Effective Field Theory interpretations of Standard Model and Higgs measurements the ATLAS experiment

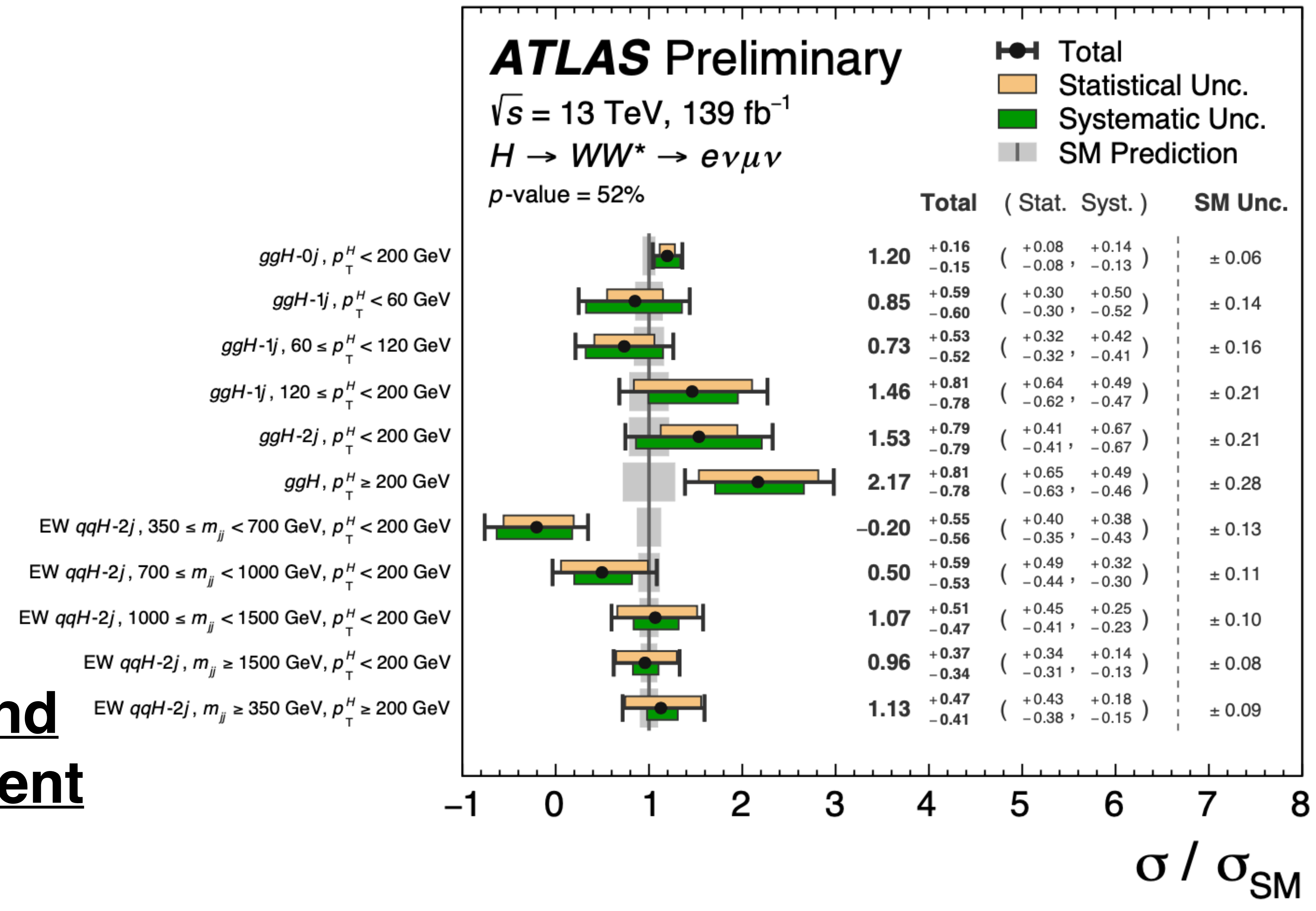
Bryan Kortman on behalf of the ATLAS collaboration

Higgs 2022 Conference, 7-11 November

ATLAS EXPERIMENT Nikhef

Introduction

ATLAS-CONF-2021-014



- **Observation** of the Higgs boson production in **Run 1**
- The experimental profile of the Higgs boson is becoming less blurry
  - Excellent **precision measurements** performed in **Run 2**
- **Run 3** ongoing! → exciting times and results ahead

- **Combine results of seemingly very different analyses and slight deviations from the SM in a near-model independent way**

- **(selection)** recent (combined) EFT interpretations of
  - Higgs boson pair searches in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ (ATL-PHYS-PUB-2022-019)
  - Combination of EW $Z(\nu\bar{\nu})\gamma jj$ production, limits on anomalous quartic gauge couplings (arXiv:2208.12741)
  - Flavour-changing neutral current (FCNC) $tqH(q = u, c), H \to \tau^+\tau^-$ (arXiv:2208.11415)

- **Featured** in this talk
  - EFT interpretation of HWW and SMWW measurement (ATL-PHYS-PUB-202-010)
  - EFT interpretation of combined single Higgs measurement (ATLAS-CONF-2021-053)
  - differential cross-sections of WW, WZ, 4l, and Z+2j production(ATL-PHYS-PUB-2021-022)
  - EFT interpretation of Higgs, EW and LEP data (ATLAS-PHYS-PUB-2022-037)

Precision is key

- Precision measurements may hold the key for observing physics beyond the SM

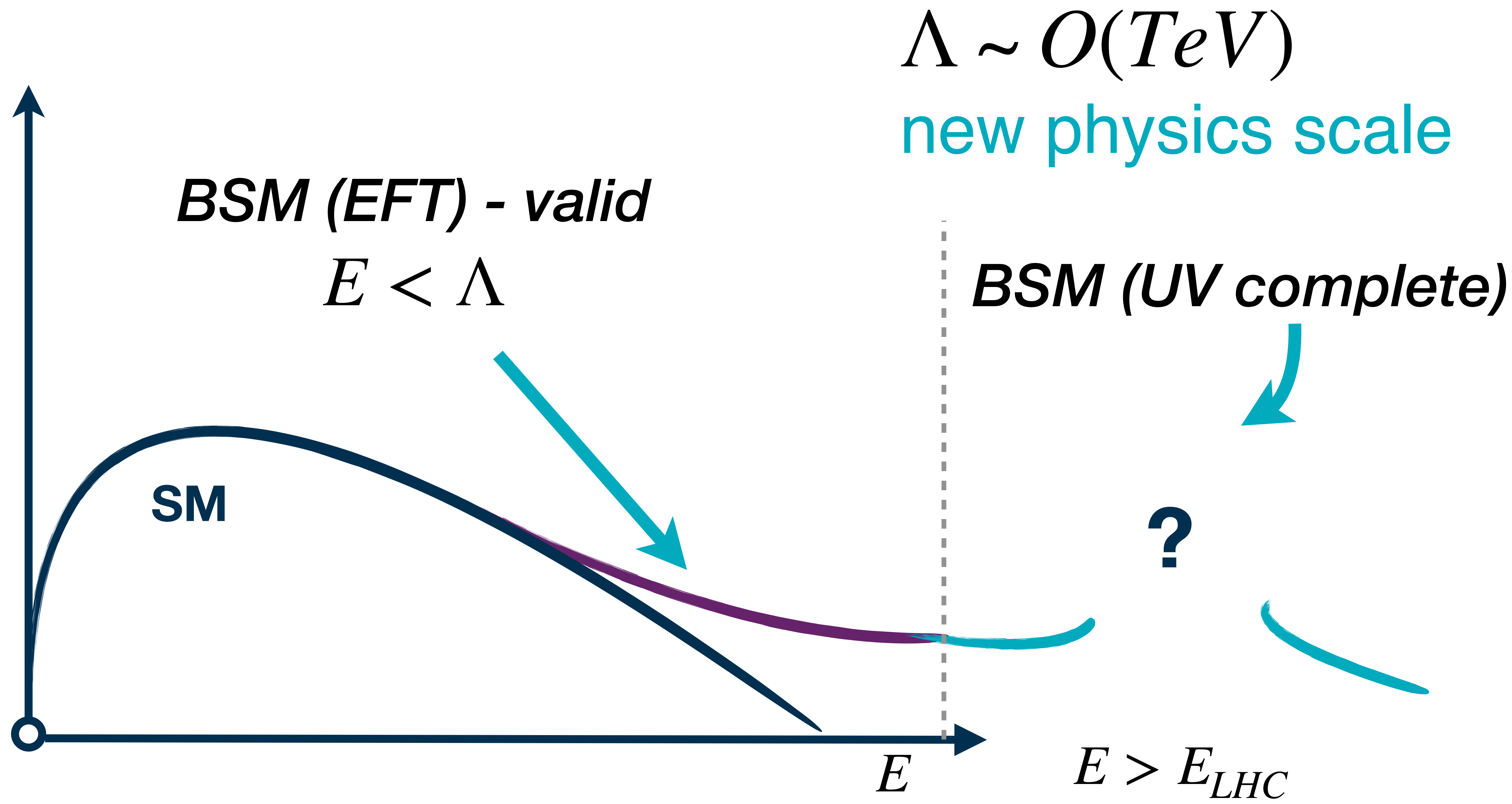
- When interpreting them the SM may written down as a low-energy approximation or EFT to an UV complete theory

$$\mathscr{L}_{SMEFT} = \mathscr{L}^4_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathscr{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathscr{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathscr{O}_i^{(7)} + \mathscr{O}(8) + \ldots = \mathscr{L}_{BSM}$$

- Deviations from the SM interpreted through:
  - Higher dimension **orthogonal** operators $\mathscr{O}_i^{(d)}$, suppressed by $\Lambda^{(d-4)}$
  - Scaled by Wilson coefficients $c_i^{(d)}$

- All new operators **respect symmetries** of the SM

- BSM scenarios show up as a **combination of operators**



SMEFT interpretations of ATLAS measurements

- A popular EFT model for interpretations is the SMEFT
- Multiple orthogonal basis available for interpretation e.g. the SILH or the Warsaw basis
- EFT operators affect
  - Input parameters:
    $\Delta G_F(c_{Hl}^{(3)}, c_{ll}), \Delta m_z^2(c_{HD}, c_{HWB})$
  - CP-Even/Odd Interactions
  - $c_{Hd}, c_{Hl}^{(3)}, c_{Hq}^{(3)}$
- **Necessary** to retain all relevant operators in interpretations
- No single measurement can constrain all operators simultaneously
  - A **Global** fit is required

Operators important in Higgs + EW + LEP

Assuming $U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$

Z,W couplings

$$\mathcal{Q}_{Hl}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$$
$$\mathcal{Q}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{Hq}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$
$$\mathcal{Q}_{Hq}^{(3)} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$$
$$\mathcal{Q}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$$
$$\mathcal{Q}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$

Bhabha scattering

$$\mathcal{Q}_{ee} = (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{le} = (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{ll} = (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)$$

input quantities

$$\mathcal{Q}_{HD} = (D_\mu H^\dagger H)(H^\dagger D^\mu H)$$
$$\mathcal{Q}_{HWB} = (H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{Q}_{Hl}^{(3)} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$$
$$\mathcal{Q}'_{ll} = (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)$$

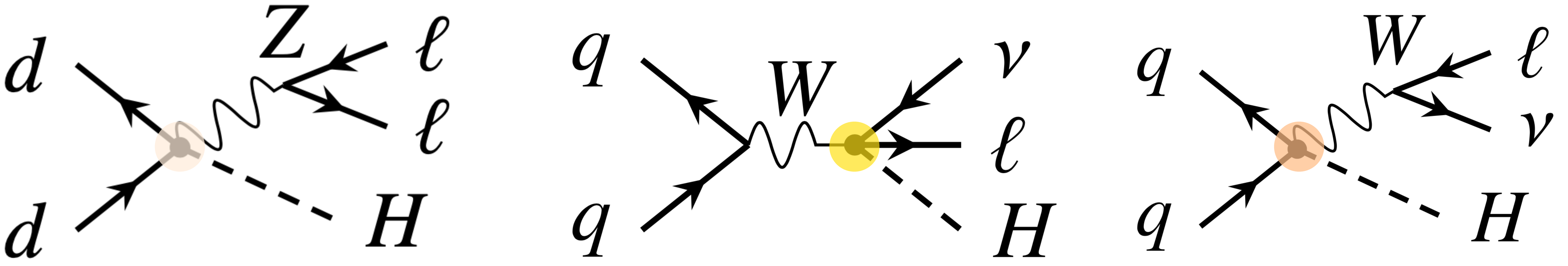
H processes

$$\mathcal{Q}_{Hbox} = (H^\dagger H)\Box(H^\dagger H)$$
$$\mathcal{Q}_{HG} = (H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}$$
$$\mathcal{Q}_{HB} = (H^\dagger H)B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{Q}_{HW} = (H^\dagger H)W^i_{\mu\nu}W^{i\mu\nu}$$
$$\mathcal{Q}_{uH} = (H^\dagger H)(\bar{q}\tilde{H}u)$$
$$\mathcal{Q}_{dH} = (H^\dagger H)(\bar{q}Hd)$$
$$\mathcal{Q}_{eH} = (H^\dagger H)(\bar{q}He)$$
$$\mathcal{Q}_{G} = \varepsilon_{abc}G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho$$
$$\mathcal{Q}_{uG} = (\bar{q}\sigma^{\mu\nu}T^a\tilde{H}u)G^a_{\mu\nu}$$

TGC

$$\mathcal{Q}_W = \varepsilon_{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$$

Ilaria Brivio

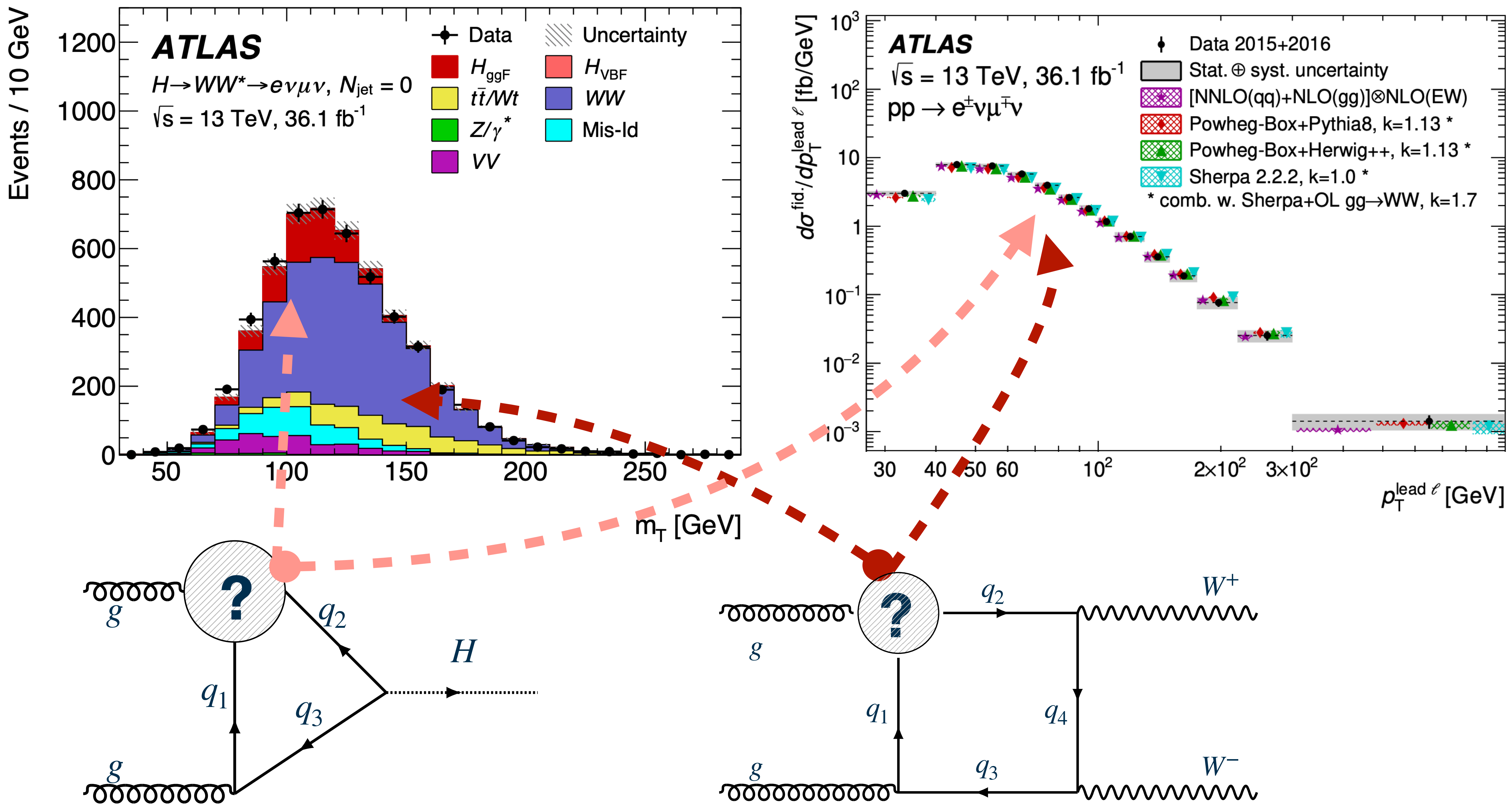


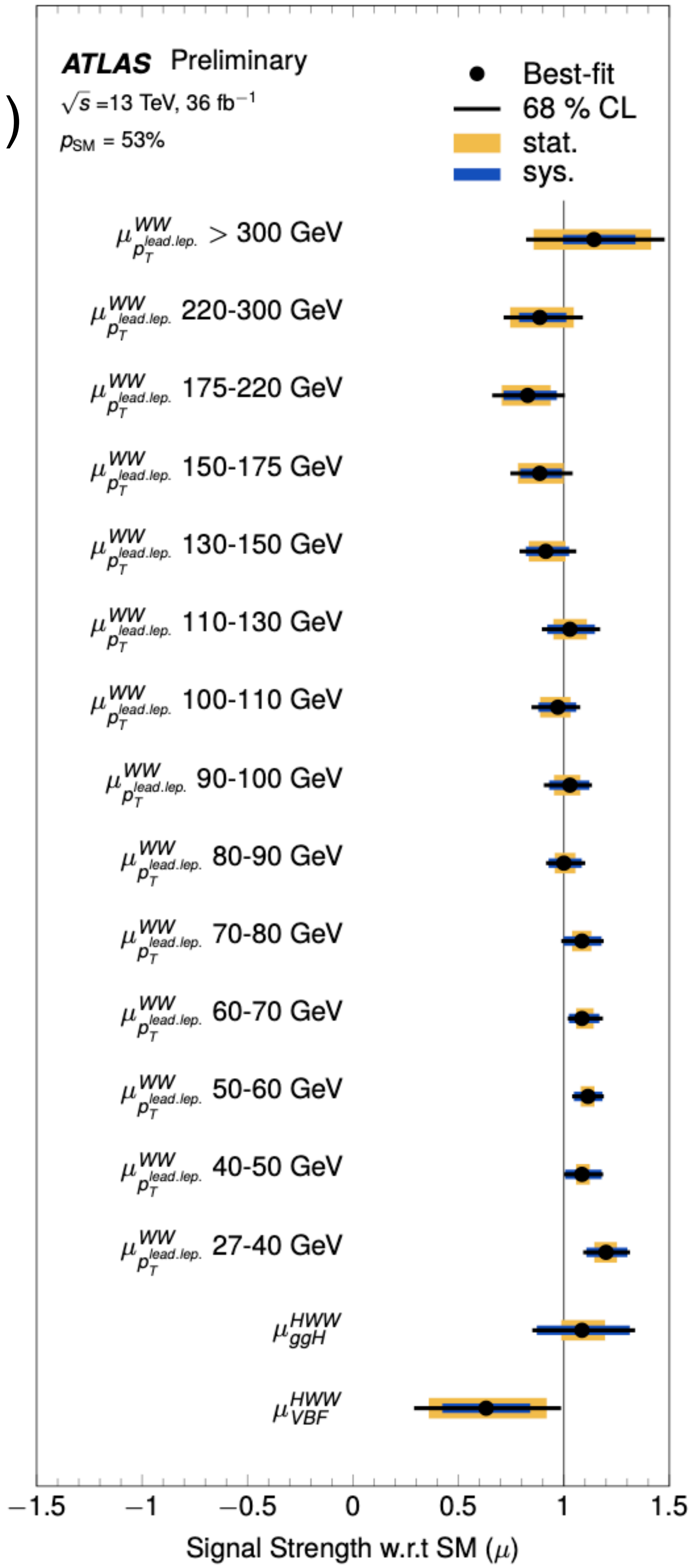
SMEFT interpretation of SM WW + $H \to WW^*$

ATL-PHYS-PUB-2021-010

- First ATLAS Run 2 combination of **Higgs** and **EW** measurements (using $36.1\ fb^{-1}$)
- Developed methodology for EW+Higgs combinations
- Orthogonality ensured via **opposite** $m_{e\mu}$ selection at 55 GeV , any overlap in data removed during combination
- Ensured **consistent statistical treatment** of EFT effects in signal and background (WW)

$H \to WW$ measurement $pp \to WW$ measurement

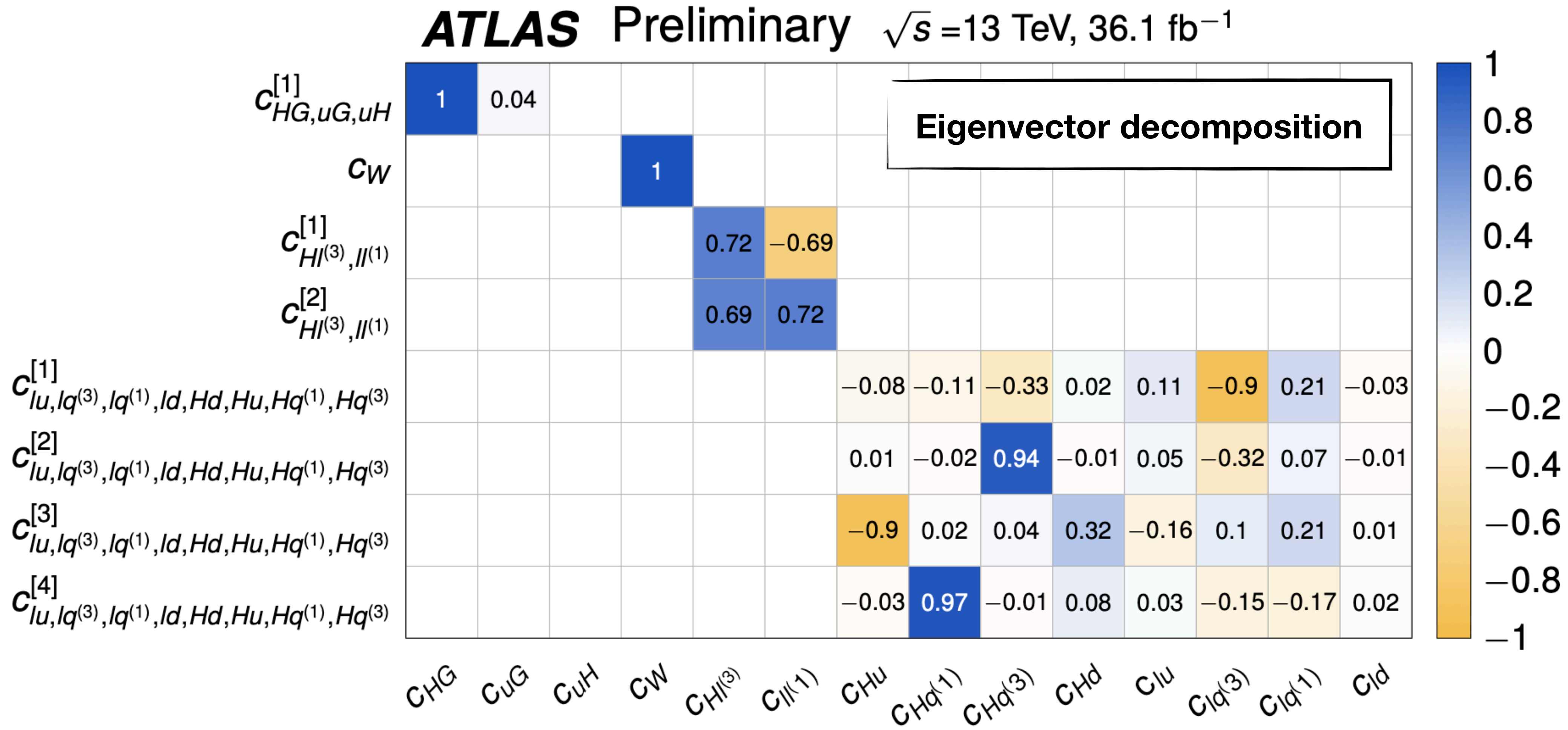


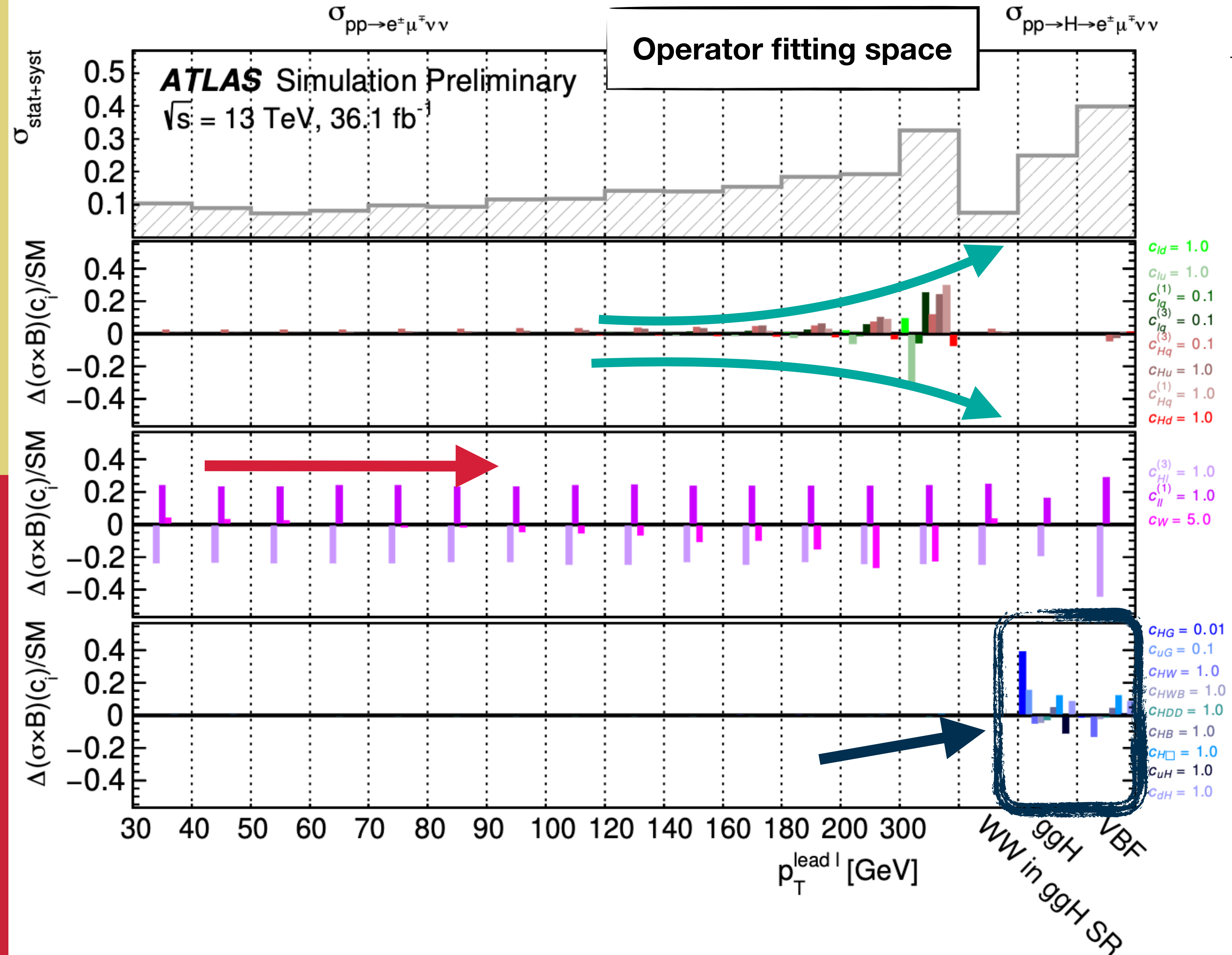


PCA of SM WW + $H \rightarrow WW^*$ combination

ATL-PHYS-PUB-2021-010

- Extracting eigenvectors (EV's) from **principal component analysis** (PCA), using Fischer info. Matrix
- **Linear** comb. of Wilson coefficients, along **sensitive** directions of parameter space
  - Grouping operators in terms of **impact** and **physics motivation**
  - **Eliminating** flat directions in the fit
  - **Fitted simultaneously** and can be translated back into Wilson coefficients

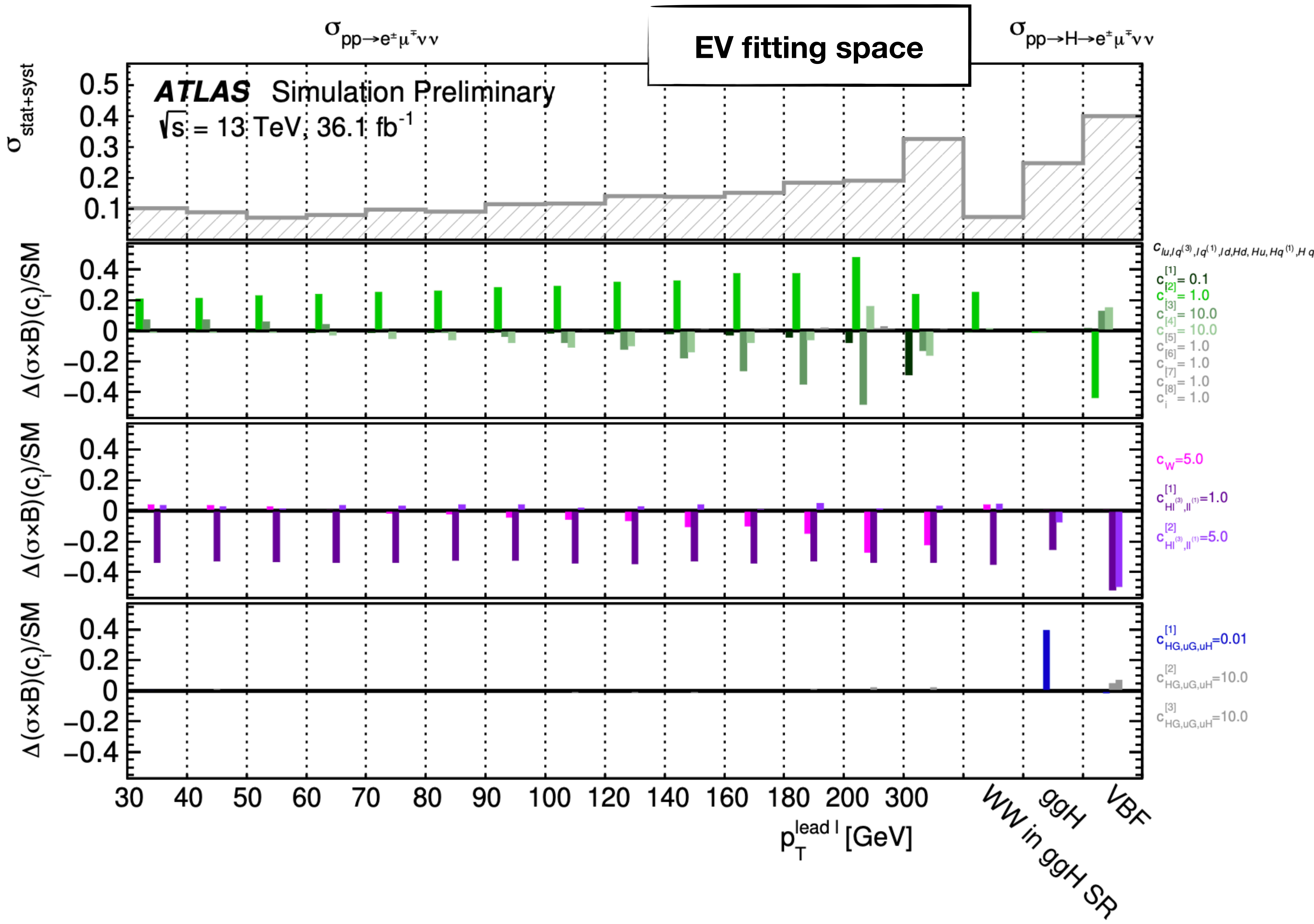




$$V_{SMEFT}^{-1} = P_{\mu^x \rightarrow c_i}^T V_{meas}^{-1} P_{\mu^x \rightarrow c_i}$$

- V_{SMEFT}^{-1}: measurement info. Matrix (Gaussian approx.)
- $P_{\mu^x \rightarrow c_i}$: SMEFT parameterisation Matrix

PCA



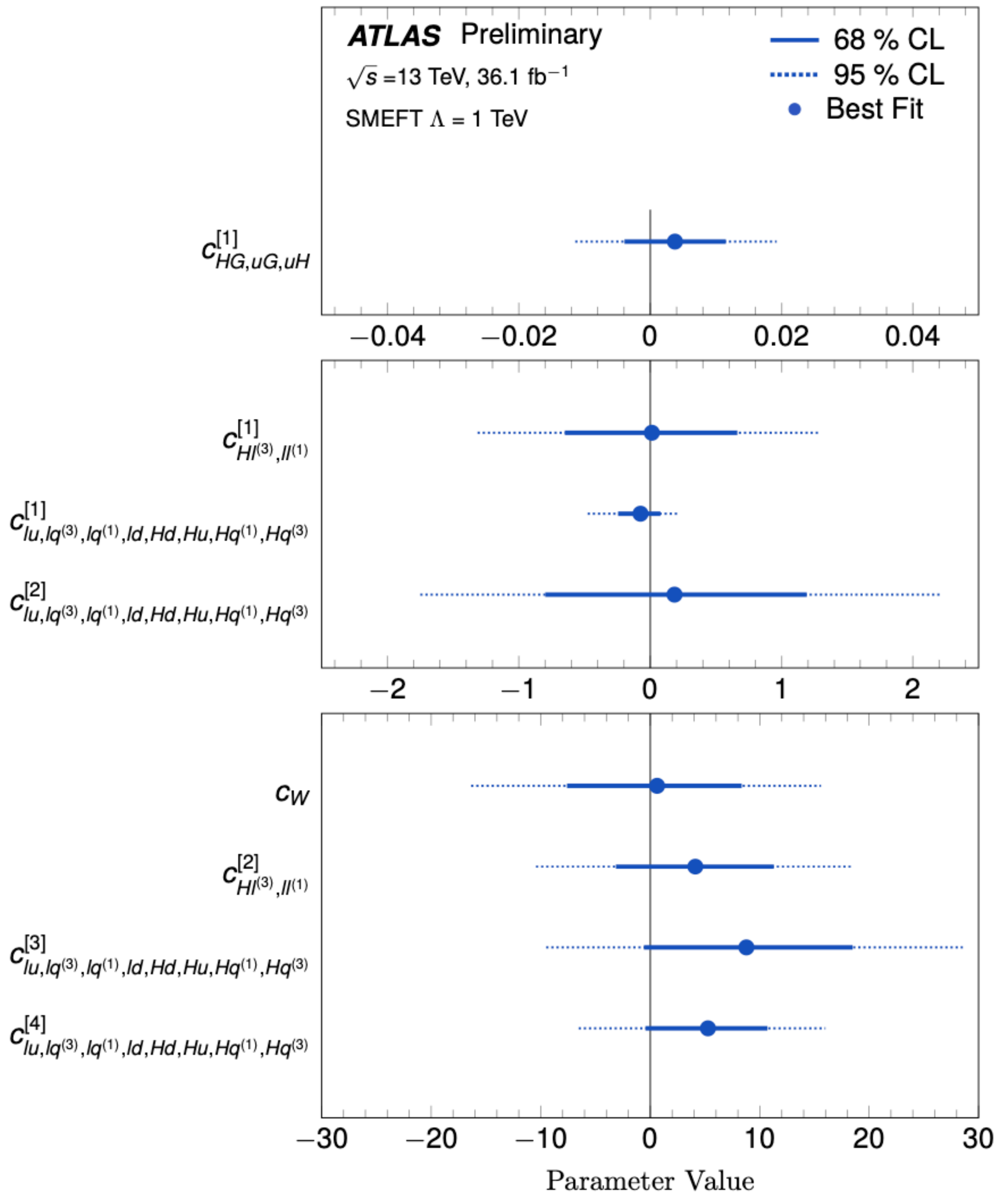
SMEFT interpretation of SM WW + $H \rightarrow WW^*$

ATL-PHYS-PUB-2021-010

- Perform fits for all 20 $c_i^{(6)}$ coefficients **one-at-a-time** with others fixed to SM ($c_i^{(6)}$=0)
- Compare 3 different combinations (**HWW**, **SMWW**, **HWW+SMWW**)

- **Flat** directions (EV's) set **constant** in the fit

- **Simultaneous** fit with **8** sensitive EV directions, **1** being a direct Wilson coefficient (c_W)



ATLAS-CONF-2021-053

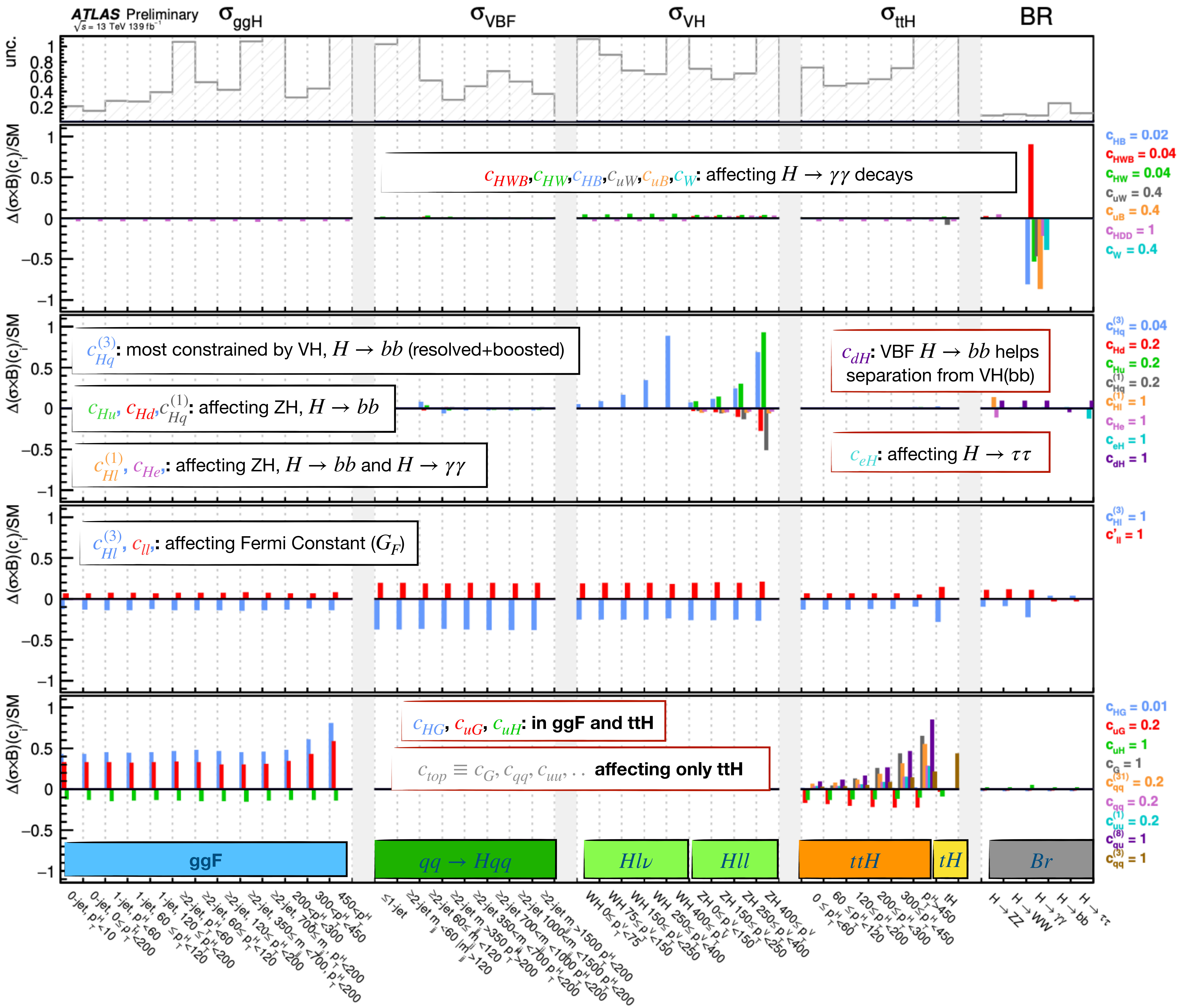
SMEFT interpretations of combined single Higgs measurements

Higgs STXS measurements

Decay Channel	Production modes	Ref.
$H \to \gamma\gamma$	ggF, VBF, VH, ttH+tH	[1]
$H \to ZZ^* \to 4l$	ggF, VBF, VH, ttH+tH	[2]
$H \to WW^* \to l\nu l\nu$	ggF, VBF	[3]
$H \to bb$	VBF, VH, ttH+tH	[4],[5],[6],[7]
$H \to \tau\tau$	ggF, VBF, VH, ttH+tH	[8]

Most important changes w.r.t previous combination

- Adding more measurements improves **sensitivity**
- Allows for **de-correlating** of Wilson coefficients



ATLAS-CONF-2021-053

SMEFT interpretations of combined single Higgs measurements

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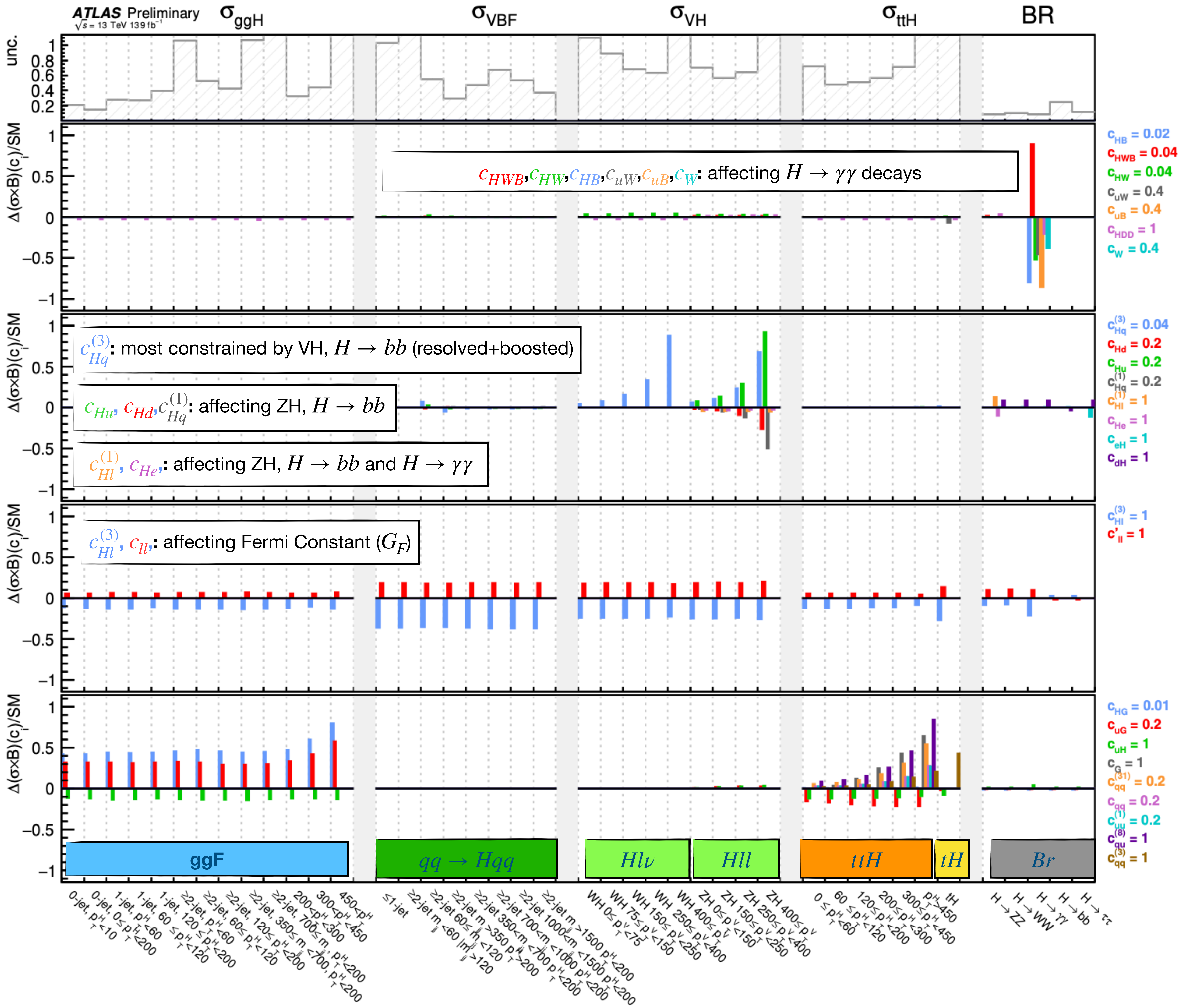
$H \to bb$	VBF, VH, ttH+tH	[4],[5],[6],[7]
$H \to \tau\tau$	ggF, VBF, VH, ttH+tH	[8]

Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}G^A_{\mu\nu}$
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}B_{\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p\gamma_\mu l_t)(\bar{l}_r\gamma^\mu l_s)$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r\widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r\widetilde{H})$	c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

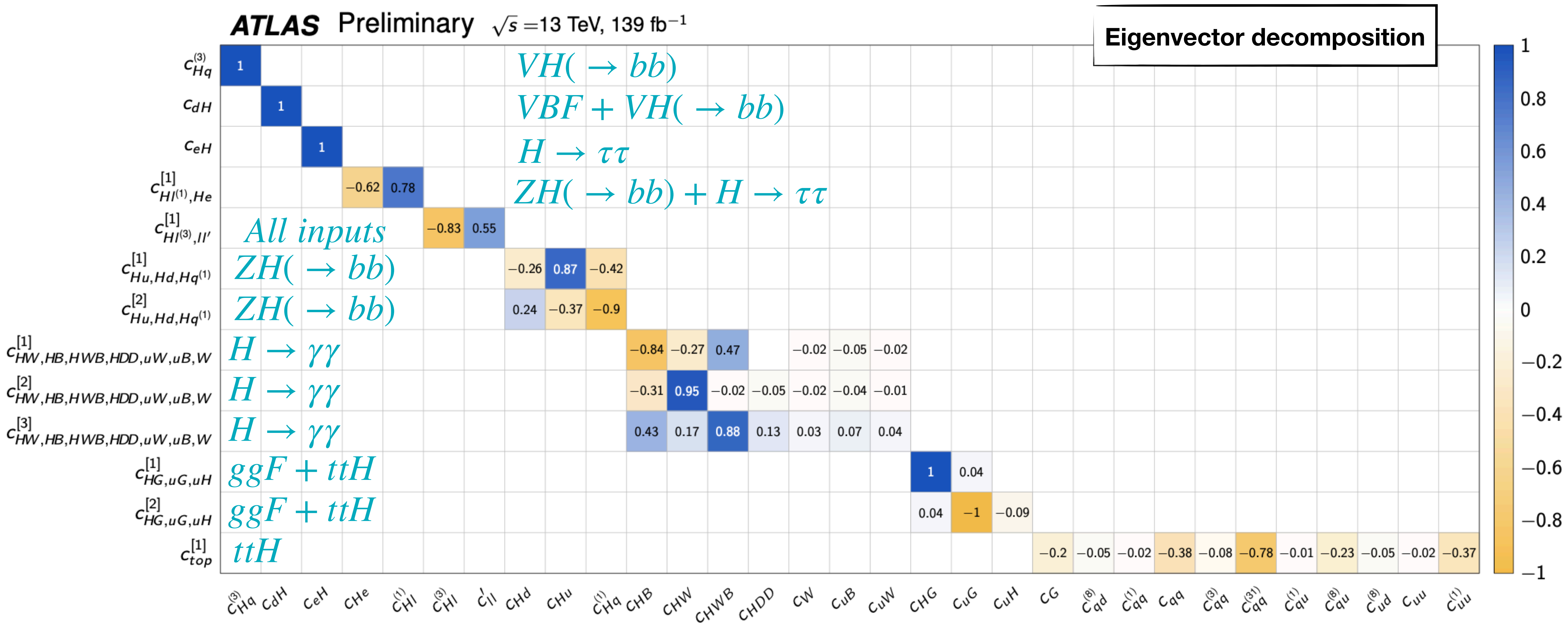
Assuming $U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$

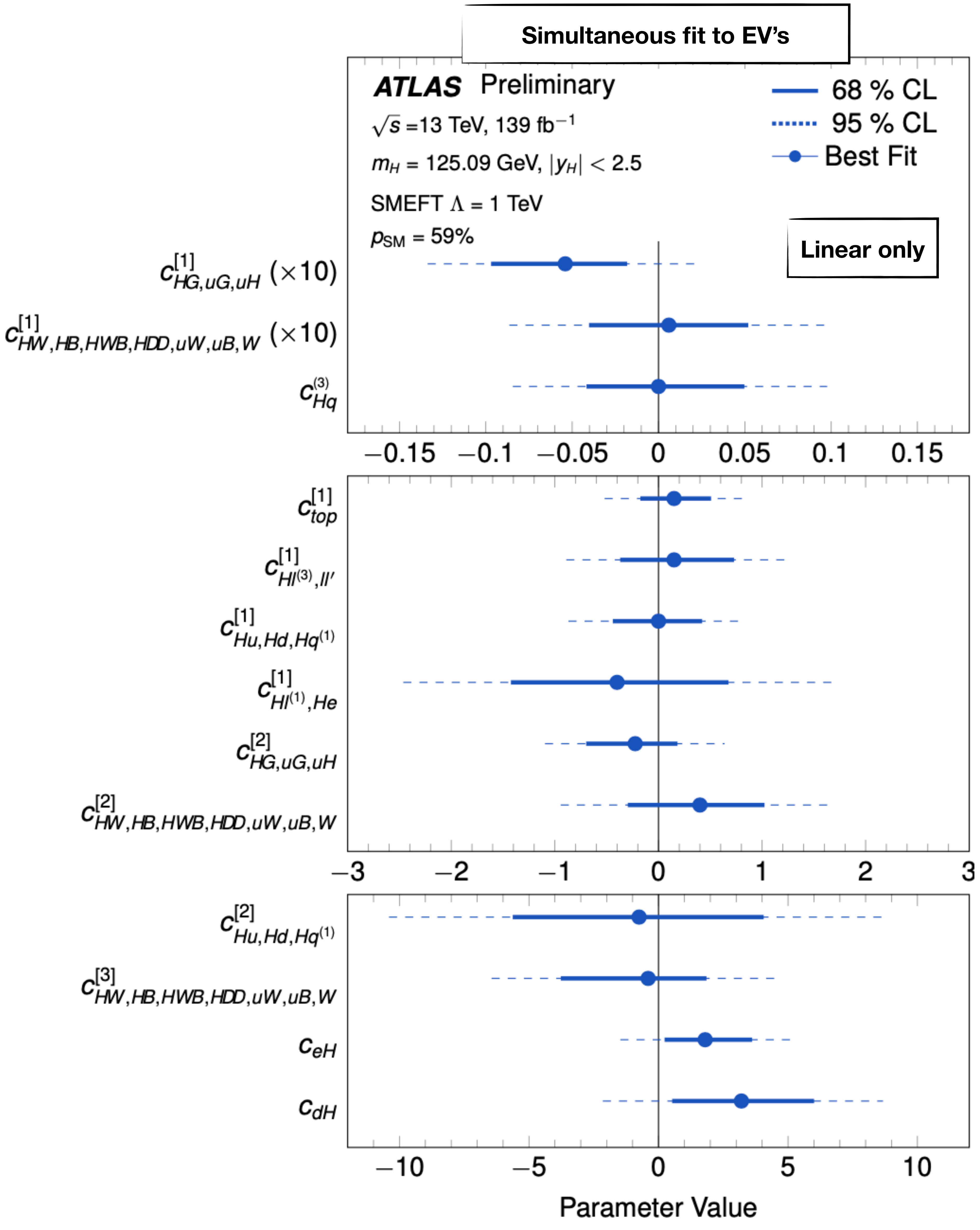
- Weak+Higgs boson interactions
- Boson ($\gamma/V/H$) Couplings to fermions
- 4-fermion interactions



ATLAS-CONF-2021-053

SMEFT interpretations of combined single Higgs measurements





- Sensitivity to **3** Wilson coefficients directly ($c_{Hq}^{(3)}$,c_{dH},c_{eH}) and **10** linear combinations of other coefficients
- c_{eH}, c_{dH},$c_{top}^{[1]}$ now **disentangled** from other parameters due to new inputs from $H \to \tau\tau$,$VBF\ H \to bb$ and $ttH\ H \to bb$
- Limits improve by up to 70% compared to the previous combination.
- **Correlations** in general significantly reduced.

EFT interpretation of differential cross-sections of WW, WZ, 4l, and Z+2j production

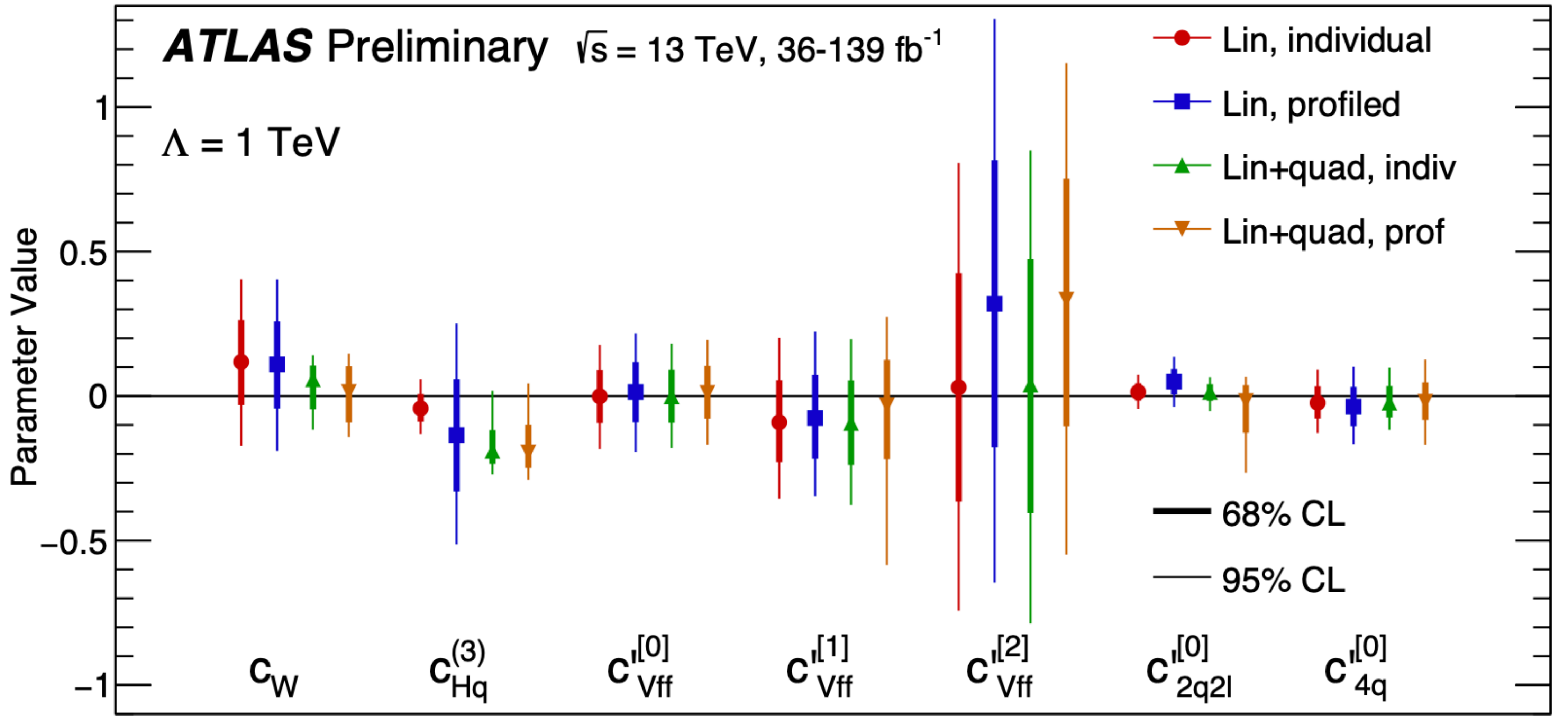
- ***EW differential distributions***

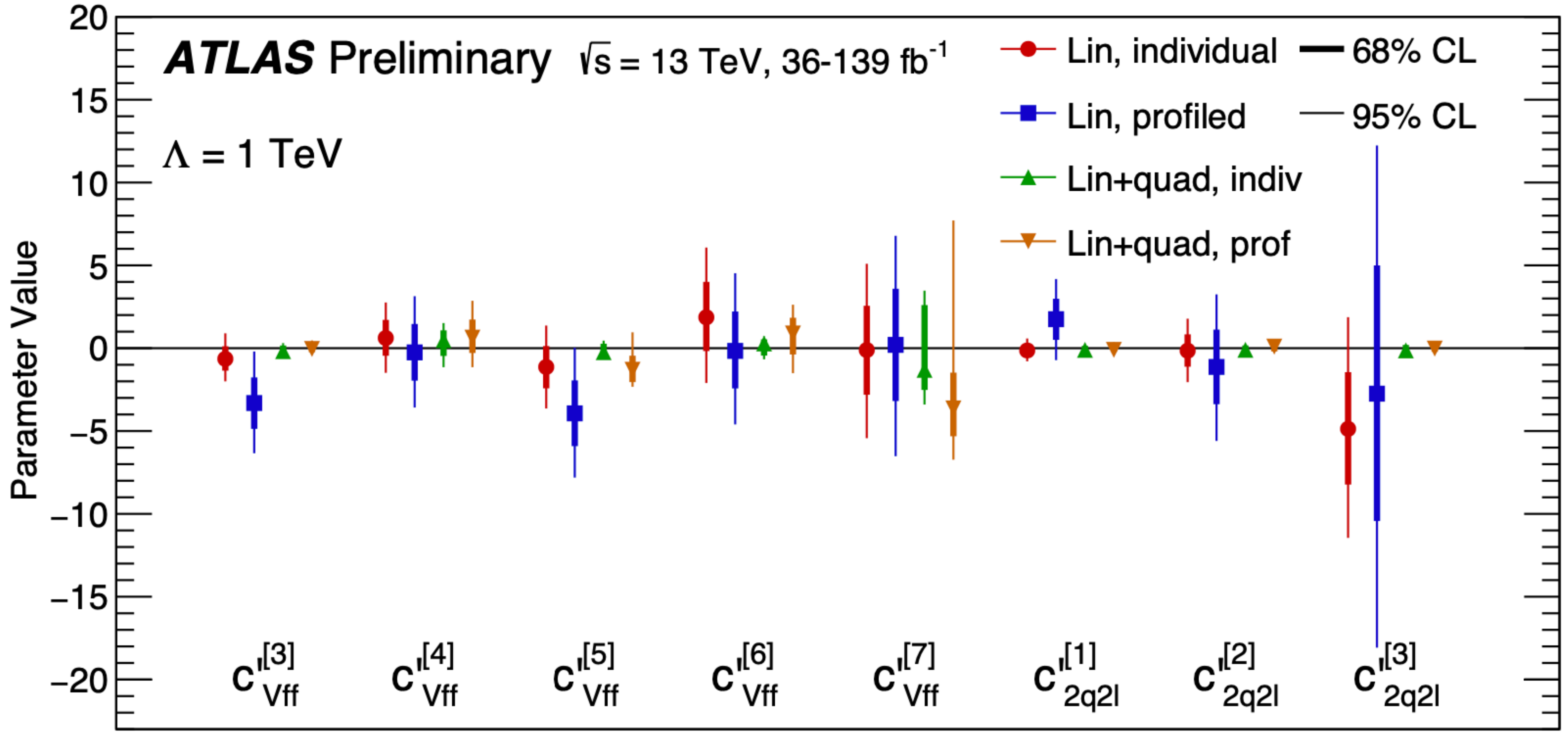
Process	Phase space req	Observable	Ref.
$pp \rightarrow e^{\pm}\nu\mu^{\mp}\nu$	$m_{ll} > 55\ GeV, p_T^{jet} < 35\ GeV$	$p_T^{lead,lep}$	[1]
$pp \rightarrow l^{\pm}\nu l^{+}l^{-}$	$m_{ll} \in (81,101)\ GeV$	m_T^{WZ}	[2]
$pp \rightarrow l^{+}l^{-}l^{+}l^{-}$	$m_{4l} > 180\ GeV$	m_{Z2}	[3]
$pp \rightarrow l^{+}l^{-}jj$	$m_{jj} > 1000\ GeV, m_{ll} \in (81,101)\ GeV$	$\Delta\phi_{jj}$	[4]

- Combination performed of **4 unfolded differential cross section** measurements

- Fit performed after PCA assuming $top\ U(3)_l$ flavour symmetry
  - **33** operators included in **15** sensitive directions, **2** direct operators
  - Basis ready for including top measurements

- **CP-even** operators (sensitive to CP-odd only in $\Delta\phi_{jj}$)
- Including all $1/\Lambda^2$ terms, some $1/\Lambda^4$ terms





ATL-PHYS-PUB-2022-037

SMEFT interpretation of Higgs, EW + electroweak precision observables

Measurement	Type	Ref.
ATLAS Higgs boson	Simplified Template Cross section(STXS)	[1]
ATLAS electroweak	Differential cross section	[2]
Electroweak precision	Electroweak precision variables (EWPO)	[3]

- Included results from **LEP**
  - Observables describing **physics at the Z-pole**
- First **global** EFT interpretation in ATLAS
  - $top\ U(3)_l$ flavour symmetry
- **Tight limits** provided by LEP
  - Only sensitive to a **limited** number of parameters
- ***Higgs STXS measurements***
- **EW differential distributions**
  WW (p_T^{l1}), WZ(m_{WZ}), 4l (m_{Z2}) and VBF Z ($\Delta\phi_{jj}$)

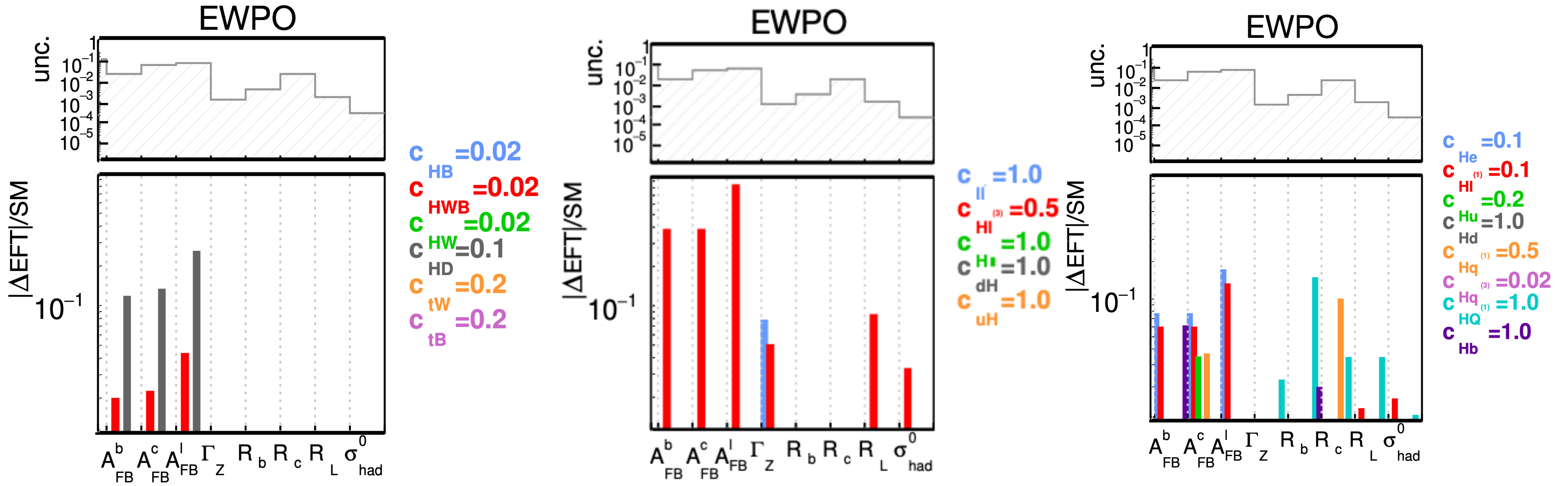
LEP/SLD EWPO

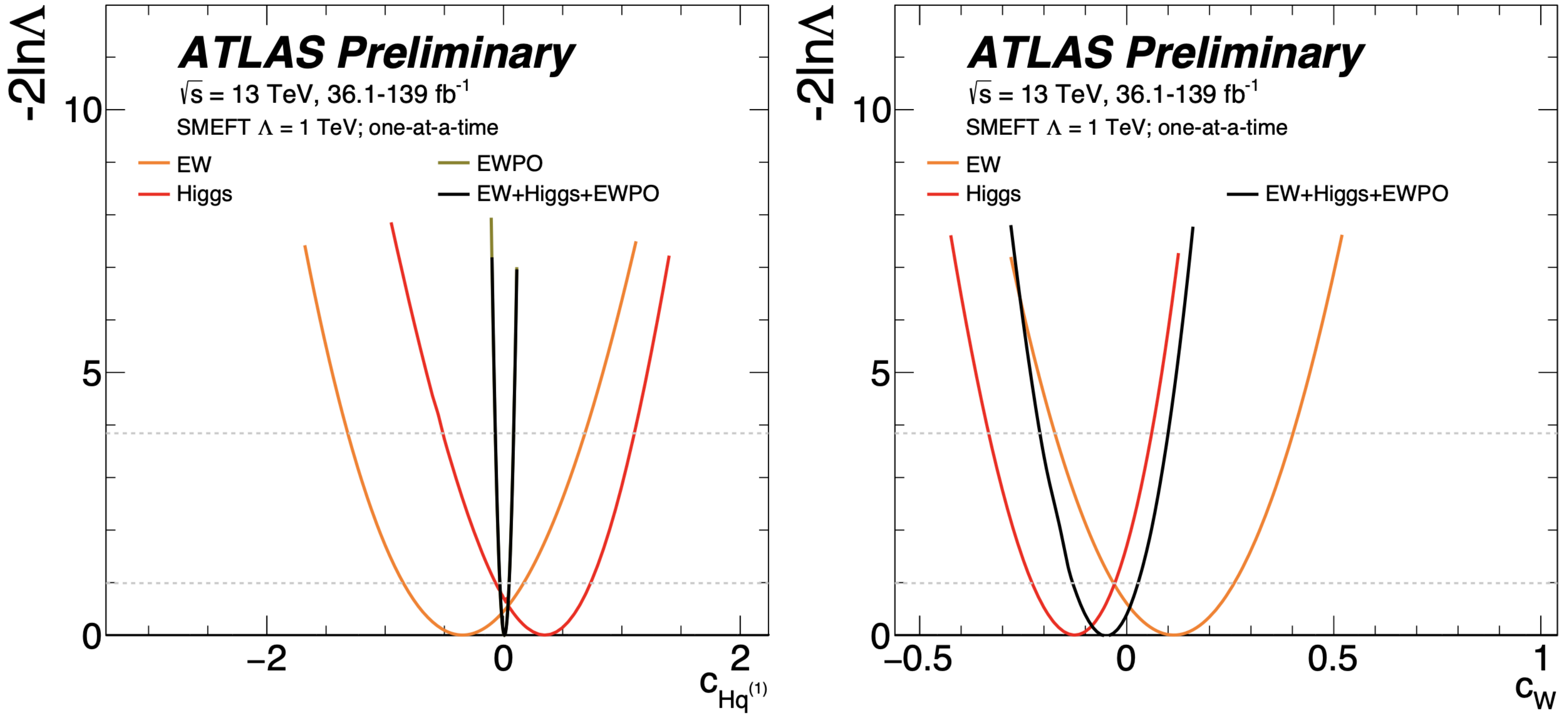
- $\Gamma_Z, R_l^0, R_b^0, A_{FB}^{0,l}, A_{FB}^{0,c}, A_{FB}^{0,b}, \sigma_{had}^0$

Decay ratio into leptons and b-quarks (R_l^0, R_b^0)

Forward-backward asymmetry of leptons, c or b-quarks ($A_{FB}^{0,l}, A_{FB}^{0,c}, A_{FB}^{0,b}$)

Hadronic pole cross section (σ_{had}^0)

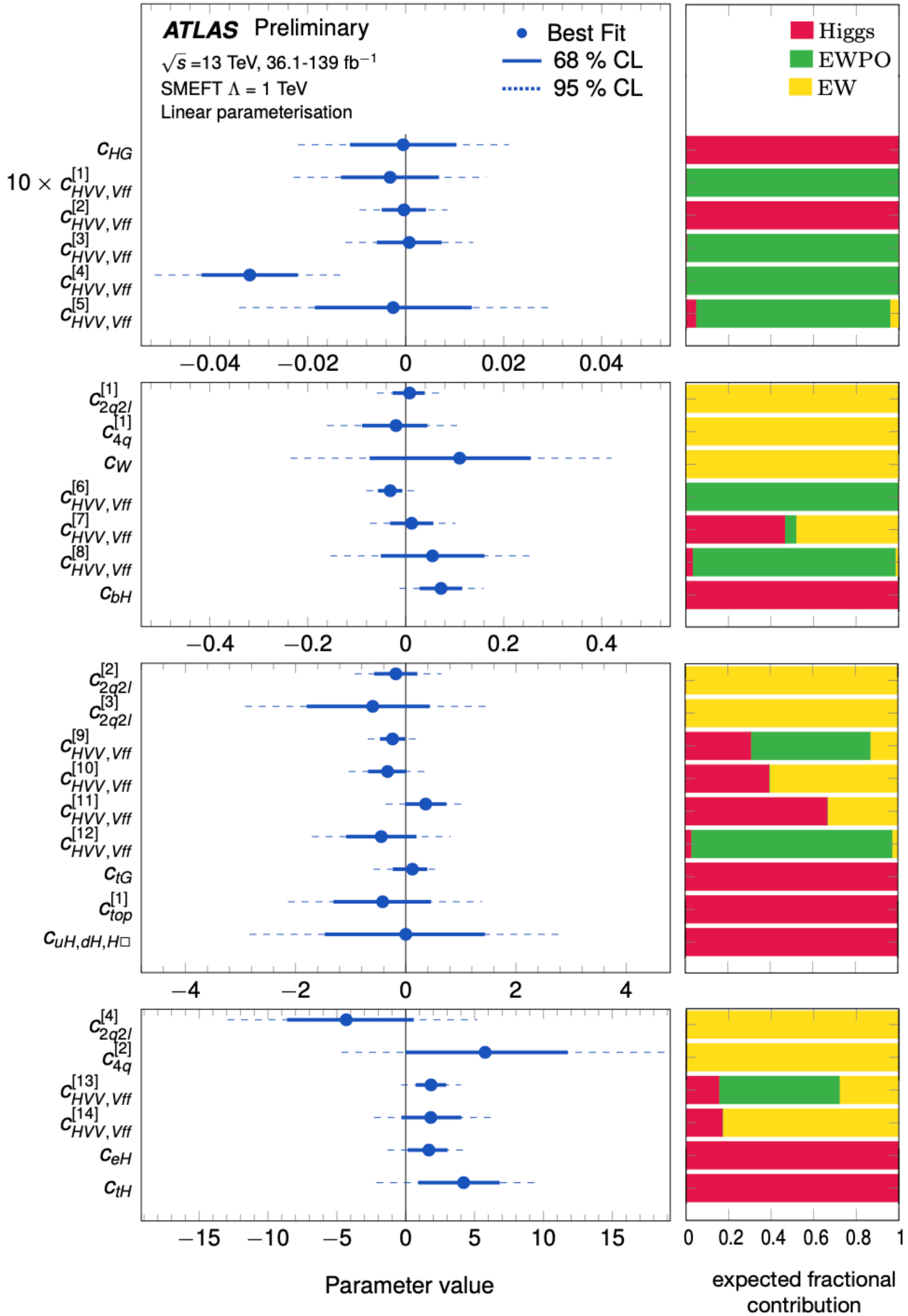




ATL-PHYS-PUB-2022-037

SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

- ***Higgs STXS measurements***
- ***EW differential distributions***
  WW (p_T^{l1}), WZ(m_{WZ}), 4l (m_{Z2}) and VBF Z ($\Delta\phi_{jj}$)
- ***LEP/SLD EWPO***
  $\Gamma_Z, R_l^0, R_b^0, A_{FB}^{0,l}, A_{FB}^{0,c}, A_{FB}^{0,b}, \sigma_{had}^0$



- Constraining **22** linear combinations and **6** individual Wilson coeff.
- Several constraints driven by either EW, Higgs, or LEP
  - Example: $c_{2q2l}^{[1]}$, c_{tG}, $c_{HVV,Vff}^{[1]}$
- Clearly shows the **complementarity** of each measurement
- **Simplified likelihood model** available for re-interpreations!

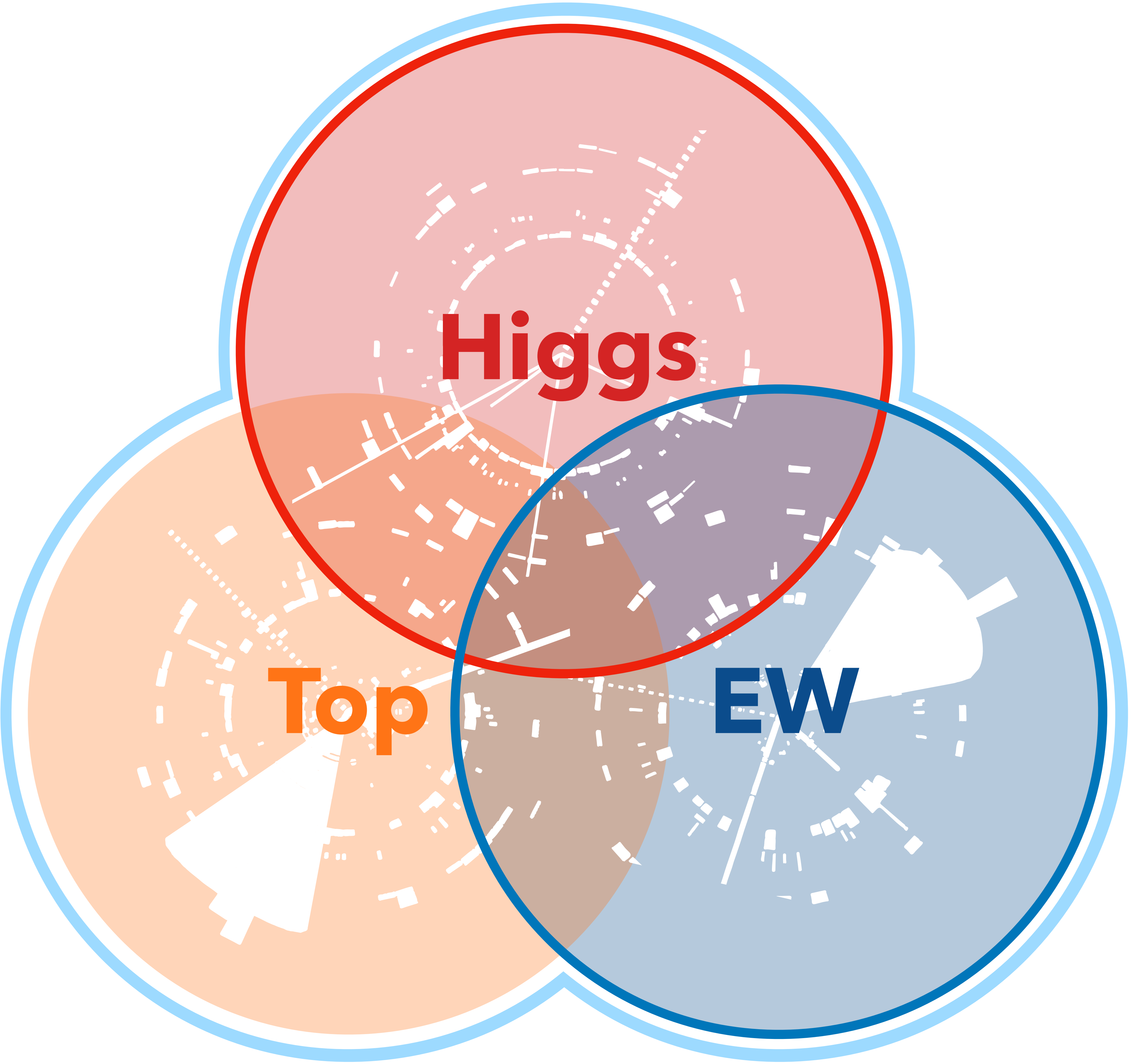
Summary

- Many Higgs and EW measurements being interpreted in terms of Effective Field Theories.

- The Combined interpretation of Higgs STXS and EW measurements has made big steps in the last few years.
  - SMWW+HWW, **7** EV's and **1** Wilson coeff. measured
  - EW combination, **13** EV's and **2** Wilson coeff. measured
  - Higgs STXS, **13** EV's and **3** Wilson coeff. measured
  - Higgs+EW+LEP, **22** EV's and **6** Wilson coeff. measured

- First global ATLAS EFT interpretation available, also providing a simplified likelihood model for re-interpretation

- Next up: including Top analyses in the global fit, treatment of truncation, Higher-order uncertainties, etc.

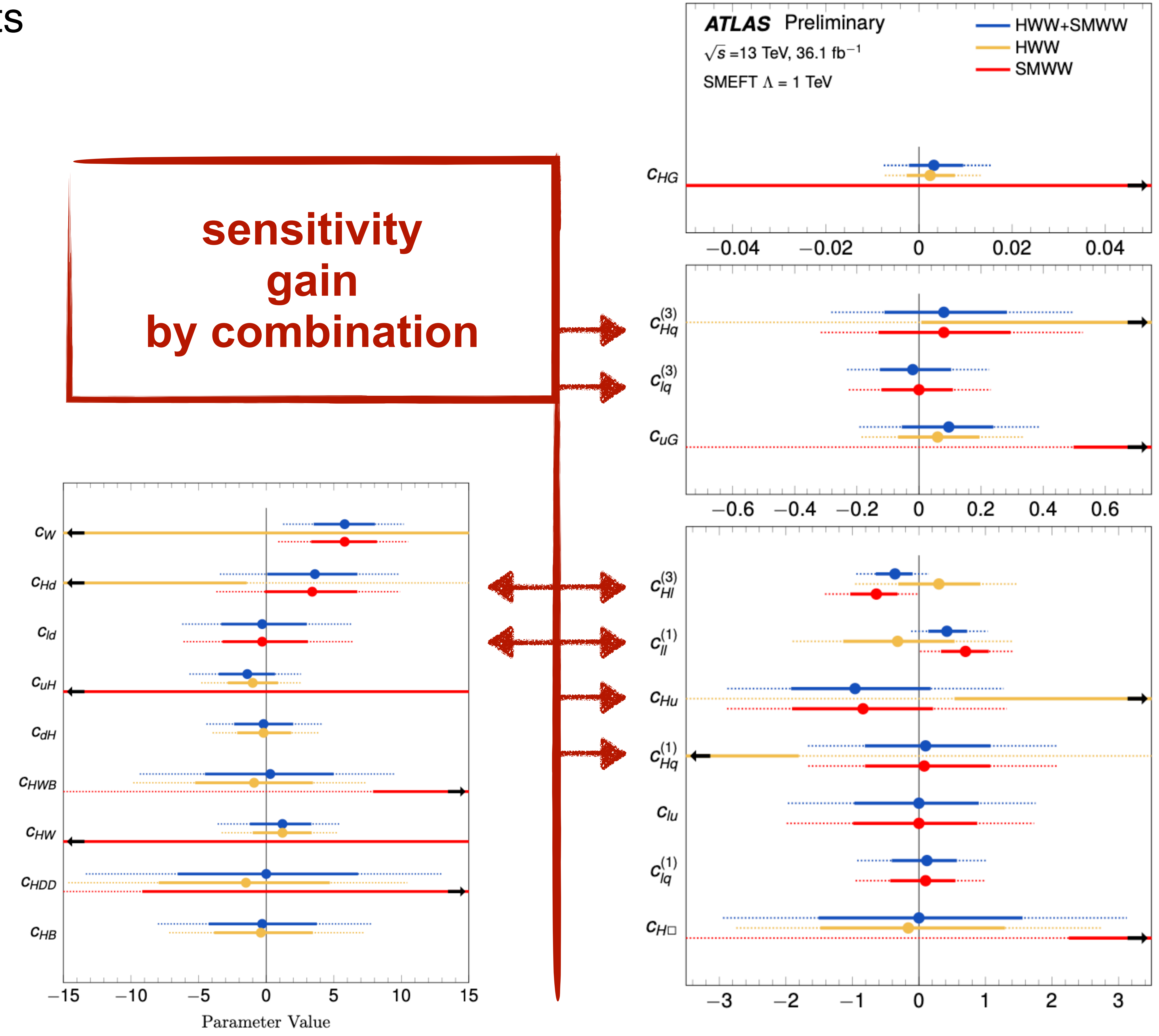


Backup

Backup

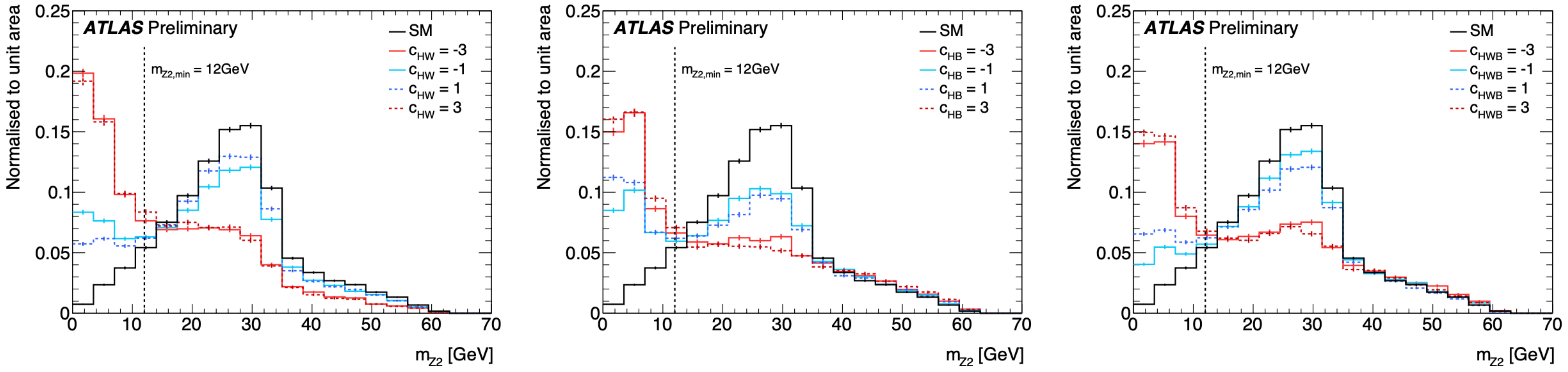
SMEFT interpretation of SM WW + $H \rightarrow WW^*$

- Observed one-at-a-time fit parameter limits
- Split for **HWW**, **SMWW**, **HWW+SMWW**



SMEFT interpretation of Higgs, EW + electroweak precision observables

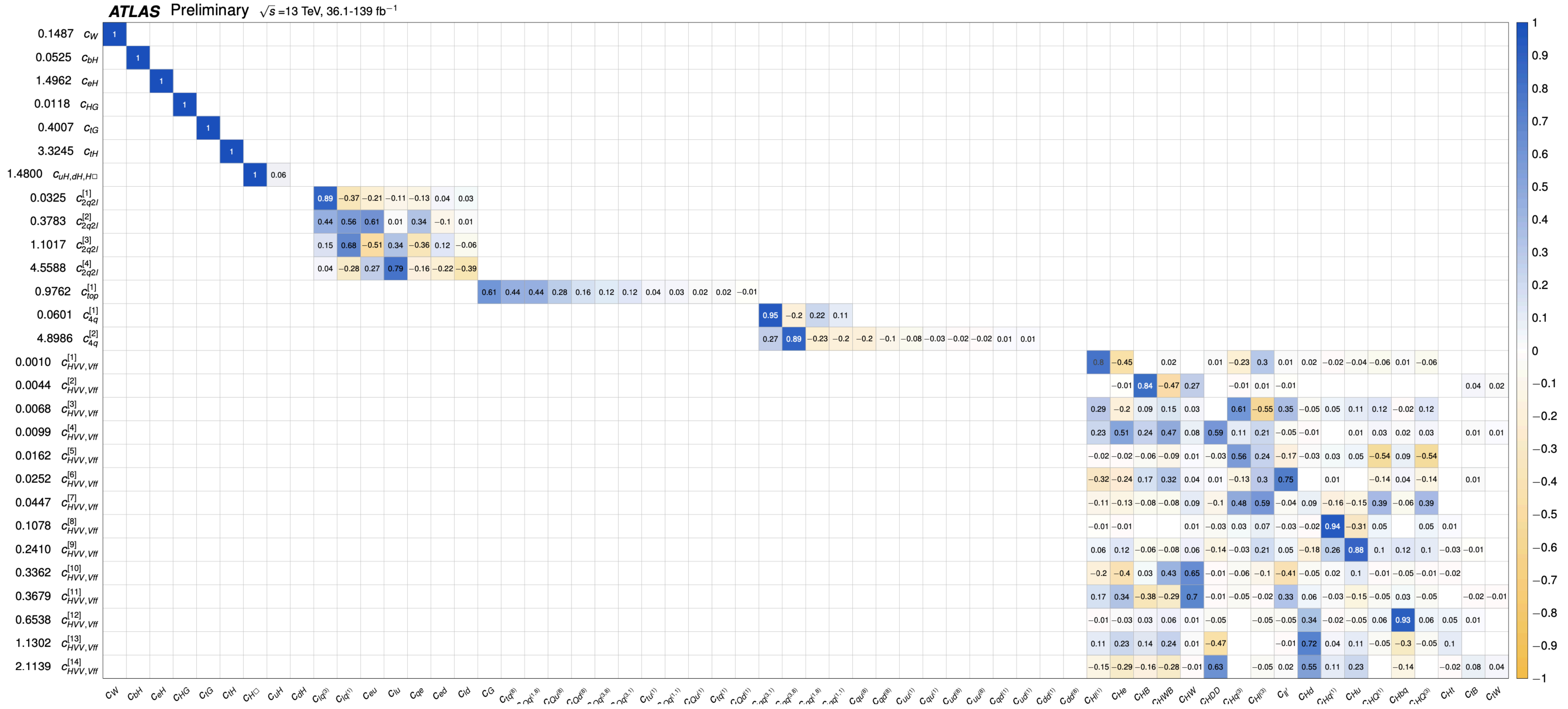
- Acceptance parametrisation applied for $H \rightarrow 4l$ decay rate.



ATL-PHYS-PUB-2022-037

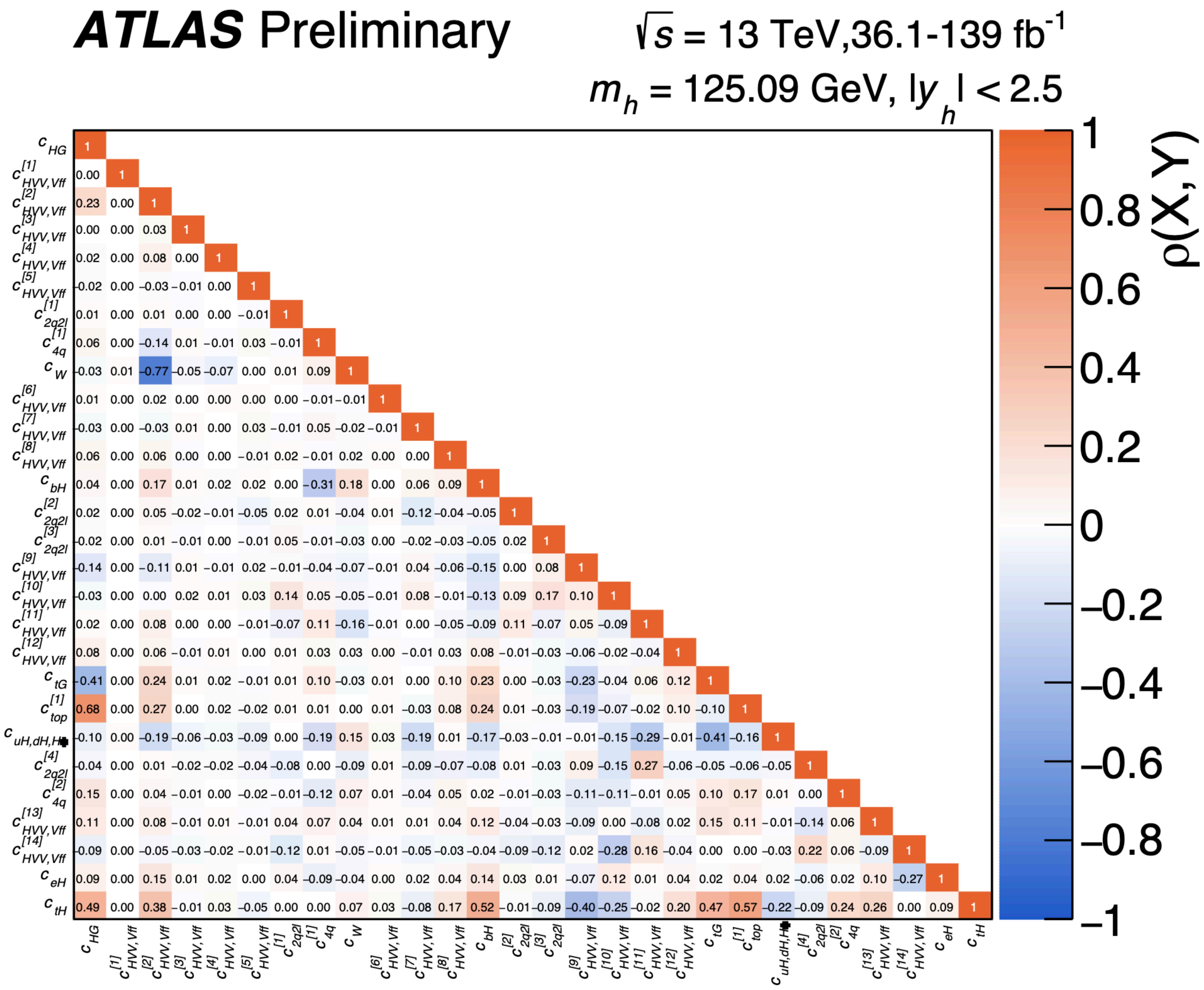
SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

- Fitted EigenVectors after PCA



SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

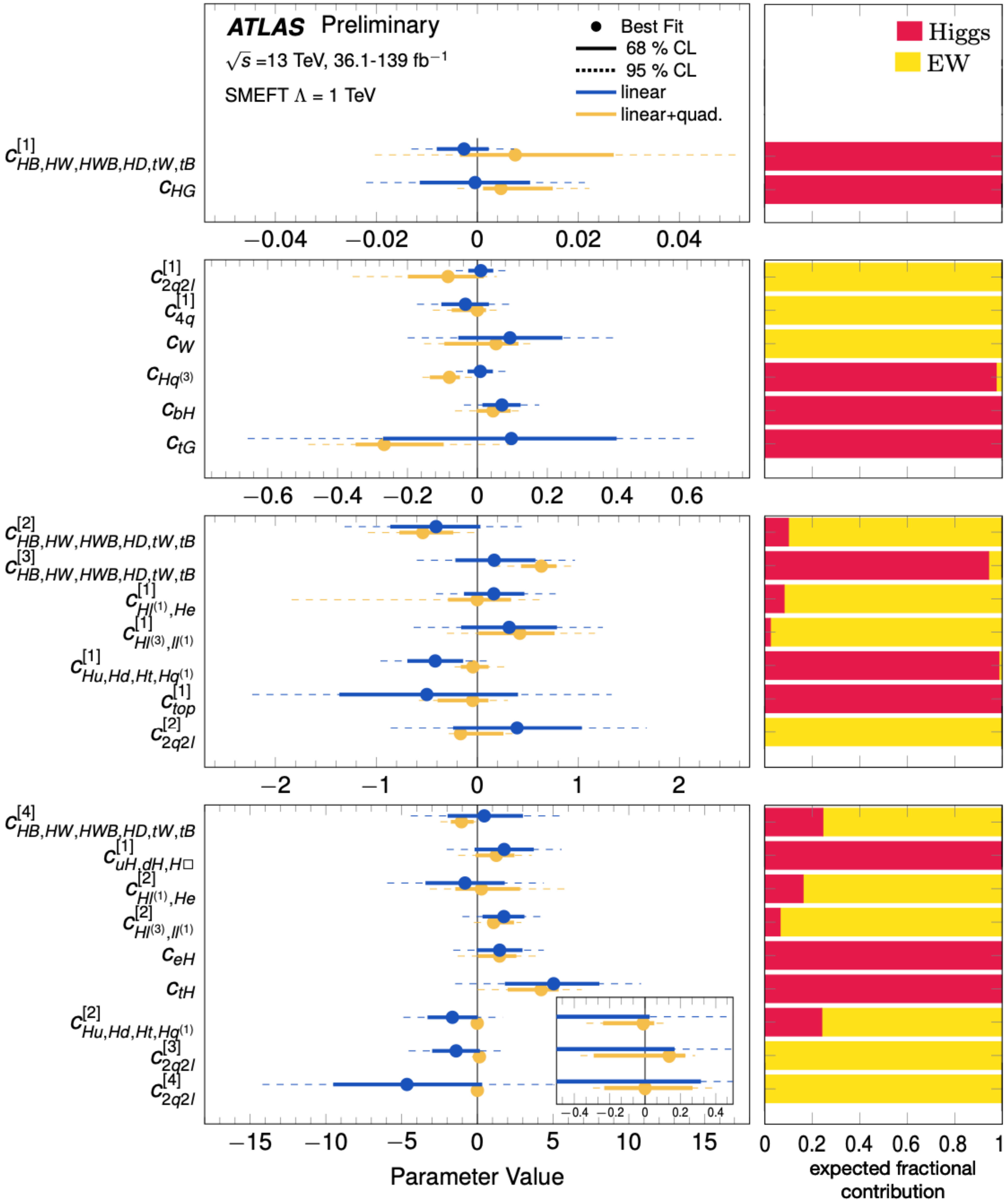
- Correlation matrix of the fitted Eigenvectors



ATL-PHYS-PUB-2022-037

SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

- Constraints on Wilson coefficients from the combined ATLAS-only analysis



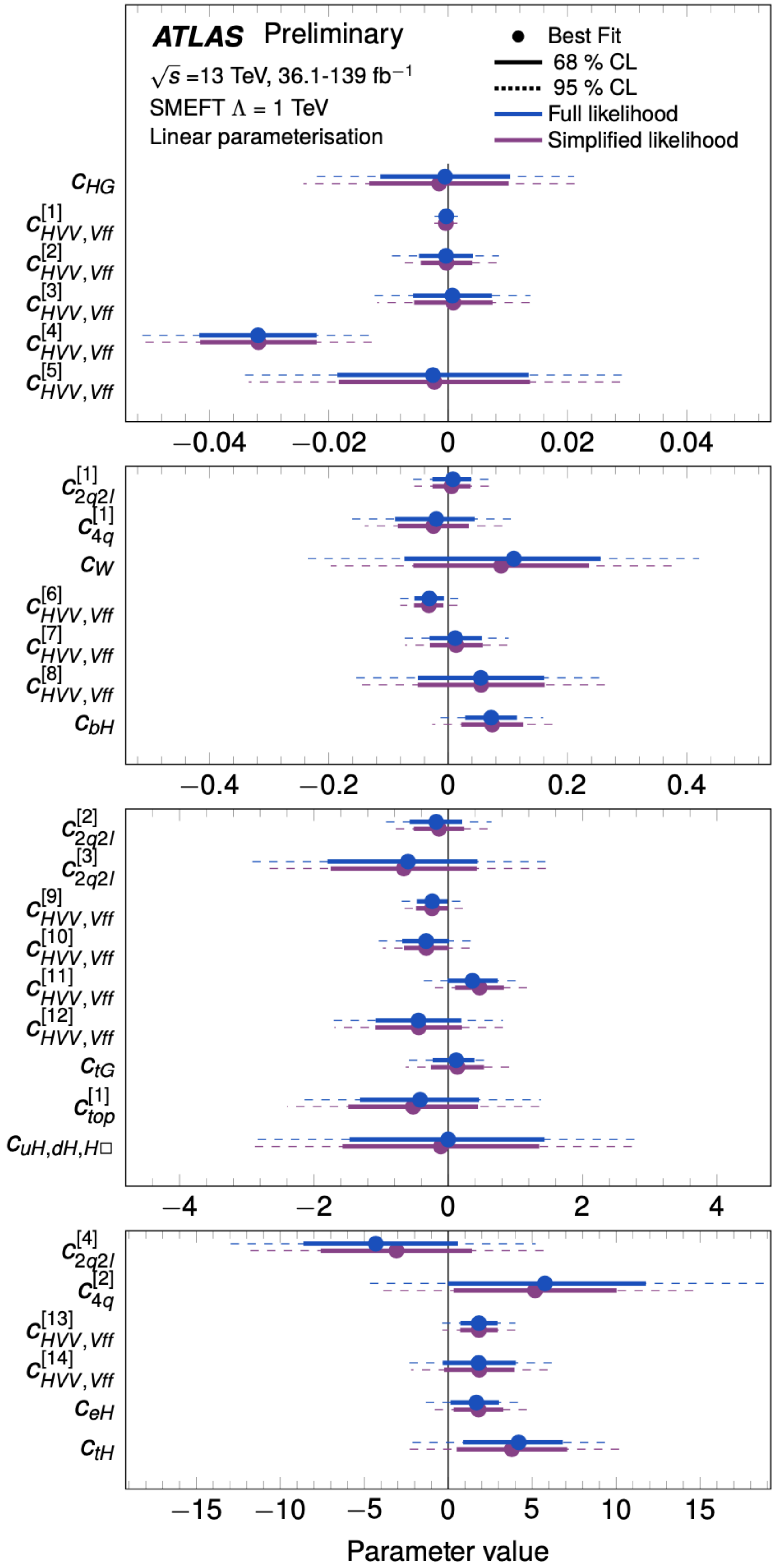
Bryan Kortman, Higgs 2022 Conference, 7-11 November

SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

- Constraints on Wilson coefficients from Full likelihood model compared to the simplified likelihood model
- Using a Gaussian approximation of the likelihood
- Using $n_\mu = 128$ in a Multivariate Gaussian

$$L(\boldsymbol{\mu}) = \frac{1}{\sqrt{(2\pi)^{n_\mu} \det(V_\mu)}} \exp\left(-\frac{1}{2}\Delta\boldsymbol{\mu}^\intercal V_\mu^{-1} \Delta\boldsymbol{\mu}\right)$$

$$\Delta\boldsymbol{\mu} = \boldsymbol{\mu} - \hat{\boldsymbol{\mu}}$$



EFT interpretation of differential cross-sections of WW, WZ, 4l, and Z+2j production

- Fitted EigenVectors after PCA

ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 36-139 fb^{-1}

EV	σ	c_W	$c^{(3)}_{Hq}$	c_{HWB}	c_{HD}	$c^{(1)}_{Hl}$	$c^{(3)}_{Hl}$	c_{He}	$c^{(1)}_{ll}$	$c^{(1)}_{Hq}$	c_{Hu}	c_{Hd}	$c^{(1)}_{lq}$	$c^{(3)}_{lq}$	c_{lu}	c_{ld}	c_{eu}	c_{ed}	c_{qe}	$c^{(11)}_{qq}$	$c^{(18)}_{qq}$	$c^{(31)}_{qq}$	$c^{(38)}_{qq}$
c_W	0.15	1.00																					
$c^{(3)}_{Hq}$	0.0498		1.00																				
$c'^{[0]}_{Vff}$	0.0863			0.81	0.38	0.14	0.37	-0.09	-0.14	0.12	-0.06	0.02											
$c'^{[1]}_{Vff}$	0.149			0.01	-0.03	0.72	-0.29	-0.47	0.39	0.13	-0.04	0.02											
$c'^{[2]}_{Vff}$	0.386			0.38	0.17	-0.31	-0.55	0.26	0.56	-0.19	0.07	-0.03											
$c'^{[3]}_{Vff}$	0.756			0.06	-0.12	-0.21	-0.17	-0.02	-0.03	0.86	0.37	-0.16											
$c'^{[4]}_{Vff}$	1.01			-0.34	0.49	0.23	0.35	0.50	0.40	0.24		-0.02											
$c'^{[5]}_{Vff}$	1.22			-0.03	0.29	0.35	-0.32	0.22	-0.45	-0.23	0.61	-0.14											
$c'^{[6]}_{Vff}$	1.68				-0.12	-0.15	0.46	-0.32	0.38	-0.26	0.65	-0.10											
$c'^{[7]}_{Vff}$	2.11			-0.28	0.69	-0.34	-0.14	-0.55	-0.08	0.02	-0.06	0.03											
$c'^{[0]}_{2q2l}$	0.0297												-0.37	0.89	-0.11	0.03	-0.21	0.04	-0.13				
$c'^{[1]}_{2q2l}$	0.338												0.56	0.44	0.02		0.61	-0.10	0.34				
$c'^{[2]}_{2q2l}$	0.932												0.68	0.14	0.31	-0.04	-0.52	0.13	-0.36				
$c'^{[3]}_{2q2l}$	3.26												-0.25	0.04	0.78	-0.39	0.27	-0.22	-0.21				
$c'^{[0]}_{4q}$	0.0568																			0.11	0.22	0.95	-0.20

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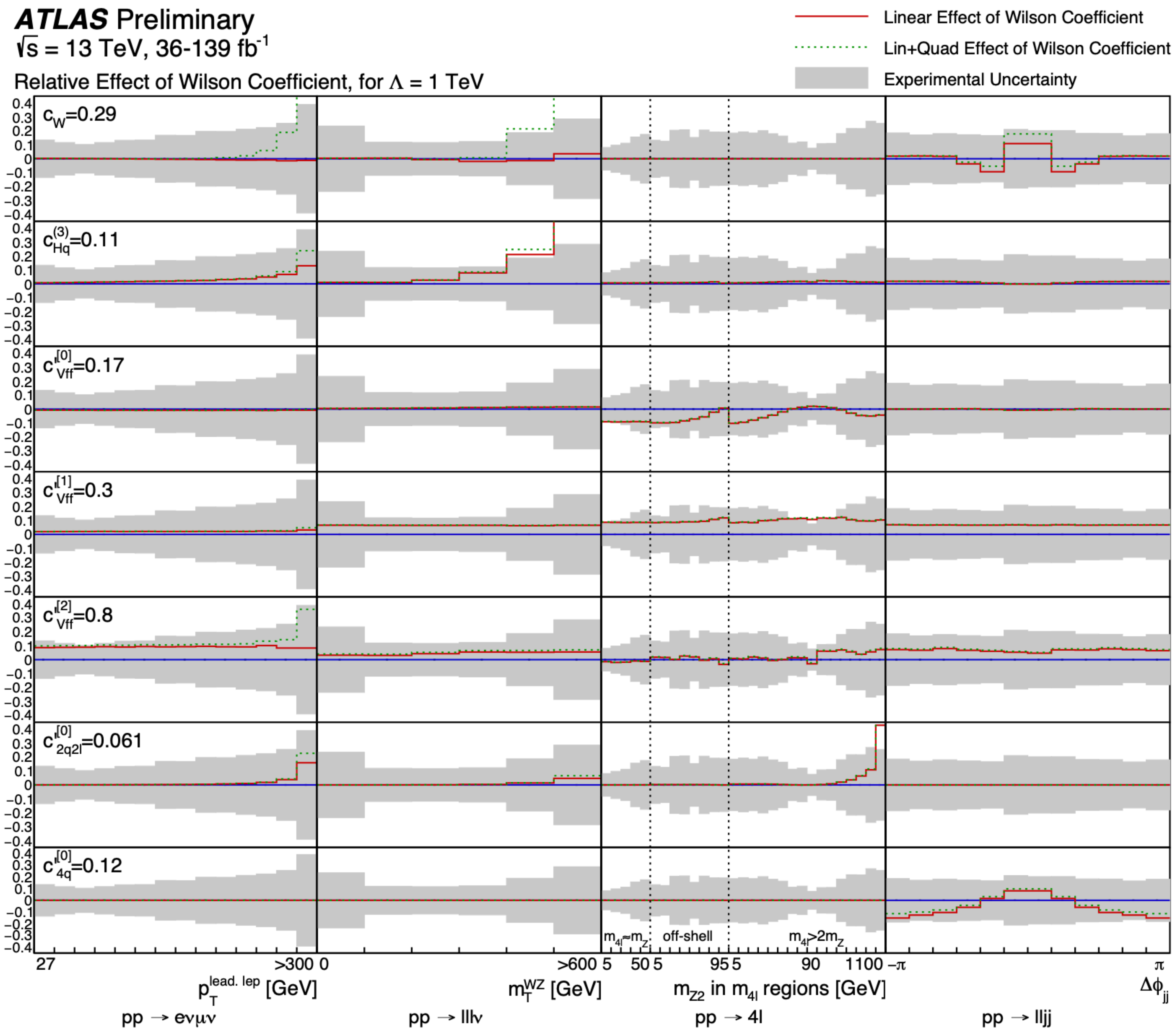
EFT interpretation of differential cross-sections of WW, WZ, 4l, and Z+2j production

- Impact plot of c_W, $c_{Hq}^{(3)}$,$c_{Vff}^{\prime[0]}$,$c_{Vff}^{\prime[1]}$, $c_{Vff}^{\prime[2]}$,$c_{2q2l}^{\prime[0]}$,$c_{4q}^{\prime[0]}$



Bryan Kortman, Higgs 2022 Conference, 7-11 November