The 17th Workshop of the LHC Higgs Working group

STXS EFT interpretations

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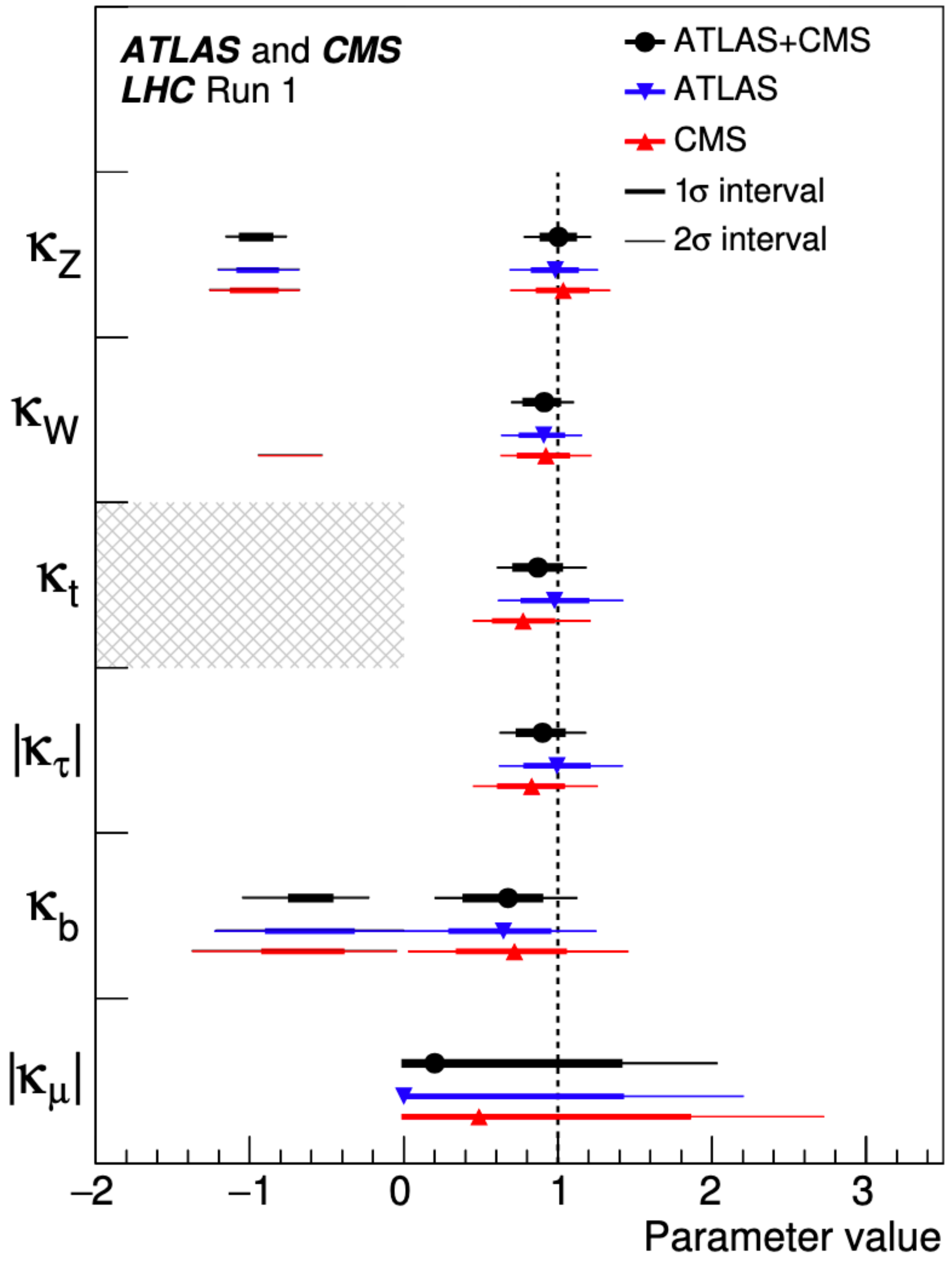
Introduction

- Extensive set of Higgs boson properties measurements from ATLAS and CMS

- Large Run 2 dataset has allowed to measure finer bins in Simplified Template Cross Section (STXS) framework separating different production modes kinematic regions
  - Unprecedented precision achieved

- κ-framework served well for initial interpretations, but
  - Not a QFT, only possible at LO
  - Designed for rates and not sensitive to growth with energy in kinematic distributions



From arXiv:[1606.02266](https://arxiv.org/abs/1606.02266)

The Standard Model Effective Field Theory

- SMEFT allows a systematic interpretation of large data sets in terms of new physics (NP)

- Extends the SM Lagrangian by adding new operators of d>4 suppressed by powers of the NP energy scale, $1/\Lambda^{d-4}$
  - Valid for Λ>> vev. Uses the same fields and keeps the same symmetries as the SM

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \sum_i \frac{c_i^{d=8}}{\Lambda^4}\mathcal{O}^{d=8} + \ldots$$

  - Only c_i/Λ^{d-4} is measurable
  - Several operator bases can be worked out, different conventions in use

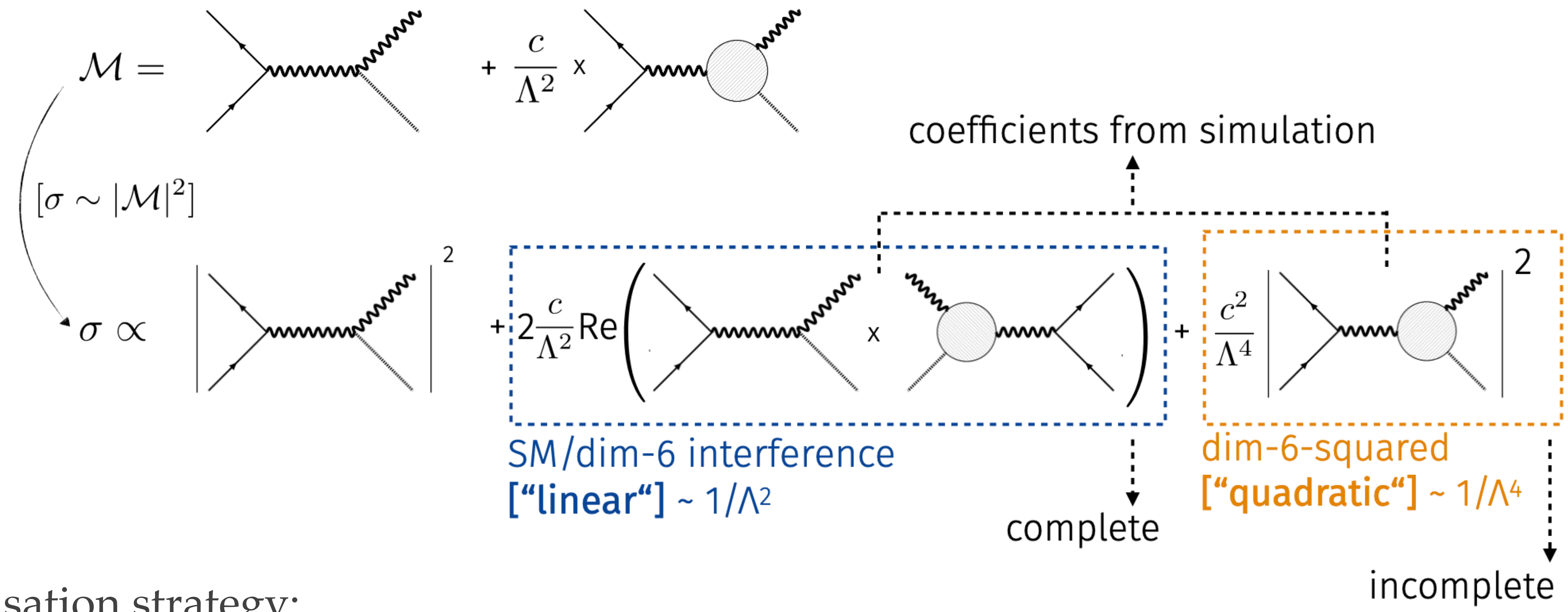
- Constrain EFT coefficients ➙ constrain large classes of UV theories

In the analyses presented in this talk:

- **Focus on dimension 6 operators**
- **Assuming $U(3)^5$ flavour symmetry**

From the SMEFT Lagrangian to STXS parametrisation

Brian Moser @ HIGGS2020



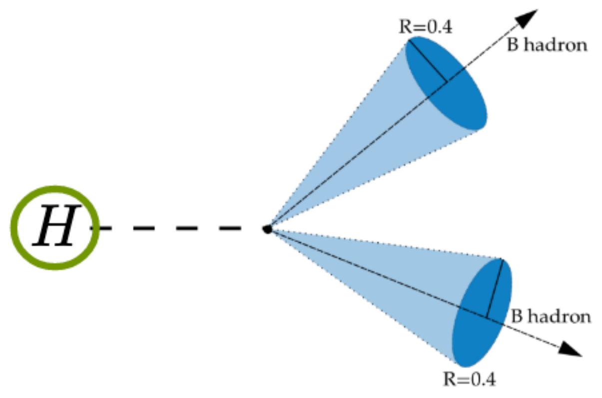
- Common parametrisation strategy:
  - Import the used SMEFT model in MadGraph and generate events for a given production mode switching on only the Wilson coefficients of interest (one-by-one or 2-by-2 for interference between 2 BSM amplitudes)
  - Analyse the generated events at particle level with a Rivet routine such as this one
  - Workout the parametrisation in each STXS bin by taking ratios to the SM predictions generated with the same setup and at the same calculation order
  - Assume same unfolding efficiencies as in the SM

VH, H→bb (ATLAS)

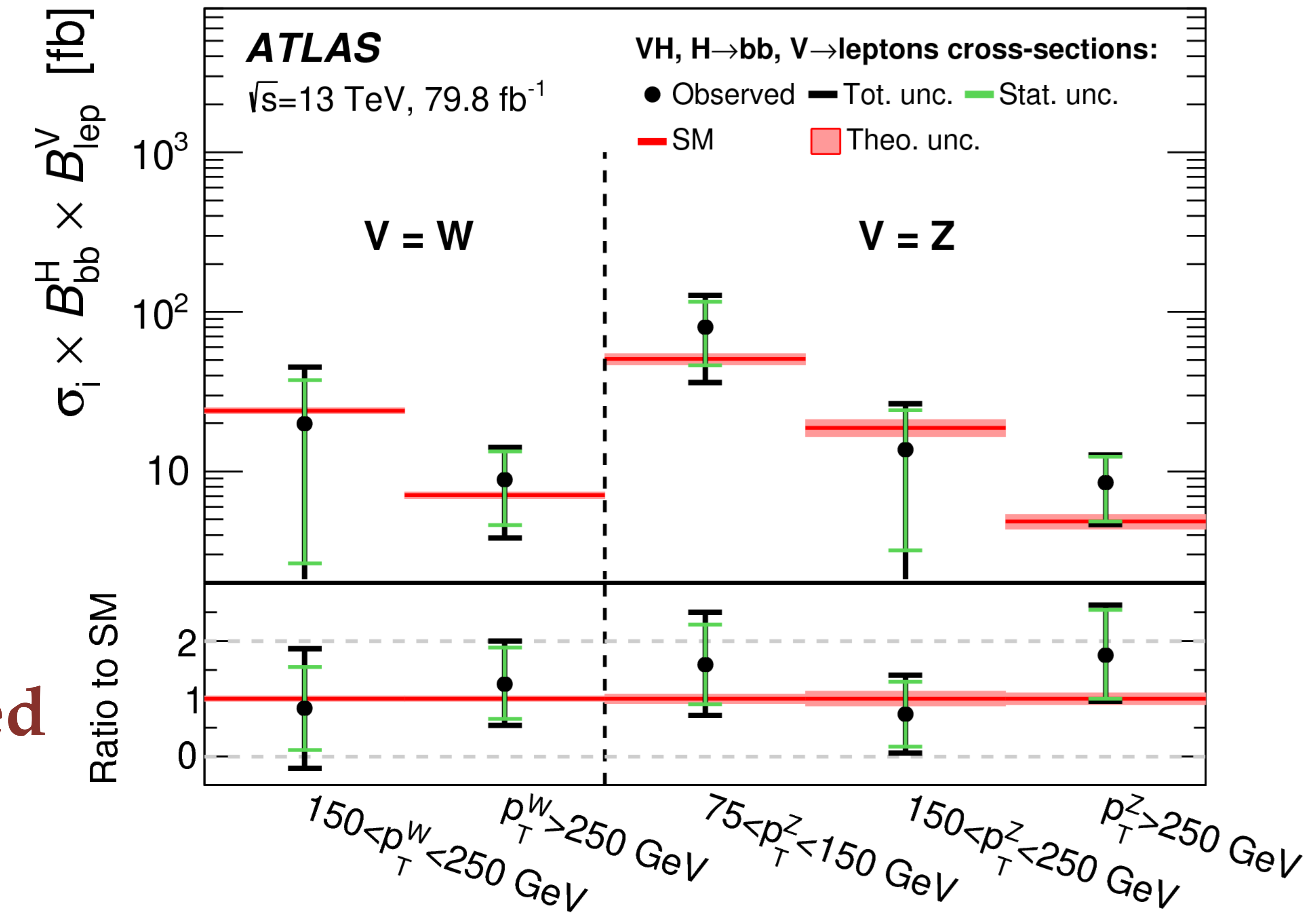
arXiv:2007.02873

arXiv:2008.02508

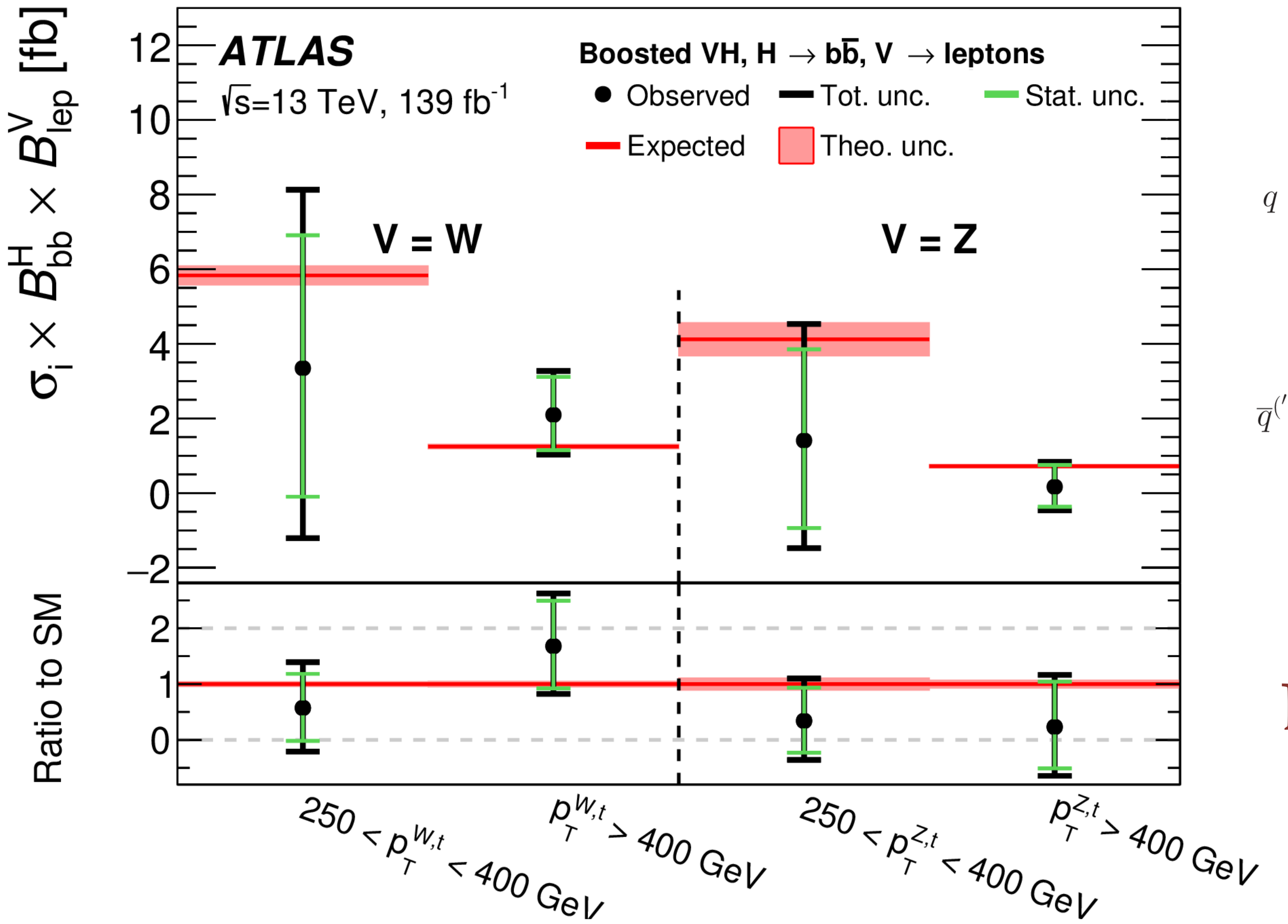
- Two analyses (resolved and boosted) using the same strategy for EFT interpretation
  - Warsaw basis as implemented in SMEFTsim in the Mw scheme.



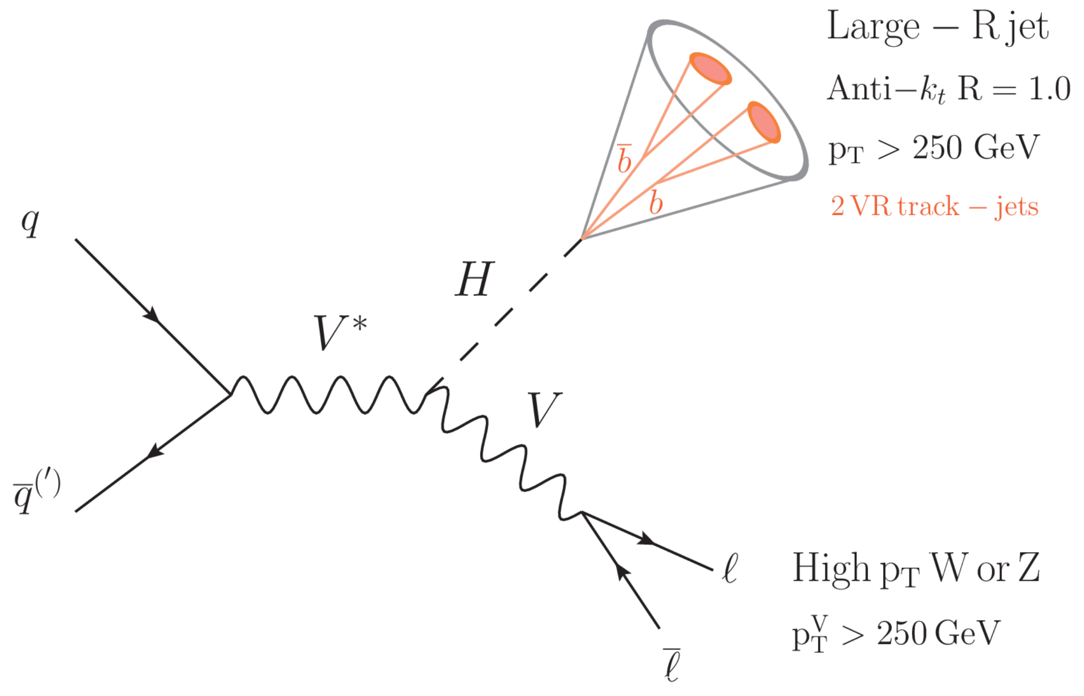
Resolved



Inclusive bin for $p_T^V > 250$ GeV



Additional splitting at high p_T^V



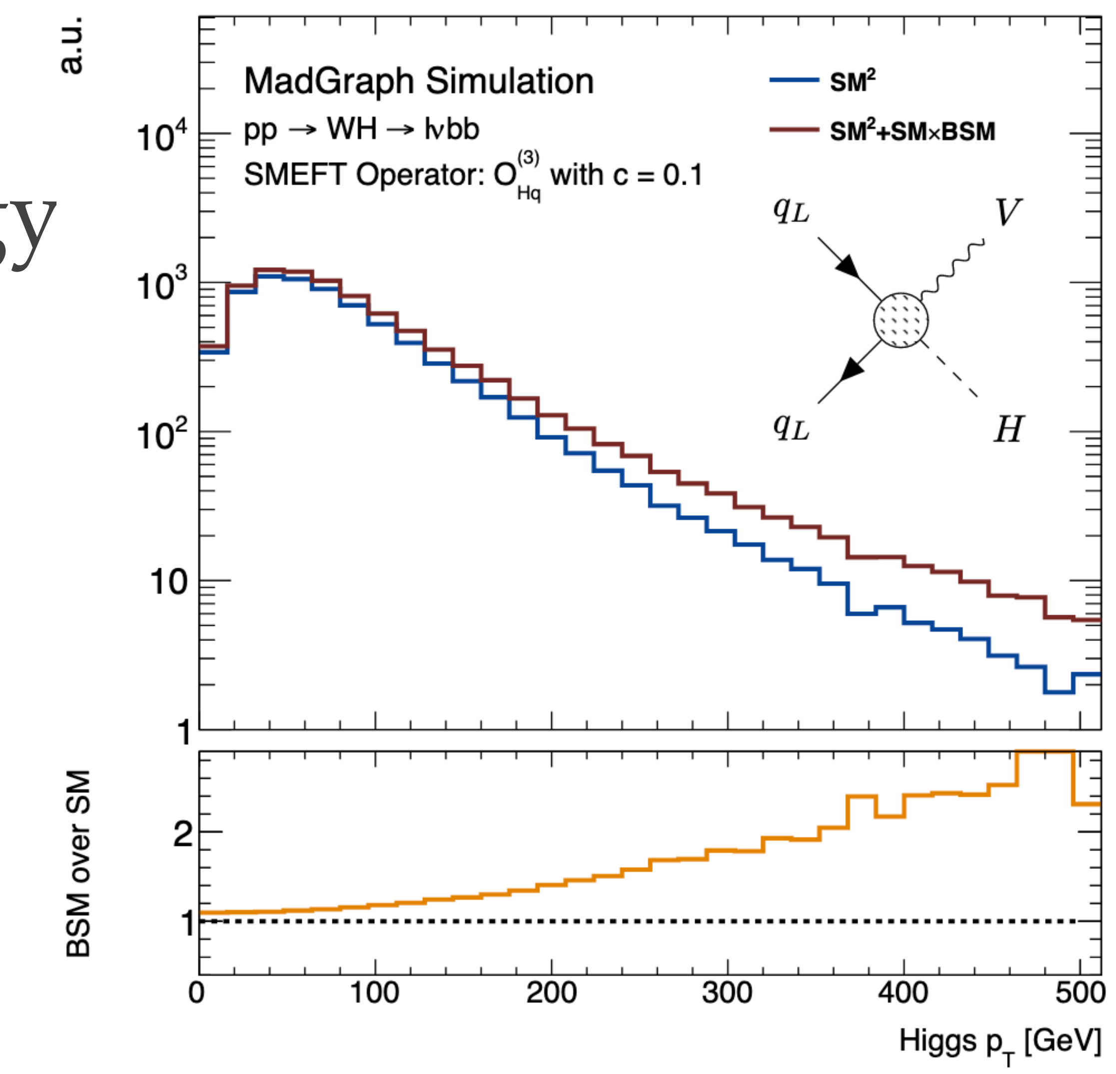
Boosted

VH, H→bb (ATLAS)

arXiv:2007.02873

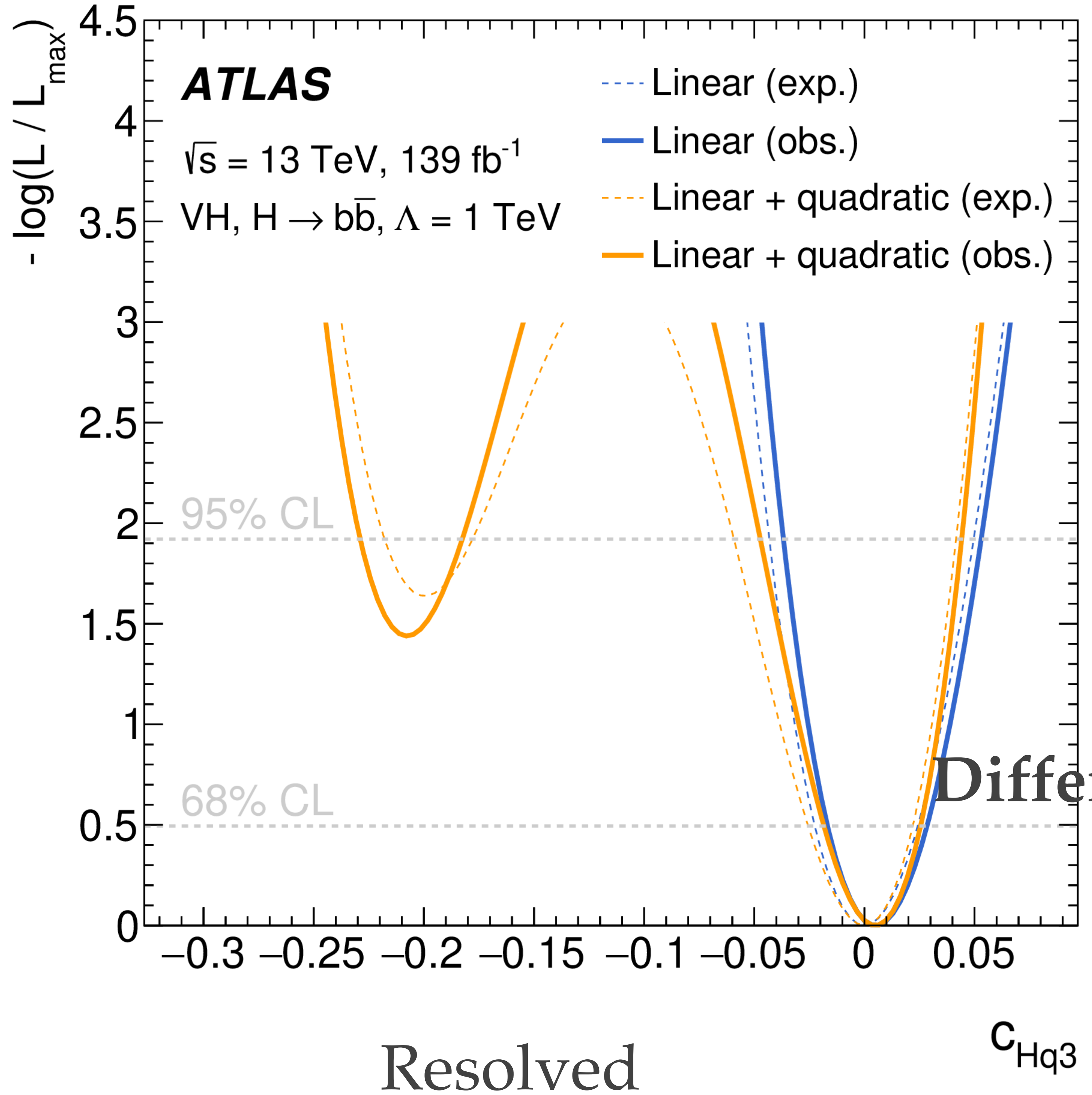
arXiv:2008.02508

- How much improvement can be achieved with higher granularity at high p_T^V?
  - 1-D likelihood scans (all other Wilson coefficients set to 0) to cHq3 which shows an energy growth
  - Boosted analysis less precise but achieves competitive constraints thanks to higher reach in p_T^H



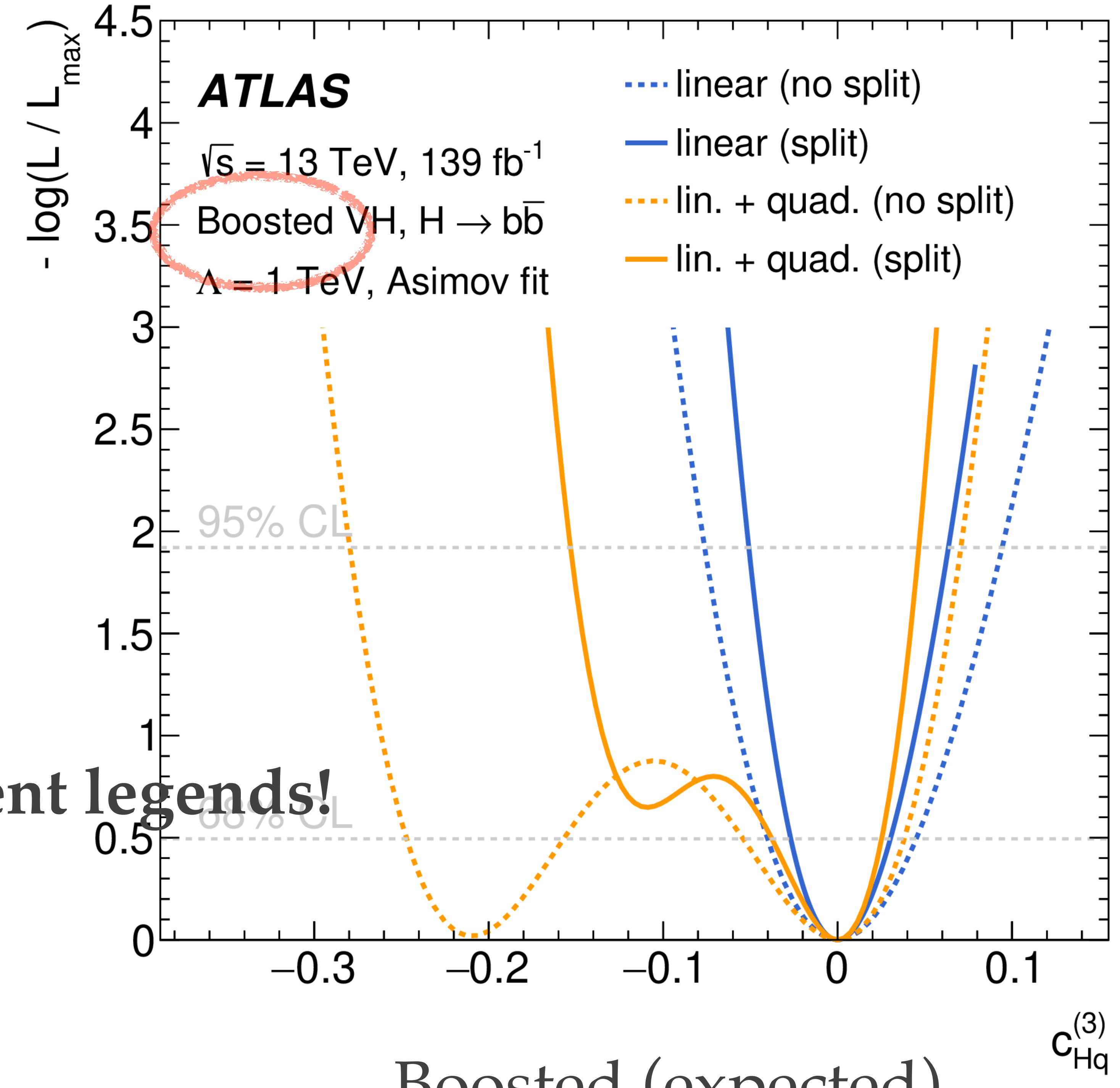
Impact of cHq3 in p_T^H

$p_T^V \sim p_T^H$



Resolved

Different legends!



Boosted (expected)

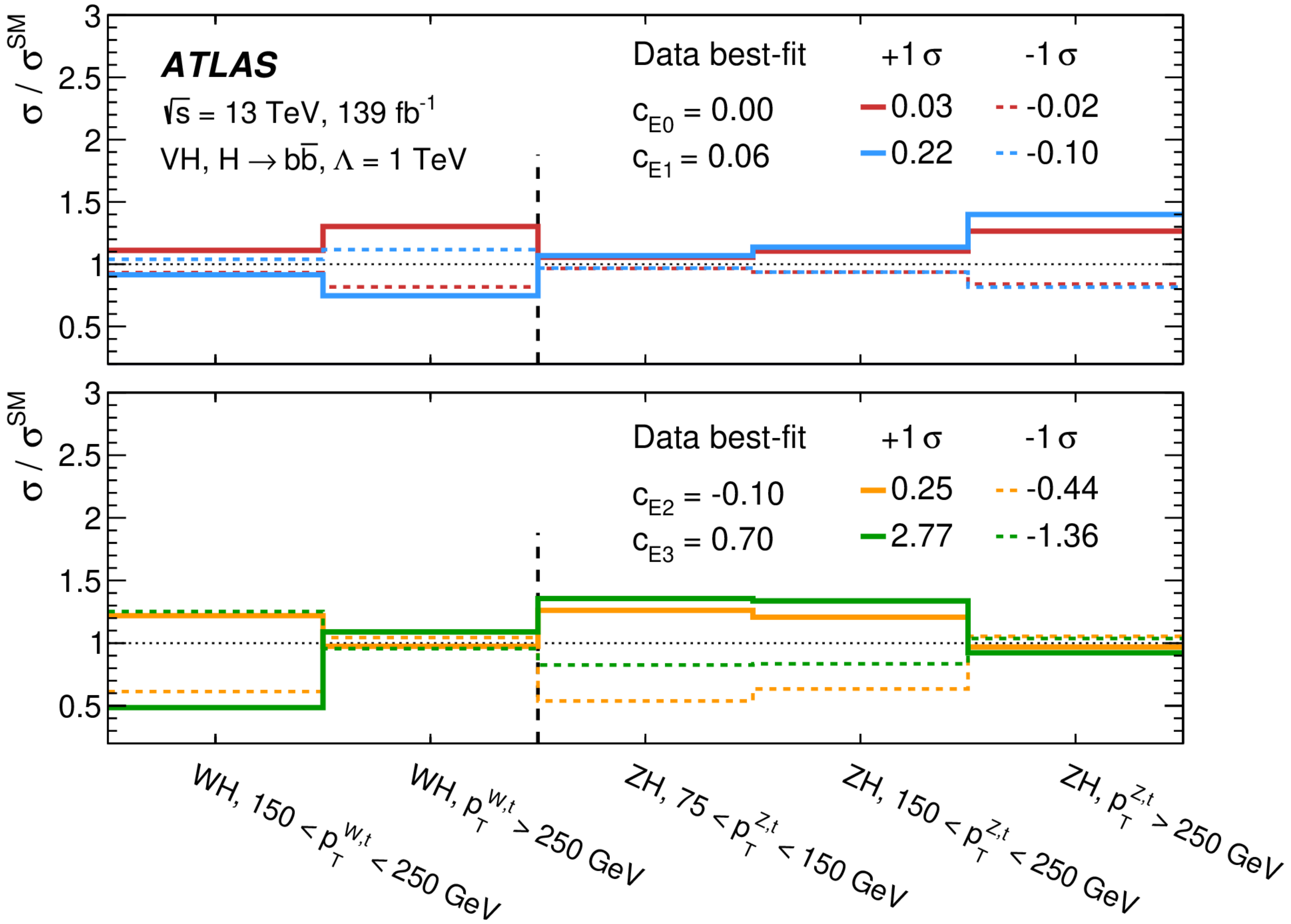
Split at 400 GeV can improve limits by a factor of ~two

VH, H→bb (ATLAS)

arXiv:2007.02873

arXiv:2008.02508

- Several operators affecting VH, H→bb in the Warsaw basis
  - Not possible to to constrain all with 4/5 measured STXS bins
  - Do a principal component analysis (PCA). Methodology from ATL-PHYS-PUB-2019-042
  - Fit simultaneously the sensitive directions

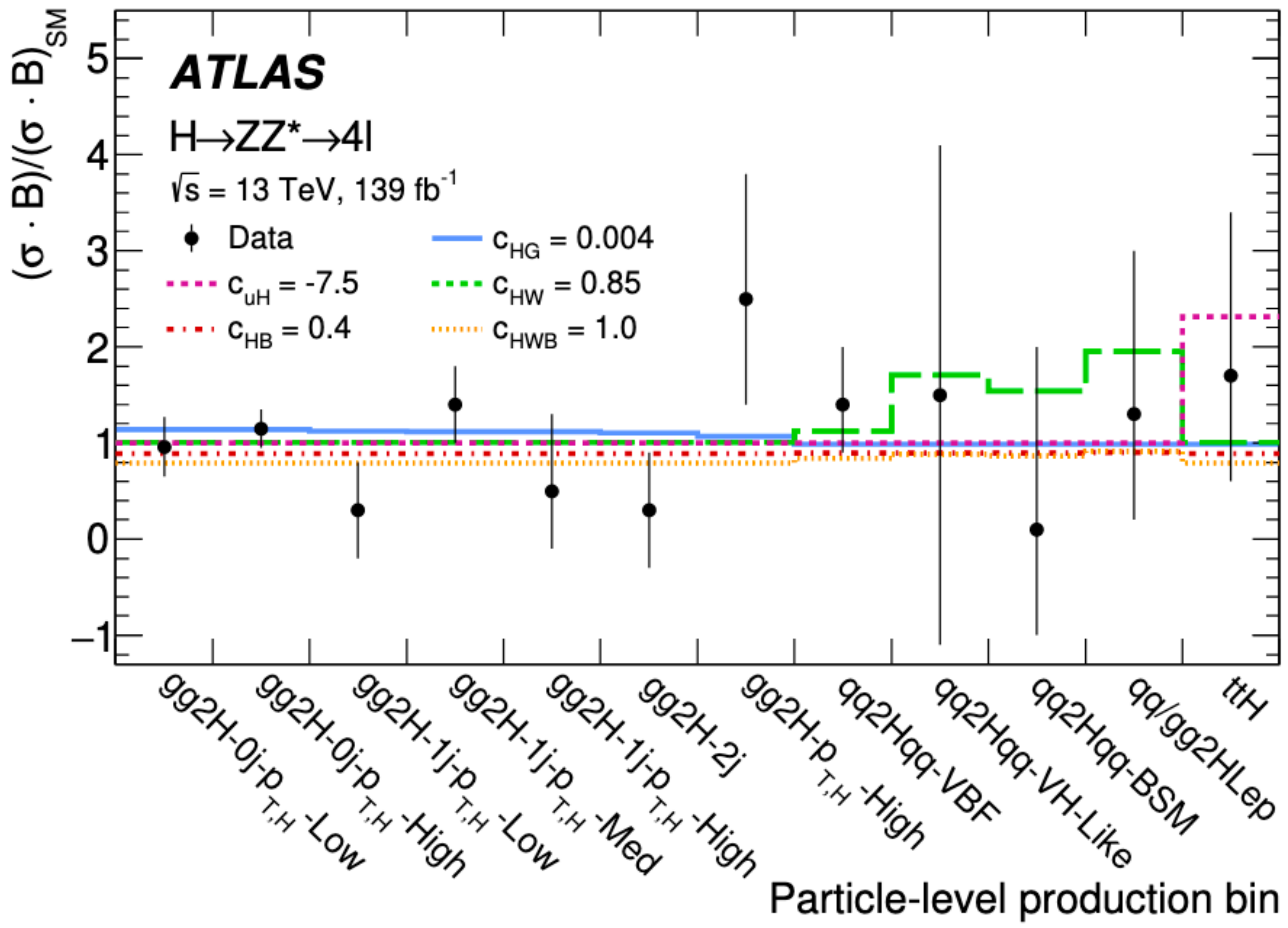


Wilson coefficient	Eigenvalue	Eigenvector
c_{E0}	2000	$0.98 \cdot c_{Hq3}$
c_{E1}	38	$0.85 \cdot c_{Hu} - 0.39 \cdot c_{Hq1} - 0.27 \cdot c_{Hd}$
c_{E2}	8.3	$0.70 \cdot \Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}} + 0.62 \cdot c_{HW}$
c_{E3}	0.2	$0.74 \cdot c_{HWB} + 0.53 \cdot c_{Hq1} - 0.32 \cdot c_{HW}$
c_{E4}	$6.4 \cdot 10^{-3}$	$0.65 \cdot c_{HW} - 0.60 \cdot \Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}} + 0.35 \cdot c_{Hq1}$

Only Wilson coefficients with an impact in an EV larger than 0.2 retained

H→4l (ATLAS)

arXiv:2004.03447



- Interpretation of STXS measurements in the Warsaw basis with Mw scheme
- Main operators affecting the measurement are selected
- Linear+quadratic terms included in the parametrisation as well as CP-even and CP-odd operators

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\tilde{W}}$	$HH^\dagger \tilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\tilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\tilde{W}B}$	$HH^\dagger \tau^l \tilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{W}B}$	VBF, VH	Yes

- CP-odd operators only appear in the quadratic terms
- For several operators, quadratic terms are relevant

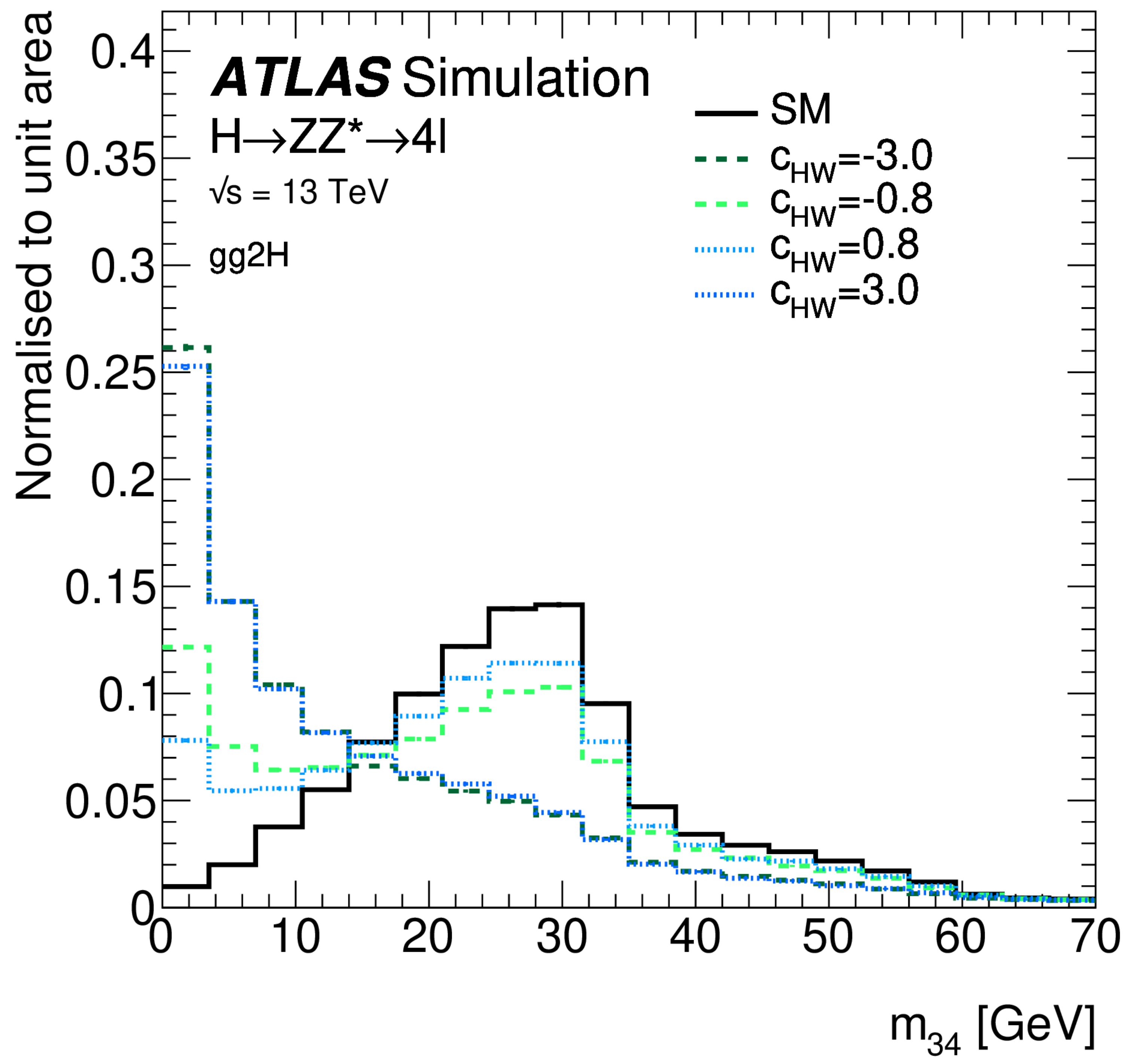
H→4l (ATLAS)

arXiv:2004.03447

- Reconstruction-level requirements on m12 and m34 to target H→ZZ*
- EFT does not have the same acceptance as SM and needs to be corrected in the parametrization
- Other effects: differences in efficiencies or classification in reco bins used in the analysis found to be negligible

Strategy:

- **Mimic reco selection at particle level**
- **Fit a 3-D Lorentzian function for cHW, cHB, cHWB for the acceptance correction relative to SM (or their CP-odd analogous assuming the CP-even ones vanish)**



$$\frac{A(\vec{c})}{A_{\rm SM}} = \alpha_0 + (\alpha_1)^2 \cdot \left[\alpha_2 + \sum_i \delta_i \cdot (c_i + \beta_i)^2 + \sum_{\substack{ij \\ i\neq j}} \delta_{(i,j)} \cdot c_i c_j + \delta_{(i,j,k)} \cdot c_i c_j c_k \right]^{-1},$$

$i\neq j\neq k$

i,j,k run over cHW, cHB, cHWB

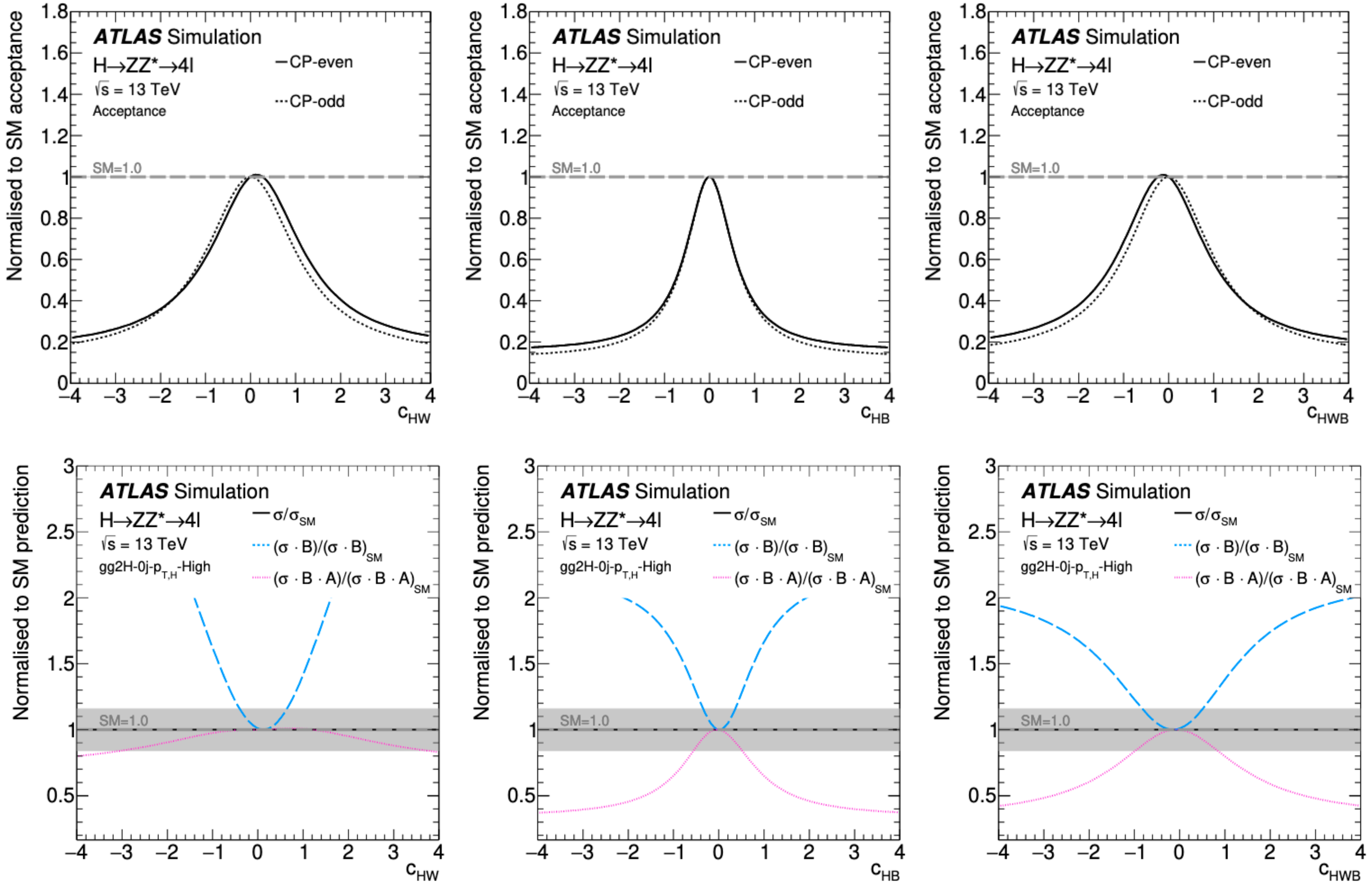
α, β and δ parameters are free in the fit

H→4l (ATLAS)

arXiv:2004.03447

- Acceptance ratios varying one parameter at each time.
- Similar for CP-even and CP-odd operators (mostly from quadratic terms)
- Common acceptance parametrisation for all prod. modes

- Effects on the expected yields normalised to SM
- Non-linear dependence: effect of the BSM terms



Blue line: w.o. acceptance
Pink line: with acceptance

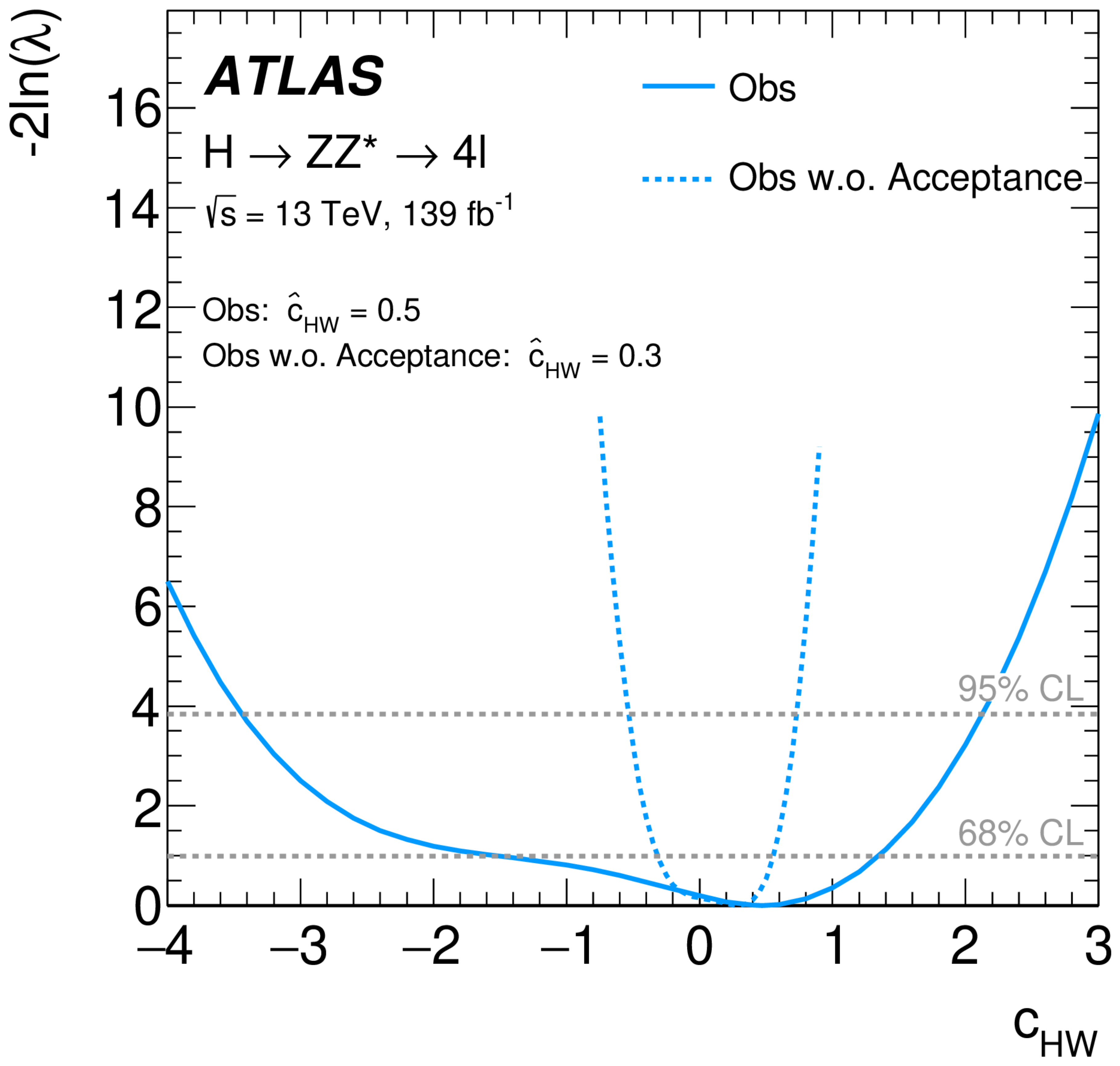
H→4l (ATLAS)

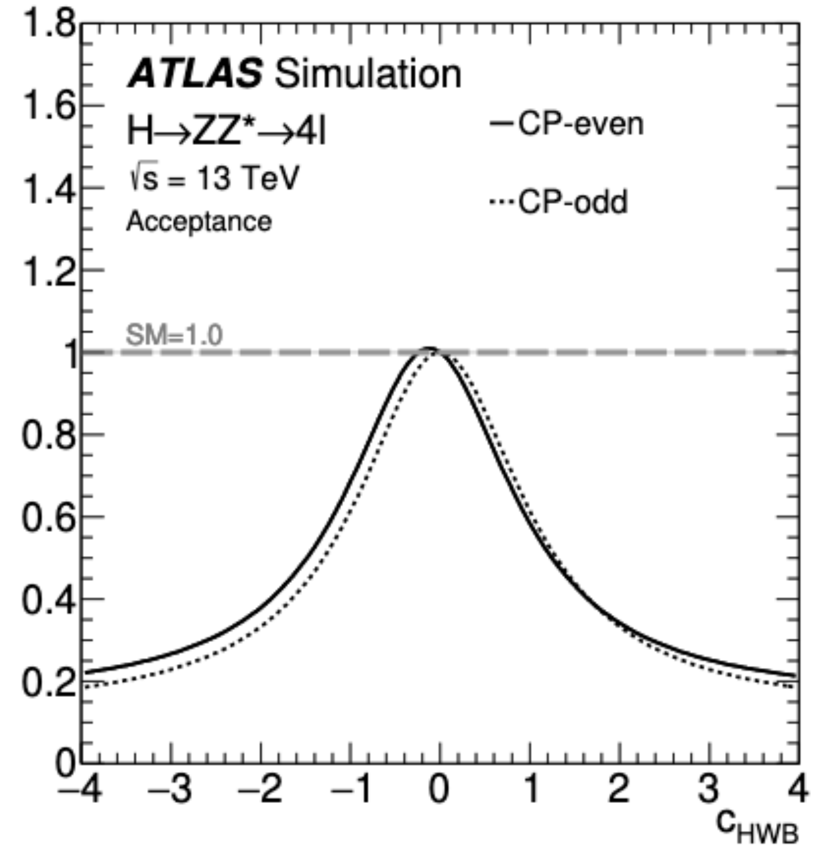
arXiv:2004.03447

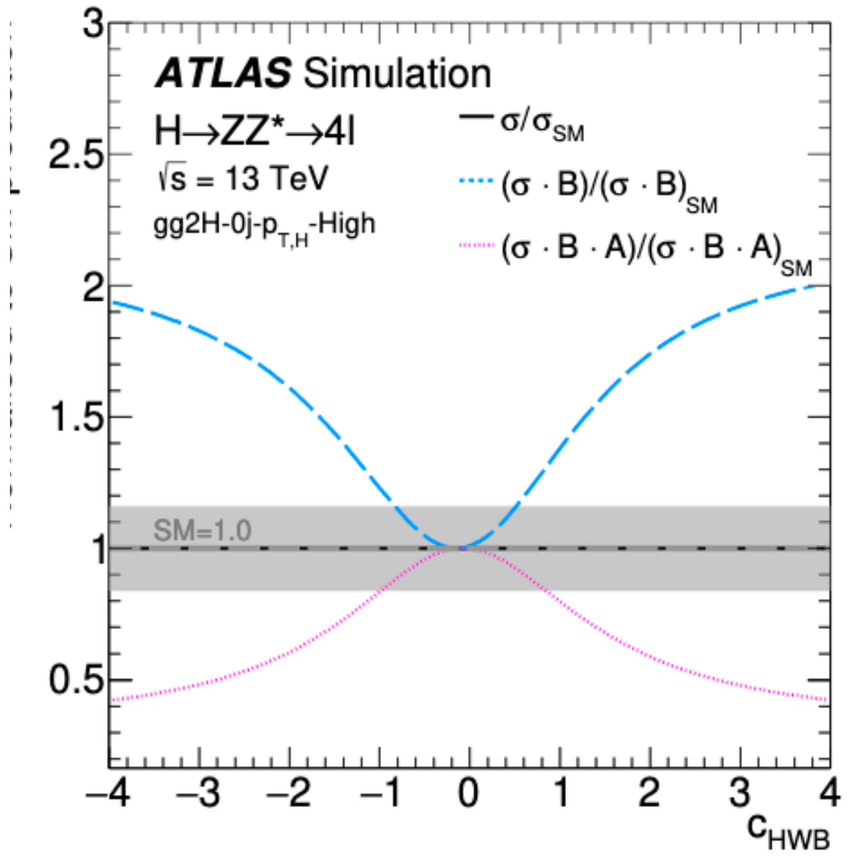
- Acceptance ratios parameter at each
- Similar for CP-eve operators (mostly terms)
- Common accepta for all prod. mode
- Effects on the ex normalised to SM
- Non-linear depe the BSM terms

Impact on 1-D scans:

Acceptance correction is essential!







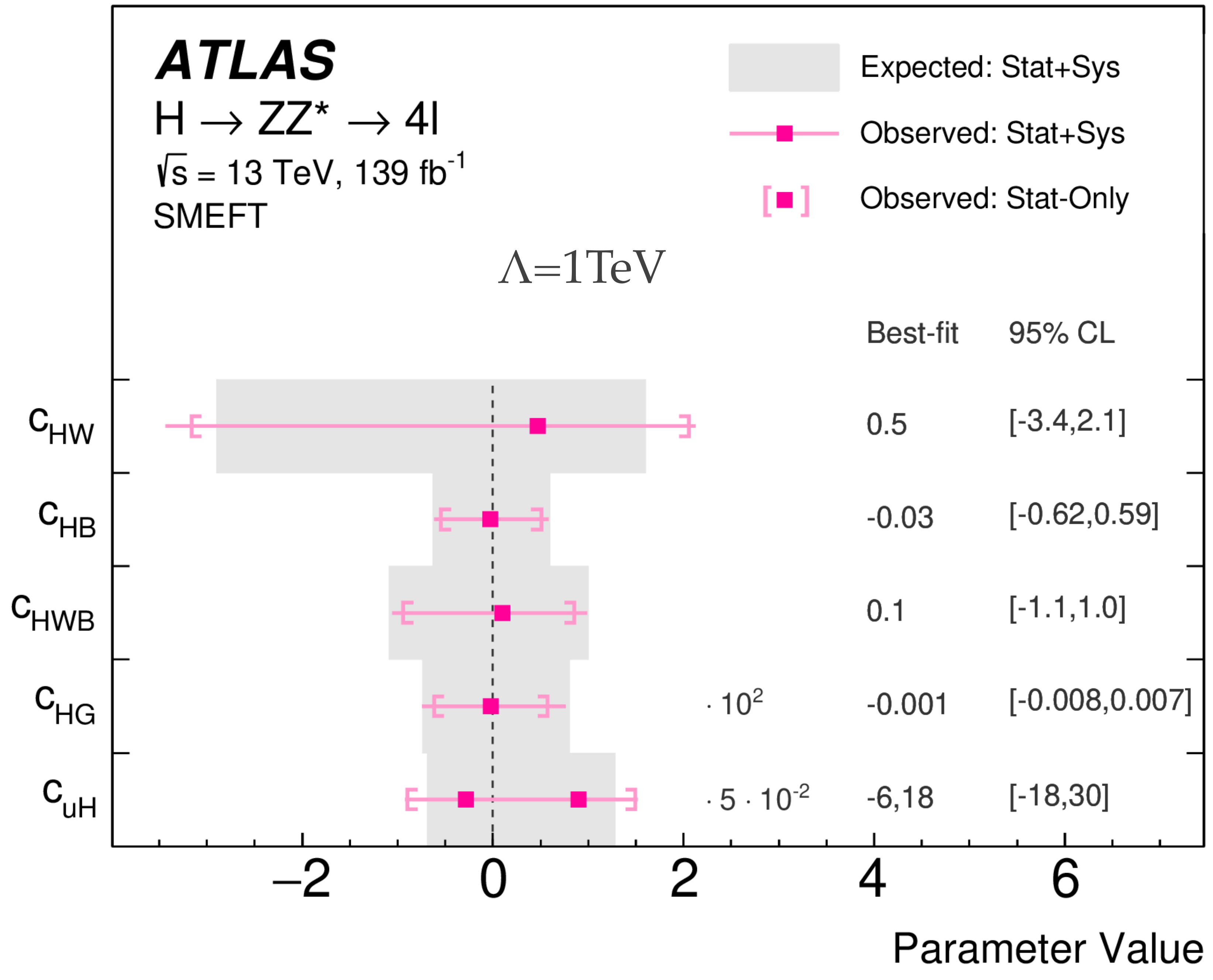
ınce

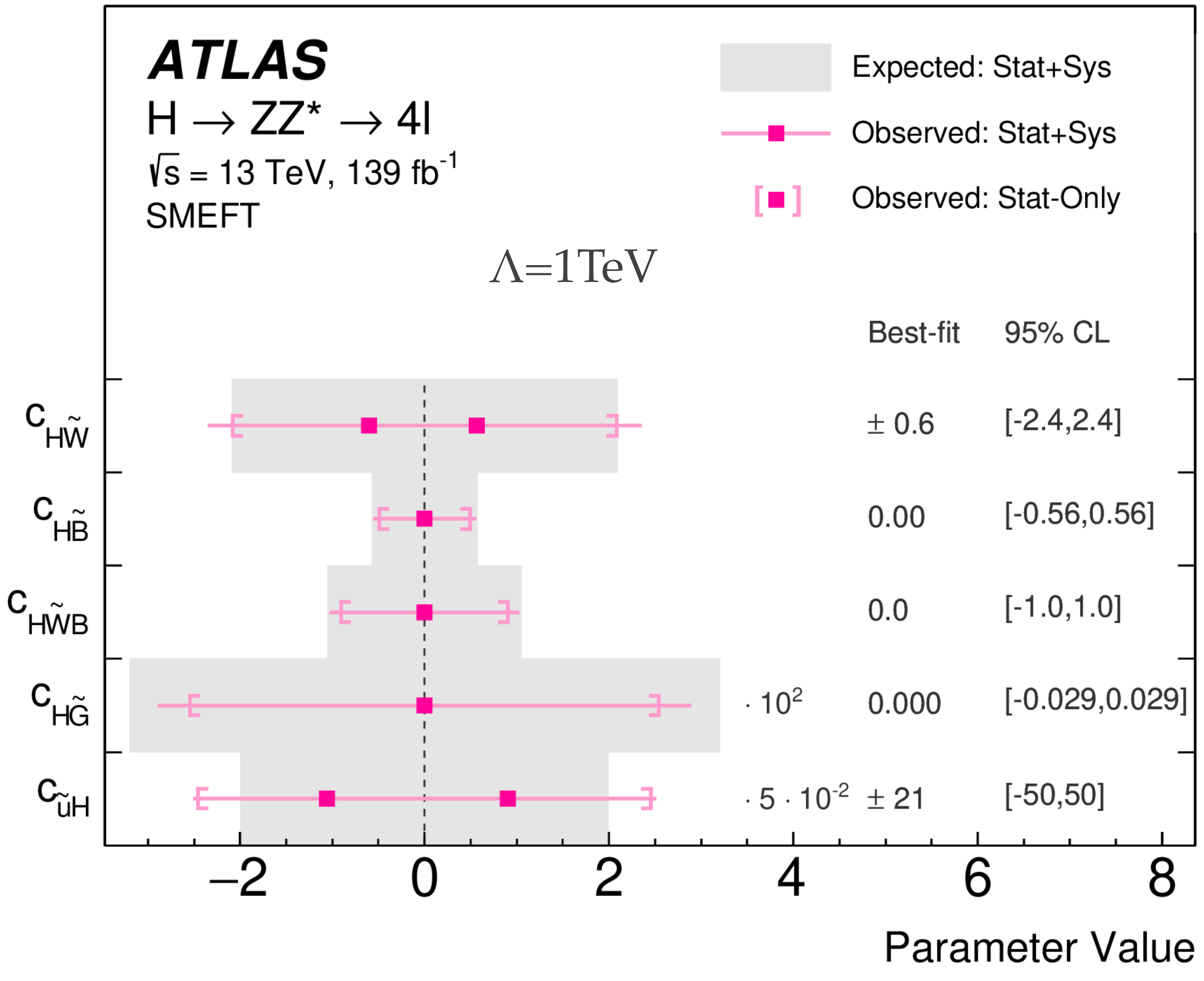
ı ınk line: with acceptance

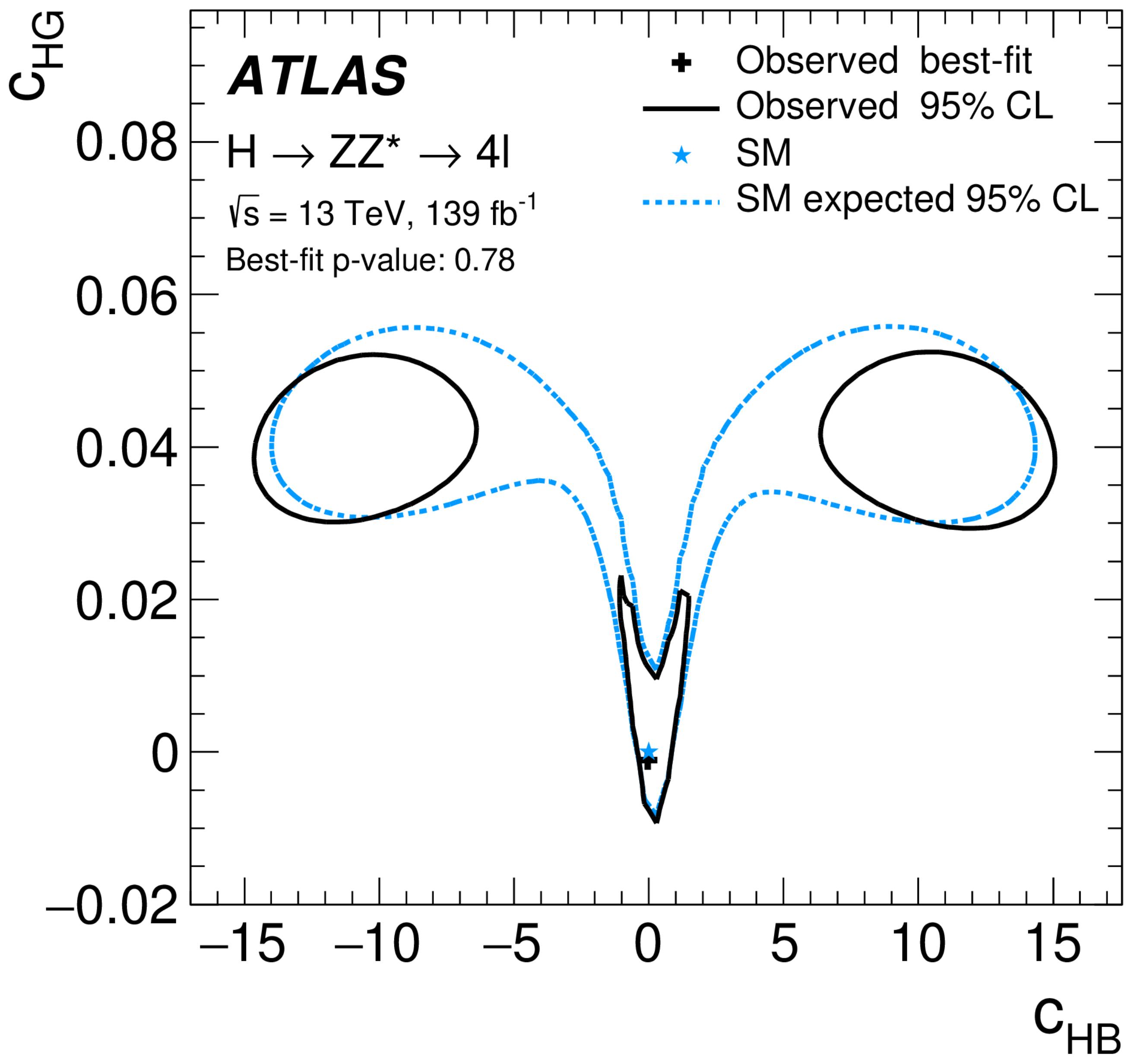
H→4l (ATLAS)

arXiv:2004.03447

- Limits from 1-D fits (all others set to SM), correlations studied through 2D scans
  - Not trivial correlations between most of the parameter pairs





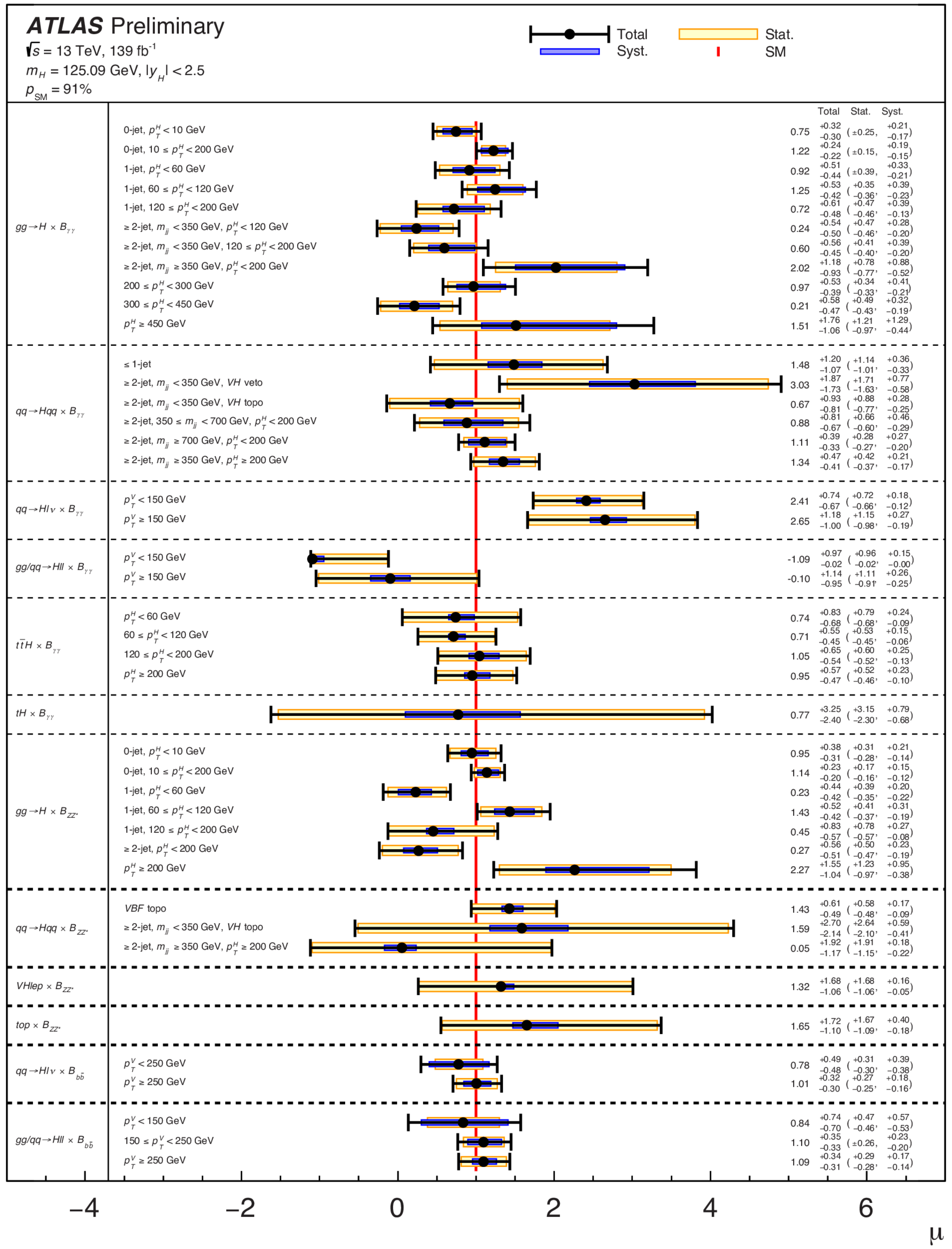


Higgs combination (ATLAS)

ATLAS-CONF-2020-053

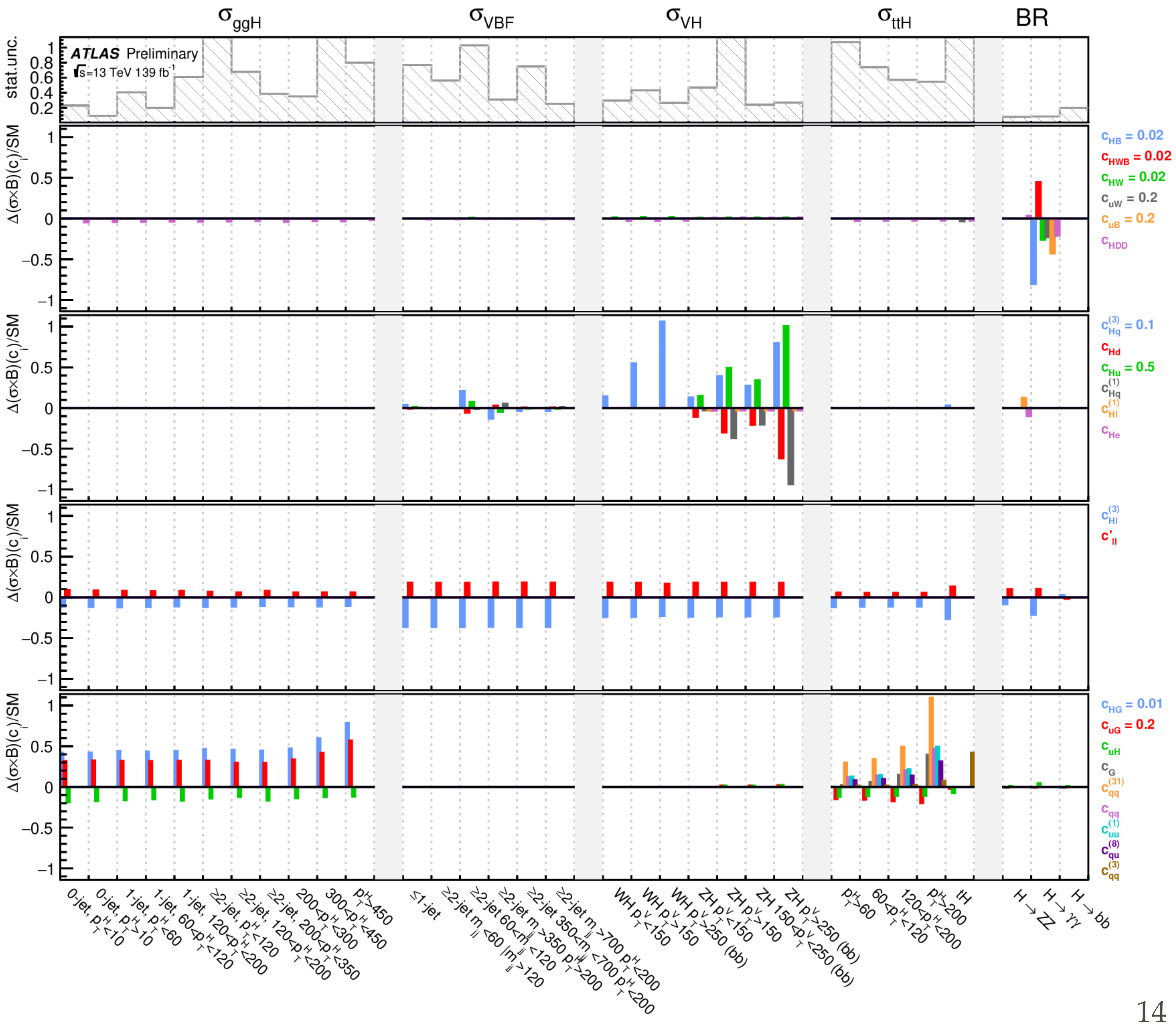
- Stage 1.2 STXS combination of H→γγ, VH(H→bb) and H→ZZ*→4l for full Run 2

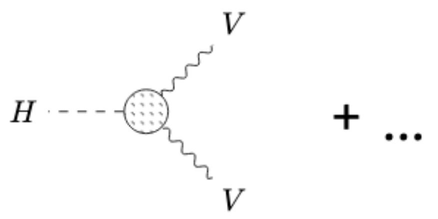
- Based on $\sigma_{STXSi} \times BR_{H\to X}$ signal strength measurement
  - Warsaw basis in Mw scheme
  - Lowest order of each production mode or decay channel: NLO QCD for ggH and ggZH from SMEFT@NLO, NLO EW for H→γγ, LO for the rest from SMEFTsim
  - Only CP-even operators (no linear contribution from CP-odd ones and not available in SMEFT@NLO)
  - Include the acceptance effects in H→ZZ*→4l for cHW, cHB and cHWB



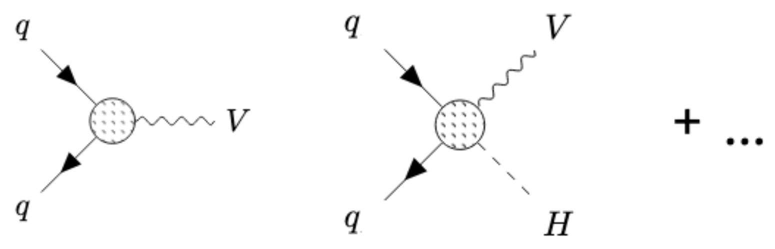
Higgs combination (ATLAS)

ATLAS-CONF-2020-053



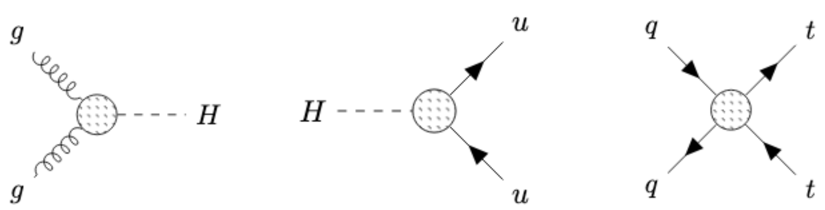


- Retain all operators that modify the production modes or BRs



- They can modify the couplings, introduce new diagrams, enter through field redefinitions or shifts to input quantities

Shifts to Gf

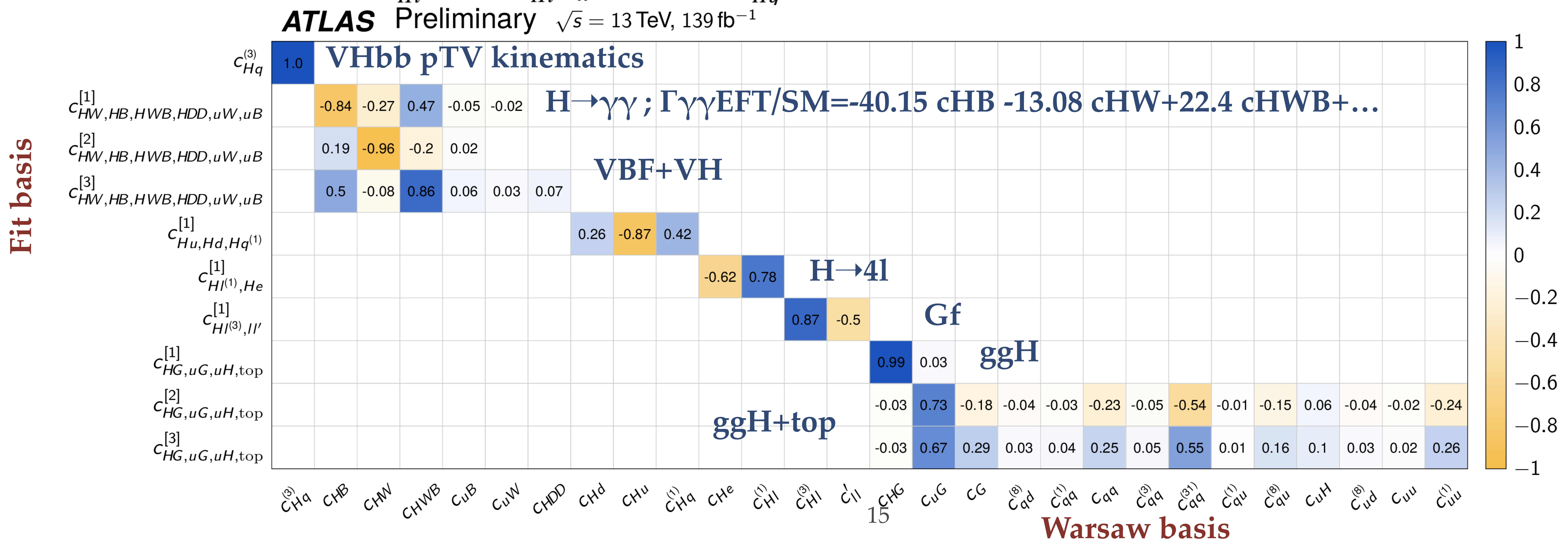


- Simultaneous fit to all relevant single coefficients not possible due to degeneracies

Higgs combination (ATLAS) [ATLAS-CONF-2020-053]

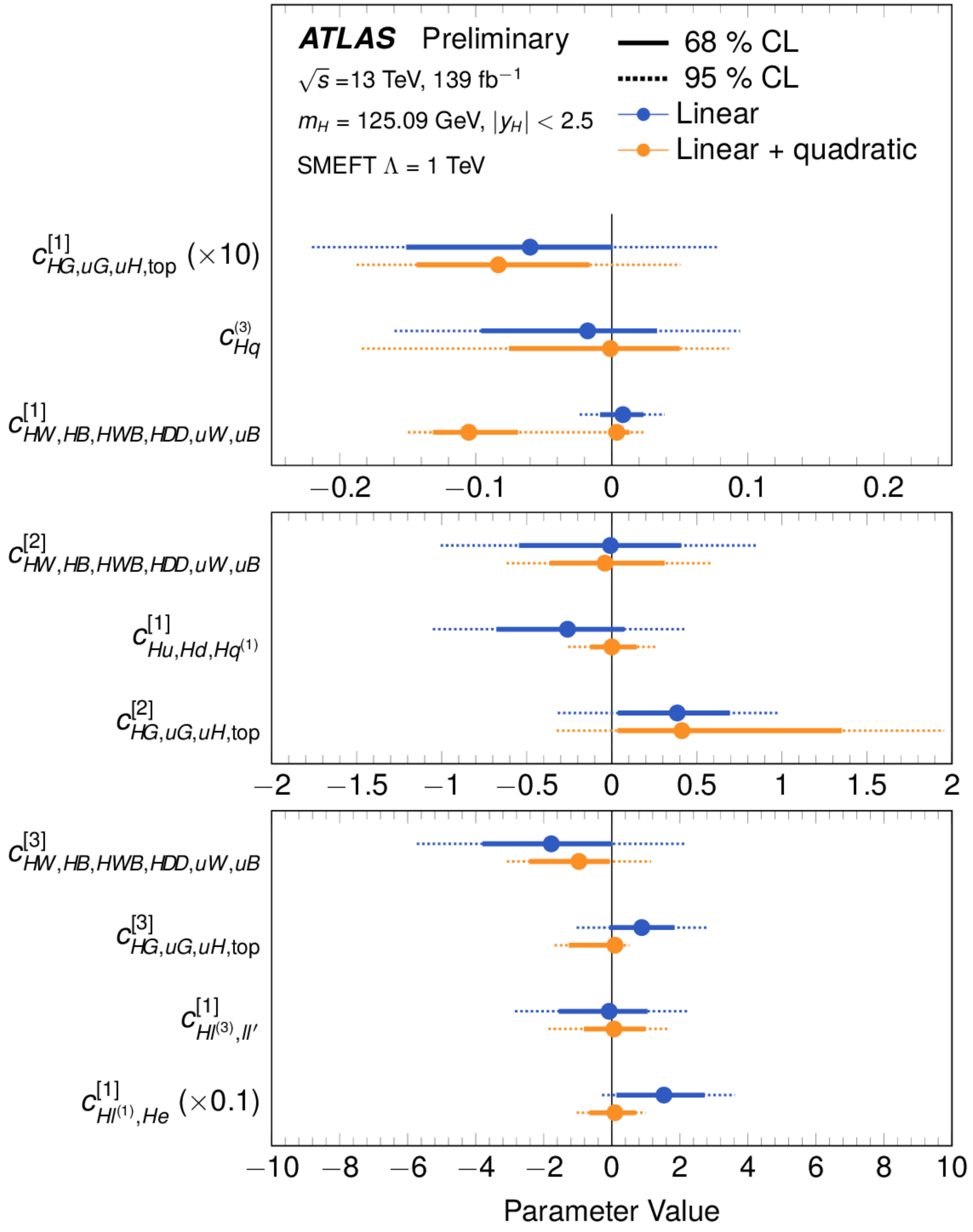
- To reduce the dimensionality of the fit a PCA is performed using the covariance matrix of the STXS measurement and propagating the EFT parametrisation
  - Second PCA on sub-covariance matrices grouping operators affecting the same prod. mode or decay rates. Identify sensitive directions and neglect blind directions

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

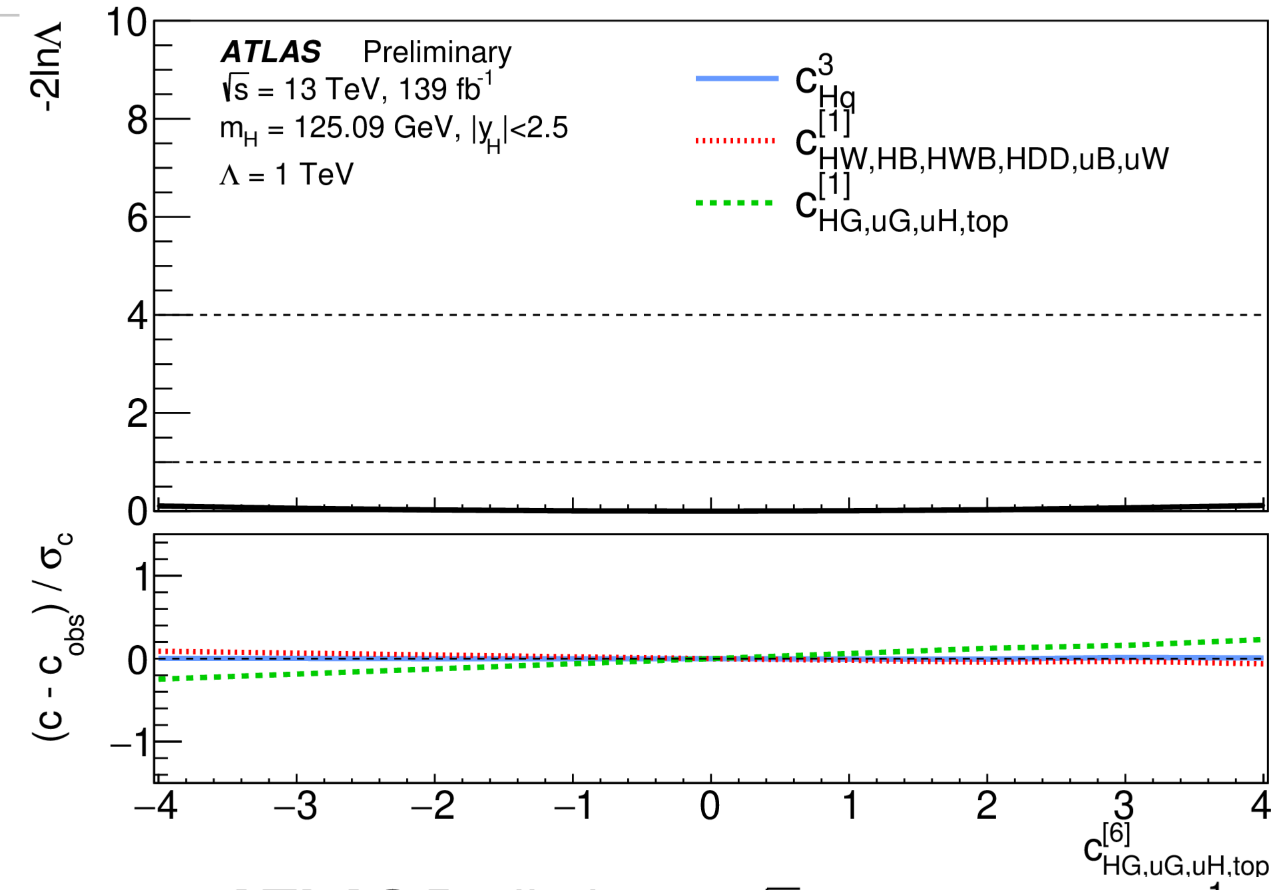


Higgs combination (ATLAS)

ATLAS-CONF-2020-053



- Very good sensitivity to the 10 fitted POI
- Quadratic terms relevant when constrained from low stat bins.
- Insensitivity to neglected direction and negligible impact on fitted POIs checked
- No reduction of "experimental" correlations (exact EVs not fitted) but checked to be linear



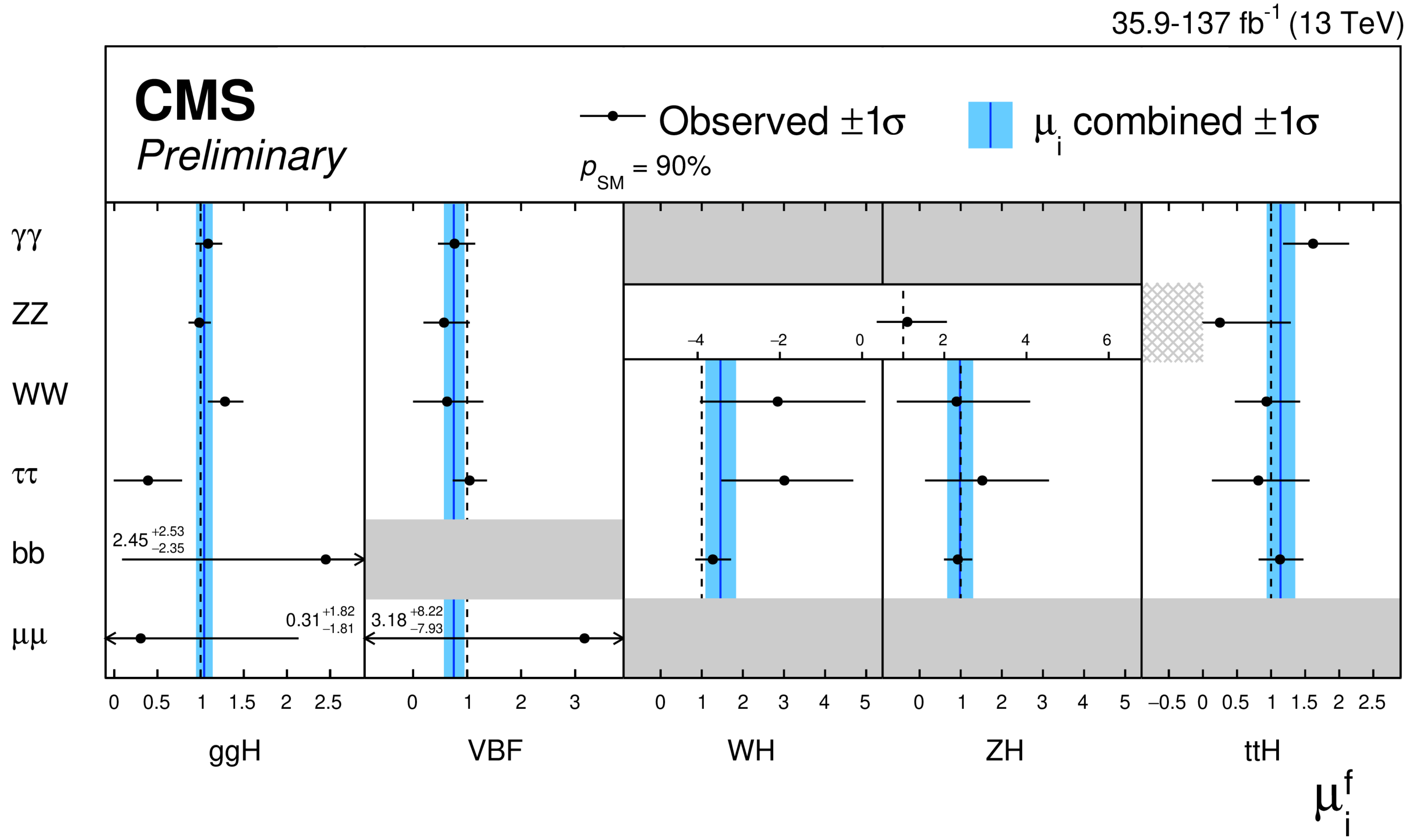
ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 139 fb^{-1}
m_H = 125.09 GeV, $|y_H|$ < 2.5

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

Higgs combination (CMS)

CMS-PAS-HIG-19-005

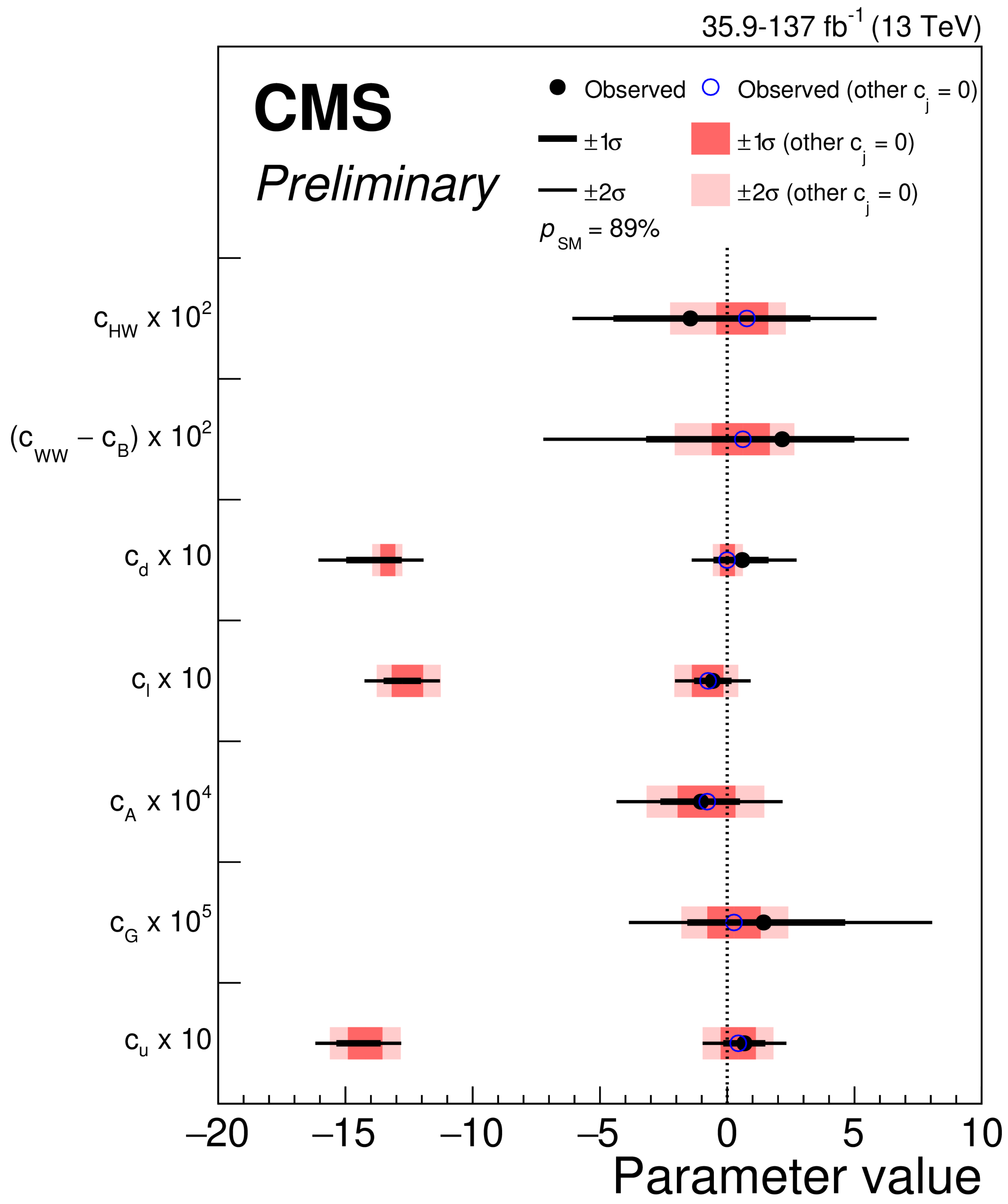
- Combined measurements of the production and decay rates of the Higgs boson and its couplings to vector bosons and fermions: H→γγ, H→bb, H→ZZ*→4l, H→ττ, H→WW*→lνlν, ttH-multilepton (up to 137 fb^{-1})



- Interpretation in the HEL Lagrangian
  - At LO. Using stage 0, 1.0 or 1.1 depending on the input channel
- Signal strength values reparametrized in terms of EFT coefficients.
- ggZH, bbH and tH fixed to SM
- Only CP-even terms not tightly constrained by other data considered
- Acceptance effects not taken into account

Higgs combination (CMS)

CMS-PAS-HIG-19-005



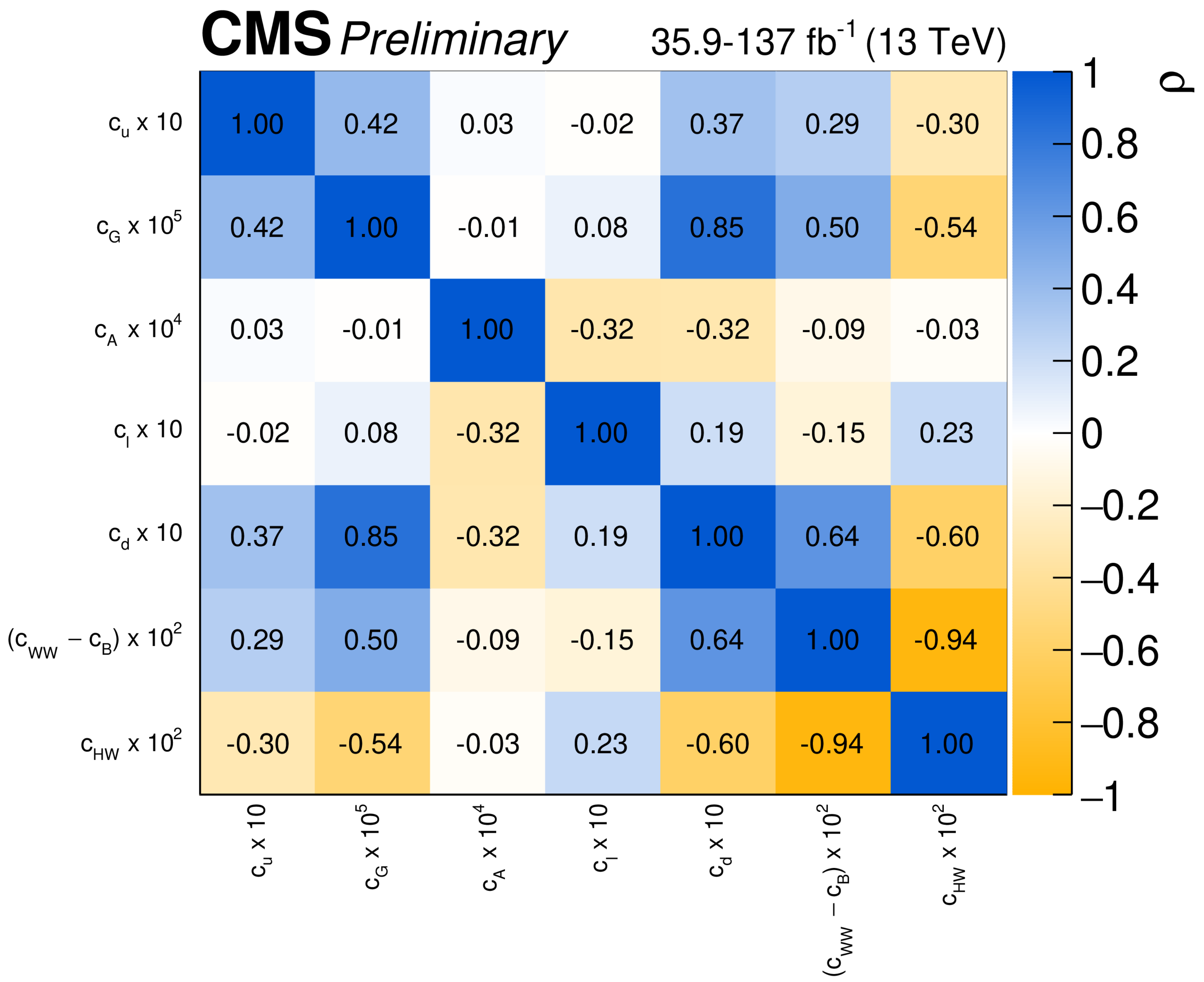
HEL Parameters	Definition	Others profiled	Fix others to SM
$c_A \times 10^4$	$c_A = \frac{m_W^2}{g'^2}\frac{f_A}{\Lambda^2}$	$-1.03^{+1.53}_{-1.59}$ $\left(^{+1.59}_{-1.56}\right)$	$-0.78^{+1.11}_{-1.16}$ $\left(^{+1.10}_{-1.11}\right)$
$c_G \times 10^5$	$c_G = \frac{m_W^2}{g_s^2}\frac{f_G}{\Lambda^2}$	$1.43^{+3.20}_{-3.00}$ $\left(^{+3.13}_{-2.74}\right)$	$0.27^{+1.05}_{-1.05}$ $\left(^{+1.03}_{-1.01}\right)$
$c_u \times 10$	$c_u = -v^2\frac{f_u}{\Lambda^2}$	$0.68^{+0.82}_{-0.83}$ $\left(^{+0.83}_{-0.79}\right)$	$0.43^{+0.69}_{-0.69}$ $\left(^{+0.68}_{-0.67}\right)$
$c_d \times 10$	$c_d = -v^2\frac{f_d}{\Lambda^2}$	$0.59^{+1.03}_{-1.13}$ $\left(^{+1.08}_{-1.05}\right)$	$-0.01^{+0.31}_{-0.28}$ $\left(^{+0.30}_{-0.28}\right)$
$c_\ell \times 10$	$c_\ell = -v^2\frac{f_\ell}{\Lambda^2}$	$-0.57^{+0.74}_{-0.73}$ $\left(^{+0.72}_{-0.77}\right)$	$-0.75^{+0.60}_{-0.64}$ $\left(^{+0.58}_{-0.60}\right)$
$c_{HW} \times 10^2$	$c_{HW} = \frac{m_W^2}{2g}\frac{f_{HW}}{\Lambda^2}$	$-1.45^{+4.72}_{-3.03}$ $\left(^{+3.93}_{-3.27}\right)$	$0.77^{+0.84}_{-1.20}$ $\left(^{+1.04}_{-1.38}\right)$
$(c_{WW} - c_B) \times 10^2$	$c_{WW} = \frac{m_W^2}{g}\frac{f_{WW}}{\Lambda^2}$, $c_B = \frac{2m_W^2}{g'}\frac{f_B}{\Lambda^2}$	$2.16^{+2.84}_{-5.35}$ $\left(^{+3.46}_{-5.00}\right)$	$0.62^{+1.06}_{-1.22}$ $\left(^{+1.09}_{-1.23}\right)$

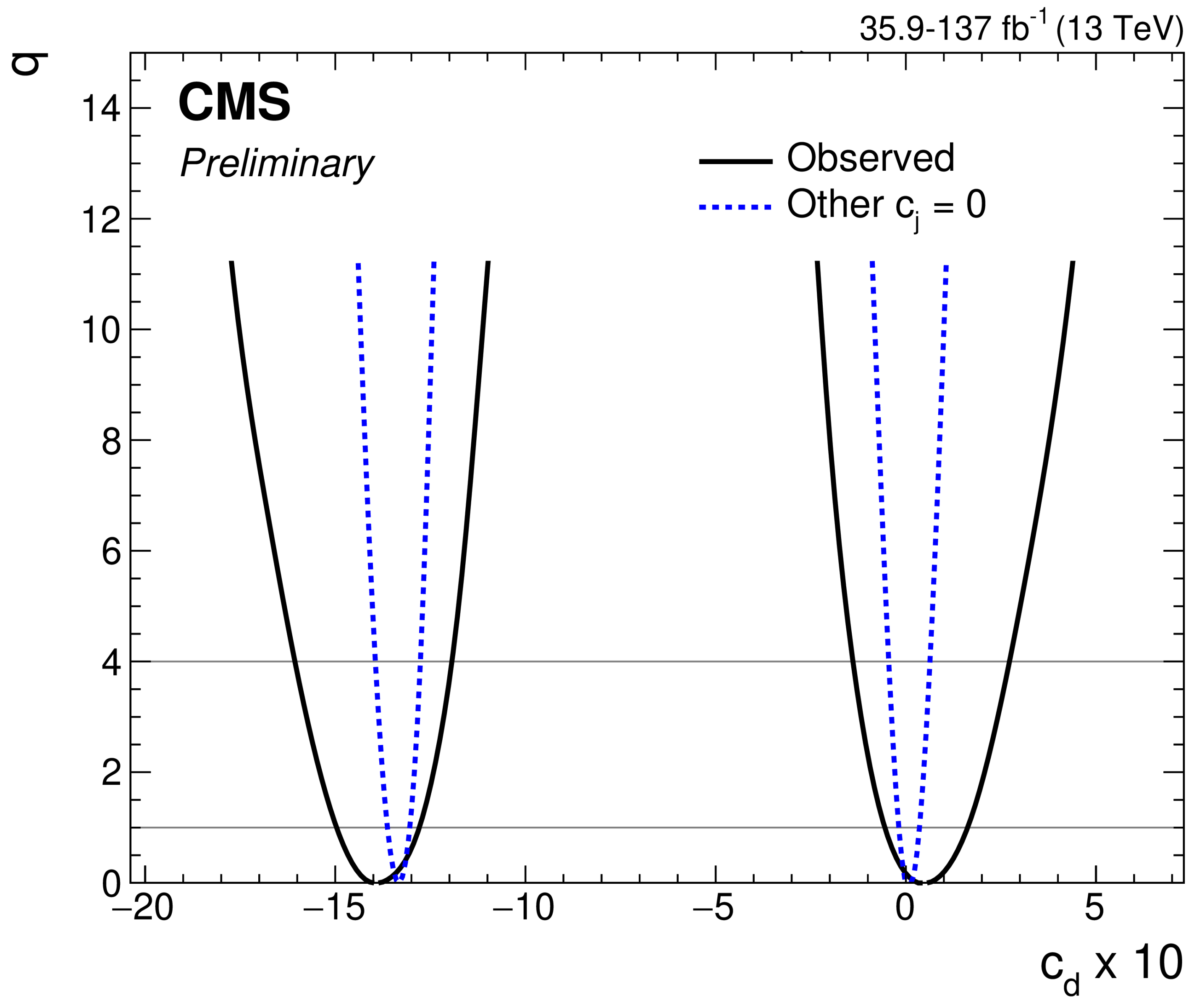
- Limits from simultaneous fit to HEL parameters
  - Very good sensitivity
  - Showed the relevance of simultaneous fits vs. 1-D fits setting other parameters to SM

Higgs combination (CMS)

CMS-PAS-HIG-19-005

- Large correlations in operators affecting HV vertices and between cG and several operators
  - Limited information about the VH production in the input channels
  - ggH only affected by cG with small dependence on the STXS bin; overall increase in ggH difficult to disentangle from overall increase in the Higgs width
- Degeneracy on parameters constraint by decay rates (e.g cd in H→bb); could be solved adding bbH





Summary

- SMEFT interpretations taking over kappa-framework interpretations of Higgs properties measurements as precision increase
  - No deviation from the SM observed
- Single analysis useful for specific studies
  - Differences in experimental acceptance in the EFT
  - Usefulness of further splittings at high transverse momentum of the Higgs.
- Analysis combination allow to constrain simultaneously several operators
- Methodologies not yet harmonised between experiments
- Ultimate goal: global EFT fits from the experimental community with Higgs, SM and top data

THANKS!

BACK UP

Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

SILH basis

$$\Delta\mathcal{L}^{(6)} = \boxed{\Delta\mathcal{L}_{SILH}} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + + \Delta\mathcal{L}_{4\psi}$$

16 operators

(12 CP even, 4 CP odd)

SILH operators

Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007) 045

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\,(H^\dagger H)^3 \\
& + \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu} \\
& + \frac{i\tilde{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)\tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)\tilde{B}_{\mu\nu} \\
& + \frac{\tilde{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}\tilde{G}^{a\mu\nu}
\end{aligned}$$

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Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2}H^\dagger H\,G^a_{\mu\nu}G^a_{\mu\nu}$	$\tilde{O}_g$	$\frac{g_s^2}{m_W^2}H^\dagger H\,\tilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2}H^\dagger H\,B_{\mu\nu}B_{\mu\nu}$	$\tilde{O}_\gamma$	$\frac{g'^2}{m_W^2}H^\dagger H\,\tilde{B}_{\mu\nu}B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger\sigma^i D_\nu H\right)W^i_{\mu\nu}$	$\tilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger\sigma^i D_\nu H\right)\widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right)B_{\mu\nu}$	$\tilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right)\tilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2}D_\mu W^i_{\mu\nu}D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2}\partial_\mu B_{\mu\nu}\partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2}D_\mu G^a_{\mu\nu}D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2}\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$	$\tilde{O}_{3W}$	$\frac{g^3}{m_W^2}\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2}f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$	$\tilde{O}_{3G}$	$\frac{g_s^3}{m_W^2}f^{abc}\tilde{G}^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

Table 1: Bosonic D=6 operators in the SILH basis.