Measurement of the HZZ Tensor Coupling in pp→H → ZZ → 4ℓ Decay Channel with the ATLAS Detector

DPG Spring Meeting Aachen 2019

Verena Walbrecht
Supervisor: Sandra Kortner

Max Planck Institute for Physics
(Werner-Heisenberg-Institut)

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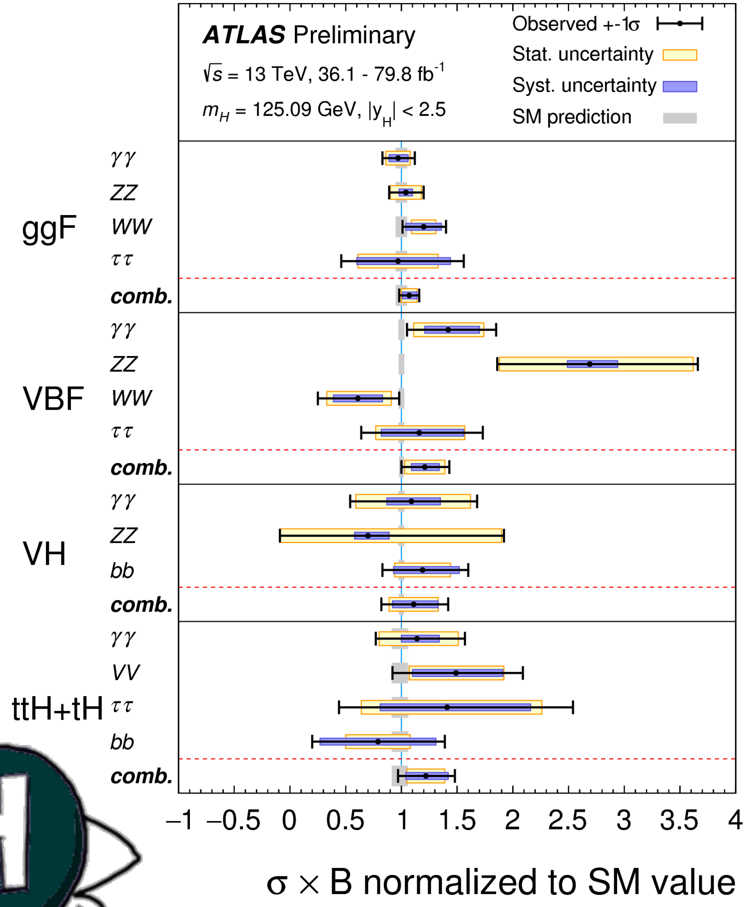
FSP 103
ATLAS

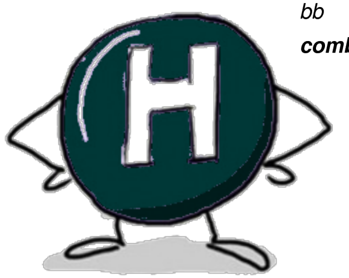
MAX-PLANCK-GESELLSCHAFT

Higgs Boson Coupling Measurements

- Measurement of (σ x BR) in several production and decay modes
- So far: no deviations from the SM observed
- But: in some channels large uncertainties
- Still possible to measure effects from physics beyond the SM
- Increasing statistics: use kinematic properties to search for BSM physics

ATLAS-CONF-2018-031





The H → ZZ → 4ℓ Decay Channel

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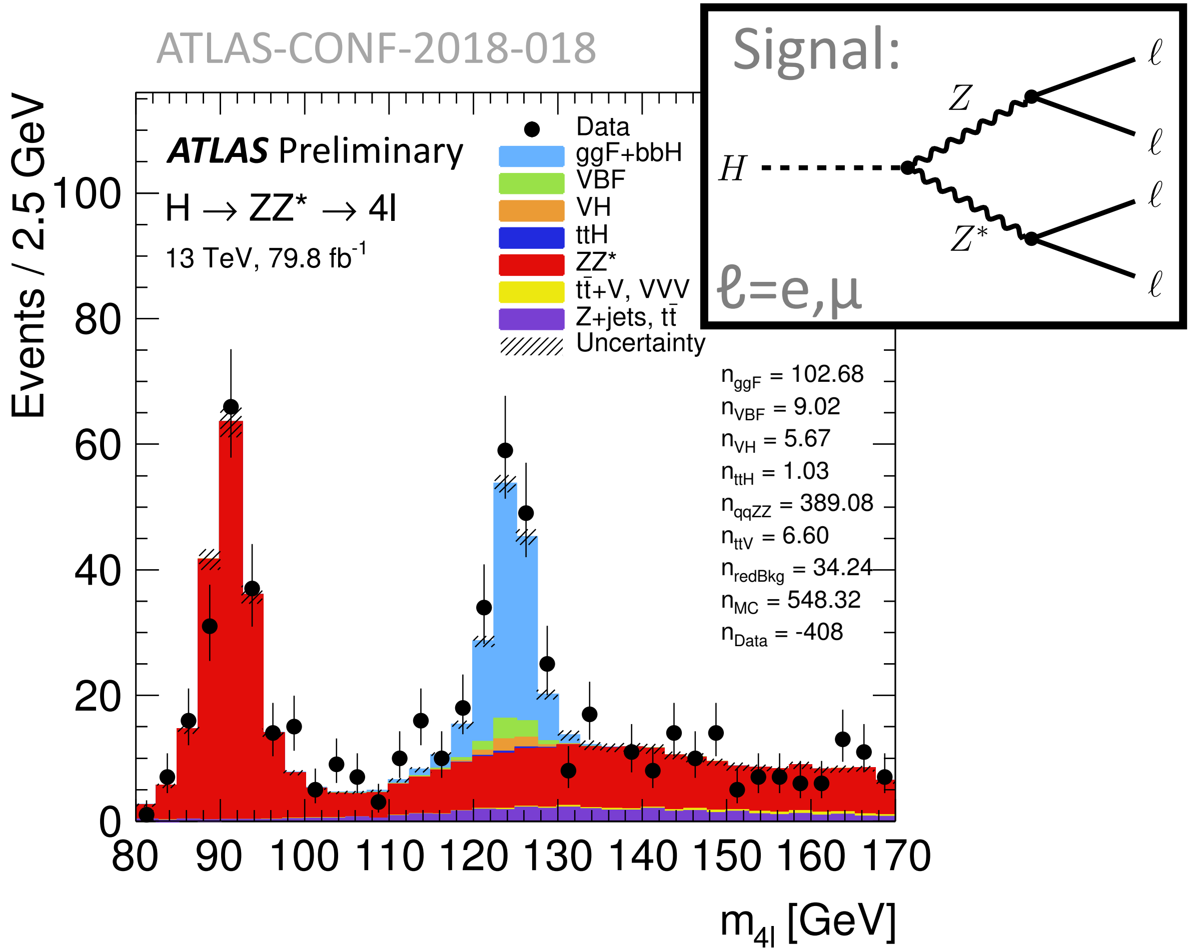

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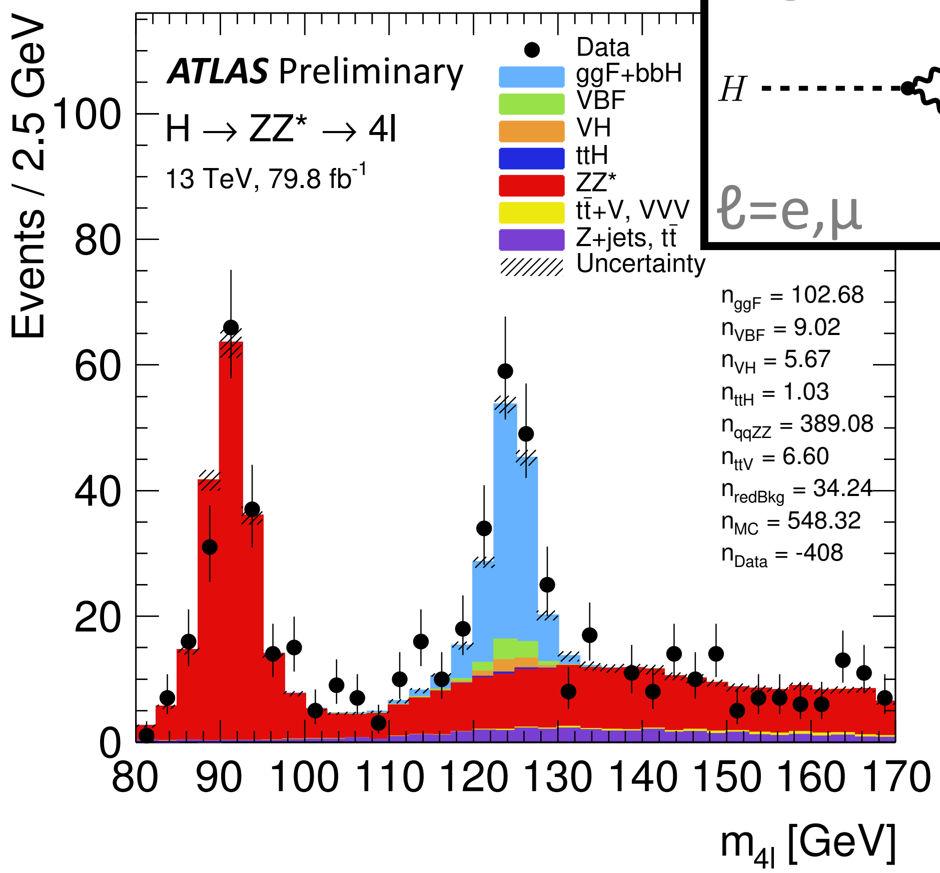

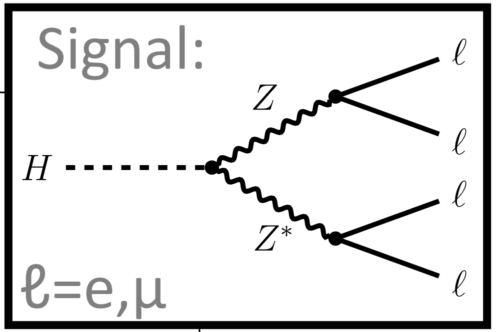

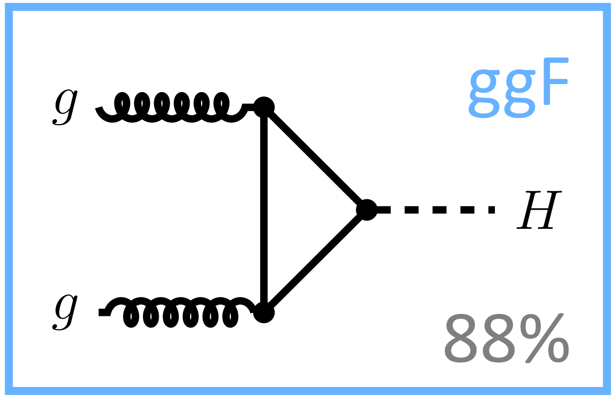

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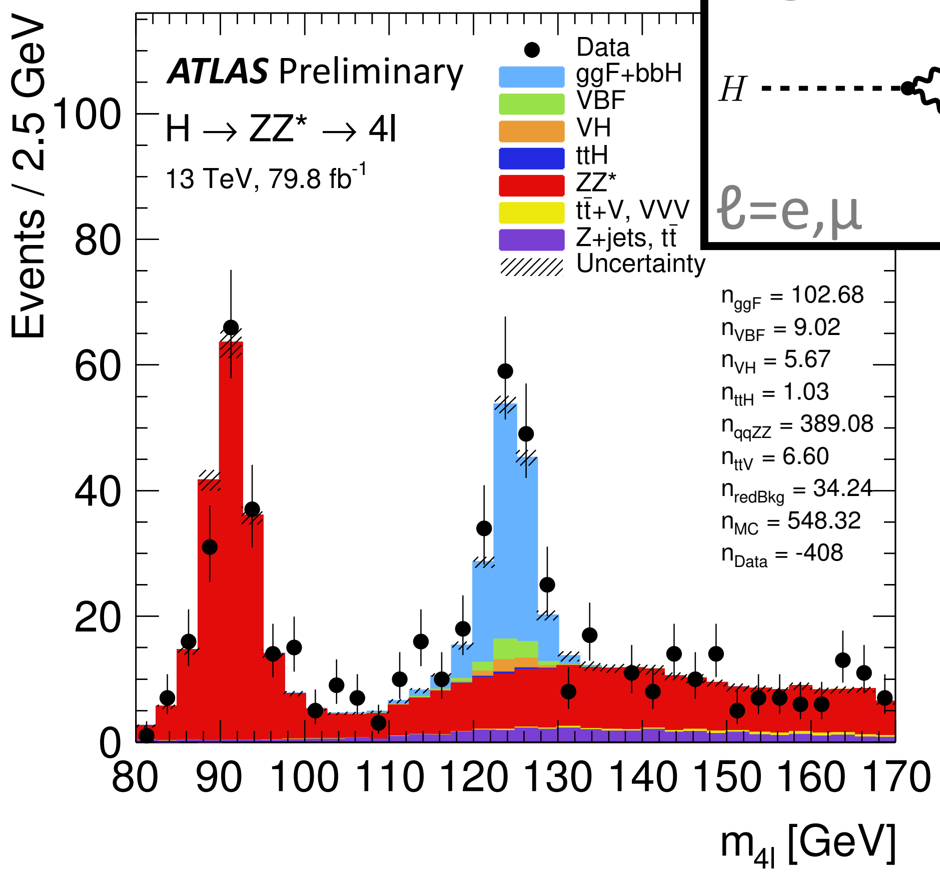

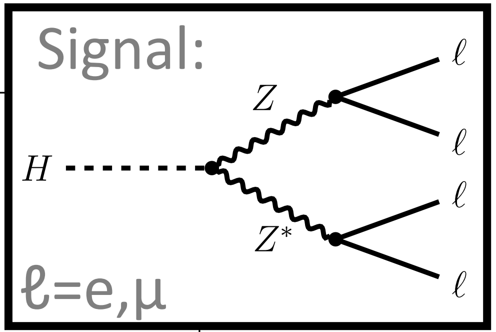

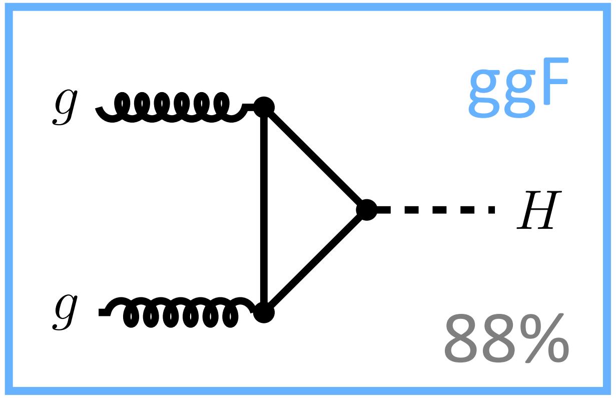

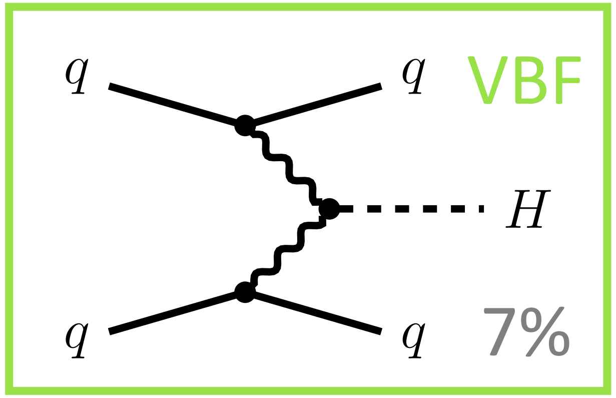

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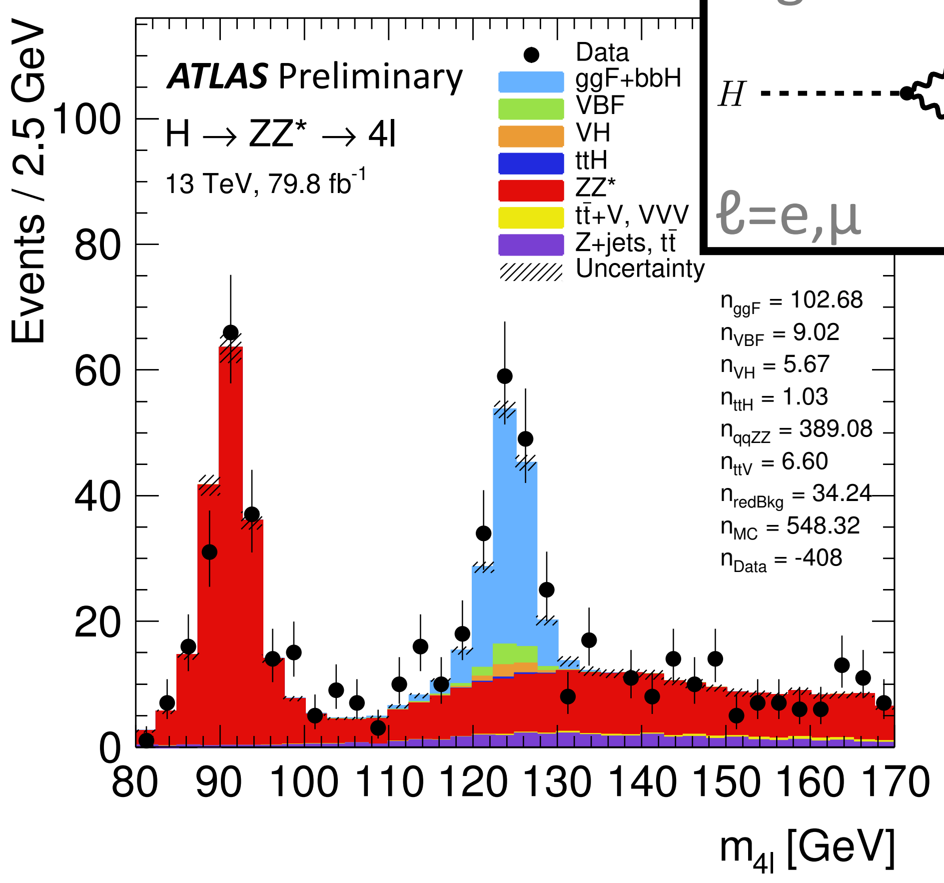

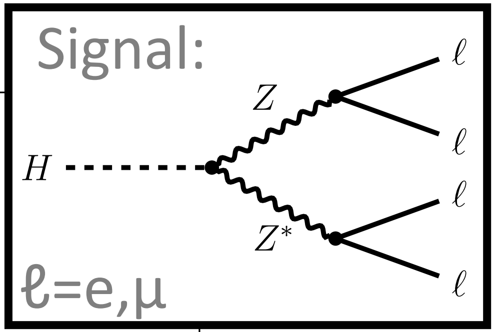

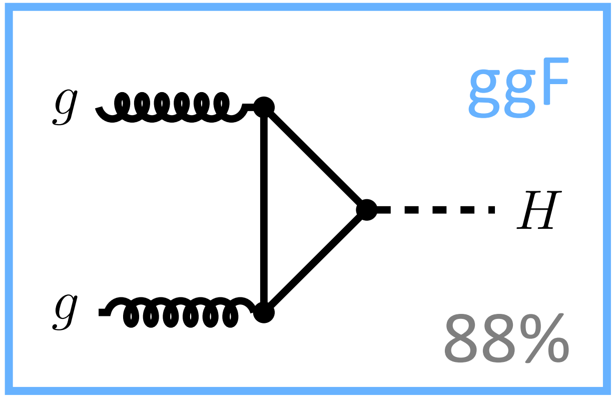

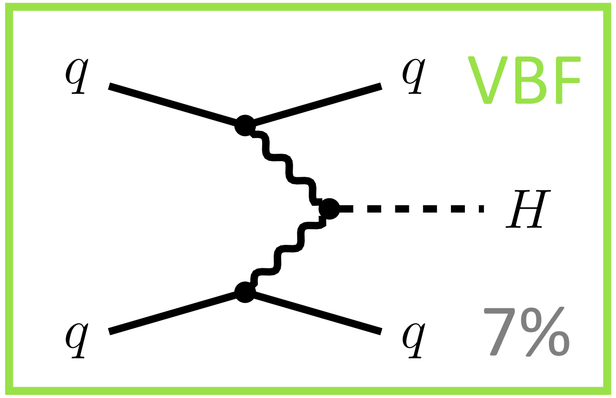

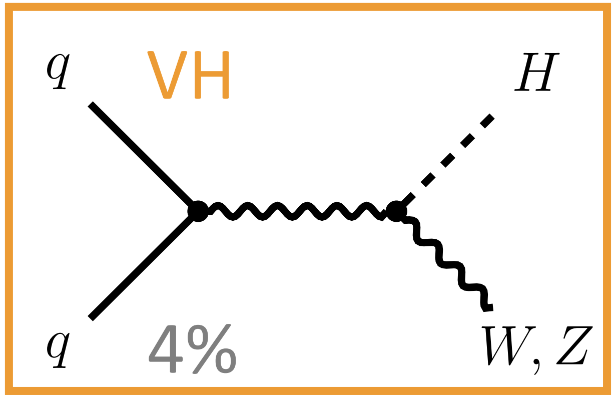

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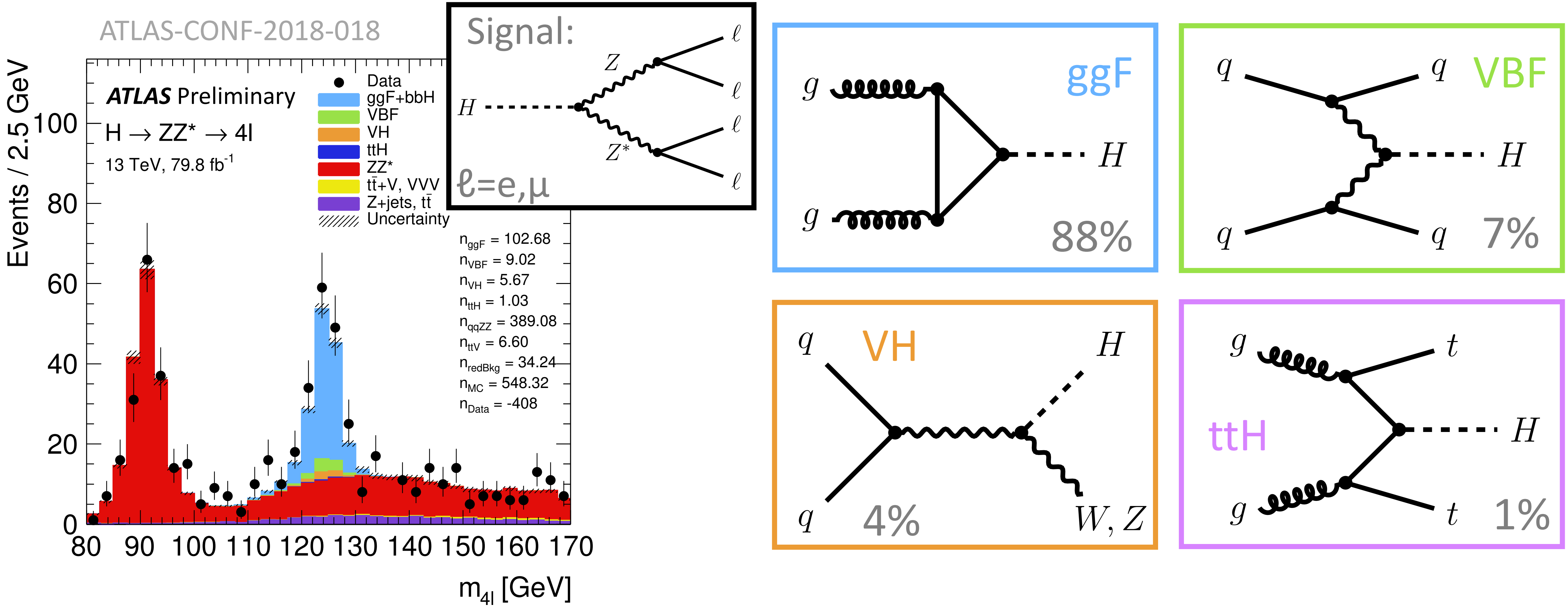

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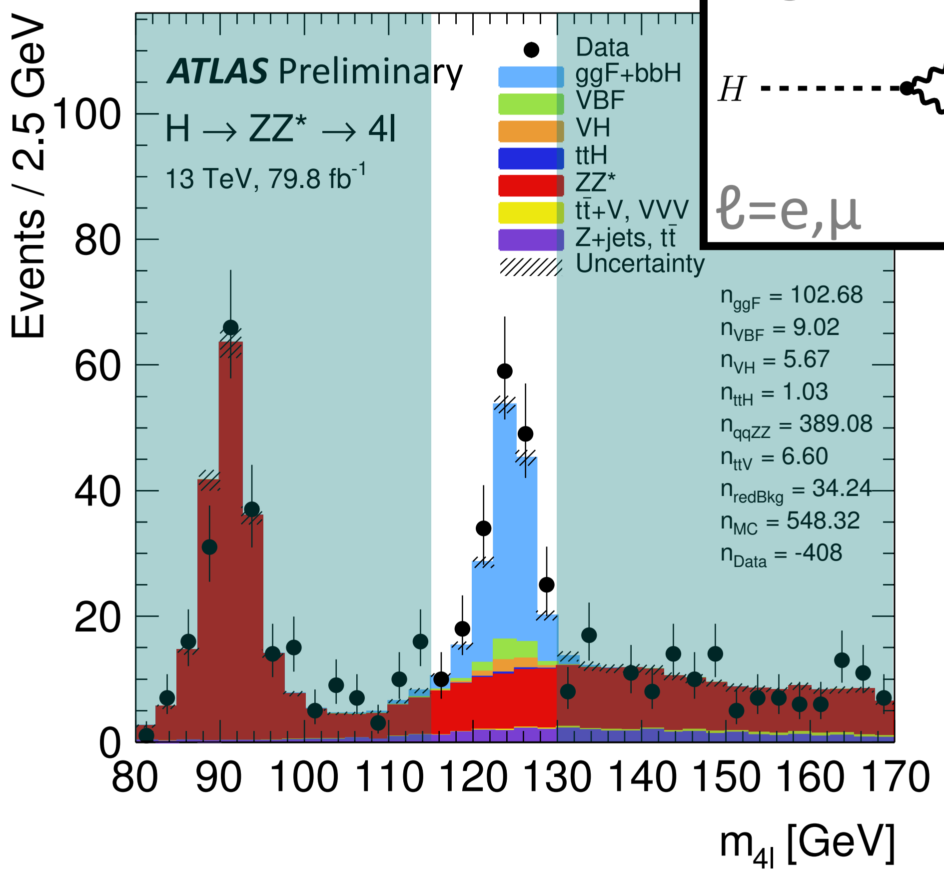
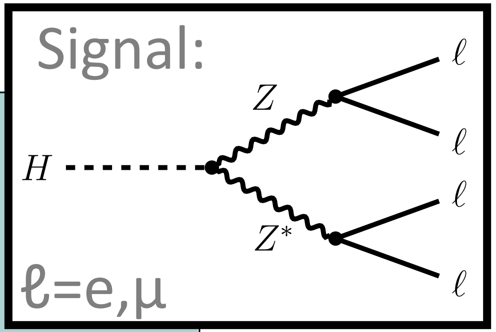
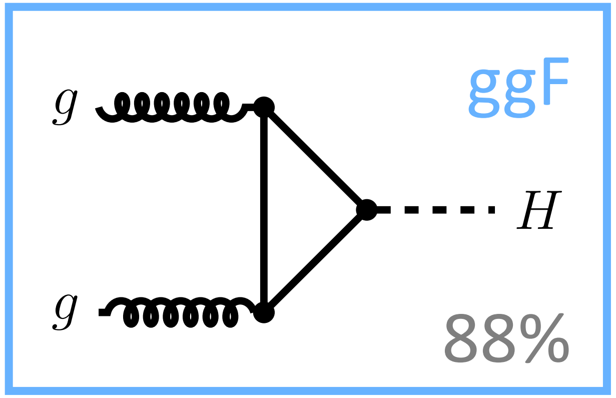
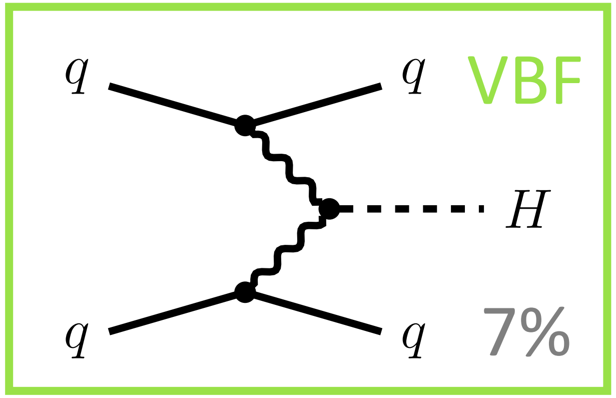
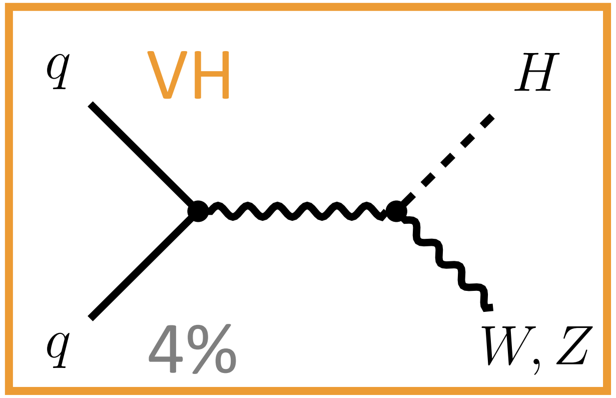
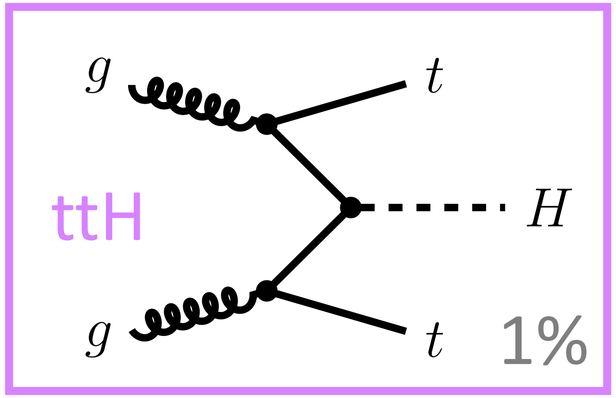






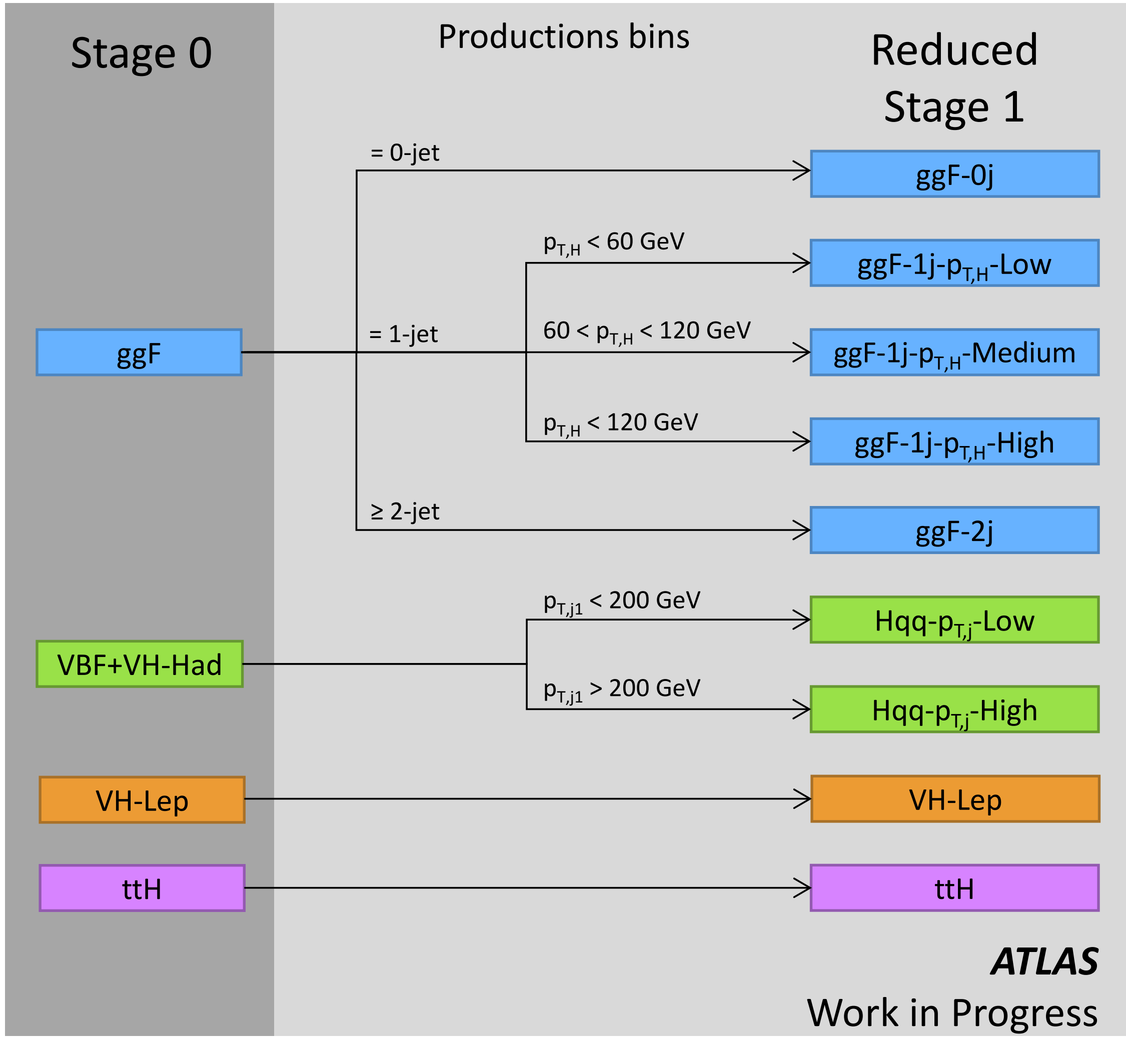






This work: 140 fb^{-1} with full Run II data

SM STXS Coupling Analysis in HZZ



STXS = simplified template cross section

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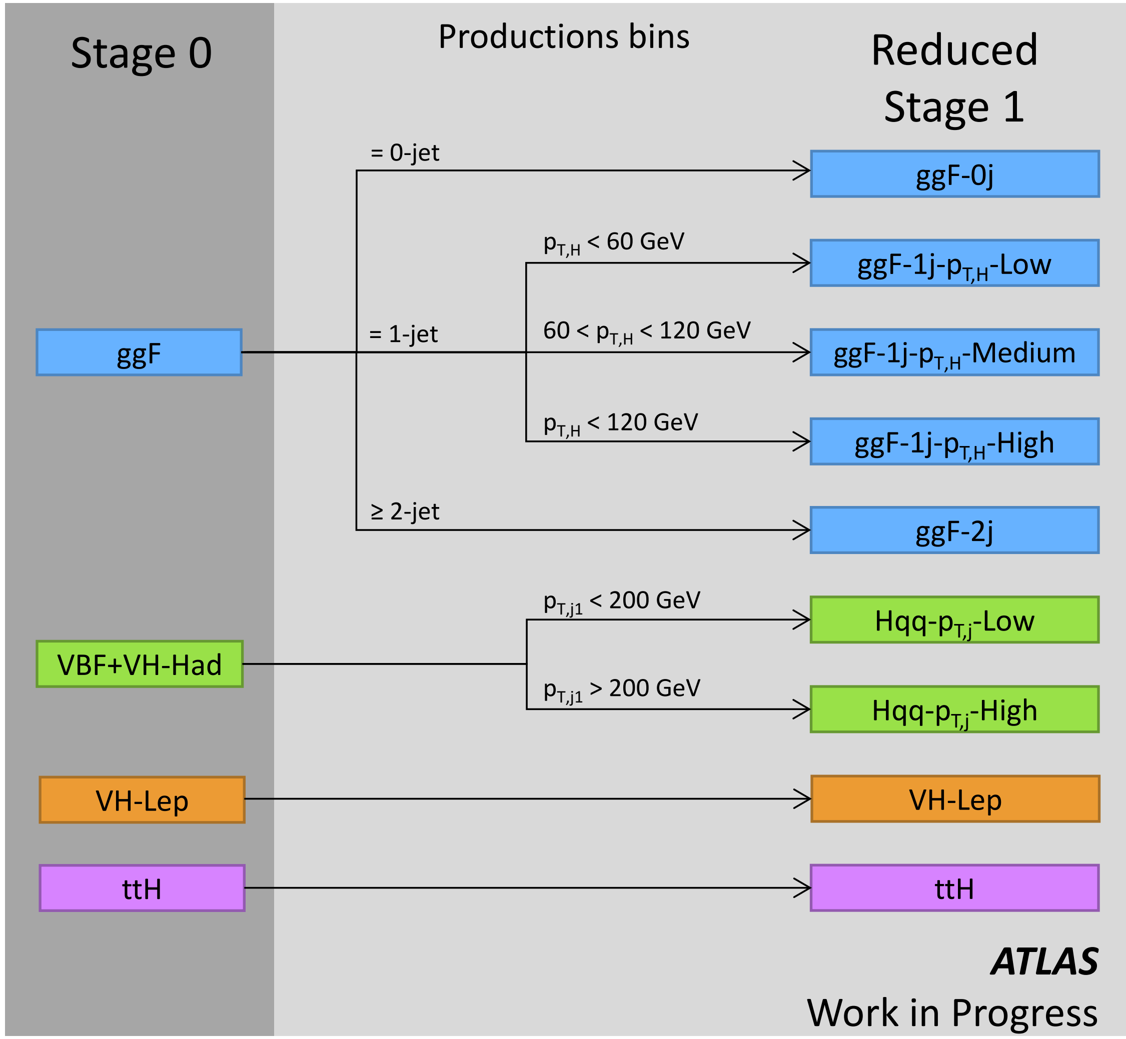
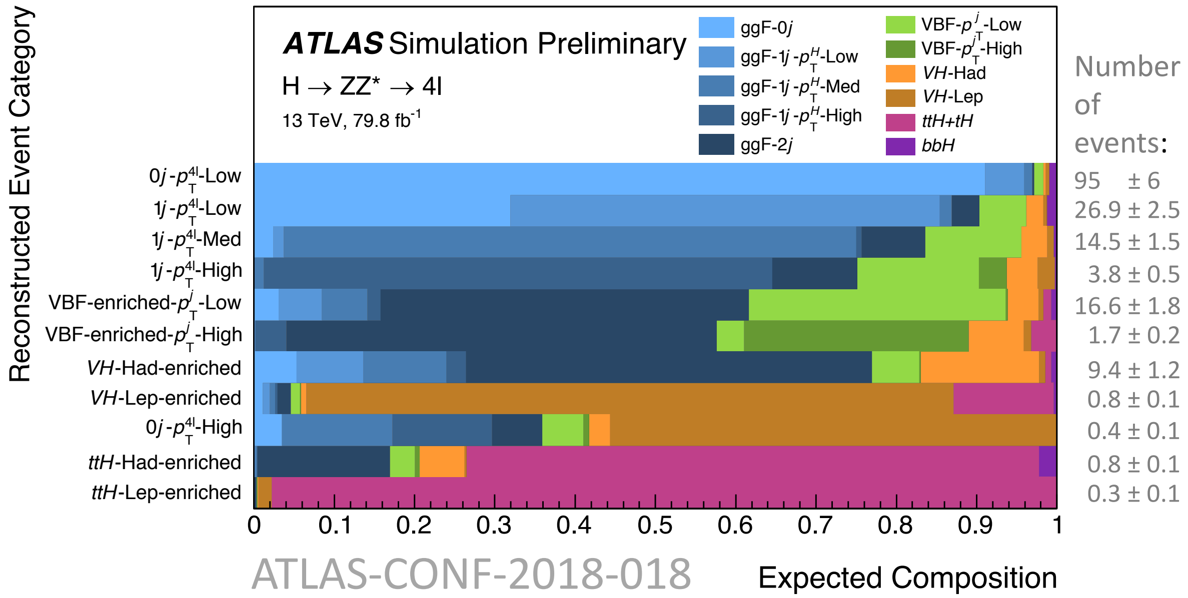


- Expected composition in STXS bins (80 fb^{-1}):



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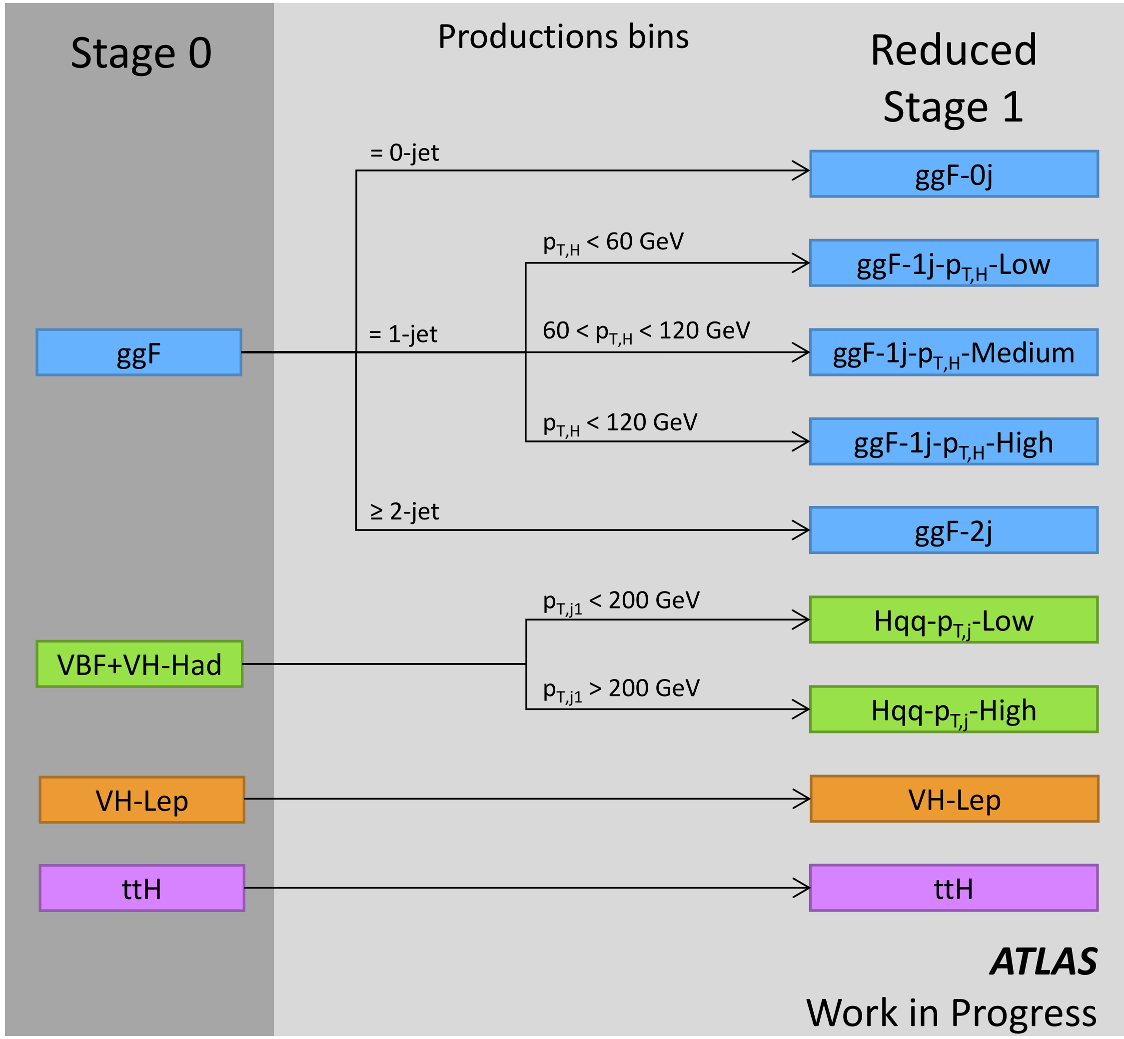

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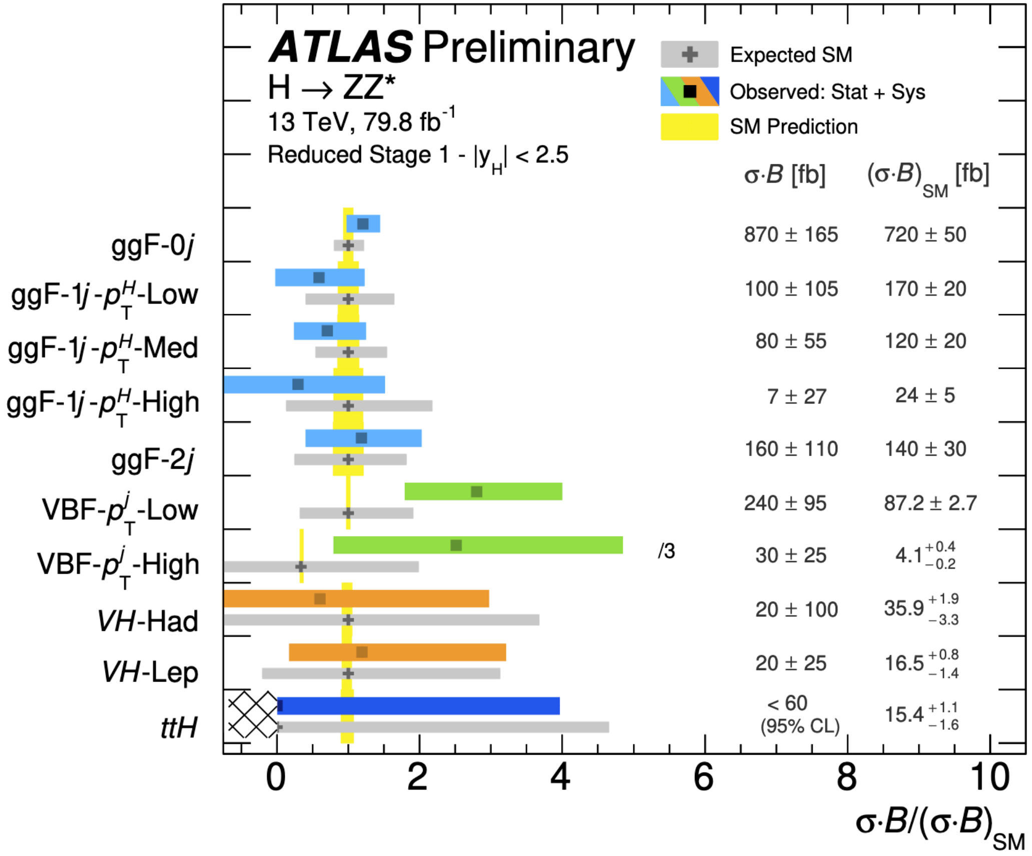
- Results (80 fb^{-1}):



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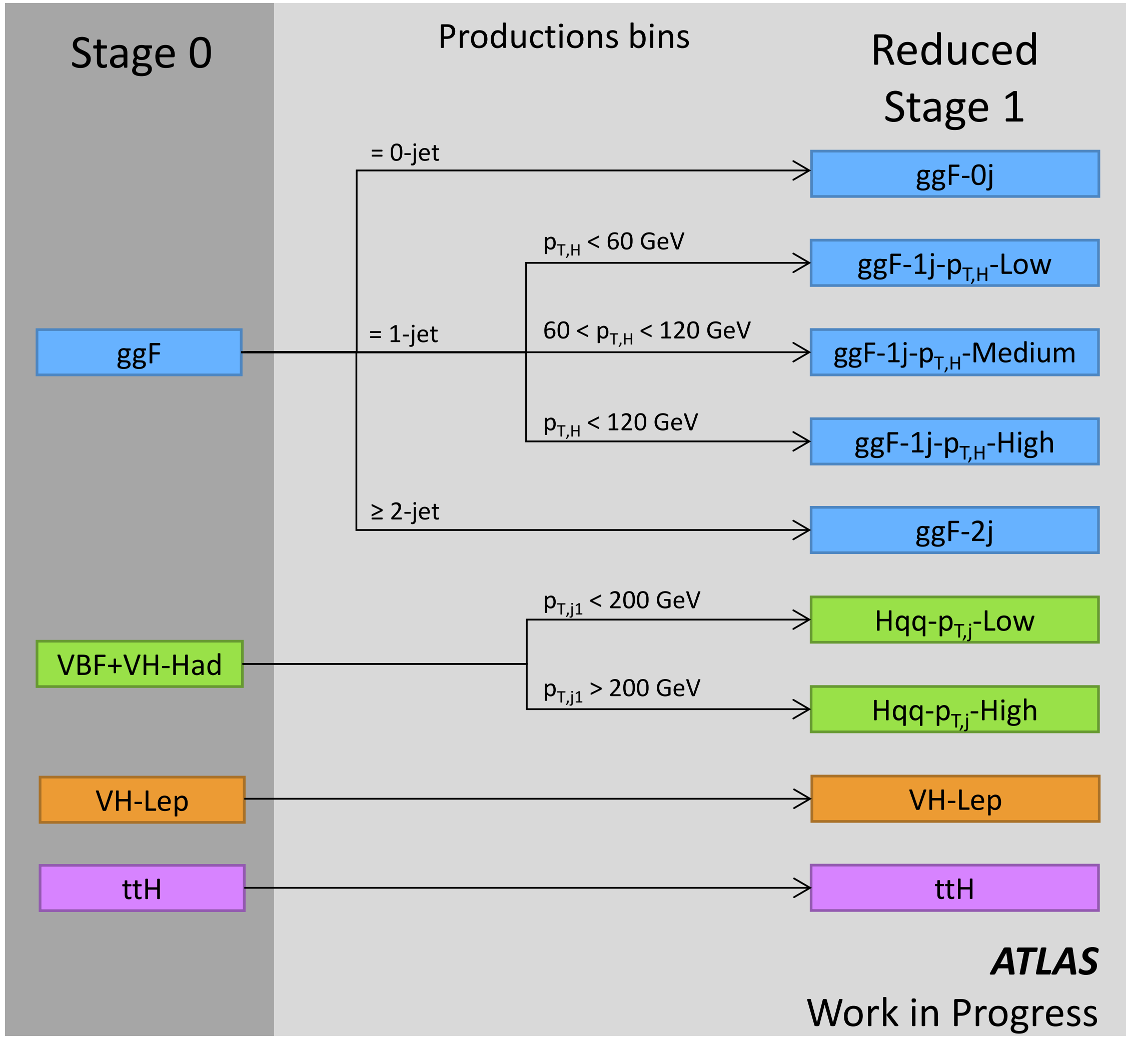

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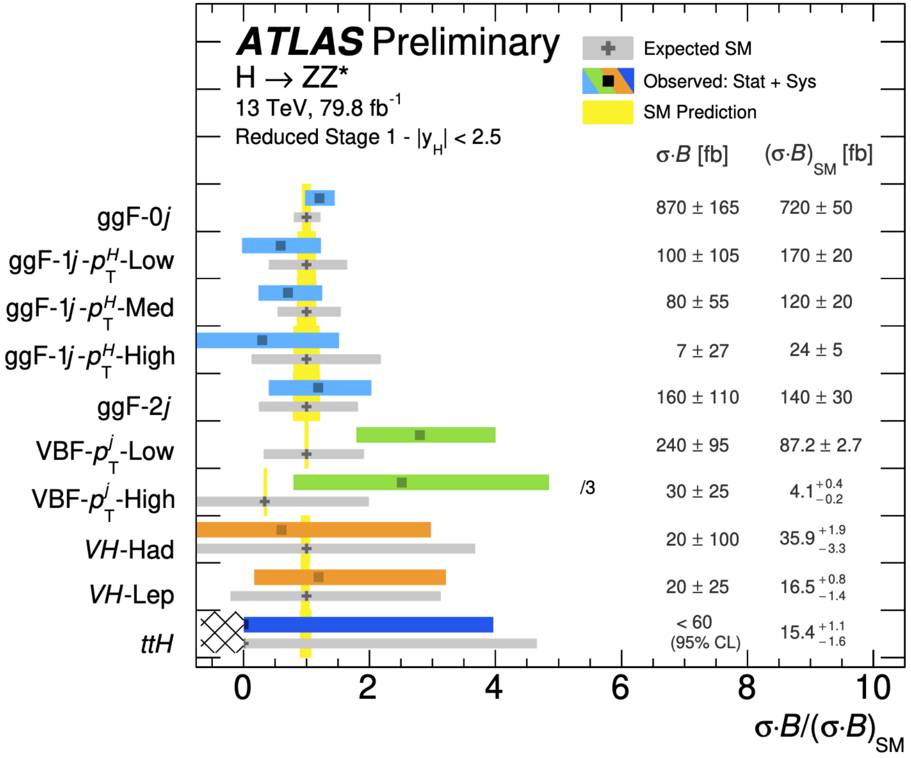
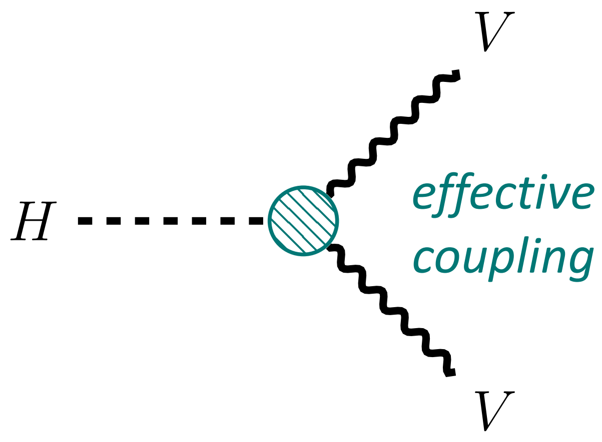


- Parametrise σ x BR in each STXS bin as a function of EFT parameters

Higgs Boson Coupling in Effective Field Theories

- Effective field theory assumption:
  Physics beyond SM appears at an energy scale $\Lambda \gg E$



arXiv:1709.06492

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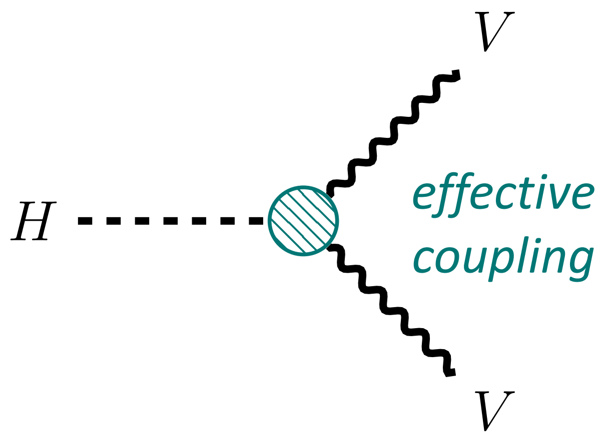
  $SU_C(3) \times SU_L(2) \times U_Y(1)$ invariant higher dimensional operators built out of SM fields:



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \qquad \mathcal{L}_{\text{d}} = \sum_{i=1}^{n_d} \frac{\bar{c}_i^d}{\Lambda^{d-4}} O_i^d \quad \text{(for d>4)}$$

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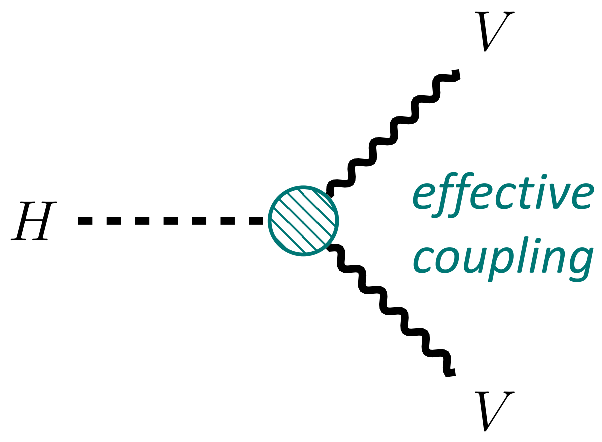

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- First lepton number conserving order: d=6

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{\bar{c}_i}{\Lambda^2} O_i$$

- Only ratio $c_i = \frac{\bar{c}_i}{\Lambda^2}$ is accessible in low-energy experiments

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Measurement of Anomalous Couplings

- Relevant CP-even Operators for H → ZZ → 4ℓ in SMEFT:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + c_{HG}\, O_{HG} + c_{uH} O_{uH} + c_{HW} O_{HW} + c_{HB} O_{HB} + c_{HWB} O_{HWB} + \ldots$$

Operator	Expression	Interaction vertex	Wilson coefficient
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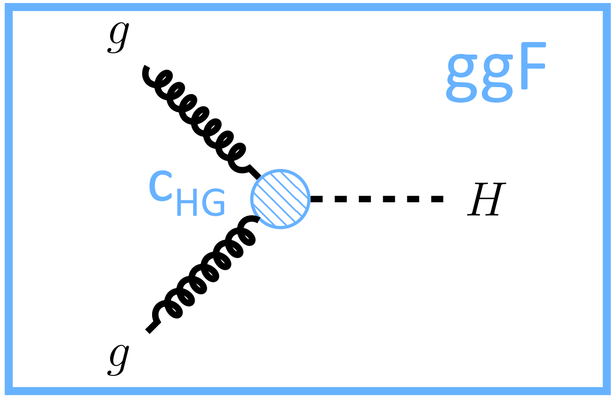

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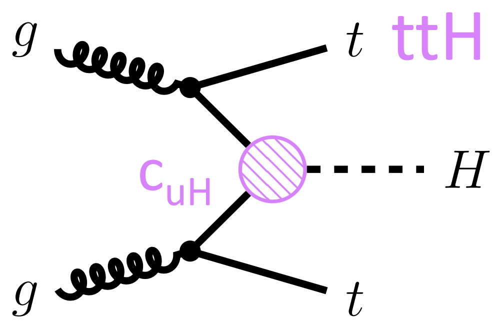

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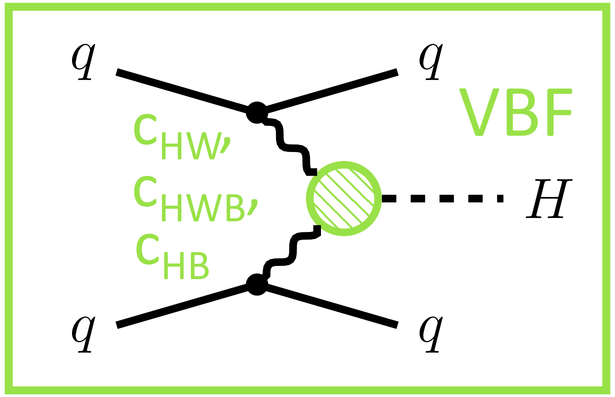

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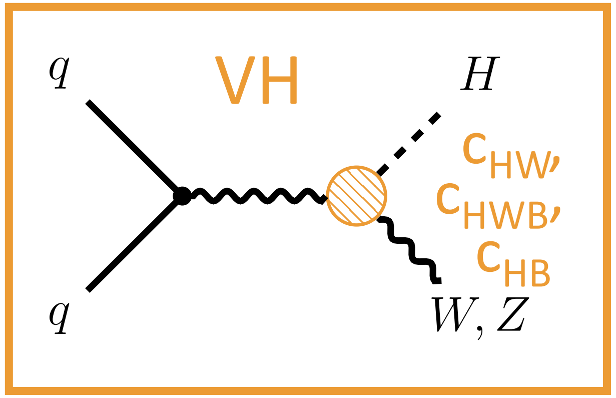

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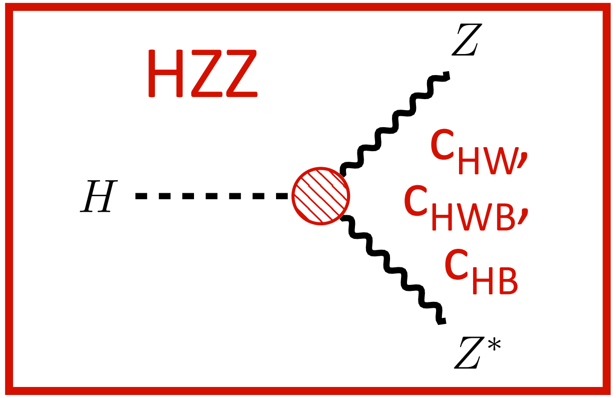
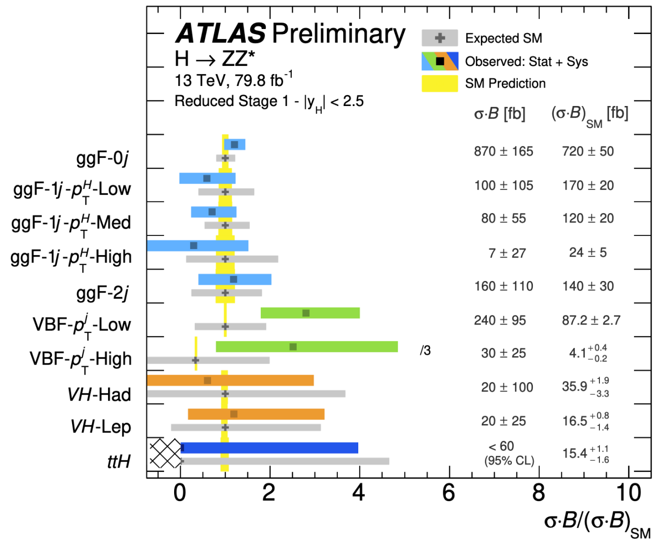


EFT Interpretation of SM Coupling Analysis

- Use STXS coupling measurements to constrain EFT parameters using SMEFT



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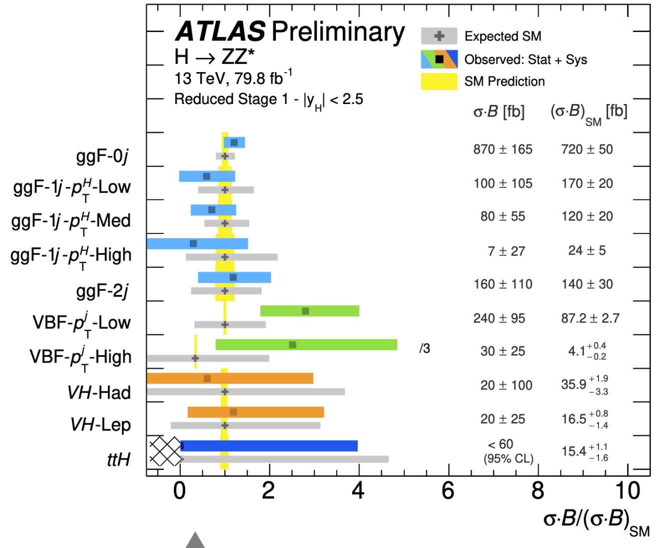

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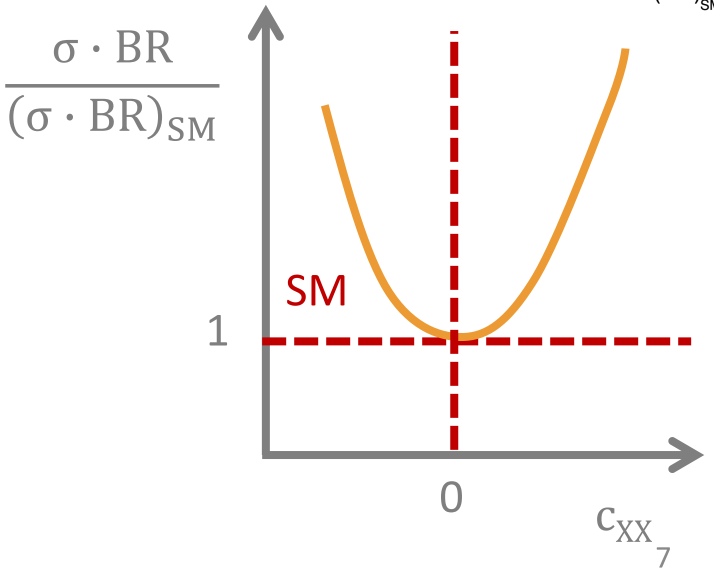

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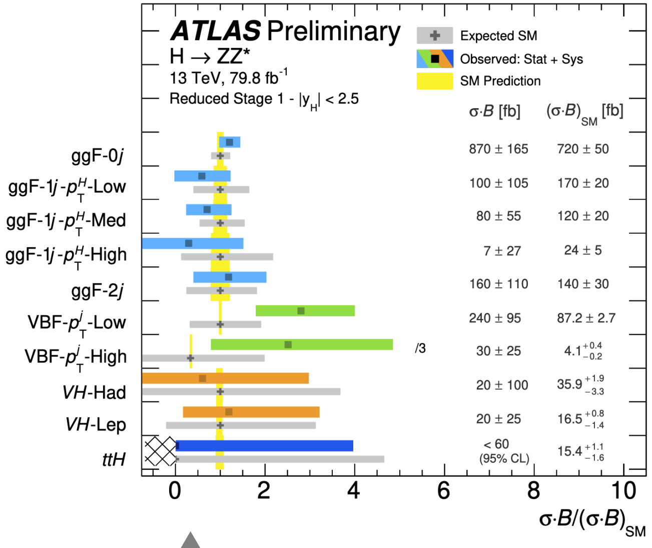

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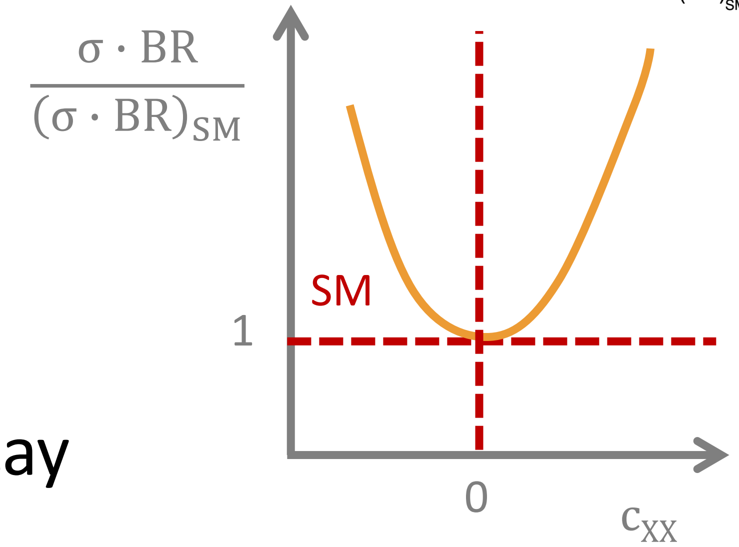

- Parametrise independently production and decay

Parametrisation of Production Cross Section

- Matrix element:

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$$\sigma = \sigma_{SM} + \sigma_{INT} + \sigma_{BSM}$$

- Cross section dependence on the couplings:

$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i A_i c_i + \sum_{ij} B_{ji} c_i c_j$$

Example: 2 Wilson Coefficients

- Cross section parametrisation:

$$\sigma/\sigma_{SM} = 1 + A_1 c_1 + B_{11} c_1^2 + A_2 c_2 + B_{22} c_2^2 + B_{12} c_1 c_2$$

- SM, A_i and B_{ij} for i=j can be obtained directly in MadGraph5:

NP^2==0 (SM):	σ = SM	
NP^2==1 (interference):	$\sigma_{A1} \Rightarrow A_1 c_1$	$\sigma_{A2} \Rightarrow A_2 c_2$
NP^2==2 (pure BSM):	$\sigma_{B11} \Rightarrow B_{11} c_1^2$	$\sigma_{B22} \Rightarrow B_{22} c_2^2$

$$A_i = \frac{\sigma_{Ai}(c_i = 1, c_j = 0)}{\sigma_{SM}}$$

$$B_{ii} = \frac{\sigma_{Bii}(c_i = 1, c_j = 0)}{\sigma_{SM}}$$

Example: 2 Wilson Coefficients

- Cross section parametrisation:

$$\sigma/\sigma_{SM} = 1 + A_1 c_1 + B_{11} c_1^2 + A_2 c_2 + B_{22} c_2^2 + B_{12} c_1 c_2$$

- SM, A_i and B_{ij} for i=j can be obtained directly in MadGraph5:

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NP^2==1 (interference):	$\sigma_{A1} \Rightarrow A_1 c_1$	$\sigma_{A2} \Rightarrow A_2 c_2$
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$$A_i = \frac{\sigma_{Ai}(c_i = 1, c_j = 0)}{\sigma_{SM}}$$

$$B_{ii} = \frac{\sigma_{Bii}(c_i = 1, c_j = 0)}{\sigma_{SM}}$$

- Extracting B_{ij} for i≠j: generate sample with NP^==2 and both couplings set

$$\sigma_{B12} = B_{11} c_1^2 + B_{22} c_2^2 + B_{12} c_1 c_2$$

$$B_{ij} = \frac{\sigma_{Bij}(c_i = 1, c_j = 1) - \sigma_{Bii}(c_i = 1, c_j = 0) - \sigma_{Bjj}(c_i = 0, c_j = 1)}{\sigma_{SM}}$$

→Subtract quadratic terms

Sample Production

- Simulation with MadGraph and showering with Pythia
- 500k events per sample
- CKKW matching for processes with different jet multiplicities
- Samples are analysed on truth level to get the fraction of the cross section in STXS bins

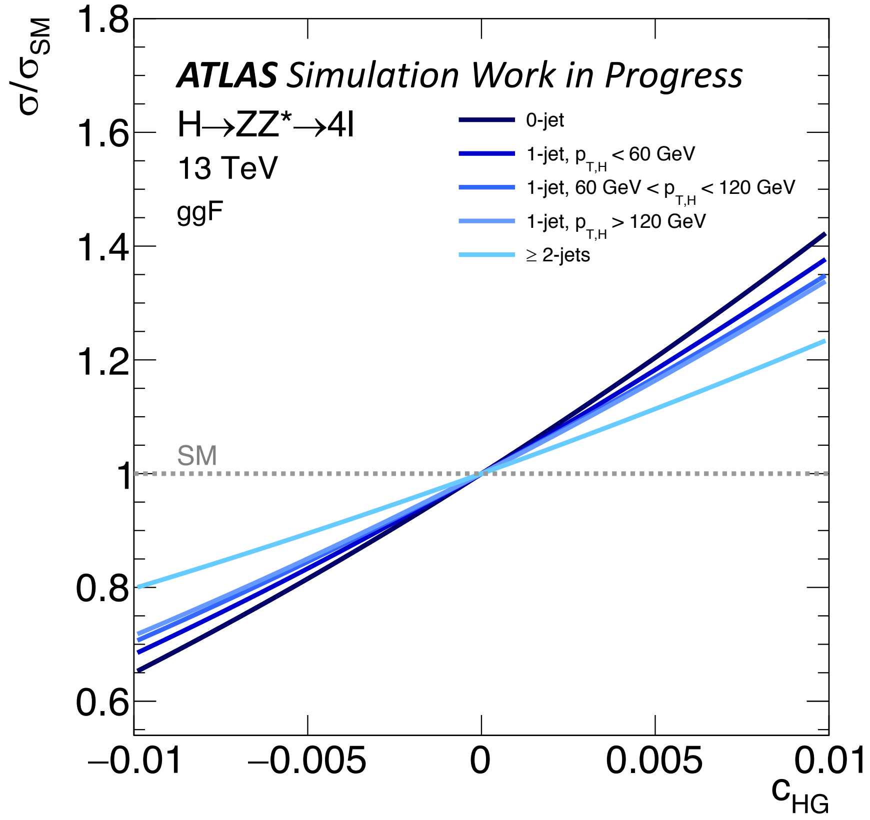
Production	MadGraph Syntax	Number of samples

ggH+bbH	`define jb = j b b~`
	`generate p p > h QED=1`
	`add process p p > h j QED=1`
	`add process p p > h jb jb QED=1`
		3

VBF+VH-Had	`generate p p > h j j QCD=0`	10
ZH-Lep	`generate p p > h l+ l-`	10
WH-Lep	`generate p p > h l+ v` `add process p p > h l- vl~`	3
ttH	`generate p p > h t t~`	3

Parametrisation for ggF

- Dependence of c_{HG} on the cross section ratio:

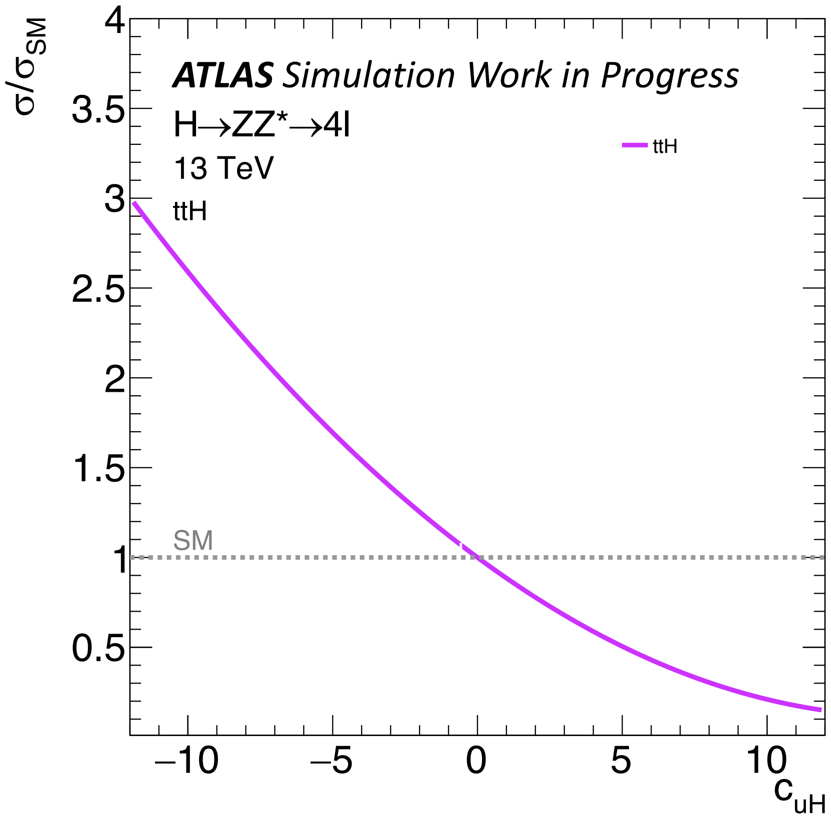


STXS bin	EFT Parametrisation	Expected SM result (140 fb^{-1})
ggF-0j	$1 + 38.87c_{HG} + 384.69c_{HG}^2$	$1.00^{+0.14}_{-0.14}$
ggF-1j-$p_{T,H}$-Low	$1 + 34.95c_{HG} + 316.85c_{HG}^2$	$1.00^{+0.41}_{-0.37}$
ggF-1j-$p_{T,H}$-Medium	$1 + 32.41c_{HG} + 281.90c_{HG}^2$	$1.00^{+0.37}_{-0.33}$
ggF-1j-$p_{T,H}$-High	$1 + 31.31c_{HG} + 285.41c_{HG}^2$	$1.00^{+0.79}_{-0.63}$
ggF-2j	$1 + 21.90c_{HG} + 174.35c_{HG}^2$	$1.00^{+0.49}_{-0.46}$

- Similar dependence in all STXS bins (quadratic terms negligible)

Parametrisation for ttH

- Dependence of c_{uH} on the cross section ratio:

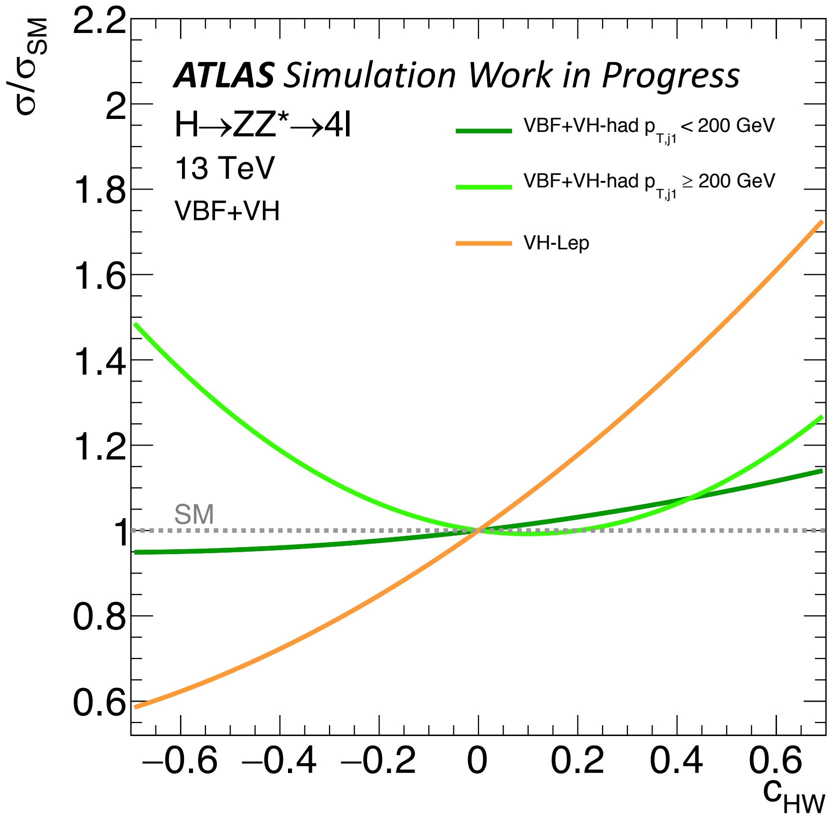


STXS bin	EFT Parametrisation	Expected SM result (140 fb^{-1})
ttH	$1 - 0.119c_{uH} + 0.004c_{uH}^2$	$1.00^{+1.13}_{-0.79}$

- Quite linear dependence (quadratic terms negligible)

Parametrisation for VBF+VH-Had and VH-Lep

- Dependence of c_{HW} on the cross section ratio:



STXS bin	EFT Parametrisation	Expected SM result (140 fb^{-1})
VBF-$p_{T,j}$-Low	$1 + 0.138c_{HW} + 0.093c_{HW}^2 + 0.004c_{HB} + 0.021c_{HB}^2 + 0.043c_{HWB} + 0.016c_{HWB}^2 + 0.012c_{HW}c_{HB} - 0.008c_{HW}c_{HWB} - 0.018c_{HB}c_{HWB}$	$1.00^{+0.63}_{-0.50}$ (VBF)
VBF-$p_{T,j}$-High	$1 - 0.157c_{HW} + 0.0784c_{HW}^2 + 0.003c_{HB} + 0.077c_{HB}^2 + 0.0049c_{HWB} + 0.0067c_{HWB}^2 + 0.017c_{HW}c_{HB} - 0.056c_{HW}c_{HWB} - 0.029c_{HB}c_{HWB}$	$1.00^{+1.92}_{-0.94}$ (VBF)
VH-Lep	$1 + 0.823c_{HW} + 0.324c_{HW}^2 + 0.035c_{HB} + 0.011c_{HB}^2 + 0.127c_{HWB} + 0.025c_{HWB}^2 - 0.221c_{HW}c_{HB} - 0.156c_{HW}c_{HWB} + 0.021c_{HB}c_{HWB}$	$1.00^{+1.37}_{-0.85}$

- c_{HW} largest dependence (others small dependence → see Backup)

Summary

- Plans for Run II Analysis:
  - Constrain CP-even EFT parameters sensitive to Higgs boson production and decay in the H → ZZ → 4ℓ decay channel (SMEFT)
  - EFT interpretation on top of the SM simplified template cross sections coupling Analysis
- So far:
  - First parametrisation of the production bins
- Next steps:
  - Parametrisation of the decay
  - Derive first limits

BACKUP

SMEFT

- Explicit definition of the $\mathcal{L}_6$ operators (non-fermion):

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
Q_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$Q_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

Introduction: SMEFT

- SMEFTsim package: https://feynrules.irmp.ucl.ac.be/wiki/SMEFT
- SMEFTsim adopts the Warsaw basis arXiv:1008.4884

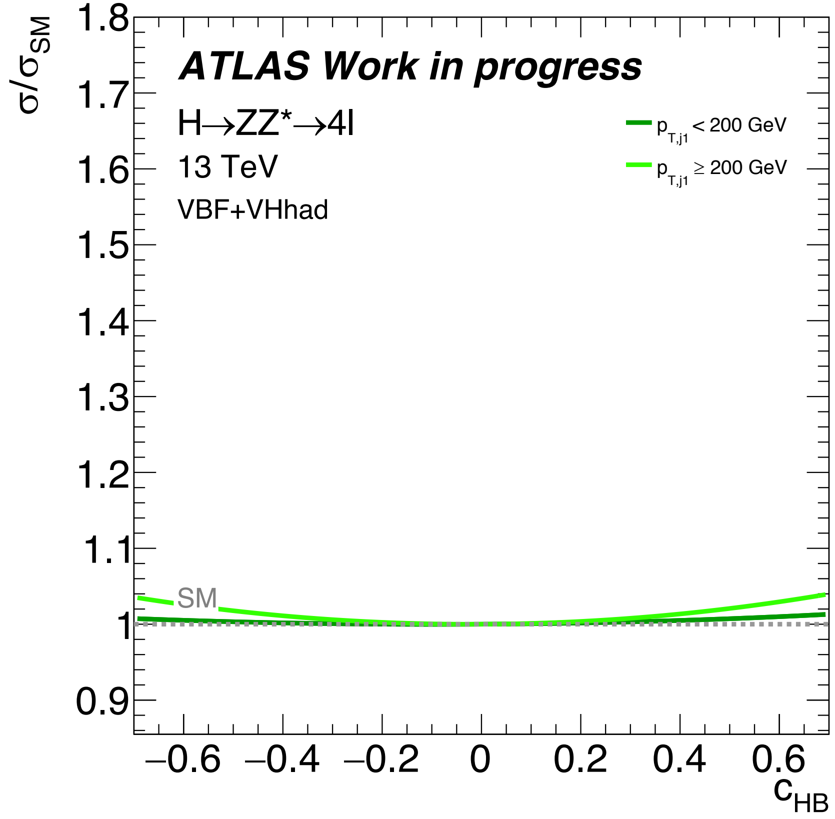
Case	CP even	CP odd	WHZ Pole parameters
General SMEFT (n_f=1)	53	23	~ 23
General SMEFT (n_f=3)	1350	1149	~ 46
$U(3)^5$ SMEFT	~ 52	~ 17	~ 24
MFV SMEFT	~ 108	-	~ 30

- The $U(3)^5$ flavour symmetric case, with non-SM CP-violating phases in Mw-scheme: $\{m_W, m_Z, G_f\}$:

SMEFTsim_A_U35_MwScheme_UFO_v2_1

Parametrisation for VBF and VH-Had

- Dependence of c_{HB} on the cross section ratio:

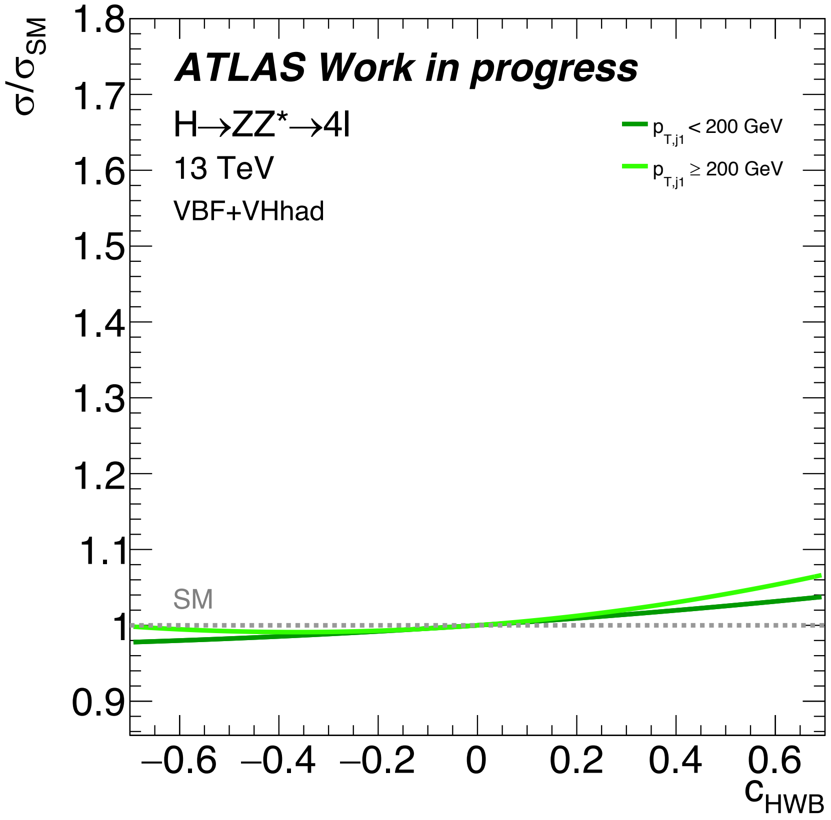


STXS bin	EFT Parametrisation
VBF-$p_{T,j}$-Low	$1 + 0.138c_{HW} + 0.093c_{HW}^2 + 0.004c_{HB} + 0.021c_{HB}^2 + 0.043c_{HWB} + 0.016c_{HWB}^2 + 0.012c_{HW}c_{HB} - 0.008c_{HW}c_{HWB} - 0.018c_{HB}c_{HWB}$
VBF-$p_{T,j}$-High	$1 - 0.157c_{HW} + 0.0784c_{HW}^2 + 0.003c_{HB} + 0.077c_{HB}^2 + 0.0049c_{HWB} + 0.0067c_{HWB}^2 + 0.017c_{HW}c_{HB} - 0.056c_{HW}c_{HWB} - 0.029c_{HB}c_{HWB}$

- Small dependence on c_{HB} and c_{HWB}

Parametrisation for VBF and VH-Had

- Dependence of c_{HWB} on the cross section ratio:

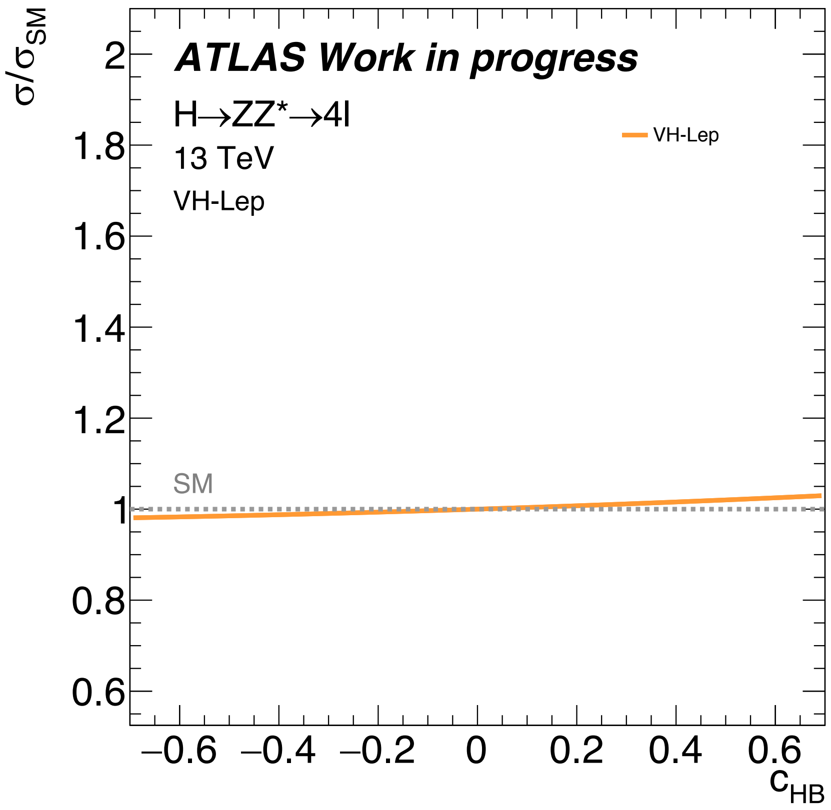


STXS bin	EFT Parametrisation
VBF-$p_{T,j}$-Low	$1 + 0.138c_{HW} + 0.093c_{HW}^2 + 0.004c_{HB} + 0.021c_{HB}^2 + 0.043c_{HWB} + 0.016c_{HWB}^2 + 0.012c_{HW}c_{HB} - 0.008c_{HW}c_{HWB} - 0.018c_{HB}c_{HWB}$
VBF-$p_{T,j}$-High	$1 - 0.157c_{HW} + 0.0784c_{HW}^2 + 0.003c_{HB} + 0.077c_{HB}^2 + 0.0049c_{HWB} + 0.0067c_{HWB}^2 + 0.017c_{HW}c_{HB} - 0.056c_{HW}c_{HWB} - 0.029c_{HB}c_{HWB}$

- Small dependence on c_{HB} and c_{HWB}

Parametrisation for VH-Lep

- Dependence of c_{HB} on the cross section ratio:

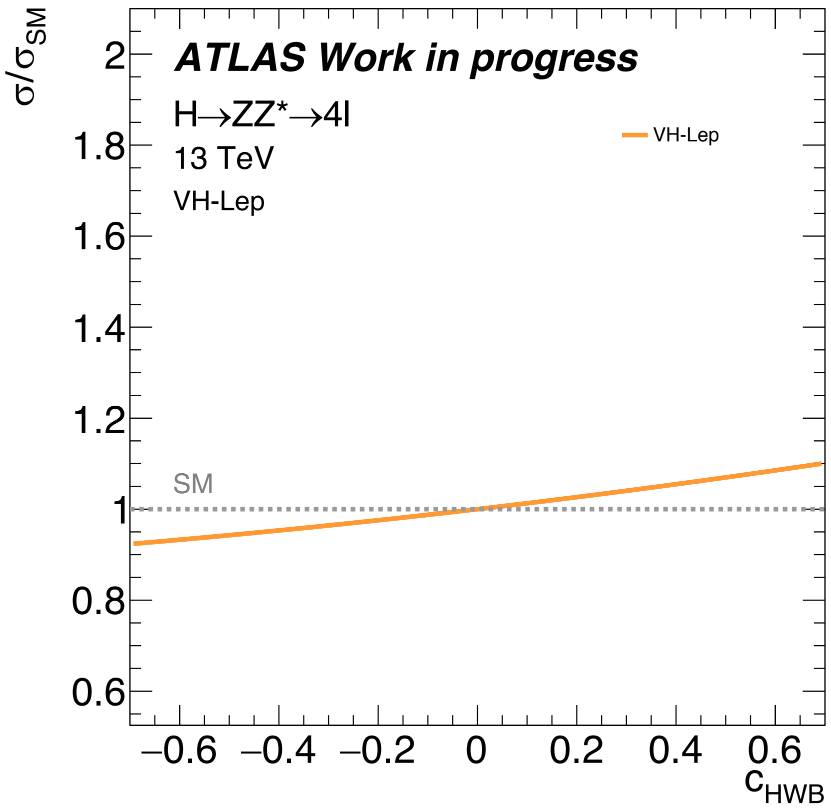


STXS bin	EFT Parametrisation
VH-Lep	$1 + 0.823c_{HW} + 0.324c_{HW}^2 + 0.035c_{HB} + 0.011c_{HB}^2 + 0.127c_{HWB} + 0.025c_{HWB}^2 - 0.221c_{HW}c_{HB} - 0.156c_{HW}c_{HWB} + 0.021c_{HB}c_{HWB}$

- c_{HW}: largest dependence

Parametrisation for VH-Lep

- Dependence of c_{HWB} on the cross section ratio:

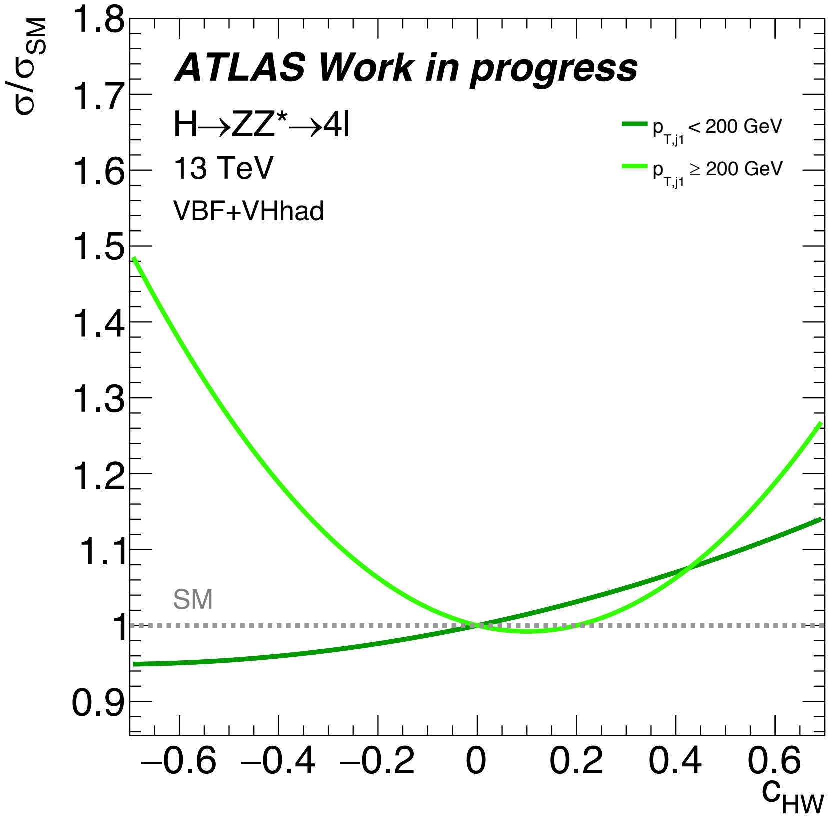


STXS bin	EFT Parametrisation
VH-Lep	$1 + 0.823c_{HW} + 0.324c_{HW}^2 + 0.035c_{HB} + 0.011c_{HB}^2 + 0.127c_{HWB} + 0.025c_{HWB}^2 - 0.221c_{HW}c_{HB} - 0.156c_{HW}c_{HWB} + 0.021c_{HB}c_{HWB}$

- c_{HW}: largest dependence

Parametrisation for VBF and VH-Had

- Dependence of c_{HW} on the cross section ratio:

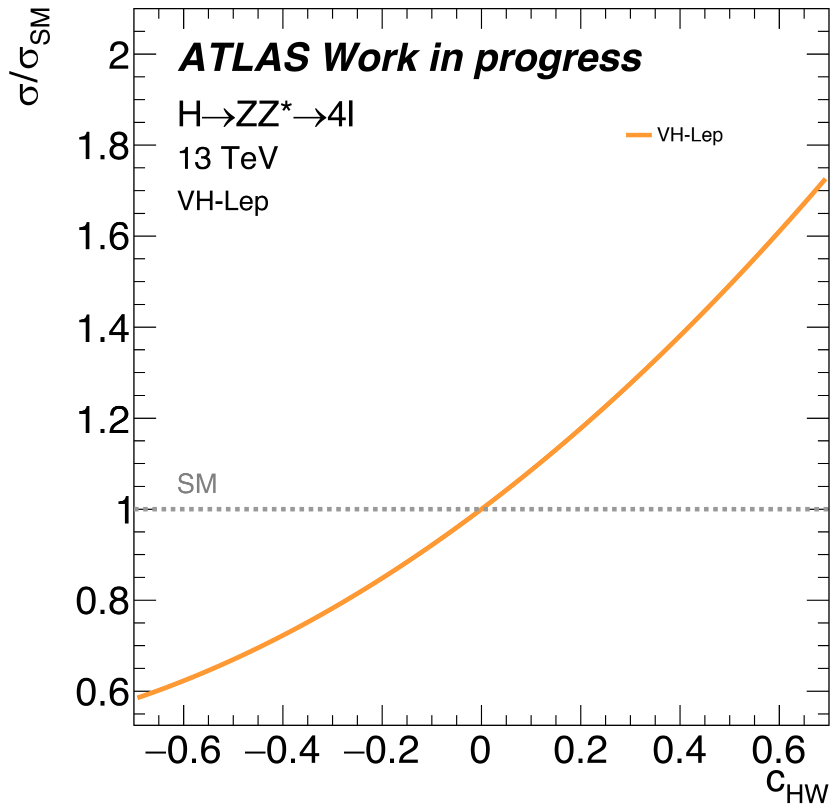


STXS bin	EFT Parametrisation	Expected SM result (140 fb^{-1})
VBF-$p_{T,j}$-Low	$1 + 0.138c_{HW} + 0.093c_{HW}^2$ $+ 0.004c_{HB} + 0.021c_{HB}^2$ $+ 0.043c_{HWB} + 0.016c_{HWB}^2$ $+ 0.012c_{HW}c_{HB} - 0.008c_{HW}c_{HWB}$ $- 0.018c_{HB}c_{HWB}$	$1.00^{+0.63}_{-0.51}$
VBF-$p_{T,j}$-High	$1 - 0.157c_{HW} + 0.0784c_{HW}^2$ $+ 0.003c_{HB} + 0.077c_{HB}^2$ $+ 0.0049c_{HWB} + 0.0067c_{HWB}^2$ $+ 0.017c_{HW}c_{HB} - 0.056c_{HW}c_{HWB}$ $- 0.029c_{HB}c_{HWB}$	$1.00^{+3.42}_{-2..43}$

- Larger sensitivity in the $p_{T,j}$-High bin

Parametrisation for VH-Lep

- Dependence of c_{HW} on the cross section ratio:



STXS bin	EFT Parametrisation	Expected SM result (140 fb^{-1})
VH-Lep	$1 + 0.823c_{HW} + 0.324c_{HW}^2 + 0.035c_{HB} + 0.011c_{HB}^2 + 0.127c_{HWB} + 0.025c_{HWB}^2 - 0.221c_{HW}c_{HB} - 0.156c_{HW}c_{HWB} + 0.021c_{HB}c_{HWB}$	$1.00^{+1.43}_{-0.85}$

- c_{HW}: largest dependence