Combined Higgs boson measurements by the ATLAS experiment and their Effective Field Theory interpretations

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On behalf of the ATLAS collaboration

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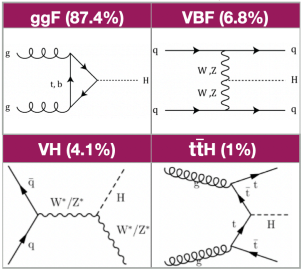
Overview

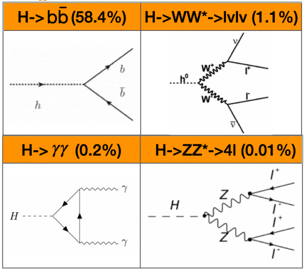
This talk will

- Highlight the precise measurements of Higgs boson cross section using the Simplified Template Cross Section (STXS) framework
- Focus on the re-interpretation using the Effective Field Theory (EFT) framework
- Review a selection of the recent ATLAS Higgs boson combined measurements
    - Higgs combined STXS ATLAS-CONF-2020-027
    - Higgs combined STXS EFT (and MSSM) interpretations ATLAS-CONF-2020-053
    - New! SM WW and H→WW* combined EFT interpretation ATL-PHYS-PUB-2021-010
    - H→inv interpretation ATLAS-CONF-2020-052

Leading production modes at $\sqrt{s} = 13$ TeV



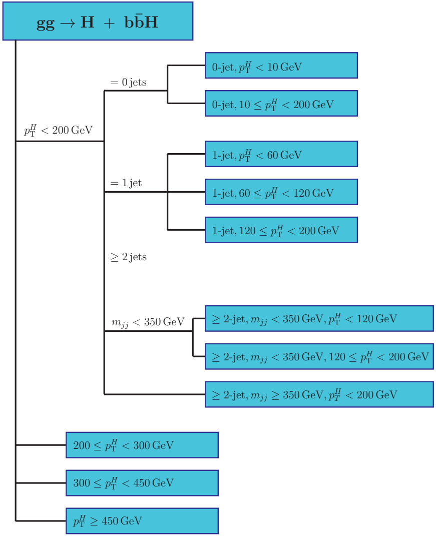
Decay channels branching ratio at $m_H = 125$ GeV (relevant to the talk)



1. Combined STXS measurement
2. EFT interpretation of the combination
3. SM WW and H→WW* combination
4. H→inv interpretation
5. Summary

STXS model

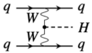
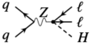
- The STXS framework partitions major Higgs production phase space into several regions (bins) to
  - avoid large theory uncertainties
  - match the experimental selections
  - provide BSM sensitivity
- The combination uses $139\ \text{fb}^{-1}$ H→ $\gamma\gamma$ and H→4l with all leading production modes (ggF, VBF, VH, $t\bar{t}$H)), and H→ $b\bar{b}$ (VH only)
- Finer granularity in some bins, e.g.
  - ggF $N_j \geq 2$ and high p_T^H regions are single bins in H→4l



SMEFT modeling

- $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$
    - $\mathcal{O}_i$, dim-6 EFT operator in Warsaw basis
    - c_i, Wilson coefficient
    - Λ, cutoff energy scale (1 TeV)
- The full linear$(1/\Lambda^2)$+quadratic$(1/\Lambda^4)$ parametrization for the i-th STXS bin

$$\sigma_i = \sigma_{\text{SM},i} \sum_{j,k}(1 + A_j^{\sigma_i} c_j + B_{jk}^{\sigma_i} c_j c_k);$$

Coefficient	Operator	Example process
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	

- branching ratio parametrized defined as the ratio of the Higgs partial width and total width parametrized to be

$$\text{BR}^{H\to X} = \frac{\Gamma^{H\to X}_{\text{SM}}}{\Gamma^{H}_{\text{SM}}} \left(\frac{1 + \sum_j A_j^{\Gamma^{H\to X}} c_j + \sum_{jk} B_{jk}^{\Gamma^{H\to X}} c_j c_k}{1 + \sum_j A_j^{\Gamma^{H}} c_j + \sum_{jk} B_{jk}^{\Gamma^{H}} c_j c_k} \right)$$

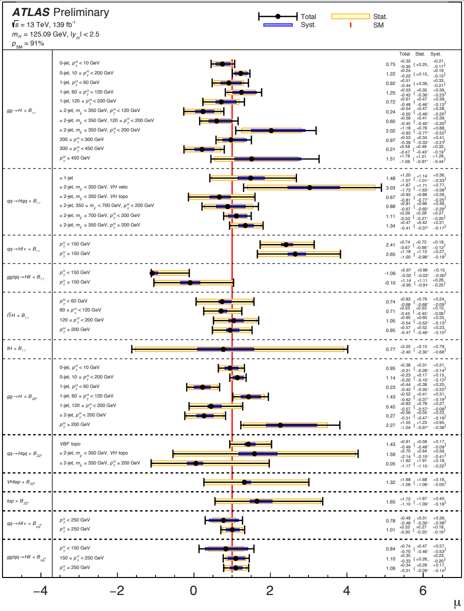
- Linear-only (quadratic terms dropped) and and linear+quadratic measurements are usually compared to see the EFT impact at $1/\Lambda^4$

SMEFT modeling cont.

- Replace signal strengths with their EFT parametrizations:

$$\mu(c_j) = \frac{\sigma_i(c_j) \times \mathrm{BR}^{H\to X}(c_j)}{\sigma_{SM,i} \times \mathrm{BR}^{H\to X}_{\mathrm{SM}}}$$

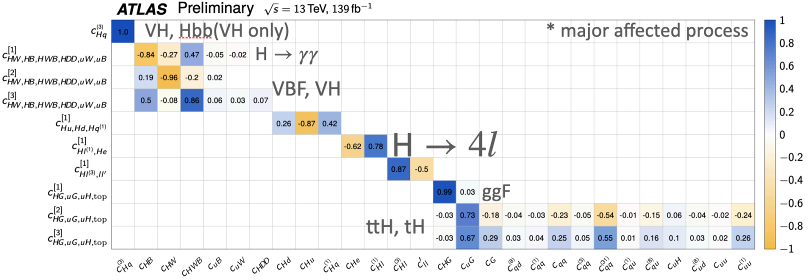
- The most crucial aspect of combined STXS EFT interpretation is the ability to fit several Wilson coefficients at once thanks to
  - increased sensitivity to common EFT operators
  - complement of sensitivity to uncommon operators



Combined STXS EFT results

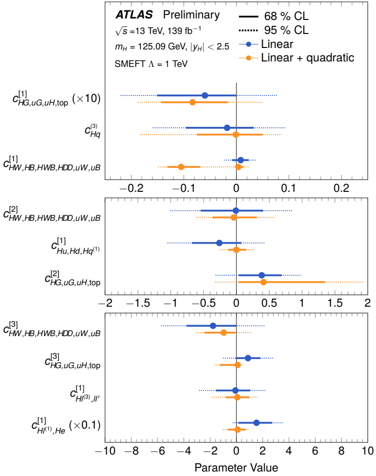
- Current STXS measurement cannot fit all Wilson coefficients at once, which motivates reduction to a new basis via eigenvector decomposition with the linear EFT parametrization and the SM expected covariance matrix
- Neglect eigenvectors that the analysis is not sensitive to (eigenvalue < 0.01)
  - The eigenvalue is the inverse square of the uncertainty expected for the corresponding parameter, i.e. eigenvalue <0.01 corresponds to expected uncertainty of ± 10
- Survey STXS regions sensitivity to the Wilson coefficients and group operators impact on the same production or decay processes

Visualization of the rotated Wilson coefficient basis

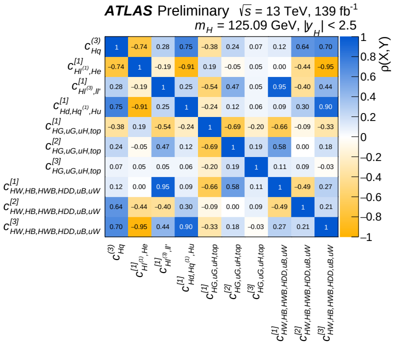


Combined STXS EFT results cont.

- Excellent sensitivity to 10 parameters of interest in the simultaneous fit

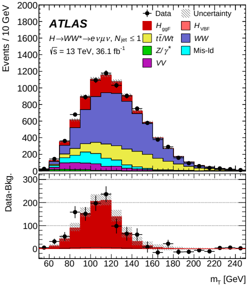


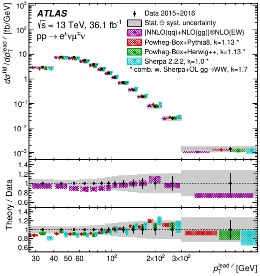
- Interpretations using both linear and linear+quadratic parametrization have been performed
- Some quadratic terms $(1/\Lambda^4)$ in the parametrization influence the limits significantly
- No significant deviation from SM

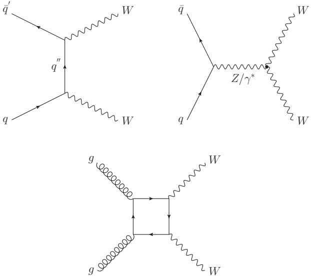


Combination overview

- Input analyses based on 36.1 fb^{-1} of data collected during 2015-2016:
  - ggF+VBF H→WW* signal strength (coupling) analysis PLB 789 (2019) 508
  - SM WW differential measurement EPJC 79 (2019) 884
- Remove WW control region from HWW analysis and use SM WW overall normalization to constrain WW background in HWW signal region
- Correlate common systematic uncertainties
- Same EFT methodology applied as STXS EFT interpretation

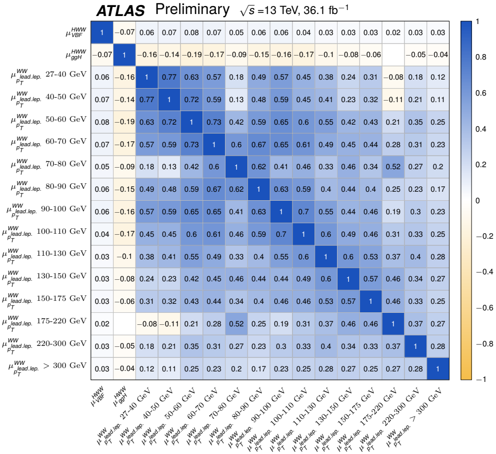


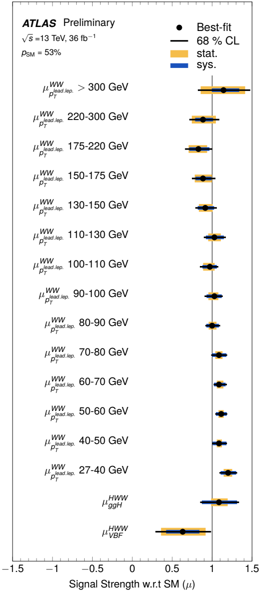




Combined SM WW and H→WW* results

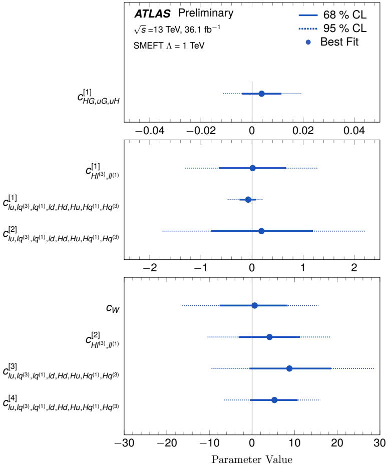
- Combined measurement conducted in signal strength style
- 14 signal strength parameters for SM WW + 2 for H→WW*



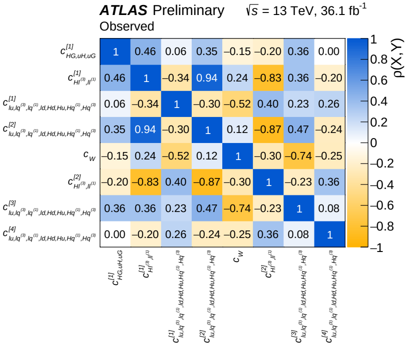


Combined SM WW and H→WW* EFT results

- Linear-only EFT parametrization $(1/\Lambda^2)$



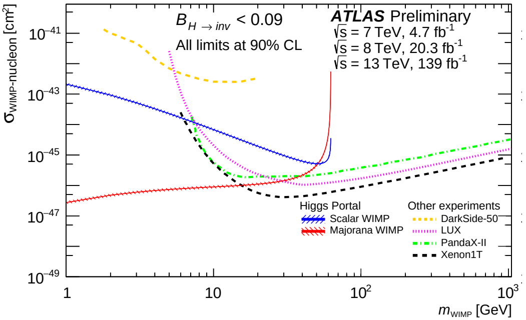
- Eigenvector method applied
- 4 parameters precisely measured (within ± 1)
- Agree with SM expectation at the level of one standard deviation



Higgs portal Dark Matter interpretation

- SM Higgs to invisible process H→ $ZZ^* \to 4\nu$, with BR(H→inv)≈ 0.1%
- Higgs production modes considered using 139 fb^{-1} of data: VBF and $t\bar{t}$H
- Best-fit value: BR(H→inv) $= 0.00 \pm 0.06$
- Observed upper limit at 90% CL: BR(H→inv)$<$0.09
- If Higgs decays to a pair of DM particles, BR(H→inv) will be larger

- Upper limit on BR(H→inv) at 90% CL translated to limit on spin-independent DM-nucleon elastic scattering cross section ($\sigma_{\text{WIMP-N}}$) and WIMP mass (m_{WIMP}) through an EFT approach
- Excluded phase space for DM as scalar or Majorana fermion WIMP at low m_{WIMP} complements limits set by direct search experiments



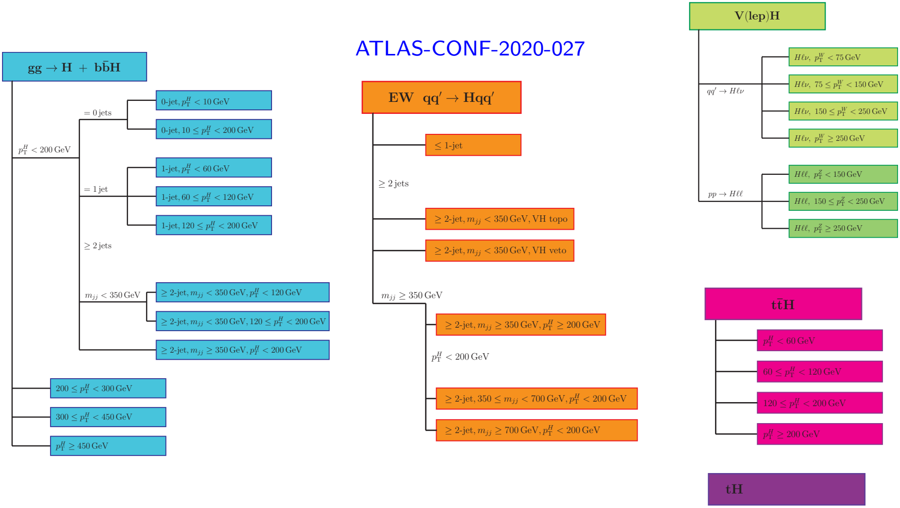
Summary

- Using the STXS framework to combine individual Higgs decay channels is proven to be successful in constraining Wilson coefficients in the SMEFT model
- Common EFT interpretation methodology for STXS measurements is largely laid down and is widely tested in both single decay channel measurements and combined measurements
- Same methodology is applied for the very first time to non-STXS measurement in the combination of SM WW and H→WW*, where many challenges were found and resolved
    - combine different flavors of analysis (e.g. unfolded fiducial differential vs signal strength style measurements)
    - parametrize EFT in the background process
    - correlate common nuisance parameters
- Exclusion of DM phase space with the Higgs portal DM interpretation via EFT approach is complementary to the direct detection experiments

6 Additional Material

STXS bins

ATLAS-CONF-2020-027

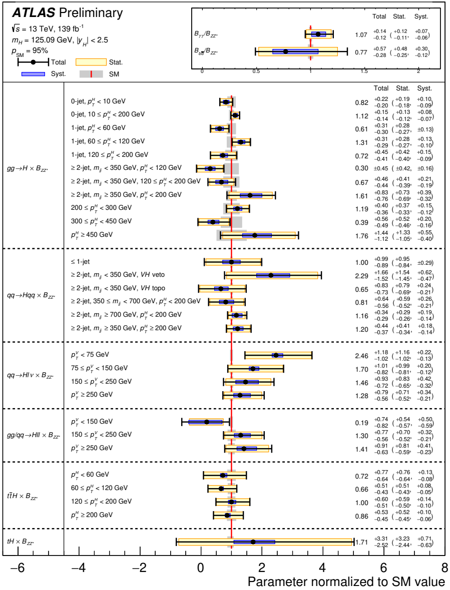


STXS results

- Common systematic uncertainties and modeling assumptions partially cancel out by parametrizing the parameters of interest with a ratio of branching ratios:

$$\sigma_i \times \mathrm{BR}^f = (\sigma_i \times \mathrm{BR}^{ZZ}) \cdot \frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}$$

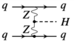
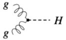
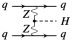
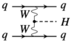
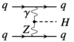
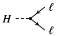
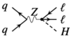
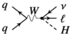
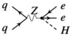
- Compatibility with SM: $p_{\mathrm{SM}} = 95\%$
- The observed (expected) upper limit at 95% CL for tH cross section is 8.4 (8.2) times the SM prediction (the most stringent limit in ATLAS).

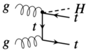
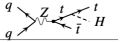
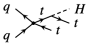
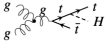


SMEFT: from Lagrangian to observable

- $\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$
  - $\mathcal{O}_i$, dim-6 EFT operator
  - c_i the corresponding Wilson coefficient (free parameters of the theory)
  - Λ the cutoff energy scale
- $\mathcal{M}_{\rm SMEFT} = \mathcal{M}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i$
- $|\mathcal{M}_{\rm SMEFT}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\sum_i \frac{c_i}{\Lambda^2} Re(\mathcal{M}^*_{\rm SM}\mathcal{M}_i) + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} Re(\mathcal{M}_i\mathcal{M}_j)$
- $\sigma_{\rm STXS} = \sigma_{\rm SM} + \sigma_{\rm int} + \sigma_{\rm BSM}$
  - $\sigma_{\rm int}$, interference between SMEFT operators and SM $(1/\Lambda^2)$
  - $\sigma_{\rm BSM}$, SMEFT contribution only $(1/\Lambda^4)$

EFT operators

Coefficient	Operator	Example process
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}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
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}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

Coefficient	Operator	Example process
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}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	
$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	
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_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	

Linear EFT parametrization

- Interference-only (linear, $1/\Lambda^2$)

$$
\begin{aligned}
(\sigma \times \mathrm{BR})^{i,H\to X} &= (\sigma \times \mathrm{BR})^{i,H\to X}_{\text{SM,((N)N)NLO}} \times \left(1 + \frac{\sigma^{i}_{\text{int,(N)LO}}}{\sigma^{i}_{\text{SM,(N)LO}}}\right) \times \left(\frac{1 + \frac{\Gamma^{H\to X}_{\text{int}}}{\Gamma^{H\to X}_{\text{SM}}}}{1 + \frac{\Gamma^{H}_{\text{int}}}{\Gamma^{H}_{\text{SM}}}}\right) \\
&= (\sigma \times \mathrm{BR})^{i,H\to X}_{\text{SM,((N)N)NLO}} \times \left(1 + \sum_j A^{\sigma_i}_j c_j\right) \times \left(\frac{1 + \sum_j A^{\Gamma^{H\to X}}_j c_j}{1 + \sum_j A^{\Gamma^{H}}_j c_j}\right) \\
&\approx (\sigma \times \mathrm{BR})^{i,H\to X}_{\text{SM,((N)N)NLO}} \times \left(1 + \sum_j \left(A^{\sigma_i}_j + A^{\Gamma^{H\to X}}_j - A^{\Gamma^{H}}_j\right) c_j\right)
\end{aligned}
$$

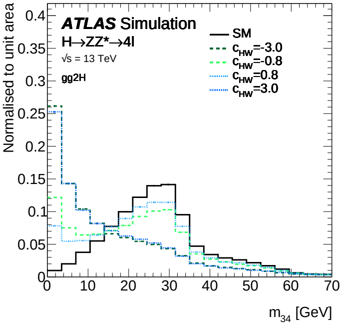
Linear+quadratic EFT parametrization

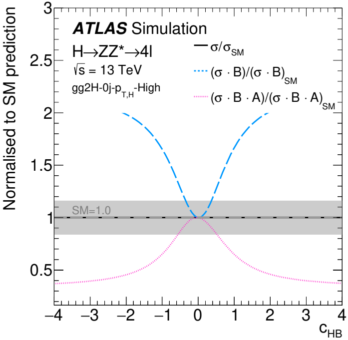
A general STXS EFT interpretation methodology given in ATL-PHYS-PUB-2019-042

$$(\sigma \times \mathrm{BR})^{i,H\to X}_{\text{SM}+\Lambda^{-4}} = (\sigma \times \mathrm{BR})^{i,H\to X}_{\text{SM},((\text{N})\text{N})\text{LO}} \left(1 + \sum_j A_j^{\sigma_i} c_j + \sum_{jk} B_{jk}^{\sigma_i} c_j c_k\right) \times \left(\frac{1 + \sum_j A_j^{\Gamma^{H\to X}} c_j + \sum_{jk} B_{jk}^{\Gamma^{H\to X}} c_j c_k}{1 + \sum_j A_j^{\Gamma^H} c_j + \sum_{jk} B_{jk}^{\Gamma^H} c_j c_k}\right)$$

EFT impact on acceptance in H→ 4l

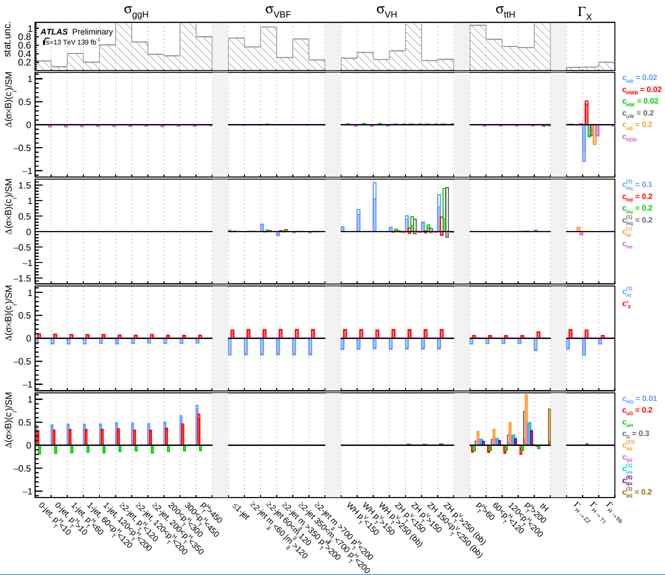
Discriminant distribution shape strongly dependent on some Wilson coefficients
Eur. Phys. J. C 80 (2020) 957





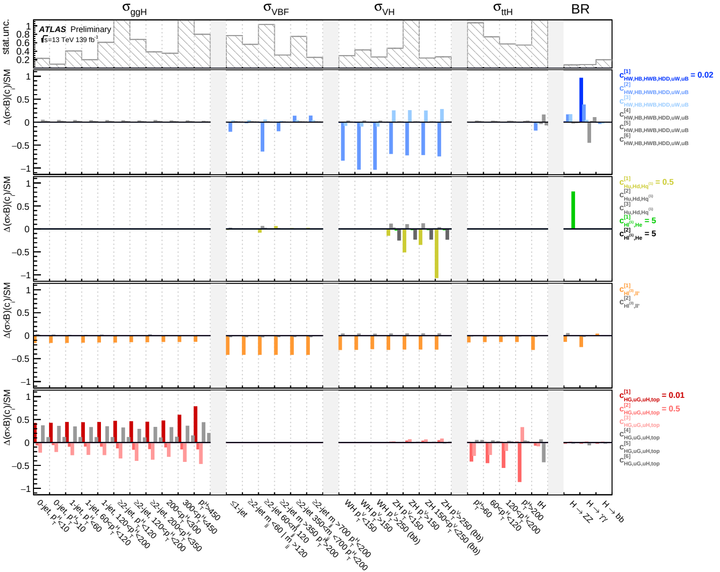
EFT impact in STXS bins (individual Wilson coefficient)

ATLAS-CONF-2020-053



EFT impact in STXS bins (eigenvector)

ATLAS-CONF-2020-053



EFT eigenvectors before grouping

Eigenvectors before grouping EFT operators that affect common processes and remove individual Wilson coefficients that have small contribution to some eigenvectors ATLAS-CONF-2020-053

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}
1	299310		-0.70	-0.23	0.39	-0.04	-0.02									0.55	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
5	19		0.10	-0.19	0.06					0.03	-0.02	-0.07	0.09	-0.13	0.10	0.02	-0.69
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
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
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
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
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
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
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01

#	λ	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															-0.02	
2	121830																
3	1960																
4	38									0.02				0.03			
5	19	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				0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9	0.08			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-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	0.03								0.06				0.06	-0.11	-0.01	
10	0.16	0.02				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036	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	-0.05			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			

EFT impact in SMWW and HWW

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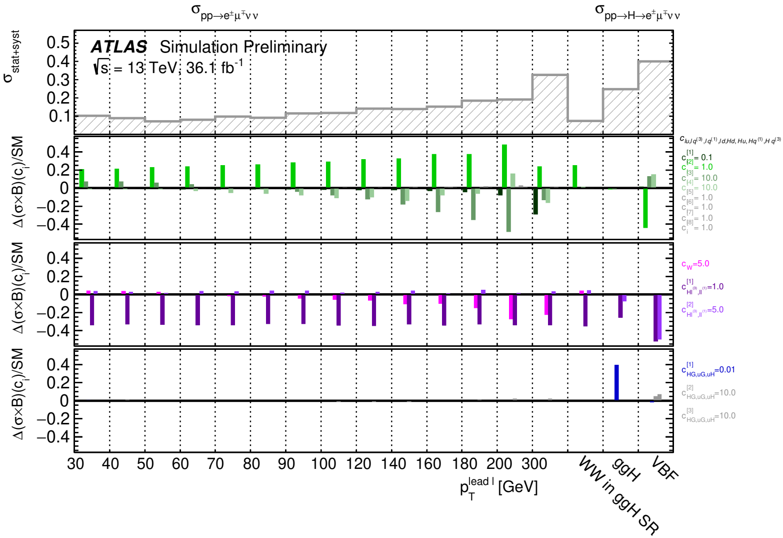

EFT sensitivity in SMWW and HWW

Constraining one Wilson coefficient at a time, some have better sensitivity in the combined measured than the standalone measurements ATL-PHYS-PUB-2021-010