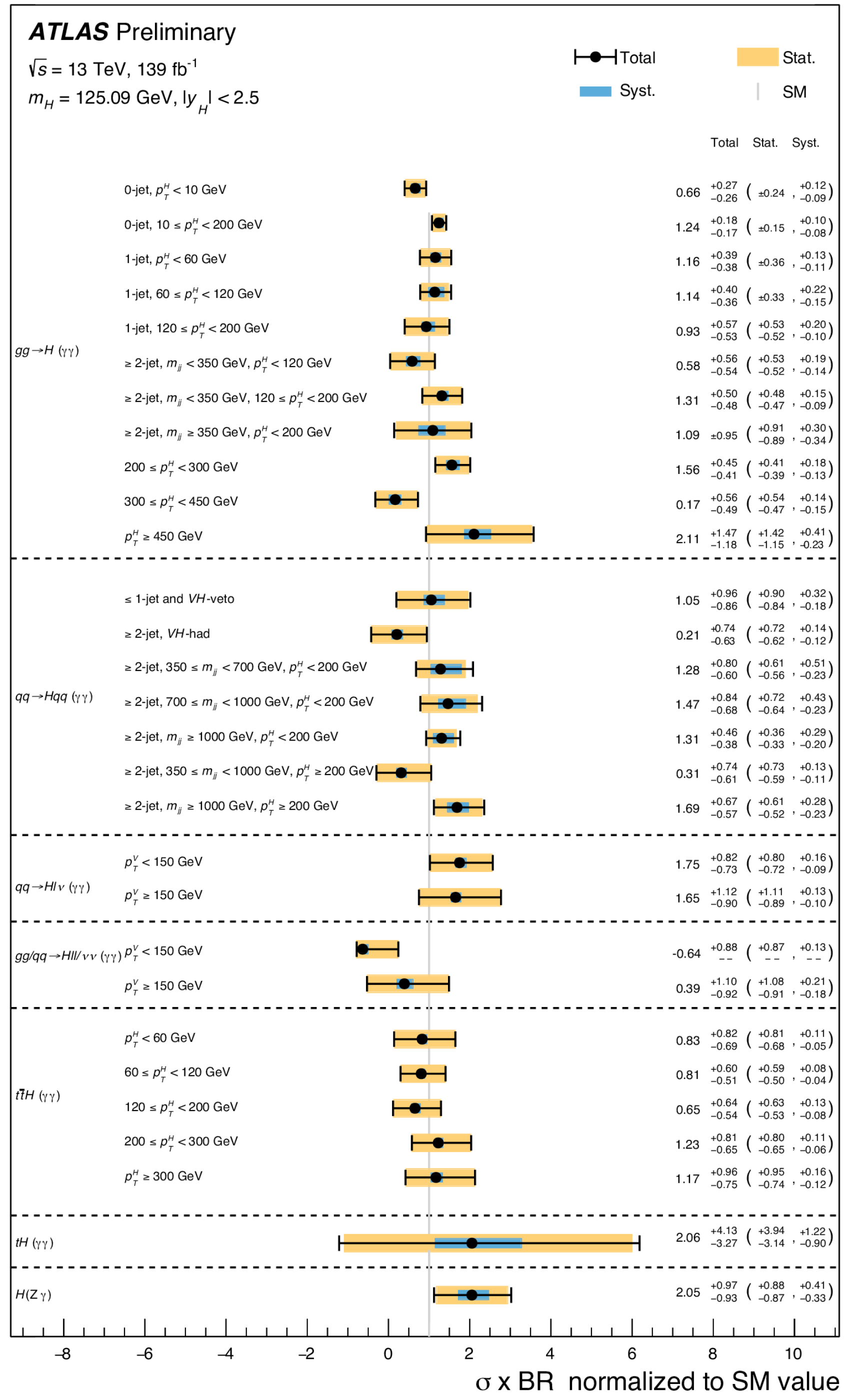
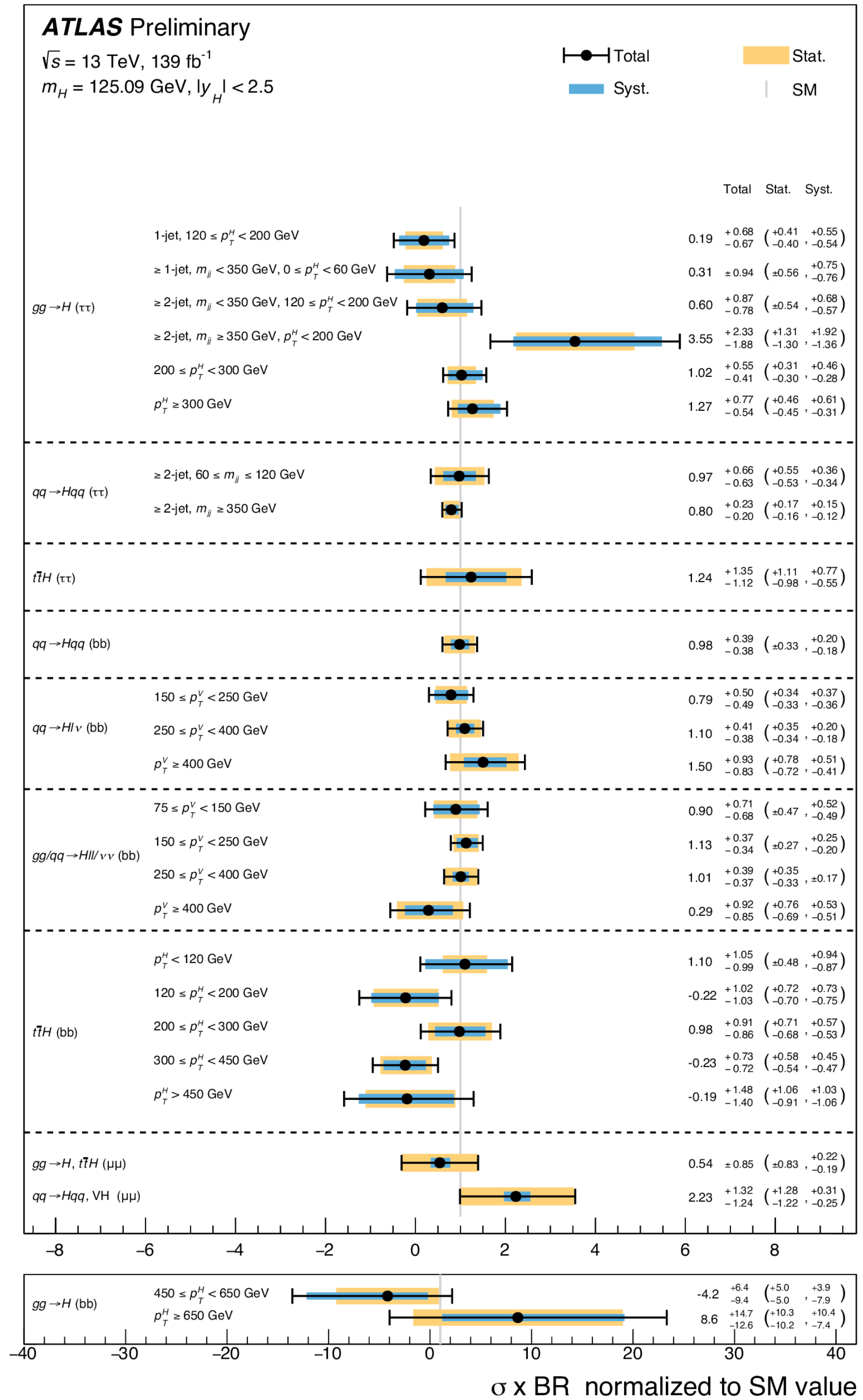






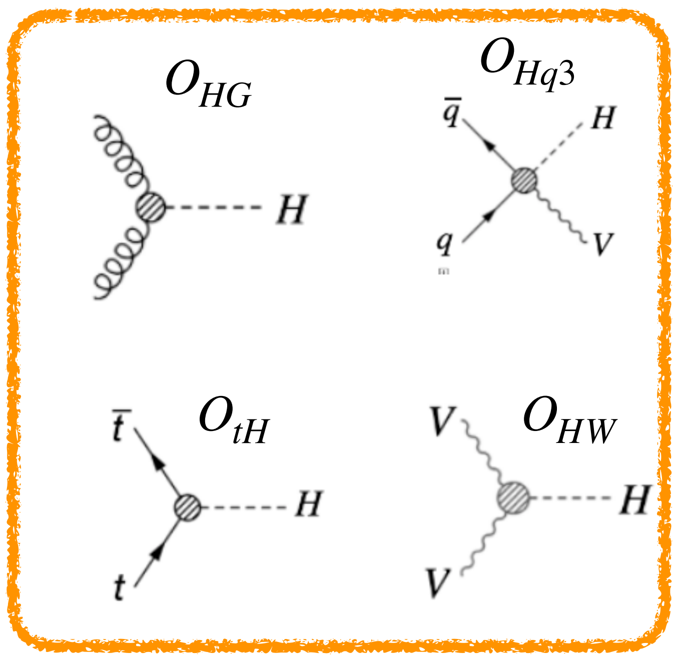
WW, ZZ

$\gamma\gamma, Z\gamma$

$\tau\tau, \mu\mu, b\bar{b}$

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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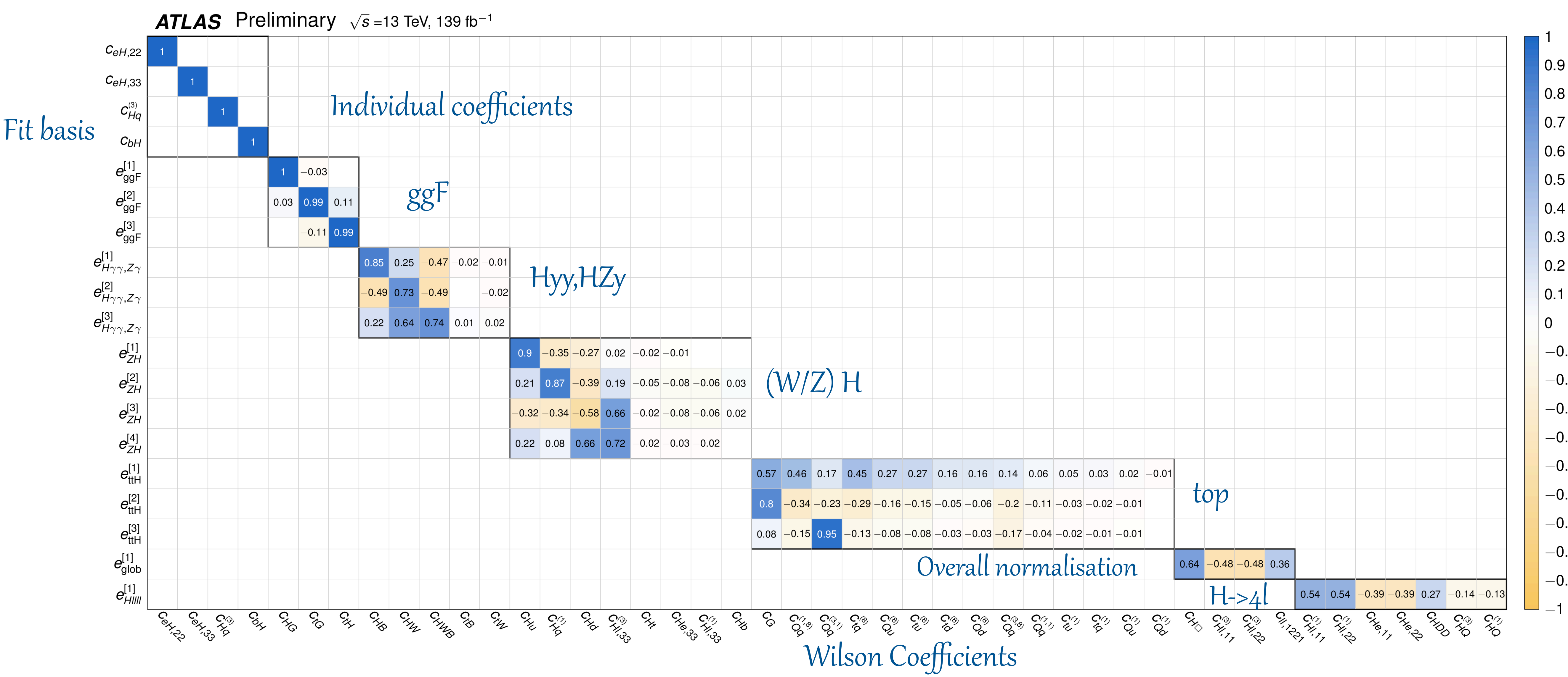
STXS sensitivity study

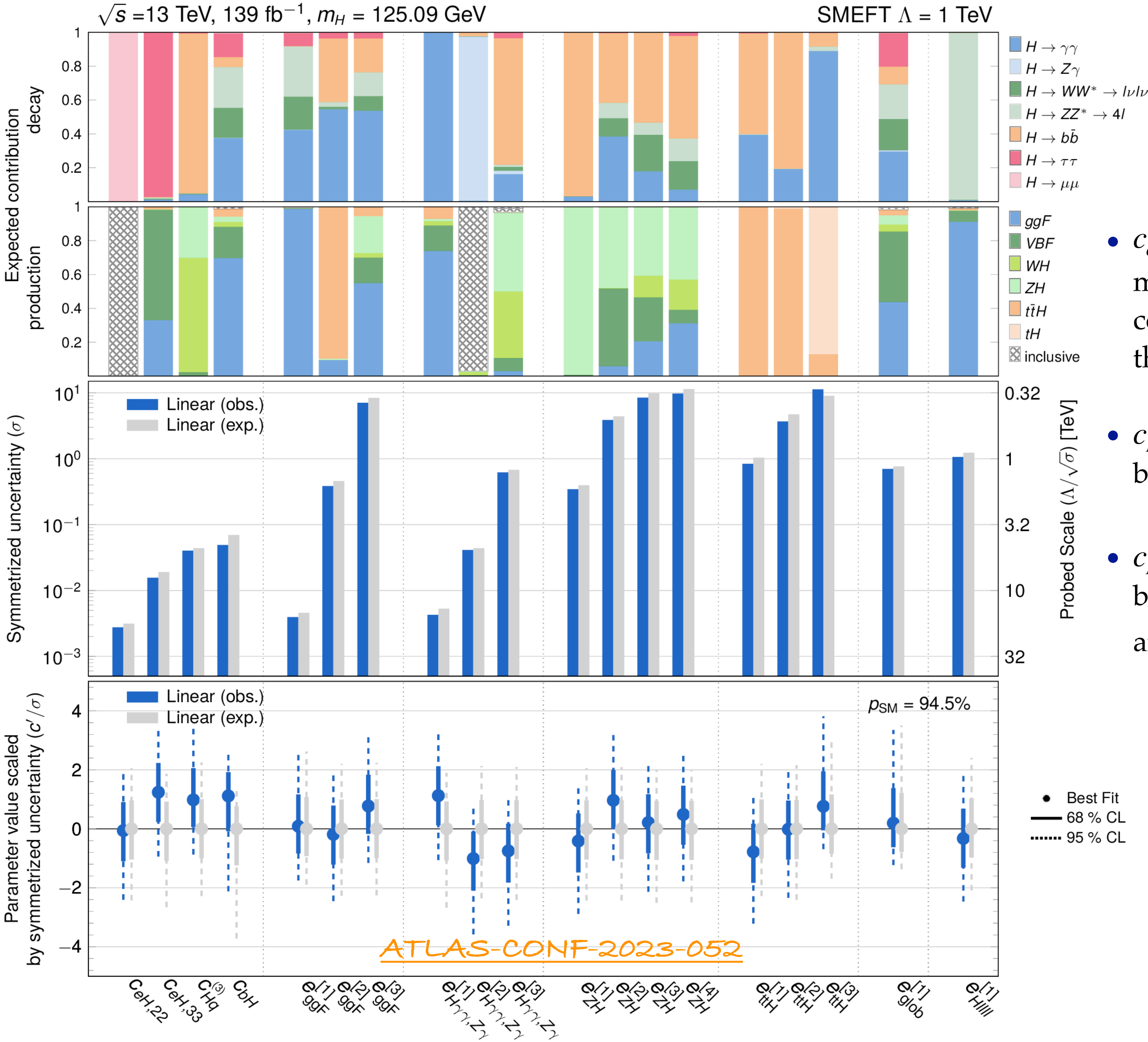
- 50 Wilson coefficients have a non-negligible impact on STXS bins.
- Not all the parameters can be constrained directly in the Warsaw basis, need to identify sensitive directions that can be reasonably constrained.
- Principal component analysis on information matrix:

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

  - Full eigenvector basis-> Negligible correlation, hard to interpret.
  - Fit basis-> Higher correlation, easy to interpret -> 19 directions



Linear STXS SMEFT results



- $c_{eH_{33}}$ and $c_{eH_{22}}$ 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.

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

Linear STXS SMEFT results

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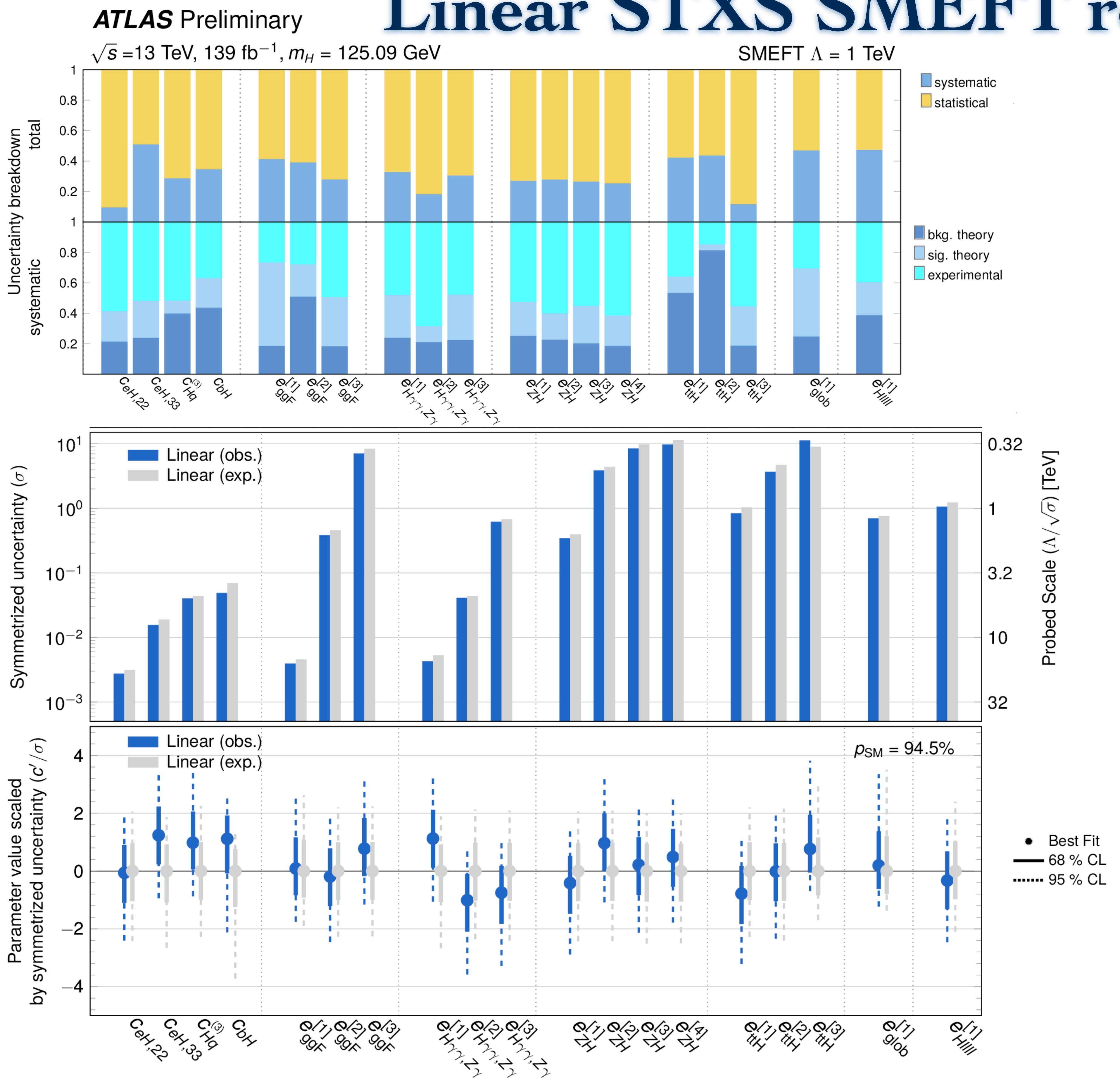

- Most of WCs are statistically dominated.
- 5 out of 19 parameters close to syst/stat parity.

Linear+quadratic STXS SMEFT results

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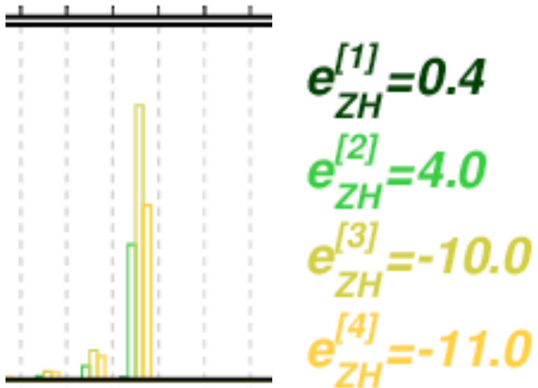
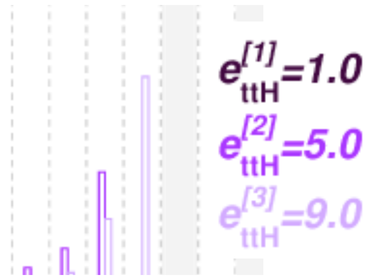
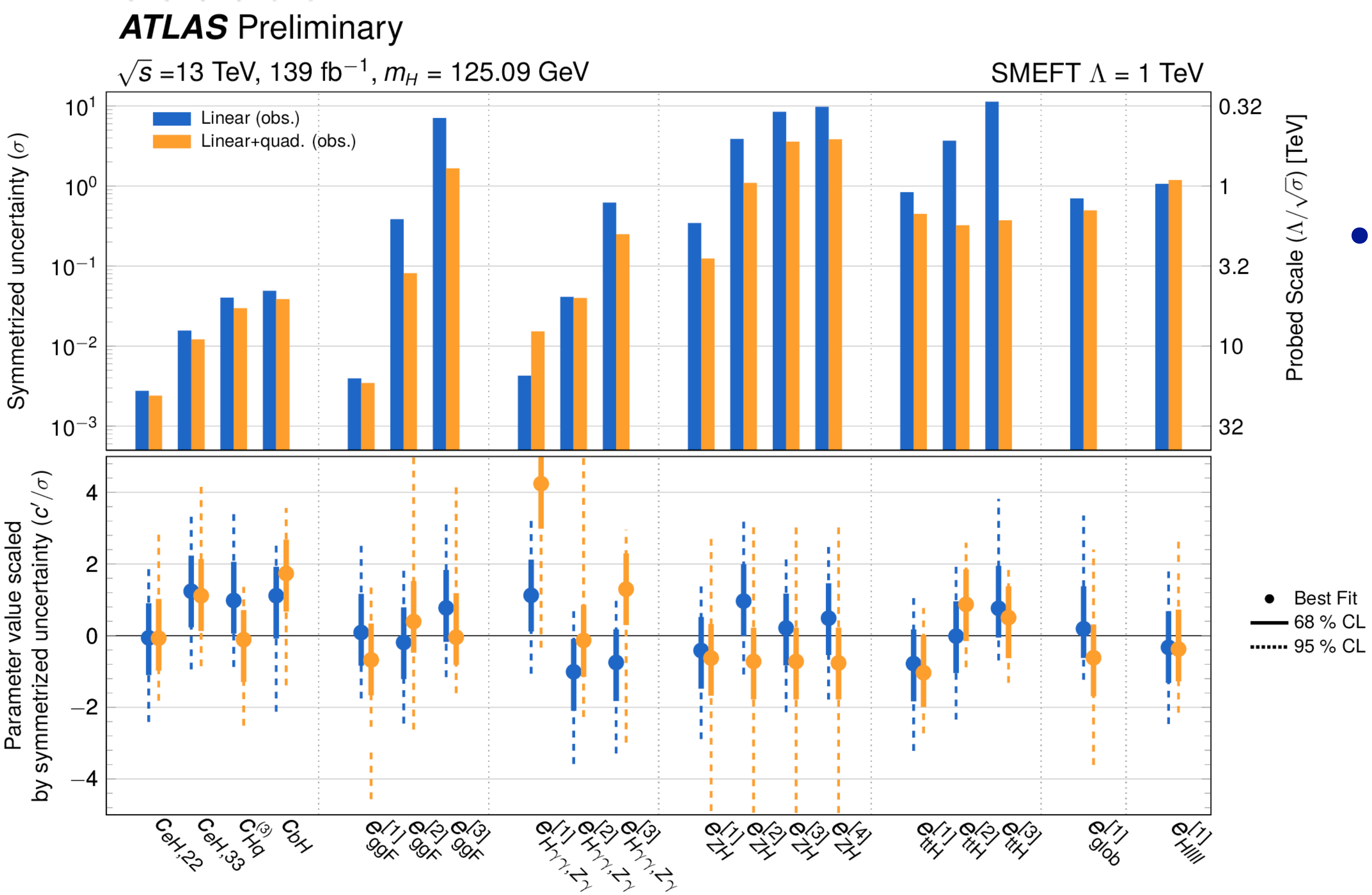
- Significant impact of quadratic terms for different parameters:
  - ZH directions significantly affected + tH ($e_{ttH}^{[3]}$)





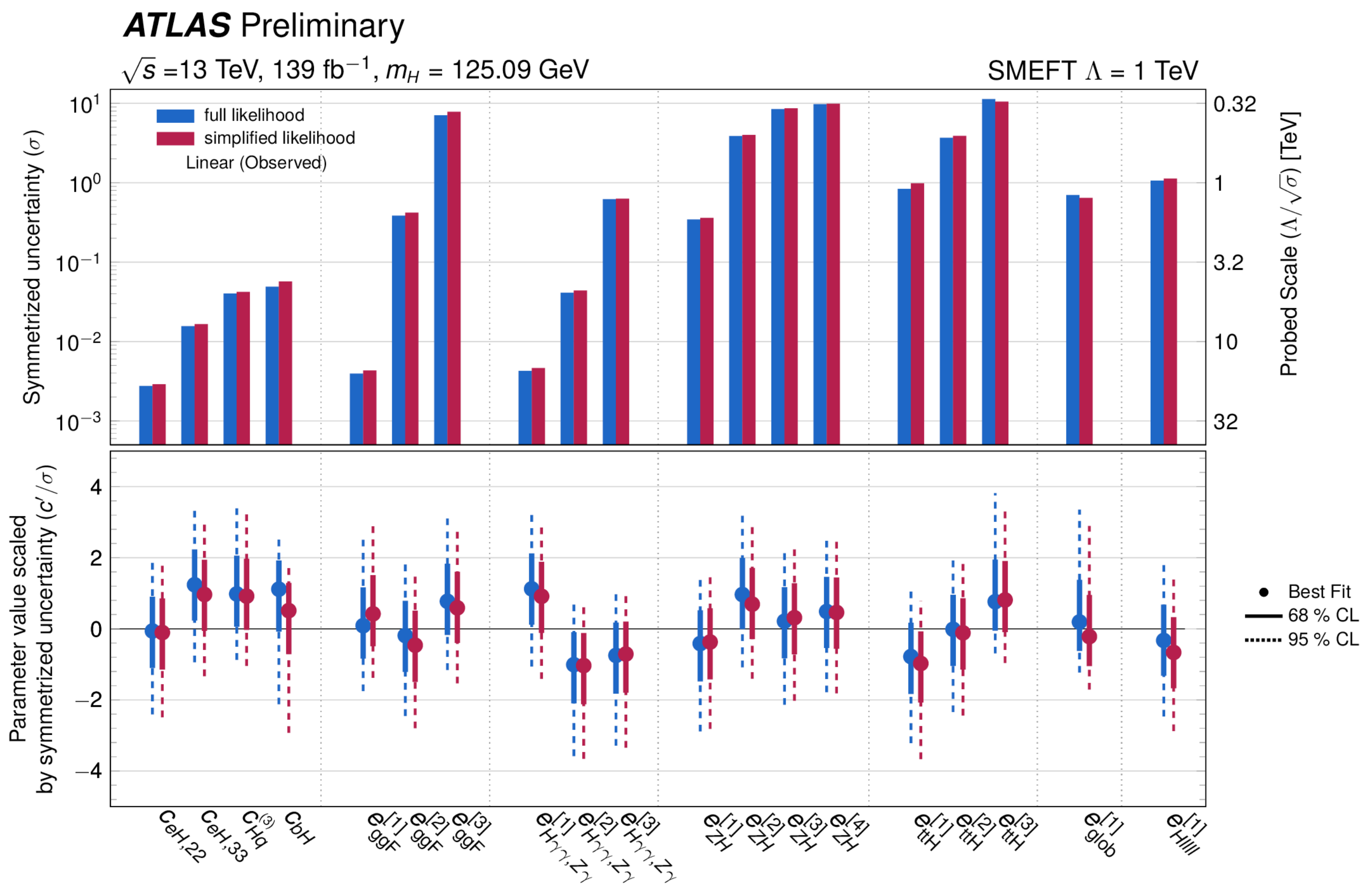
- Double minima structure observed for several parameters.
- For now treating difference between $1/\Lambda^2$ and $1/\Lambda^4$ as magnitude indicator of effect missing SM-Dim8 interference.

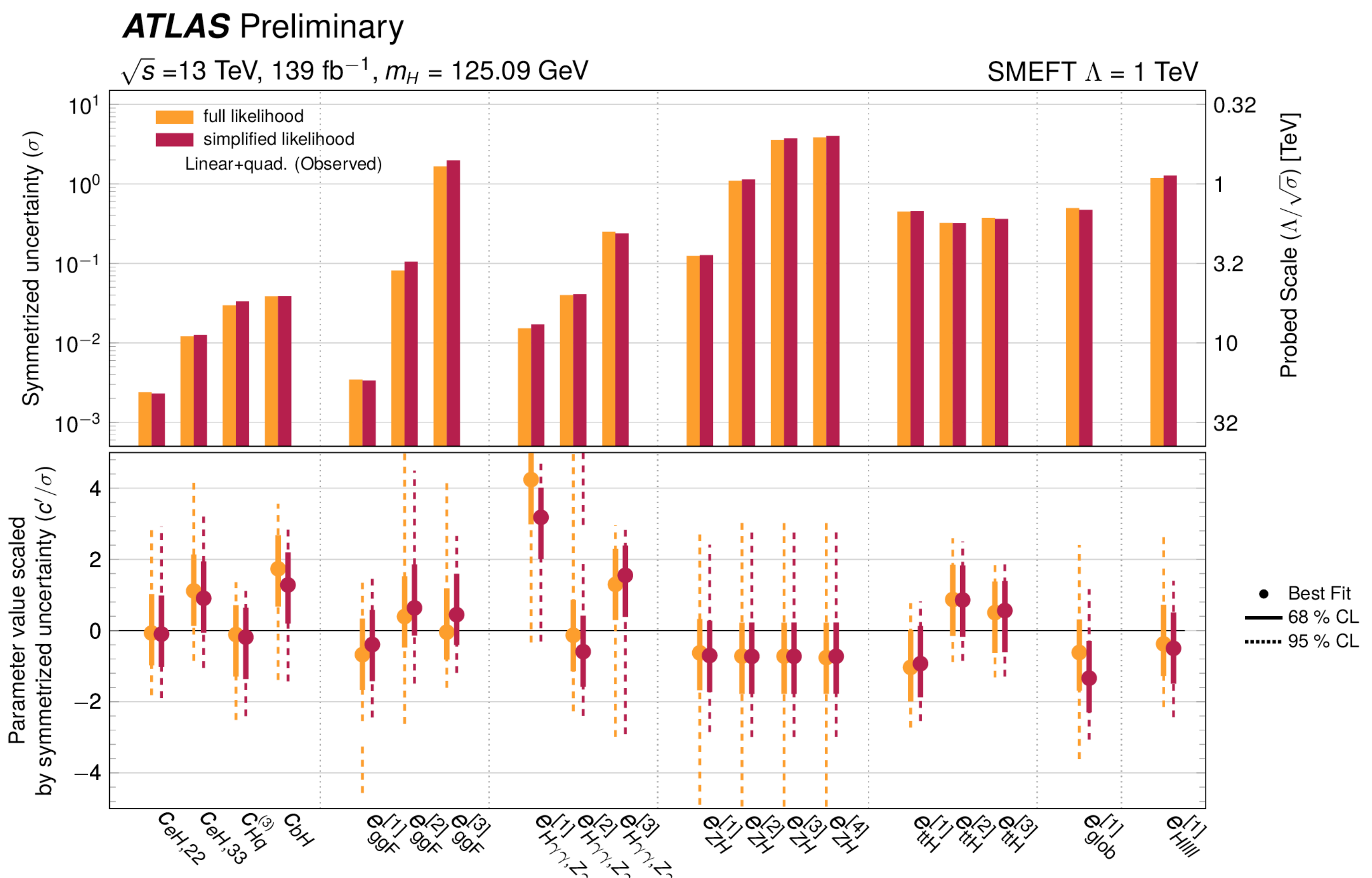


- Next steps:
  1. Collect & implement available dim-8 calculations (=incomplete but growing set)
  2. Develop a more sophisticated strategy to quote truncation uncertainty using partial calculations

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.





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EFT to 2HDM

EFT to 2HDM

Further details in Andrea's talk on Friday

- 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 , ν the VEV, Y_i the Yukawa-couplings ($Y_i = \sqrt{2}m_i/\nu$), M_A is the common mass of the heavy decoupled scalars.

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

EFT to 2HDM

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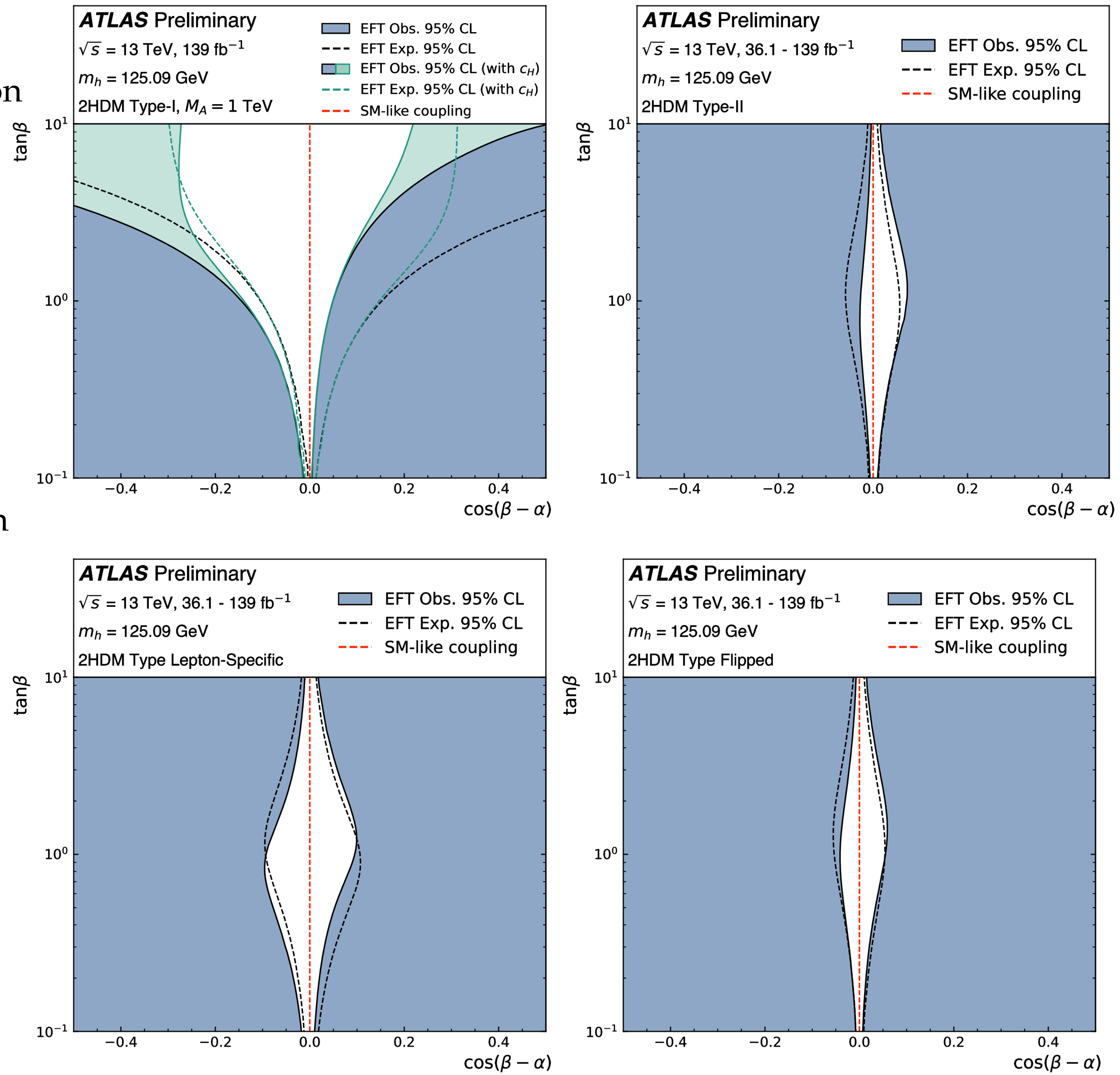
- Relevant coefficients parametrised as function of the 2HDM parameters.
- Linear expansion is performed.
- No constraints from vector boson couplings in SMEFT model (would occur in dim-8)-> relevant for constraining Type I at high *tanβ*
- Others: the region with flipped coupling sign does not appear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

Mapping is affected by missing SMEFT dimension-8 operators:

- constraints from SMEFT parameters weaker than from k-parameters



Detailed comparison w.r.t kappa results in backup

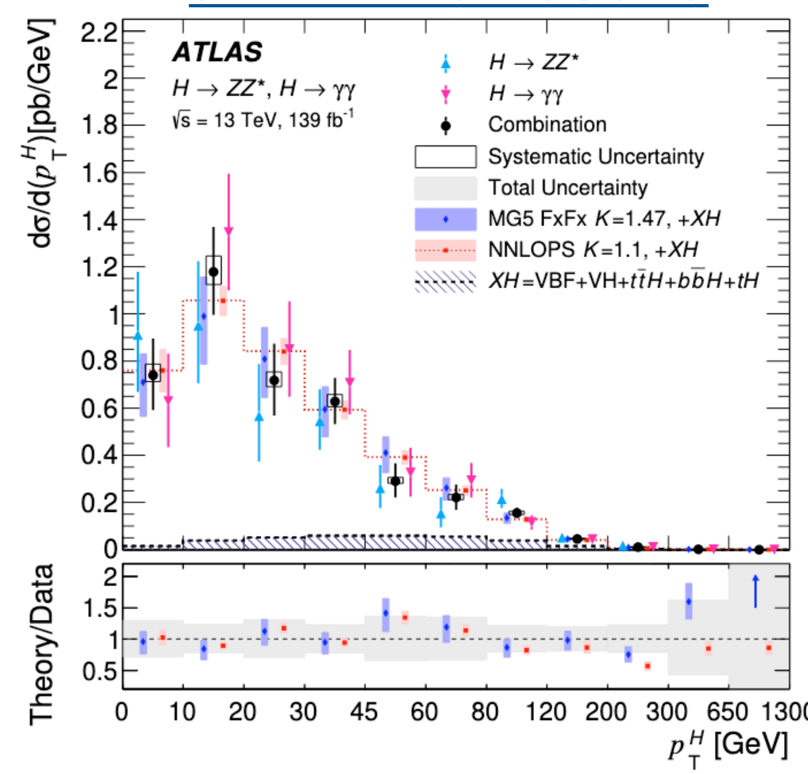
Differential interpretation

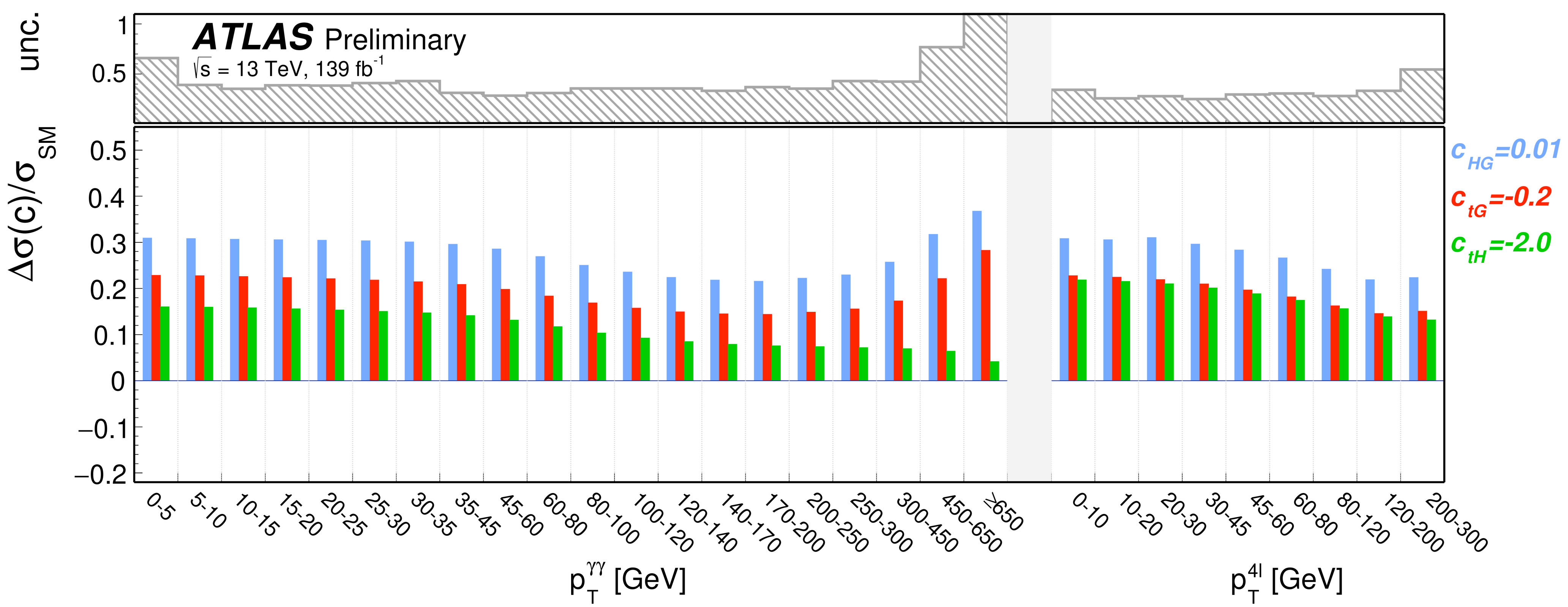
Differential SMEFT interpretation

- 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 $H \to \gamma\gamma$ & $H \to 4l$

arxiv: 2207.08615





Differential SMEFT interpretation

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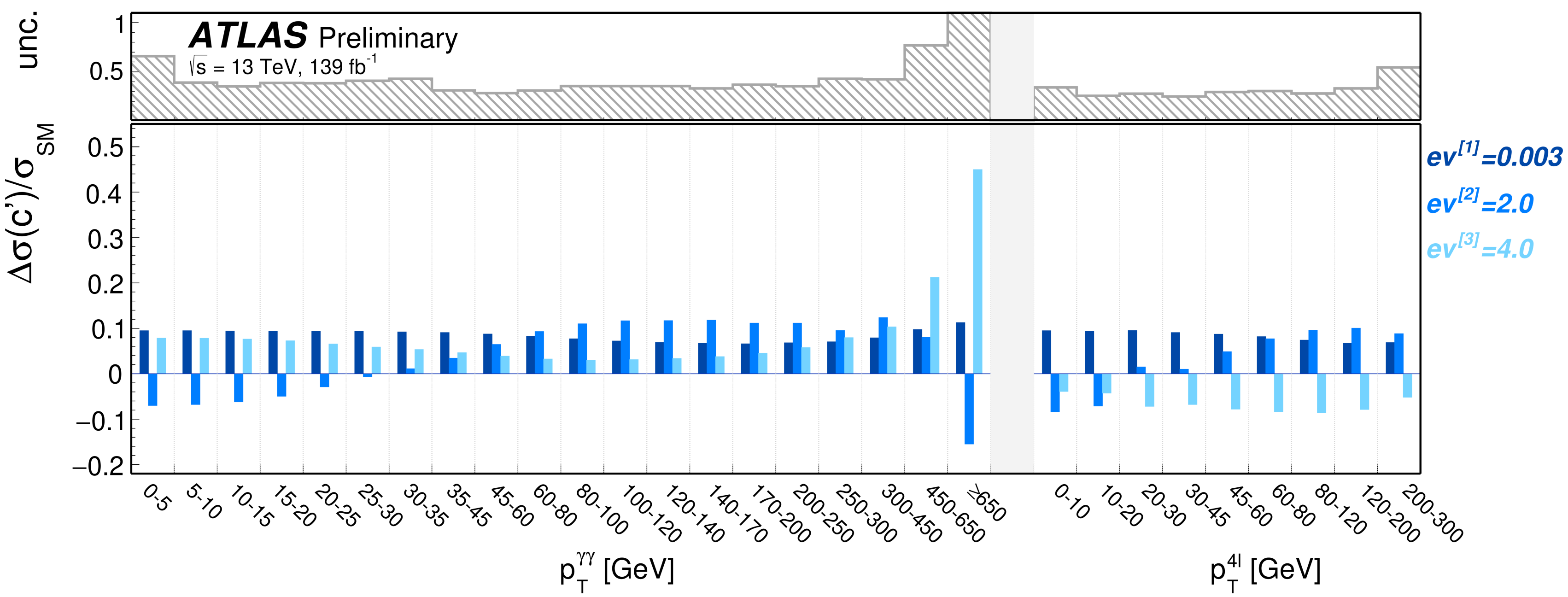
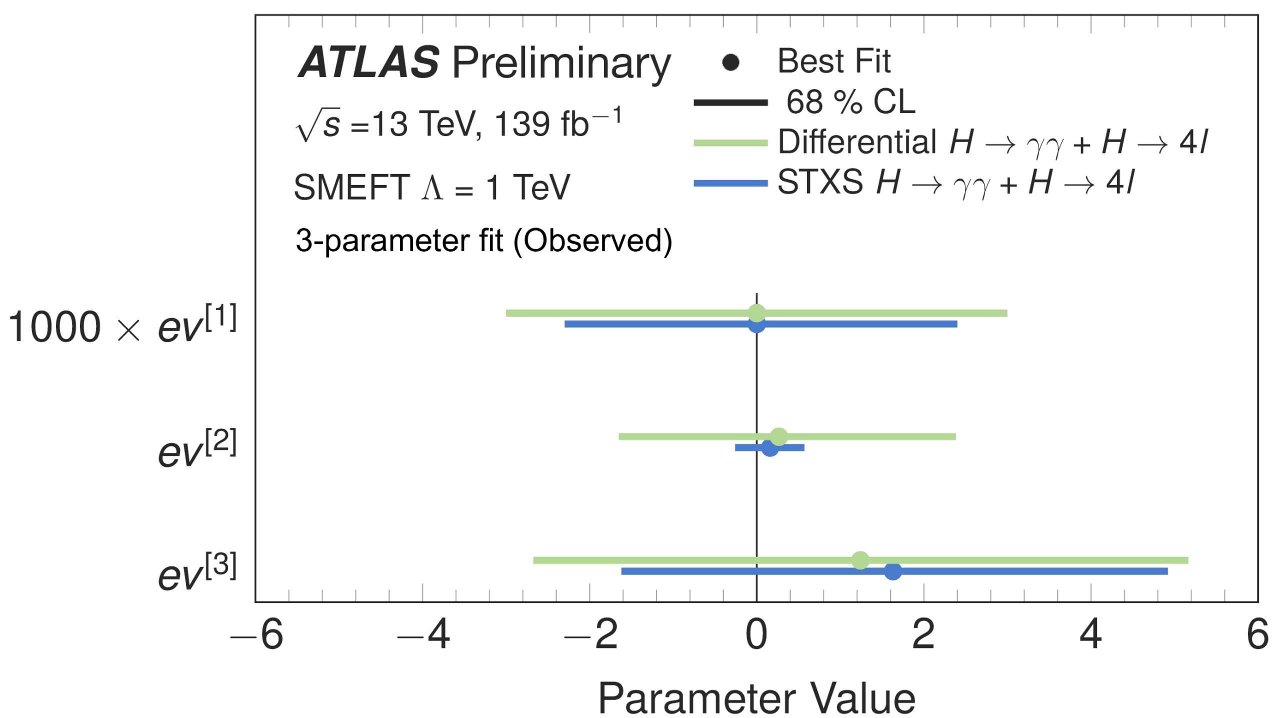
- High correlation-> new basis and most sensitive directions can be obtained with an eigenvector decomposition.



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

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.

Global combination

ATLAS Global combination

HIGGS+EW

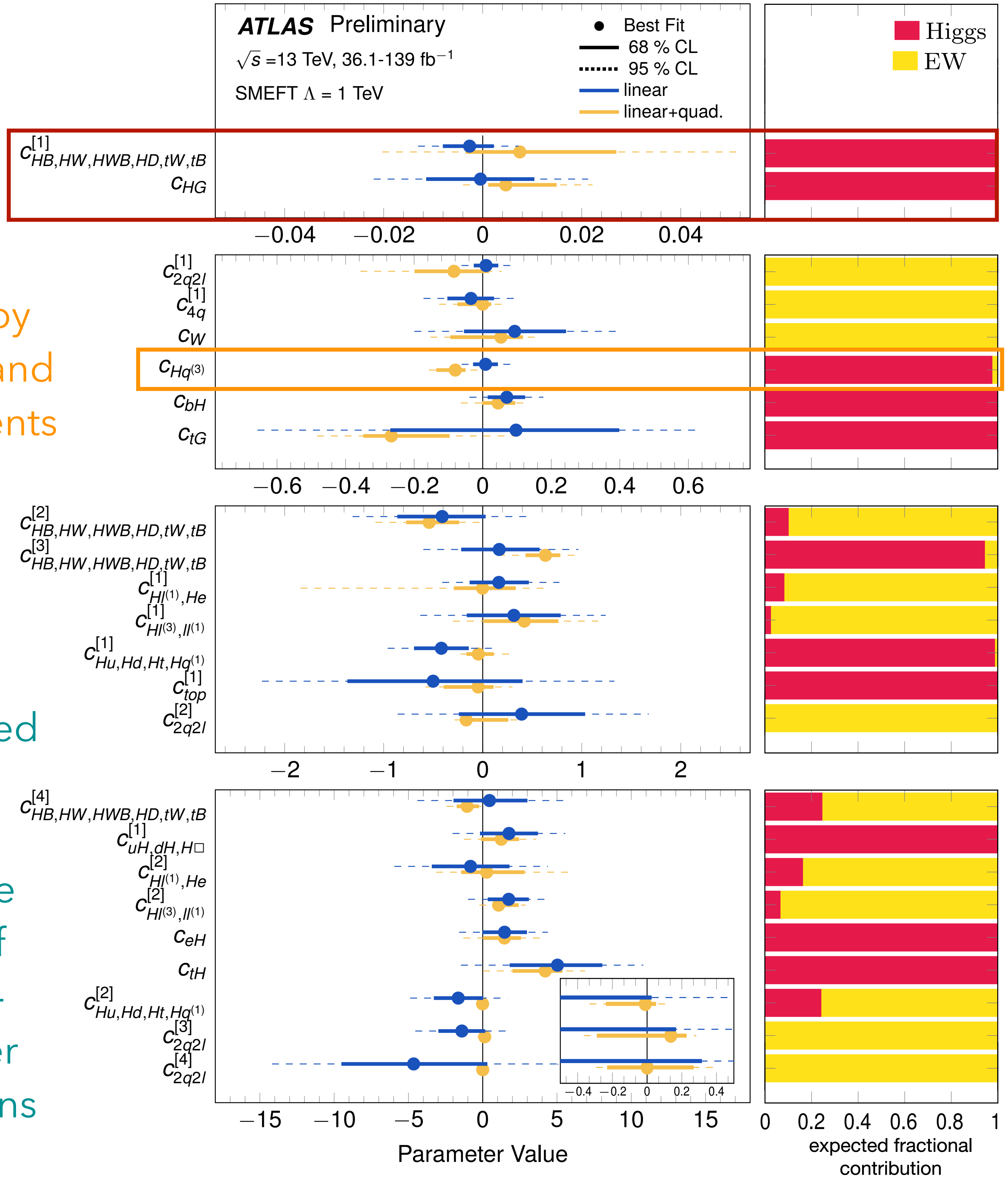
ATL-PHYS-PUB-2022-037

- Previous round of Higgs combination used in the context of the ATLAS Global combination (Higgs + EW + EWPO results in backup)
- 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

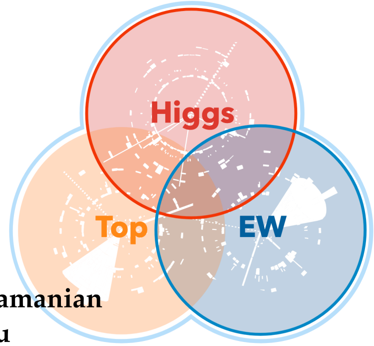


Road towards Global Combination(s)

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

- Within Higgs (w.r.t. 2023 Higgs combination)
  - Rare processes $H \rightarrow cc$, $VBF \rightarrow H\gamma$
  - Off-shell regions of $H \rightarrow WW$ and $H \rightarrow ZZ$
  - Angular observables sensitive to CP-odd operators (in both production & decay)
- Higgs pair production
  - First meeting to discuss LHC H+HH combination in EFT context on 29th March (indico) - LHC EFT HH Note
  - First studies of HH fits in SMEFT already available (ATLAS HH-> 4b + HH->bbyy - talk by Elisabeth)
- Outside Higgs – many opportunities for combinations
  - with other processes: dibosons, top-quarks
  - Constraints from LEP/SLC 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!!!



Sketch from R.Balasubramanian
inspired by Ken Mimasu

Thanks for your attention!

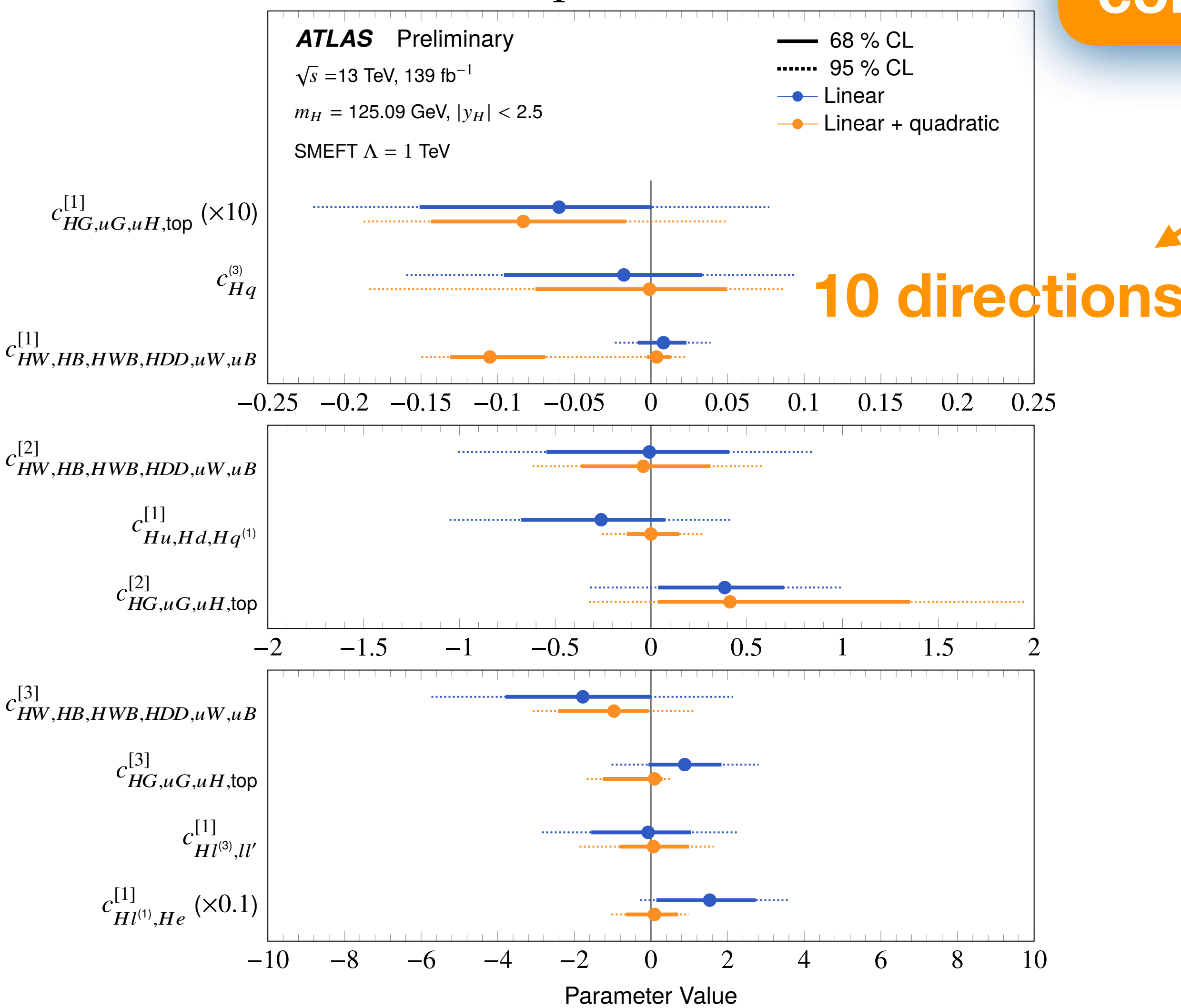
Higgs combination

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

- Operator grouping dictated by experimental sensitivity to physics.
- No strong tensions with the SM, 59% compatibility.
- Additional sensitivity from the $H \to \tau\tau$, $VBF, H \to b\bar{b}$ and $t\bar{t}H$, $H \to b\bar{b}$ input channels-> c_{eH}, c_{dH} + independent constraints for $c_{top}^{[1]}$.
- Sensitivity to the most sensitive directions in each of the remaining groups of the parameters is in general improved by up to 70%.

- Sizeable sensitivity to operators suppressed by Λ^4 in all of the measured parameters.

Previous combination



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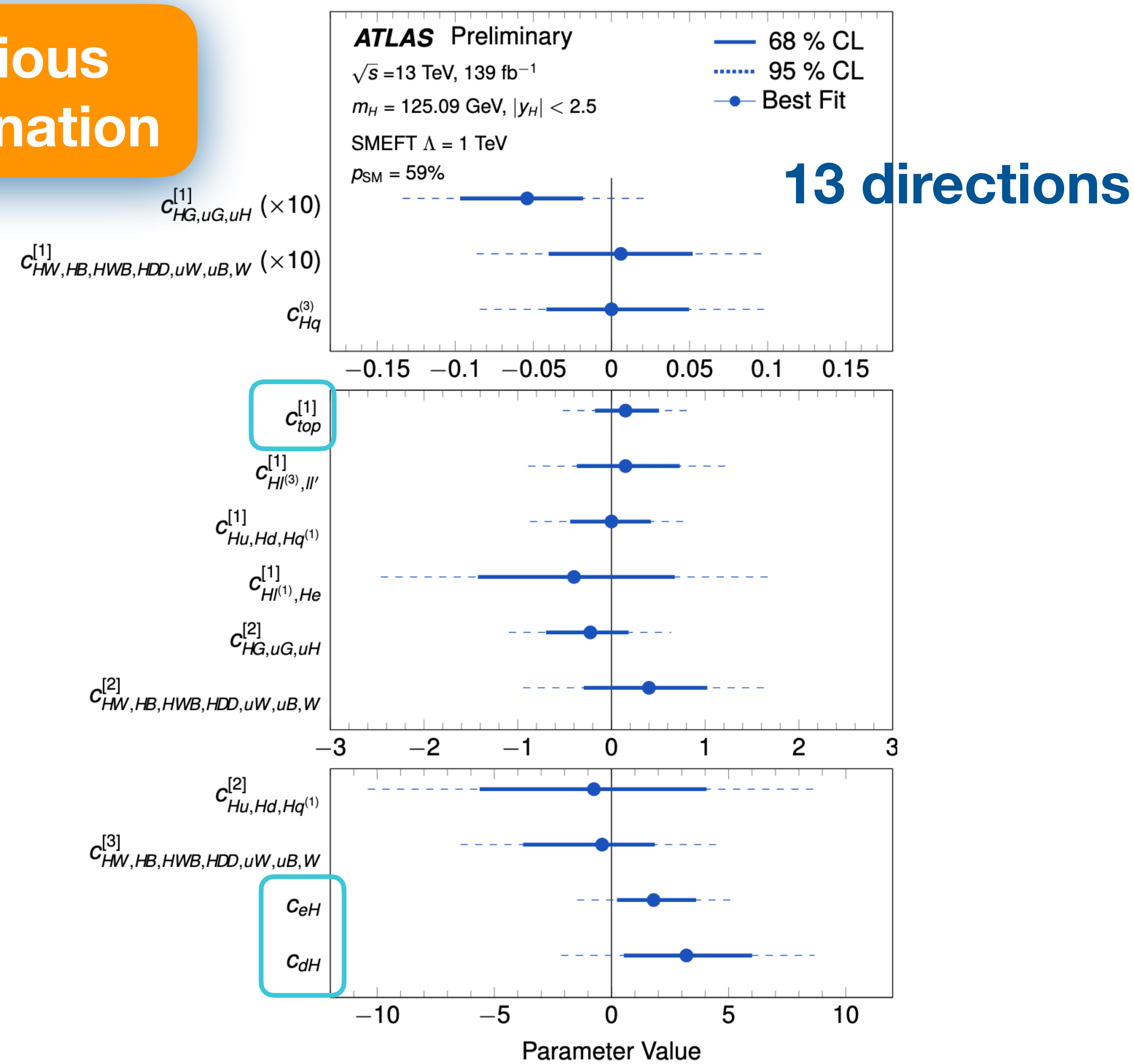

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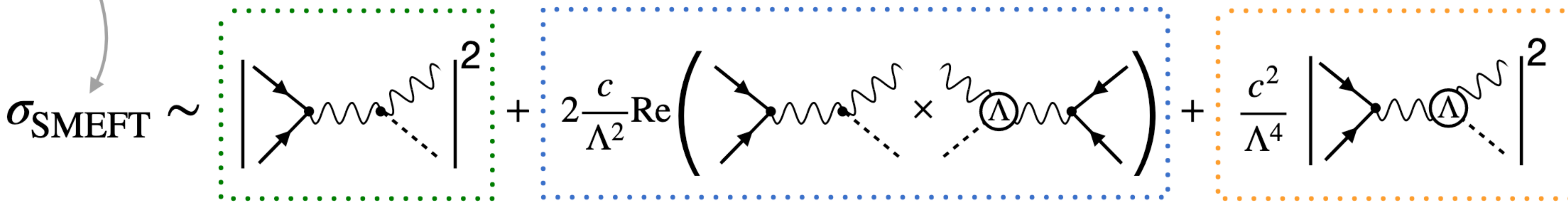
SMEFT parameterisation

e.g. σ^{STXS}

SM

SM / dim-6 interference
"linear": $(v/\Lambda)^2$, $(E/\Lambda)^2$

dim-6 squared
"quad.": $(v/\Lambda)^4$, $(E/\Lambda)^4$



- Warsaw basis, assuming $\Lambda = 1$ TeV.
- SMEFTsim + SMEFT@NLO
- Results are usually provided for linear model (+ linear-quadratic models).
- SMEFTsim: different flavour symmetries used to reduce the number of Wilson coefficients.

  ("$U(3)^5$ flavour symmetry","topU3l", "top")

$U(3)^5$ flavour symmetry

$\mathrm{U}(3)_q \times \mathrm{U}(3)_u \times \mathrm{U}(3)_d \times \mathrm{U}(3)_l \times \mathrm{U}(3)_e$

All quark generations treated similarly — *All lepton generations treated similarly*

Relax t,b →

topU3l flavour symmetry

$\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d \times \mathrm{U}(3)_l \times \mathrm{U}(3)_e$

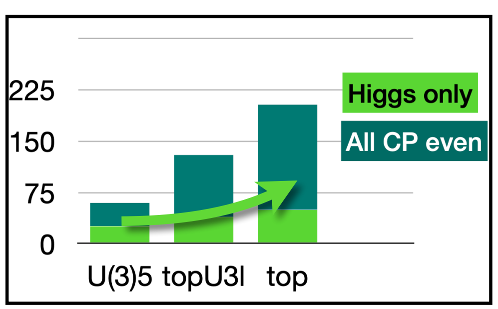
First two quark generations treated similarly — *All lepton generations treated similarly*

Relax leptons →

top flavour symmetry

$\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d \times \mathrm{U}(1)_e \times \mathrm{U}(1)_\mu \times \mathrm{U}(1)$

First two quark generations treated similarly

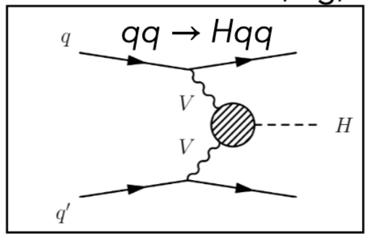


# of CP-even d=6 operators

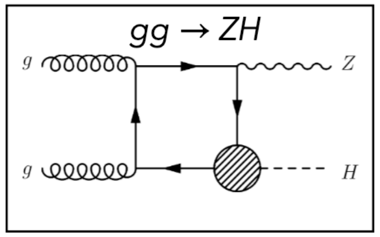
SMEFT parameterisation

The impact of dim-6 CP-even operators is estimated using both MC truth and analytical predictions for all the Wilson coefficients that have numerically relevant contributions (62).

Tree-level insertion, eg,



NLO-QCD



- Dimension-six operator effects are calculated:
  - at tree level using SMEFTsim 3.0.
  - for processes that are loop-induced in the SM, thus ggH and ggZH production, Higgs boson decays into gluons -> SMEFTatNLO.
  - Analytic formulas for $H \to \gamma\gamma$ including NLO EW corrections and LEP observables.
- Theory uncertainties on SM predictions, no additional uncertainties on SMEFT.
- Acceptance corrections to account for kinematic differences between SM and SMEFT in Higgs boson decays on both **linear** and **linear+quadratic** terms.
- Effects of width changes of intermediate particles ("propagator corrections") included.

v3.0

SMEFT impact on STXS bins and decay - fit basis

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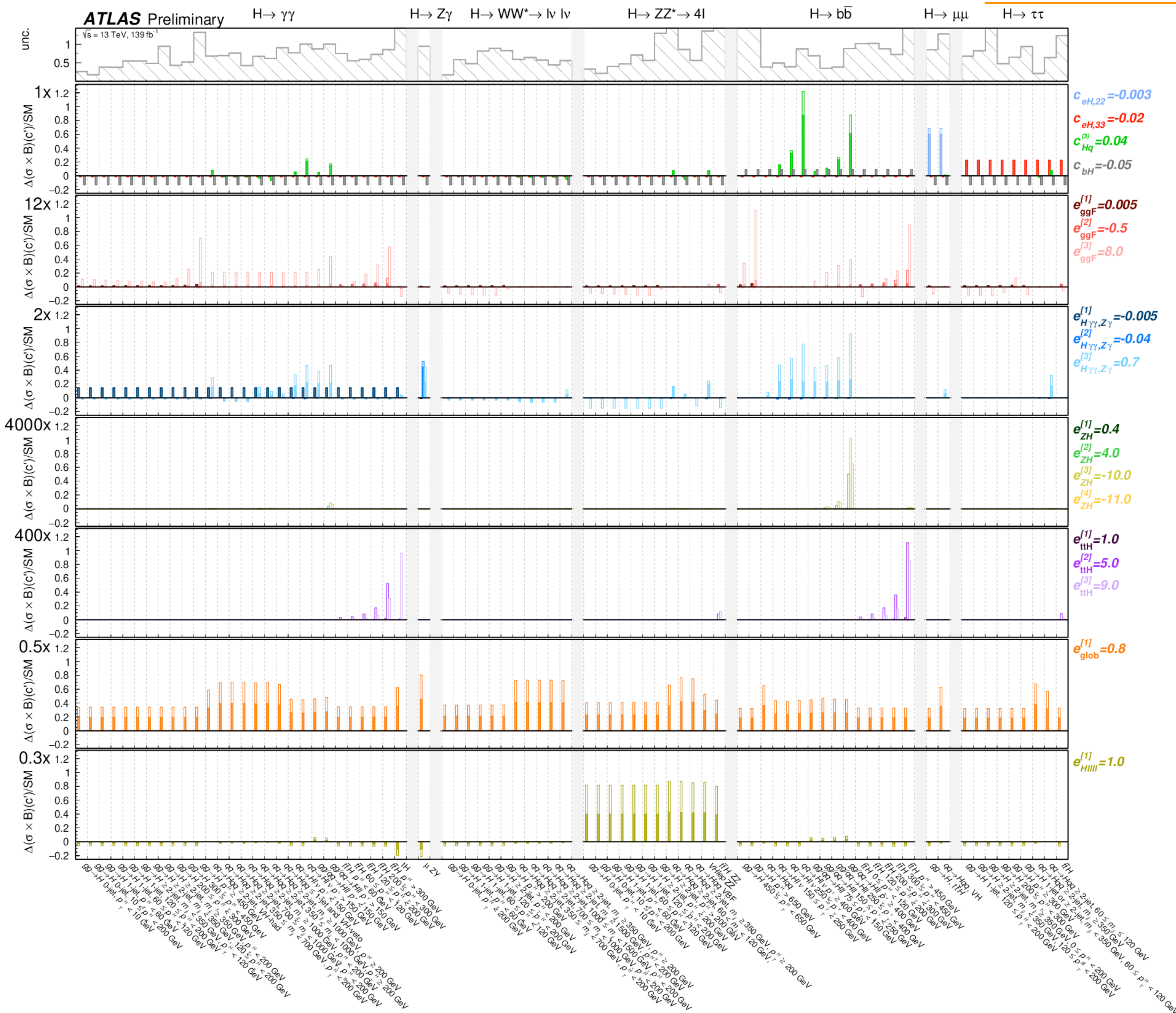

STXS: acceptance corrections for HWW/H4l decays

- 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.
- Acceptance corrections for STXS interpretation have been included for $H \to WW^*$ and $H \to 4l$ channels, linear and linear+quadratic results.
- Future: harmonised approach to acceptance possible in Run-3 with introduction of decay-side STXS definition.

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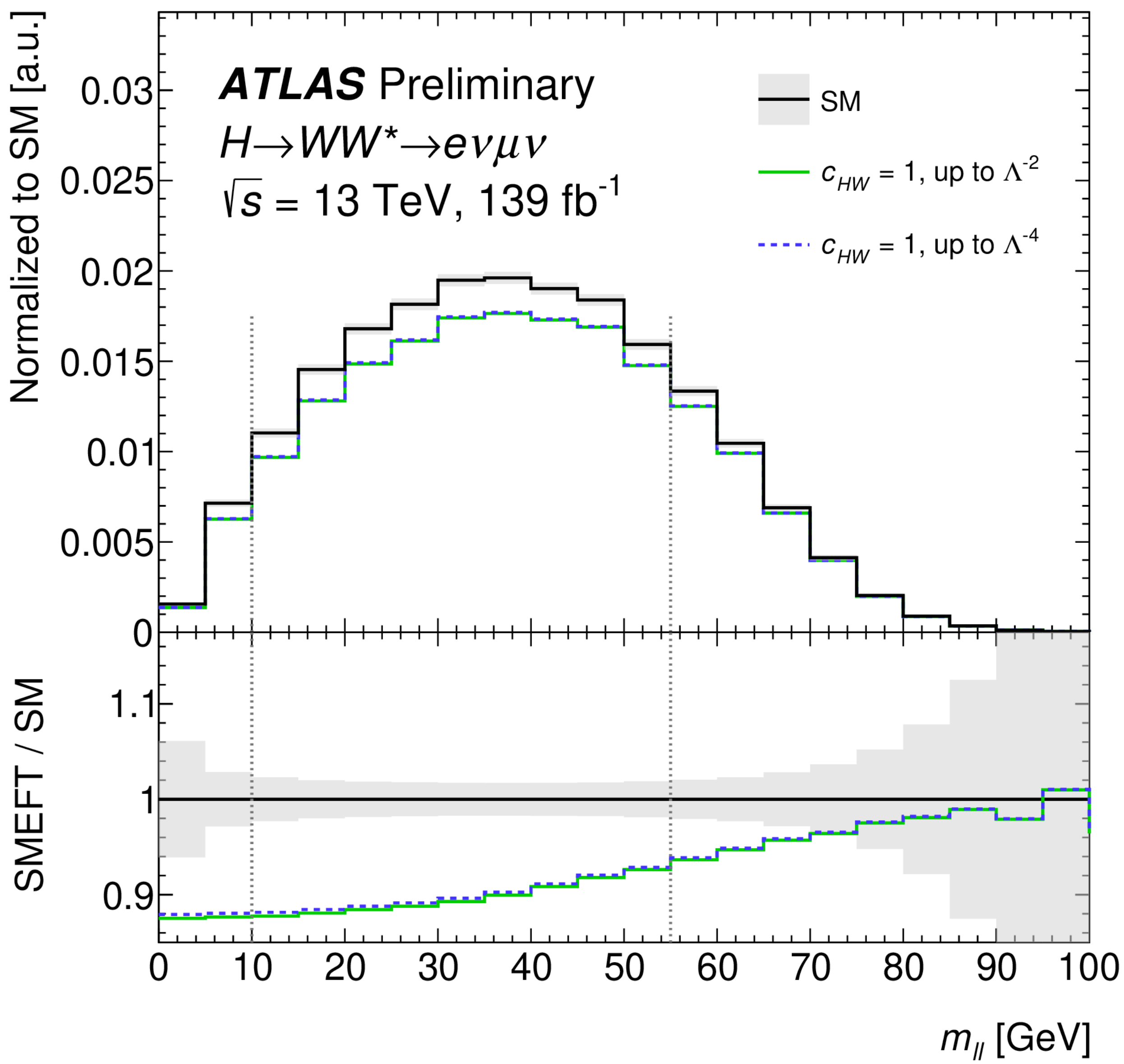

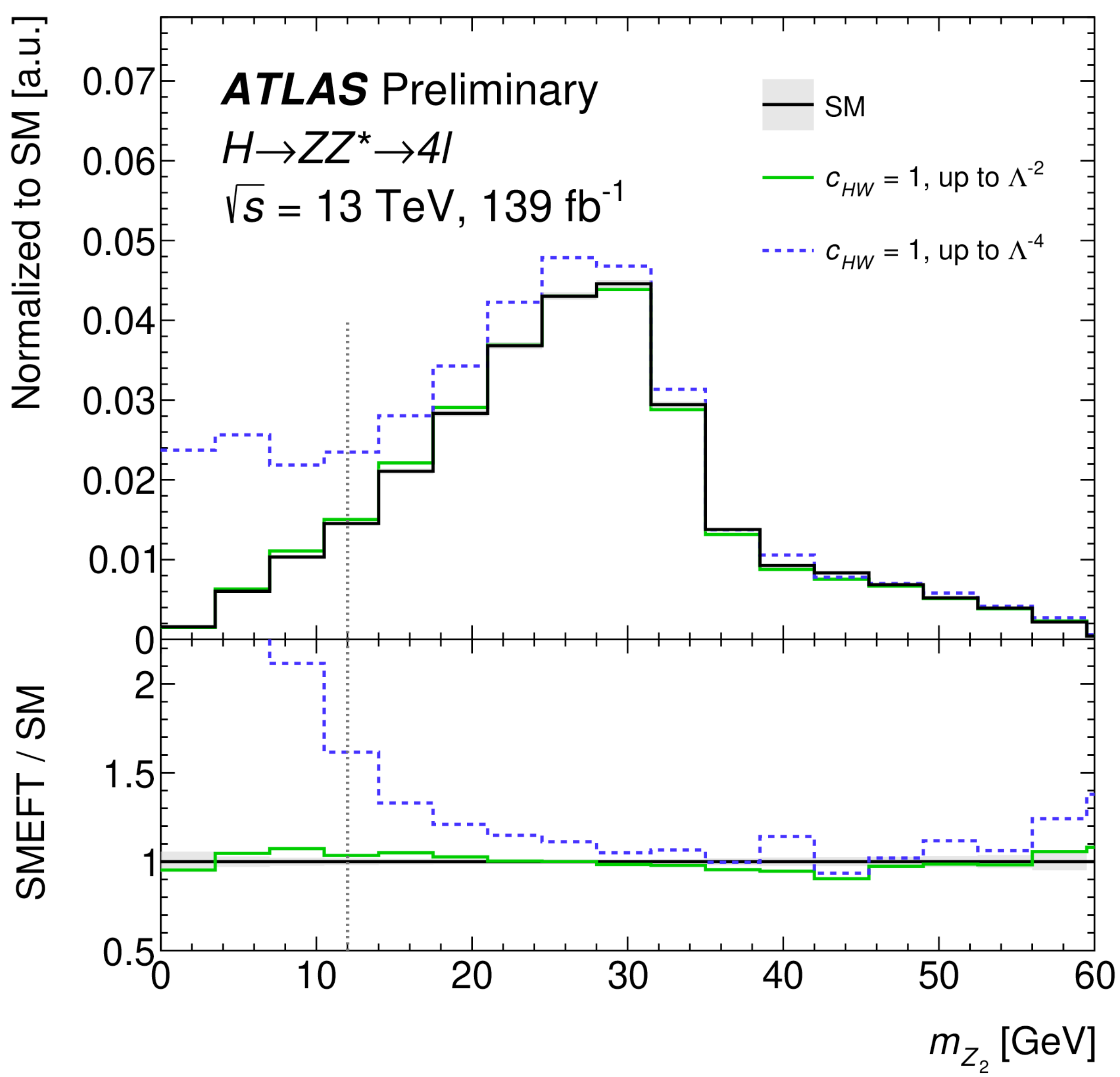

Linear STXS SMEFT results

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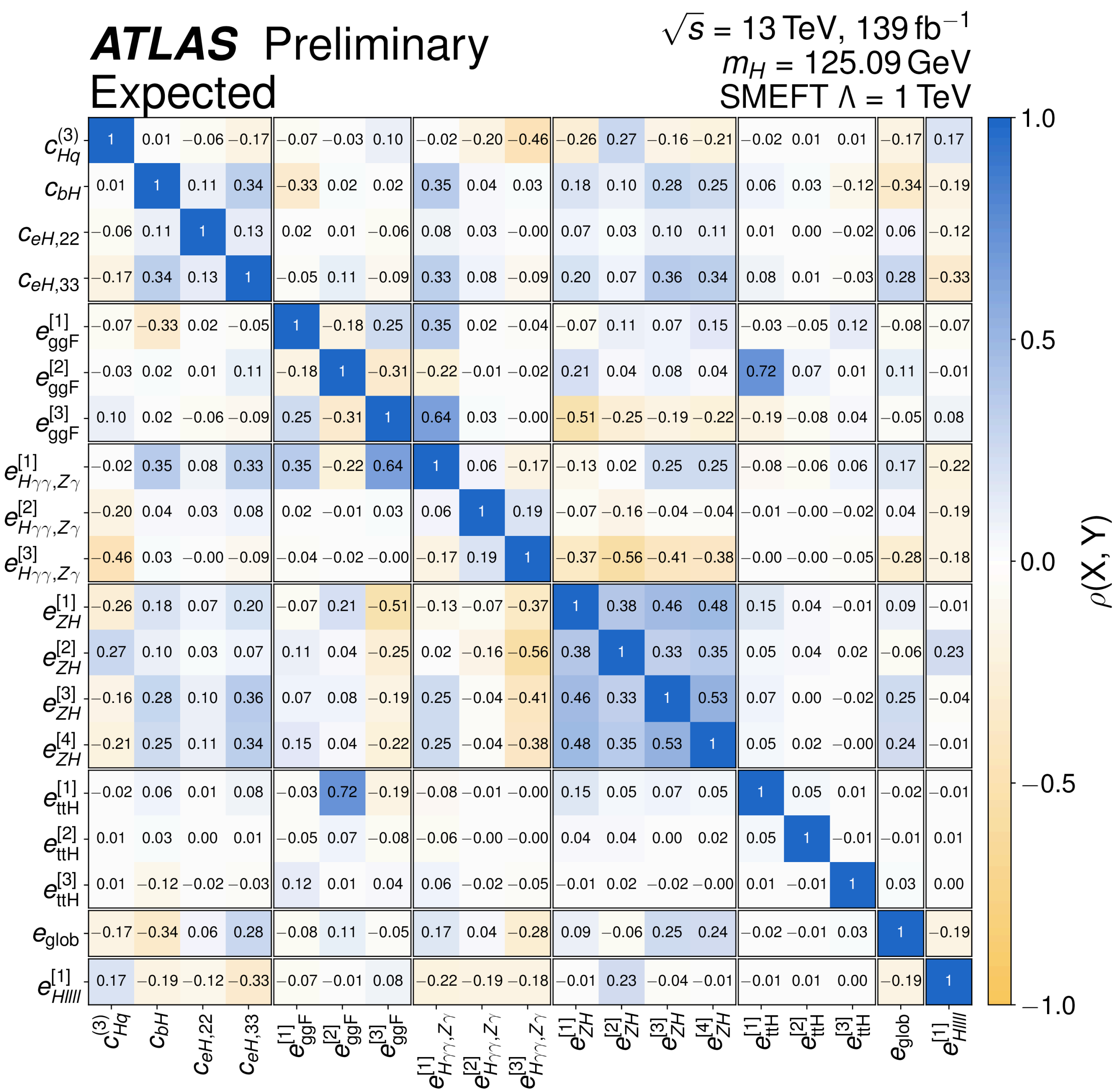
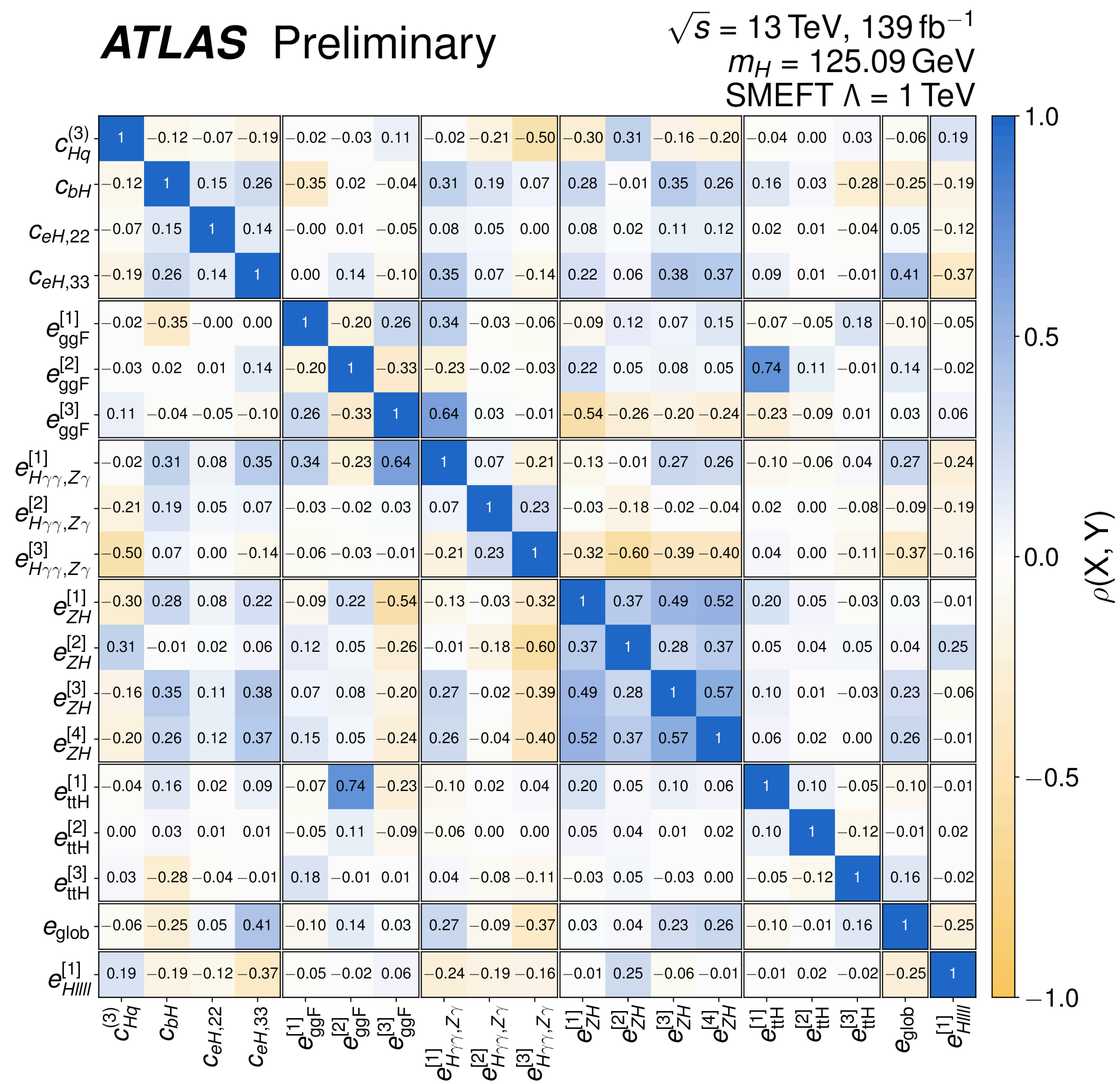
- Residual correlations present between $e^{[2]}_{ggF}$ and $e^{[1]}_{ttH}$ and $e^{[3]}_{ggF}$ and $e^{[2]}_{H\gamma\gamma,Z\gamma}$ and which are caused by a common sensitivity to ttH production and ggF $H \to \gamma\gamma$, respectively.





Linear+quadratic STXS SMEFT results

Operators in Warsaw basis: $c_{eH,22}$, $c_{eH,33}$, $c_{Hq}^{(3)}$ and c_{bH}

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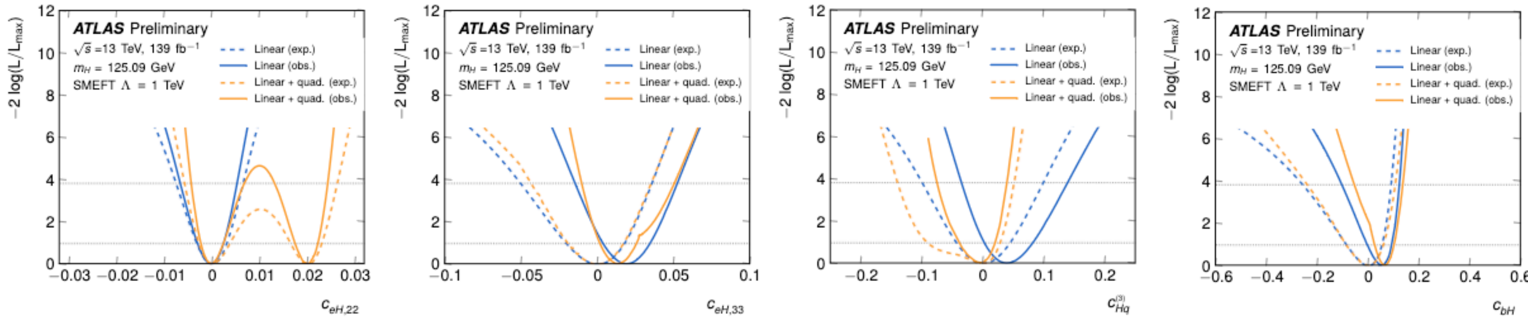
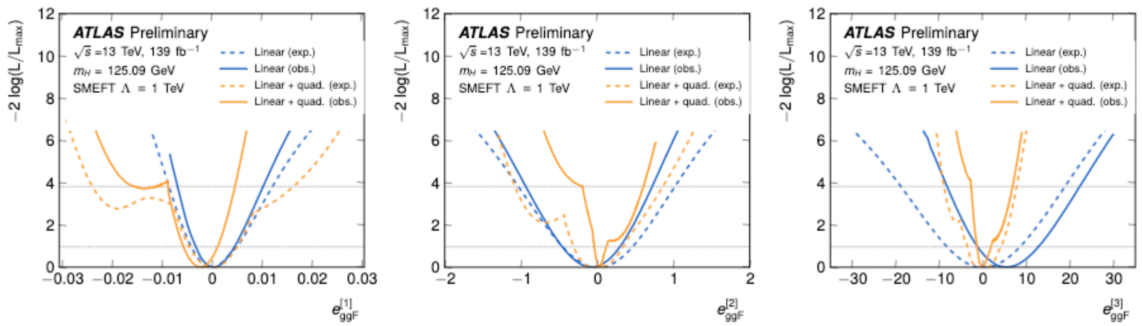


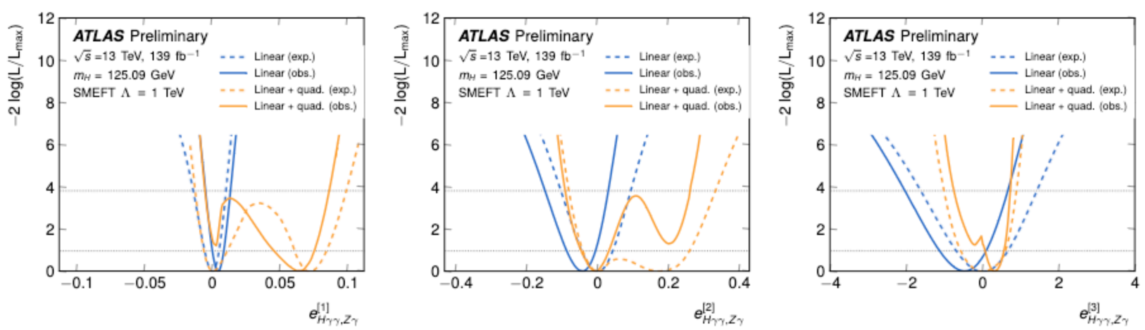
(a) (b) (c) (d)

Eigenvector group ggF



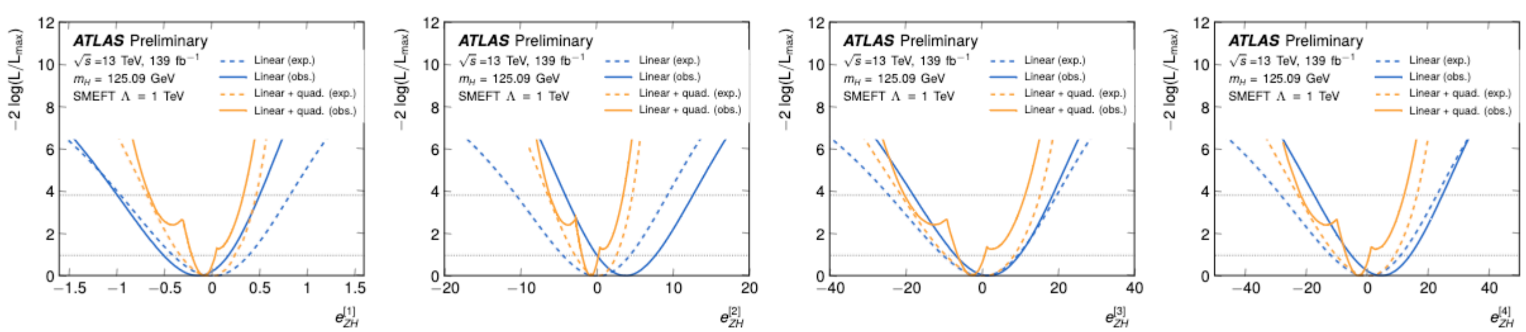
(e) (f) (g)

Eigenvector group $H \to \gamma\gamma, Z\gamma$



(h) (i) (j)

Eigenvector group ZH



Linear+quadratic STXS SMEFT results

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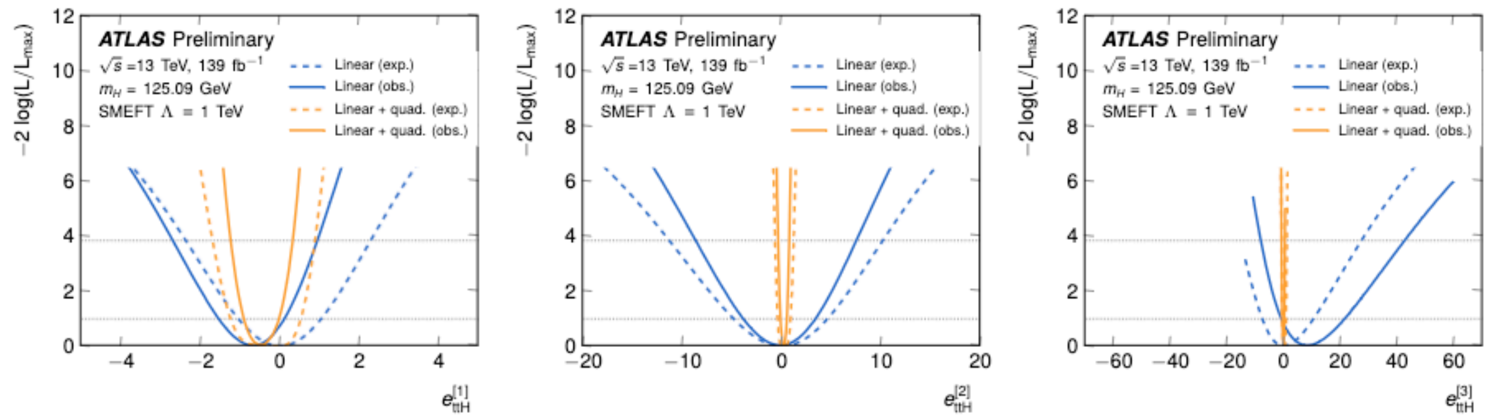
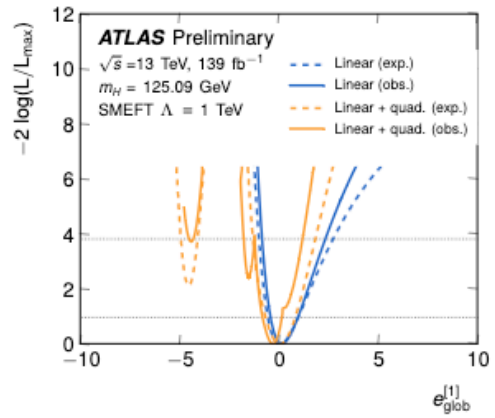
Eigenvector group *top*



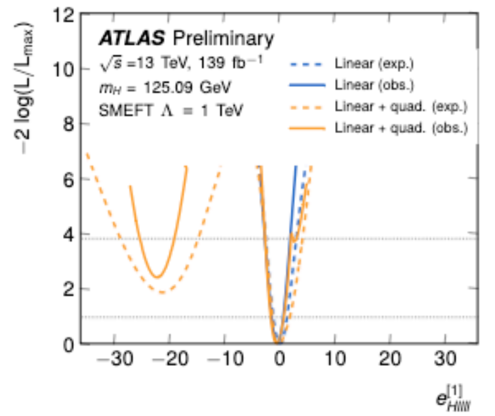
(a) (b) (c)

Eigenvector group *overall normalization*



(d)

Eigenvector group $H \rightarrow ZZ^*$



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.

2HDM

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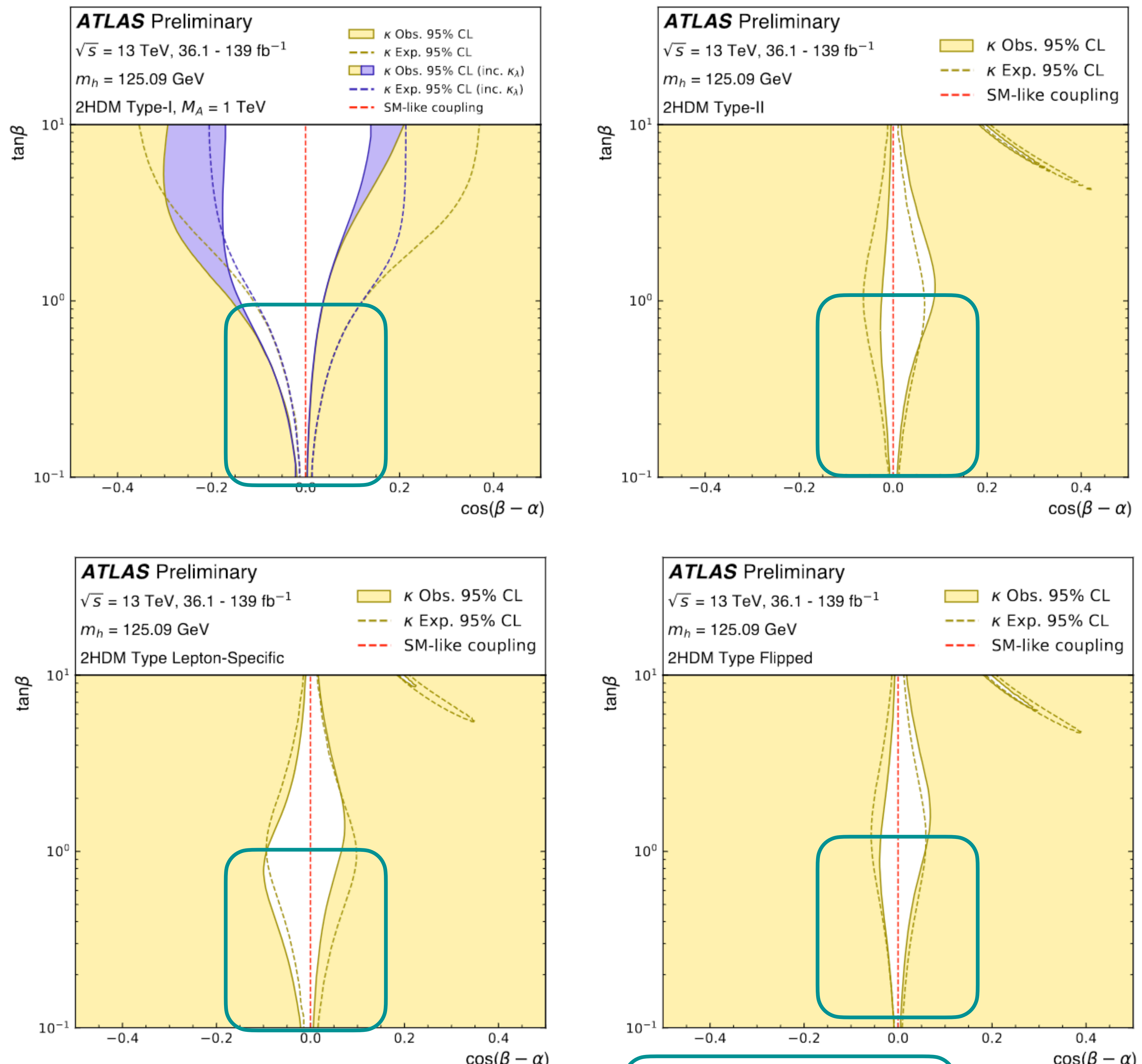


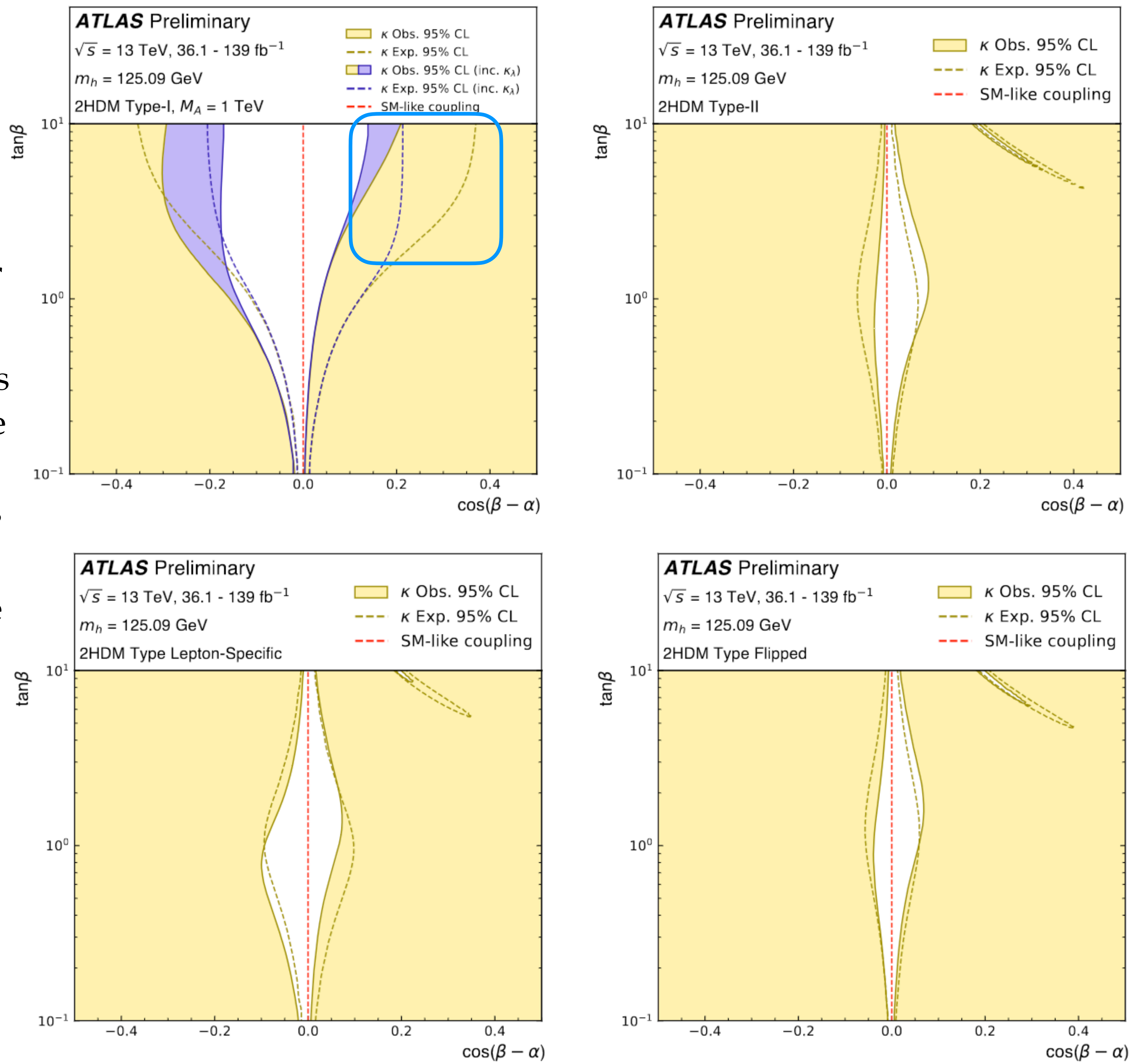
All models: similar exclusion regions in the tan β, cos$(\beta - \alpha)$ plane: for low values ($\lesssim$ 1) of tanβ a small region is consistent with the Higgs boson production and decay rates.

2HDM

ATLAS-CONF-2023-052

Type I:

- In the large tan β region, for positive $\cos(\beta-\alpha)$, the observed exclusion region is significantly larger than the expected one: values of the coupling strength modifiers to b, t quarks and τ leptons smaller than one and of the couplings to W, Z bosons larger than one are favoured.

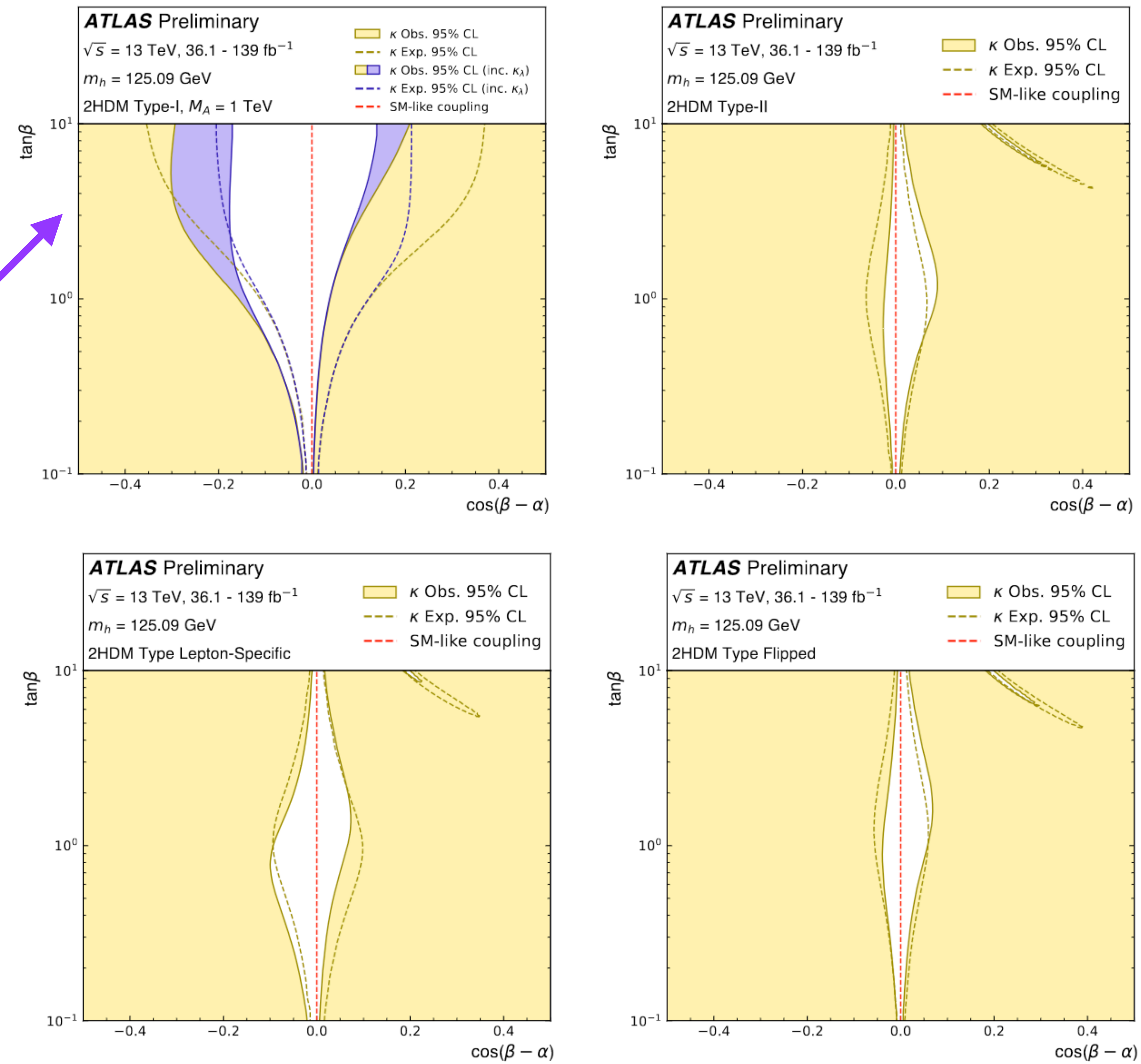


2HDM

ATLAS-CONF-2023-052

- κ_λ constraints mostly affects the high tanβ region (already constrained in all scenarios except Type 1); the width of the 95% CL interval for cos$(\beta - \alpha)$ at large tan β is reduced by about 50%

- m_A of 1 TeV when κ_λ is included



2HDM

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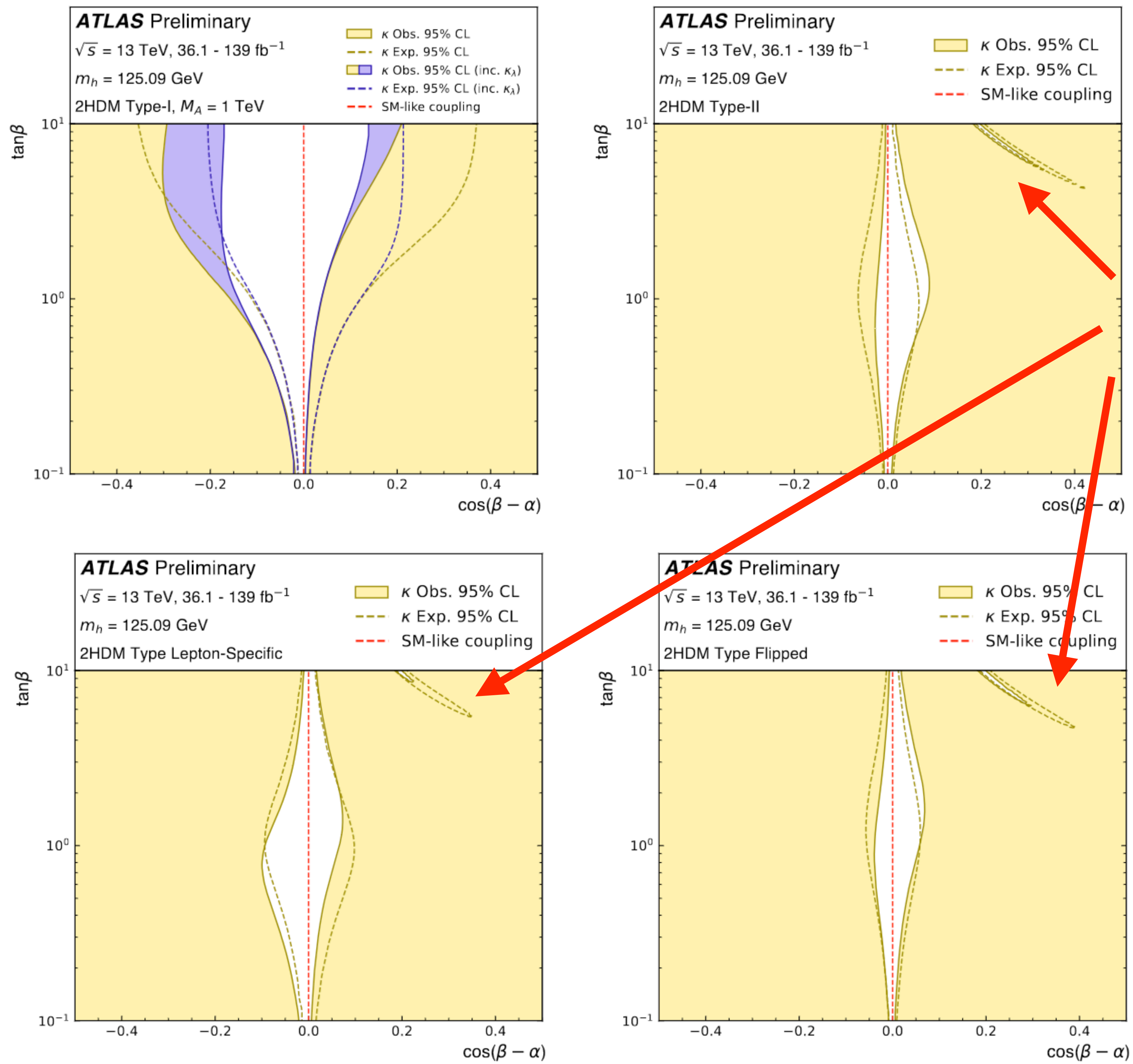


Region with $\cos(\beta + \alpha) \approx 0$

Couplings with similar magnitude but opposite sign to SM.

Lack of (sign) constraining power for leptons and down-type quarks in measurements.

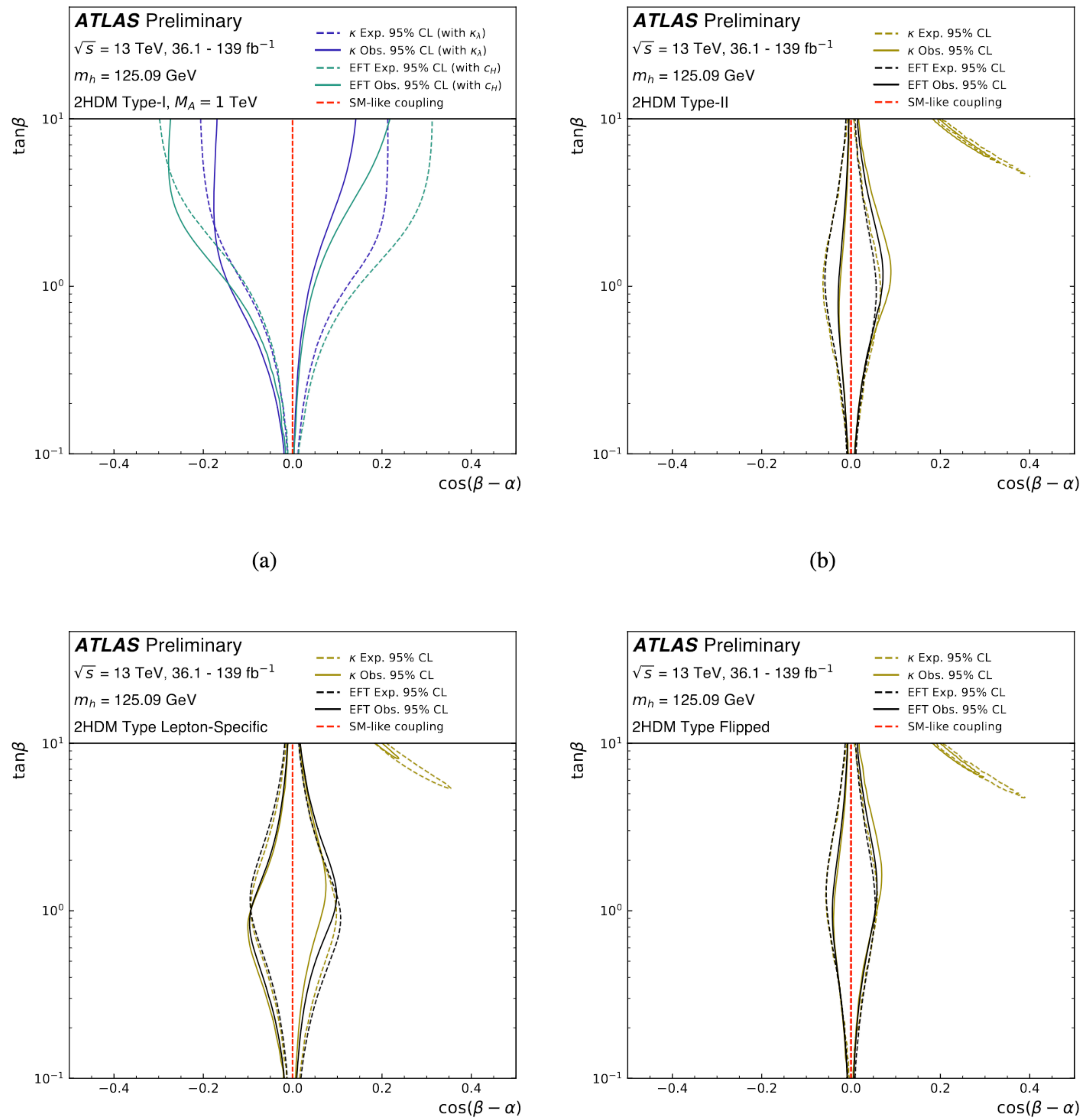
EFT to 2HDM

ATLAS-CONF-2023-052

- 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 Gaussian and has a single maximum.

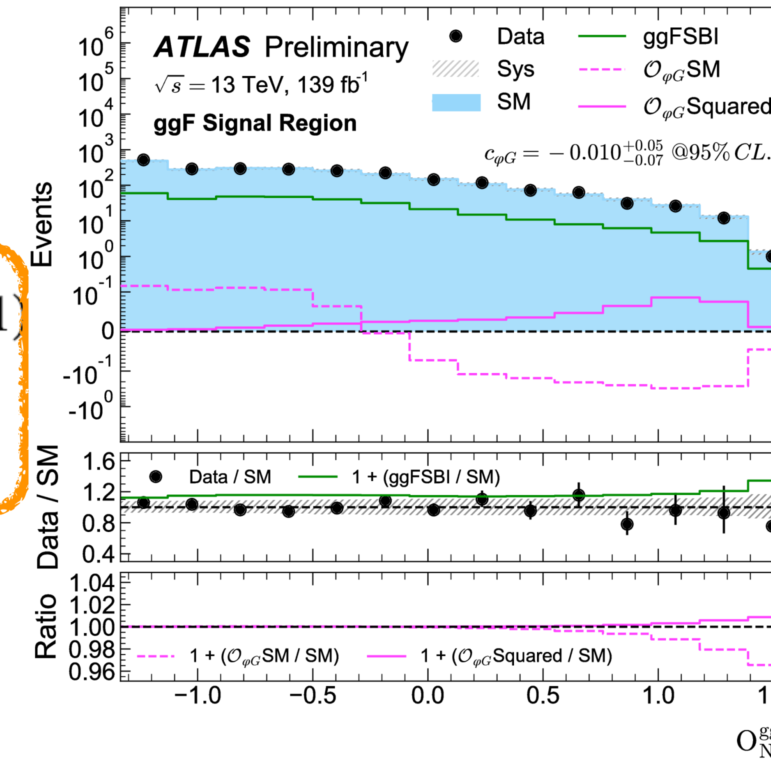


Mapping is affected by missing SMEFT dimension-8 operators:

- constraints from SMEFT parameters weaker than from k-parameters

SMEFT interpretation of off-shell H->ZZ

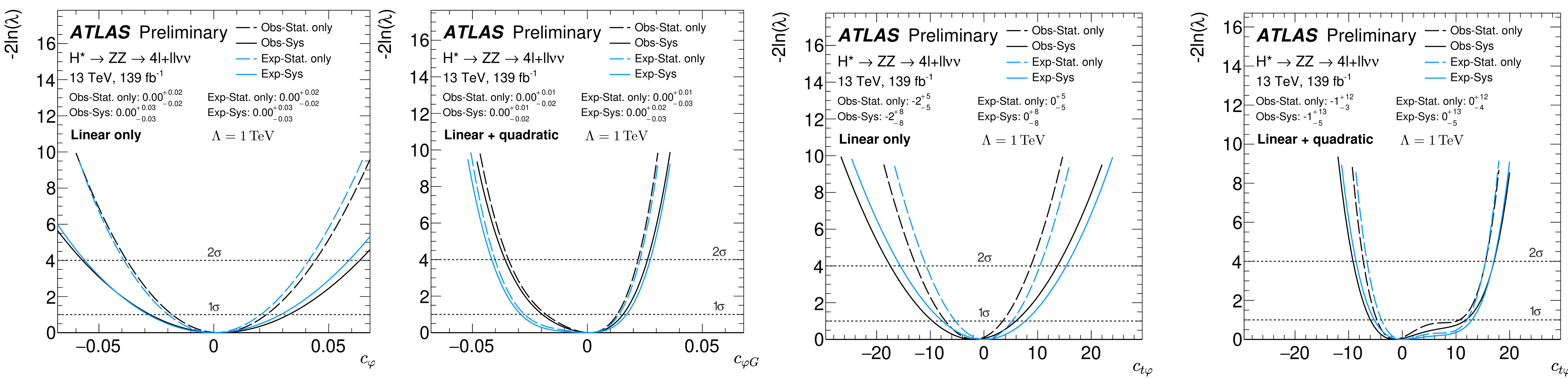
- Higgs boson decays to $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ final states.
- Off-shell Higgs boson events offer the opportunity to probe a higher energy scale.



$$\frac{\sigma^{\text{SMEFT}}(c_t, c_g)}{\sigma^{\text{SM}}} \simeq (c_t + c_g)^2 \left(1 - \frac{7}{15}\frac{c_g}{c_t + c_g}\frac{m_H^2}{4m_t^2}\right)$$

$$c_{t\varphi} = -\frac{y_t \Lambda^2}{v^2}(c_t - 1)$$

$$c_{\varphi G} = \frac{g_s^2 \Lambda^2}{48\pi^2 v^2} c_g$$

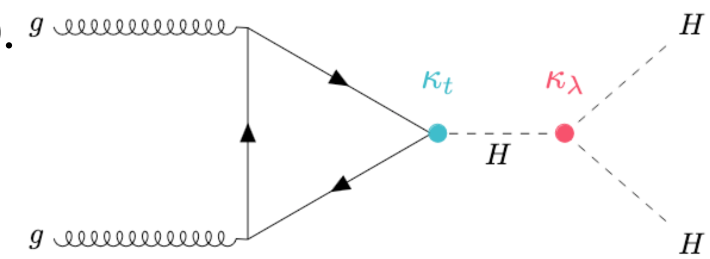


ATL-PHYS-PUB-2023-012

DiHiggs: $HH \to b\bar{b}b\bar{b}$

arXiv:2301.03212

- Non-resonant HH production ggF production mode - 4b decay channel (126 fb^{-1}).
- Analysis categorisations to improve sensitivity to BSM physics.



- The interpretations are performed with two EFT frameworks,

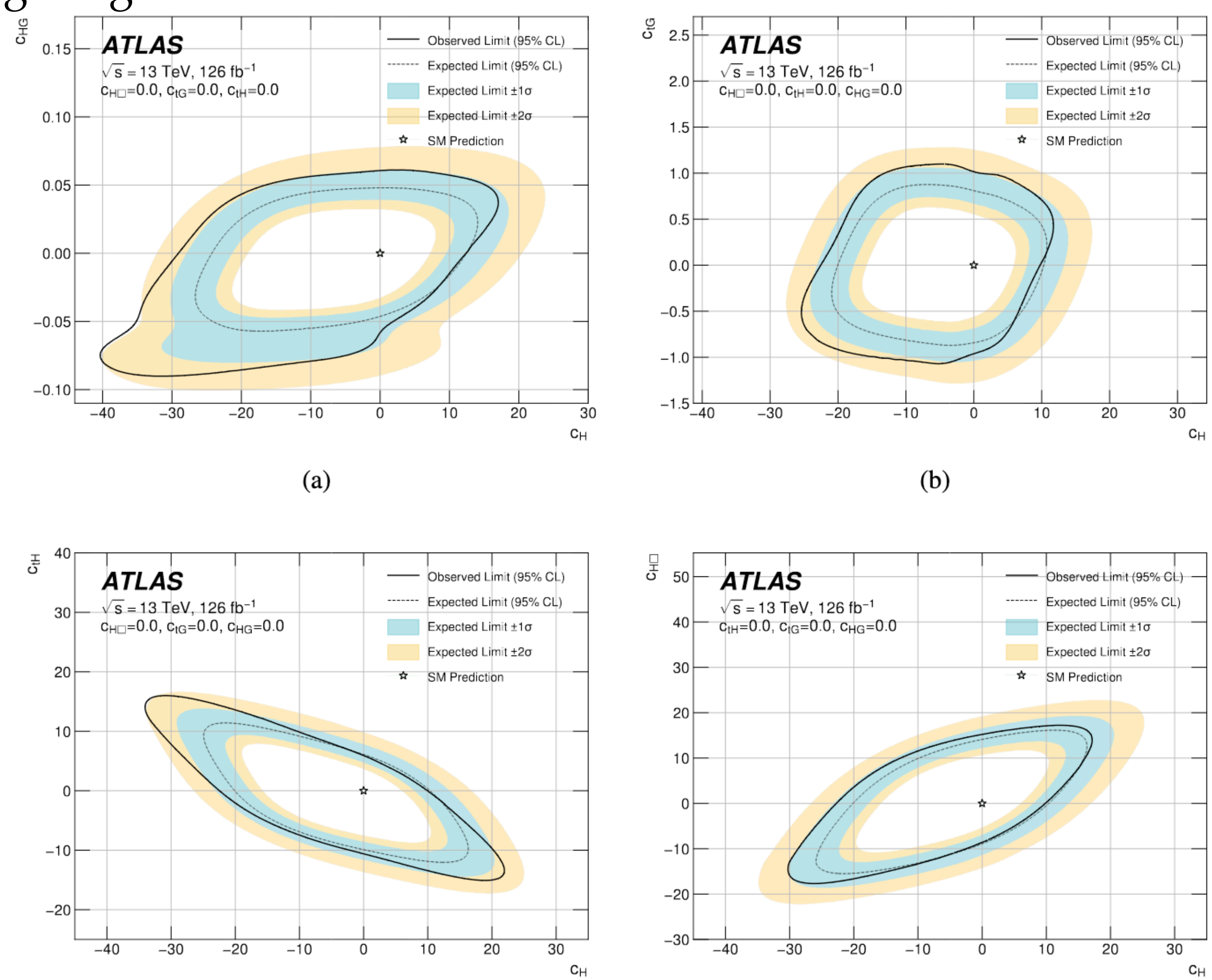
Higgs Effective Field Theory (HEFT) and SM Effective Field Theory (SMEFT).
- first LHC SMEFT interpretation for HH.

- The different BSM scenarios are considered re-weighting the SM non-resonant HH ggF sample.

  - 1D and 2D limits for the 5 Wilson coefficients: c_H, $c_{H\Box}$, c_{tH}, c_{tG}, c_{HG}. SMEFT@NLO

linear+quadratic results, one WC at a time

Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\Box}$	−9.3	13.9	−8.9	14.5
c_{tH}	−10.0	6.4	−10.7	6.2
c_{tG}	−0.97	0.94	−1.12	1.15



ATLAS Global combination

ATL-PHYS-PUB-2022-037

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

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

Higgs Combination

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55$ GeV, $p_T^{jet} < 35$ GeV	$p_T^{lead. lep.}$	36
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)$ GeV	m_T^{WZ}	36
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180$ GeV	m_{Z2}	139
$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000$ GeV, $m_{\ell\ell} \in (81, 101)$ GeV	$\Delta\phi_{jj}$	139

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

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

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R_{ℓ}^{0}	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R_{c}^{0}	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R_{b}^{0}	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A_{FB}^{0,c}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A_{FB}^{0,b}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ_{had}^{0} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

Precision Electroweak Measurements on the Z Resonance

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

ATLAS Global combination

Higgs Combination

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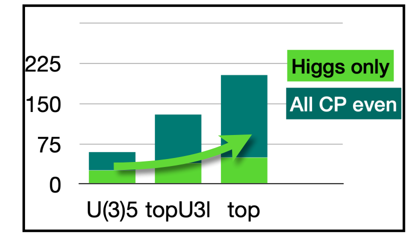
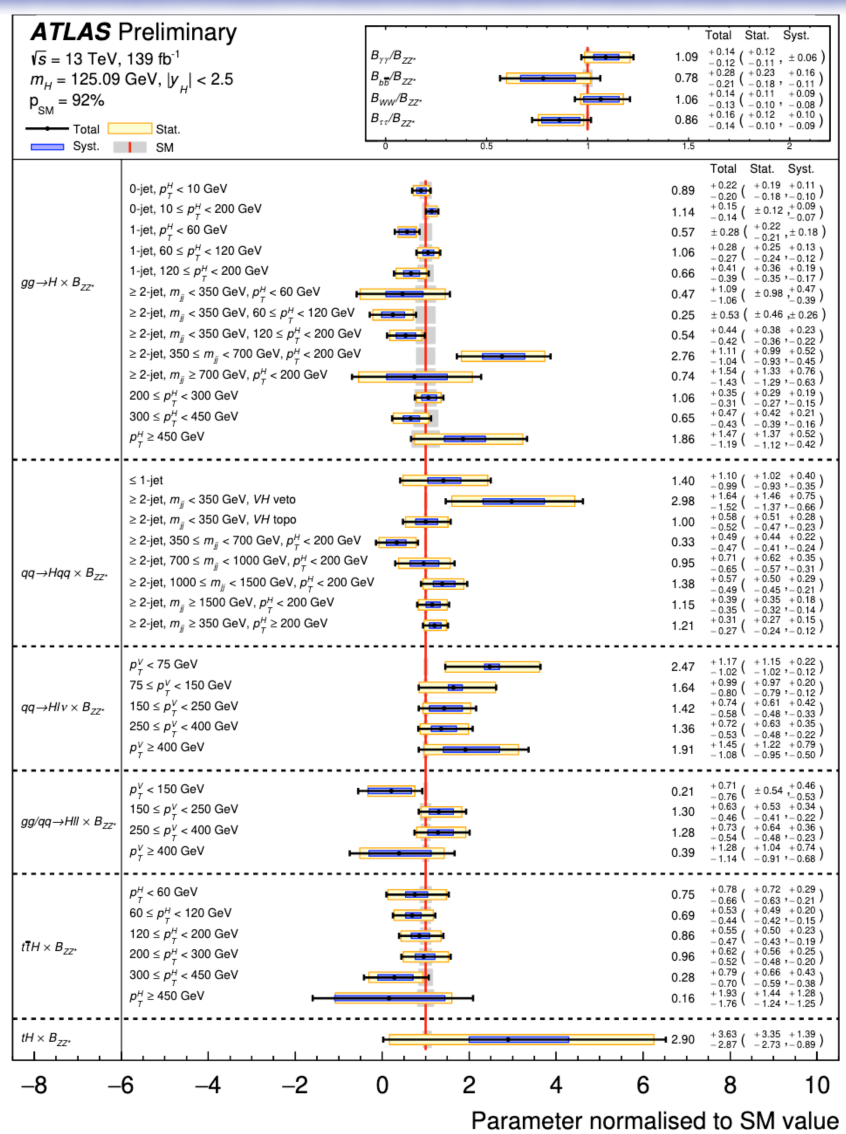
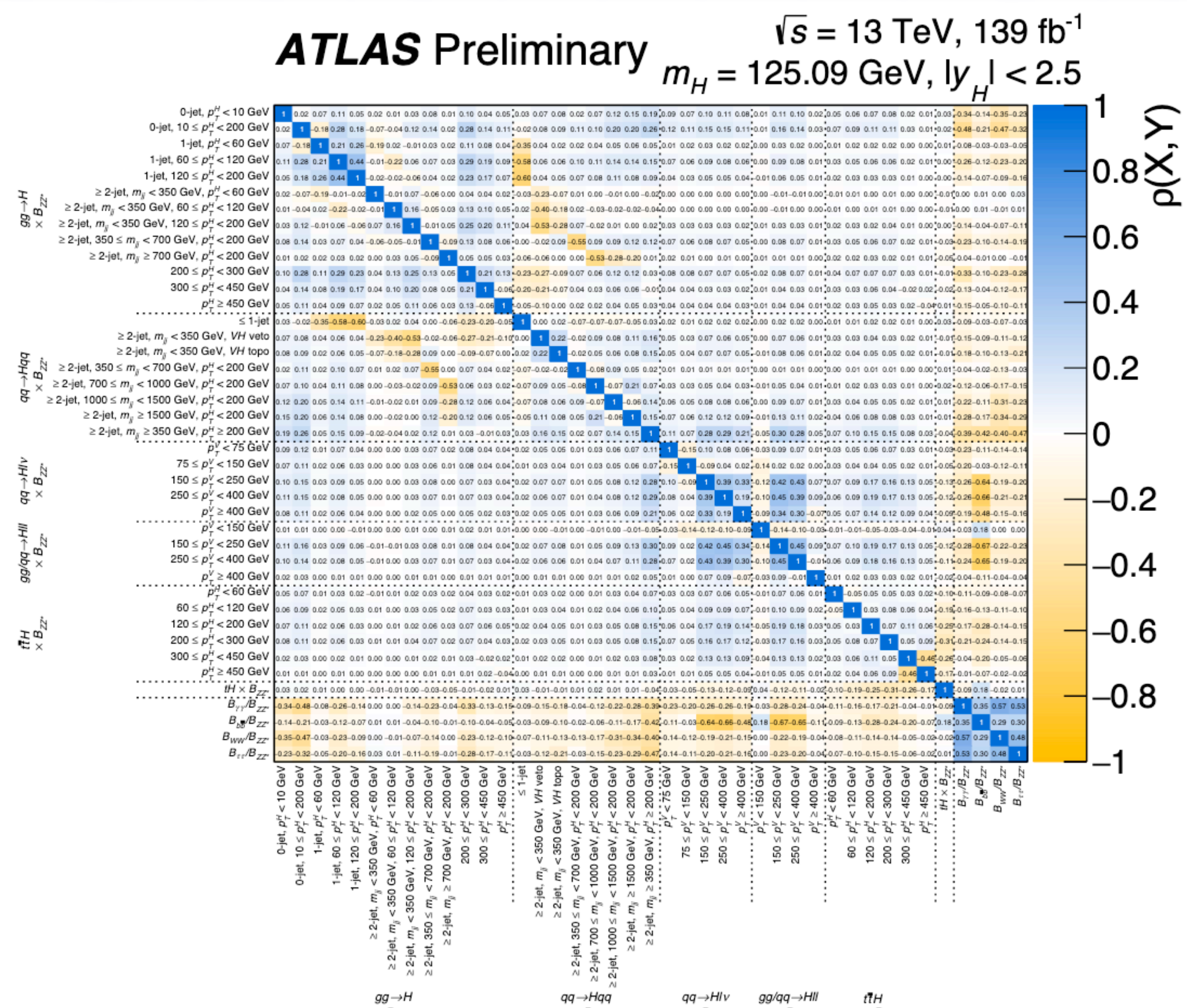


# of CP-even d=6 operators

SMEFTsim: "topU3l" flavour symmetry"



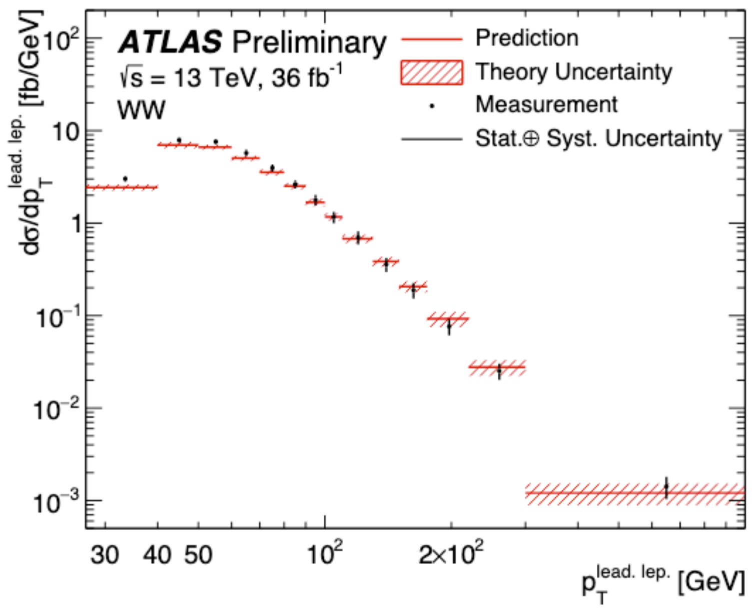


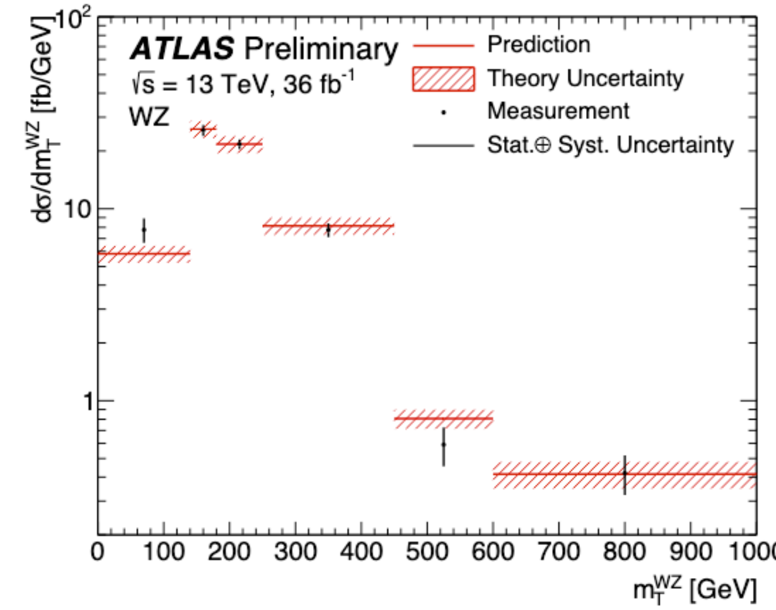
ATLAS Global combination

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

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

Multivariate gaussian





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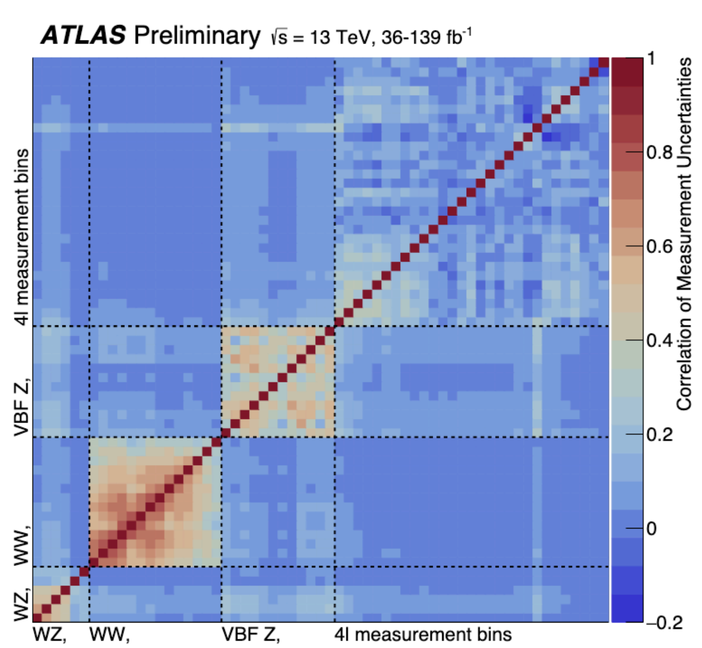

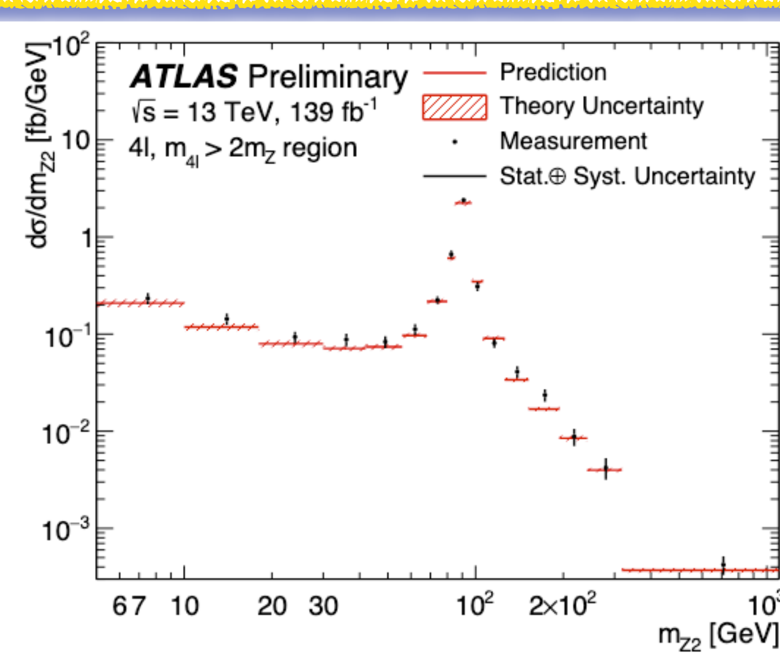

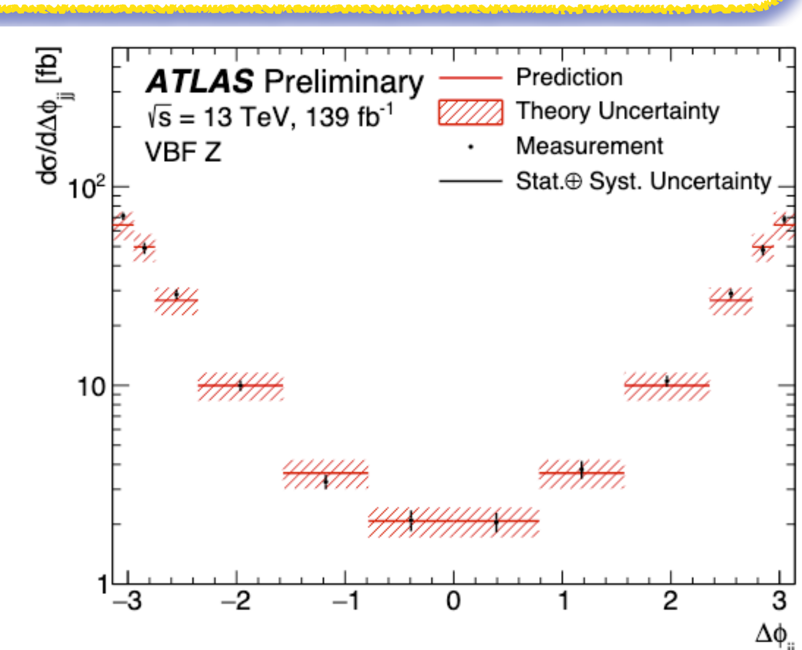

ATLAS Global combination

Precision Electroweak Measurements on the Z Resonance

$$\Gamma_Z, R^0_\ell, R^0_c, R^0_b, A^{0,\ell}_{FB}, A^{0,c}_{FB}, A^{0,b}_{FB}, \sigma^0_{had}$$

Hadronic pole cross section

Ratio of partial decay widths **Forward-backward asymmetry**

- Tight limit provided by LEP-> only sensitive to a limited number of parameters.
- Parametrisation of EW pole observables only in the linear approximations:
  - Two different fit setups: Higgs+EW and Higgs+EW+EWPO
- The likelihood is modelled as a multivariate Gaussian, both theoretical and experimental uncertainties are included in the covariance matrix.

EWPD in the SMEFT to dimension eight

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R^0_ℓ	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
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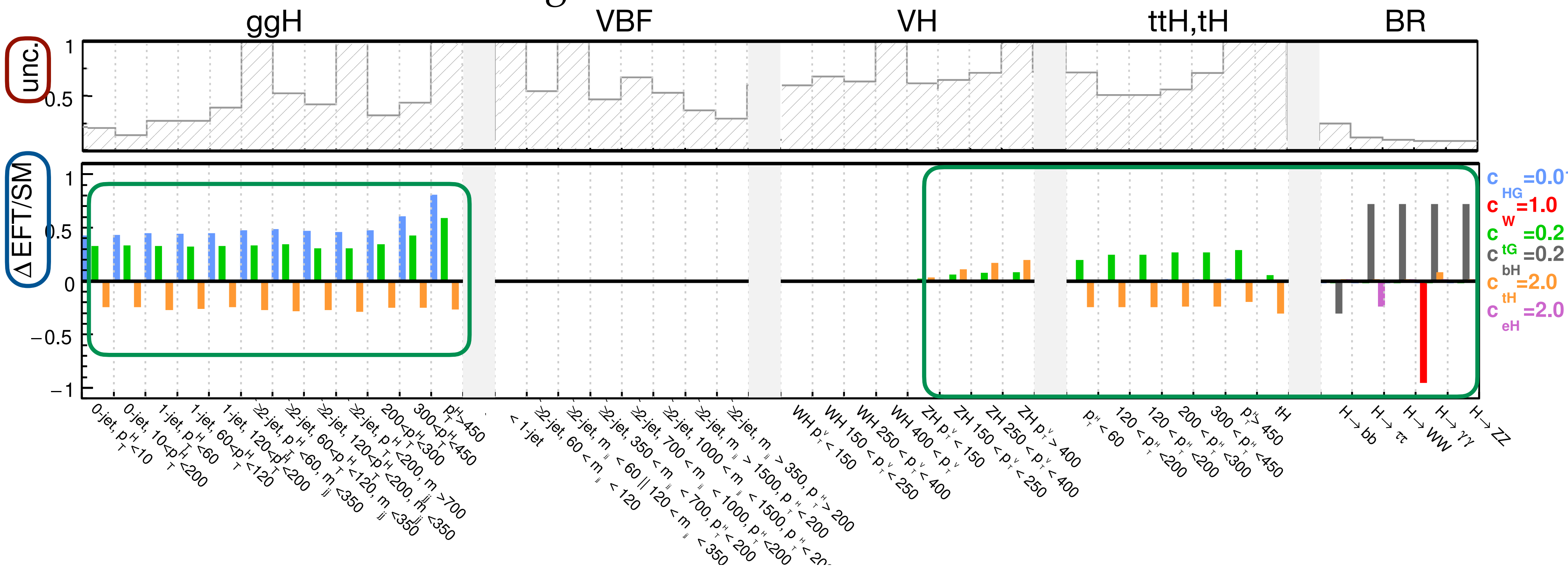
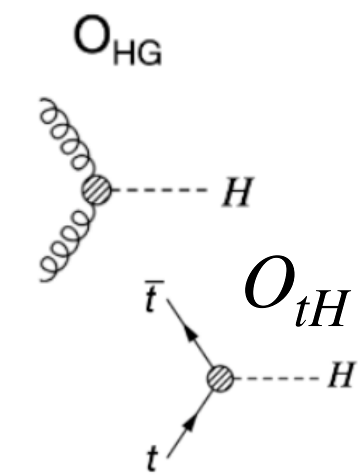
- **Electroweak precision observables measured at LEP and SLC**
- Eight pseudo observables describing the physics at the Z-pole are interpreted.
- Measurement probed with high sensitivity O(1 - 0.01 %)

ATLAS Global combination

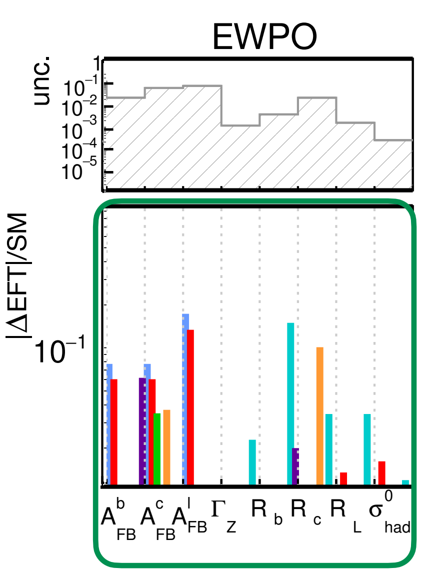
Impact of linear SMEFT parameterisation shown for bins along with corresponding measurement uncertainty

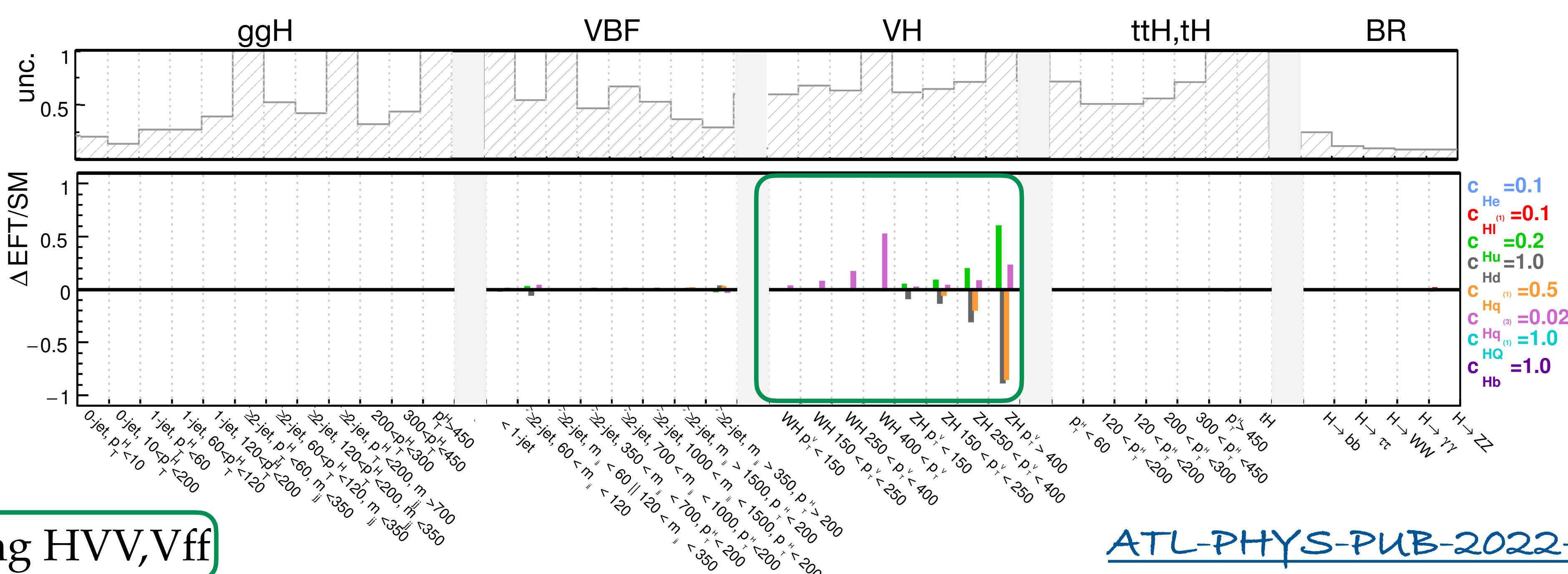
- Relative impact of linear SMEFT terms with Wilson coefficients c_{HG}, c_W , c_{tG}, c_{bH} , c_{tH} , and c_{eH} on the Higgs STXS cross sections and branching ratios.





The corresponding selected values of Wilson coefficients are shown



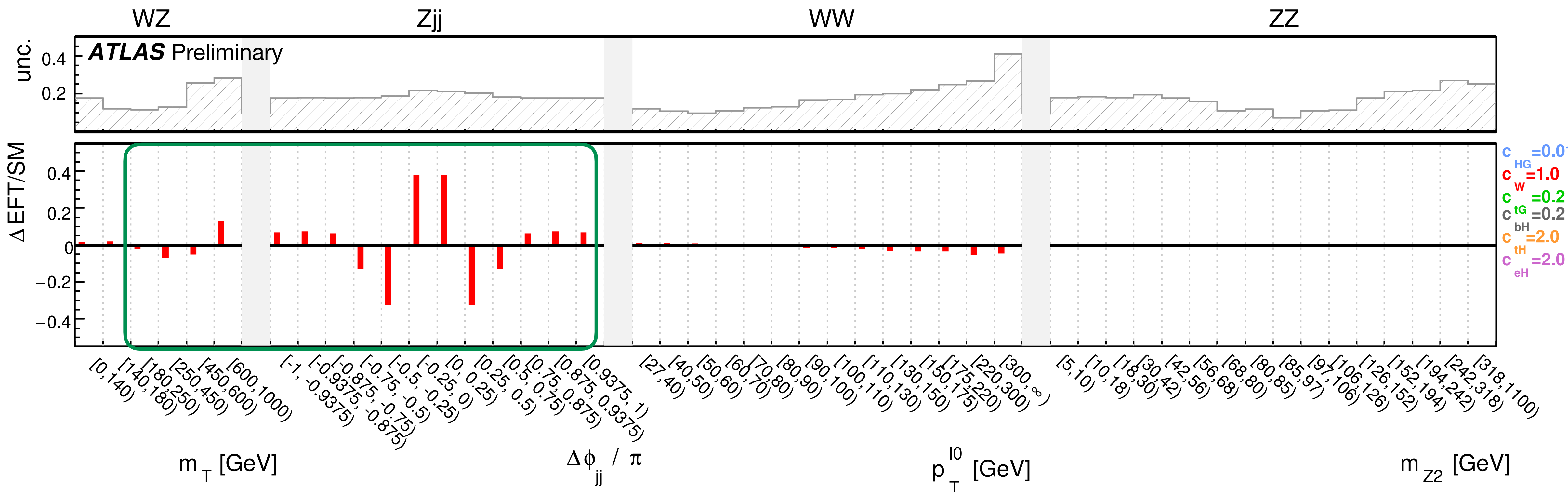


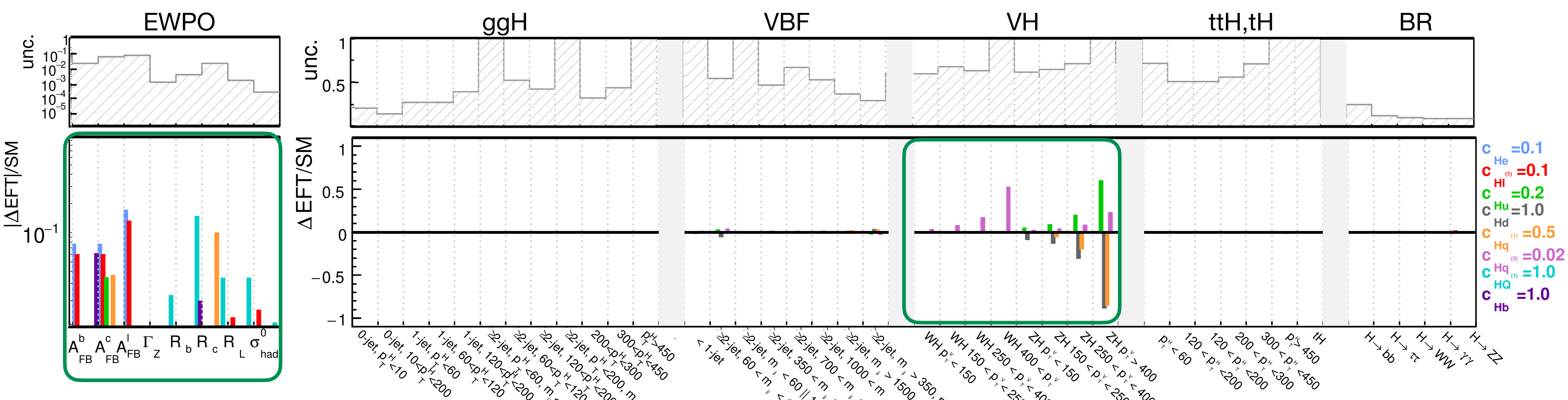
operators affecting HVV,Vff

ATL-PHYS-PUB-2022-037

ATLAS Global combination

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



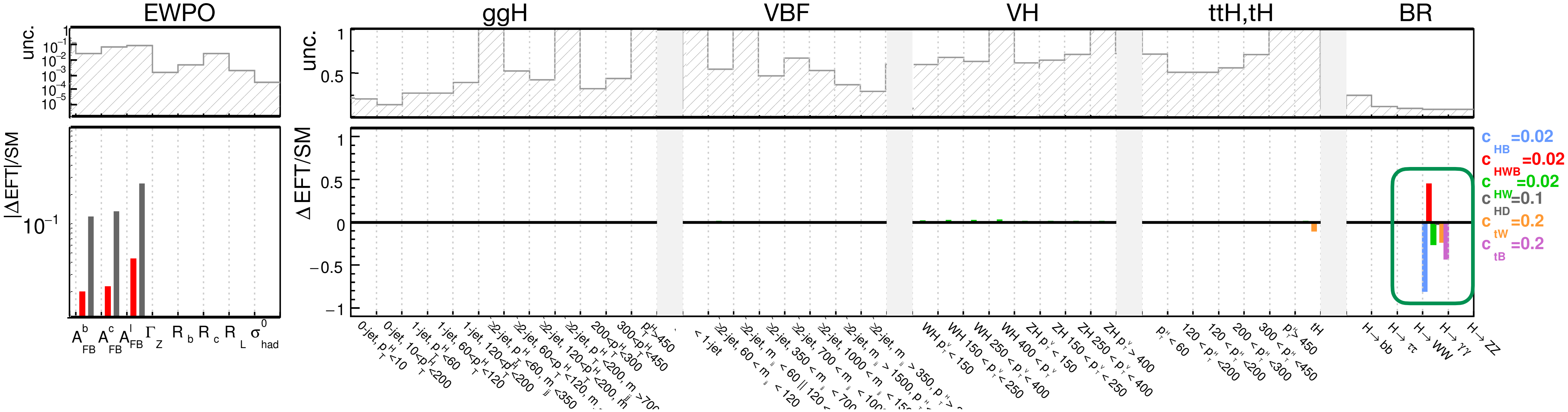


operators affecting HVV,Vff

ATL-PHYS-PUB-2022-037

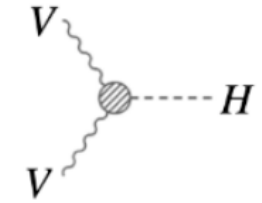
ATLAS Global combination

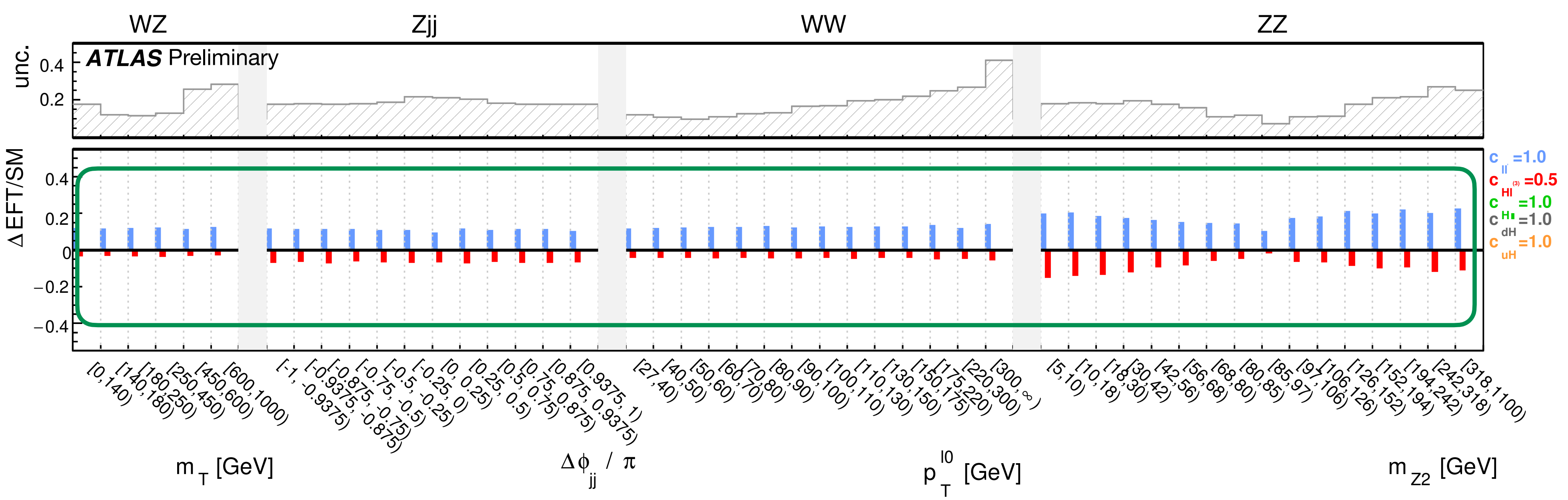
Impact of linear SMEFT parameterisation shown for bins along with corresponding measurement uncertainty



mostly affecting the $H \to \gamma\gamma$ branching ratio

O_{HW}

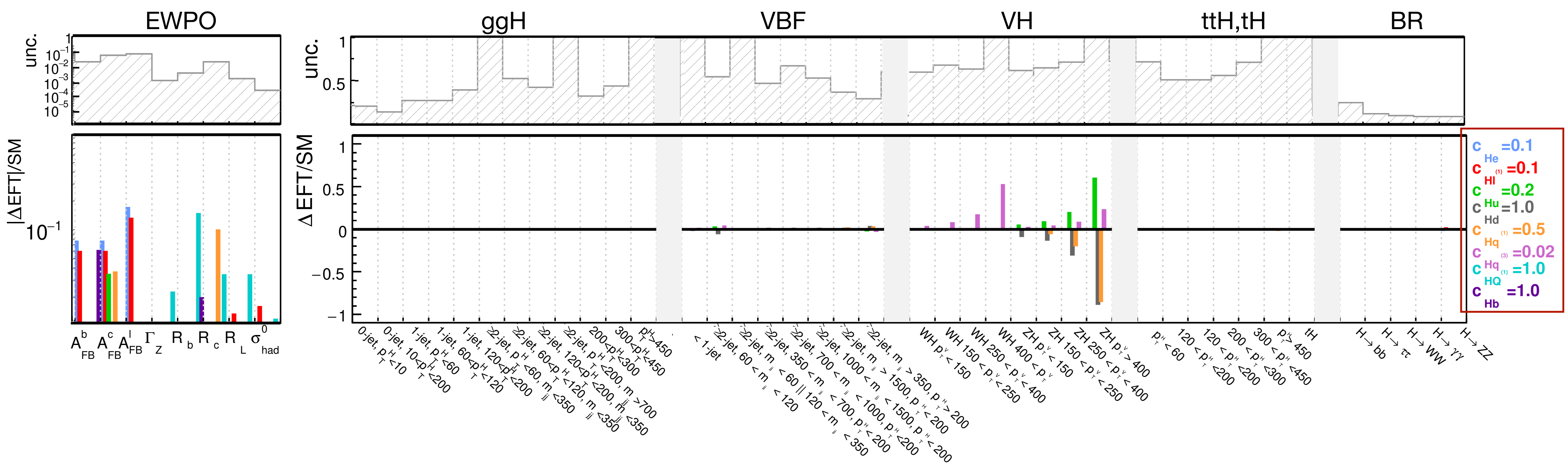


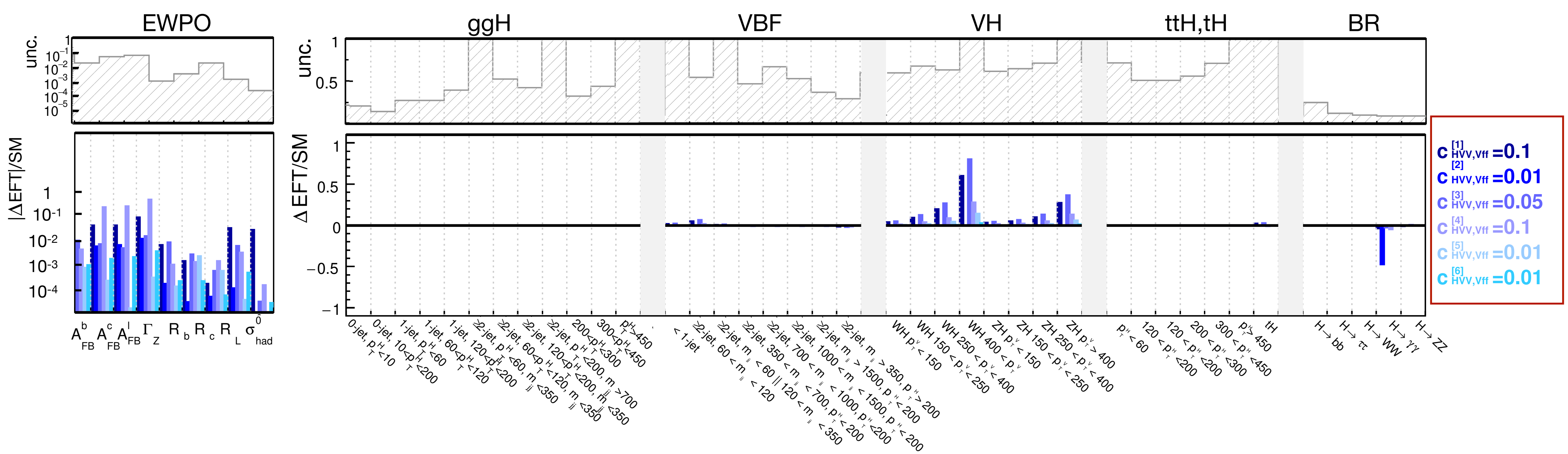


overall normalisation, modifications to Fermi constant (cHl3, cll1)

ATLAS Global combination

- SMEFT impact on measurements shown in Warsaw basis and fit basis-> allows to understand the impact of the different fit directions on measurements.





ATLAS Global combination: one at a time

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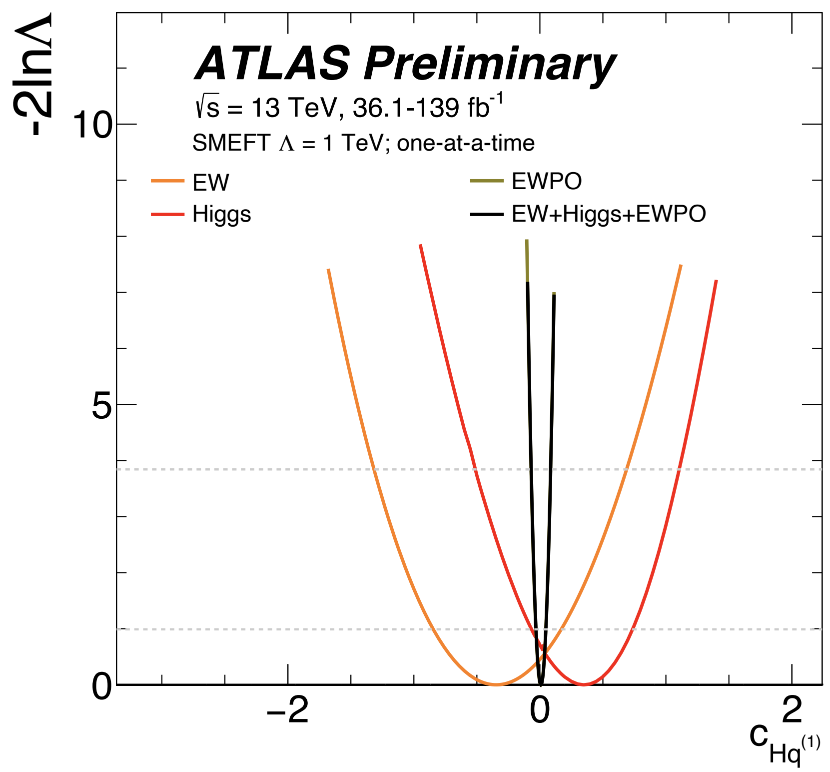
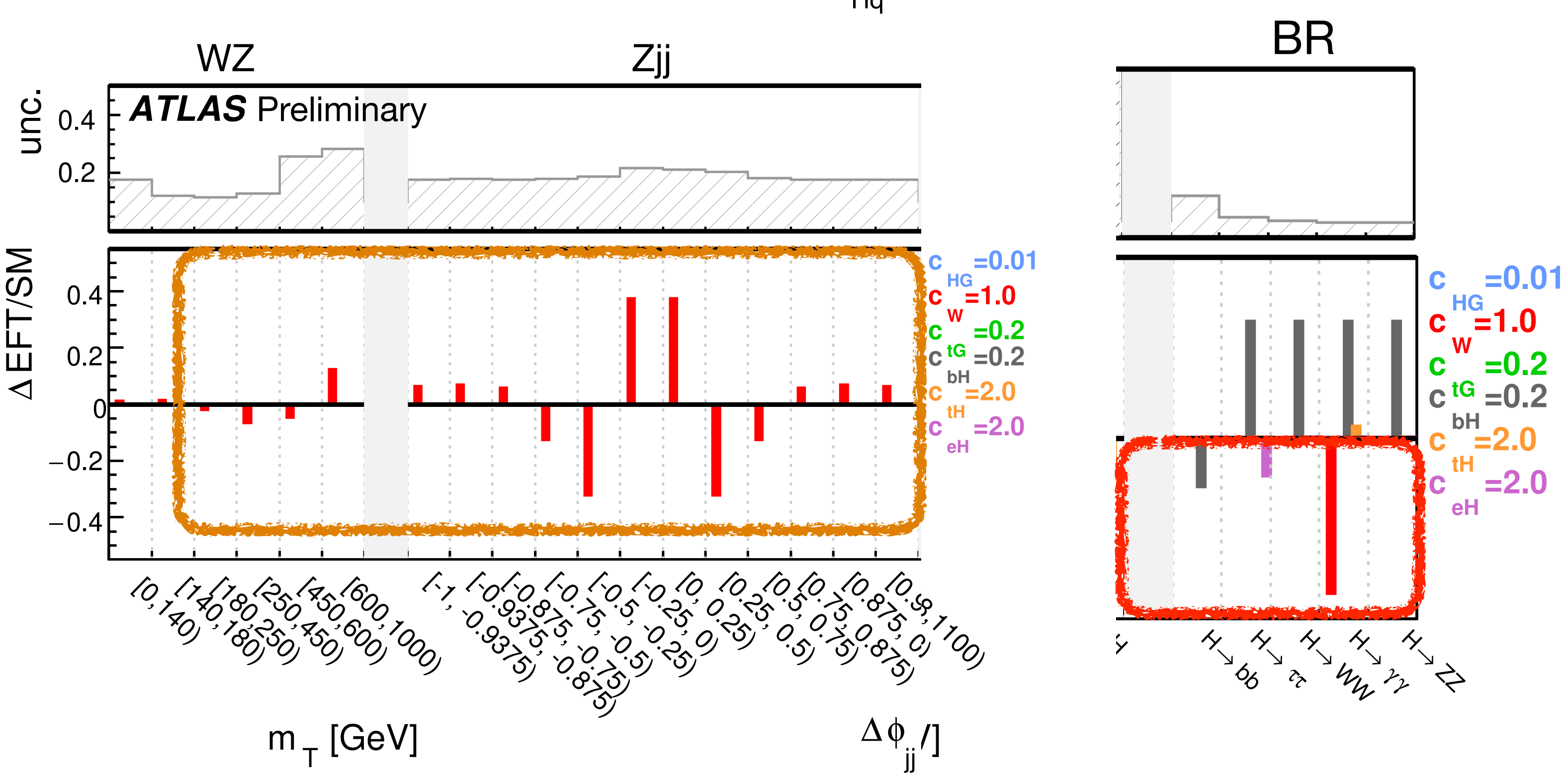
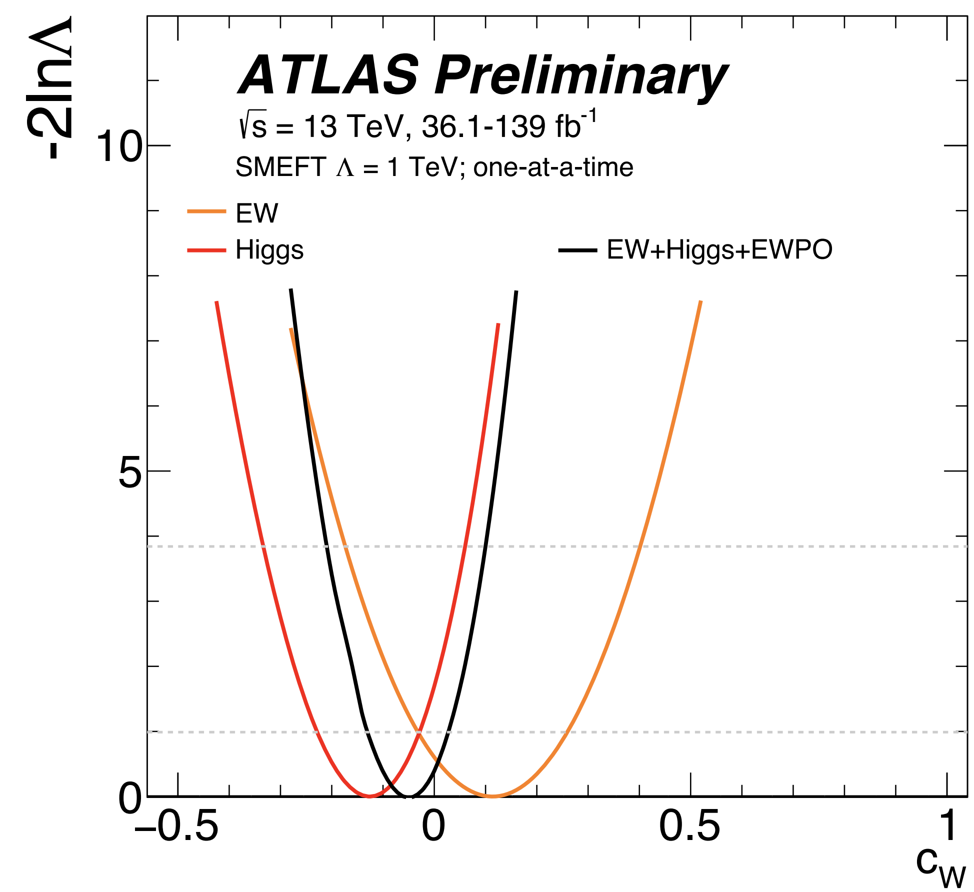


- One parameter at a time scans to compare sensitivity to an operator across the 3 measurement groups:
  - all remaining Wilson coefficients fixed to zero;
  - correlations between operators are neglected.





ATLAS Global combination

HIGGS+EW

- Constraining **7** individual and **17** linear combinations of Wilson coefficients.
- Data overlap across datasets checked -> remove from the combination whenever relevant.

- Principal component analysis to identify sensitive directions-> a modified basis of linear combinations of WCs is defined.

- Sensitivity eigenvectors instead of original Wilson Coefficient.
- Linear and linear+quadratic results.

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

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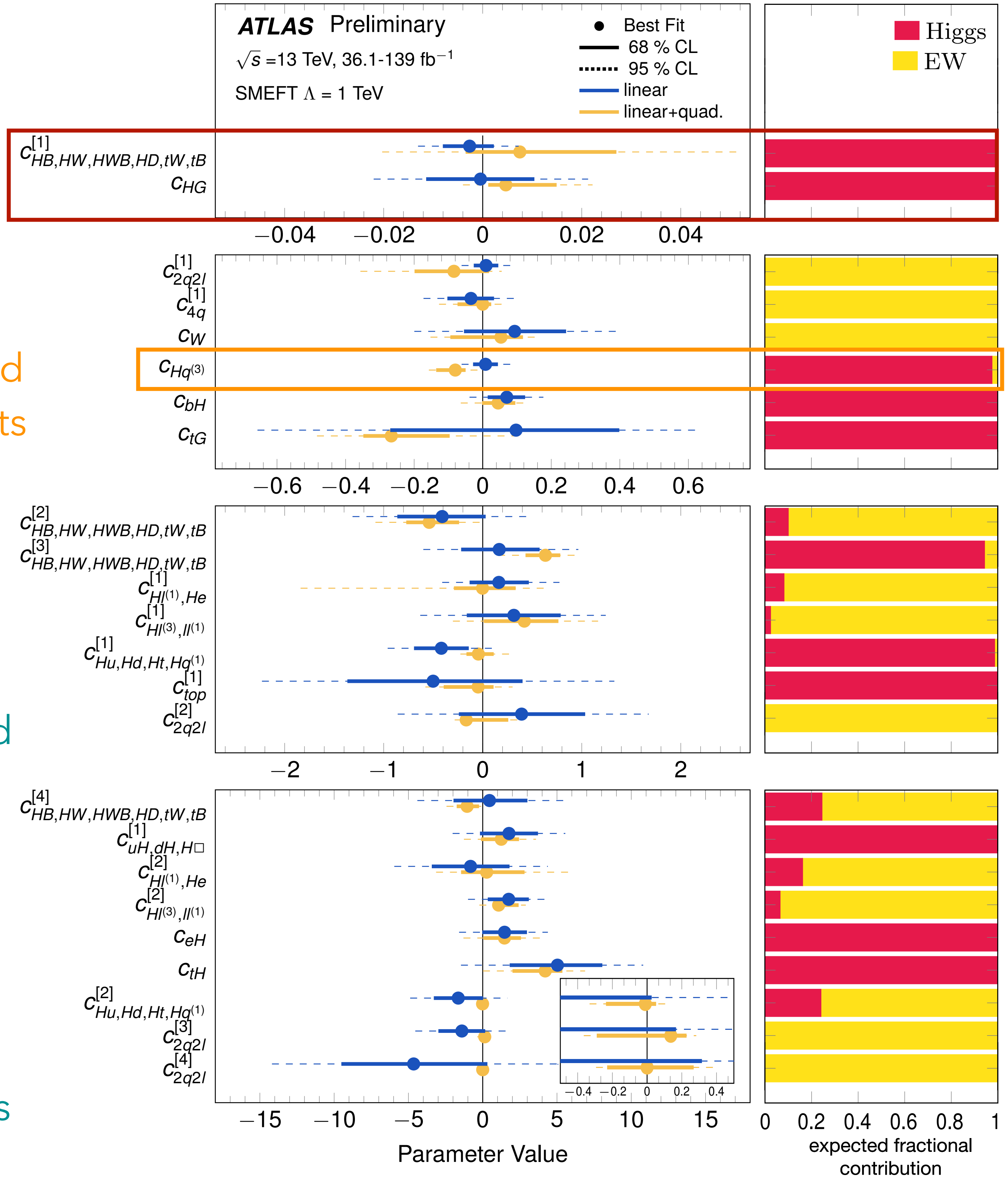
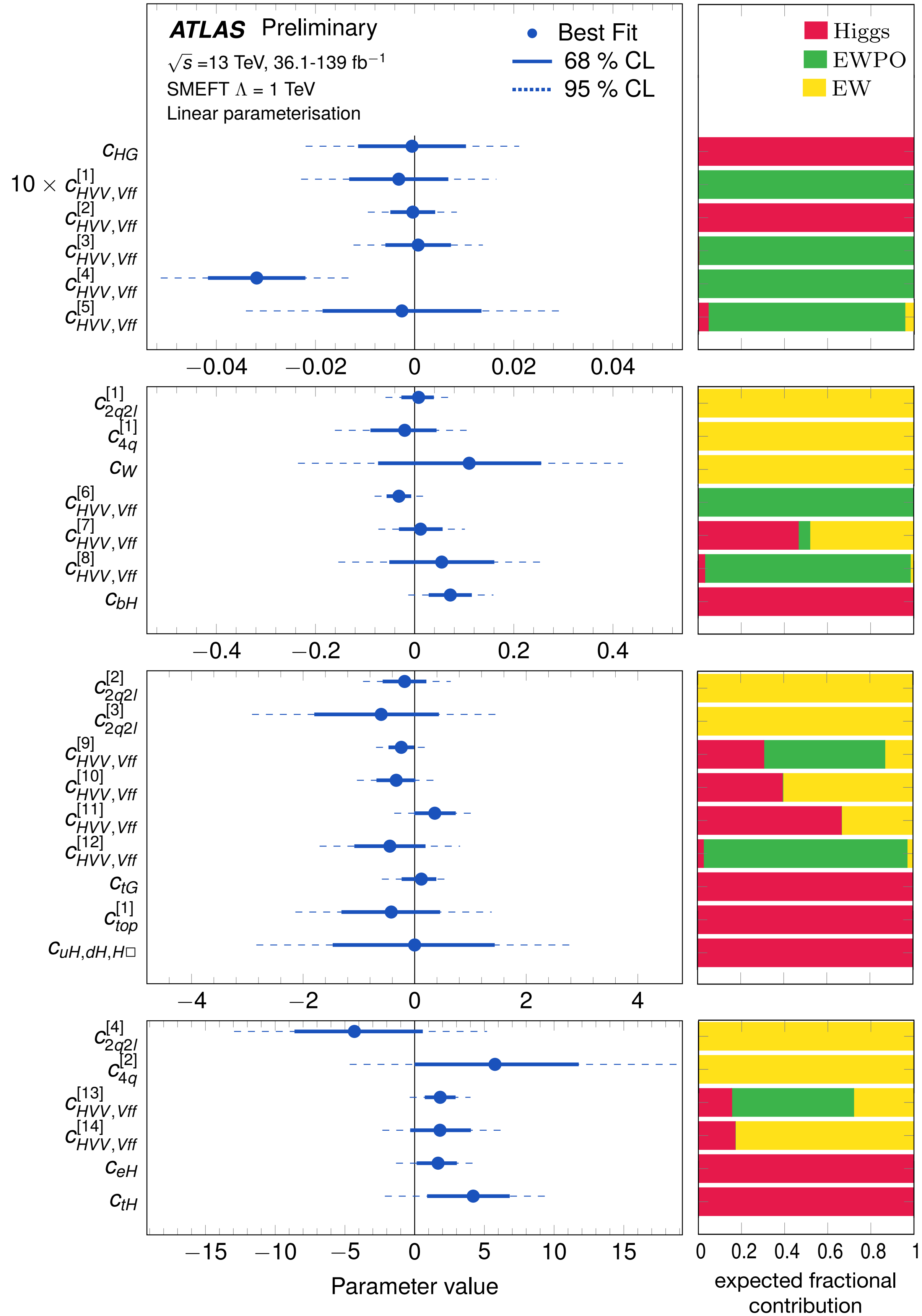


ATLAS Global combination

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.



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ATLAS Global combination: re-interpretation

arXiv:2302.06660

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