Global Effective Field Theory fits from ATLAS

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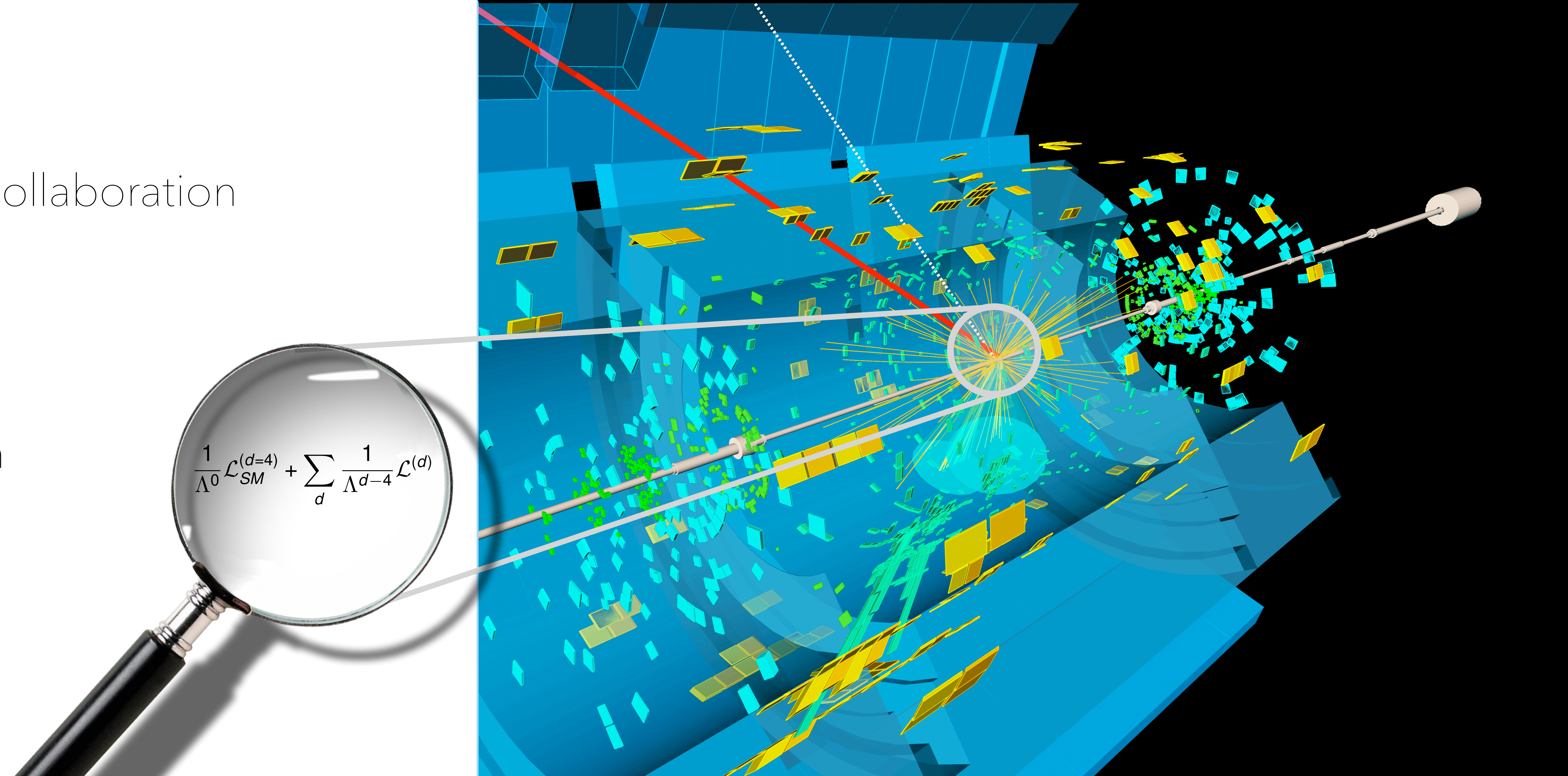
on behalf of the ATLAS Collaboration

8th RIF workshop, Durham

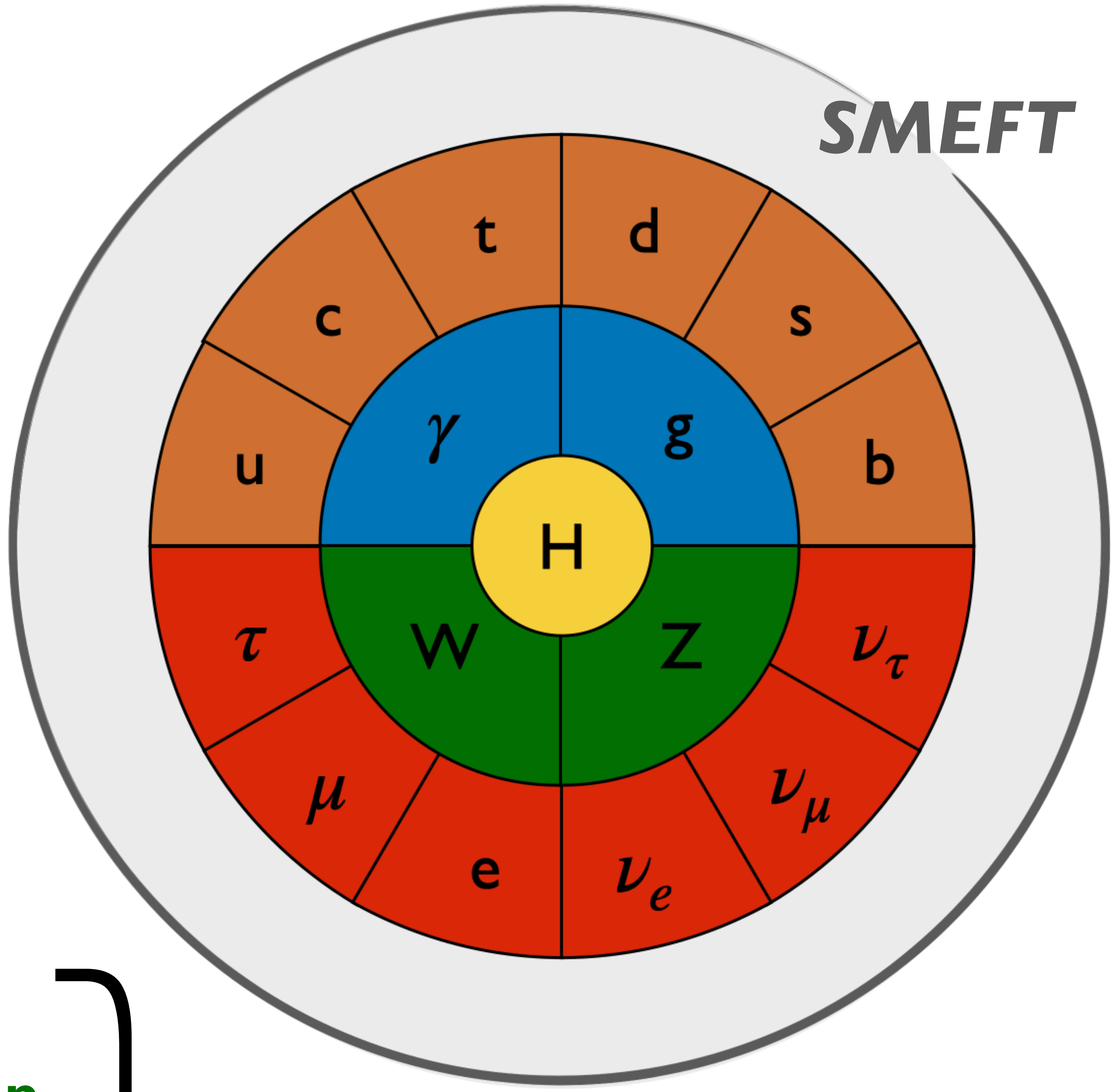


31-08-2023

Introduction

Effective field theory allows to consistently extend Standard Model and probe for deformation arising from a large class of heavy New Physics scenarios

Large number of parameters need to be measured - calls for a **global approach** making use of measurements from **different physics sectors** and **experiments** to uncover deviations in data



This talk,

First global fit from the ATLAS collaboration

Higgs boson and **Electroweak** measurements based on ATLAS data and **electroweak precision observables** from LEP & SLD

Interface between theory and experiment for (re)interpretation

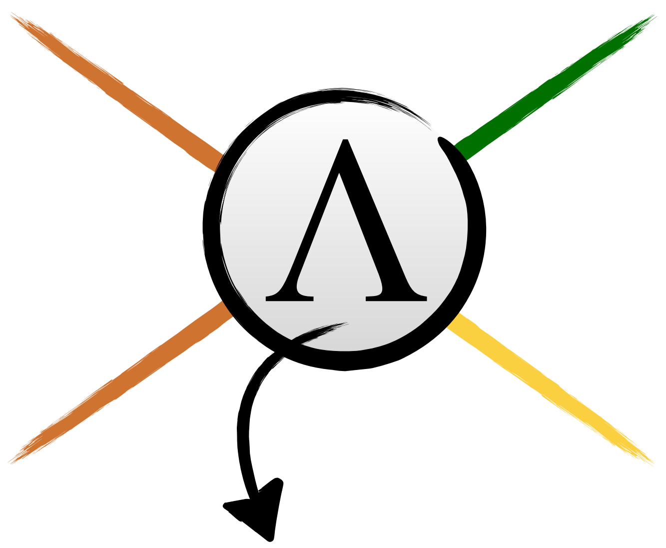
Simplified likelihood function as a statistical proxy to the full experimental likelihood function

} ATL-PHYS-PUB-2022-037

Towards the next global fit

a peek into the updated SMEFT fit of combined **Higgs boson** (ATLAS-CONF-2023-052) measurements

Effective Field Theory Lagrangian



much larger than vev

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + O\left(\frac{1}{\Lambda^{d>2}}\right)$$

$\propto \frac{1}{\Lambda^0}$

Weinberg operator
violates Baryon & Lepton no.
$\Lambda \sim$ Majorana ν mass scale

2499 SMEFT operators at dimension 6 with $\Delta L, \Delta B = 0$

Wilson Coefficients
parameters of interest

- Effective field theory captures **SM as low-energy approx.** of a more fundamental (UV) theory at higher energy, **EFT** results can be translated **to dedicated UV models** → ***matching***

- Operators built from SM fields, **all allowed local interactions** respecting symmetries

- Corresponding **Wilson coefficients** (c_i) **new measurable parameters**, capture deformations from a large class of UV theories

- Some measurements serve as **input parameters to SMEFT** to make predictions for observable : $\{m_W, m_Z, G_F\}$ **scheme** used

CP and flavour considerations

- 2499 operators at d=6 : additional flavour symmetry in SMEFT dictated by experimental considerations, allow to scale down complexity of operators !

- For combined fits: mainly CP-even observables are considered → **CP-even operators** leading contribution

10.1007/JHEP 04 (2021) 073 Brivio

U(3)⁵ scheme

85 (**60**) operators

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

All quark generations treated similarly

All lepton generations treated similarly

Relax t,b →

topU3l scheme

182 (**129**) operators

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

First two quark generations treated similarly

All lepton generations treated similarly

Relax leptons →

top scheme

275 (**204**) operators

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

First two quark generations treated similarly

- Constraints in ***top scheme*** carry least flavour symmetry → dedicated operators in top and lepton sectors

- Concerted effort to update to ***top scheme*** - Global EFT fit based on ***topU3l*** whereas updated Higgs combination based on ***top***

Input measurements to the global fit

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

- **Simplified template cross-sections** from 5 major Higgs decay channels
- Higgs boson separated out by production mode further split into bins based on **kinematic splitting** & **event info.** (p_T^V, p_T^H, m_{jj}, N_{jets})
- Measurement **uncertainties O(10%)** in bulk of distribution **to O(100%)** in tails

Process	Observable	$\mathcal{L}$ [fb^{-1}]
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$p_T^{\text{lead. lep.}}$	36
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	m_T^{WZ}	36
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	m_{Z2}	139
$pp \to \ell^{+}\ell^{-}jj$	$\Delta\phi_{jj}$	139

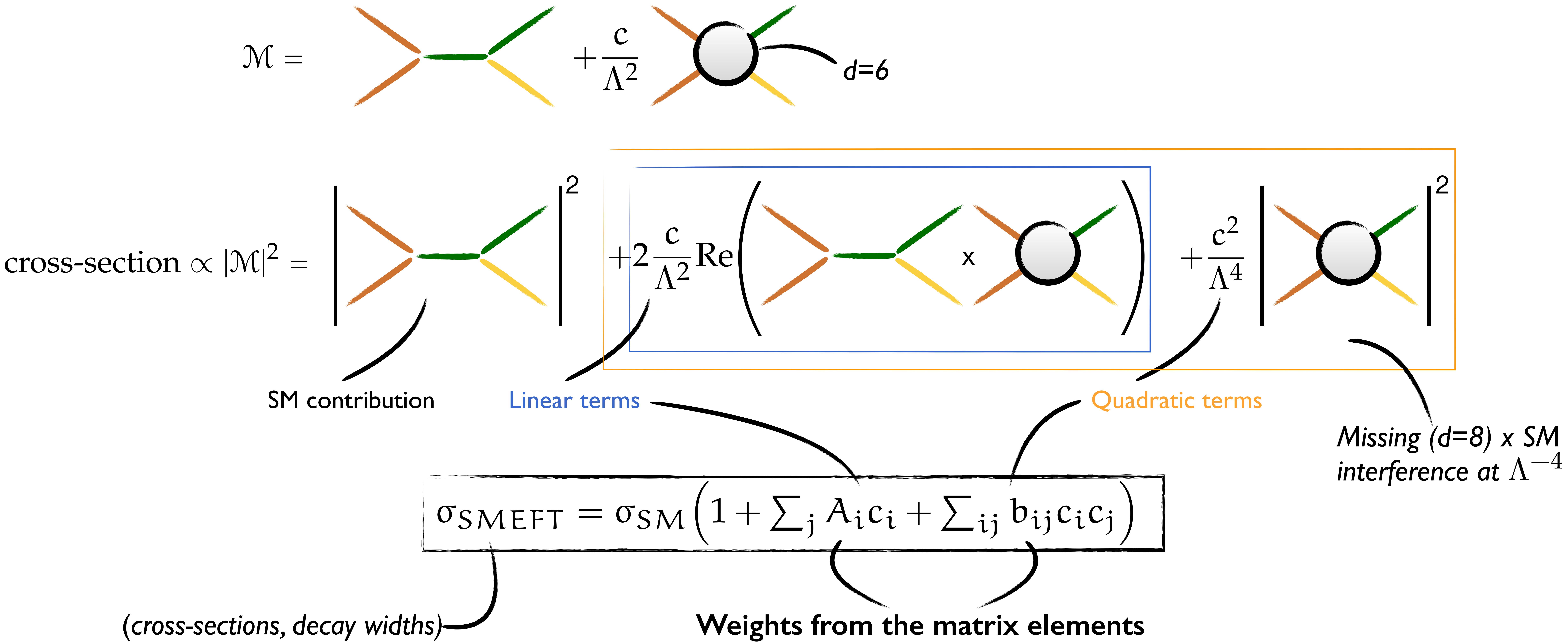
- **One observable** considered for **each EW process**, chosen by sensitivity to SMEFT variations
- Measurement **uncertainties O(10%)** in bulk of distributions to **O(30%)** in tails

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
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	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^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

- **Electroweak precision observables** measured at **LEP & SLC**
- ***Z-pole observables***: Z-width (Γ_Z), 3-ratio parameters (R^0), 3-forward back asymmetries (A_{FB}^0), and hadronic pole cross-section (σ^0_{had})
- Measurement probed with high sensitivity, **uncertainties O(1 - 0.01 %)**

From Lagrangian to Observables

Continuous signal modelling of observable cross-section in terms of Wilson coefficients



Modelling Observables in SMEFT

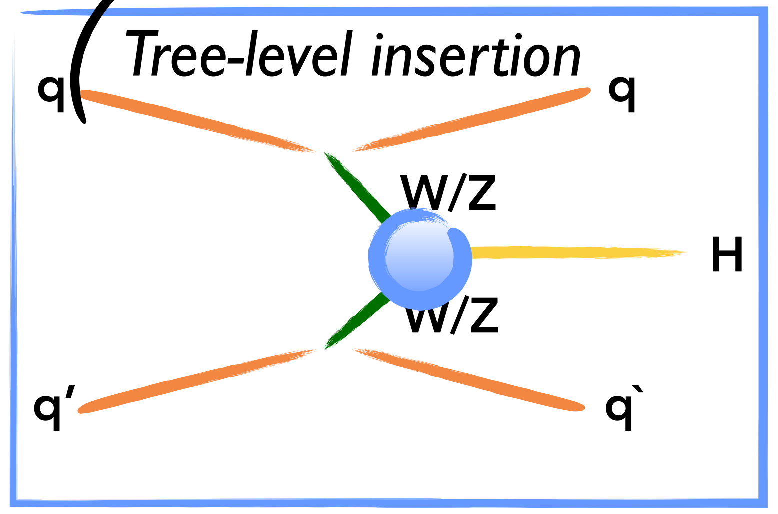
Continuous signal model: $\sigma_{SMEFT} = \sigma_{SM}\left(1+\sum_j A_i c_i + \sum_{ij} b_{ij} c_i c_j\right)$

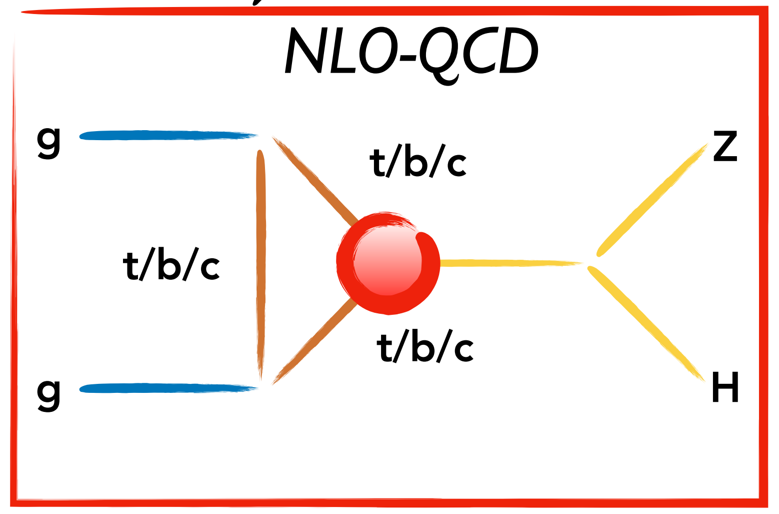
Weights primarily estimated from Monte-Carlo simulations using SMEFT models with Madgraph + Pythia

- **SMEFTsim** is used for processes with SM-tree diagrams at LO
- **SMEFTatNLO** used for process with SM-loop diagrams at LO ($gg \to H, gg \to ZH, H \to gg$)

SMEFTsim

SMEFT@NLO

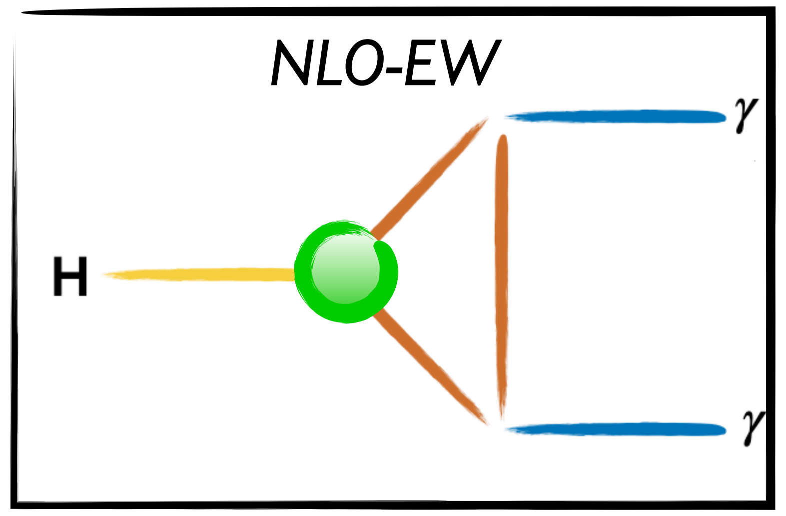




Analytical calculations also employed in particular cases:

NLO-EW corrections to BR(H→$\gamma\gamma$)

Predictions for EWPO in SMEFT derived from calculations 10.1007/JHEP 06 (2021) 076 **Corbett et al**



10.1103/Phys. Rev. D 98, 095005

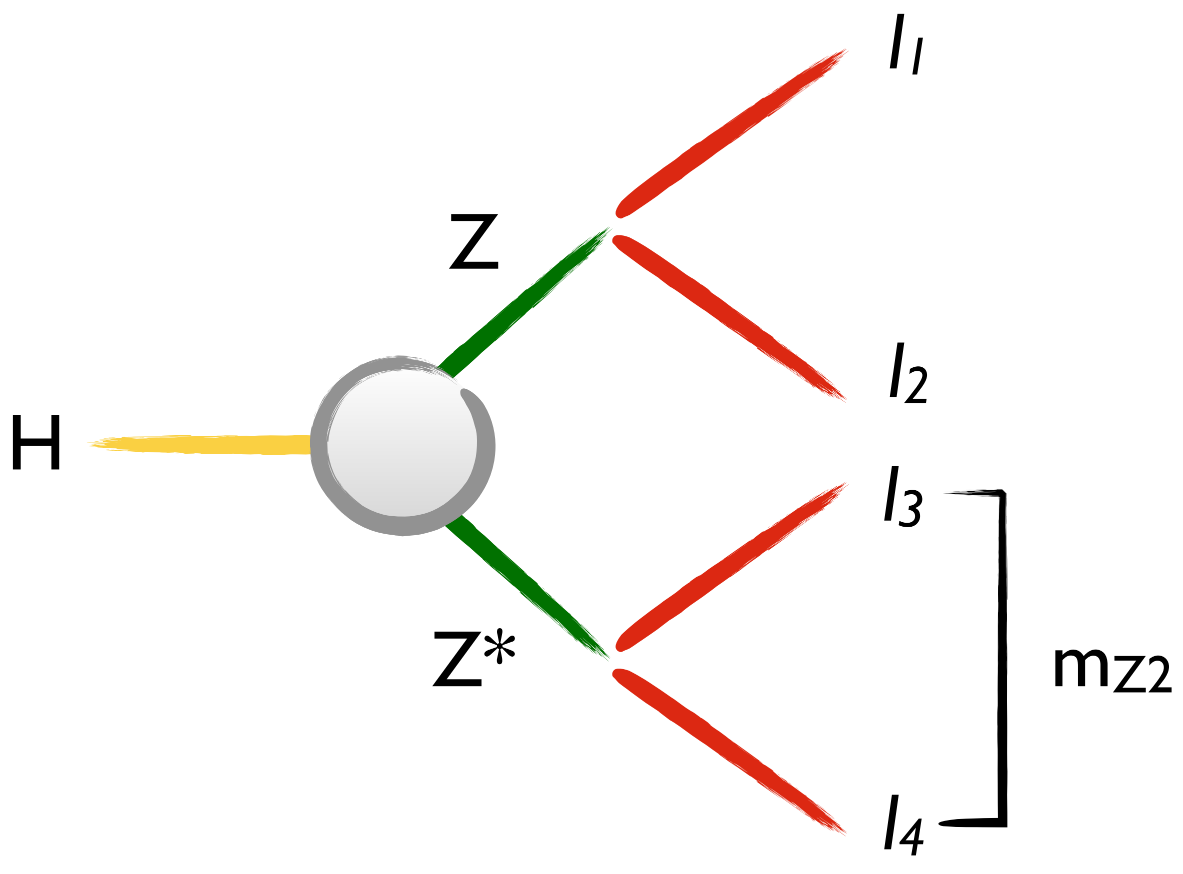
Dawson, Giardino

All Wilson coefficients that affect the relevant signal process are considered, background are not reparameterised

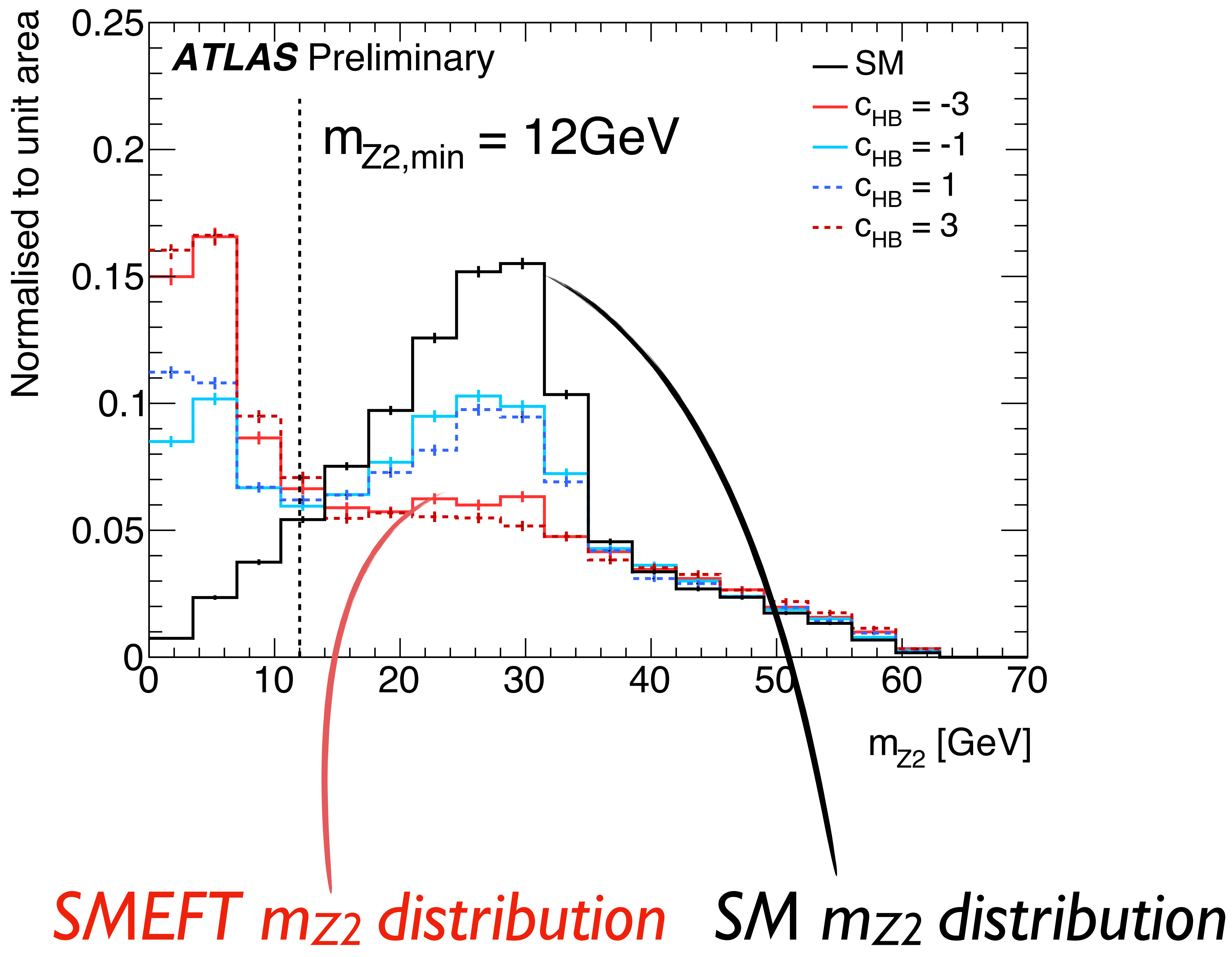
Impact of Experimental Acceptance

SMEFT parameterisation can be affected by analysis selections involved in Higgs boson reconstruction

$$O_{HB} = c_{HB}\, H^{\dagger}\sigma^{i}H\, W^{i}_{\mu\nu}B^{\mu\nu}$$



invariant mass of sub-leading lepton pair



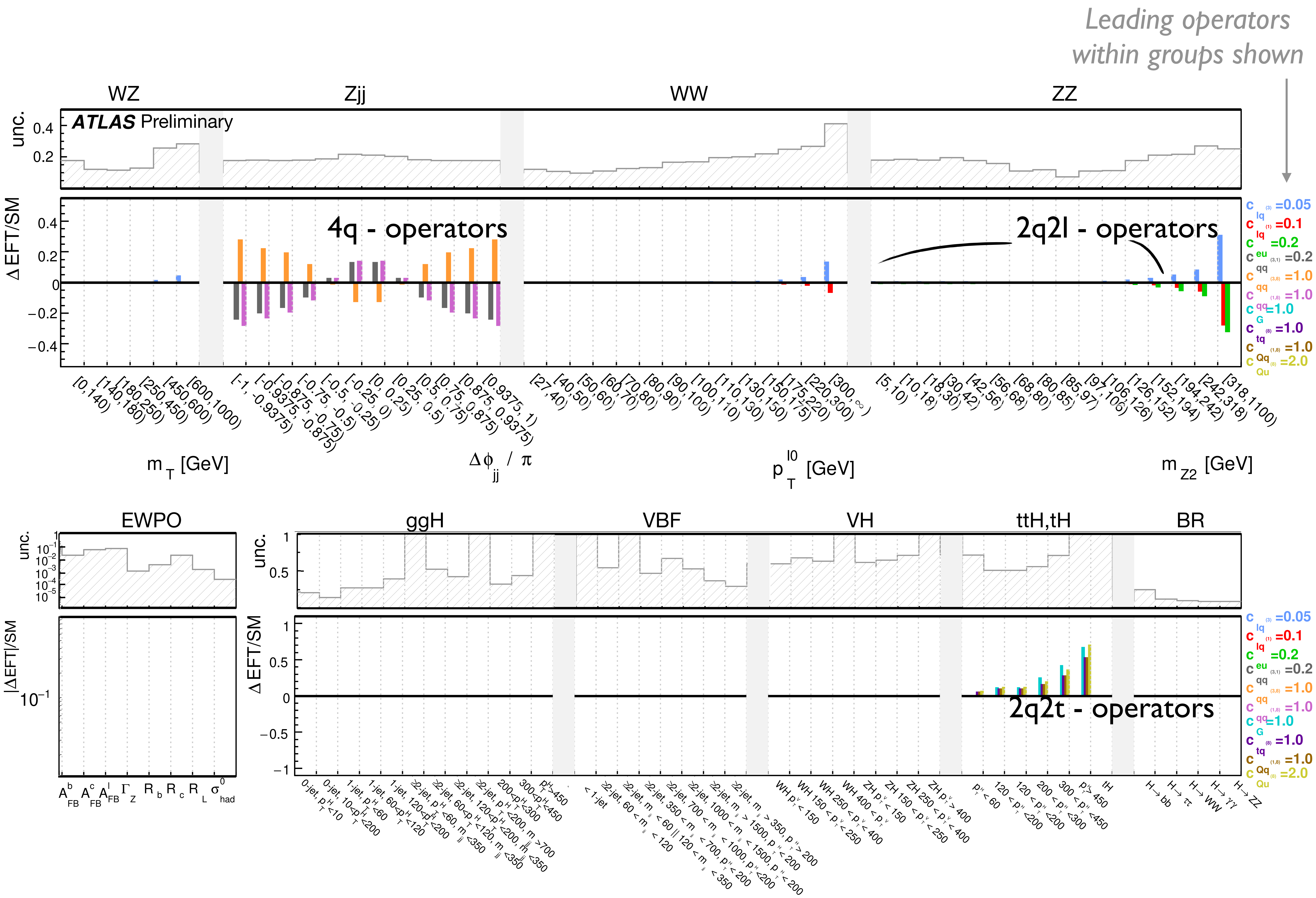
For instance, in $H \rightarrow 4l$, ***c_{HW}, c_{HWB}, c_{HB}*** introduce photon-mediated diagrams in SMEFT → sensitive to ***m_{Z2} selection***

Minimal impact expected on global fit as operators better constrained in $H \rightarrow \gamma\gamma$ decay

Impact of analysis selections in $H \rightarrow 4l$ and $H \rightarrow l\nu l\nu$ accounted in SMEFT parameterisation

Operators affecting measurements : 4 fermion operators

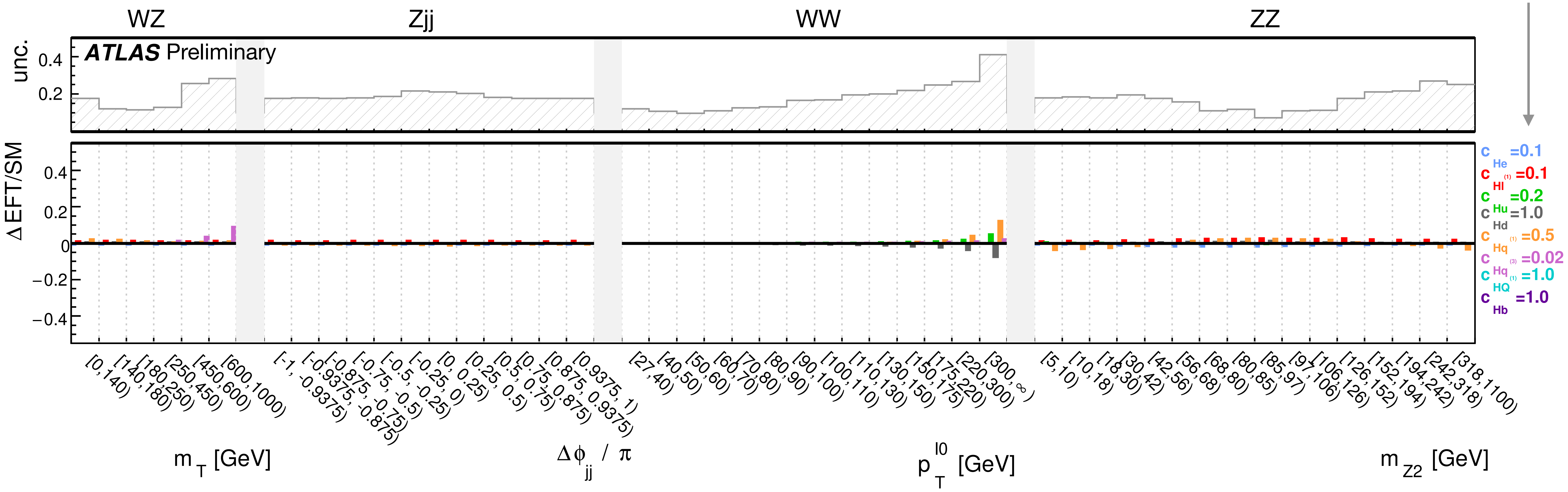
Group	Coefficient	Operator	LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
2q2l	$c_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$			✓
	$c_{lq}^{(3)}$	$(\bar{l}\gamma_\mu \tau^I l)(\bar{q}\gamma^\mu \tau^I q)$			✓
	c_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$			✓
WW, ZZ	c_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$			✓
	c_{lu}	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$			✓
	c_{ld}	$(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$			✓
	c_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$			✓
4q	$c_{qq}^{(1,1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$			✓
	$c_{qq}^{(1,8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$			✓
	$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$			✓
	$c_{qq}^{(3,8)}$	$(\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$			✓
	$c_{uu}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$			✓
	$c_{uu}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$			✓
	$c_{dd}^{(1)}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$			✓
Zjj	$c_{dd}^{(8)}$	$(\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$			✓
	$c_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$			✓
	$c_{ud}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$			✓
	$c_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$			✓
	$c_{qu}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$			✓
	$c_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$			✓
	$c_{qd}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$			✓
2q2t	$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$		✓	
	$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$		✓	
	$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$		✓	
	$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$		✓	
	$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$		✓	
	$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$		✓	
	$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$		✓	
	$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$		✓	
	$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$		✓	
	$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$		✓	
	$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$		✓	

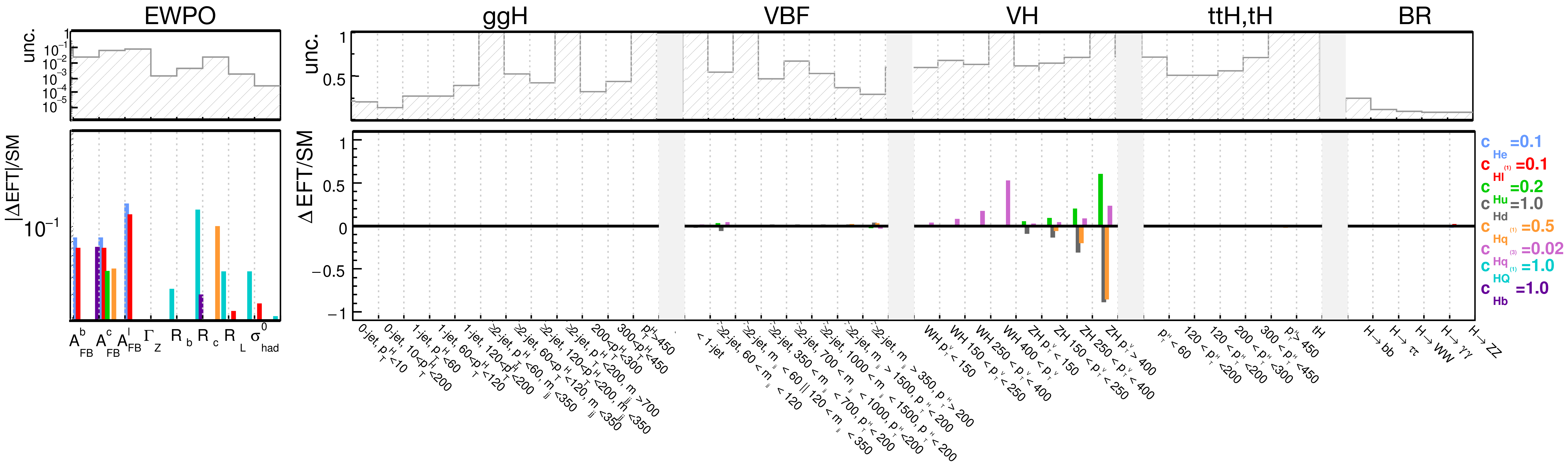


Operators entering global fit : ψ^2H^2D

			LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
	$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	
	c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$		✓	✓
	c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$		✓	✓
	c_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$		✓	✓
	c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$		✓	
	c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		✓	
	c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$		✓	
	c_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	✓	✓	✓
	c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		✓	
	c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\tilde{H})$		✓	
	c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$		✓	
	c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$		✓	
ψ^2H^2D	$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓
ψ^2H^2D	$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓
ψ^2H^2D	c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	✓	✓	✓
ψ^2H^2D	$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓
ψ^2H^2D	$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓
ψ^2H^2D	c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓
ψ^2H^2D	c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓
ψ^2H^2D	$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	✓	✓	
ψ^2H^2D	$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{Q}\tau^I\gamma^\mu Q)$	✓	✓	
ψ^2H^2D	c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	✓		
ψ^2H^2D	c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	✓	✓	
	c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}\, G_{\mu\nu}^A$		✓	
	c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\tilde{H}\, W_{\mu\nu}^I$		✓	
	c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\tilde{H}\, B_{\mu\nu}$		✓	
	c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓		✓

Leading operators within groups shown





Identifying sensitive directions within parameter space

Fitted parameters defined based on sensitivity of measurements using Fisher information to identify sensitive directions in SMEFT parameter space (*directions with expected unc. < 5 considered*)

Definition of sensitive parameters (28/62)

HVV,Vff group (14/18)

	$c_{Hl^{(1)}}$	c_{He}	c_{HB}	c_{HWB}	c_{HW}	c_{HDD}	$c_{Hq^{(3)}}$	$c_{Hl^{(3)}}$	$c_{ll'}$	c_{Hd}	$c_{Hq^{(1)}}$	c_{Hu}	$c_{HQ^{(1)}}$	c_{Hbq}	$c_{HQ^{(3)}}$	c_{Ht}	c_{tB}	c_{tW}
$c^{[1]}_{HVV,Vff}$	0.8	−0.45		0.02		0.01	−0.23	0.3	0.01	0.02	−0.02	−0.04	−0.06	0.01	−0.06			
$c^{[2]}_{HVV,Vff}$		−0.01	0.84	−0.47	0.27		−0.01	0.01	−0.01								0.04	0.02
$c^{[3]}_{HVV,Vff}$	0.29	−0.2	0.09	0.15	0.03		0.61	−0.55	0.35	−0.05	0.05	0.11	0.12	−0.02	0.12			
$c^{[4]}_{HVV,Vff}$	0.23	0.51	0.24	0.47	0.08	0.59	0.11	0.21	−0.05	−0.01		0.01	0.03	0.02	0.03		0.01	0.01
$c^{[5]}_{HVV,Vff}$	−0.02	−0.02	−0.06	−0.09	0.01	−0.03	0.56	0.24	−0.17	−0.03	0.03	0.05	−0.54	0.09	−0.54			
$c^{[6]}_{HVV,Vff}$	−0.32	−0.24	0.17	0.32	0.04	0.01	−0.13	0.3	0.75		0.01		−0.14	0.04	−0.14		0.01	
$c^{[7]}_{HVV,Vff}$	−0.11	−0.13	−0.08	−0.08	0.09	−0.1	0.48	0.59	−0.04	0.09	−0.16	−0.15	0.39	−0.06	0.39			
$c^{[8]}_{HVV,Vff}$	−0.01	−0.01			0.01	−0.03	0.03	0.07	−0.03	−0.02	0.94	−0.31	0.05		0.05	0.01		
$c^{[9]}_{HVV,Vff}$	0.06	0.12	−0.06	−0.08	0.06	−0.14	−0.03	0.21	0.05	−0.18	0.26	0.88	0.1	0.12	0.1	−0.03	−0.01	
$c^{[10]}_{HVV,Vff}$	−0.2	−0.4	0.03	0.43	0.65	−0.01	−0.06	−0.1	−0.41	−0.05	0.02	0.1	−0.01	−0.05	−0.01	−0.02		
$c^{[11]}_{HVV,Vff}$	0.17	0.34	−0.38	−0.29	0.7	−0.01	−0.05	−0.02	0.33	0.06	−0.03	−0.15	−0.05	0.03	−0.05		−0.02	−0.01
$c^{[12]}_{HVV,Vff}$	−0.01	−0.03	0.03	0.06	0.01	−0.05		−0.05	−0.05	0.34	−0.02	−0.05	0.06	0.93	0.06	0.05	0.01	
$c^{[13]}_{HVV,Vff}$	0.11	0.23	0.14	0.24	0.01	−0.47			−0.01	0.72	0.04	0.11	−0.05	−0.3	−0.05	0.1		
$c^{[14]}_{HVV,Vff}$	−0.15	−0.29	−0.16	−0.28	−0.01	0.63		−0.05	0.02	0.55	0.11	0.23		−0.14		−0.02	0.08	0.04

Warsaw basis (6/6)

	c_W	c_{bH}	c_{eH}	c_{HG}	c_{tG}	c_{tH}
c_W	1					
c_{bH}		1				
c_{eH}			1			
c_{HG}				1		
c_{tG}					1	
c_{tH}						1

Higgs normalisation (1/3)

	$c_{H\Box}$	c_{uH}	c_{dH}
$c_{uH,dH,H\Box}$	1	0.06	

2q2l group (4/7)

	$c_{lq^{(3)}}$	$c_{lq^{(1)}}$	c_{eu}	c_{lu}	c_{qe}	c_{ed}	c_{ld}
$c^{[1]}_{2q2l}$	0.89	−0.37	−0.21	−0.11	−0.13	0.04	0.03
$c^{[2]}_{2q2l}$	0.44	0.56	0.61	0.01	0.34	−0.1	0.01
$c^{[3]}_{2q2l}$	0.15	0.68	−0.51	0.34	−0.36	0.12	−0.06
$c^{[4]}_{2q2l}$	0.04	−0.28	0.27	0.79	−0.16	−0.22	−0.39

c_G, 2q2t group (1/12)

	c_G	$c_{tq^{(8)}}$	$c_{Qq^{(1,8)}}$	$c_{Qu^{(8)}}$	$c_{Qd^{(8)}}$	$c_{Qq^{(3,8)}}$	$c_{Qq^{(3,1)}}$	$c_{tu^{(1)}}$	$c_{Qq^{(1,1)}}$	$c_{Qu^{(1)}}$	$c_{tq^{(1)}}$	$c_{Qd^{(1)}}$
$c^{[1]}_{top}$	0.61	0.44	0.44	0.28	0.16	0.12	0.12	0.04	0.03	0.02	0.02	−0.01

4q group (2/14)

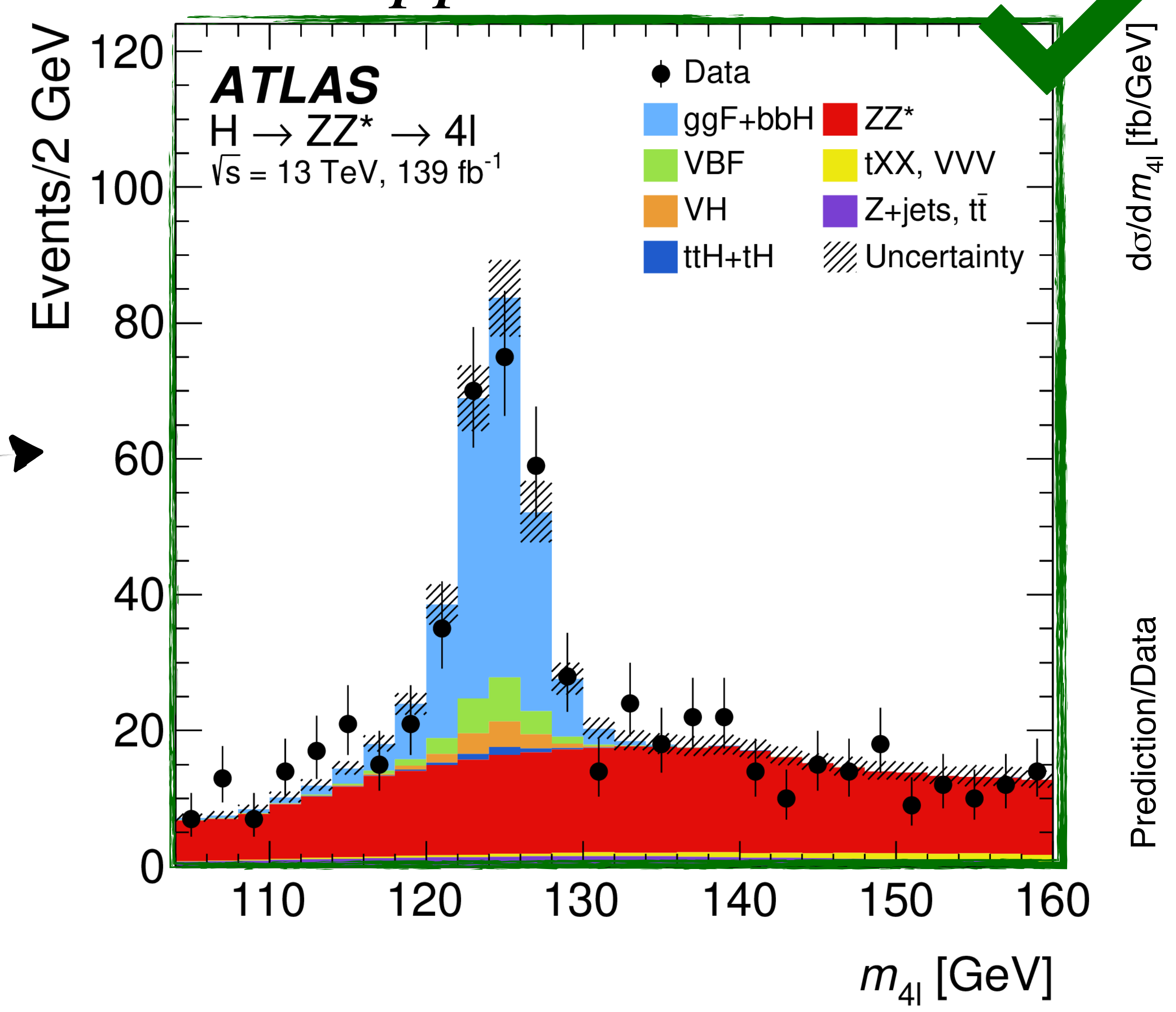
	$c_{qq^{(3,1)}}$	$c_{qq^{(3,8)}}$	$c_{qq^{(1,8)}}$	$c_{qq^{(1,1)}}$	$c_{qu^{(8)}}$	$c_{qd^{(8)}}$	$c_{uu^{(1)}}$	$c_{qu^{(1)}}$	$c_{ud^{(8)}}$	$c_{uu^{(8)}}$	$c_{qd^{(1)}}$	$c_{ud^{(1)}}$	$c_{dd^{(1)}}$	$c_{dd^{(8)}}$
$c^{[1]}_{4q}$	0.95	−0.2	0.22	0.11										
$c^{[2]}_{4q}$	0.27	0.89	−0.23	−0.2	−0.2	−0.1	−0.08	−0.03	−0.02	−0.02	0.01	0.01		

Statistical combination

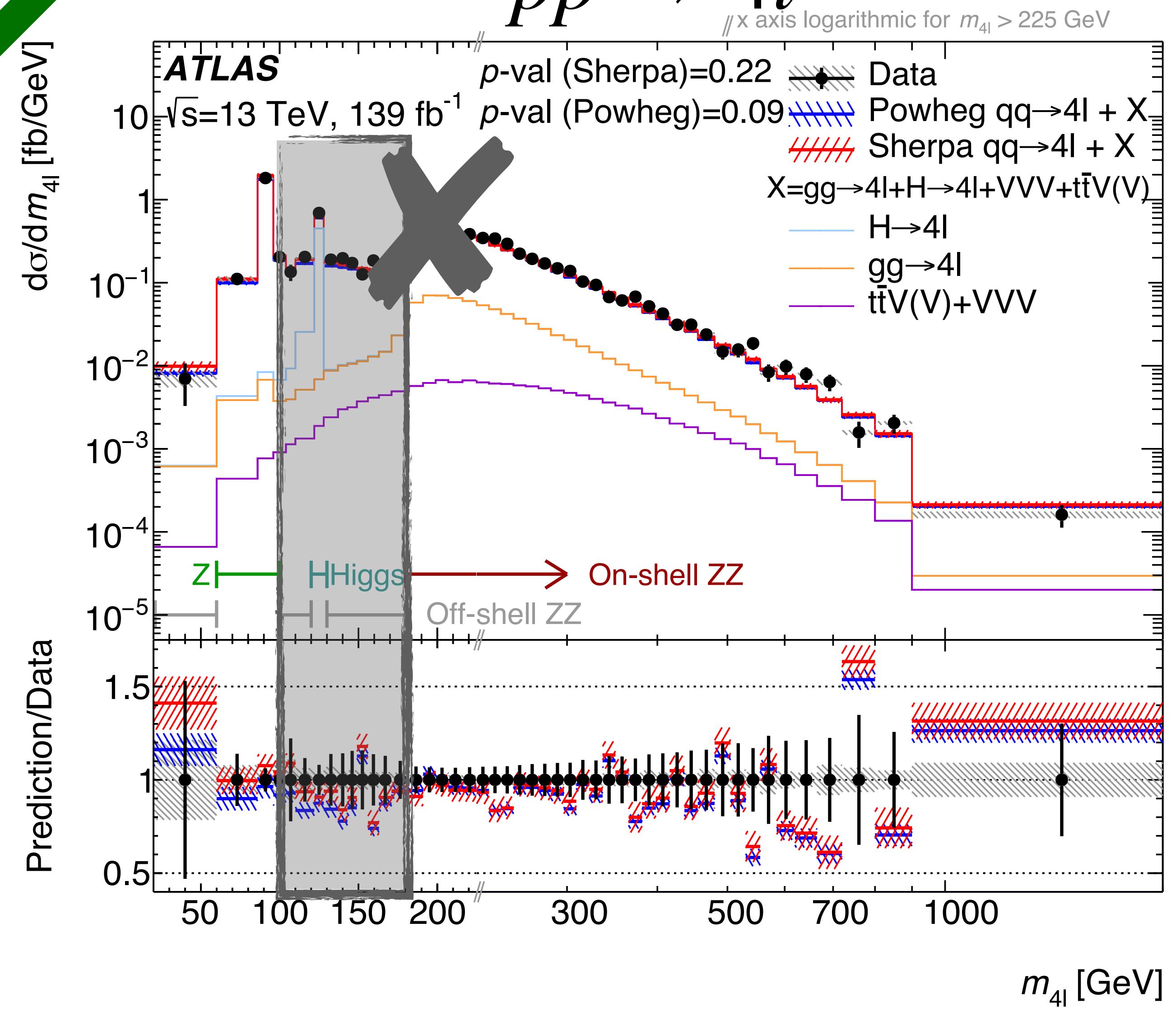
Overlapping categories between ATLAS measurements,

- off-shell region from $pp \to 4l$ analysis **excluded** to avoid overlap with control region used in $H \to 4l$
- WW-0jet control region in $H \to WW^* \to l\nu l\nu$ is excluded due to overlap with $pp \to WW \to l\nu l\nu$ and WW signal normalisation is used instead

$pp \to H \to 4l$



$pp \to 4l$



Common sources of systematic uncertainties treated as correlated between ATLAS measurements

For EWPO, experimental & theoretical uncertainties captured in a single covariance matrix

Combined global likelihood obtained as a product of individual likelihood function

$$\prod_{b}^{n_{\text{bins}}} \text{Poisson}\left(N_b \middle| N_b^{\text{pred}}(\boldsymbol{c}, \boldsymbol{\theta})\right)$$

Higgs analyses categories

$$\times \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}} \det(V)}} \exp\left(-\frac{1}{2} \Delta \boldsymbol{x}^{\top}(\boldsymbol{c}, \boldsymbol{\theta})\, V^{-1} \Delta \boldsymbol{x}(\boldsymbol{c}, \boldsymbol{\theta})\right)$$

Electroweak measurements

$$\times \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}} \det(V)}} \exp\left(-\frac{1}{2} \Delta \boldsymbol{x}^{\top}(\boldsymbol{c})\, V^{-1} \Delta \boldsymbol{x}(\boldsymbol{c})\right)$$

EWPO constraints

$$\times \prod_{i}^{n_{\text{theo syst}}} f_i\left(\theta_{\text{theo syst},i}\right) \times \prod_{i}^{n_{\text{exp syst}}} f_i\left(\theta_{\text{exp syst},i}\right)$$

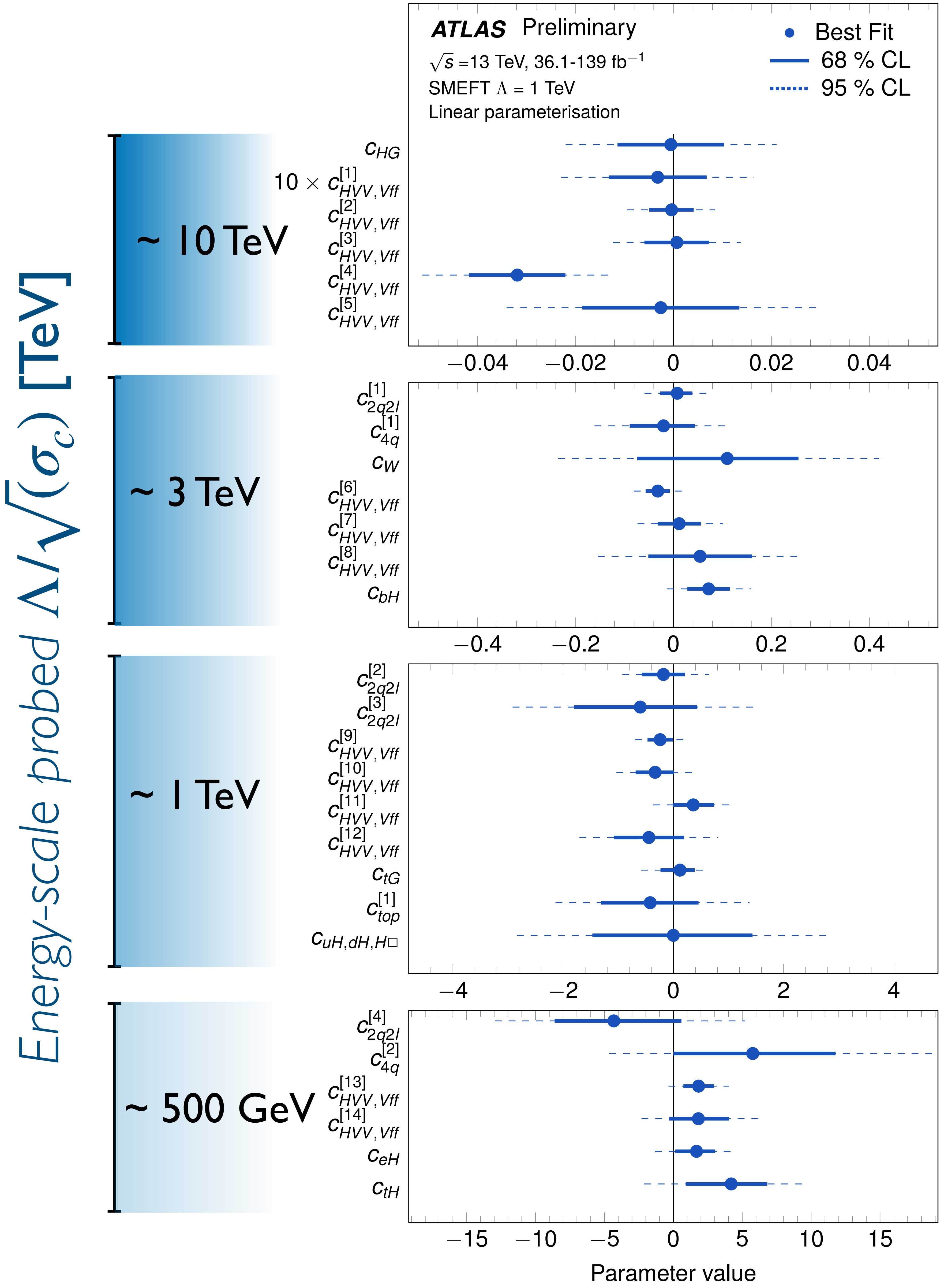
Constraint term of systematic effects

Global fit results

Simultaneous fit to 28 parameters based on **linear parameterisation** in general, good agreement with the Standard Model

Sensitivity to deviations across a large energy-scale ~500 GeV to ~ 10 TeV

Impact of quadratic terms checked in fit to Higgs + Electroweak measurements and quite substantial for some operators (*backup*)



Global fit results

Electroweak precision observables

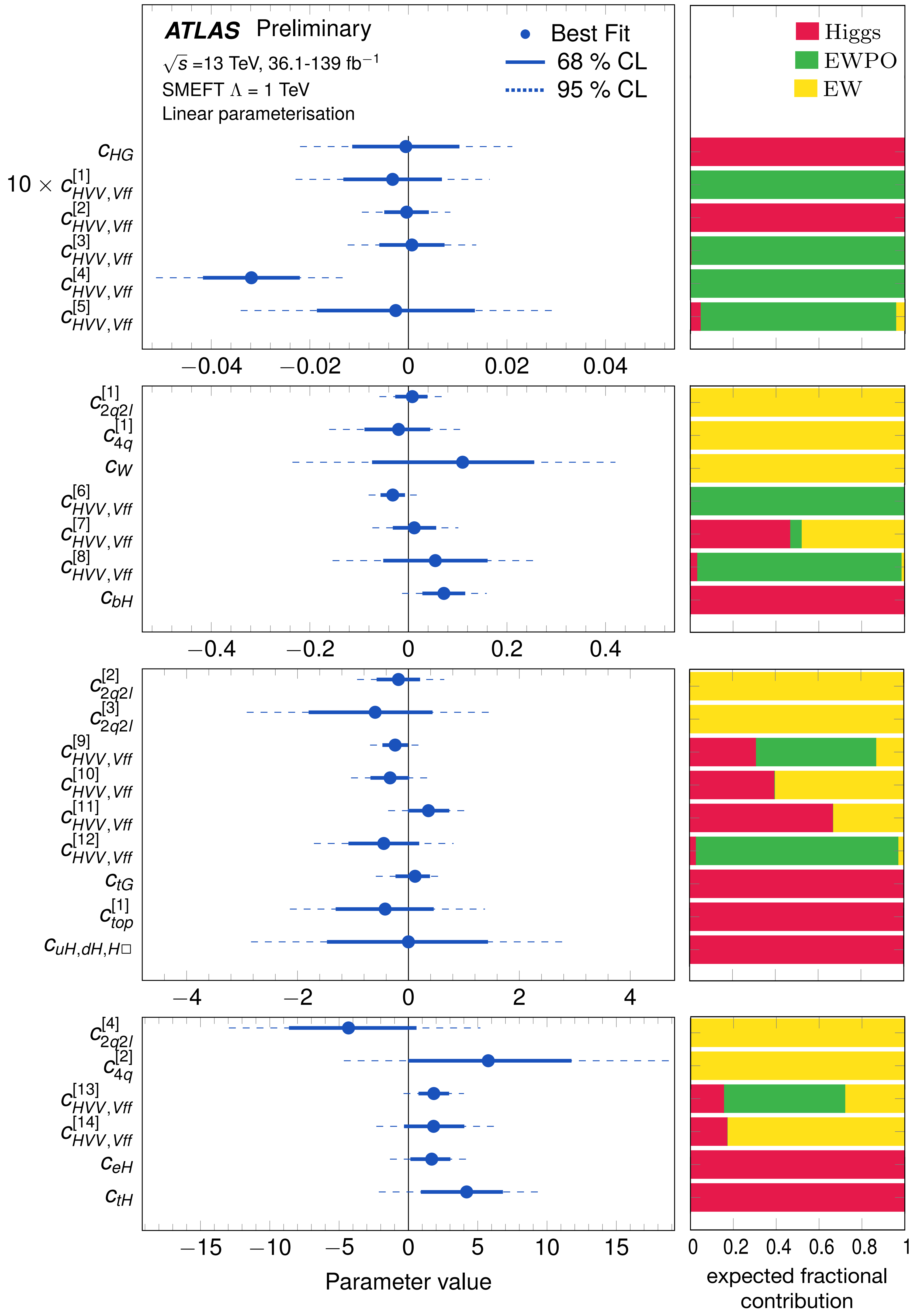
- sensitivity to 7 parameters with 4 out 6 most precise parameters
- Large pull in $A_{FB}^{0,b}$ reflected in parameter $c_{HVV,Vff}^{[4]}$

Higgs boson measurements

- 8 parameters only constrained by the Higgs sector
- loop-induced SM process gg→H and H→$\gamma\gamma$ provide tightest constraints of O(0.01)
- Remaining operator sensitivity range from O(0.1 - 5)

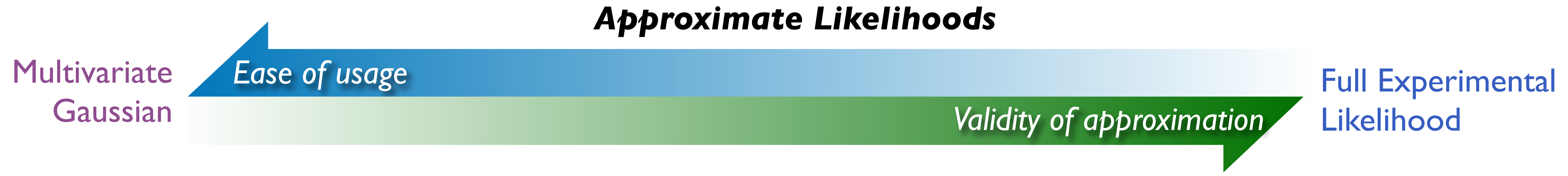
Electroweak measurements

- constraint 8 parameters
- direct constraint to weak boson self-coupling c_W
- sensitivity to four-fermion operators (c_{2q2l}, c_{4q})



Interface between theory & experiment

Experimental likelihood function captures all relevant statistical information of measurement (*calibration, theory uncertainties, etc*) & corresponding SMEFT parameterisation



<u>Simplified likelihood</u>

Multivariate Gaussian approximation of the signal-strength measurements → **best-fit + covariance matrix**

signal-strength parameterisation captured by polynomial functions: $\mu_i(c) = 1 + \sum_j A_i \, . \, c_j + + \sum_{j,k \geq j} B_{jk} \, . \, c_j c_k$

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

$$L(c) = L(\mu(c))$$

$$\prod_b^{n_\text{bins}} \text{Poisson}\left(N_b \middle| N_b^\text{pred}\left(\boldsymbol{c}, \boldsymbol{\theta}\right)\right)$$

Higgs analyses categories

$$\times \frac{1}{\sqrt{(2\pi)^{n_\text{bins}} \det\left(V\right)}} \exp\left(-\frac{1}{2} \Delta\boldsymbol{x}^\intercal \left(\boldsymbol{c}, \boldsymbol{\theta}\right) V^{-1} \Delta\boldsymbol{x} \left(\boldsymbol{c}, \boldsymbol{\theta}\right)\right)$$

Electroweak measurements

$$\times \frac{1}{\sqrt{(2\pi)^{n_\text{bins}} \det\left(V\right)}} \exp\left(-\frac{1}{2} \Delta\boldsymbol{x}^\intercal \left(\boldsymbol{c}\right) V^{-1} \Delta\boldsymbol{x} \left(\boldsymbol{c}\right)\right)$$

EWPO constraints

$$\times \prod_i^{n_\text{theo syst}} f_i\left(\theta_{\text{theo syst},i}\right) \times \prod_i^{n_\text{exp syst}} f_i\left(\theta_{\text{exp syst},i}\right)$$

Constraint term of systematic effects

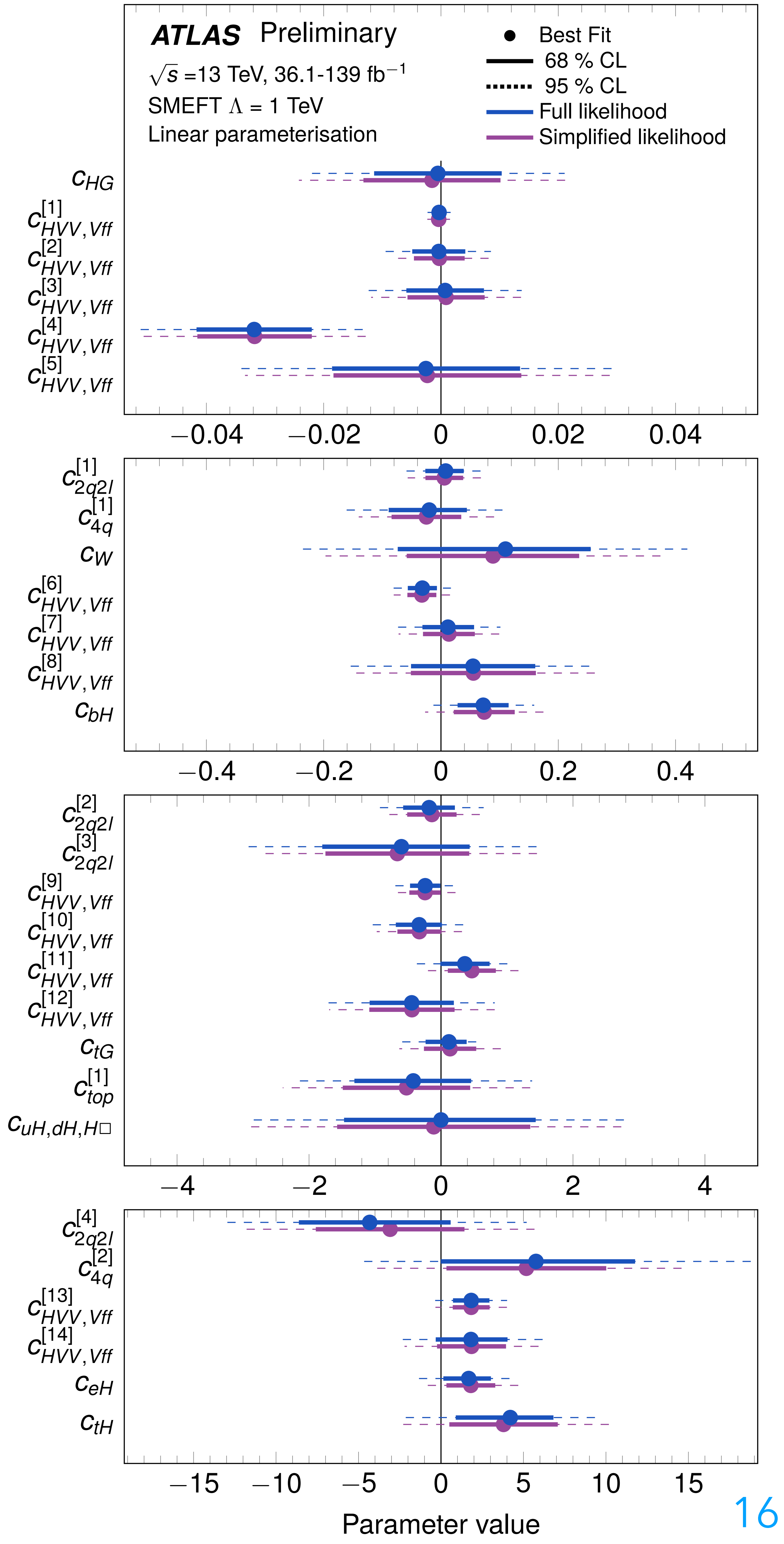
Interface between theory & experiment

Simplified likelihood provides a good approximation of overall constraint,
but no additional information on systematic uncertainties!

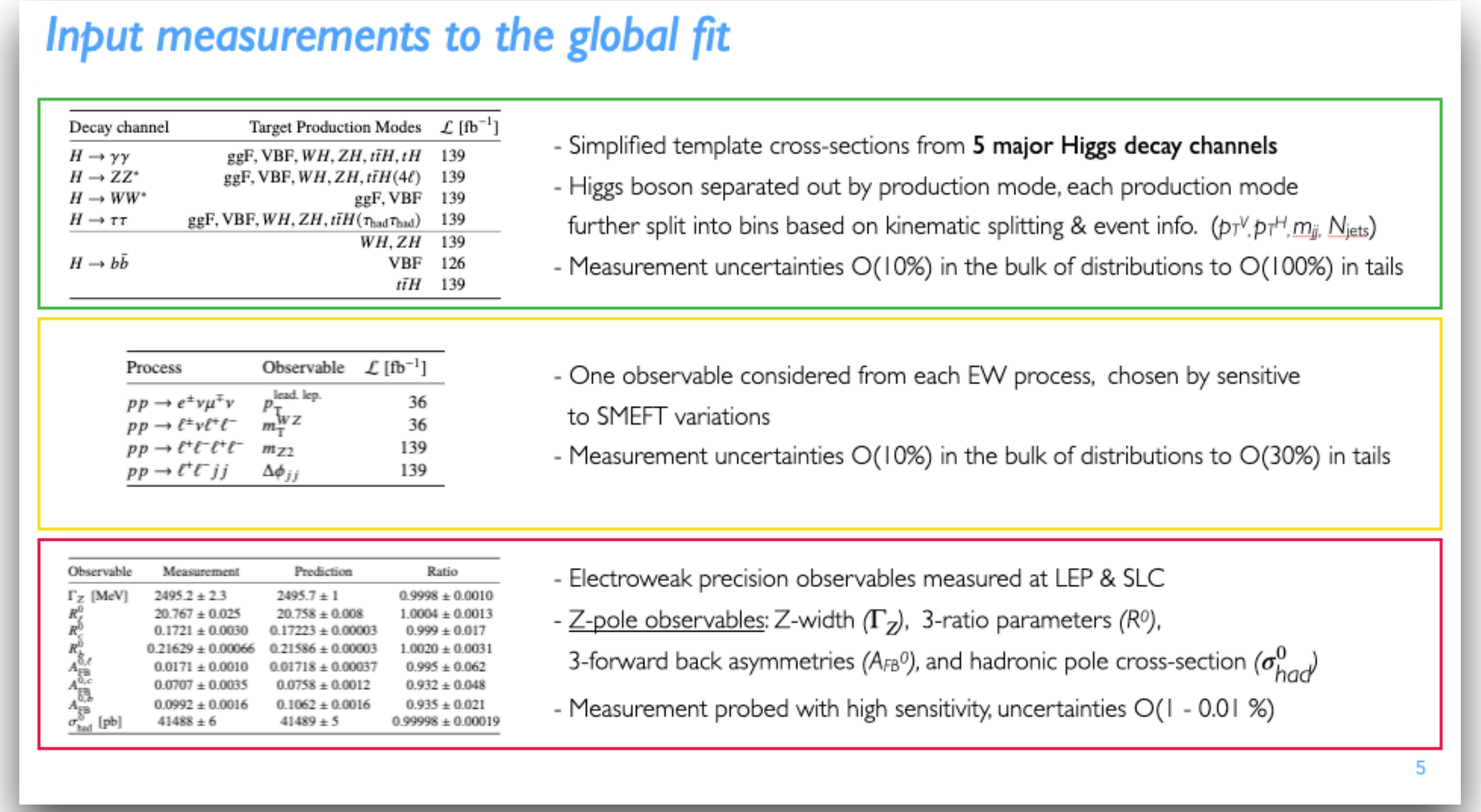
Available on public page of ATLAS publication note ATL-PHYS-PUB-2022-037
i. **best-fit + covariance matrix** of 128 signal-strength measurements
ii. Linear parameterisation for relevant parameters
Iii. definition of fit-basis directions

Expected to provide all above ingredients on **HEPdata** for upcoming ATLAS paper on global EFT fit
- Quadratic terms → **large complexity from cross-terms** (B_{ij}) not an issue for digital format

multivariate Gaussian provides a reliable approximation !



Towards the next global fit



Input measurements to the global fit

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

- Simplified template cross-sections from **5 major Higgs decay channels**
- Higgs boson separated out by production mode, each production mode further split into bins based on kinematic splitting & event info. ($p_T^V, p_T^H, m_{jj}, N_{jets}$)
- Measurement uncertainties O(10%) in the bulk of distributions to O(100%) in tails

Process	Observable	$\mathcal{L}$ [fb^{-1}]
$pp \to e^\pm \nu \mu^\mp \nu$	$p_T^{\text{lead. lep.}}$	36
$pp \to \ell^\pm \nu \ell^+ \ell^-$	m_T^{WZ}	36
$pp \to \ell^+ \ell^- \ell^+ \ell^-$	m_{Z2}	139
$pp \to \ell^+ \ell^- jj$	$\Delta\phi_{jj}$	139

- One observable considered from each EW process, chosen by sensitive to SMEFT variations
- Measurement uncertainties O(10%) in the bulk of distributions to O(30%) in tails

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
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A^{0,\ell}_{FB}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A^{0,b}_{FB}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

- Electroweak precision observables measured at LEP & SLC
- Z-pole observables: Z-width (Γ_Z), 3-ratio parameters (R^0), 3-forward back asymmetries (A_{FB}^0), and hadronic pole cross-section (σ^0_{had})
- Measurement probed with high sensitivity, uncertainties O(1 - 0.01 %)

5

ATLAS global fit to grow more with additional inputs :

i. **top sector :** challenging measurements due to composite phase space of top-processes, see Kirill's talk earlier for challenges in the top sector.

ii. **Electroweak sector :** currently only a couple of full Run-2 analyses, expect updated analyses and new analyses such as Drell-Yan, etc

iii. **Higgs sector :** Updated SMEFT interpretation of combined Higgs measurements (*remaining part of the talk*)

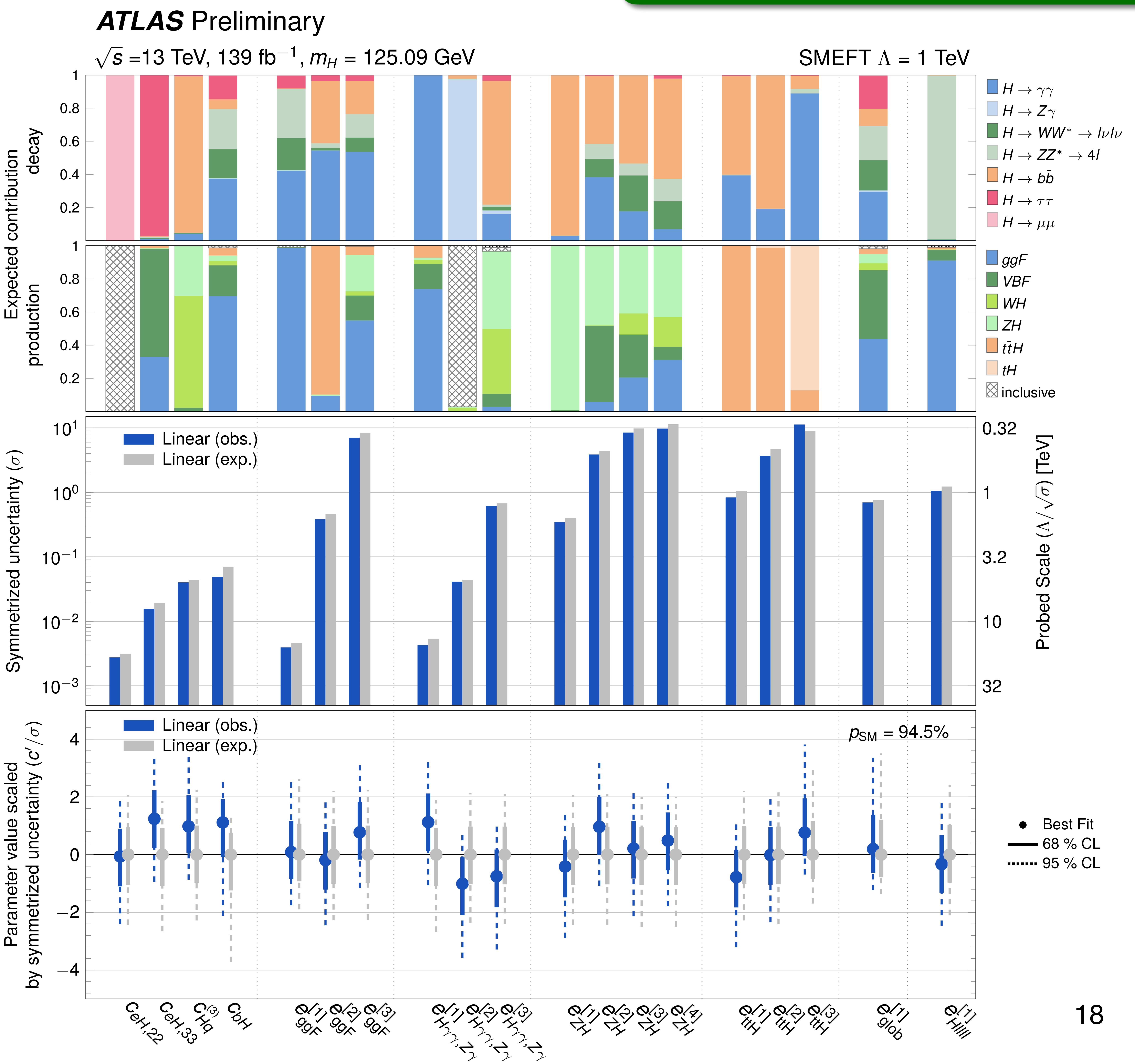
Currently only d=6 operators considered, important d=8 predictions for relevant process emerging

- For instance, **ggH variations** 11.1103/Phys. Rev. D 105, 076004 **Martin, Trott**

Simplified likelihood combination ATLAS+CMS effort ongoing within the LHCEFTWG, useful for harmonising and working towards ATLAS + CMS global EFT fits. (See Fabian's talk at the previous LHCEFTWG meeting)

Updated Higgs SMEFT interpretation

(NEW) ATLAS-CONF-2023-052



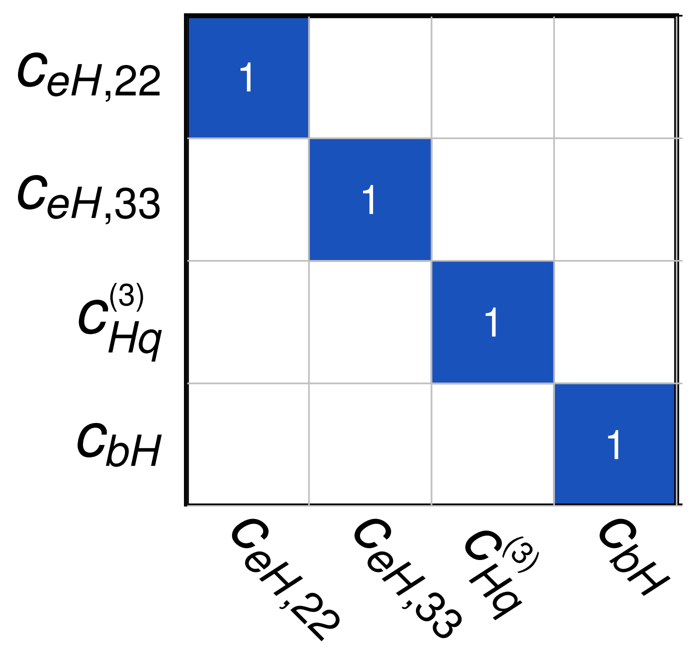
Detailed look into SMEFT constraints from Higgs sector including analyses rare decay modes ($H \to Z\gamma, H \to \mu\mu$)

Parameterisation based on ***top scheme***
→ dedicated treatment of leptons

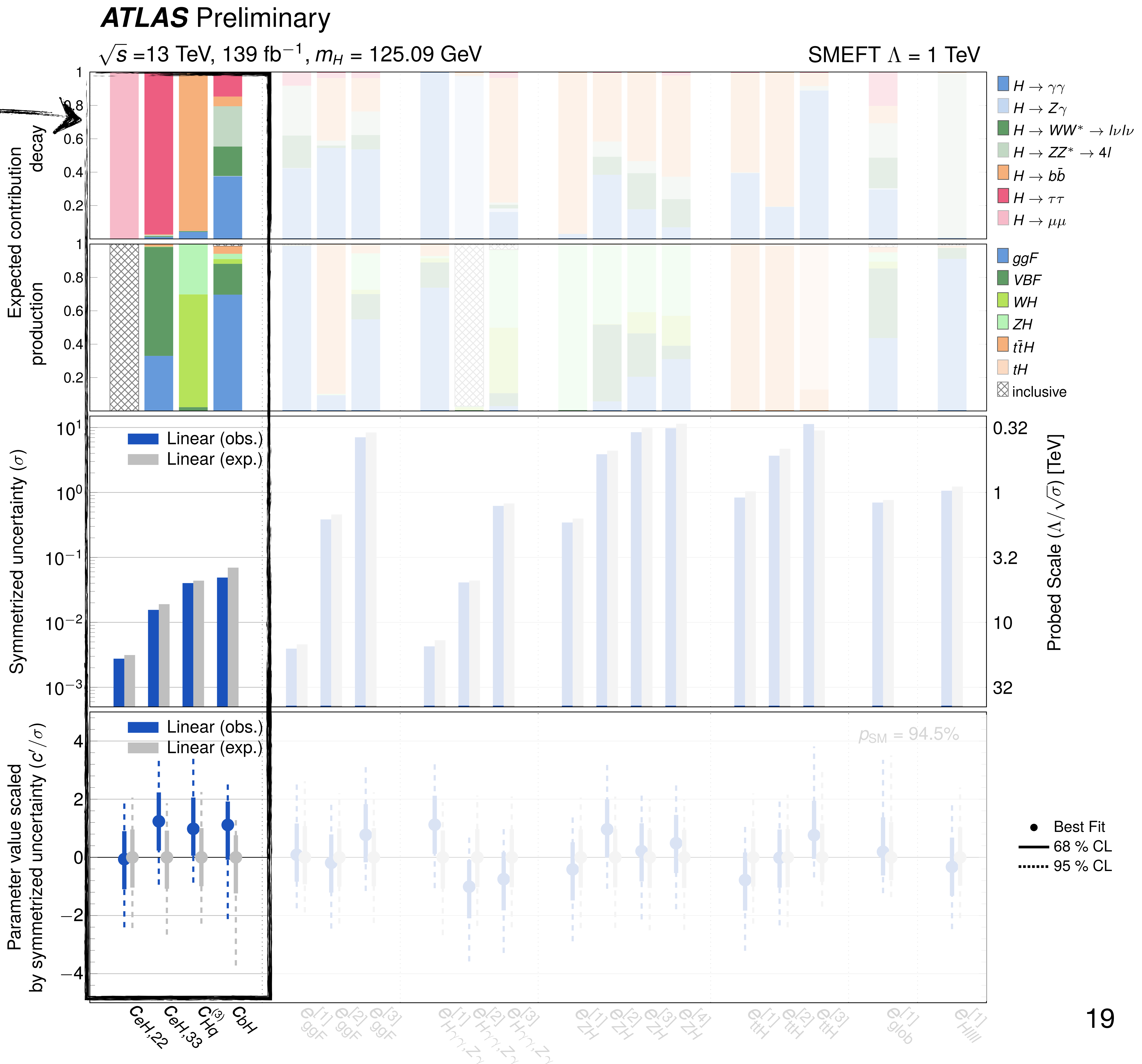
19 parameters in total based on a sensitivity study with expected unc. <10

Updated Higgs SMEFT interpretation

Warsaw basis

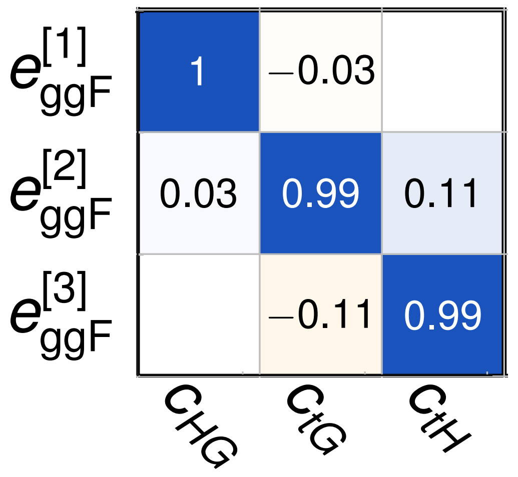


- (μ, τ, b) Yukawa modifiers constrained by branching ratio measurements
- $c^{(3)}_{Hq}$ constrained by p^T_V measured in VH production

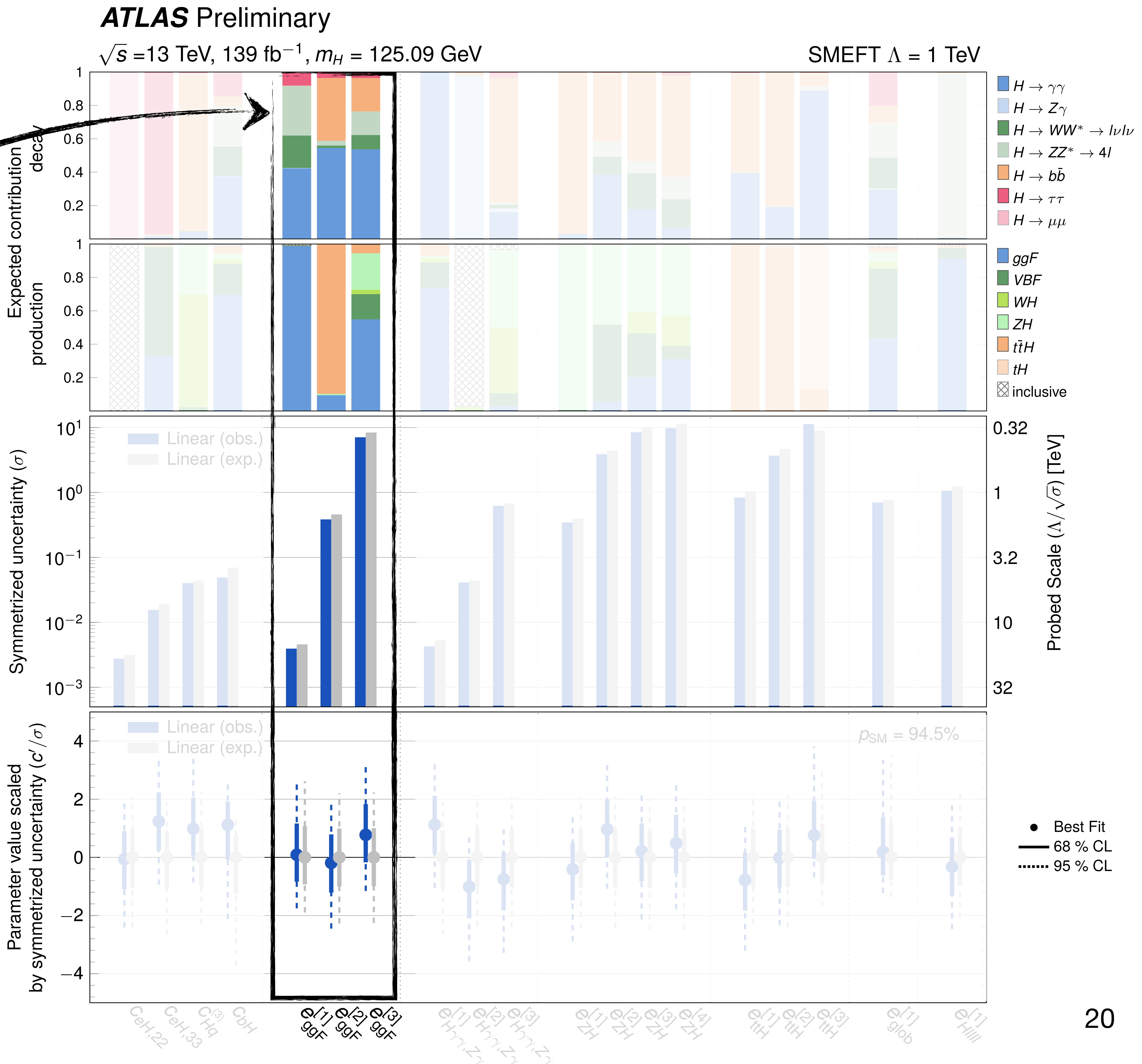


Updated Higgs SMEFT interpretation

ggF group



All three linear direction in group constrained, by ggF and ttH production

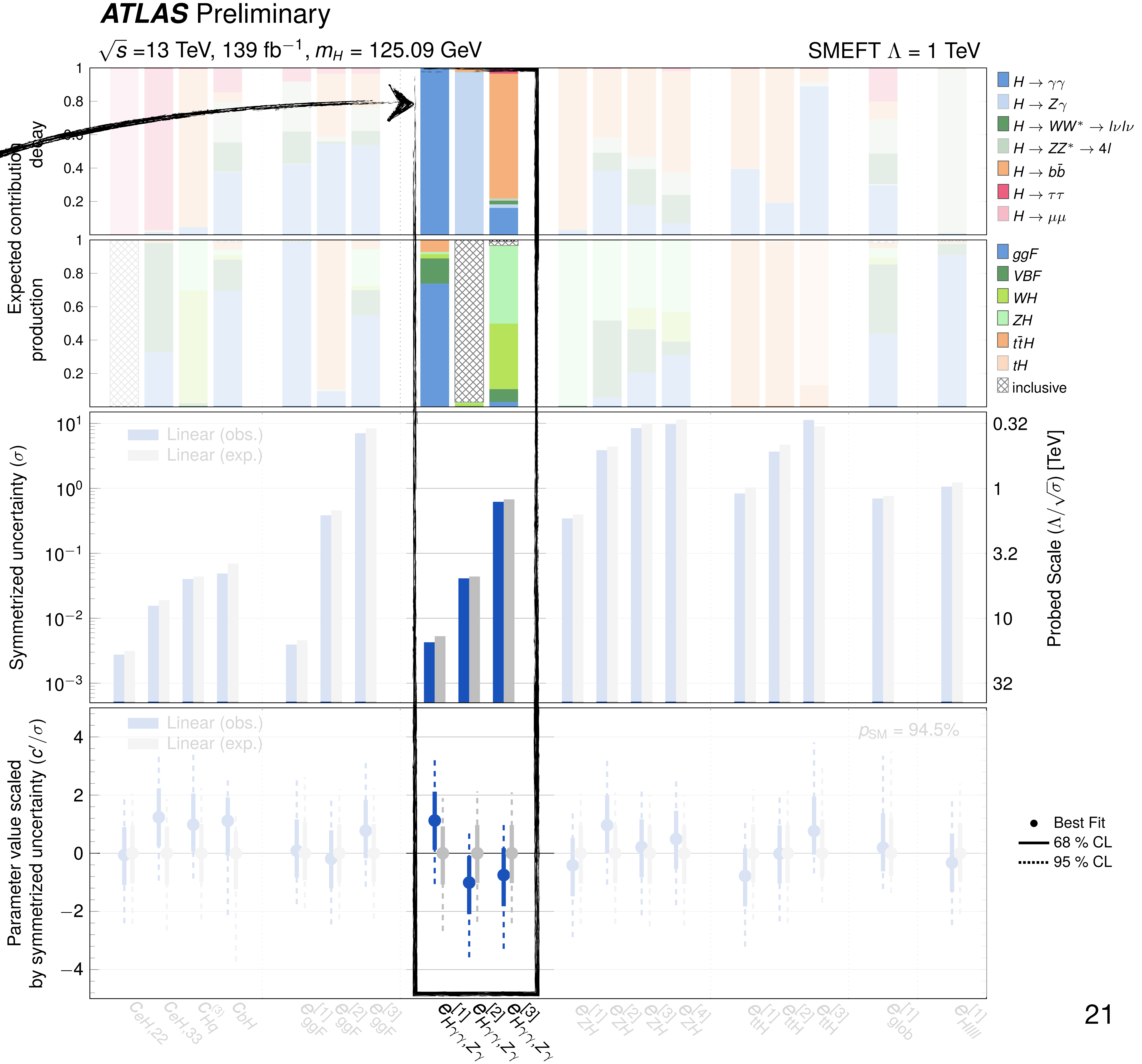


Updated Higgs SMEFT interpretation

$H\gamma\gamma,z\gamma$ group

	c_{HB}	c_{HW}	c_{HWB}	c_{tB}	c_{tW}
$e^{[1]}_{H\gamma\gamma,Z\gamma}$	0.85	0.25	−0.47	−0.02	−0.01
$e^{[2]}_{H\gamma\gamma,Z\gamma}$	−0.49	0.73	−0.49		−0.02
$e^{[3]}_{H\gamma\gamma,Z\gamma}$	0.22	0.64	0.74	0.01	0.02

3/5 parameters constrained by $BR(H \to \gamma\gamma)$ & $BR(H \to Z\gamma)$, least sensitive direction constrained by VH production

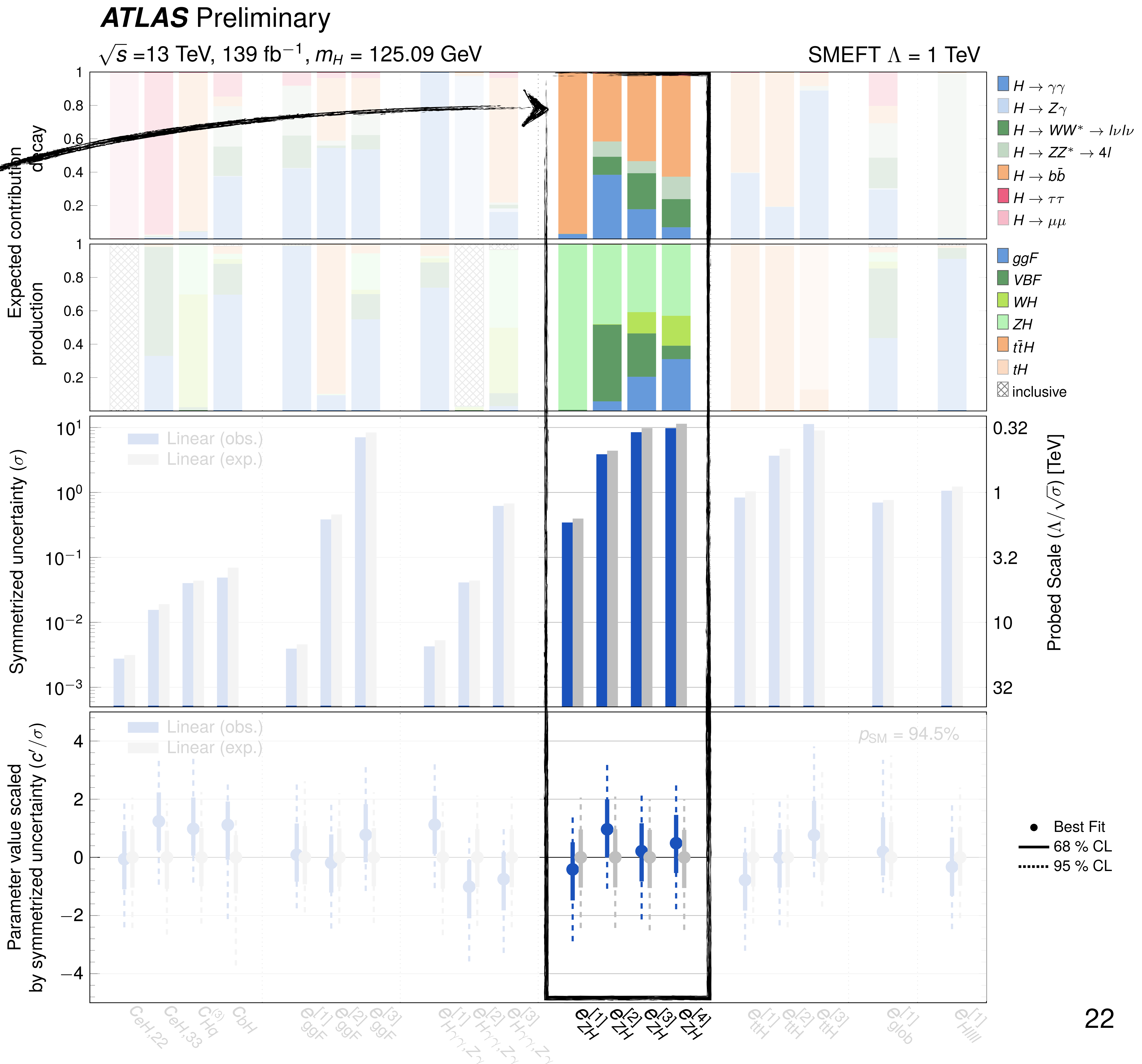


Updated Higgs SMEFT interpretation

ZH group

	c_{Hu}	$c_{Hq}^{(1)}$	c_{Hd}	$c_{Hl,33}^{(3)}$	c_{Ht}	$c_{He,33}$	$c_{Hl,33}^{(1)}$	c_{Hb}
$e_{ZH}^{[1]}$	0.9	−0.35	−0.27	0.02	−0.02	−0.01		
$e_{ZH}^{[2]}$	0.21	0.87	−0.39	0.19	−0.05	−0.08	−0.06	0.03
$e_{ZH}^{[3]}$	−0.32	−0.34	−0.58	0.66	−0.02	−0.08	−0.06	0.02
$e_{ZH}^{[4]}$	0.22	0.08	0.66	0.72	−0.02	−0.03	−0.02	

constrained primarily by p_T^Z distribution from ZH production, some trailing contribution entering through W, Z propagator corrections in Higgs production and decay

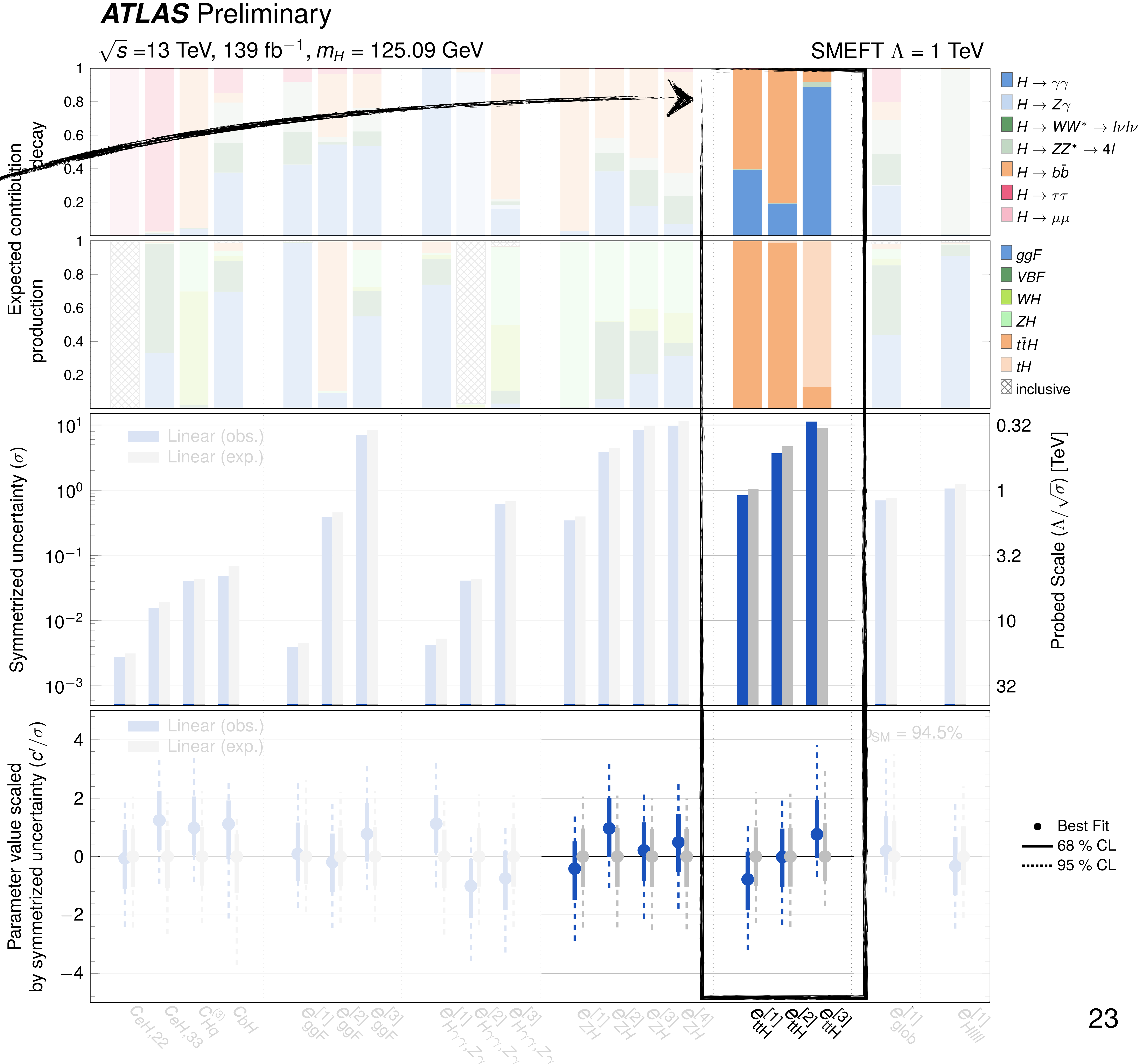


Updated Higgs SMEFT interpretation

ttH group

	c_G	$c_{Qq}^{(1,8)}$	$c_{Qq}^{(3,1)}$	$c_{tq}^{(8)}$	$c_{Qu}^{(8)}$	$c_{tu}^{(8)}$	$c_{td}^{(8)}$	$c_{Qd}^{(8)}$	$c_{Qq}^{(3,8)}$	$c_{Qq}^{(1,1)}$	$c_{tu}^{(1)}$	$c_{tq}^{(1)}$	$c_{Qu}^{(1)}$	$c_{Qd}^{(1)}$
$e_{ttH}^{[1]}$	0.57	0.46	0.17	0.45	0.27	0.27	0.16	0.16	0.14	0.06	0.05	0.03	0.02	−0.01
$e_{ttH}^{[2]}$	0.8	−0.34	−0.23	−0.29	−0.16	−0.15	−0.05	−0.06	−0.2	−0.11	−0.03	−0.02	−0.01	
$e_{ttH}^{[3]}$	0.08	−0.15	0.95	−0.13	−0.08	−0.08	−0.03	−0.03	−0.17	−0.04	−0.02	−0.01	−0.01	

Constraint by p_T^H distribution measured in ttH production,
last direction weakly constrained by tH production

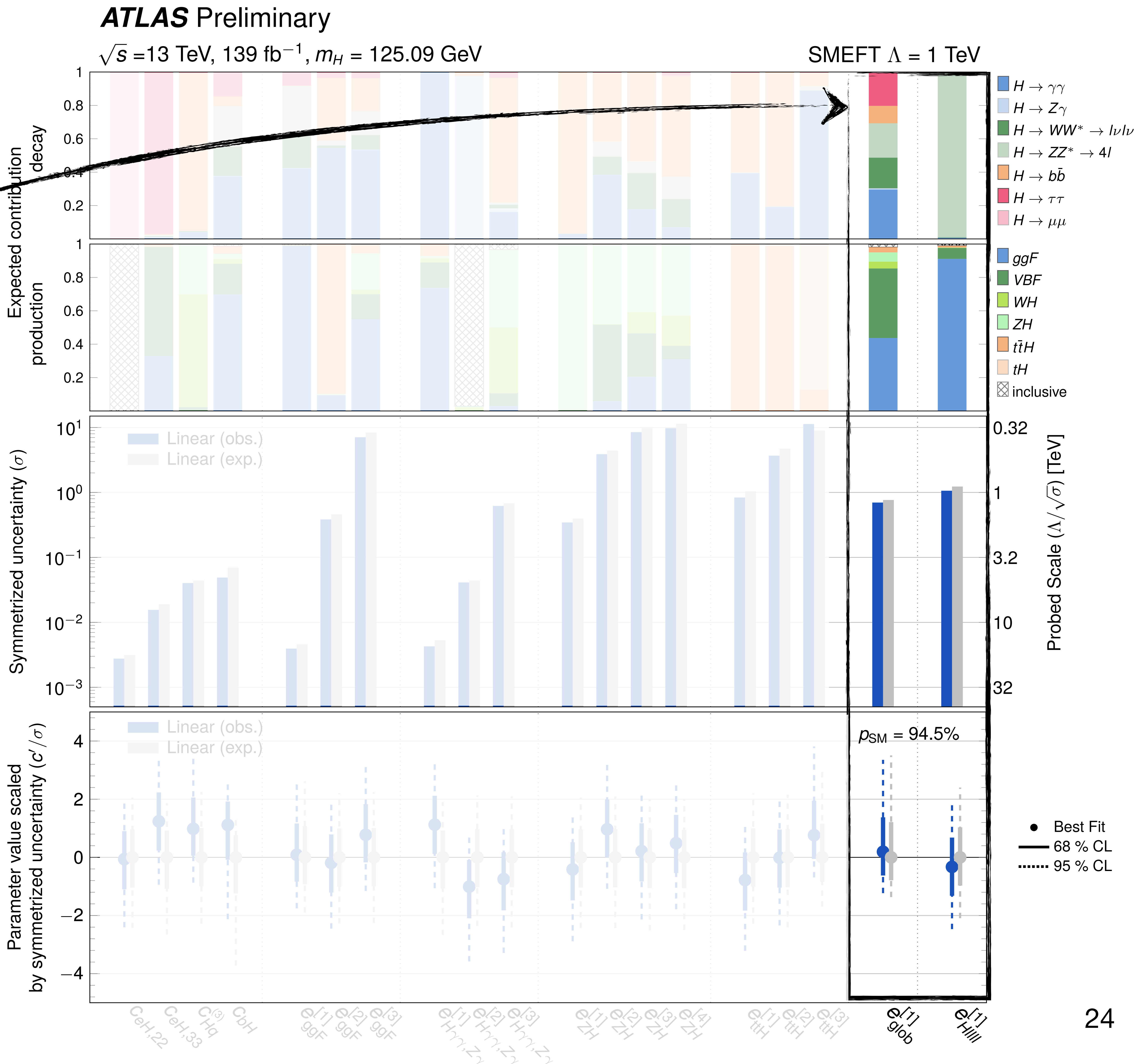


Updated Higgs SMEFT interpretation

global normalisation, $H \rightarrow 4l$

	$C_{H\Box}$	$C_{Hl,11}^{(3)}$	$C_{Hl,22}^{(3)}$	$C_{ll,1221}$	$C_{Hl,11}^{(1)}$	$C_{Hl,22}^{(1)}$	$C_{He,11}$	$C_{He,22}$	C_{HDD}	$C_{HQ}^{(3)}$	$C_{HQ}^{(1)}$
$e_{glob}^{[1]}$	0.64	−0.48	−0.48	0.36							
$e_{Hllll}^{[1]}$					0.54	0.54	−0.39	−0.39	0.27	−0.14	−0.13

One operator each constraining global Higgs normalisation e_{glob} and $H \rightarrow 4l$ branching ratio



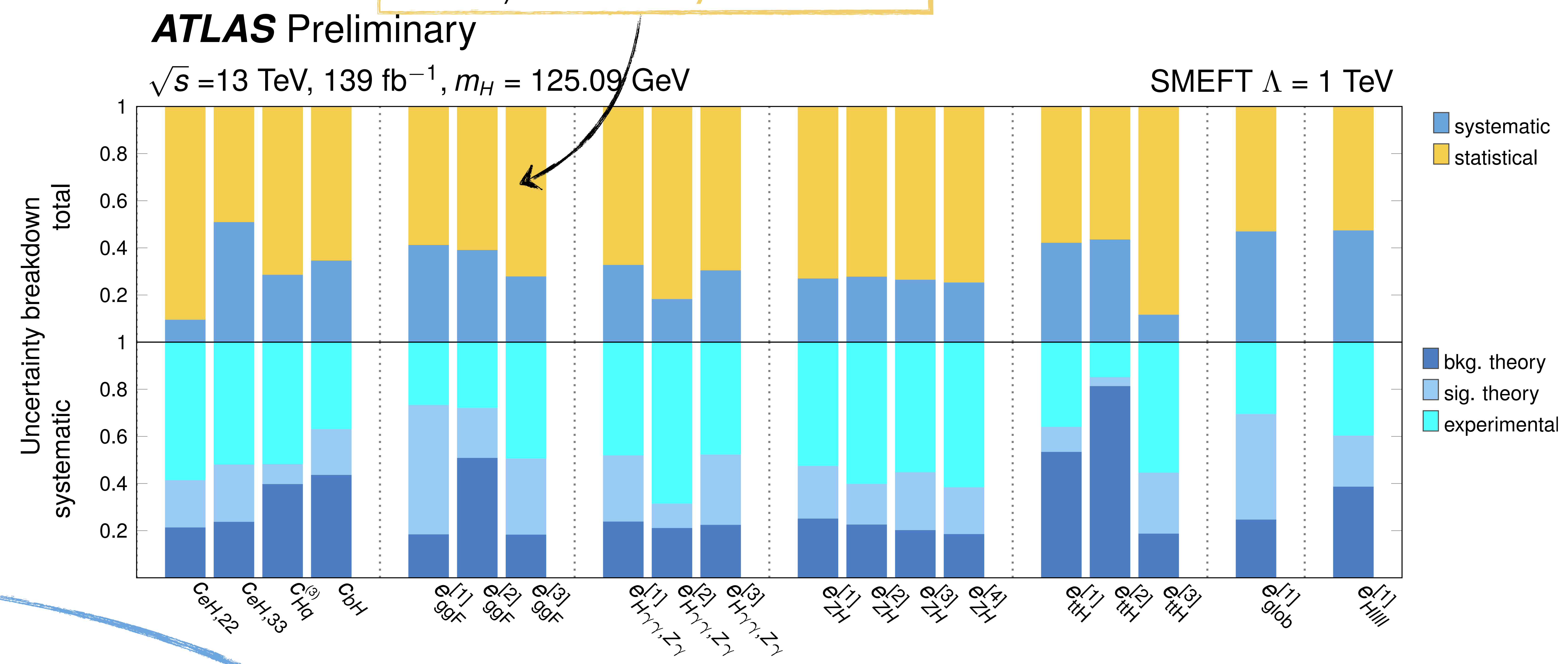
Uncertainty breakdown of SMEFT parameters

Uncertainty breakdowns inform about leading source of uncertainty and are important for guiding improvements for future results !

SMEFT parameters uncertainties mainly statistically dominated

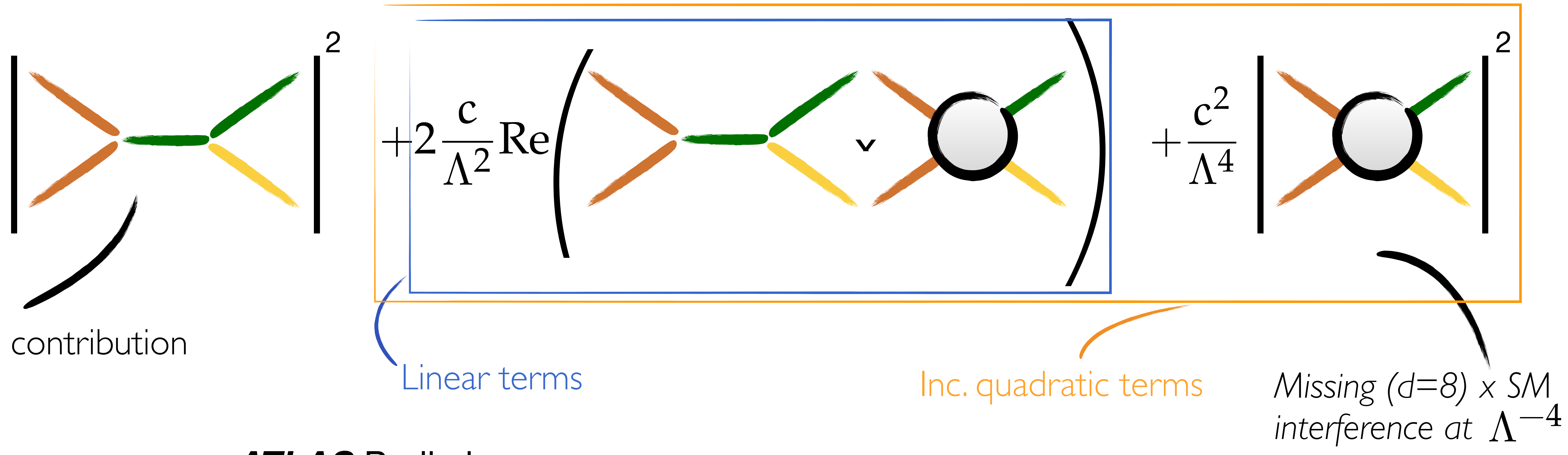
40% systematic contribution to unc. of $e^{[1,2]}_{\text{ggF}}$, $e^{[1,2]}_{\text{ttH}}$

50% systematic contribution to unc. of $c_{eH,33}$, $e^{[1]}_{glob}$ and $e^{[1]}_{Hllll}$



leading source of systematic uncertainty for these parameters are signal theory ($e^{[1]}_{\text{ggF}}, e^{[1]}_{\text{glob}}$) , background theory ($e^{[2]}_{\text{ggF}}, e^{[1,2]}_{\text{ttH}}$) and experimental ($c_{eH,22}, e_{Hllll}$)

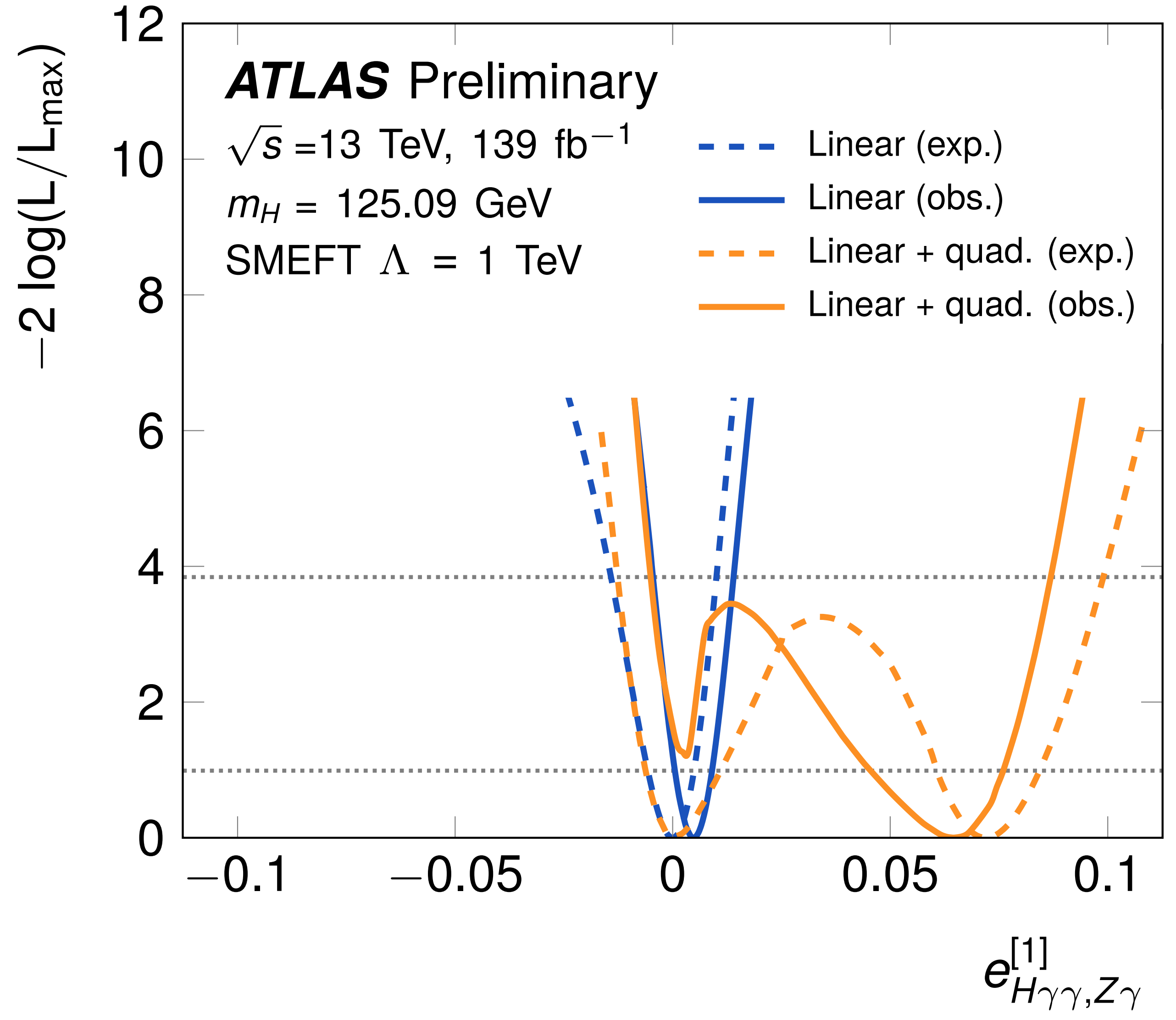
Impact of Quadratic terms

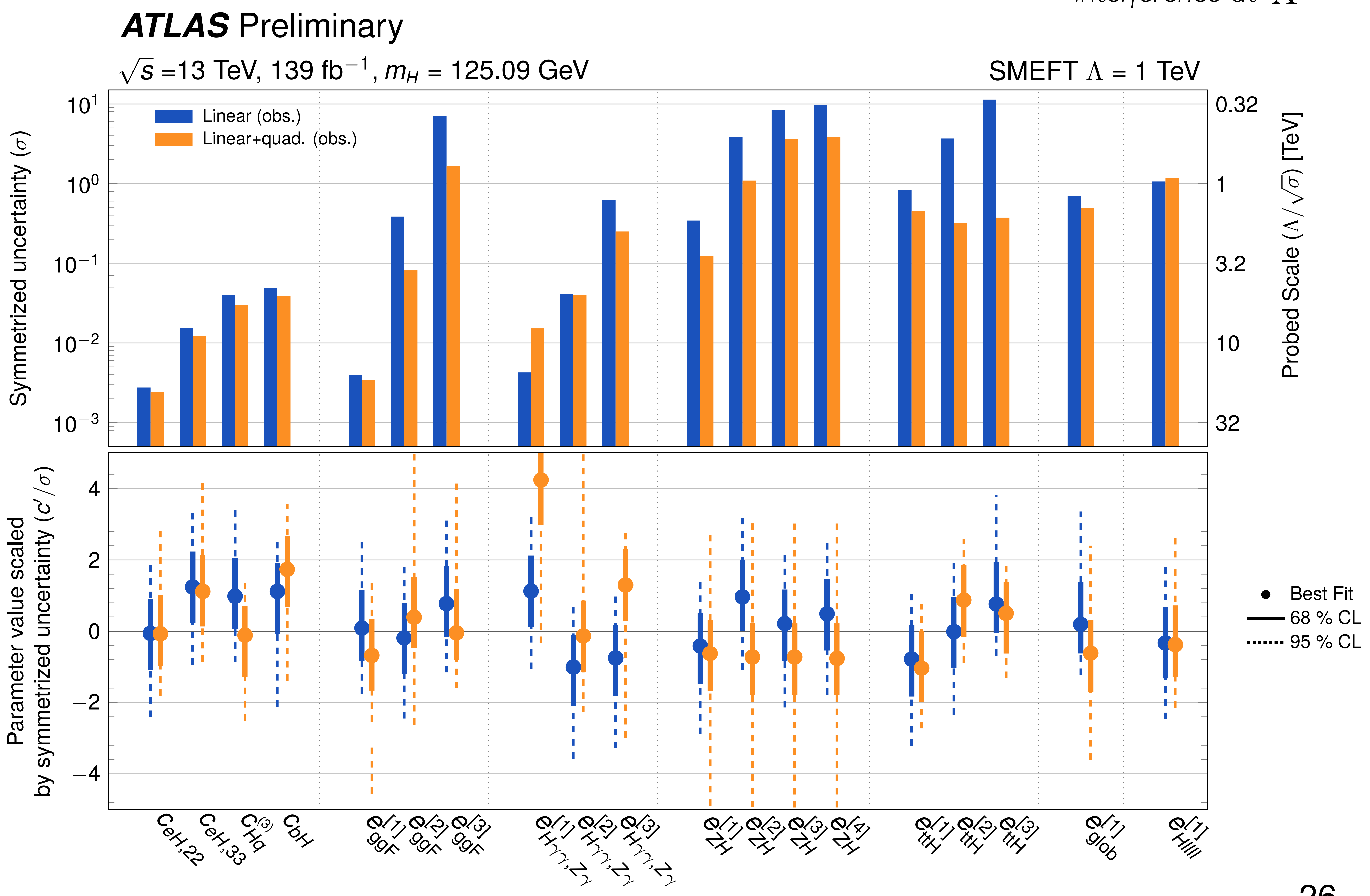


- Fit with quadratic terms allow to qualitatively describe missing d=8 x SM interference terms

- Constraints generally tighter, most notably for $e^{[2,3]}_{\text{ttH}}, e^{[1-4]}_{\text{ZH}}, e^{[2,3]}_{\text{ggF}}$

- Quadratic terms introduce multiple minima





Matching SMEFT constraints to 2HDM

Matching relations from
10.1103/Phys. Rev. D 102, 055012 Dawson et al

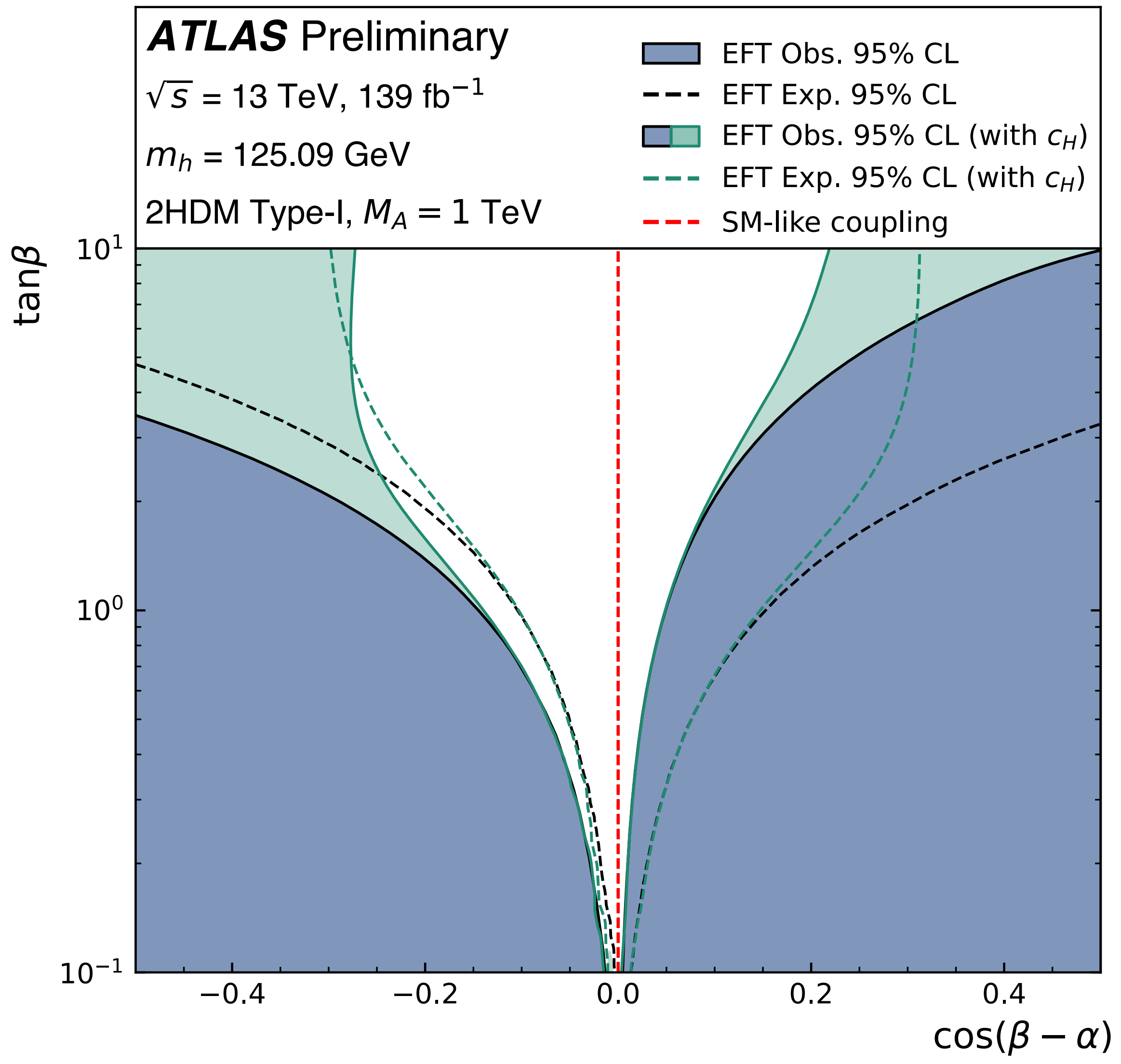
2-Higgs doublet model: additional Higgs doublet
five Higgs boson - charged ($H^{\pm}$), CP-even (h, H), & pseudo-scalar (A)

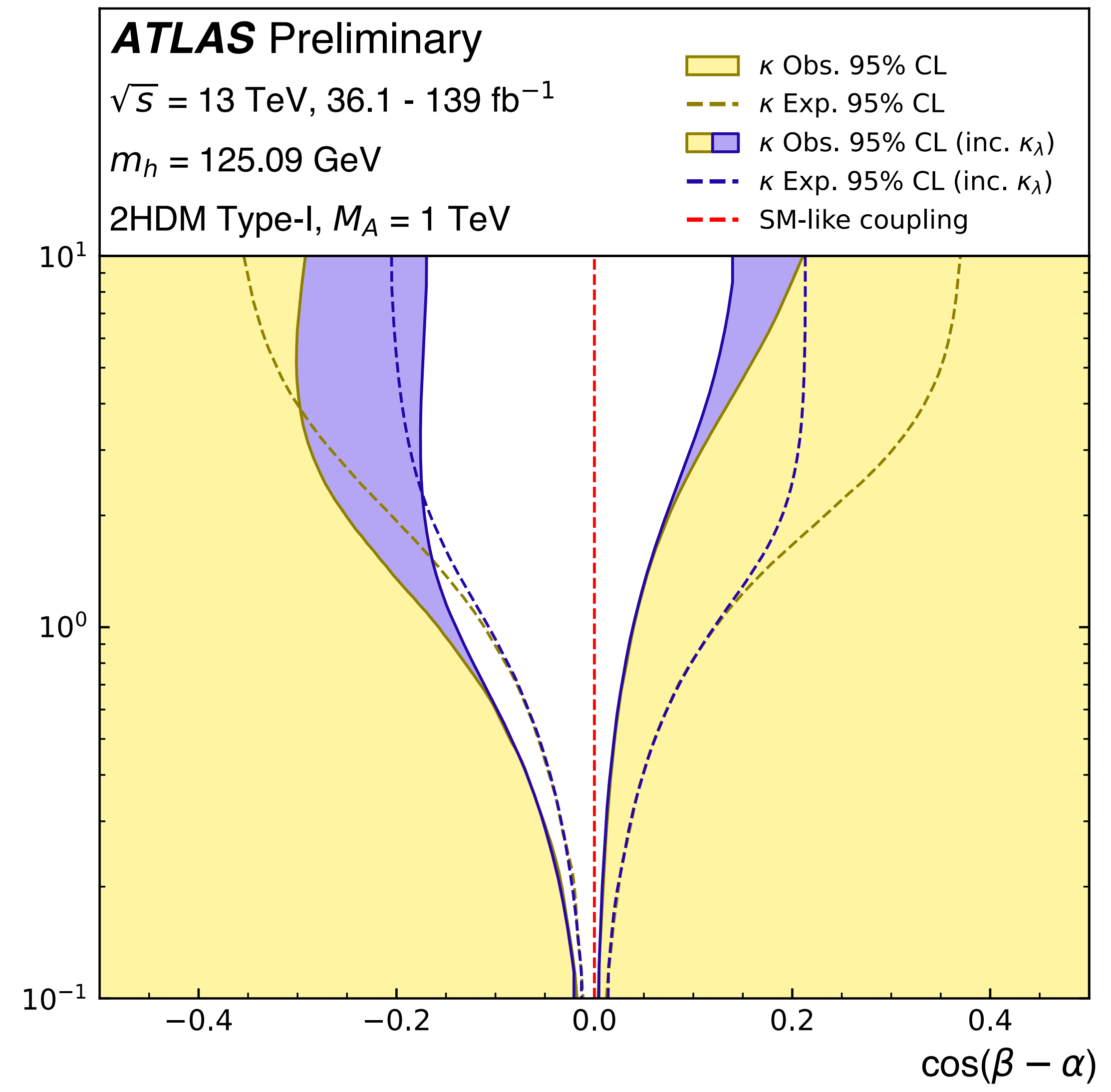
mixing of observed Higgs boson with other Higgs bosons tested
$\tan(\beta)$: ratio of vev of two doublets
$H_{SM} = h\sin(\beta-\alpha) + H\cos(\beta-\alpha)$

SMEFT matching valid in alignment limit $cos(\beta-\alpha)\rightarrow 0$,
observed Higgs boson aligns with light-Higgs of 2HDM

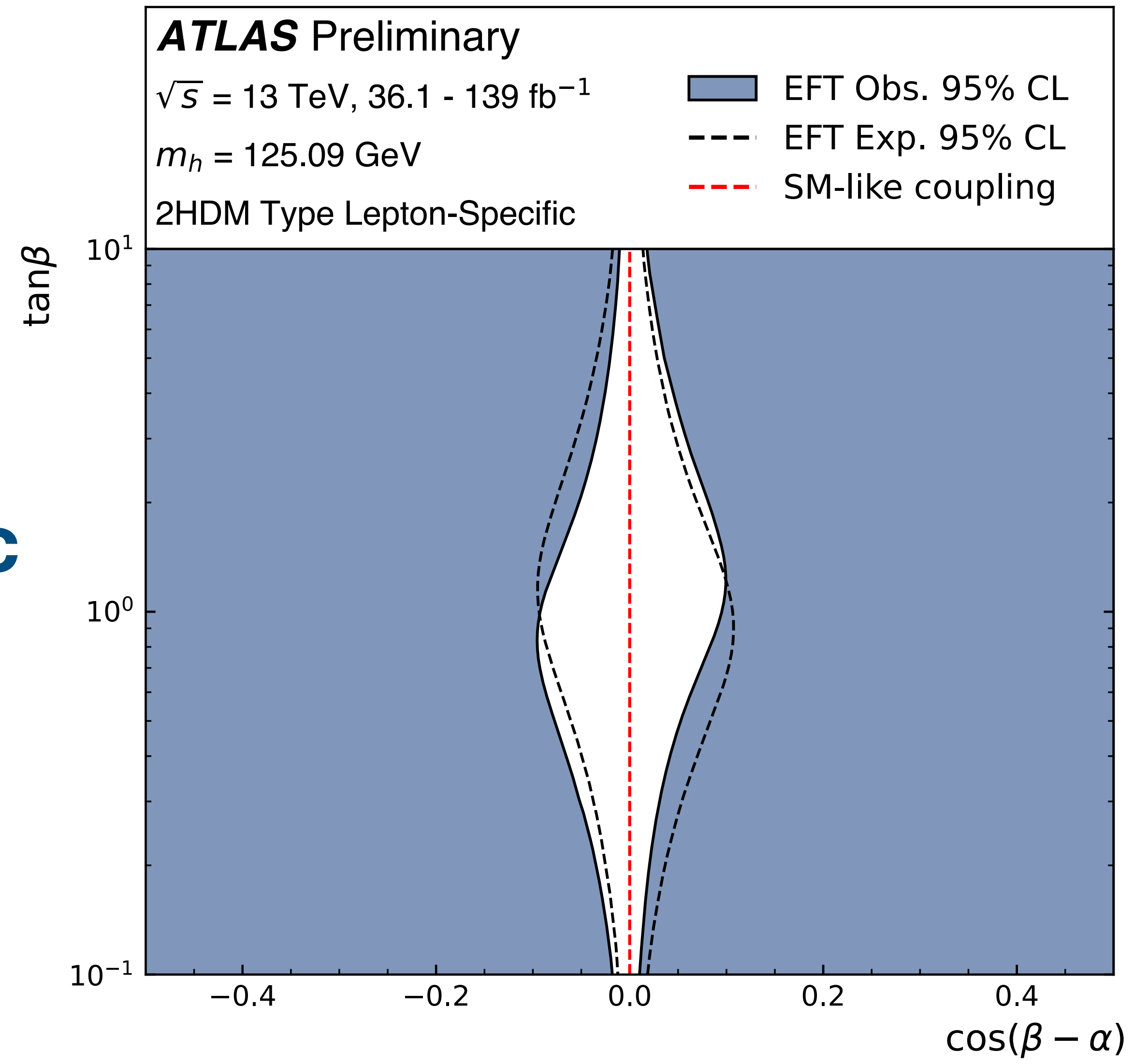
SMEFT matching performed using d=6 linear terms only
- missing constraint from HVV coupling which enter at d=8
- No petal-like structure caused by absence of quadratic terms

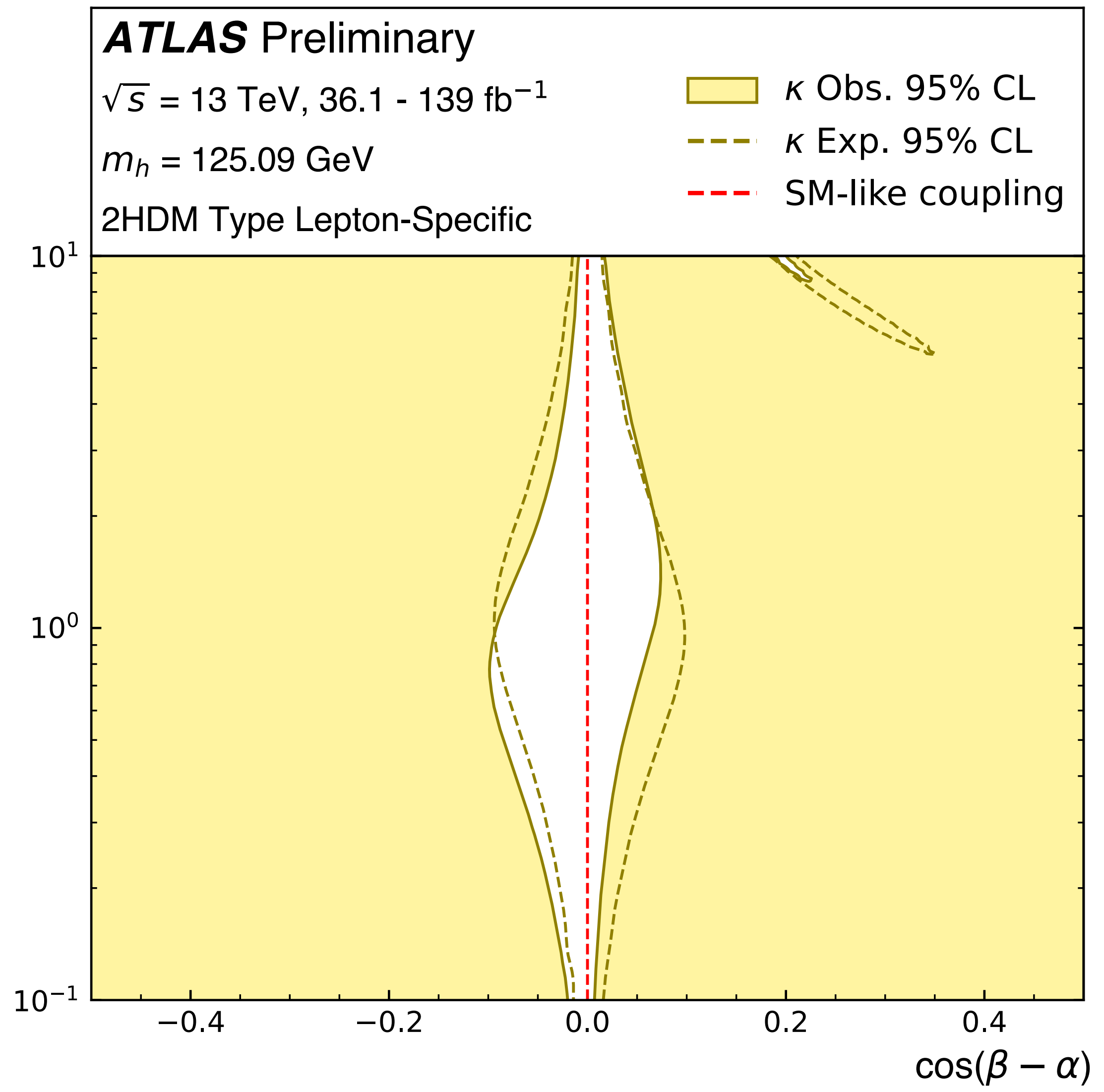
Type-I





Lepton Specific





SMEFT → 2HDM

κ → 2HDM

Coupling dependence in backup

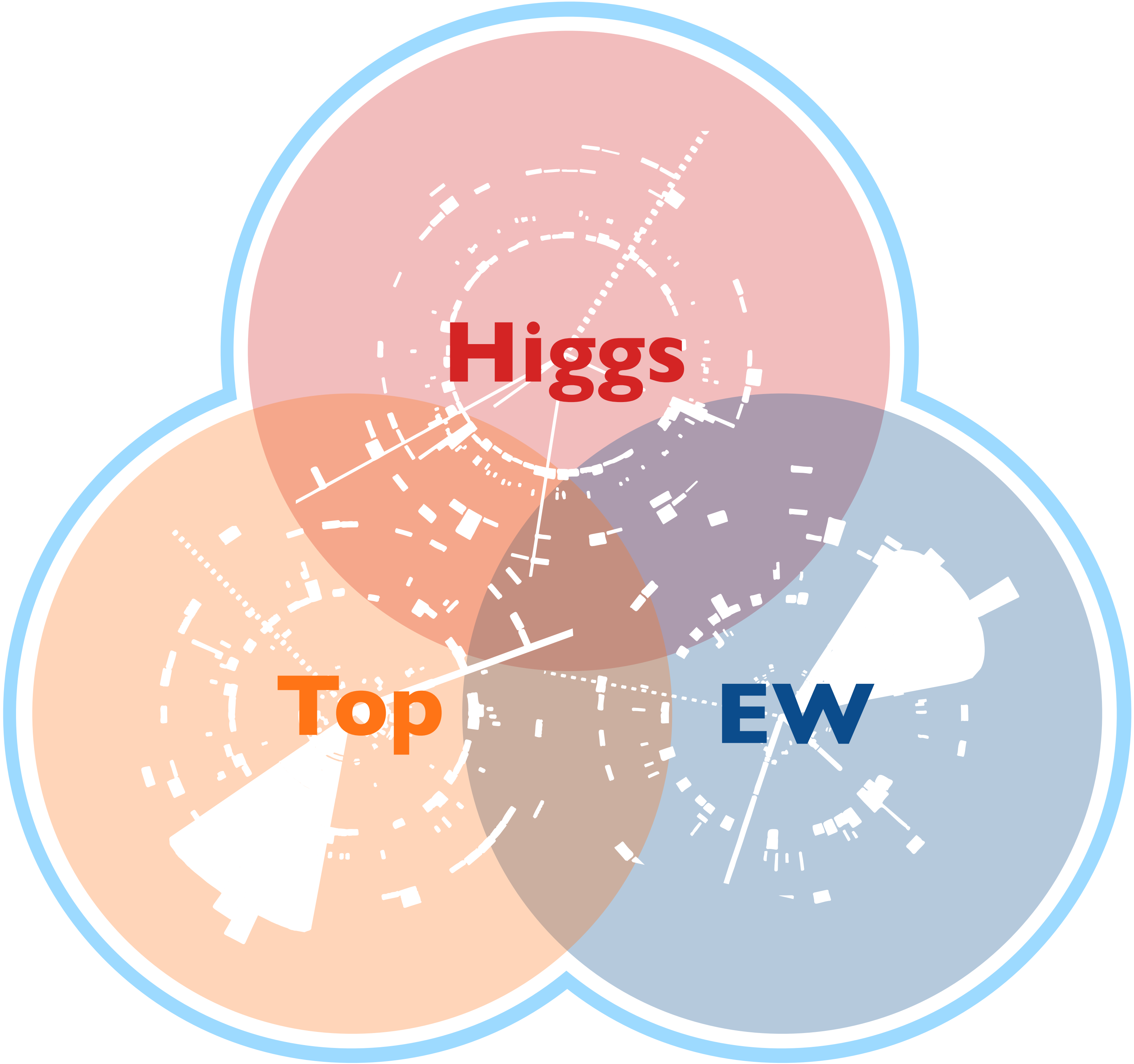
Summary & Conclusions

<u>Global EFT fit from ATLAS</u>
- First global fit from ATLAS constraints 28 parameters making use of measurements from Higgs boson and Electroweak ATLAS measurements with electroweak precision observables

<u>(Re)interpretation</u>
- Simplified likelihood based on multivariate Gaussian serves as a good proxy to full experimental likelihood function

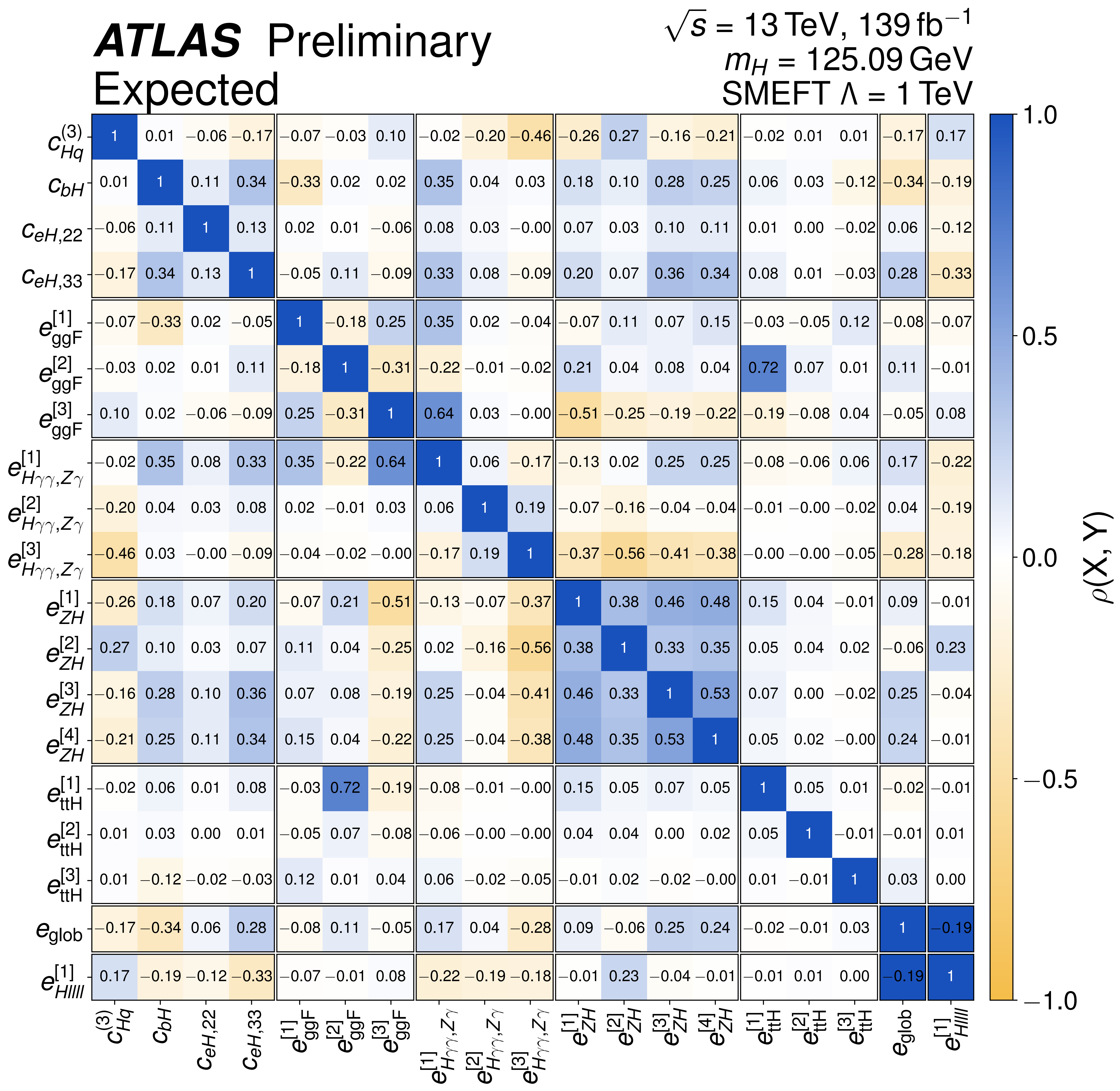
<u>Towards the next global fit</u>
- Presented latest update on combined Higgs boson interpretation
- Lot of developments anticipated in next global fit from ATLAS
  (more inputs, detailed studies of the constraints, matching to UV model)

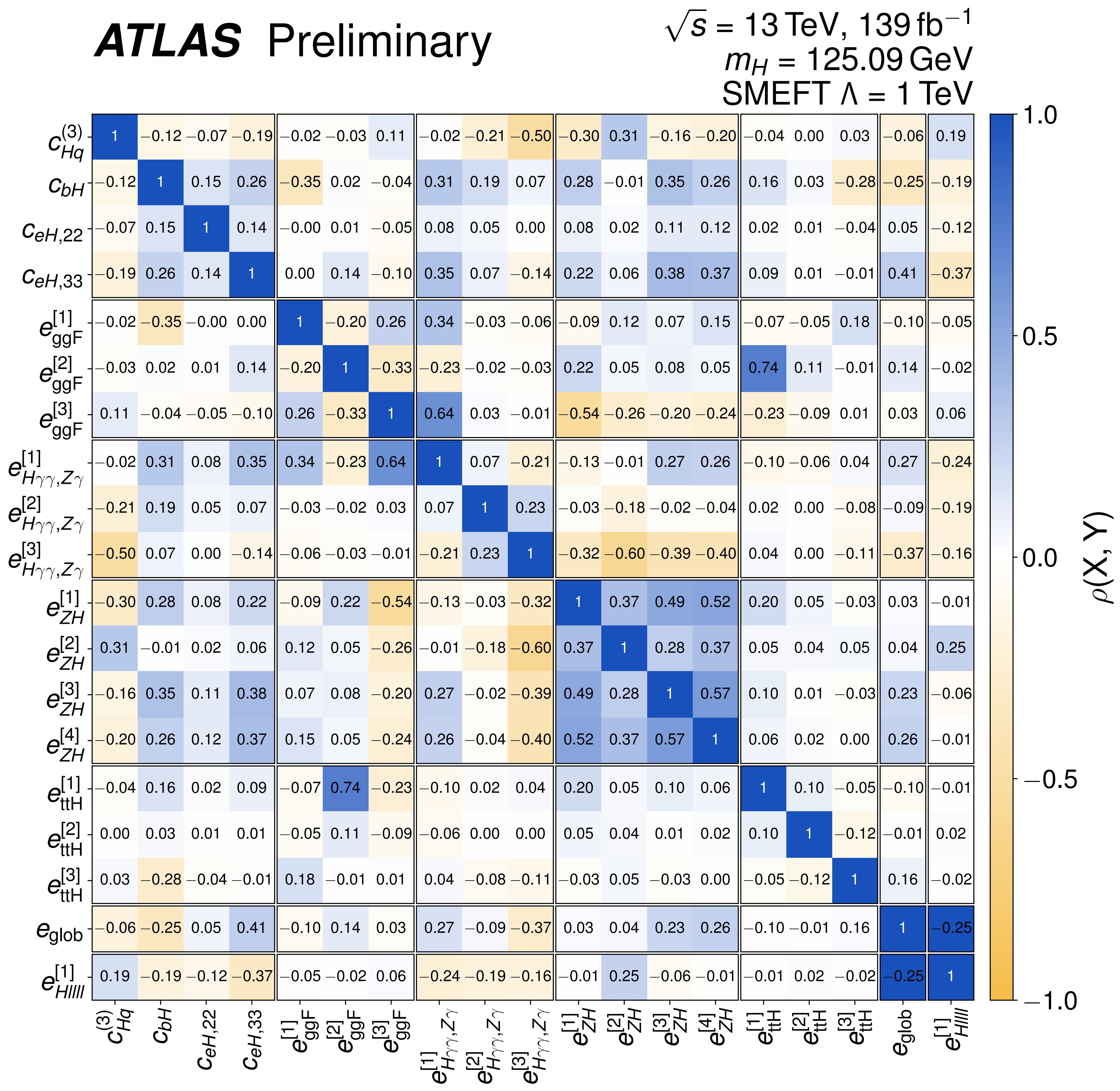
Looking forward to further developments in Global SMEFT interpretation in the future !



Backup

SMEFT fit correlations





2HDM relations

Coupling	Type I	Type II	Lepton-specific	Flipped
$u,\ c,\ t$	$s_{\beta-\alpha}+c_{\beta-\alpha}/\tan\beta$			
$d,\ s,\ b$	$s_{\beta-\alpha}+c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha}-c_{\beta-\alpha}\times\tan\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha}-c_{\beta-\alpha}\times\tan\beta$
$e,\ \mu,\ \tau$	$s_{\beta-\alpha}+c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha}-c_{\beta-\alpha}\times\tan\beta$	$s_{\beta-\alpha}-c_{\beta-\alpha}\times\tan\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/\tan\beta$
$W,\ Z$	$s_{\beta-\alpha}$			
H	$s^3_{\beta-\alpha}+\left(3-2\frac{\bar{m}^2}{m_h^2}\right)c^2_{\beta-\alpha}s_{\beta-\alpha}+2\cot(2\beta)\left(1-\frac{\bar{m}^2}{m_h^2}\right)c^3_{\beta-\alpha}$			

SMEFT parameters	Type I	Type II	Lepton-specific	Flipped
$\frac{v^2 c_{tH}}{\Lambda^2}$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{bH}}{\Lambda^2}$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$
$\frac{v^2 c_{eH,22}}{\Lambda^2}$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$	$-Y_\mu c_{\beta-\alpha}\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{eH,33}}{\Lambda^2}$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$	$-Y_\tau c_{\beta-\alpha}\tan\beta$	$Y_\tau c_{\beta-\alpha}\tan\beta$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_H}{\Lambda^2}$	$c^2_{\beta-\alpha}M_A^2/v^2$	$c^2_{\beta-\alpha}M_A^2/v^2$	$c^2_{\beta-\alpha}M_A^2/v^2$	$c^2_{\beta-\alpha}M_A^2/v^2$