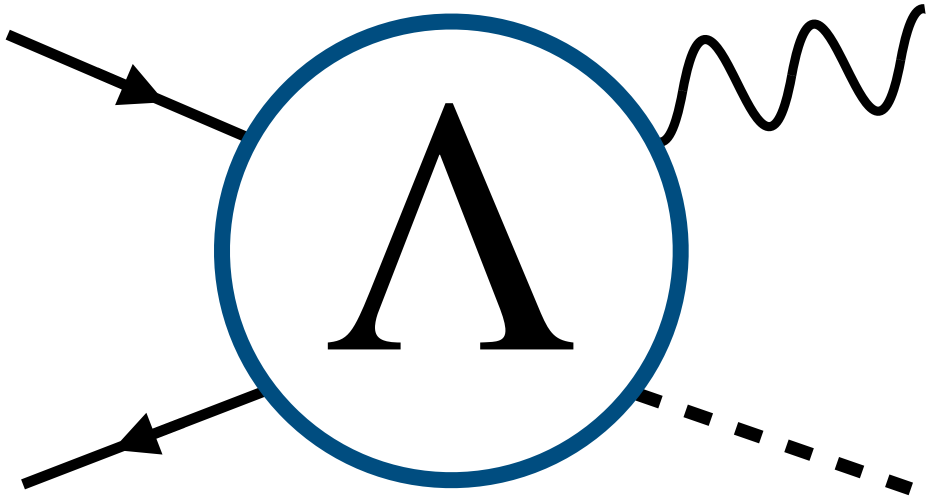
Recent EFT interpretations of Higgs (and diboson) measurements at ATLAS



Philipp Windischhofer

University of Oxford

For the ATLAS Collaboration

HEFT 2021, April 14-16, 2021, USTC

What can you expect?

A summary of our activities in using Higgs boson measurements to constrain the Standard Model EFT (SMEFT)

See Lailin's overview talk yesterday

(Our) answers to questions such as

How to ensure our measurements can reliably probe SMEFT effects?

How to extract SMEFT constraints?

How to present these results?

from the point of view of two recent results:

Higgs combination

[ATLAS-CONF-2020-053]

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ^* \rightarrow 4l$

$VH, H \rightarrow bb$

Higgs + diboson combination

[ATL-PHYS-PUB-2021-010]

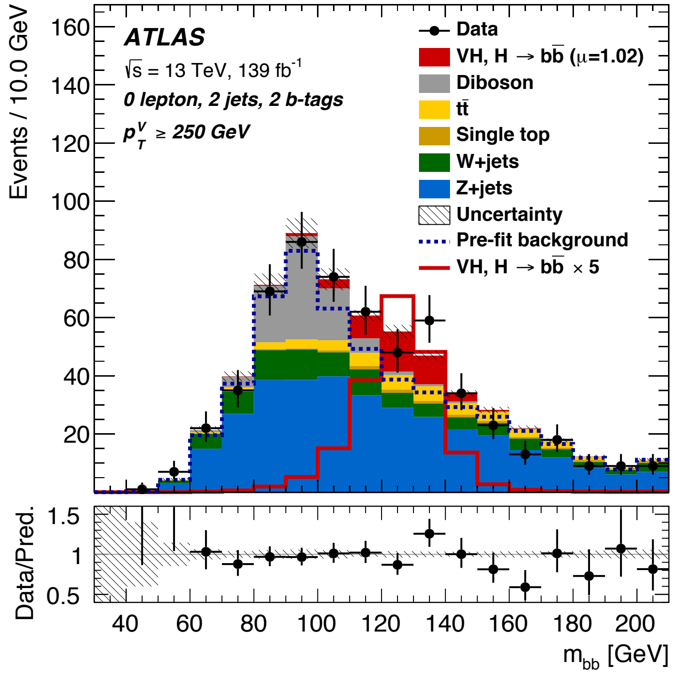
$H \rightarrow WW^*$

$pp \rightarrow WW$

From event distributions to SMEFT constraints

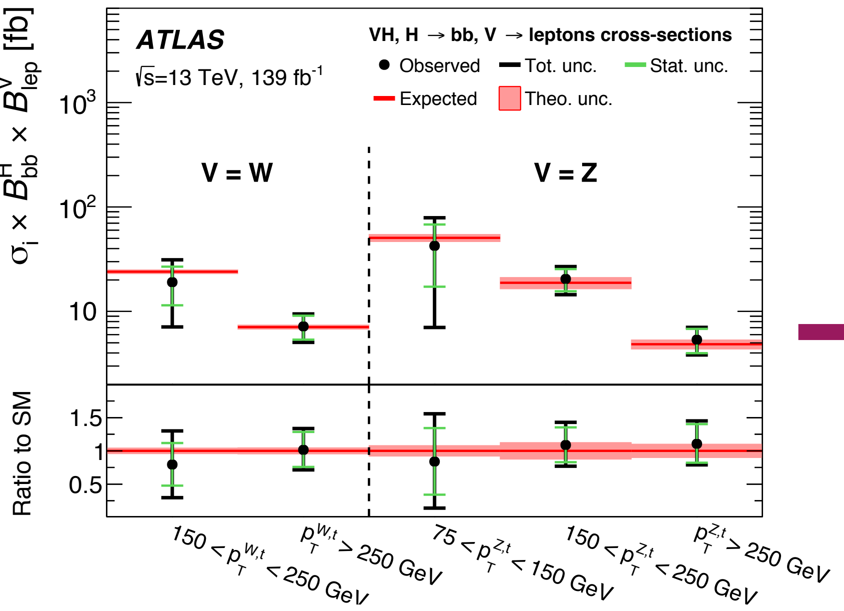
A typical trajectory of an ATLAS Higgs EFT result

[ATLAS-CONF-2020-053]



Reconstructed distributions

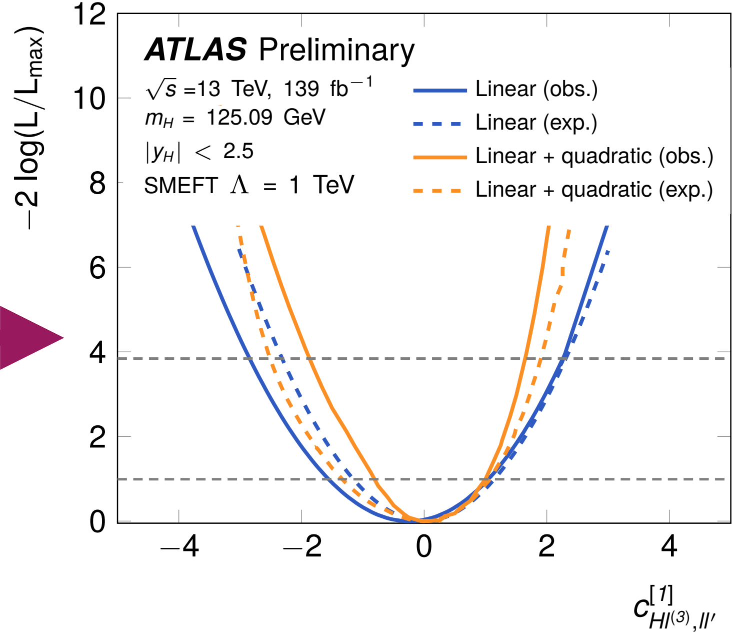
[arXiv:2007.02873]



Fiducial cross-sections (STXS), differential cross-sections, …

"Inputs for EFT interpretation"

[ATLAS-CONF-2020-053]



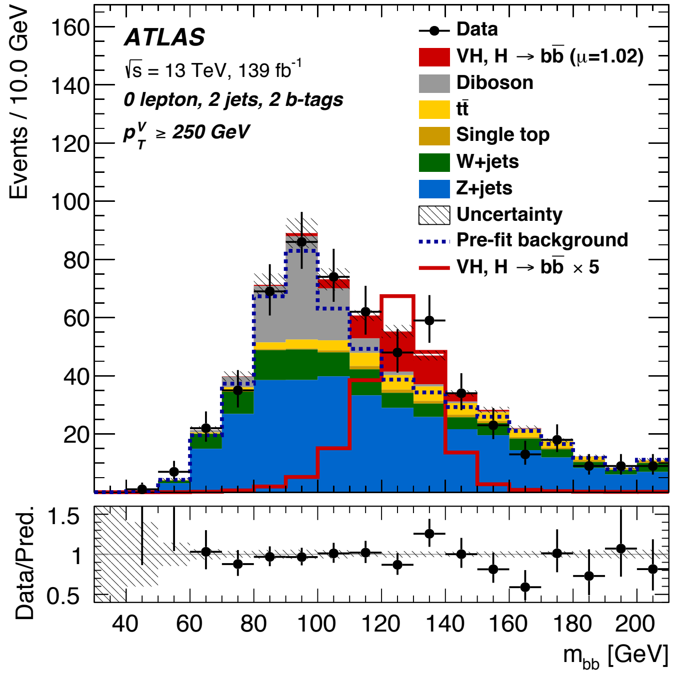
SMEFT constraints

Note: *all systematic uncertainties kept for EFT result!*

From event distributions to SMEFT constraints

A typical trajectory of an ATLAS Higgs EFT result

[ATLAS-CONF-2020-053]



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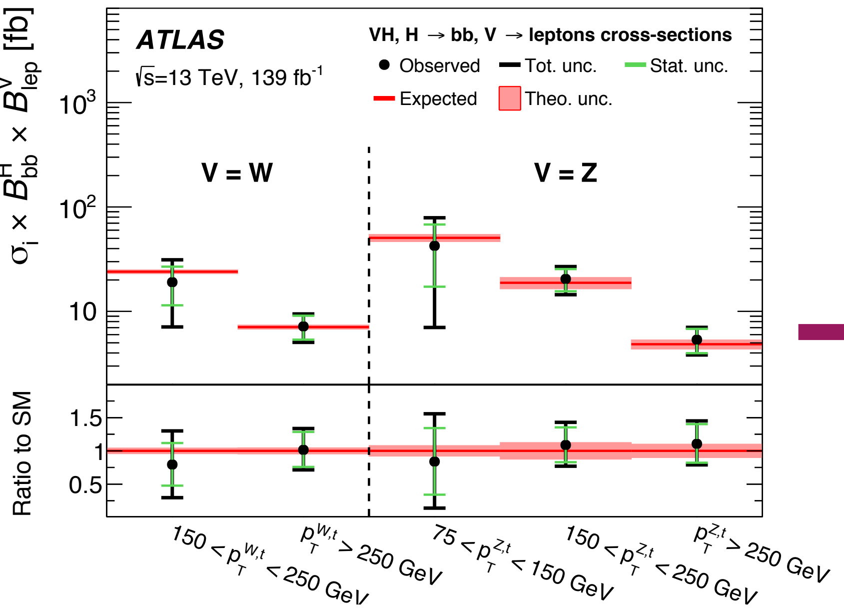
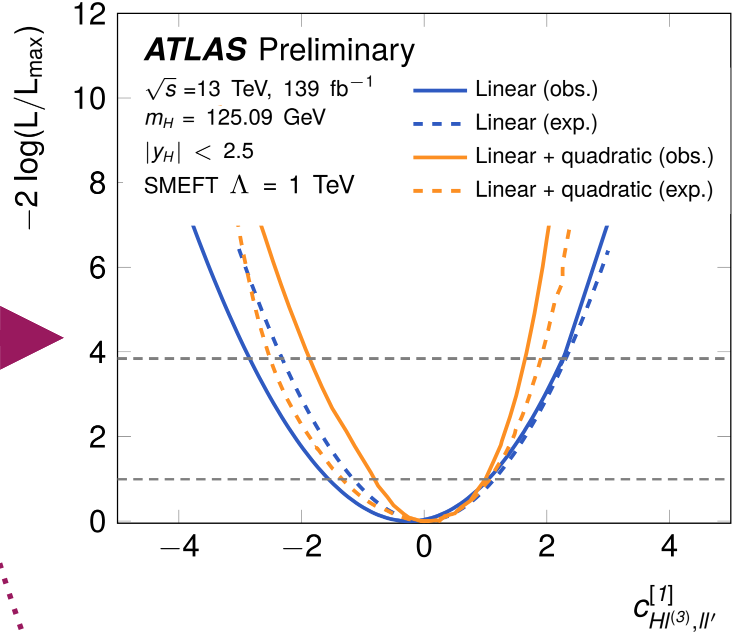


Fiducial cross-sections (STXS), differential cross-sections, …

"Inputs for EFT interpretation"

[ATLAS-CONF-2020-053]



SMEFT constraints

Unfolding of detector effects

Behaviour can be modified in SMEFT!

(e.g. signal acceptance changes, see later)

Parametrisation of SMEFT modifications

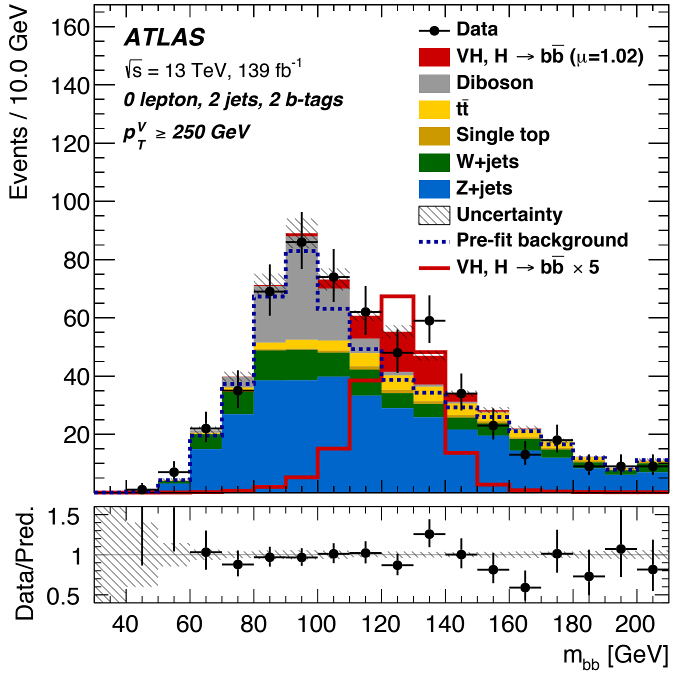
Generator-level simulation sufficient (detector effects already removed!)

Note: *all systematic uncertainties kept for EFT result!*

From event distributions to SMEFT constraints

A typical trajectory of an ATLAS Higgs EFT result

[ATLAS-CONF-2020-053]



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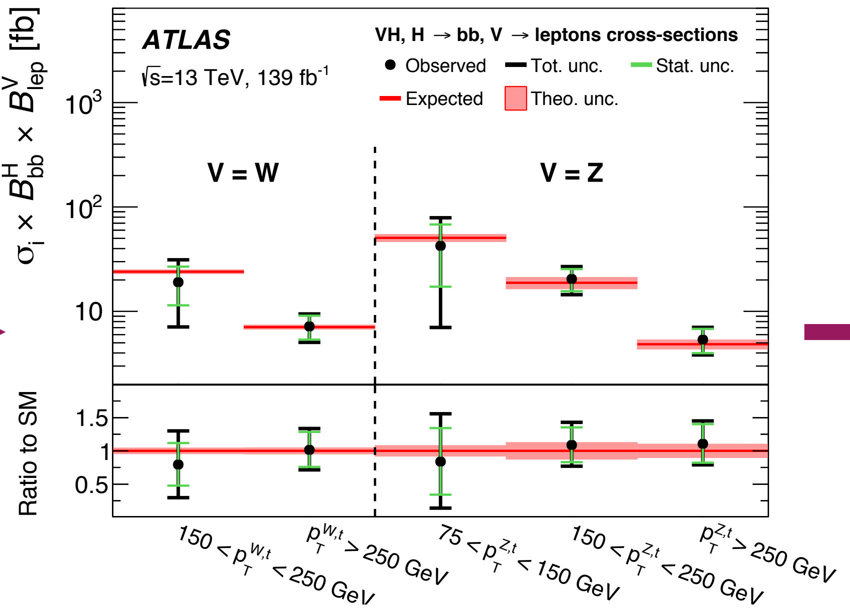
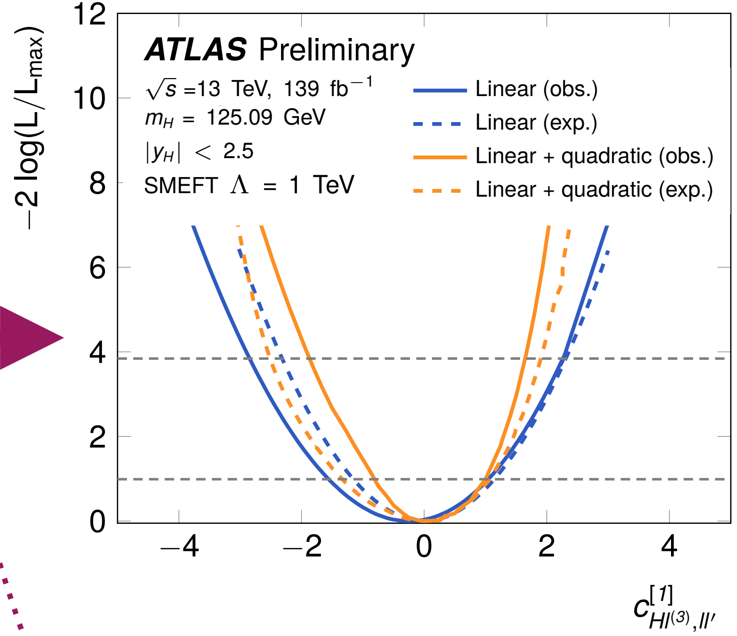


[ATLAS-CONF-2020-053]



Reconstructed distributions

Fiducial cross-sections (STXS), differential cross-sections, …

"Inputs for EFT interpretation"

SMEFT constraints

Unfolding of detector effects

Behaviour can be modified in SMEFT!

(e.g. signal acceptance changes, see later)

Parametrisation of SMEFT modifications

Generator-level simulation sufficient (detector effects already removed!)

Note: *all systematic uncertainties kept for EFT result!*

Simplified template cross-sections (STXS)

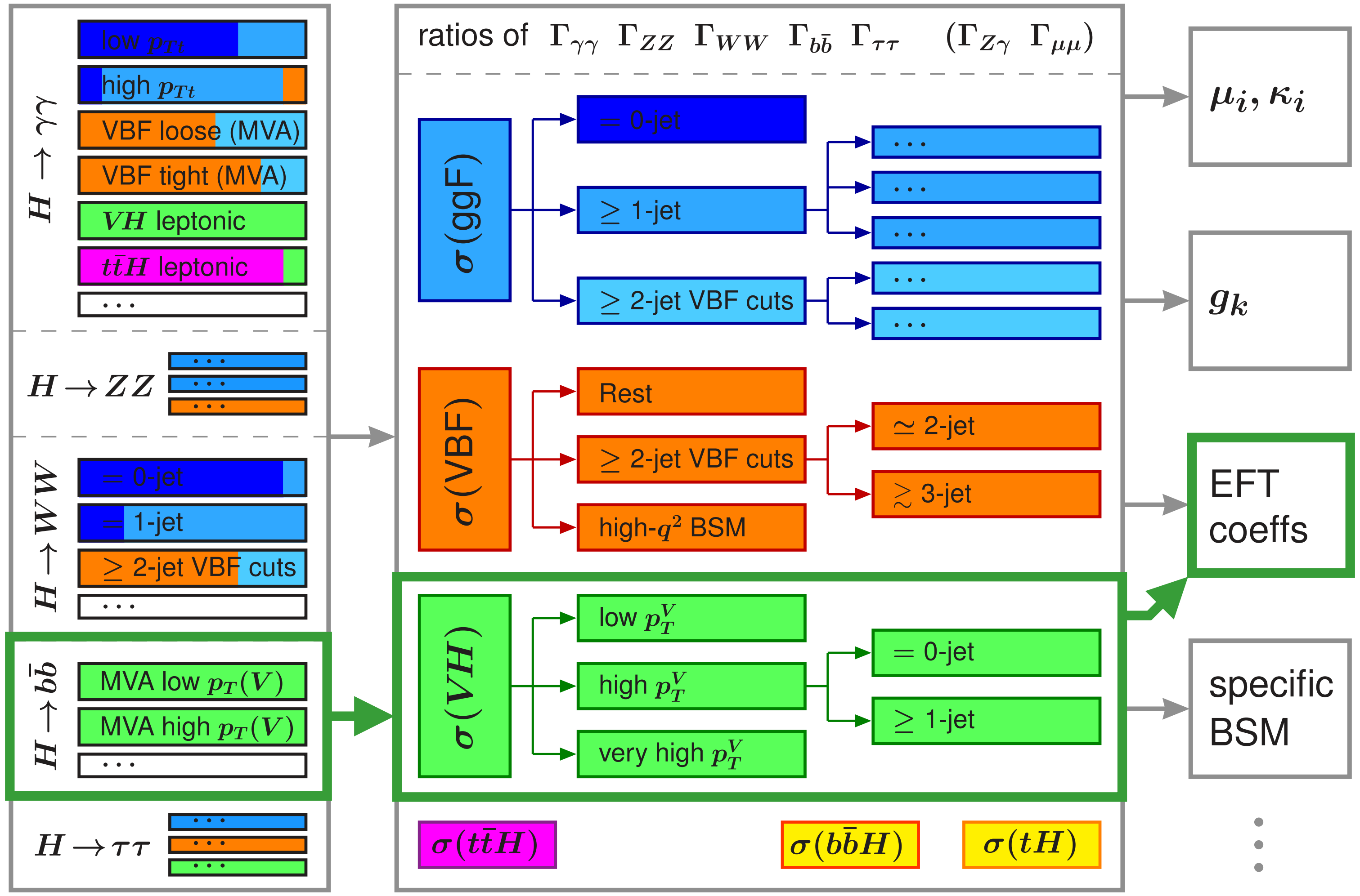
STXS = Higgs production cross-sections in well-defined fiducial volumes

Inclusive signal strength ⟶ STXS ⟶ Differential cross-section

Compromise between exp. **sensitivity** and **model-dependence**

Isolate regions with possible BSM effects (e.g. p_T^V)

Staged definition: more data → more STXS bins



Original definition from YR4, more granular bins in use now

The Standard Model EFT (SMEFT)

The Standard Model as an effective theory

Weinberg operator
(not relevant for Higgs physics)

Only partially enumerated,
odd dimensions violate
B and / or L (not considered)

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i}\mathscr{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2}\mathscr{O}_i^{(6)} + \dots$$

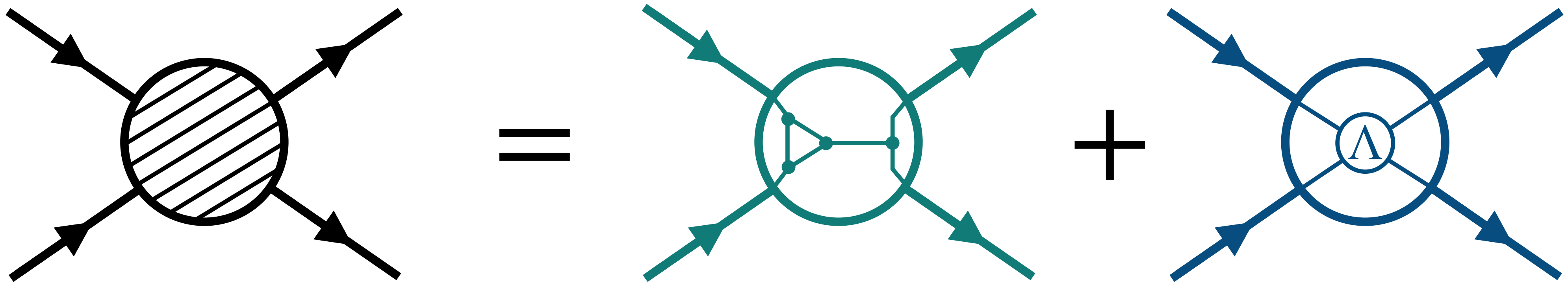
Uniquely determined
by symmetry

3- and 4-point interactions

2499 operators with ΔL=ΔB=0

76 with global U(3)^5 flavour symmetry

Corrections to SM interactions +
new contact interactions



Cross-sections in the SMEFT

e.g. σ^{STXS}

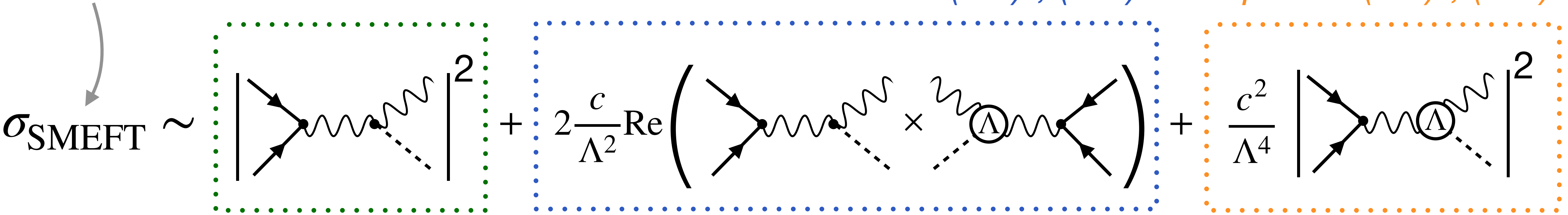
SM

SM / dim-6 interference

"linear": $(v/\Lambda)^2$, $(E/\Lambda)^2$

dim-6 squared

"quad.": $(v/\Lambda)^4$, $(E/\Lambda)^4$



$$= \quad \sigma_{\text{SM}} \times \underbrace{\left(1 + \alpha_i c_i^{(6)} + \beta_{ij} c_i^{(6)} c_j^{(6)} \right)}$$

Multiplicative modification of SM cross-section

Observables (also decay rates) **are polynomial in Wilson coefficients** $c_i^{(6)}$

Parametrisation of SMEFT modifications

Observables are polynomial in Wilson coefficients $c_i^{(6)}$:

$$\rightarrow 1+\alpha_i c_i^{(6)} + \beta_{ij} c_i^{(6)} c_j^{(6)}$$

$$\frac{[\sigma \times \mathrm{Br}(H \to \mathrm{f\,.\,s.})]_{\mathrm{SMEFT}}}{[\sigma \times \mathrm{Br}(H \to \mathrm{f\,.\,s.})]_{\mathrm{SM}}} = \frac{\sigma_{\mathrm{SMEFT}}}{\sigma_{\mathrm{SM}}} \times \frac{\dfrac{\Gamma(H \to \mathrm{f\,.\,s.})_{\mathrm{SMEFT}}}{\Gamma(H \to \mathrm{f\,.\,s.})_{\mathrm{SM}}}}{\dfrac{\Gamma(H)_{\mathrm{SMEFT}}}{\Gamma(H)_{\mathrm{SM}}}}$$

$$\rightarrow 1+ A_i^f c_i^{(6)} + B_{ij}^f c_i^{(6)} c_j^{(6)}$$

$$\rightarrow 1+ A_i c_i^{(6)} + B_{ij} c_i^{(6)} c_j^{(6)}$$

(Expanded further in powers of Λ^{-2})

Parametrisation of SMEFT modifications

Observables are polynomial in Wilson coefficients $c_i^{(6)}$:

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$$1+A_i^f c_i^{(6)}+B_{ij}^f c_i^{(6)}c_j^{(6)}$$

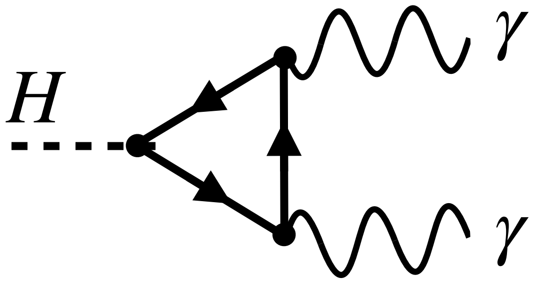
$$1+A_i c_i^{(6)}+B_{ij}c_i^{(6)}c_j^{(6)}$$

(Expanded further in powers of Λ^{-2})

Coefficients for linear and quadratic contributions obtained from simulation:

MadGraph + SMEFT@NLO for loop-induced processes *(e.g. gg→ZH, H→gg)*

MadGraph + SMEFTsim for tree-level processes (LO)



Analytic results where available

(e.g. H→ɣɣ from Phys. Rev. D 98, 095005)

Use Warsaw basis, {m_W, m_Z, G_F} input scheme, $U(3)^5$ flavour symmetry, Λ=1TeV

Parametrisation of SMEFT modifications

Observables are polynomial in Wilson coefficients $c_i^{(6)}$:

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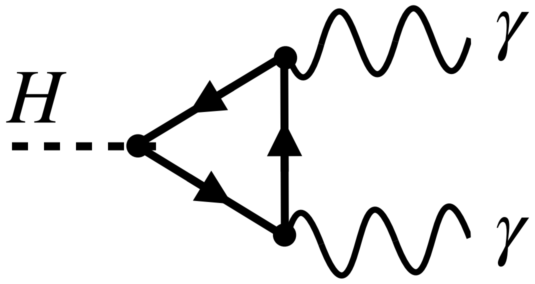
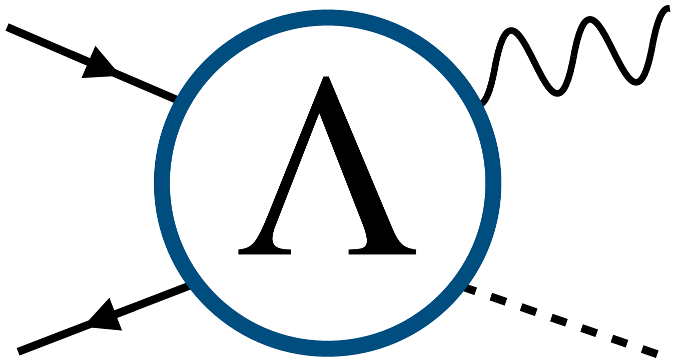


Use Warsaw basis, {m_W, m_Z, G_F} input scheme, $U(3)^5$ flavour symmetry, Λ=1TeV

Used to rescale the SM prediction (typically of different order)



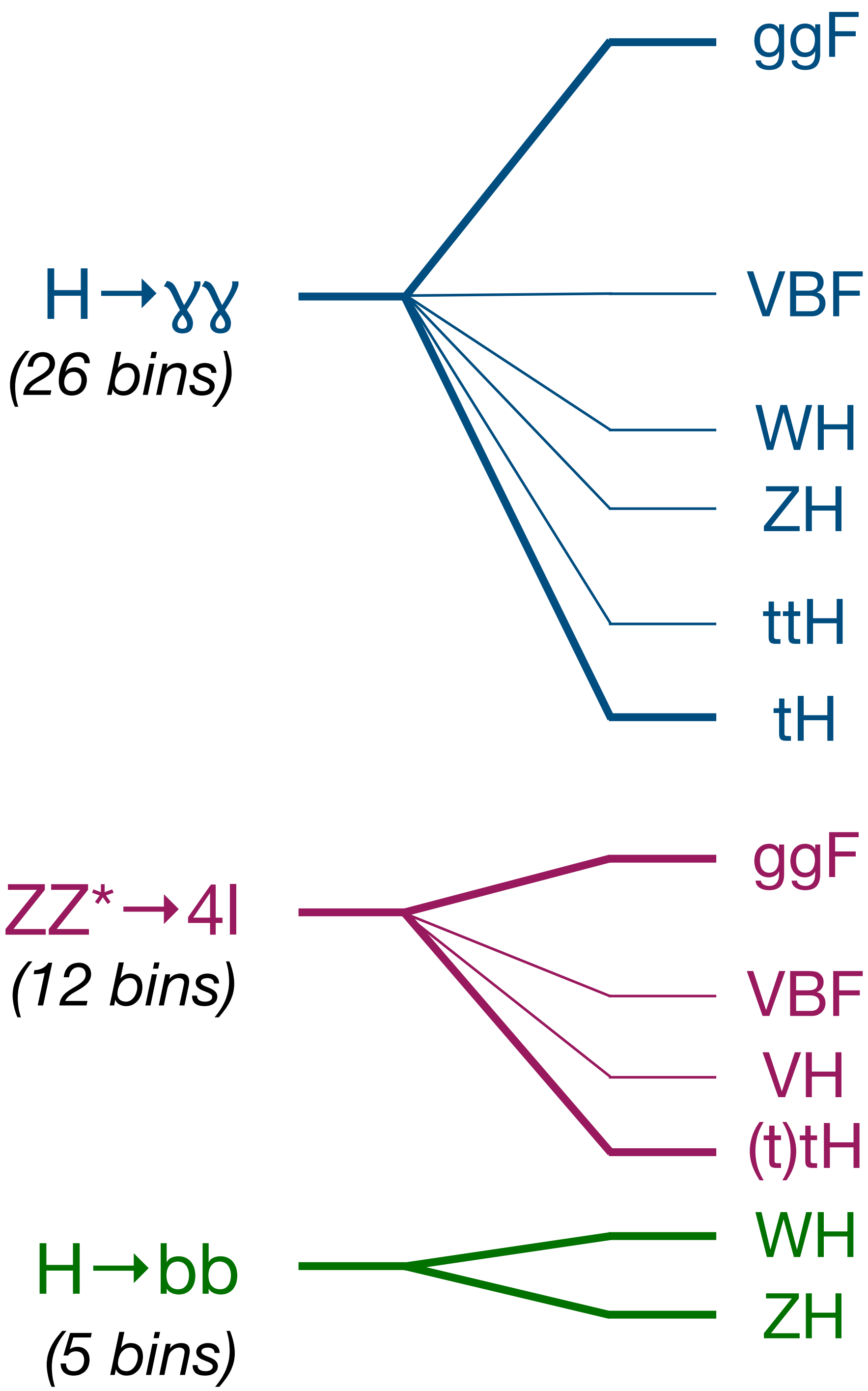
Higgs combination

[ATLAS-CONF-2020-053]

STXS measurement

Simultaneous measurement of STXS bins for H→γγ, H→ZZ*→4l and VH, H→bb

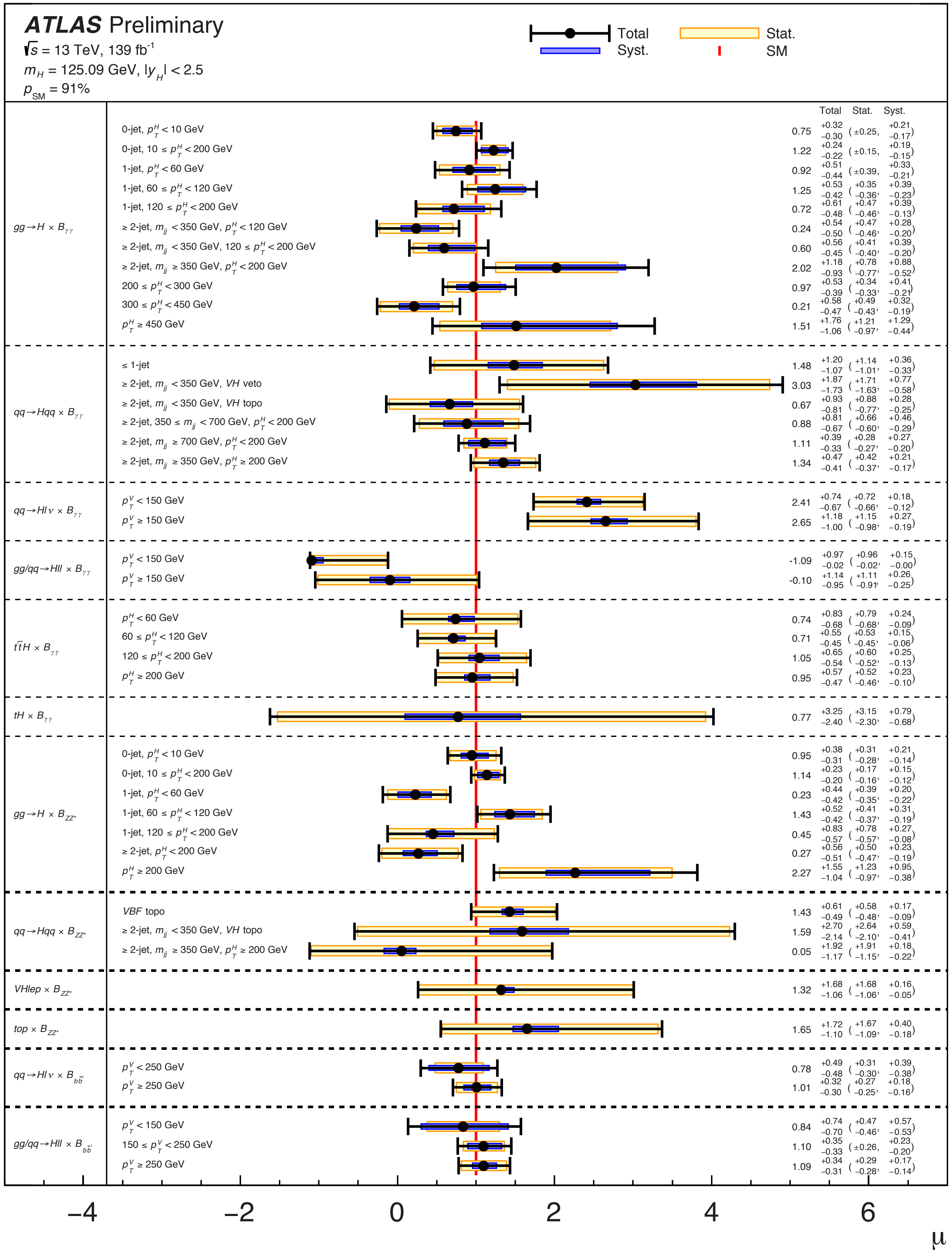
(all with 139fb^{-1})



H→γγ
(26 bins)
- ggF
- VBF
- WH
- ZH
- ttH
- tH

H→ZZ*→4l
(12 bins)
- ggF
- VBF
- VH
- (t)tH

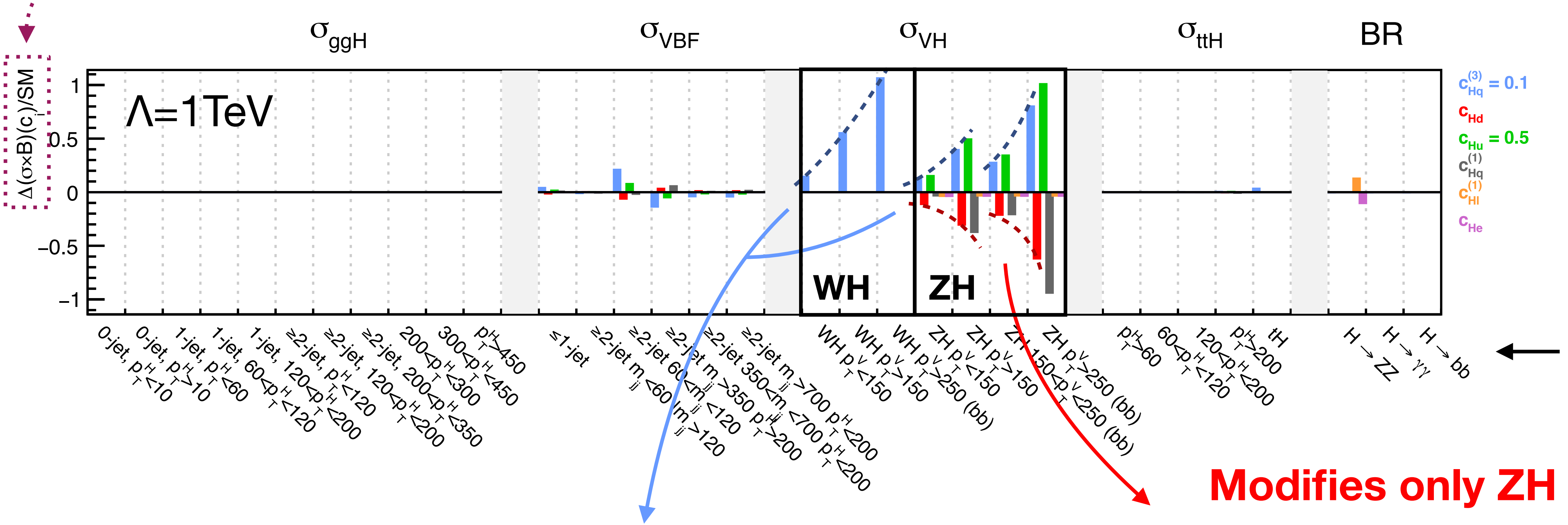
H→bb
(5 bins)
- WH
- ZH



SMEFT modifications to σ x Br

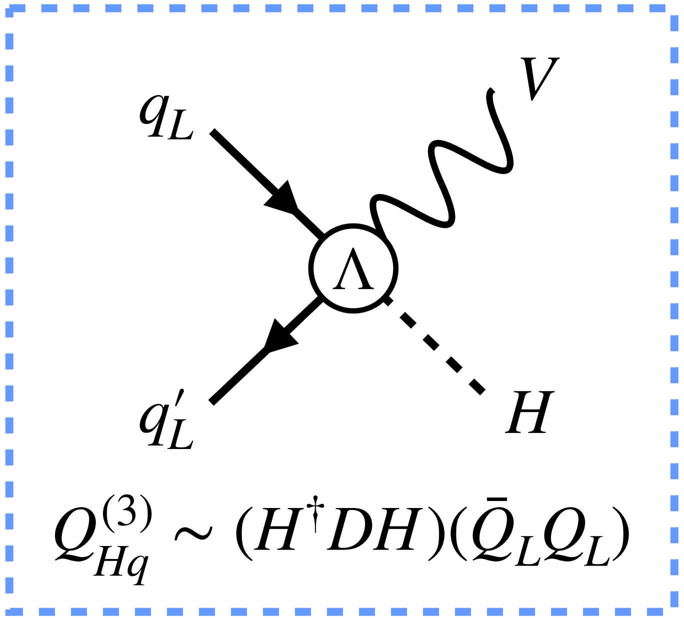
Higher impact for processes at higher scales (~ p_T^V)

Rel. modification of σ x Br *(uses linear terms only)*



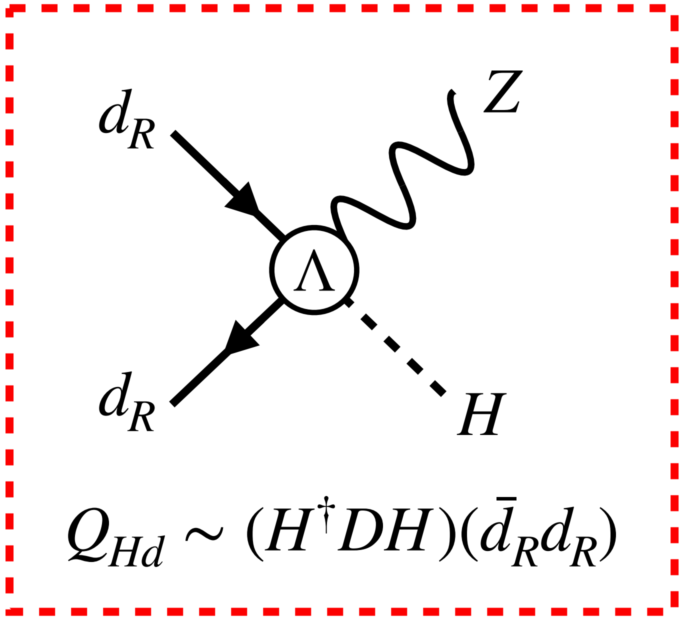
STXS bins

Modifies both WH & ZH



$$Q_{Hq}^{(3)} \sim (H^\dagger D H)(\bar{Q}_L Q_L)$$

Modifies only ZH

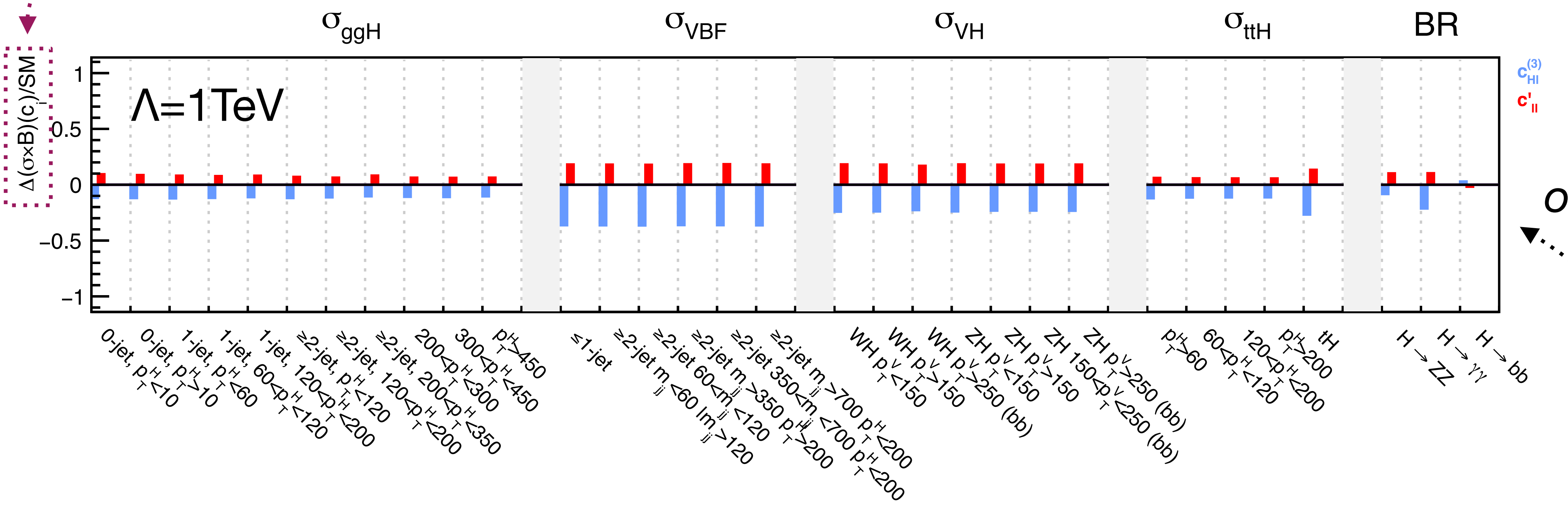


$$Q_{Hd} \sim (H^\dagger D H)(\bar{d}_R d_R)$$

SMEFT modifications to σ x Br

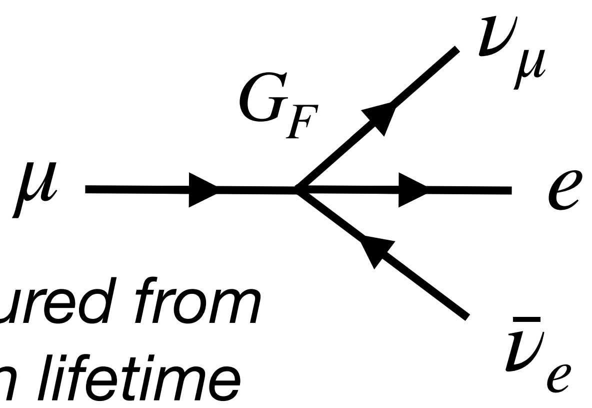
Modifications to Higgs vev and g_{EW}

Rel. modification of σ x Br *(uses linear terms only)*

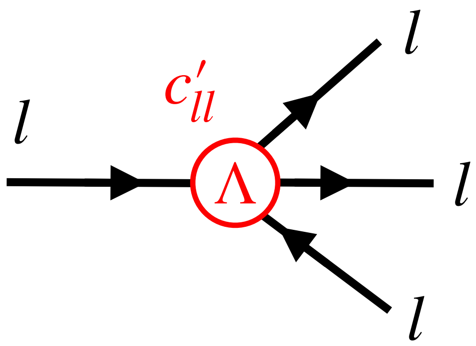


Modifications of cross-sections

SMEFT: relation between Fermi constant and g_{EW} depends on $c_{Hl}^{(3)}$ and c_{ll}'

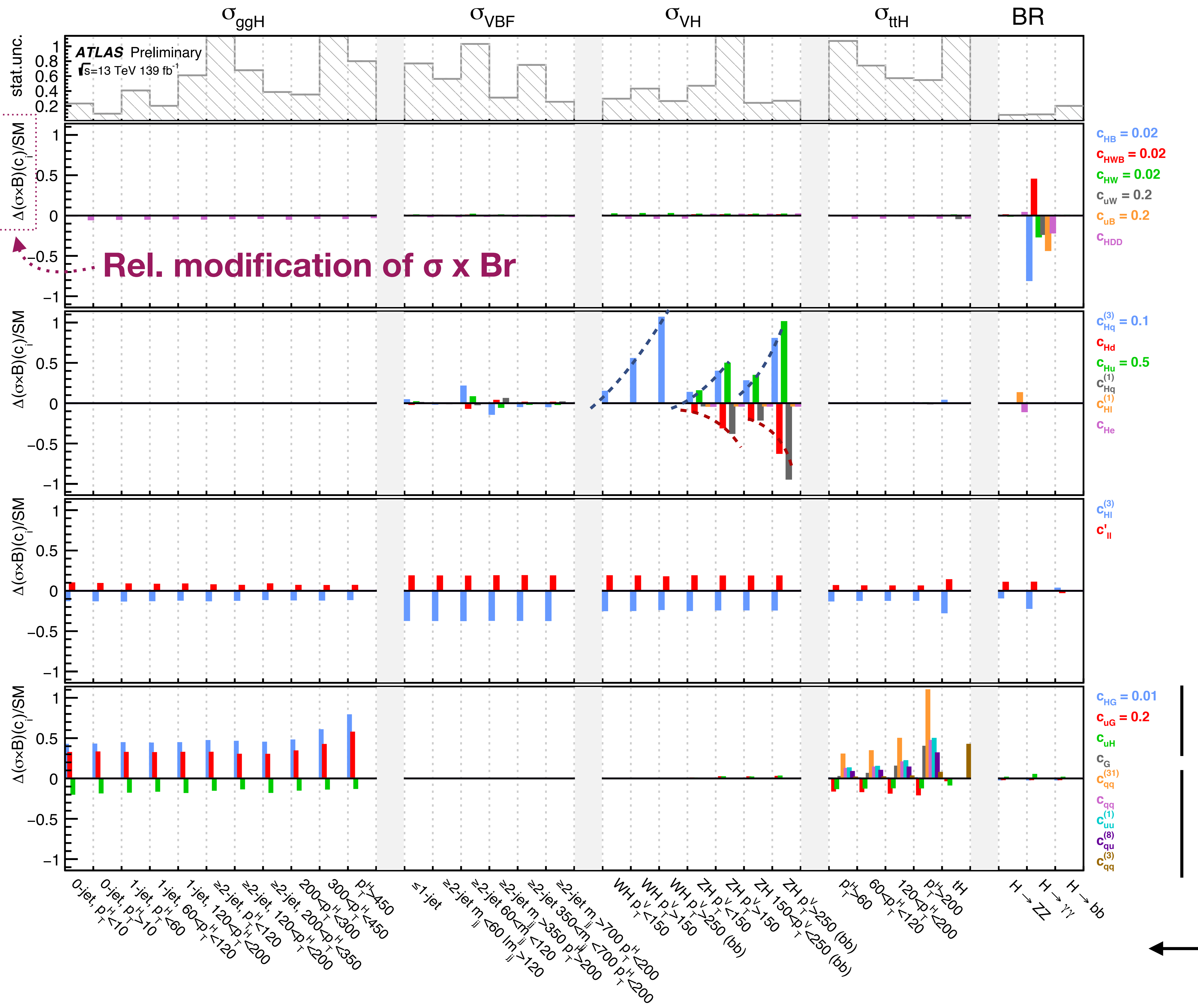


Measured from muon lifetime



$Q_{ll} \sim (\bar{L}L)^2$

All operators at a glance



Higgs-gauge interactions

Higgs-fermion-gauge interactions

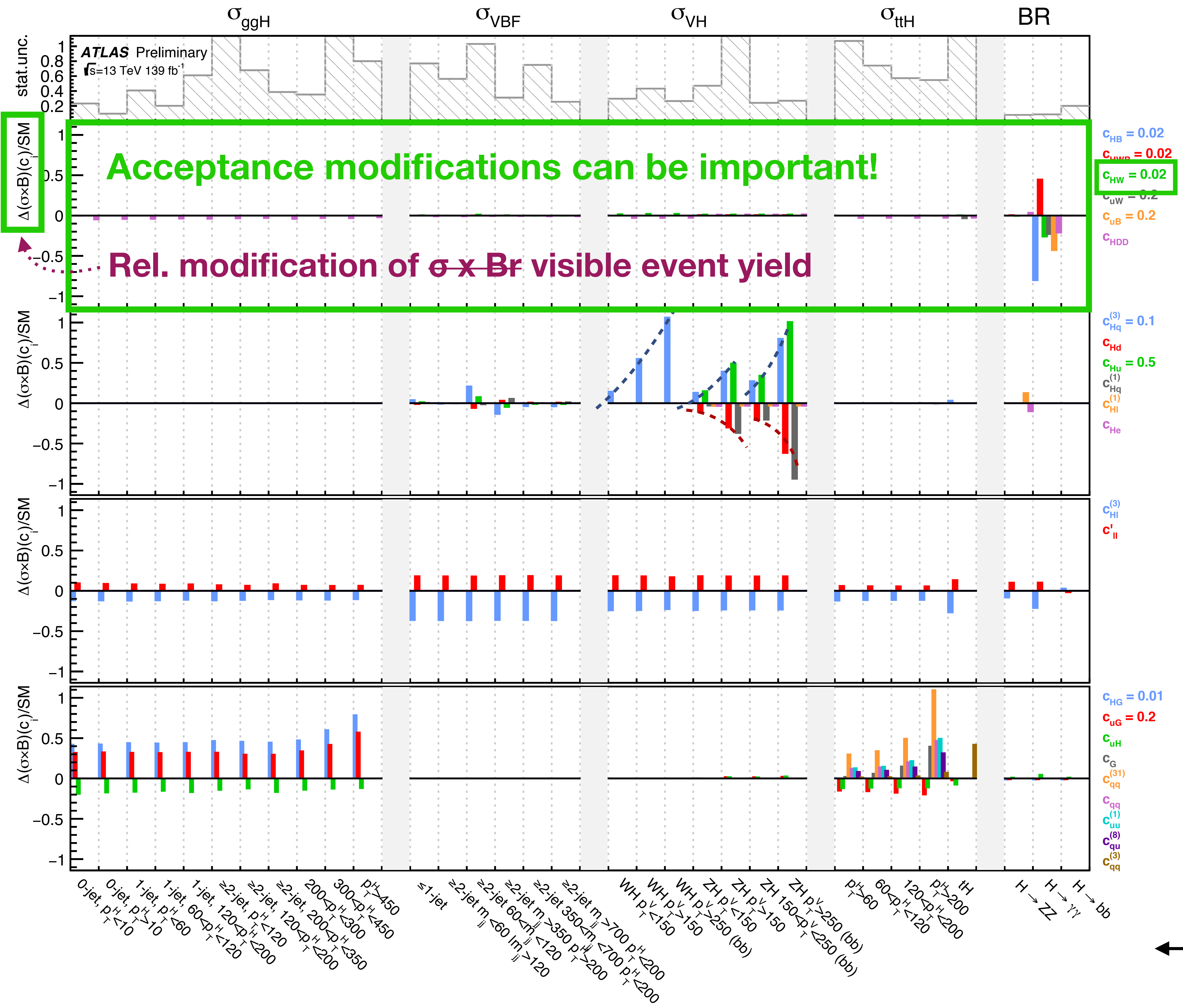
Modifications to g_{EW}

Higgs-(fermion)-gauge interactions

4-fermion interactions

← STXS bins

All operators at a glance



Acceptance modifications can be important!

Rel. modification of ~~σ x Br~~ visible event yield

Higgs-gauge interactions

Higgs-fermion-gauge interactions

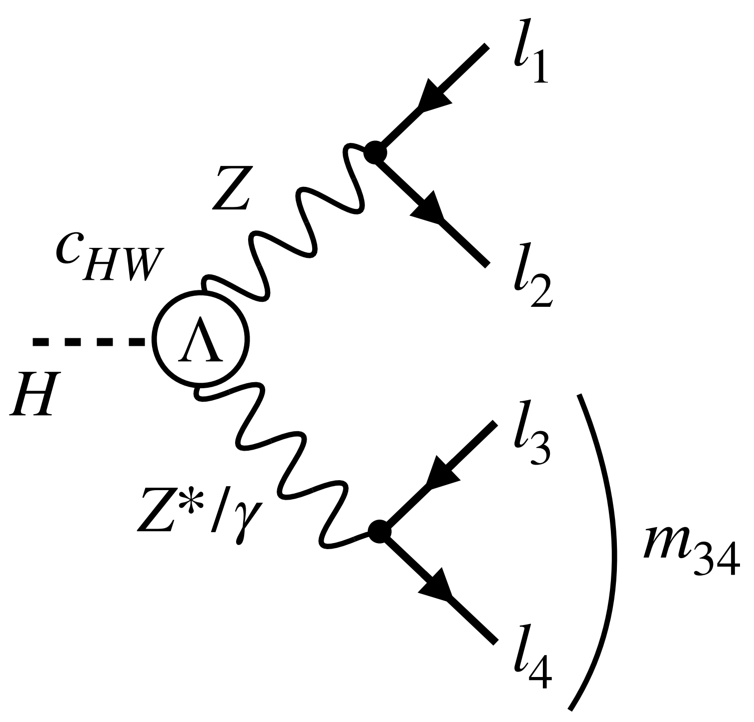
Modifications to g_{EW}

Higgs-(fermion)-gauge interactions

4-fermion interactions

← STXS bins

Acceptance modifications in H→ZZ*→4l



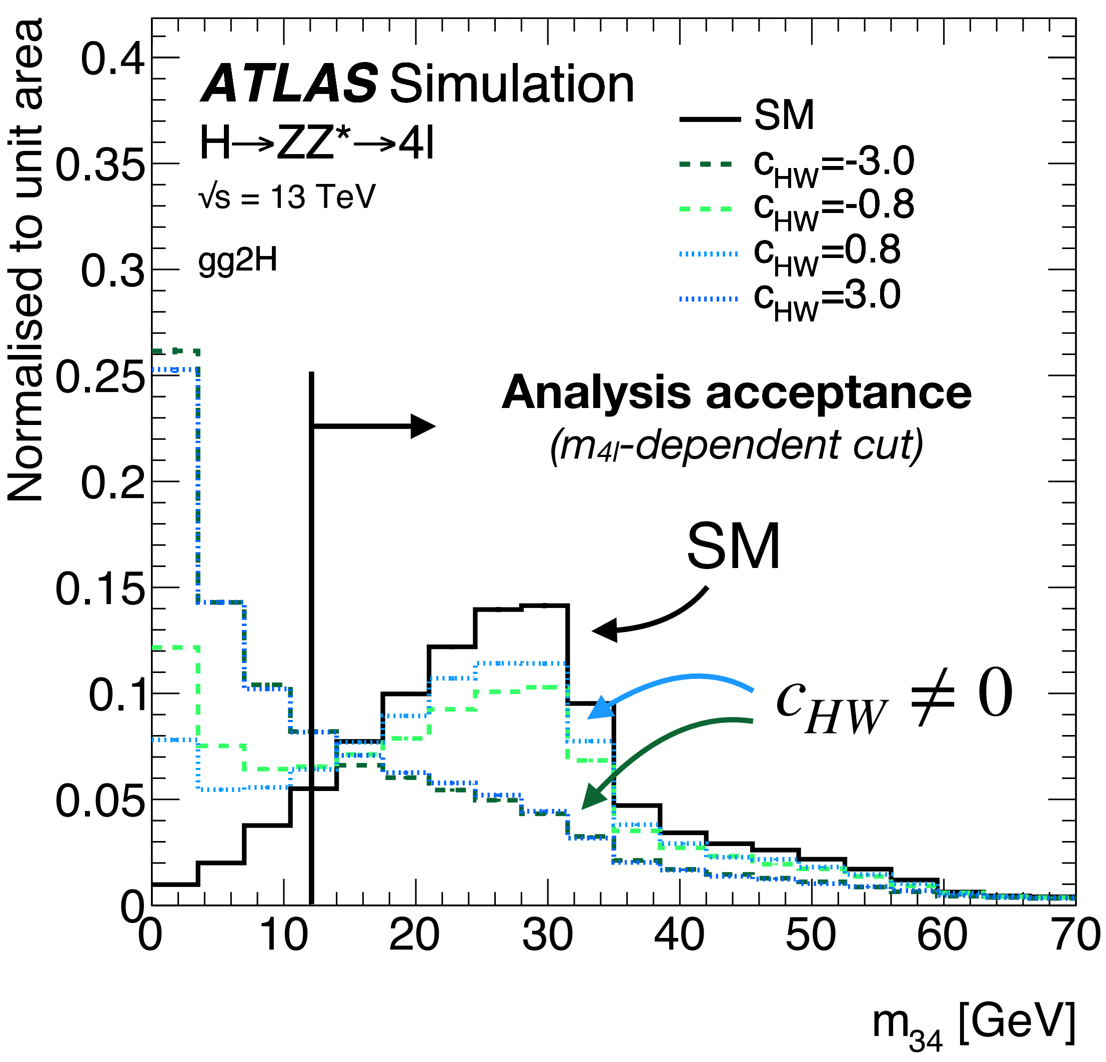
H→4l analysis applies cut on inv. mass of off-shell Z (m_{34})

m_{34}-distribution can change significantly in SMEFT (e.g. caused by c_{HW})

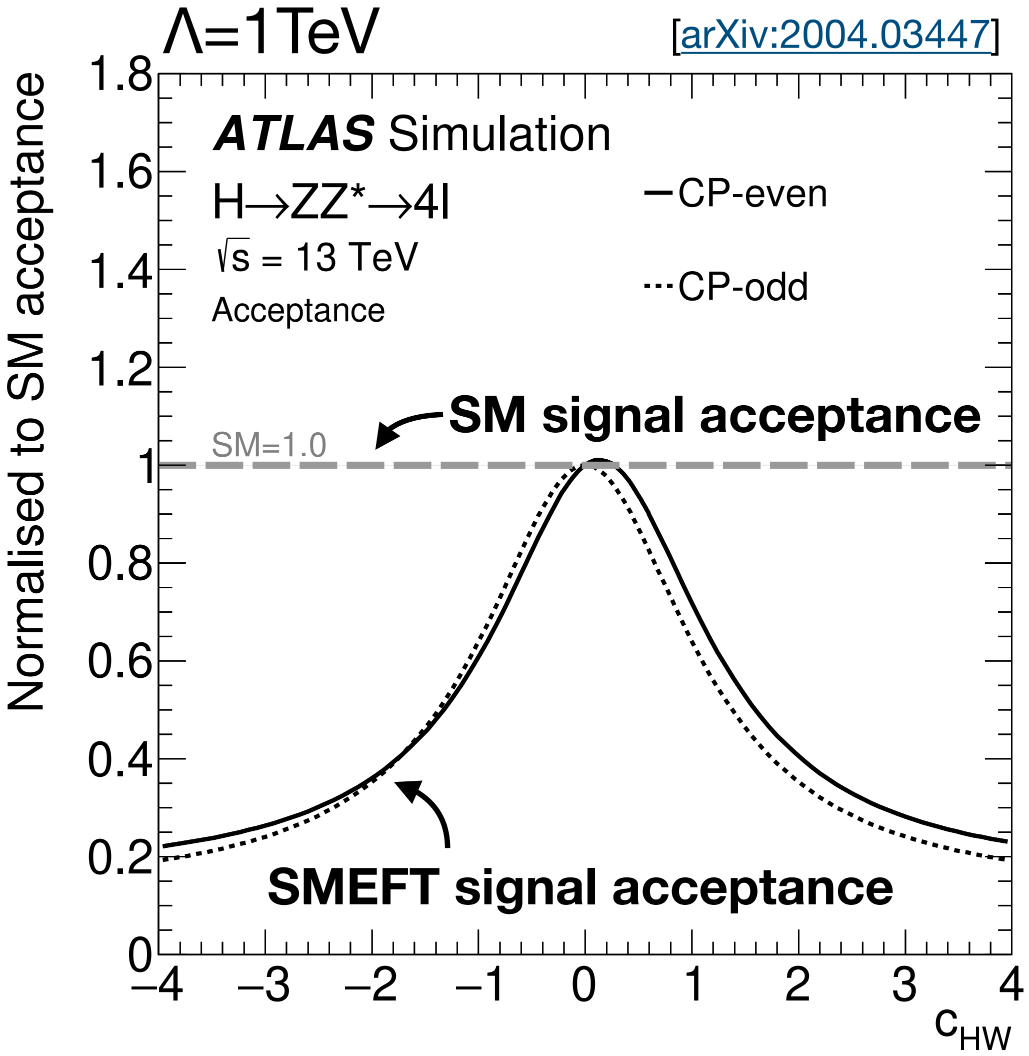
Analysis signal acceptance drops!

Λ=1TeV

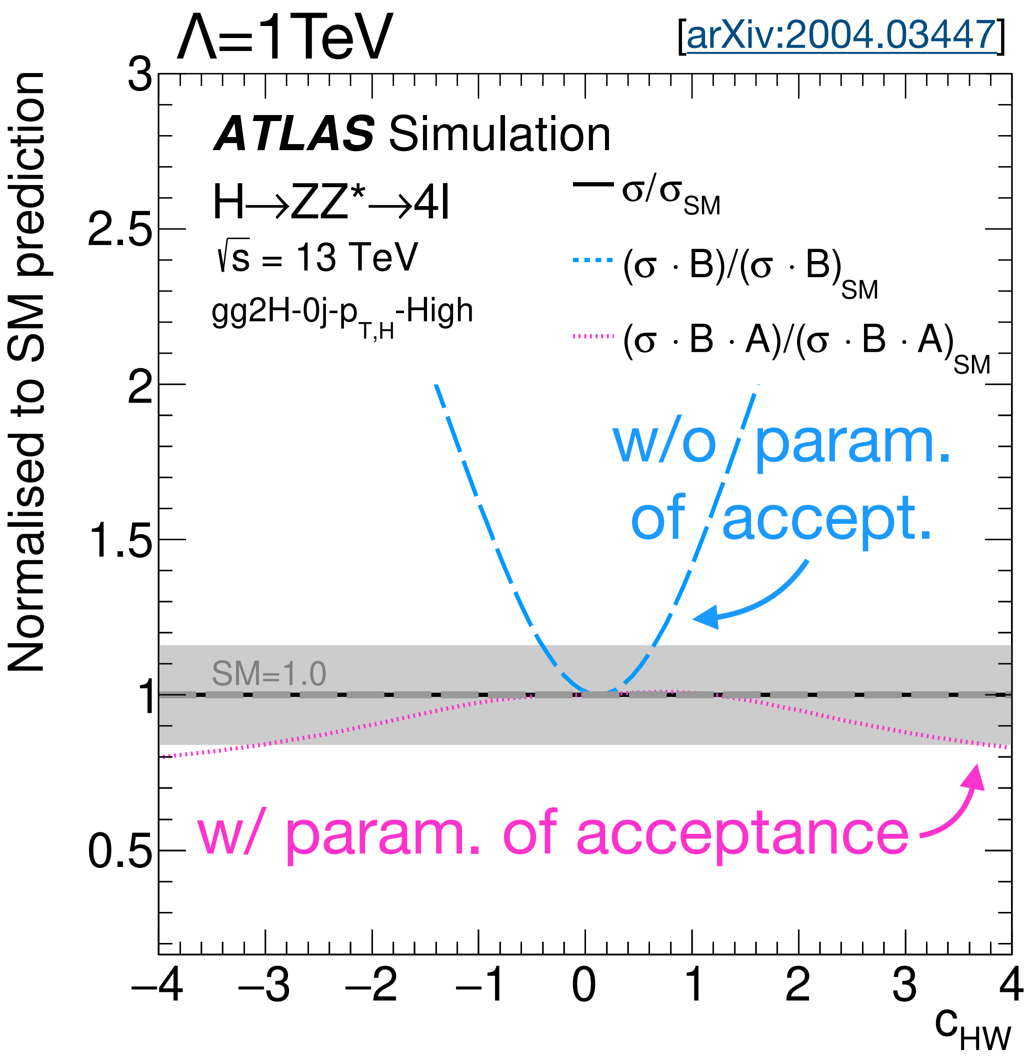
[arXiv:2004.03447]



Acceptance modifications in H→ZZ*→4l



Analysis signal acceptance drops!

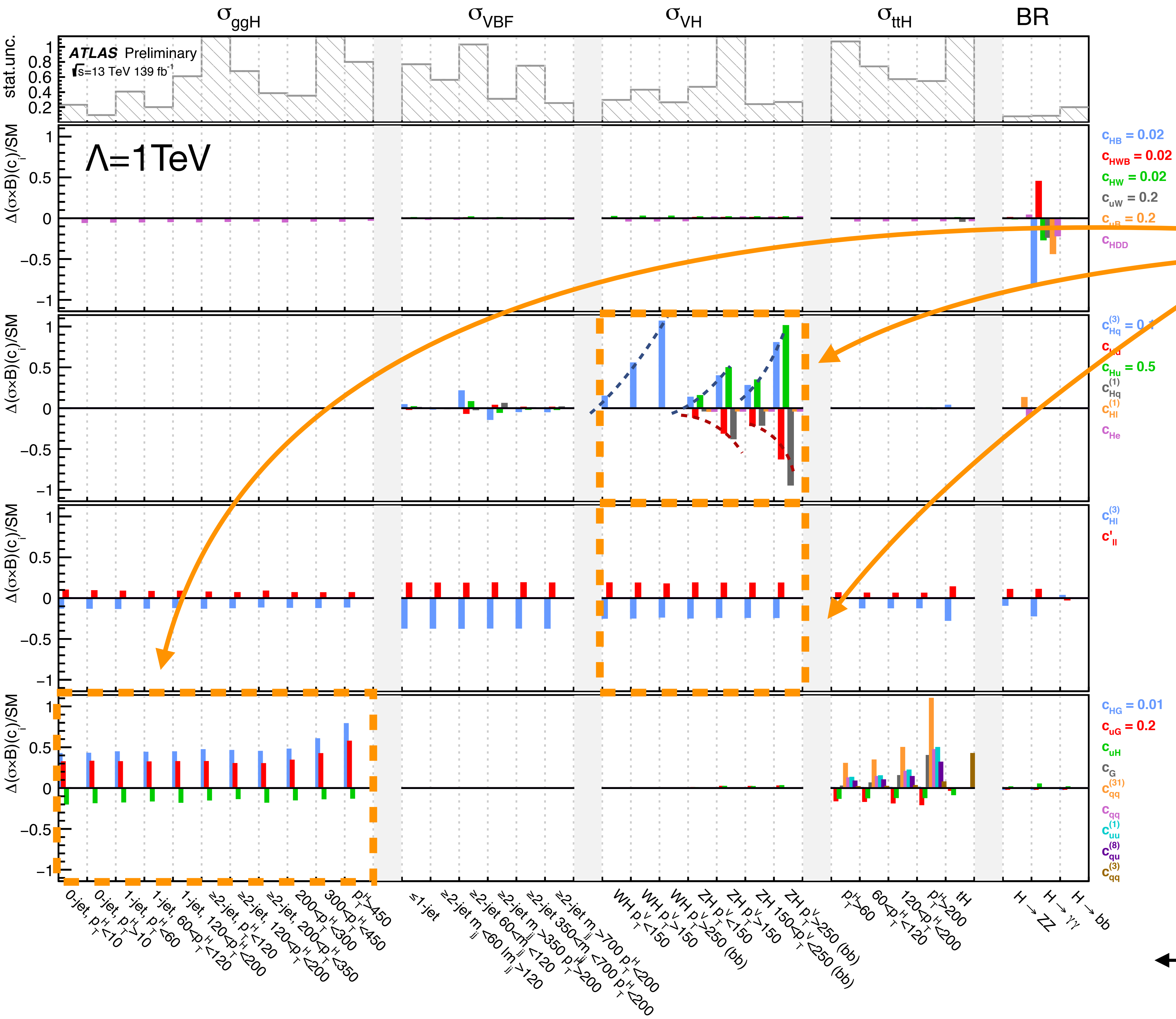


Parametrisation of σ x Br

Acceptance modification totally changes trend!

SMEFT-modifications to analysis acceptance significant!

All operators at a glance



Impact of many operators degenerate!

No simultaneous constraints possible

↓

*Identify operator **combinations** that can be **independently constrained***

← STXS bins

Principal components

Group together operators with similar effects (on the available data) …

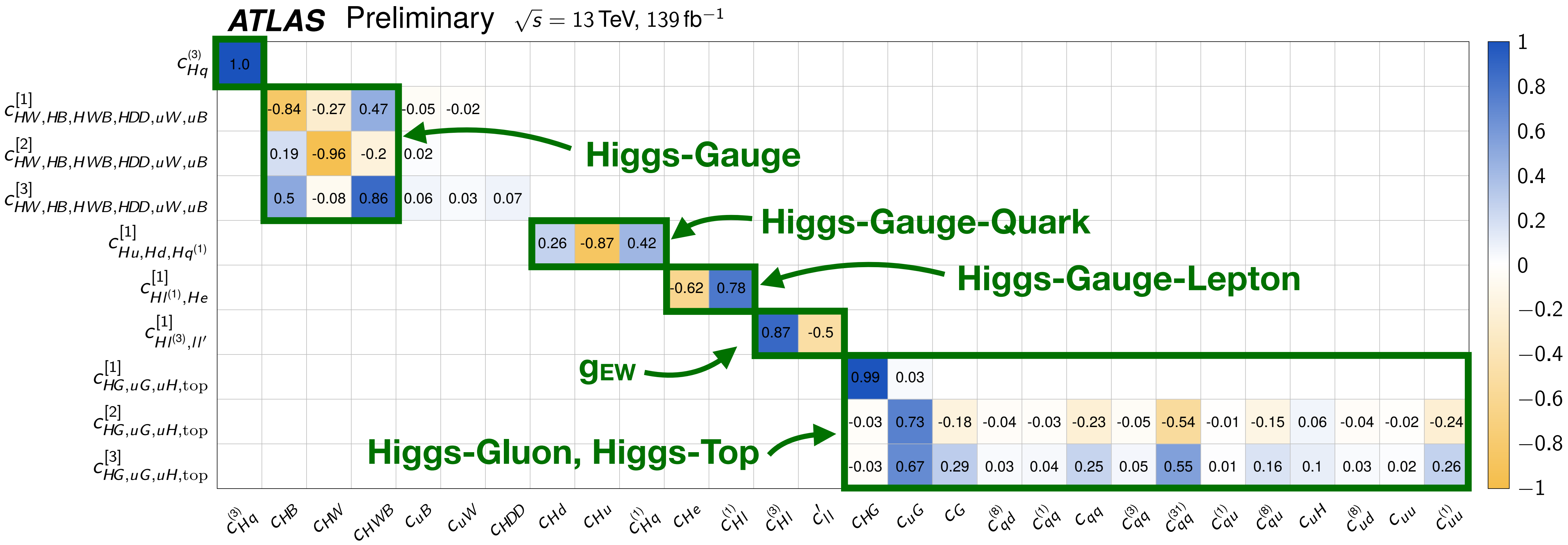
… **drop combinations that cannot be well constrained** (on the available data) …

… **and keep the rest**

"Principal component analysis"

Can "simultaneously" constrain 10 operator combinations

(with manageable correlations)

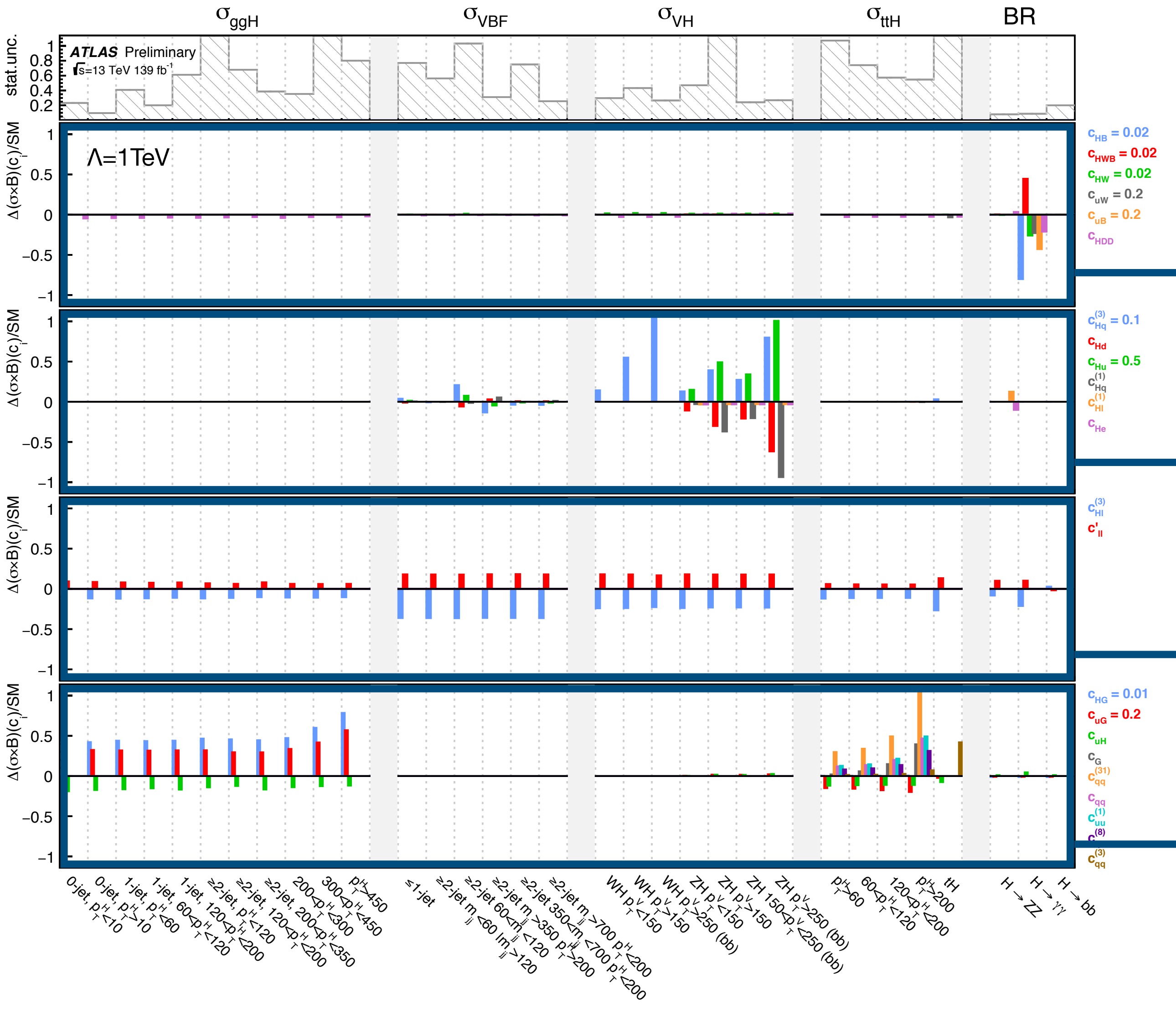


	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c_{ll}'	c_{HG}	c_{uG}	c_{G}	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$
$c_{Hq}^{(3)}$	1.0																											
$c^{[1]}_{HW,HB,HWB,HDD,uW,uB}$		-0.84	-0.27	0.47	-0.05	-0.02																						
$c^{[2]}_{HW,HB,HWB,HDD,uW,uB}$		0.19	-0.96	-0.2	0.02																							
$c^{[3]}_{HW,HB,HWB,HDD,uW,uB}$		0.5	-0.08	0.86	0.06	0.03	0.07																					
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$								0.26	-0.87	0.42																		
$c^{[1]}_{Hl^{(1)},He}$											-0.62	0.78																
$c^{[1]}_{Hl^{(3)},ll'}$													0.87	-0.5														
$c^{[1]}_{HG,uG,uH,\mathrm{top}}$															0.99	0.03												
$c^{[2]}_{HG,uG,uH,\mathrm{top}}$															-0.03	0.73	-0.18	-0.04	-0.03	-0.23	-0.05	-0.54	-0.01	-0.15	0.06	-0.04	-0.02	-0.24
$c^{[3]}_{HG,uG,uH,\mathrm{top}}$															-0.03	0.67	0.29	0.03	0.04	0.25	0.05	0.55	0.01	0.16	0.1	0.03	0.02	0.26

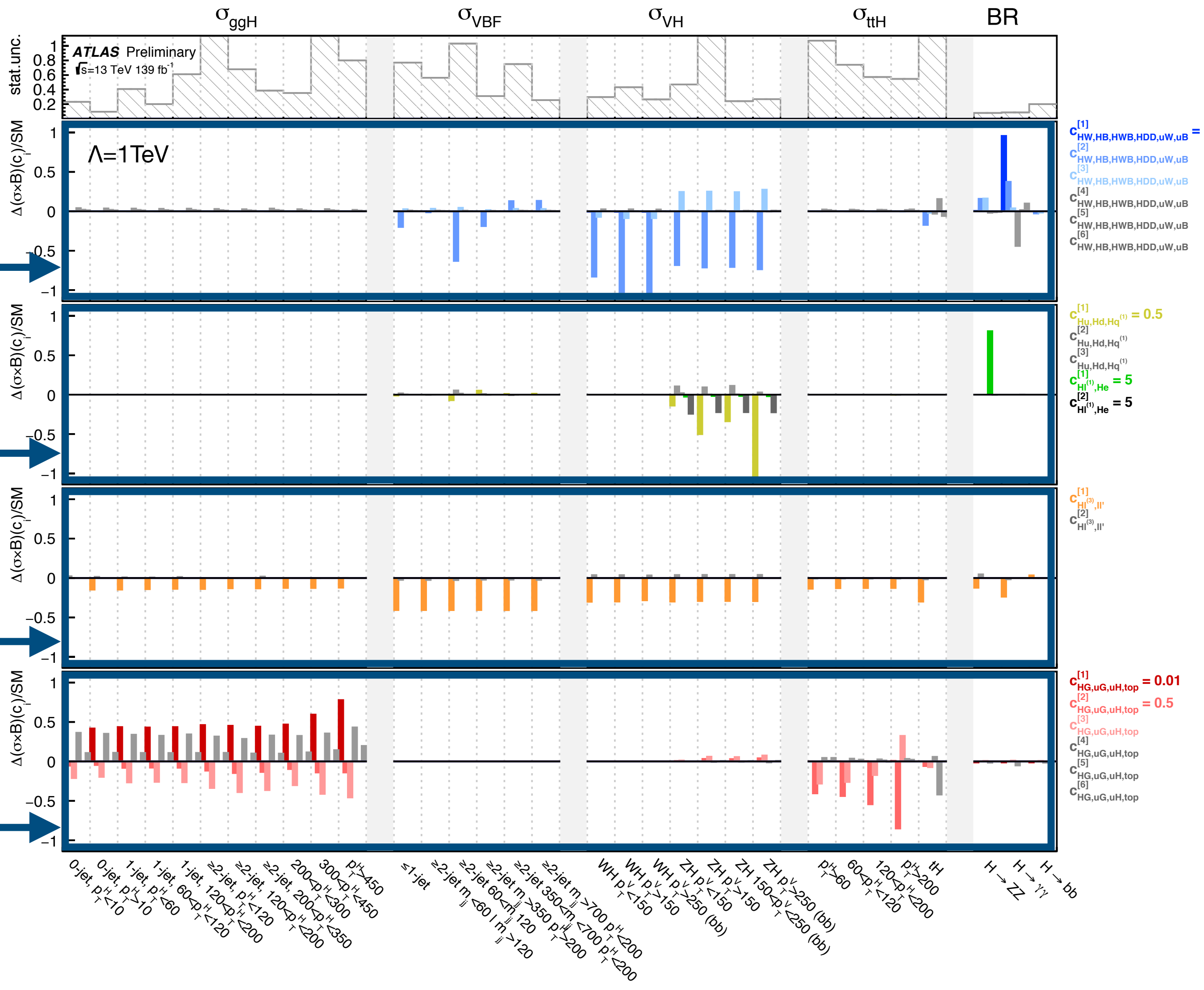
⟵ Warsaw basis operators ⟶

Principal components

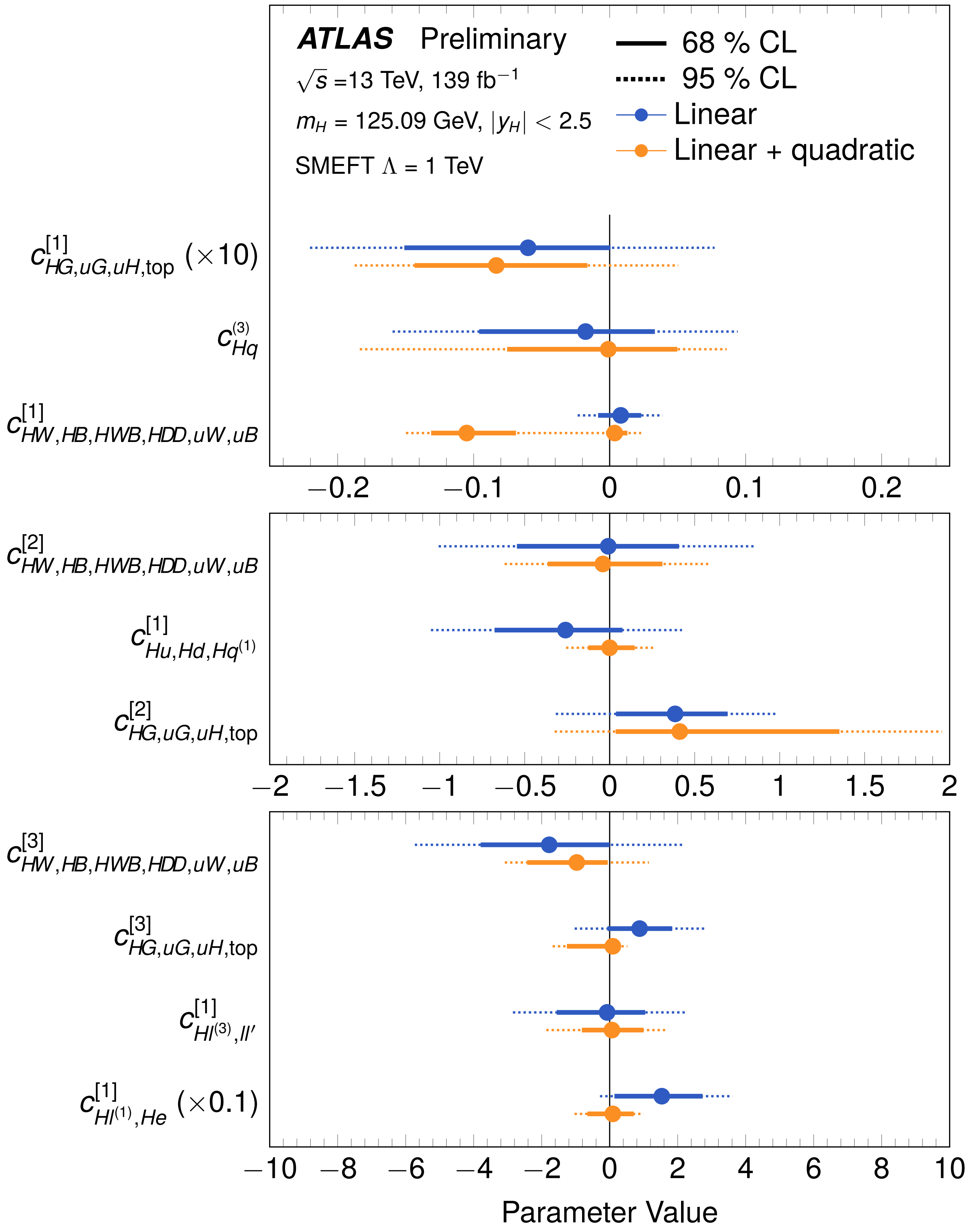
Warsaw basis



Principal components



One-dimensional limits



1d-limits on Wilson coefficients from **simultaneous fit** to **10 operator combinations**

Limits on Wilson coefficients range from $\mathcal{O}(0.1)$ to $\mathcal{O}(5)$

scales probed

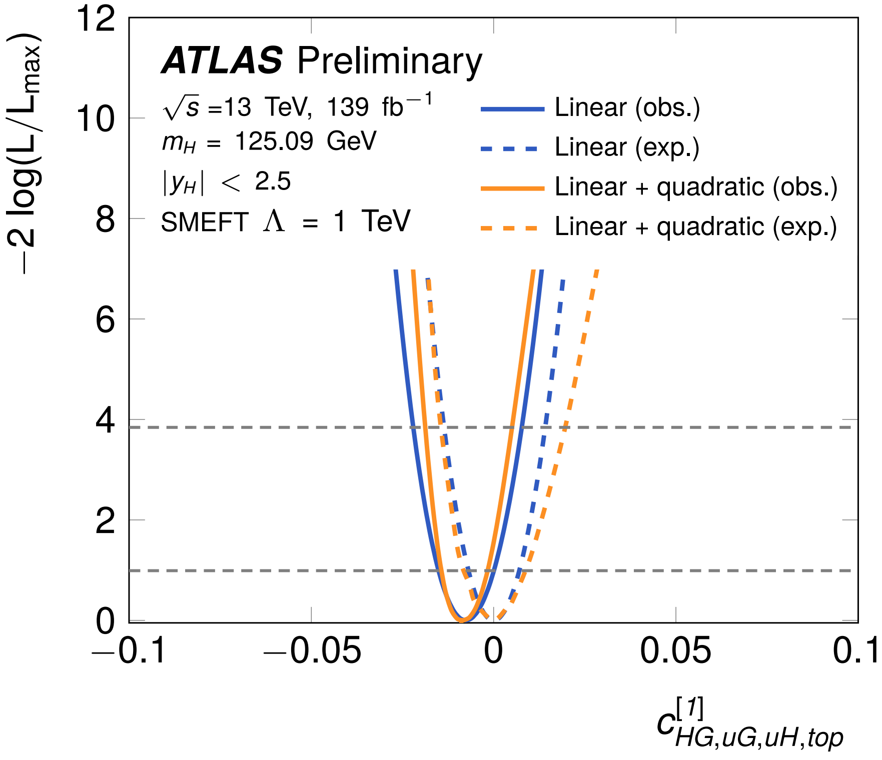
$$\frac{\Lambda}{\sqrt{c_i}} = 3\,\text{TeV}$$

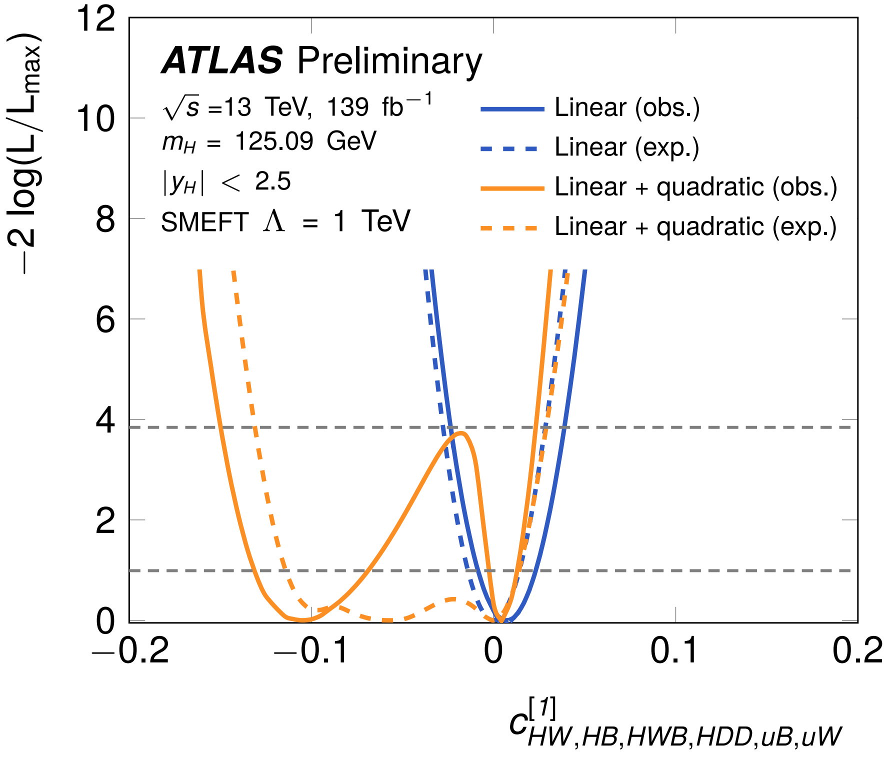
$$\frac{\Lambda}{\sqrt{c_i}} = 0.45\,\text{TeV}$$

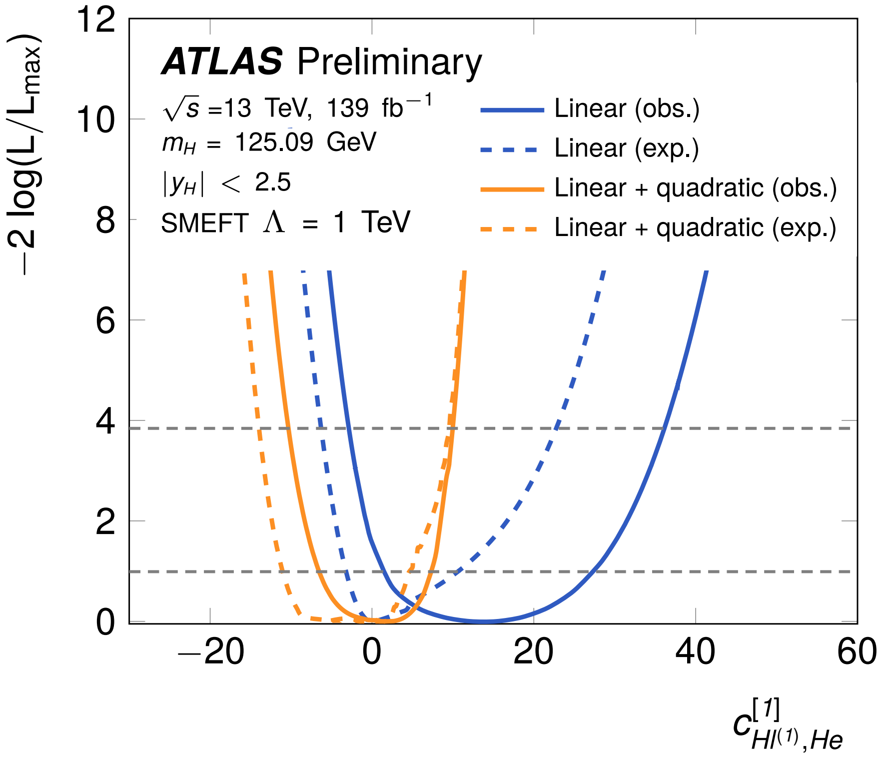
Impact of parametrisation

Compare 1d-limits for linear and linear + quadratic parametrisations

(all other Wilson coefficients profiled)



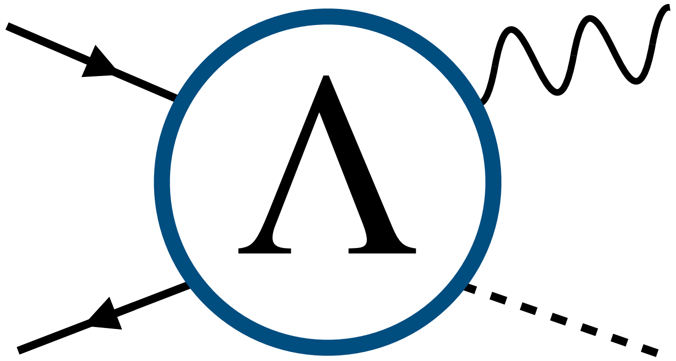




Limits generally in good agreement …

… but significant differences for few operator combinations

… indicative of sensitivity to Λ^{-4} effects ("theory uncertainty")



Higgs + diboson combination

[ATL-PHYS-PUB-2021-010]

Higgs + diboson combination

Combined measurement of H→WW*→eνμν (ggH and VBF) **and pp→WW→eνμν, based on existing analyses** (36 fb^{-1})

Challenging combination:

Orthogonal signal (region) **definition** ($m_{e\mu} \gtrsim 55$ GeV)
(CRs originally overlapping; made orthogonal)

WW as background of H→WW*

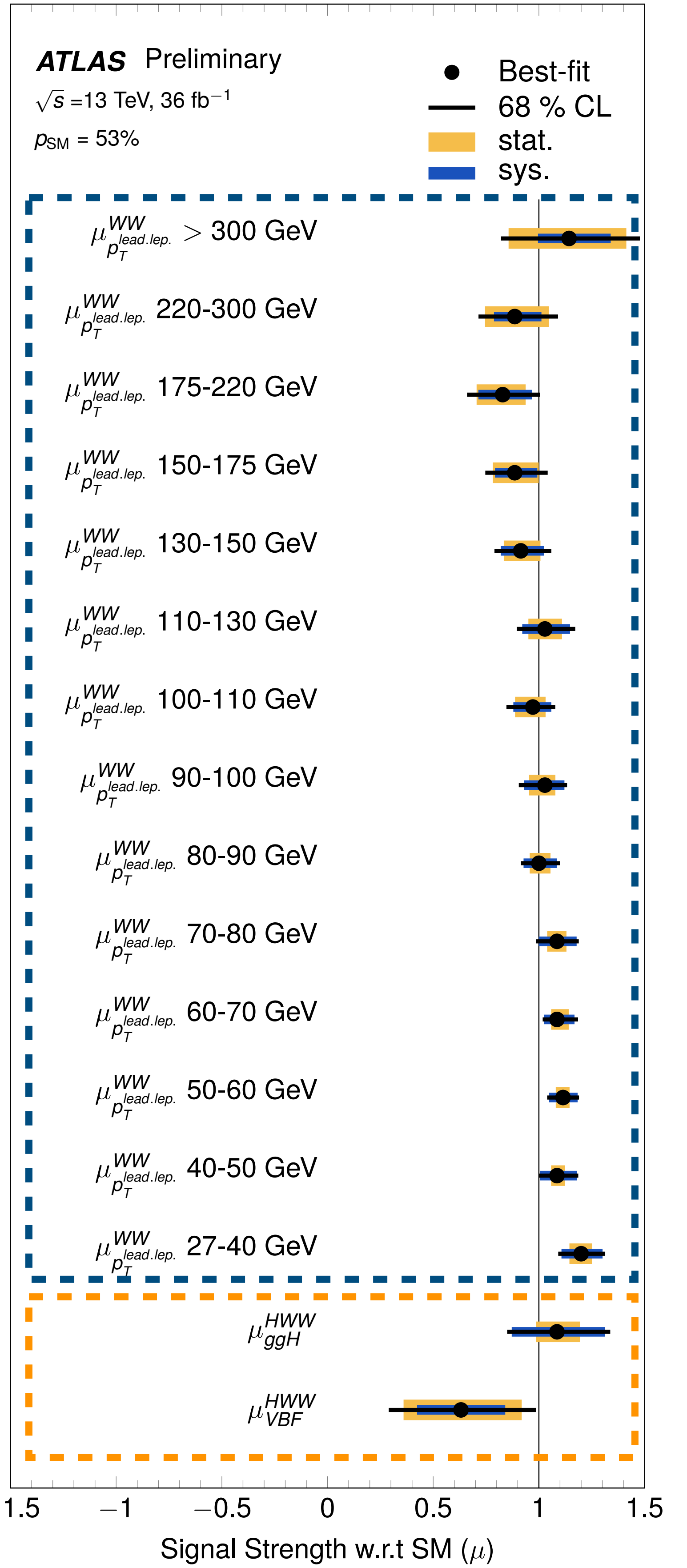
Acceptance modifications
O(10%) for $\mathcal{O}_{HW}$

… paving the way for future global fits

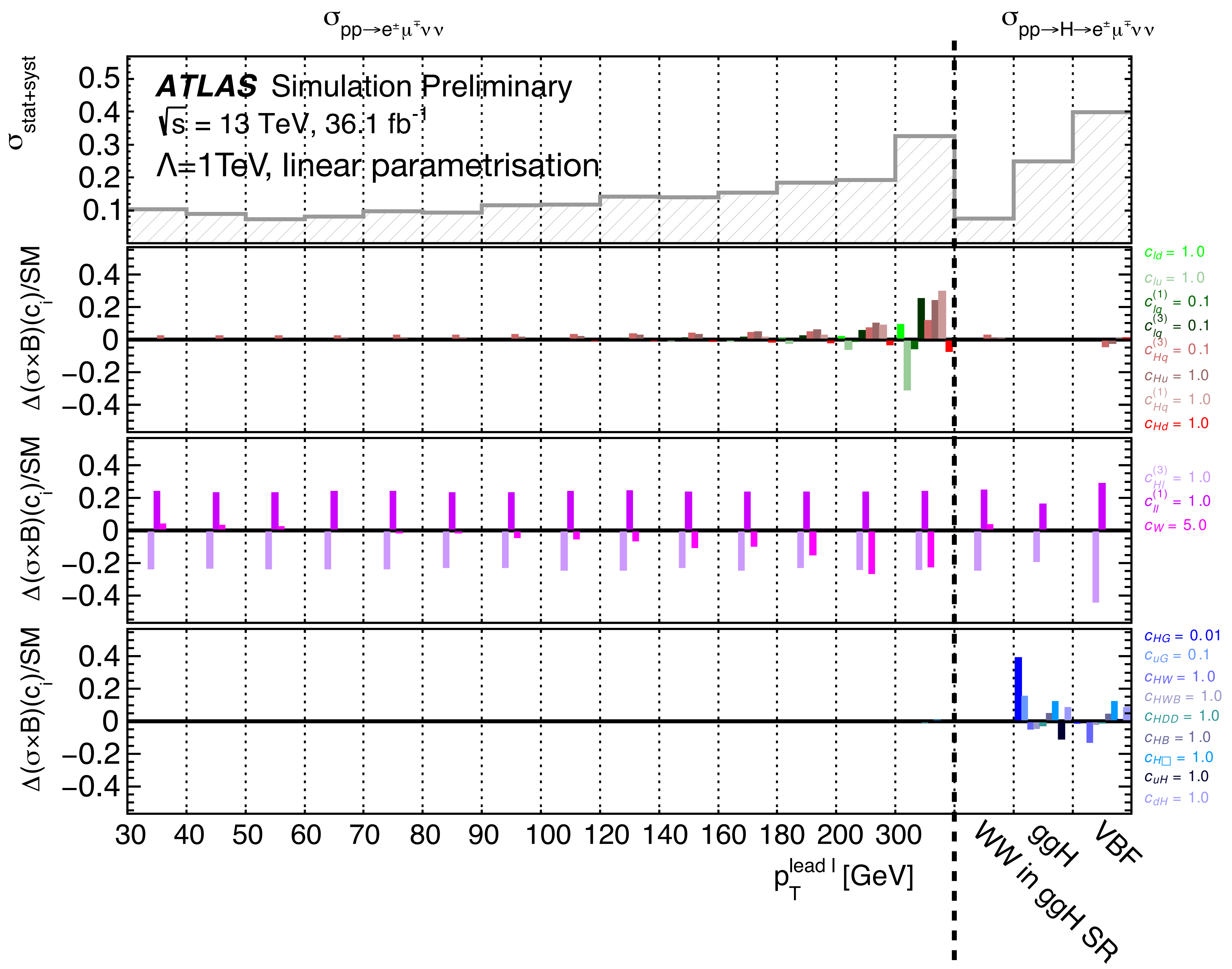
Inputs to SMEFT interpretation:

pp→WW: differential cross-section w.r.t. p_T of leading lepton $\frac{d\sigma}{dp_T^{\text{lead. lep.}}}$

H→WW*: inclusive ggH and VBF signal strengths



All operators at a glance



4-fermion interactions

Modifications to g_{EW}

Higgs-fermion-gauge interactions

Higgs / gauge / fermion interactions

pp→WW differential cross-section

H→WW*

One-dimensional limits

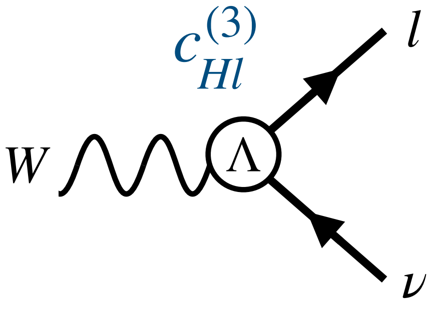
1d-limits on Wilson coefficients of individual Warsaw-basis operators

Only linear parametrisation considered

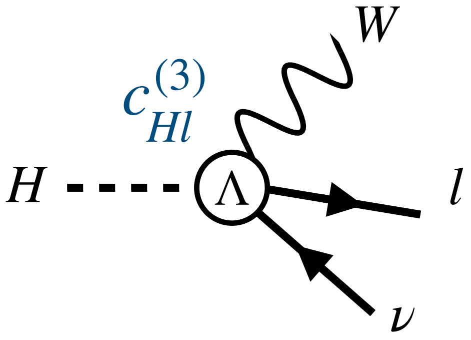
(principal components listed in backup)

Exploit complementarity of different measurements

$$\mathscr{O}_{Hl}^{(3)} \sim (H^\dagger D H)(\bar{L}L)$$

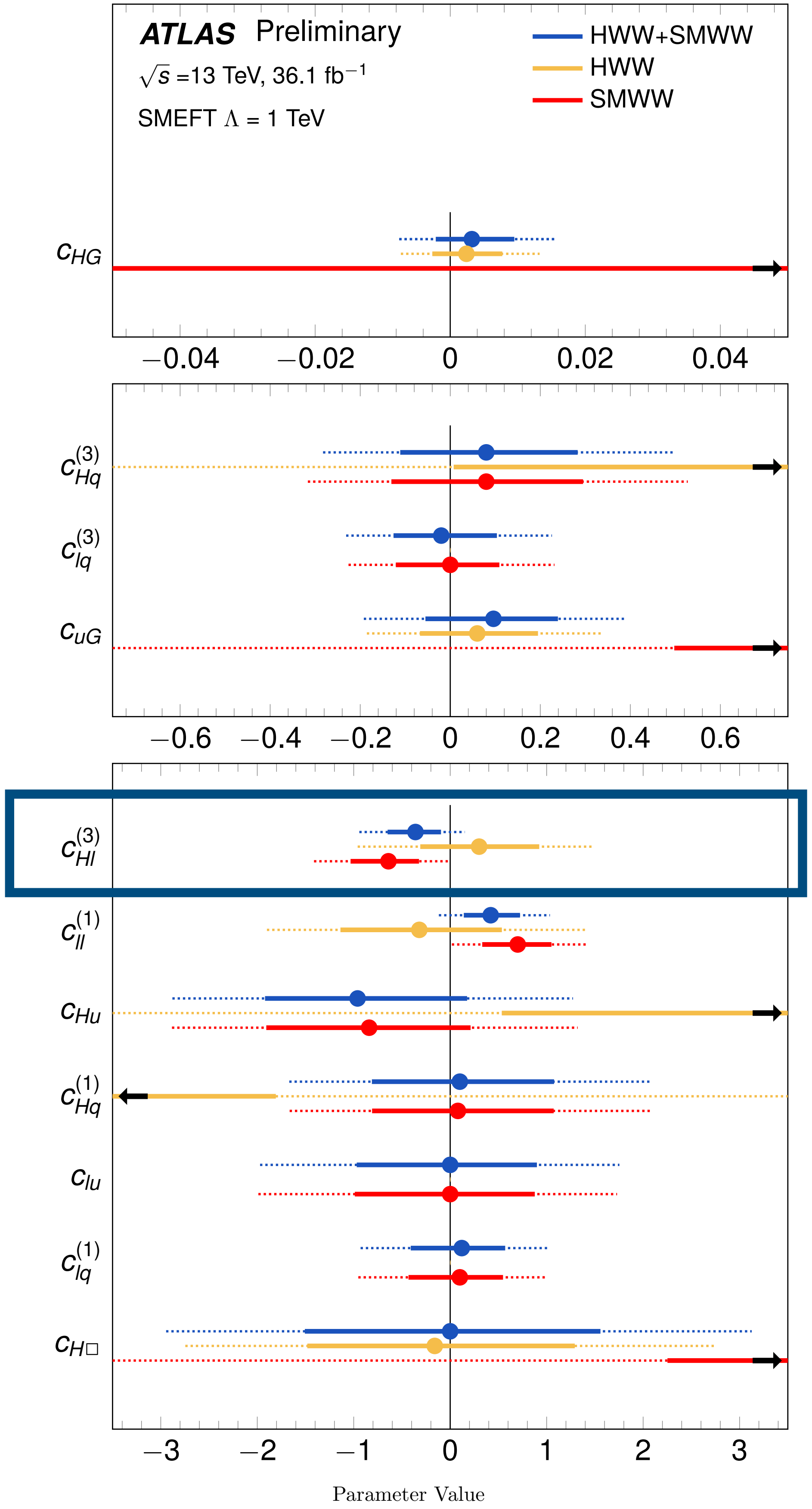


pp→WW



H→WW*

SMEFT is a global scheme!



Summary and outlook

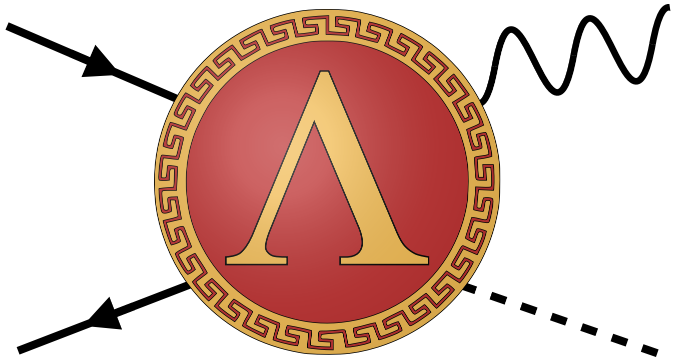
EFT interpretations of Higgs measurements at ATLAS advancing rapidly!

Starting from **existing measurements** of **STXS**
or **differential cross-sections**

Modifications to **analysis acceptance included** where relevant
“An analysis is not a black box!”

Moving towards **larger-scale combinations** (ATLAS global EFT fit)
with the **full dataset**
“SMEFT is a global scheme!”

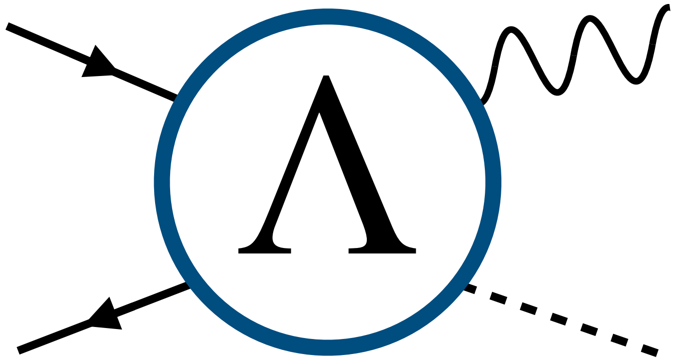
Stay tuned for more results!



Backup

The letter lambda was used by the Spartan army
as a symbol of Lacedaemon (900s–192 BC).

https://en.wikipedia.org/wiki/Sparta



Higgs combination

[ATLAS-CONF-2020-053]

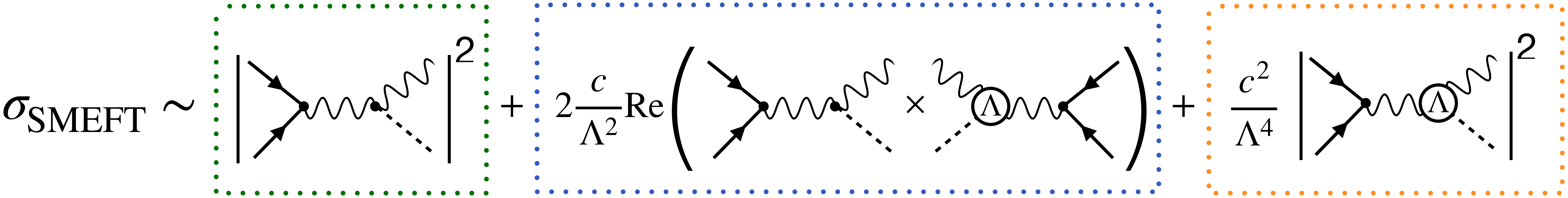
Observables in the SMEFT

Cross-sections:

SM

SM / dim-6 interference
"linear", (E/Λ)²

dim-6 squared
"quadratic", (E/Λ)⁴



$$= \quad \sigma_{\text{SM}} \times \left(1 + \alpha_i c_i^{(6)} + \beta_{ij} c_i^{(6)} c_j^{(6)} \right)$$

Multiplicative modification of SM cross-section

Partial decay widths:

$$\frac{\Gamma(H \to f)_{\text{SMEFT}}}{\Gamma(H \to f)_{\text{SM}}} = 1 + A_i^f c_i^{(6)} + B_{ij}^f c_i^{(6)} c_j^{(6)}$$

Total decay widths:

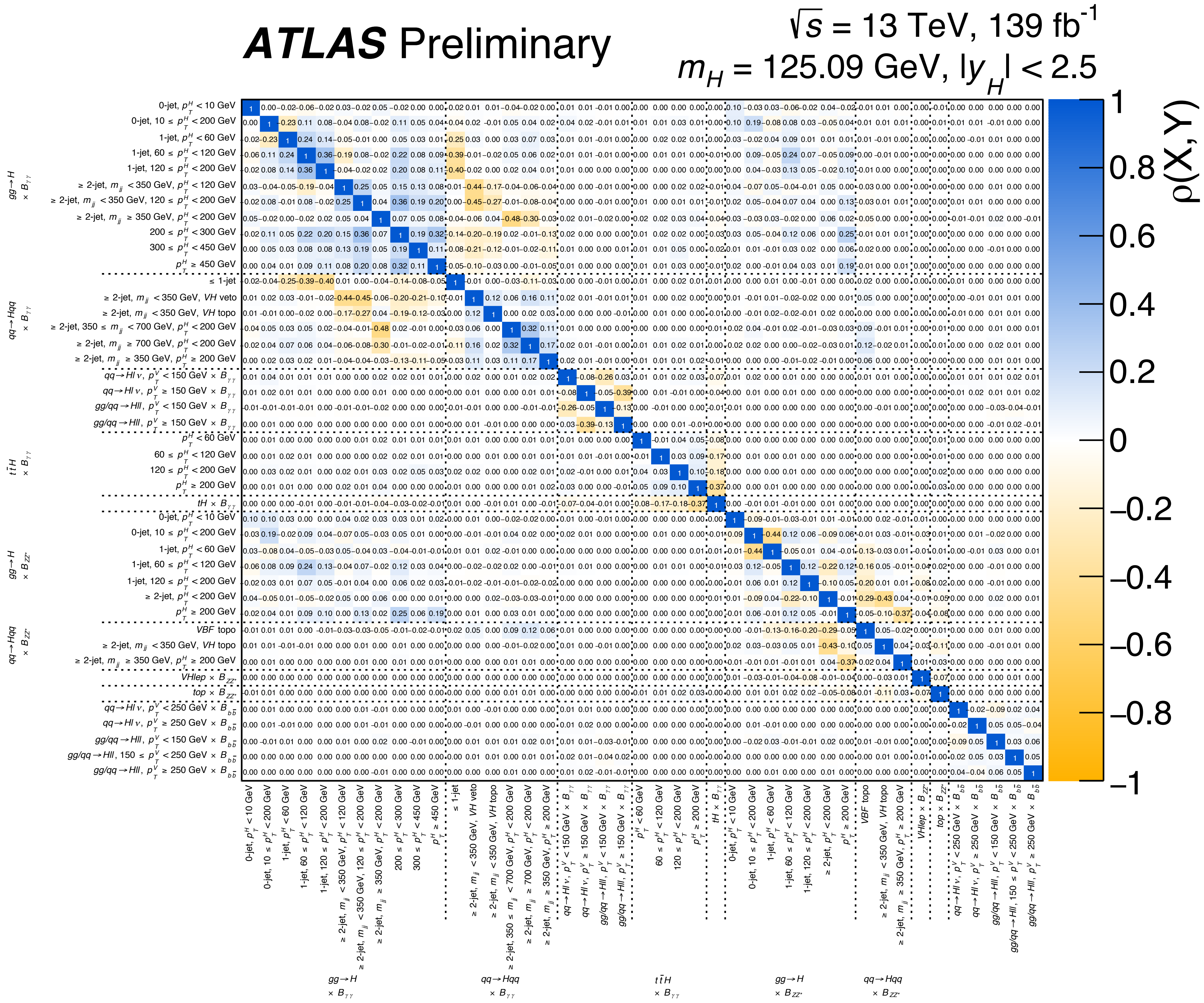
$$\frac{\Gamma(H)_{\text{SMEFT}}}{\Gamma(H)_{\text{SM}}} = 1 + A_i c_i^{(6)} + B_{ij} c_i^{(6)} c_j^{(6)}$$

Observables are polynomial in Wilson coefficients c_i

Merging of STXS bins

STXS Region Stage-0	STXS Region Stage-1.2	$H\to\gamma\gamma$	$H\to ZZ^*\to 4\ell$	$H\to b\bar{b}$ (VH)
ggH	$N_{\text{jets}}=0,\ p_T^H<10$	$N_{\text{jets}}=0,\ p_T^H<10$	$N_{\text{jets}}=0,\ p_T^H<10$	
	$N_{\text{jets}}=0,\ 10<p_T^H$	$N_{\text{jets}}=0,\ 10<p_T^H$	$N_{\text{jets}}=0,\ 10<p_T^H$	
	$N_{\text{jets}}=1,\ p_T^H<60$	$N_{\text{jets}}=1,\ p_T^H<60$	$N_{\text{jets}}=1,\ p_T^H<60$	
	$N_{\text{jets}}=1,\ 60<p_T^H<120$	$N_{\text{jets}}=1,\ 60<p_T^H<120$	$N_{\text{jets}}=1,\ 60<p_T^H<120$	
	$N_{\text{jets}}=1,\ 120<p_T^H<200$	$N_{\text{jets}}=1,\ 120<p_T^H<200$	$N_{\text{jets}}=1,\ 120<p_T^H<200$	
	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ p_T^H<60$	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ p_T^H<120$	$N_{\text{jets}}\geq 2,\ p_T^H\leq 200$	
	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ 60<p_T^H<120$	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ p_T^H<120$	$N_{\text{jets}}\geq 2,\ p_T^H\leq 200$	
	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ 120<p_T^H<200$	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ 120<p_T^H<200$	$N_{\text{jets}}\geq 2,\ p_T^H\leq 200$	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_T^H<200,\ p_T^{Hjj}<25$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ p_T^H<200$	$N_{\text{jets}}\geq 2,\ p_T^H\leq 200$	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_T^H<200,\ 25<p_T^{Hjj}$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ p_T^H<200$	$N_{\text{jets}}\geq 2,\ p_T^H\leq 200$	
	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_T^H<200,\ p_T^{Hjj}<25$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ p_T^H<200$	$N_{\text{jets}}\geq 2,\ p_T^H\leq 200$	
	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_T^H<200,\ 25<p_T^{Hjj}$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ p_T^H<200$	$N_{\text{jets}}\geq 2,\ p_T^H\leq 200$	
	$200<p_T^H<300$	$200<p_T^H<300$	$200<p_T^H$	
	$300<p_T^H<450$	$300<p_T^H<450$	$200<p_T^H$	
	$450<p_T^H<650$	$450<p_T^H$	$200<p_T^H$	
	$650<p_T^H$	$450<p_T^H$	$200<p_T^H$	
$qq\to Hqq$ "VBF", "$qqVH$ had"	$N_{\text{jets}}=0$	$N_{\text{jets}}\leq 1$		
	$N_{\text{jets}}=1$	$N_{\text{jets}}\leq 1$		
	$N_{\text{jets}}\geq 2,\ m_{jj}<60$	$N_{\text{jets}}\geq 2,\ m_{jj}<60\vee 120<m_{jj}<350$	VBF	
	$N_{\text{jets}}\geq 2,\ 60<m_{jj}<120$	$N_{\text{jets}}\geq 2,\ 60<m_{jj}<120$	$N_{\text{jets}}\geq 2,\ 60<m_{jj}<120$	
	$N_{\text{jets}}\geq 2,\ 120<m_{jj}<350$	$N_{\text{jets}}\geq 2,\ m_{jj}<60\vee 120<m_{jj}<350$	VBF	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}\ 200<p_T^H$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ 200<p_T^H$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ 200<p_T^H$	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_T^H<200,\ p_T^{Hjj}<25$	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_T^H<200$	VBF	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_T^H<200,\ 25<p_T^{Hjj}$	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_T^H<200$	VBF	
	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_T^H<200,\ p_T^{Hjj}<25$	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_T^H<200$	VBF	
	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_T^H<200,\ 25<p_T^{Hjj}$	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_T^H<200$	VBF	
$qq\to H\ell\nu$ "$qqWH$ lep"	$p_T^V<75$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ p_T^V<150$	VH lep	$WH\ p_T^V<250$
	$75<p_T^V<150$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ p_T^V<150$	VH lep	$WH\ p_T^V<250$
	$150<p_T^V<250$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ 150<p_T^V$	VH lep	$WH\ p_T^V<250$
	$250<p_T^V<400$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ 150<p_T^V$	VH lep	$WH\ 250<p_T^V$
	$400<p_T^V$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ 150<p_T^V$	VH lep	$WH\ 250<p_T^V$
$qq\to H\ell\ell$ "$qqZH$ lep"	$p_T^V<75$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ p_T^V<150$	VH lep	$ZH\ p_T^V<150$
	$75<p_T^V<150$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ p_T^V<150$	VH lep	$ZH\ p_T^V<150$
	$150<p_T^V<250$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_T^V$	VH lep	$ZH\ 150<p_T^V<250$
	$250<p_T^V<400$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_T^V$	VH lep	$ZH\ 250<p_T^V$
	$400<p_T^V$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_T^V$	VH lep	$ZH\ 250<p_T^V$
$gg\to H\ell\ell$ "$ggZH$ lep"	$p_T^V<75$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ p_T^V<150$	VH lep	$ZH\ p_T^V<150$
	$75<p_T^V<150$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ p_T^V<150$	VH lep	$ZH\ p_T^V<150$
	$150<p_T^V<250$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_T^V$	VH lep	$ZH\ 150<p_T^V<250$
	$250<400$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_T^V$	VH lep	$ZH\ 250<p_T^V$
	$250<p_T^V$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_T^V$	VH lep	$ZH\ 250<p_T^V$
$t\bar{t}H$	$p_T^H<60$	$p_T^H<60$	$t(t)H$	
	$60<p_T^H<120$	$60<p_T^H<120$	$t(t)H$	
	$120<p_T^H<200$	$120<p_T^H<200$	$t(t)H$	
	$200<p_T^H<300$	$200<p_T^H$	$t(t)H$	
	$300<p_T^H$	$200<p_T^H$	$t(t)H$	
	$b\bar{b}H$	merged with ggH		
	tH	tH	$t(t)H$	

Correlations of combined STXS measurement

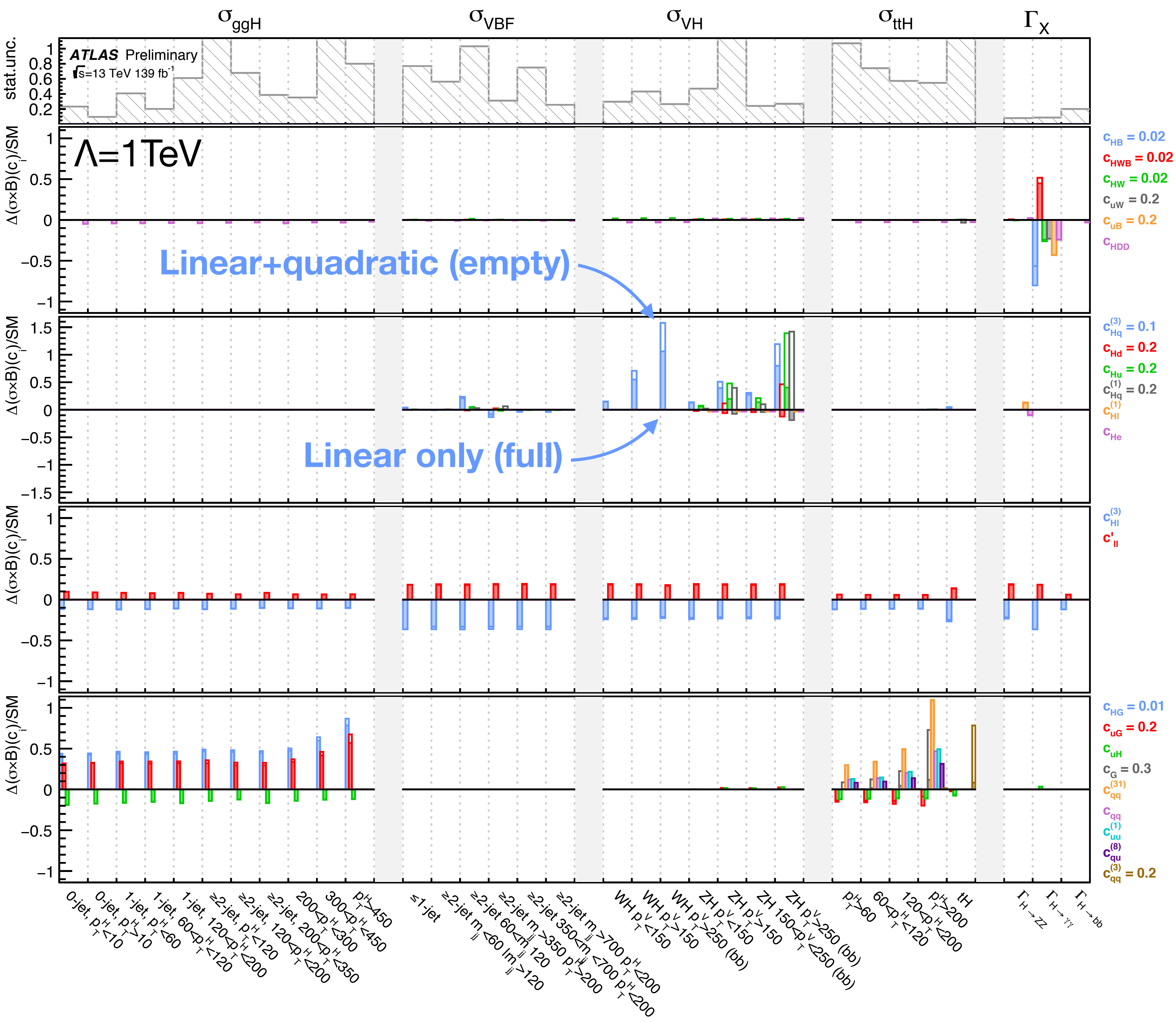


Operator definitions

Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r \widetilde{H})$
$c^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$c^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$c^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$c^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$

Wilson coefficient	Operator
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
c'_{ll}	$(\bar{l}_p \gamma_\mu l_t)(\bar{l}_r \gamma^\mu l_s)$
$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$
$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$
$c^{(31)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$
c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
$c^{(1)}_{uu}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$
$c^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$
$c^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$c^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$c^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
c_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

Linear vs. linear+quadratic parametrisation

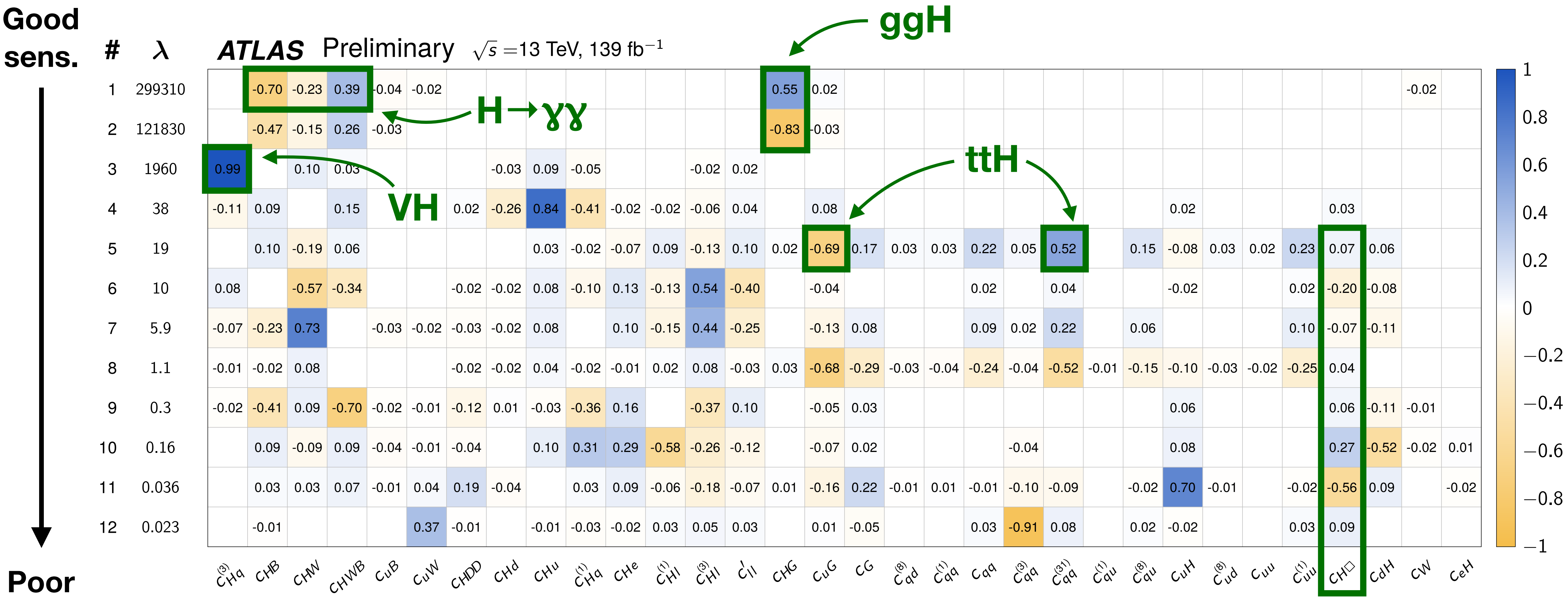


Linear+quadratic (empty)

Linear only (full)

Extraction of principal components

1) Find eigenbasis of Hessian of likelihood around SM: $$(H_{\text{SMEFT}})_{ij} = \left.\frac{\partial^2 \log L}{\partial c_i \partial c_j}\right|_{\text{exp}}$$



Good sens.

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

#	λ	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c_{ll}'	c_{HG}	c_{uG}	c_{G}	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$	$c_{H\Box}$	c_{dH}	c_{W}	c_{eH}
1	299310		-0.70	-0.23	0.39	-0.04	-0.02									0.55	0.02															-0.02	
2	121830		-0.47	-0.15	0.26	-0.03										-0.83	-0.03																
3	1960	0.99		0.10	0.03				-0.03	0.09	-0.05			-0.02	0.02																		
4	38	-0.11	0.09		0.15			0.02	-0.26	0.84	-0.41	-0.02	-0.02	-0.06	0.04		0.08									0.02				0.03			
5	19		0.10	-0.19	0.06					0.03	-0.02	-0.07	0.09	-0.13	0.10	0.02	-0.69	0.17	0.03	0.03	0.22	0.05	0.52		0.15	-0.08	0.03	0.02	0.23	0.07	0.06		
6	10	0.08		-0.57	-0.34			-0.02	-0.02	0.08	-0.10	0.13	-0.13	0.54	-0.40		-0.04				0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9	-0.07	-0.23	0.73		-0.03	-0.02	-0.03	-0.02	0.08		0.10	-0.15	0.44	-0.25		-0.13	0.08			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-0.01	-0.02	0.08				-0.02	-0.02	0.04	-0.02	-0.01	0.02	0.08	-0.03	0.03	-0.68	-0.29	-0.03	-0.04	-0.24	-0.04	-0.52	-0.01	-0.15	-0.10	-0.03	-0.02	-0.25	0.04			
9	0.3	-0.02	-0.41	0.09	-0.70	-0.02	-0.01	-0.12	0.01	-0.03	-0.36	0.16		-0.37	0.10		-0.05	0.03								0.06				0.06	-0.11	-0.01	
10	0.16		0.09	-0.09	0.09	-0.04	-0.01	-0.04		0.10	0.31	0.29	-0.58	-0.26	-0.12		-0.07	0.02				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036		0.03	0.03	0.07	-0.01	0.04	0.19	-0.04		0.03	0.09	-0.06	-0.18	-0.07	0.01	-0.16	0.22	-0.01	0.01	-0.01	-0.10	-0.09		-0.02	0.70	-0.01		-0.02	-0.56	0.09		-0.02
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01	-0.05			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			

Poor sens.

ggH

H→γγ

VH

ttH

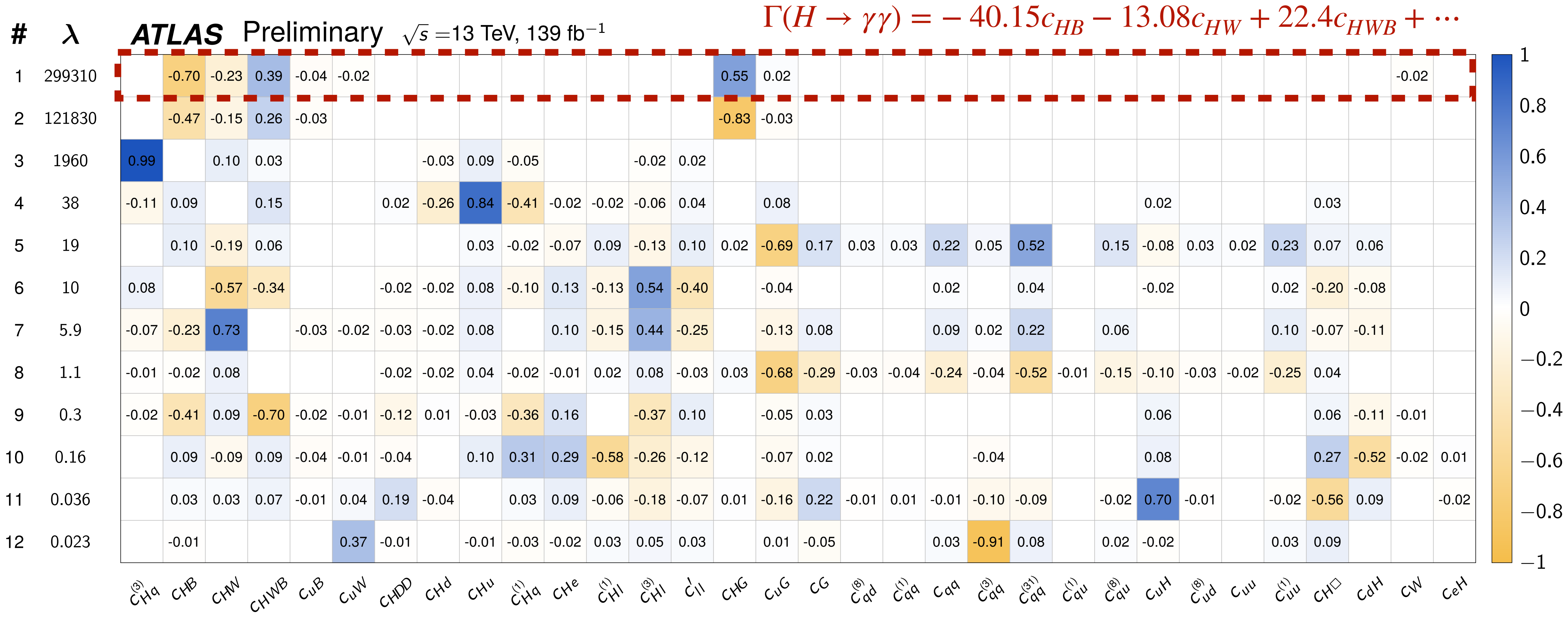
Higgs wave-function renormalisation

(scales inclusive cross-section)

Extraction of principal components

1) Find eigenbasis of Hessian of likelihood around SM: $(H_{\text{SMEFT}})_{ij} = \left.\dfrac{\partial^2 \log L}{\partial c_i \partial c_j}\right|_{\text{exp}}$

Good sens.



$\Gamma(H \to \gamma\gamma) = -40.15c_{HB} - 13.08c_{HW} + 22.4c_{HWB} + \cdots$

#	λ	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c'_{ll}	c_{HG}	c_{uG}	c_G	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$	$c_{H\Box}$	c_{dH}	c_W	c_{eH}
1	299310		-0.70	-0.23	0.39	-0.04	-0.02									0.55	0.02															-0.02	
2	121830		-0.47	-0.15	0.26	-0.03										-0.83	-0.03																
3	1960	0.99		0.10	0.03				-0.03	0.09	-0.05			-0.02	0.02																		
4	38	-0.11	0.09		0.15			0.02	-0.26	0.84	-0.41	-0.02	-0.02	-0.06	0.04		0.08									0.02				0.03			
5	19		0.10	-0.19	0.06					0.03	-0.02	-0.07	0.09	-0.13	0.10	0.02	-0.69	0.17	0.03	0.03	0.22	0.05	0.52		0.15	-0.08	0.03	0.02	0.23	0.07	0.06		
6	10	0.08		-0.57	-0.34			-0.02	-0.02	0.08	-0.10	0.13	-0.13	0.54	-0.40		-0.04				0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9	-0.07	-0.23	0.73		-0.03	-0.02	-0.03	-0.02	0.08		0.10	-0.15	0.44	-0.25		-0.13	0.08			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-0.01	-0.02	0.08				-0.02	-0.02	0.04	-0.02	-0.01	0.02	0.08	-0.03	0.03	-0.68	-0.29	-0.03	-0.04	-0.24	-0.04	-0.52	-0.01	-0.15	-0.10	-0.03	-0.02	-0.25	0.04			
9	0.3	-0.02	-0.41	0.09	-0.70	-0.02	-0.01	-0.12	0.01	-0.03	-0.36	0.16		-0.37	0.10		-0.05	0.03								0.06				0.06	-0.11	-0.01	
10	0.16		0.09	-0.09	0.09	-0.04	-0.01	-0.04		0.10	0.31	0.29	-0.58	-0.26	-0.12		-0.07	0.02				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036		0.03	0.03	0.07	-0.01	0.04	0.19	-0.04		0.03	0.09	-0.06	-0.18	-0.07	0.01	-0.16	0.22	-0.01	0.01	-0.01	-0.10	-0.09		-0.02	0.70	-0.01		-0.02	-0.56	0.09		-0.02
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01	-0.05			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			

Poor sens.

Extraction of principal components

2) Find eigenbases in physics-motivated subspaces of operators:

$$\begin{aligned}\{c_i\} \;=\; & \boxed{\{c^{(3)}_{Hq}\}} \times \\ & \{c_{HG}, c_{uG}, c_{uH}, c^{(1)}_{qq}, c_{qq}, c^{(3)}_{qq}, c^{(31)}_{qq}, c_{uu}, c^{(1)}_{uu}, c^{(8)}_{ud}, c^{(1)}_{qu}, c^{(8)}_{qu}, c^{(8)}_{qd}, c_G\} \times \\ & \boxed{\{c_{HW}, c_{HB}, c_{HWB}, c_{HDD}, c_{uW}, c_{uB},\}} \times \\ & \{c^{(1)}_{Hl}, c_{He}\} \times \\ & \{c^{(3)}_{Hl}, c'_{ll}\} \times \\ & \{c_{Hu}, c_{Hd}, c^{(1)}_{Hq}\}\end{aligned}$$

Parameter		Definition	Eigenvalue	Fit Parameter
$c^{(3)}_{Hq}$		$c^{(3)}_{Hq}$	1900	✓
$c^{[i]}_{HW,HB,HWB,HDD,uW,uB}$	1	$-0.27c_{HW} - 0.84c_{HB} + 0.47c_{HWB} - 0.02c_{uW} - 0.05c_{uB}$	245000	✓
	2	$-0.96c_{HW} + 0.19c_{HB} - 0.20c_{HWB} + 0.02c_{uB}$	33	✓
	3	$-0.08c_{HW} + 0.50c_{HB} + 0.86c_{HWB} + 0.07c_{HDD} + 0.03c_{uW} + 0.06c_{uB}$	4	✓
	4	$0.03c_{HWB} - 0.85c_{HDD} + 0.32c_{uW} + 0.43c_{uB}$	0.017	
	5	$-0.01c_{HW} + 0.07c_{HB} + 0.05c_{HWB} - 0.44c_{HDD} - 0.86c_{uW} - 0.23c_{uB}$	0.0077	
	6	$-0.01c_{HW} + 0.06c_{HB} + 0.04c_{HWB} - 0.29c_{HDD} + 0.39c_{uW} - 0.87c_{uB}$	0.0025	

Low sensitivity, not included

Extraction of principal components

2) Find eigenbases in physics-motivated subspaces of operators:

$$\begin{aligned}\{c_i\} \quad = \quad & \{c^{(3)}_{Hq}\} \times \\ & \boxed{\{c_{HG}, c_{uG}, c_{uH}, c^{(1)}_{qq}, c_{qq}, c^{(3)}_{qq}, c^{(31)}_{qq}, c_{uu}, c^{(1)}_{uu}, c^{(8)}_{ud}, c^{(1)}_{qu}, c^{(8)}_{qu}, c^{(8)}_{qd}, c_G\}} \times \\ & \{c_{HW}, c_{HB}, c_{HWB}, c_{HDD}, c_{uW}, c_{uB}, \} \times \\ & \{c^{(1)}_{Hl}, c_{He}\} \times \\ & \{c^{(3)}_{Hl}, c'_{ll}\} \times \\ & \{c_{Hu}, c_{Hd}, c^{(1)}_{Hq}\}\end{aligned}$$

Parameter		Definition	Eigenvalue	Fit Parameter
$c^{[i]}_{HG,uG,uH,top}$	1	$+0.999c_{HG} + 0.038c_{uG}$	176000	✓
	2	$-0.03c_{HG}+0.73c_{uG}-0.03c^{(1)}_{qq}-0.23c_{qq}-0.05c^{(3)}_{qq}-0.54c^{(31)}_{qq}-0.02c_{uu}-0.24c^{(1)}_{uu}-0.04c^{(8)}_{ud}-0.01c^{(1)}_{qu}-0.15c^{(8)}_{qu}-0.04c^{(8)}_{qd}-0.18c_G+0.06c_{uH}$	20	✓
	3	$-0.03c_{HG}+0.67c_{uG}+0.04c^{(1)}_{qq}+0.25c_{qq}+0.05c^{(3)}_{qq}+0.55c^{(31)}_{qq}+0.02c_{uu}+0.26c^{(1)}_{uu}+0.03c^{(8)}_{ud}+0.01c^{(1)}_{qu}+0.16c^{(8)}_{qu}+0.03c^{(8)}_{qd}+0.29c_G+0.1c_{uH}$	1.3	✓
	4	$+0.11c_{uG} + 0.01c_{qq} - 0.018c^{(3)}_{qq} + 0.029c^{(31)}_{qq} + 0.012c^{(1)}_{uu} - 0.993c_{uH}$	0.14	
	5	$+0.02c_{qq} - 1.0c^{(3)}_{qq} + 0.06c^{(31)}_{qq} + 0.03c^{(1)}_{uu} + 0.02c^{(8)}_{qu} + 0.02c_{uH}$	0.02	

Low sensitivity, not included

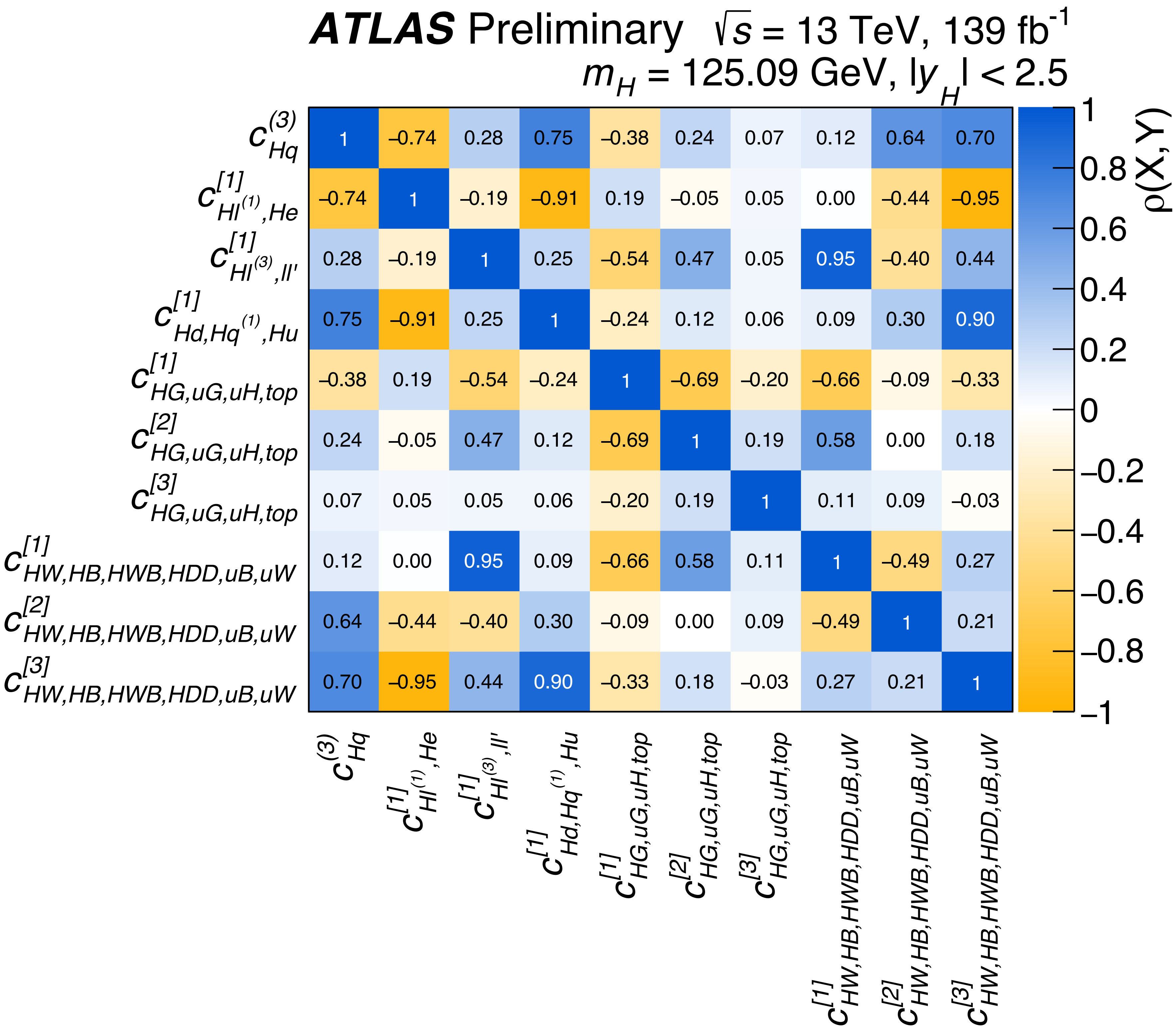
Extraction of principal components

2) Find eigenbases in physics-motivated subspaces of operators:

$$\begin{aligned}\{c_i\} \;=\; & \{c_{Hq}^{(3)}\} \times \\ & \{c_{HG}, c_{uG}, c_{uH}, c_{qq}^{(1)}, c_{qq}, c_{qq}^{(3)}, c_{qq}^{(31)}, c_{uu}, c_{uu}^{(1)}, c_{ud}^{(8)}, c_{qu}^{(1)}, c_{qu}^{(8)}, c_{qd}^{(8)}, c_G\} \times \\ & \{c_{HW}, c_{HB}, c_{HWB}, c_{HDD}, c_{uW}, c_{uB}, \} \times \\ & \boxed{\{c_{Hl}^{(1)}, c_{He}\}} \times \\ & \boxed{\{c_{Hl}^{(3)}, c_{ll}'\}} \times \\ & \boxed{\{c_{Hu}, c_{Hd}, c_{Hq}^{(1)}\}}\end{aligned}$$

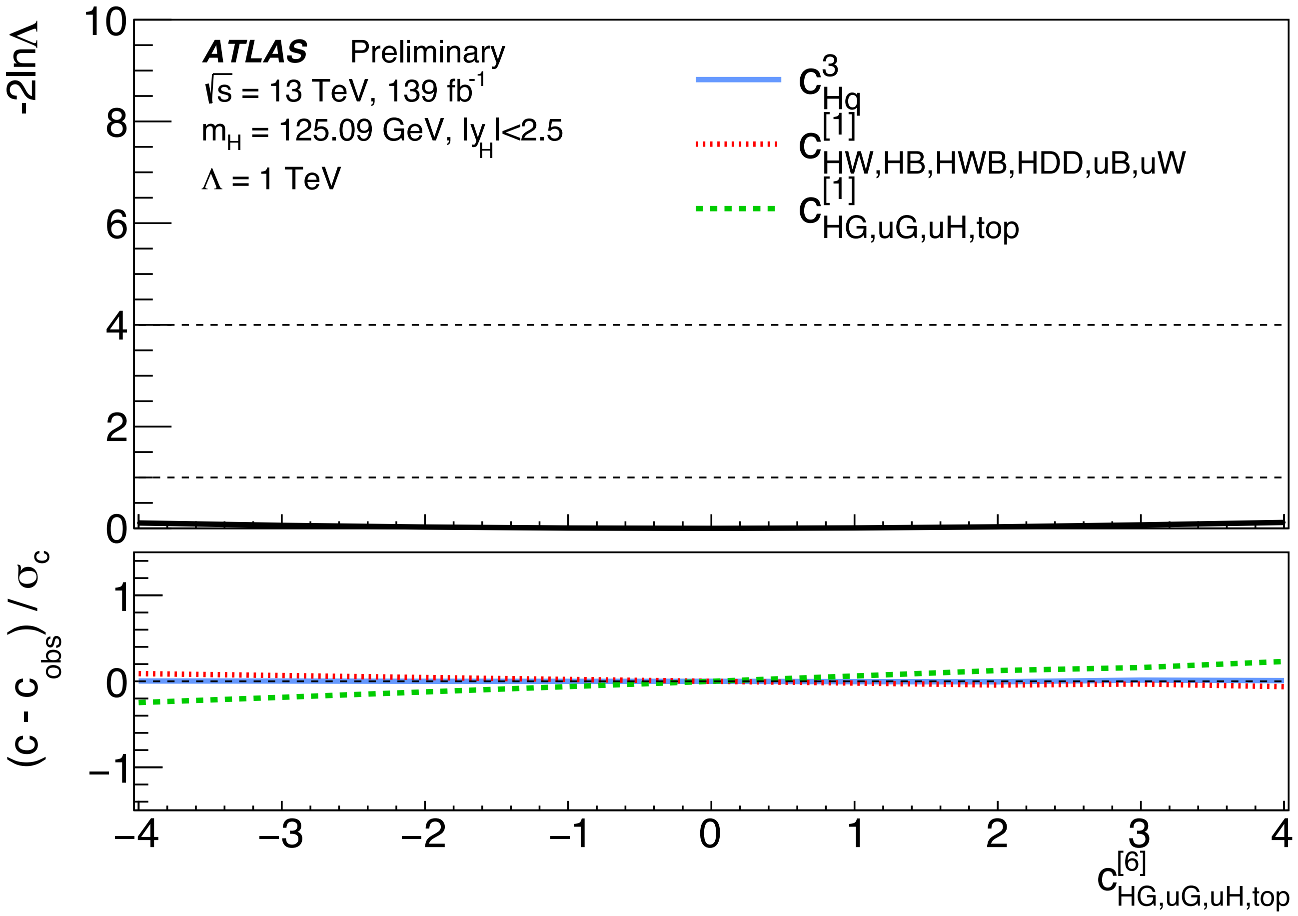
Parameter	Definition	Eigenvalue	Fit Parameter
$c^{[1]}_{Hl^{(1)},He}$	$+0.78c_{Hl}^{(1)} - 0.62c_{He}$	2.6	✓
$c^{[2]}_{Hl^{(1)},He}$	$+0.62c_{Hl}^{(1)} + 0.78c_{He}$	0.056	
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$	$-0.87c_{Hu} + 0.26c_{Hd} + 0.42c_{Hq}^{(1)}$	59	✓
$c^{[2]}_{Hu,Hd,Hq^{(1)}}$	$+0.41c_{Hu} - 0.09c_{Hd} + 0.91c_{Hq}^{(1)}$	0.10	
$c^{[3]}_{Hu,Hd,Hq^{(1)}}$	$-0.28c_{Hu} - 0.96c_{Hd} + 0.03c_{Hq}^{(1)}$	0.0018	
$c^{[1]}_{Hl^{(3)},ll'}$	$0.87c_{Hl}^{(3)} - 0.50c_{ll}'$	27	✓
$c^{[2]}_{Hl^{(3)},ll'}$	$0.50c_{Hl}^{(3)} + 0.87c_{ll}'$	0.33	

Correlations from simultaneous fit to 10 operator combinations



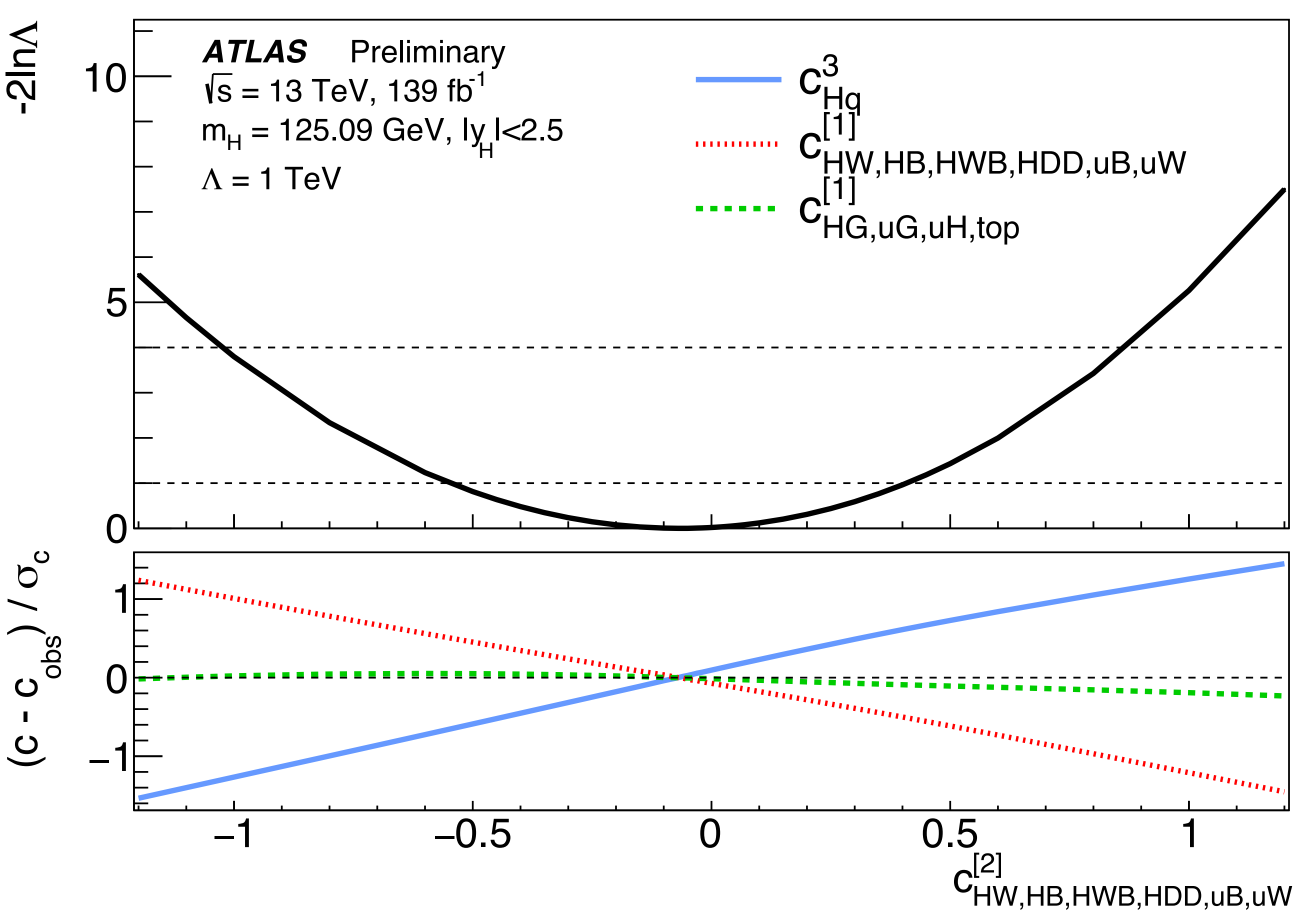
	$c_{Hq}^{(3)}$	$c_{Hl^{(1)},He}^{[1]}$	$c_{Hl^{(3)},ll'}^{[1]}$	$c_{Hd,Hq^{(1)},Hu}^{[1]}$	$c_{HG,uG,uH,top}^{[1]}$	$c_{HG,uG,uH,top}^{[2]}$	$c_{HG,uG,uH,top}^{[3]}$	$c_{HW,HB,HWB,HDD,uB,uW}^{[1]}$	$c_{HW,HB,HWB,HDD,uB,uW}^{[2]}$	$c_{HW,HB,HWB,HDD,uB,uW}^{[3]}$
$c_{Hq}^{(3)}$	1	–0.74	0.28	0.75	–0.38	0.24	0.07	0.12	0.64	0.70
$c_{Hl^{(1)},He}^{[1]}$	–0.74	1	–0.19	–0.91	0.19	–0.05	0.05	0.00	–0.44	–0.95
$c_{Hl^{(3)},ll'}^{[1]}$	0.28	–0.19	1	0.25	–0.54	0.47	0.05	0.95	–0.40	0.44
$c_{Hd,Hq^{(1)},Hu}^{[1]}$	0.75	–0.91	0.25	1	–0.24	0.12	0.06	0.09	0.30	0.90
$c_{HG,uG,uH,top}^{[1]}$	–0.38	0.19	–0.54	–0.24	1	–0.69	–0.20	–0.66	–0.09	–0.33
$c_{HG,uG,uH,top}^{[2]}$	0.24	–0.05	0.47	0.12	–0.69	1	0.19	0.58	0.00	0.18
$c_{HG,uG,uH,top}^{[3]}$	0.07	0.05	0.05	0.06	–0.20	0.19	1	0.11	0.09	–0.03
$c_{HW,HB,HWB,HDD,uB,uW}^{[1]}$	0.12	0.00	0.95	0.09	–0.66	0.58	0.11	1	–0.49	0.27
$c_{HW,HB,HWB,HDD,uB,uW}^{[2]}$	0.64	–0.44	–0.40	0.30	–0.09	0.00	0.09	–0.49	1	0.21
$c_{HW,HB,HWB,HDD,uB,uW}^{[3]}$	0.70	–0.95	0.44	0.90	–0.33	0.18	–0.03	0.27	0.21	1

Likelihood scans



Operator combination with no sensitivity

“flat direction”, fixed in fit

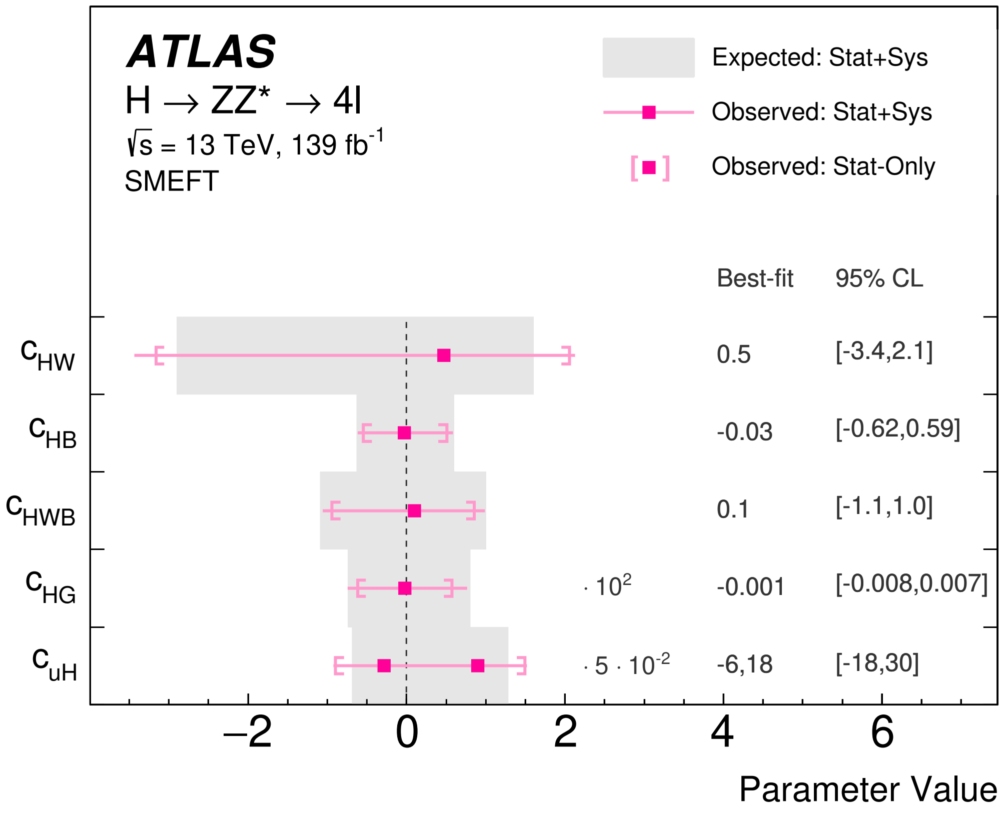


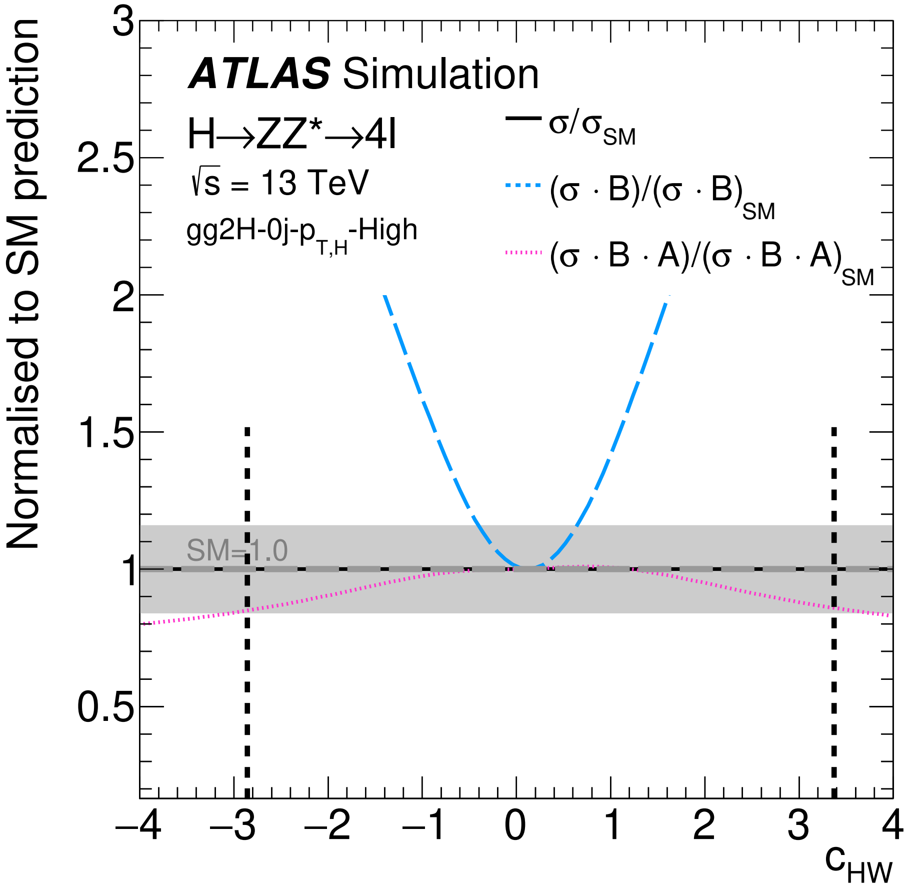
Operator combination with good sensitivity

Importance of acceptance modifications

HZZ standalone constraints:

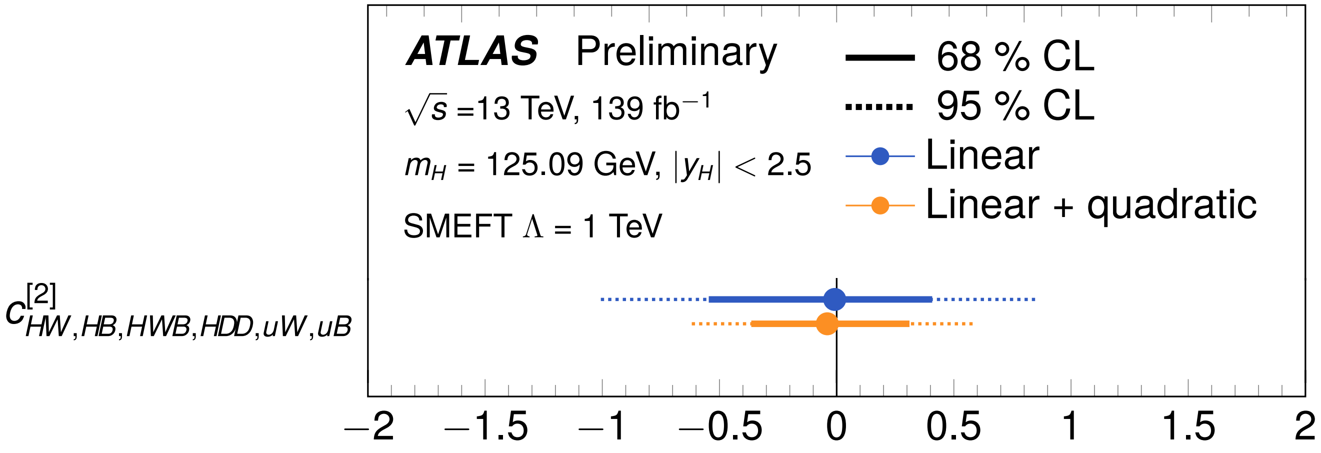
[arXiv:2004.03447]

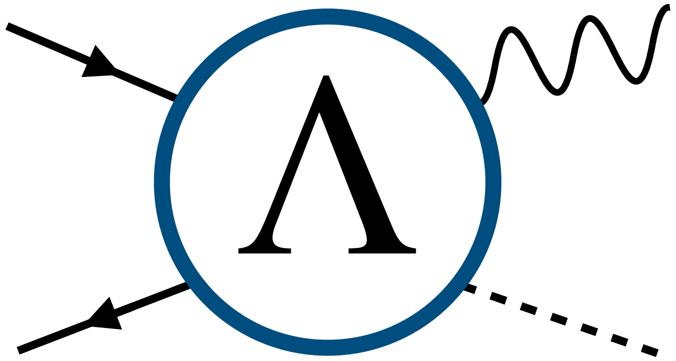




Combined constraints:

~0.96 cHW + … →

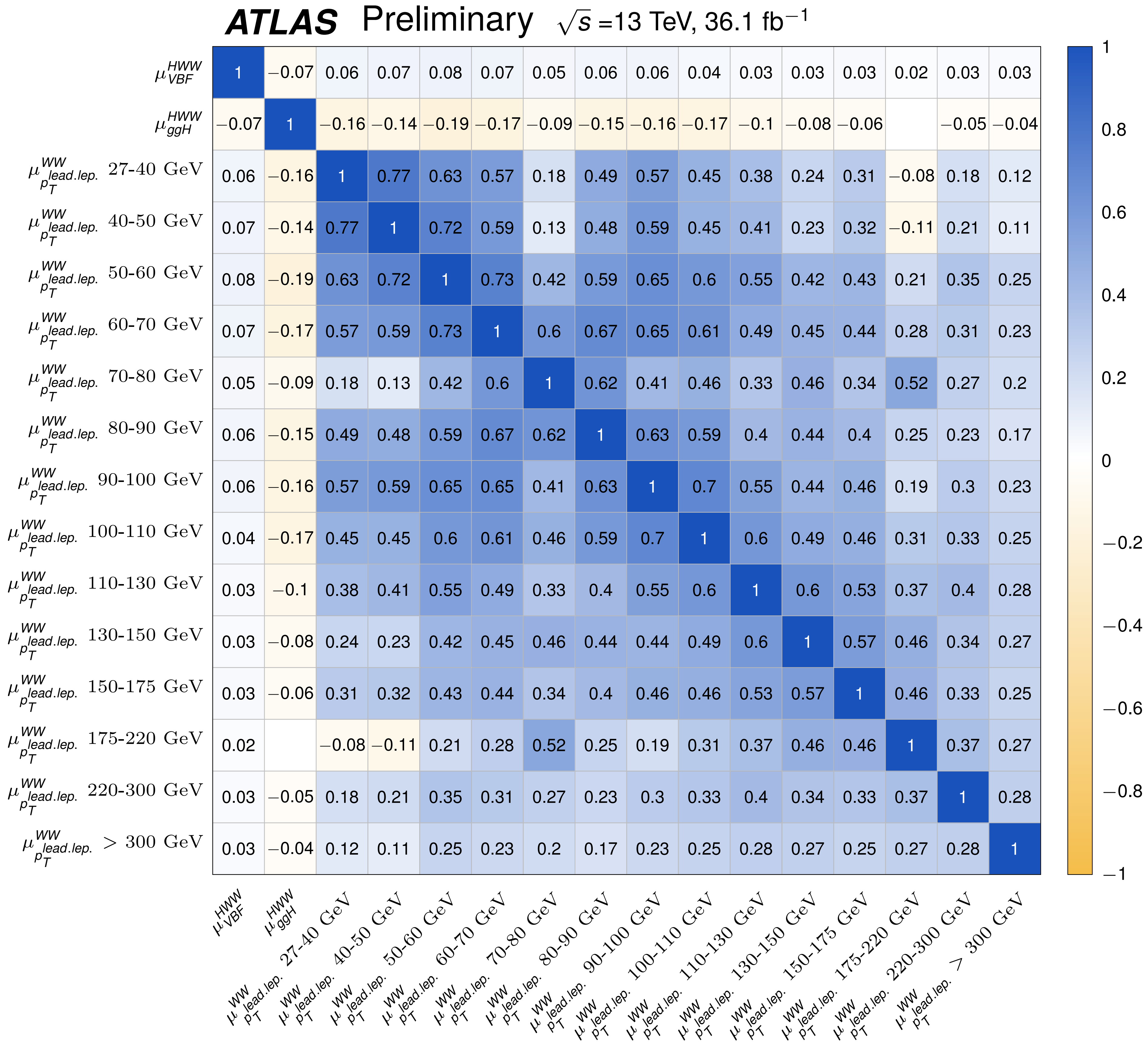




Higgs + diboson combination

[ATL-PHYS-PUB-2021-010]

Correlations of input measurements



	μ^{HWW}_{VBF}	μ^{HWW}_{ggH}	$\mu^{WW}_{p_T^{lead.lep.}}$ 27-40 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 40-50 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 50-60 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 60-70 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 70-80 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 80-90 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 90-100 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 100-110 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 110-130 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 130-150 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 150-175 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 175-220 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ 220-300 GeV	$\mu^{WW}_{p_T^{lead.lep.}}$ $>$ 300 GeV
μ^{HWW}_{VBF}	1	−0.07	0.06	0.07	0.08	0.07	0.05	0.06	0.06	0.04	0.03	0.03	0.03	0.02	0.03	0.03
μ^{HWW}_{ggH}	−0.07	1	−0.16	−0.14	−0.19	−0.17	−0.09	−0.15	−0.16	−0.17	−0.1	−0.08	−0.06		−0.05	−0.04
$\mu^{WW}_{p_T^{lead.lep.}}$ 27-40 GeV	0.06	−0.16	1	0.77	0.63	0.57	0.18	0.49	0.57	0.45	0.38	0.24	0.31	−0.08	0.18	0.12
$\mu^{WW}_{p_T^{lead.lep.}}$ 40-50 GeV	0.07	−0.14	0.77	1	0.72	0.59	0.13	0.48	0.59	0.45	0.41	0.23	0.32	−0.11	0.21	0.11
$\mu^{WW}_{p_T^{lead.lep.}}$ 50-60 GeV	0.08	−0.19	0.63	0.72	1	0.73	0.42	0.59	0.65	0.6	0.55	0.42	0.43	0.21	0.35	0.25
$\mu^{WW}_{p_T^{lead.lep.}}$ 60-70 GeV	0.07	−0.17	0.57	0.59	0.73	1	0.6	0.67	0.65	0.61	0.49	0.45	0.44	0.28	0.31	0.23
$\mu^{WW}_{p_T^{lead.lep.}}$ 70-80 GeV	0.05	−0.09	0.18	0.13	0.42	0.6	1	0.62	0.41	0.46	0.33	0.46	0.34	0.52	0.27	0.2
$\mu^{WW}_{p_T^{lead.lep.}}$ 80-90 GeV	0.06	−0.15	0.49	0.48	0.59	0.67	0.62	1	0.63	0.59	0.4	0.44	0.4	0.25	0.23	0.17
$\mu^{WW}_{p_T^{lead.lep.}}$ 90-100 GeV	0.06	−0.16	0.57	0.59	0.65	0.65	0.41	0.63	1	0.7	0.55	0.44	0.46	0.19	0.3	0.23
$\mu^{WW}_{p_T^{lead.lep.}}$ 100-110 GeV	0.04	−0.17	0.45	0.45	0.6	0.61	0.46	0.59	0.7	1	0.6	0.49	0.46	0.31	0.33	0.25
$\mu^{WW}_{p_T^{lead.lep.}}$ 110-130 GeV	0.03	−0.1	0.38	0.41	0.55	0.49	0.33	0.4	0.55	0.6	1	0.6	0.53	0.37	0.4	0.28
$\mu^{WW}_{p_T^{lead.lep.}}$ 130-150 GeV	0.03	−0.08	0.24	0.23	0.42	0.45	0.46	0.44	0.44	0.49	0.6	1	0.57	0.46	0.34	0.27
$\mu^{WW}_{p_T^{lead.lep.}}$ 150-175 GeV	0.03	−0.06	0.31	0.32	0.43	0.44	0.34	0.4	0.46	0.46	0.53	0.57	1	0.46	0.33	0.25
$\mu^{WW}_{p_T^{lead.lep.}}$ 175-220 GeV	0.02		−0.08	−0.11	0.21	0.28	0.52	0.25	0.19	0.31	0.37	0.46	0.46	1	0.37	0.27
$\mu^{WW}_{p_T^{lead.lep.}}$ 220-300 GeV	0.03	−0.05	0.18	0.21	0.35	0.31	0.27	0.23	0.3	0.33	0.4	0.34	0.33	0.37	1	0.28
$\mu^{WW}_{p_T^{lead.lep.}}$ $>$ 300 GeV	0.03	−0.04	0.12	0.11	0.25	0.23	0.2	0.17	0.23	0.25	0.28	0.27	0.25	0.27	0.28	1

Selected operators

Wilson coefficient and operator		Affected Processes				
$c_i^{(6)}$	$\mathcal{O}_i^{(6)}$	$qq \to e\nu\mu\nu$	$qq \to Hqq$	$gg \to H$	$\Gamma^f_{H\to e\mu\nu\nu}$	Γ^{tot}_H
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	✓				✓
c_{HW}	$H^\dagger H W^I_{\mu\nu}W^{I\mu\nu}$		✓		✓	✓
c_{HWB}	$(H^\dagger\tau^I H W^I_{\mu\nu}B^{\mu\nu})$	✓	✓			✓
c_{HB}	$H^\dagger H B_{\mu\nu}B^{\mu\nu}$		✓			✓
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	✓	✓	✓	✓	✓
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	✓	✓	✓
c_{HG}	$H^\dagger H G^A_{\mu\nu}G^{A\mu\nu}$			✓		✓
c_{dH}	$(H^\dagger H)(\bar q_p d_r H)$					✓
c_{uH}	$(H^\dagger H)(\bar q_p u_r H)$			✓		✓
c_{eH}	$(H^\dagger H)(\bar l_p e_r H)$					✓
c_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)(\tilde H G^A_{\mu\nu})$			✓		✓
c_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)(\tau^I\tilde H W^I_{\mu\nu})$					✓
c_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)(\tilde H B_{\mu\nu})$					✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar d\gamma^\mu d)$	✓	✓			
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar u\gamma^\mu u)$	✓	✓			
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q\gamma^\mu q)$	✓	✓			
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q\tau^I\gamma^\mu q)$	✓	✓			✓
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}^\mu H)(\bar l\gamma^\mu l)$	✓				
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l\tau^I\gamma^\mu l)$	✓	✓	✓	✓	✓
$c_{ll}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	✓	✓	✓	✓	✓
c_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$	✓				
$c_{lq}^{(1)}$	$(\bar l_p\gamma_\mu\ l_r)(\bar q_s\gamma^\mu q_t)$	✓				
$c_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	✓				
c_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$	✓				

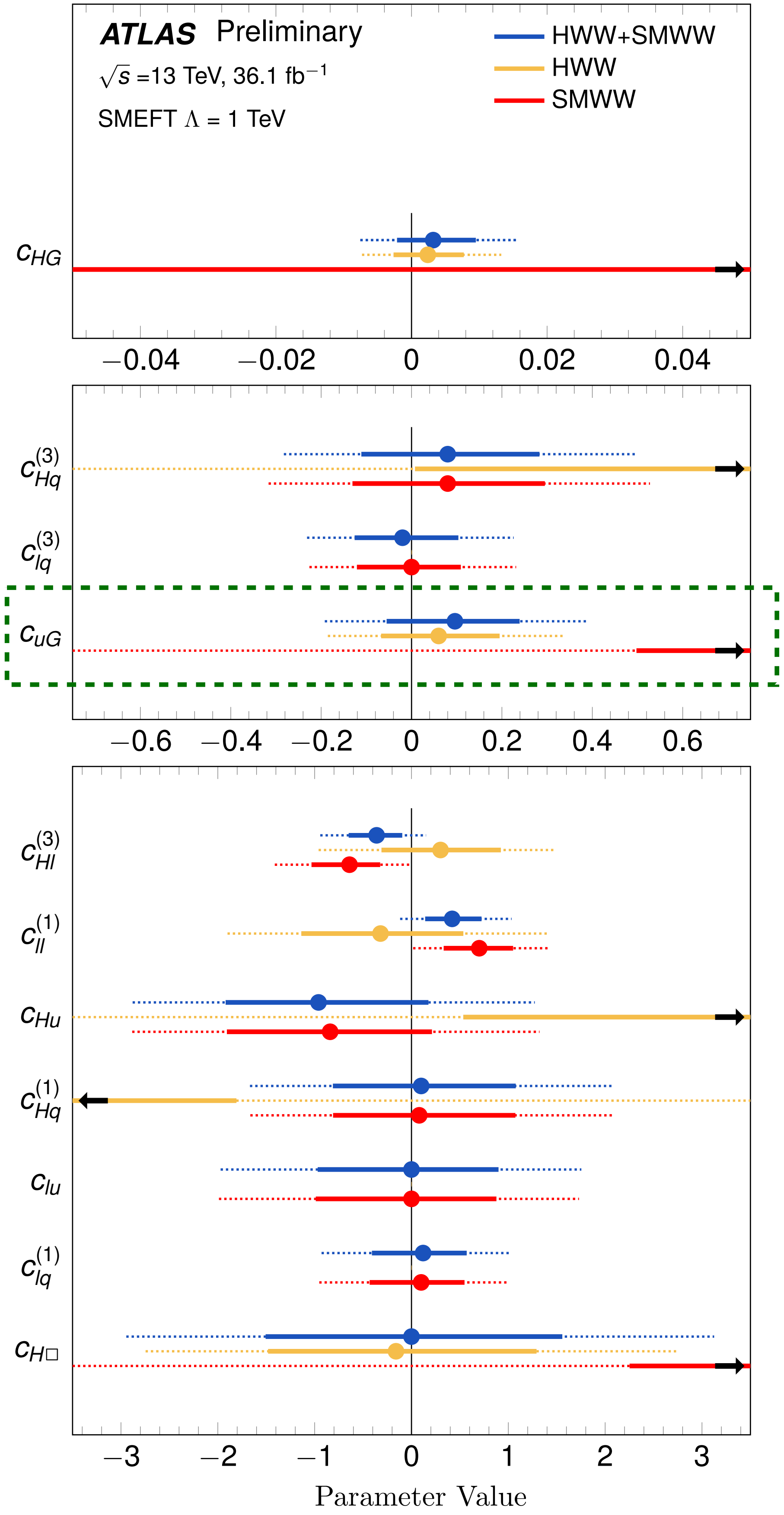
Full set of one-dimensional limits

ggH →

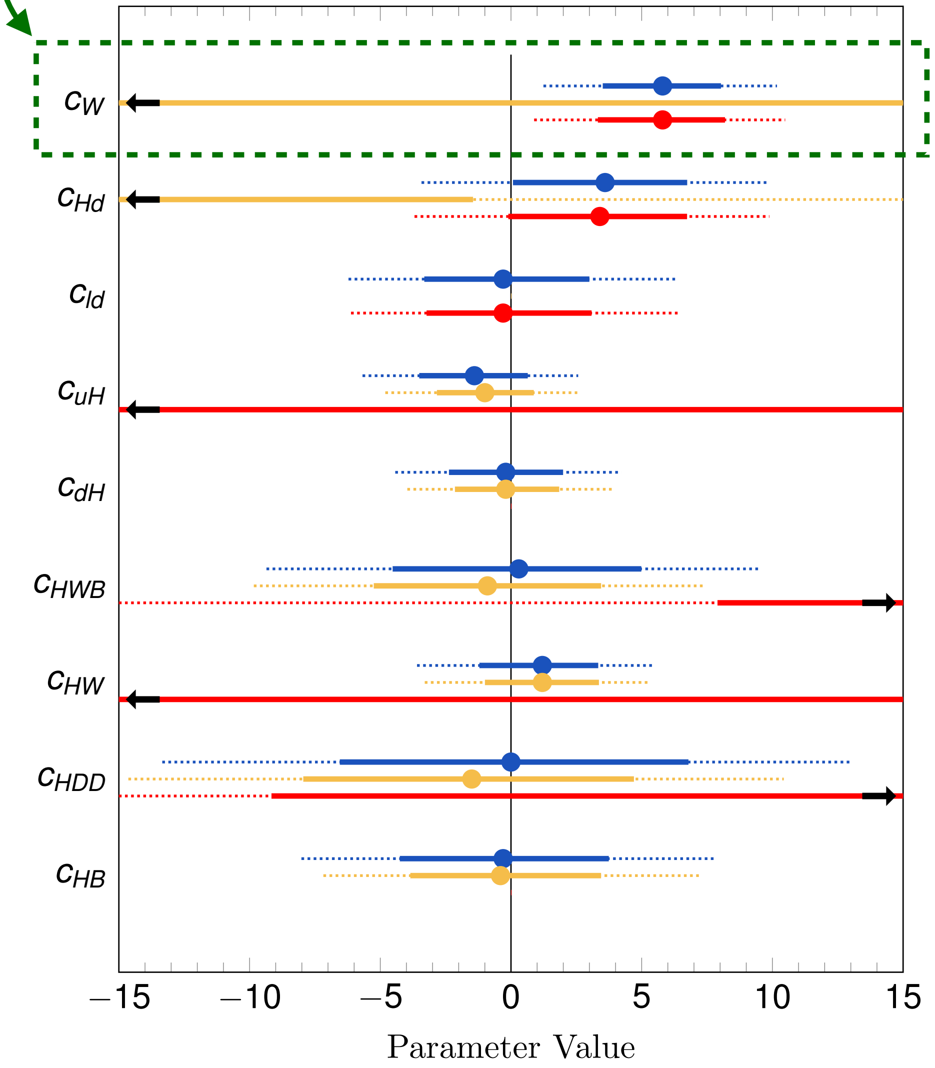
WW, VBF →

high-pT WW →

ggH →



Low sensitivity, interference suppressed!

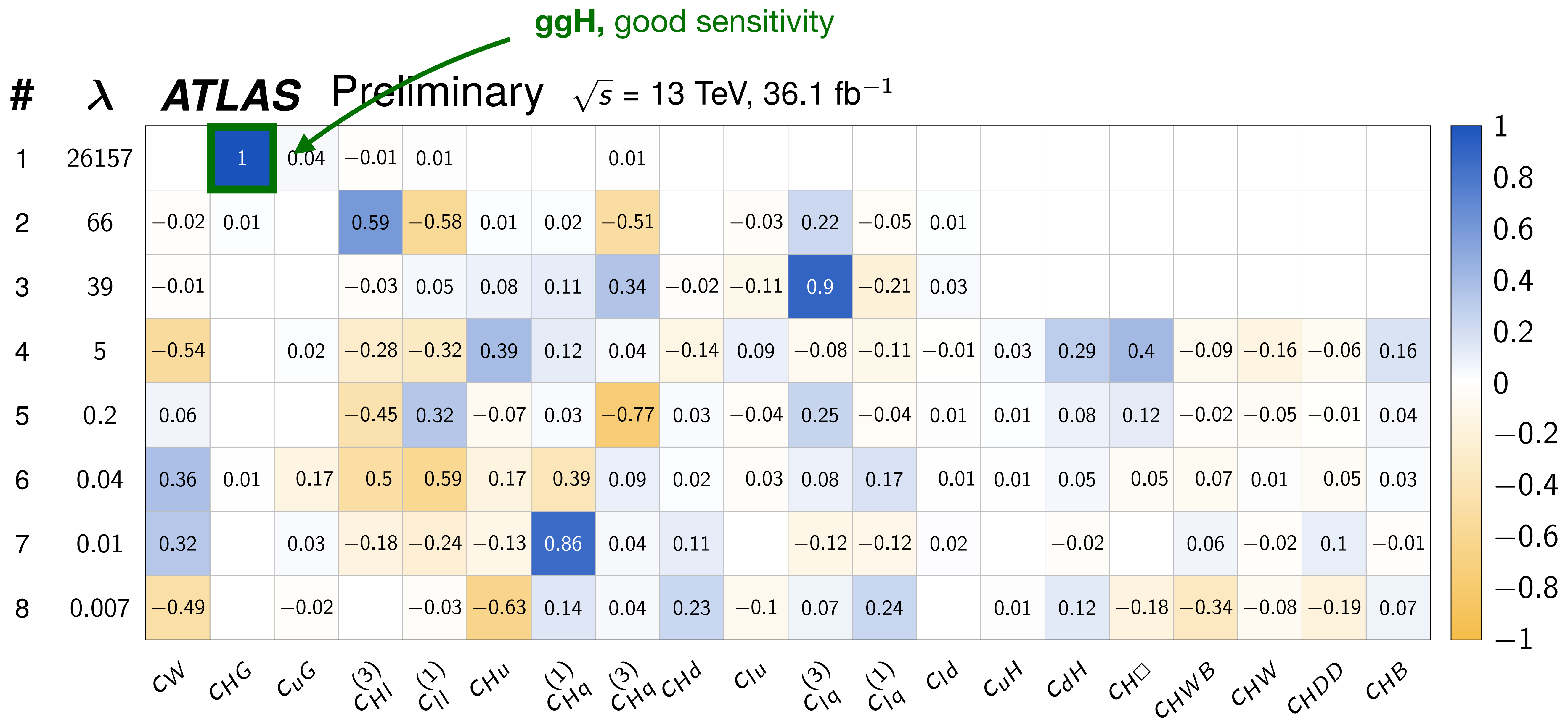


Combined limit worse, analysis significance reduced due to overlap removal

Only linear parametrisation considered

Structure of principal components

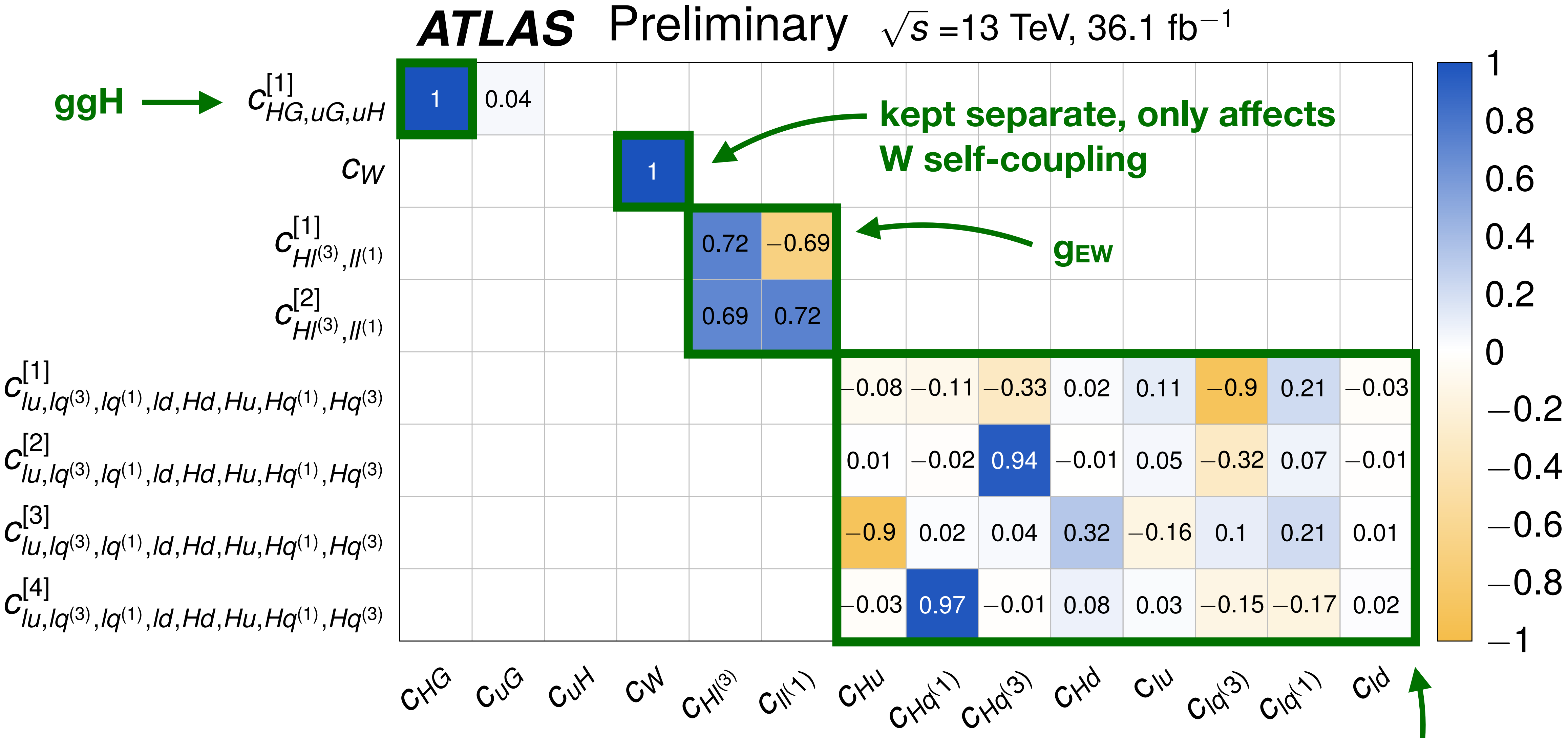
(Only linear parametrisation considered.)



#	λ	CW	CHG	CuG	$CHl^{(3)}$	$Cll^{(1)}$	CHu	$CHq^{(1)}$	$CHq^{(3)}$	CHd	Clu	$Clq^{(3)}$	$Clq^{(1)}$	Cld	CuH	CdH	$CH\Box$	$CHWB$	CHW	$CHDD$	CHB
1	26157		1	0.04	−0.01	0.01			0.01												
2	66	−0.02	0.01		0.59	−0.58	0.01	0.02	−0.51		−0.03	0.22	−0.05	0.01							
3	39	−0.01			−0.03	0.05	0.08	0.11	0.34	−0.02	−0.11	0.9	−0.21	0.03							
4	5	−0.54		0.02	−0.28	−0.32	0.39	0.12	0.04	−0.14	0.09	−0.08	−0.11	−0.01	0.03	0.29	0.4	−0.09	−0.16	−0.06	0.16
5	0.2	0.06			−0.45	0.32	−0.07	0.03	−0.77	0.03	−0.04	0.25	−0.04	0.01	0.01	0.08	0.12	−0.02	−0.05	−0.01	0.04
6	0.04	0.36	0.01	−0.17	−0.5	−0.59	−0.17	−0.39	0.09	0.02	−0.03	0.08	0.17	−0.01	0.01	0.05	−0.05	−0.07	0.01	−0.05	0.03
7	0.01	0.32		0.03	−0.18	−0.24	−0.13	0.86	0.04	0.11		−0.12	−0.12	0.02		−0.02		0.06	−0.02	0.1	−0.01
8	0.007	−0.49		−0.02		−0.03	−0.63	0.14	0.04	0.23	−0.1	0.07	0.24		0.01	0.12	−0.18	−0.34	−0.08	−0.19	0.07

Chosen principal components

(Only linear parametrisation considered.)



	c_{HG}	c_{uG}	c_{uH}	c_{W}	$c_{Hl^{(3)}}$	$c_{ll^{(1)}}$	c_{Hu}	$c_{Hq^{(1)}}$	$c_{Hq^{(3)}}$	c_{Hd}	c_{lu}	$c_{lq^{(3)}}$	$c_{lq^{(1)}}$	c_{ld}
$c^{[1]}_{HG,uG,uH}$	1	0.04												
c_{W}				1										
$c^{[1]}_{Hl^{(3)},ll^{(1)}}$					0.72	−0.69								
$c^{[2]}_{Hl^{(3)},ll^{(1)}}$					0.69	0.72								
$c^{[1]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$							−0.08	−0.11	−0.33	0.02	0.11	−0.9	0.21	−0.03
$c^{[2]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$							0.01	−0.02	0.94	−0.01	0.05	−0.32	0.07	−0.01
$c^{[3]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$							−0.9	0.02	0.04	0.32	−0.16	0.1	0.21	0.01
$c^{[4]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$							−0.03	0.97	−0.01	0.08	0.03	−0.15	−0.17	0.02

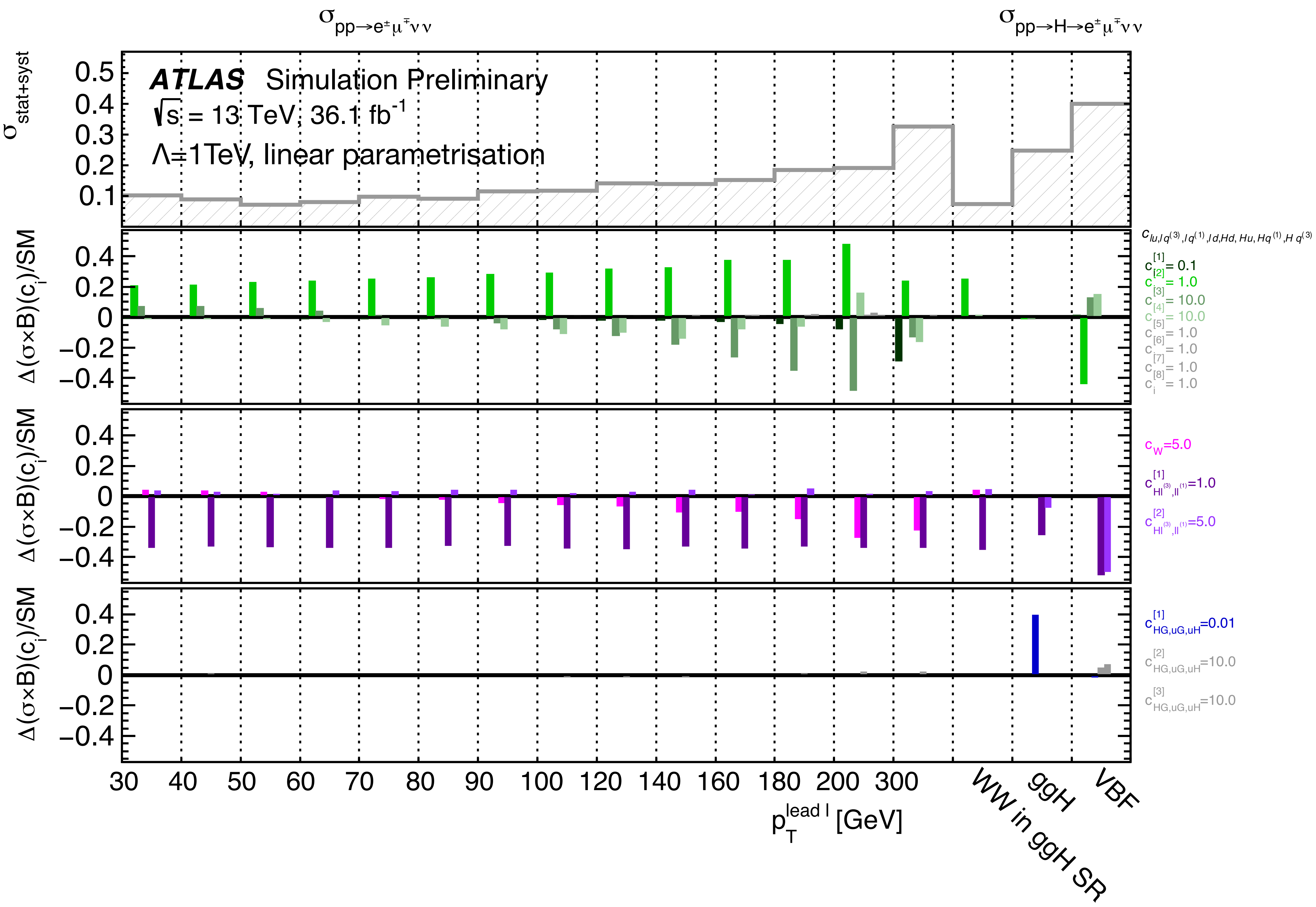
ggH

kept separate, only affects W self-coupling

g_{EW}

high-pT WW

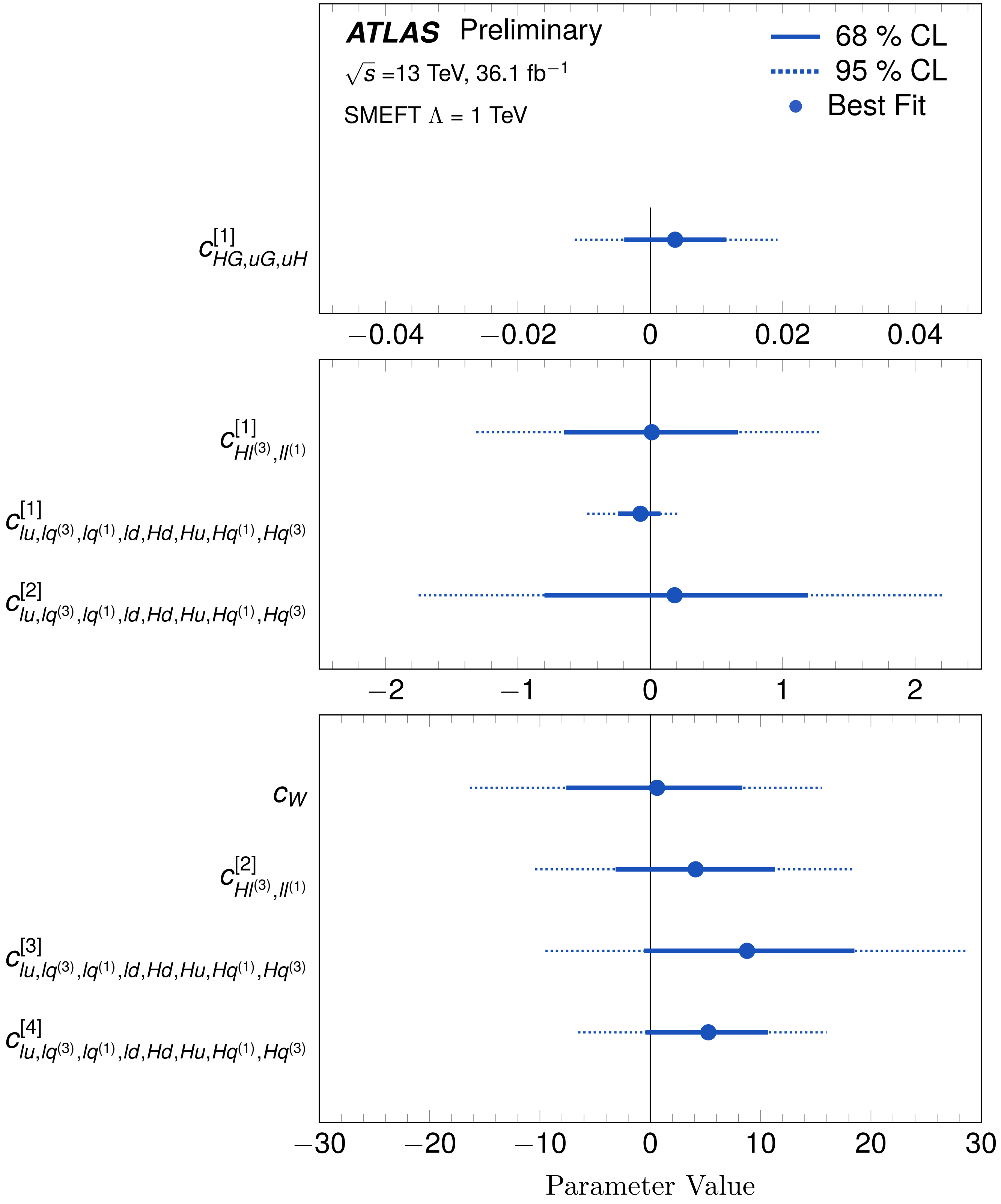
Impact of principal components

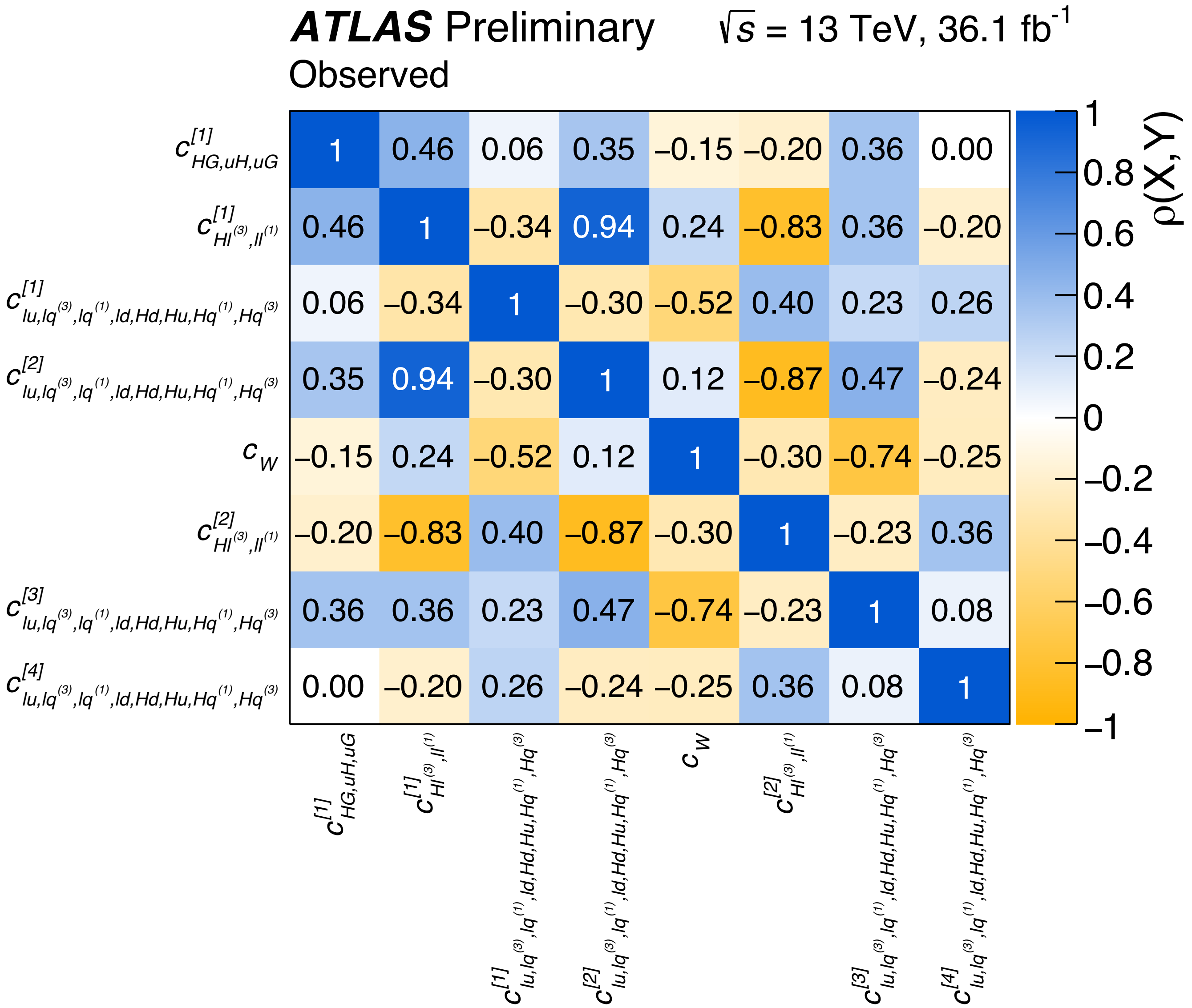


1d-limits on principal components

Eight combinations constrained simultaneously

(Only linear parametrisation considered.)



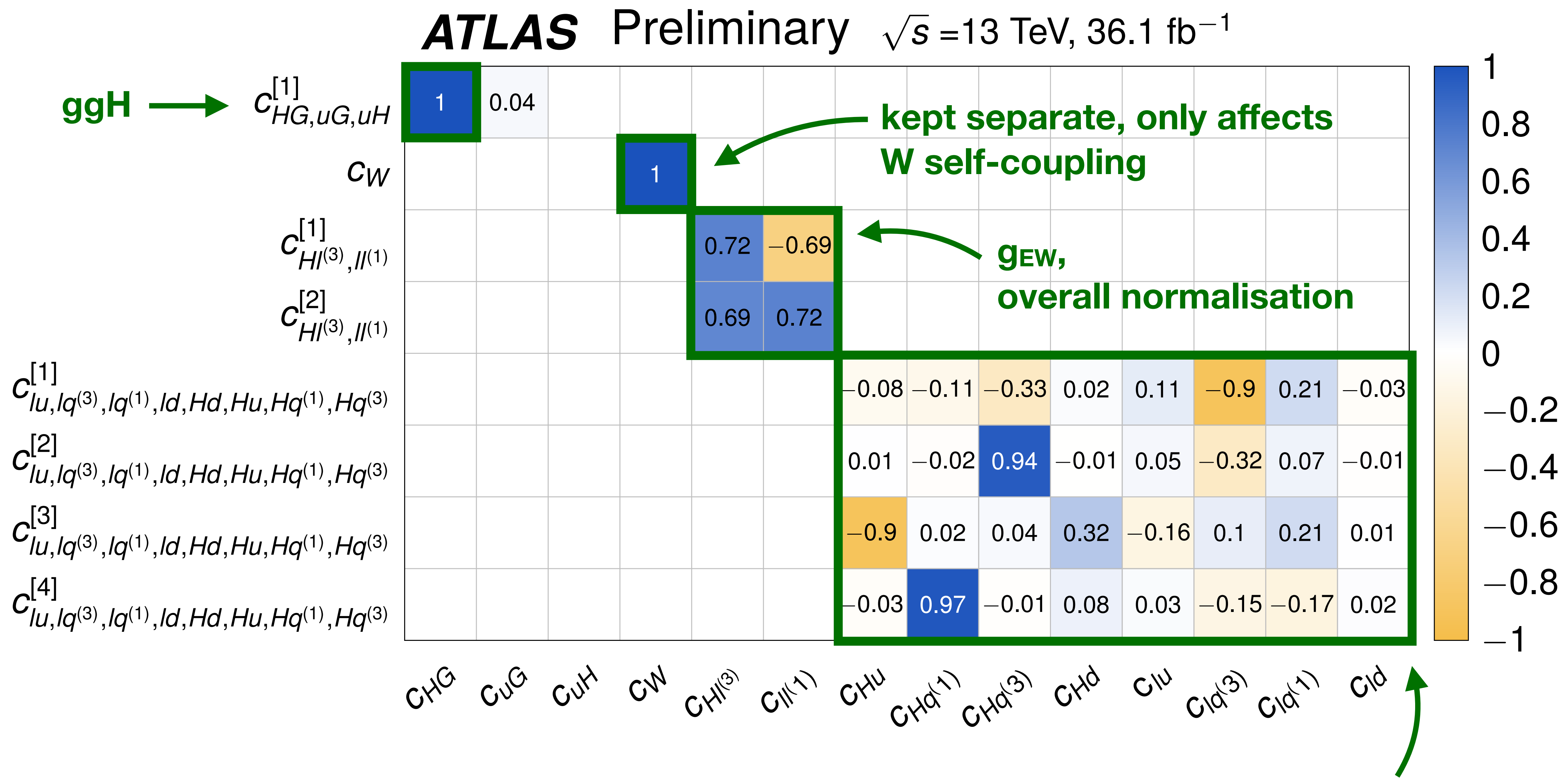


	$c^{[1]}_{HG,uH,uG}$	$c^{[1]}_{Hl^{(3)},ll^{(1)}}$	$c^{[1]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$	$c^{[2]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$	c_W	$c^{[2]}_{Hl^{(3)},ll^{(1)}}$	$c^{[3]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$	$c^{[4]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$
$c^{[1]}_{HG,uH,uG}$	1	0.46	0.06	0.35	−0.15	−0.20	0.36	0.00
$c^{[1]}_{Hl^{(3)},ll^{(1)}}$	0.46	1	−0.34	0.94	0.24	−0.83	0.36	−0.20
$c^{[1]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$	0.06	−0.34	1	−0.30	−0.52	0.40	0.23	0.26
$c^{[2]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$	0.35	0.94	−0.30	1	0.12	−0.87	0.47	−0.24
c_W	−0.15	0.24	−0.52	0.12	1	−0.30	−0.74	−0.25
$c^{[2]}_{Hl^{(3)},ll^{(1)}}$	−0.20	−0.83	0.40	−0.87	−0.30	1	−0.23	0.36
$c^{[3]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$	0.36	0.36	0.23	0.47	−0.74	−0.23	1	0.08
$c^{[4]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$	0.00	−0.20	0.26	−0.24	−0.25	0.36	0.08	1

Principal components

Eight operator combinations constrained simultaneously

Grouped according to physics impact



	c_{HG}	c_{uG}	c_{uH}	c_W	$c_{Hl^{(3)}}$	$c_{ll^{(1)}}$	c_{Hu}	$c_{Hq^{(1)}}$	$c_{Hq^{(3)}}$	c_{Hd}	c_{lu}	$c_{lq^{(3)}}$	$c_{lq^{(1)}}$	c_{ld}
$c^{[1]}_{HG,uG,uH}$	1	0.04												
c_W				1										
$c^{[1]}_{Hl^{(3)},ll^{(1)}}$					0.72	−0.69								
$c^{[2]}_{Hl^{(3)},ll^{(1)}}$					0.69	0.72								
$c^{[1]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$							−0.08	−0.11	−0.33	0.02	0.11	−0.9	0.21	−0.03
$c^{[2]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$							0.01	−0.02	0.94	−0.01	0.05	−0.32	0.07	−0.01
$c^{[3]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$							−0.9	0.02	0.04	0.32	−0.16	0.1	0.21	0.01
$c^{[4]}_{lu,lq^{(3)},lq^{(1)},ld,Hd,Hu,Hq^{(1)},Hq^{(3)}}$							−0.03	0.97	−0.01	0.08	0.03	−0.15	−0.17	0.02

ggH

kept separate, only affects W self-coupling

g_{EW}, overall normalisation

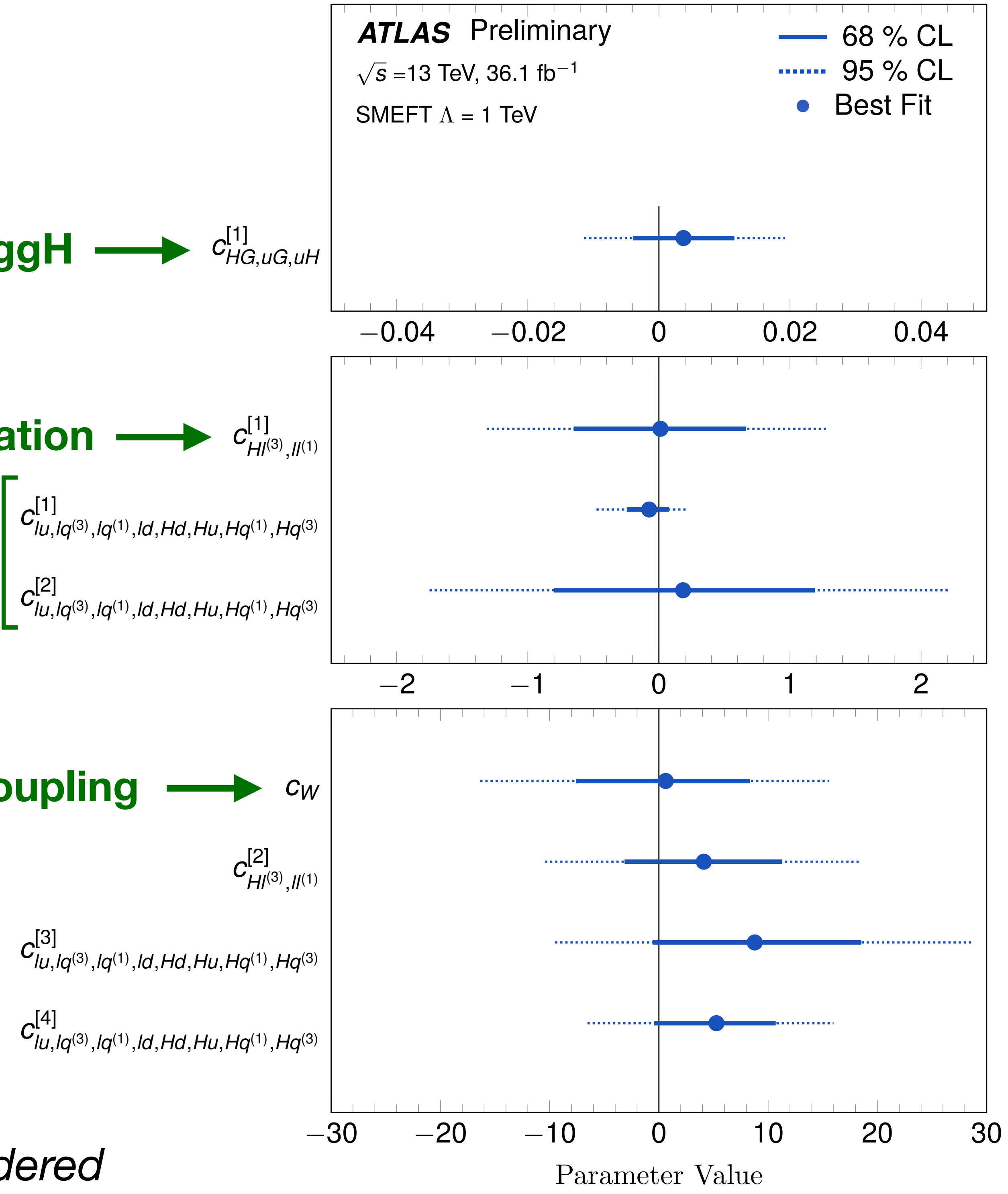
high-pT WW

Only linear parametrisation considered

Principal components

Eight operator combinations constrained simultaneously

Grouped according to physics impact



ggH →

g_{EW}, overall normalisation →

high-pT WW →

W self-coupling →

Only linear parametrisation considered