Comparison of Higgs EFT interpretations and direct searches from ATLAS

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on behalf of the ATLAS Collaboration

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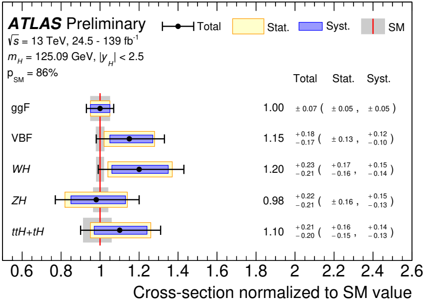
Introduction and context

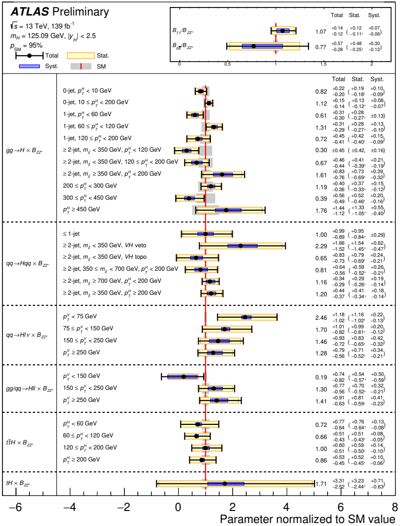
- Searches and measurements performed in many different channels
- Different strategies:
  - direct searches for new physics: new resonances or couplings
  - measurements: probe SM cross sections and couplings
- Both can focus on specific model or be more generic
  - concrete models: optimise sensitivity, but can not probe all models
  - generic measurements: less sensitive (in some channels at least) but can be interpreted very widely
- Some common, rather general benchmark models used in different fields
- EFT fits should allow "maximally generic" interpretation for BSM physics at high scales:
  - just starting really: many things to still improve, will improve with larger statistics
  - ideally could use EFT to match any specific model: not as trivial, would need some feedback and discussions!

Example: Higgs cross section measurements

Cross section measurements with varying granularity: ATLAS-CONF-2020-027



Interpretations in κ-framework, EFT, 2HDM, MSSM, ...

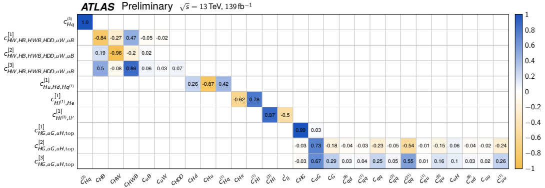


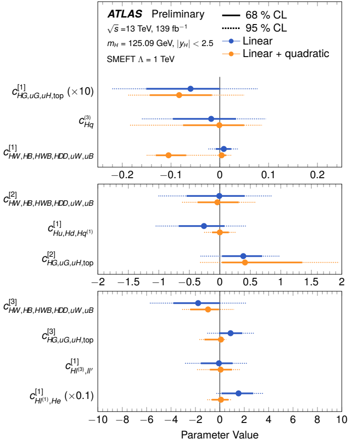
EFT example: Higgs STXS interpretation

ATLAS-CONF-2020-053

Aim at most general possible EFT interpretation: fit all sensitive directions, explicitely show that neglected ones have no impact on fitted ones

→ should allow for “easy” usage of the results for further combinations or interpretations in concrete models...



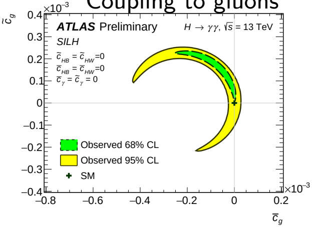


Provide correlation matrix and comparison with linear + quadratic results

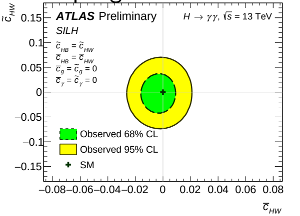
More specific EFT interpretation examples

Differential cross sections in p_T^H, N_j, m_{jj}, $\delta\phi_{jj}$, p_T^{j1} used to constrain CP-odd SILH operators

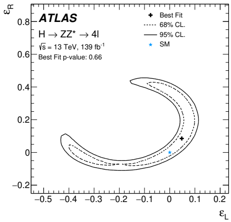
Coupling to gluons

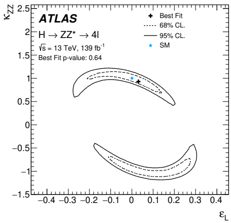


Coupling to vector bosons



Pseudo-observable fit on m_{12} versus m_{34} cross section measurements in $H \to ZZ^* \to 4\ell$

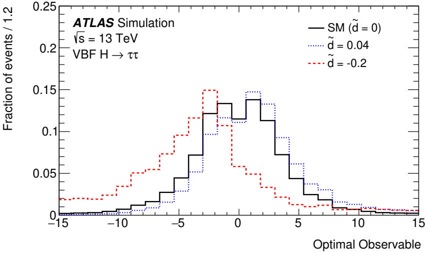


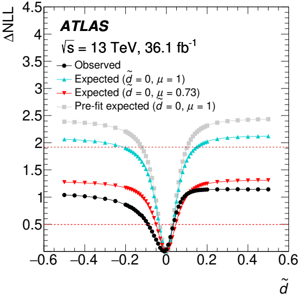


More specific EFT interpretation examples

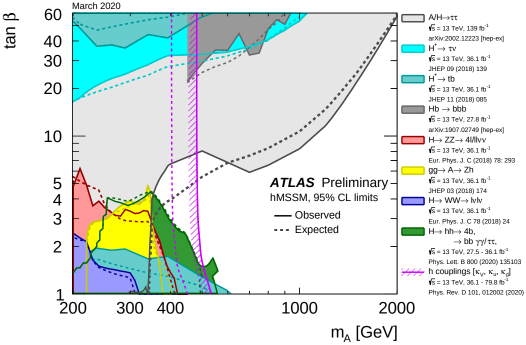
Search for CP-violation in VBF in $H \to \tau\tau$

- CP-odd contribution added as EFT Lagrangian with strength $\tilde{d}$
- Optimal observable built from matrix element ratio of EFT "interference-terms" to SM

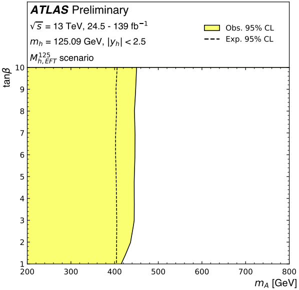




MSSM benchmark models defined by MSSM subgroup of LHC cross section working group:



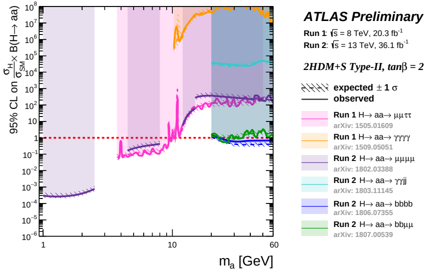
- 7 benchmark models for couplings interpretation
- 2 of them in term of effective couplings
- Caveat: these are pecisely the ones were we could not compare to direct searches!



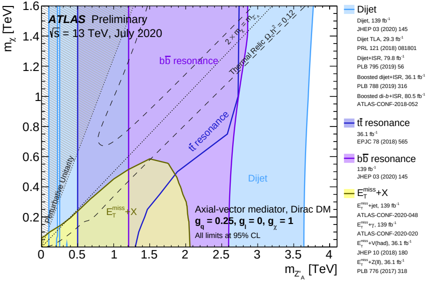
- Can be probed in direct (heavy Higgs) searches
- Good complementarity from Higgs coupling measurements

Other benchmark models

2HDM models: exotic searches; also some 2HDM models probed from Higgs couplings



Dark matter interpretations of searches: different models; more plots



Summary and outlook

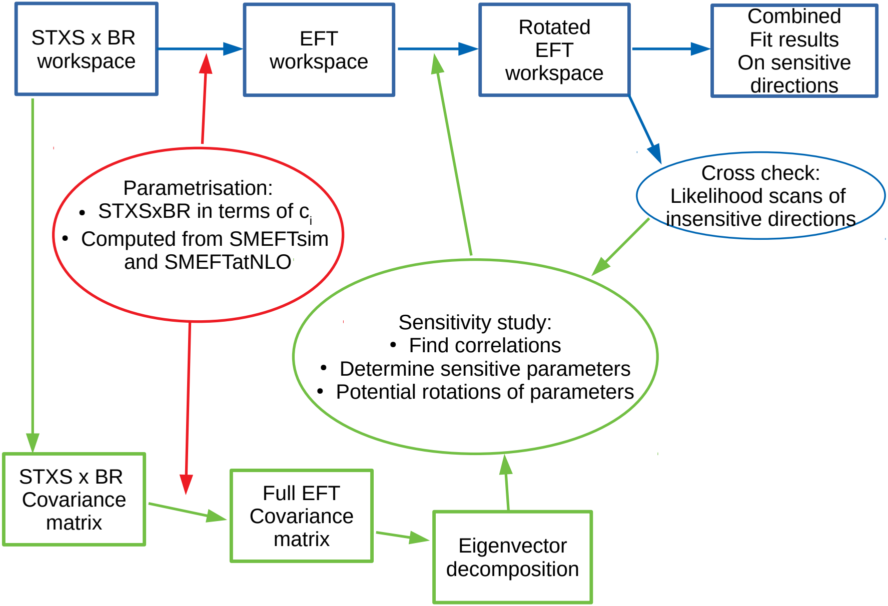
- Many analyses performing EFT interpretations: either specifically targetting certain operators or general
- Cross section measurements also allow interpretations in many other benchmark models
- Comparison of measurements and results from direct searches in the benchmark models
- Would like to be able to use the EFT interpretations to:
  - compare search and measurement limits: there might be a BSM scale issue
  - re-interpret into any possible concrete model that fulfills EFT conditions: theoretically not very well defined and sensitivity not expected to be very large
- We had some exchange with theorists on that topic in the past and found that it was difficult to realise; but it is a very interesting discussion that should be continued!

Backup

Full eigenvector decomposition

No.	Eigenvalue	Eigenvector
1	299310	$-0.02c_W + 0.55c_{HG} - 0.23c_{HW} - 0.70c_{HB} + 0.39c_{HWB} + 0.02c_{uG} - 0.02c_{uW} - 0.04c_{uB}$
2	121830	$-0.83c_{HG} - 0.15c_{HW} - 0.47c_{HB} + 0.26c_{HWB} - 0.03c_{uG} - 0.03c_{uB}$
3	1960	$0.10c_{HW} + 0.03c_{HWB} - 0.02c^{(3)}_{Hl} - 0.05c^{(1)}_{Hq} + 0.99c^{(3)}_{Hq} + 0.09c_{Hu} - 0.03c_{Hd} + 0.02c'_{ll}$
4	38	$+0.03c_{H\Box} + 0.02c_{HDD} + 0.09c_{HB} + 0.15c_{HWB} + 0.02c_{uH} + 0.08c_{uG} - 0.02c^{(1)}_{Hl} - 0.06c^{(3)}_{Hl} - 0.02c_{He} - 0.41c^{(1)}_{Hq} - 0.11c^{(3)}_{Hq} + 0.84c_{Hu} - 0.26c_{Hd} + 0.04c'_{ll}$
5	19	$+0.17c_G + 0.07c_{H\Box} + 0.02c_{HG} - 0.19c_{HW} + 0.10c_{HB} + 0.06c_{HWB} - 0.08c_{uH} + 0.06c_{dH} - 0.69c_{uG} + 0.09c^{(1)}_{Hl} - 0.13c^{(3)}_{Hl} - 0.07c_{He} - 0.02c^{(1)}_{Hq} + 0.03c_{Hu} + 0.10c'_{ll} + 0.03c^{(1)}_{qq} + 0.22c_{qq} + 0.05c^{(3)}_{qq} + 0.52c^{(31)}_{qq} + 0.02c_{uu} + 0.23c^{(1)}_{uu} + 0.03c^{(8)}_{ud} + 0.15c^{(8)}_{qu} + 0.03c^{(8)}_{qd}$
6	10	$-0.20c_{H\Box} - 0.02c_{HDD} - 0.57c_{HW} - 0.34c_{HWB} - 0.02c_{uH} - 0.08c_{dH} - 0.04c_{uG} - 0.13c^{(1)}_{Hl} + 0.54c^{(3)}_{Hl} + 0.13c_{He} - 0.10c^{(1)}_{Hq} + 0.08c^{(3)}_{Hq} + 0.08c_{Hu} - 0.02c_{Hd} - 0.40c'_{ll} + 0.02c_{qq} + 0.04c^{(31)}_{qq} + 0.02c^{(1)}_{uu}$
7	5.9	$+0.08c_G - 0.07c_{H\Box} - 0.03c_{HDD} + 0.73c_{HW} - 0.23c_{HB} - 0.11c_{dH} - 0.13c_{uG} - 0.02c_{uW} - 0.03c_{uB} - 0.15c^{(1)}_{Hl} + 0.44c^{(3)}_{Hl} + 0.10c_{He} - 0.07c^{(3)}_{Hq} + 0.08c_{Hu} - 0.02c_{Hd} - 0.25c'_{ll} + 0.09c_{qq} + 0.02c^{(3)}_{qq} + 0.22c^{(31)}_{qq} + 0.10c^{(1)}_{uu} + 0.06c^{(8)}_{qu}$
8	1.1	$-0.29c_G + 0.04c_{H\Box} - 0.02c_{HDD} + 0.03c_{HG} + 0.08c_{HW} - 0.02c_{HB} - 0.10c_{uH} - 0.68c_{uG} + 0.02c^{(1)}_{Hl} + 0.08c^{(3)}_{Hl} - 0.01c_{He} - 0.02c^{(1)}_{Hq} - 0.01c^{(3)}_{Hq} + 0.04c_{Hu} - 0.02c_{Hd} - 0.03c'_{ll} - 0.04c^{(1)}_{qq} - 0.24c_{qq} - 0.04c^{(3)}_{qq} - 0.52c^{(31)}_{qq} - 0.02c_{uu} - 0.25c^{(1)}_{uu} - 0.03c^{(8)}_{ud} - 0.01c^{(1)}_{qu} - 0.15c^{(8)}_{qu} - 0.03c^{(8)}_{qd}$
9	0.30	$+0.03c_G - 0.01c_W + 0.06c_{H\Box} - 0.12c_{HDD} + 0.09c_{HW} - 0.41c_{HB} - 0.70c_{HWB} + 0.06c_{uH} - 0.11c_{dH} - 0.05c_{uG} - 0.01c_{uW} - 0.02c_{uB} - 0.37c^{(3)}_{Hl} + 0.16c_{He} - 0.36c^{(1)}_{Hq} - 0.02c^{(3)}_{Hq} - 0.03c_{Hu} + 0.01c_{Hd} + 0.10c'_{ll}$
10	0.16	$+0.02c_G - 0.02c_W + 0.27c_{H\Box} - 0.04c_{HDD} - 0.09c_{HW} + 0.09c_{HB} + 0.09c_{HWB} + 0.01c_{eH} + 0.08c_{uH} - 0.52c_{dH} - 0.07c_{uG} - 0.01c_{uW} - 0.04c_{uB} - 0.58c^{(1)}_{Hl} - 0.26c^{(3)}_{Hl} + 0.29c_{He} + 0.31c^{(1)}_{Hq} + 0.10c_{Hu} - 0.12c'_{ll} - 0.04c^{(3)}_{qq}$
11	0.036	$+0.22c_G - 0.56c_{H\Box} + 0.19c_{HDD} + 0.01c_{HG} + 0.03c_{HW} + 0.03c_{HB} + 0.07c_{HWB} - 0.02c_{eH} + 0.70c_{uH} + 0.09c_{dH} - 0.16c_{uG} + 0.04c_{uW} - 0.01c_{uB} - 0.06c^{(1)}_{Hl} - 0.18c^{(3)}_{Hl} + 0.09c_{He} + 0.03c^{(1)}_{Hq} - 0.04c_{Hd} - 0.07c'_{ll} + 0.01c^{(1)}_{qq} - 0.01c_{qq} - 0.10c^{(3)}_{qq} - 0.09c^{(31)}_{qq} - 0.02c^{(1)}_{uu} - 0.01c^{(8)}_{ud} - 0.02c^{(8)}_{qu} - 0.01c^{(8)}_{qd}$
12	0.023	$-0.05c_G + 0.09c_{H\Box} - 0.01c_{HDD} - 0.01c_{HB} - 0.02c_{uH} + 0.01c_{uG} + 0.37c_{uW} + 0.03c^{(1)}_{Hl} + 0.05c^{(3)}_{Hl} - 0.02c - 0.03c^{(1)} - 0.01c + 0.03c' + 0.03c - 0.91c^{(3)} + 0.08c^{(31)} + 0.03c^{(1)} + 0.02c^{(8)}$

Overview of the procedure



General EFT settings / choices

- SMEFT with Warsaw basis, dim-6 operators with $U(3)^5$ flavour symmetry, m_Z, m_W, G_f input scheme, CP-even, $\Lambda = 1\,\text{TeV}$
- MG5+Pythia8, interfaced with STXS rivet routine (modified for contact interactions)
- Generator level cuts (currently no common agreement)
  - object cuts to match STXS definitions, *dr* cuts to avoid divergencies
  - very inclusive: can be quite different from experimental acceptance

Parameter	Value	Default	Comment
`lhaid`	90400 `PDF4LHC15_nlo_30_pdfas`	263000 `NNPDF30_lo_as_0130`	sets α_s to the default value assumed in the PDF fit ($\alpha_s = 0.118$ for 90400)
`drll, drjj, drbb, drjb`	0.05	0.4	Avoid bias in the selection, minimum value of 0.05 chosen to avoid divergences.
`ptj, ptb`	20 GeV	20 GeV	Chosen to match jet selection of the Rivet routine.
`ptl`	0 GeV	10 GeV	Cut applied only to charged leptons.
`etal`	10	2.5	Cut applied only to charged leptons.
`ktdurham`	30 GeV	X	Merging scale for CKKW-L scheme.

Process definitions

- Process definition rather well defined
- Exist few (probably not very significant) diagrams which are not straight forward (at least for us experimentalists) to classify in terms of STXS production modes

ggF+bbH	generate p p > h QED=1 add process p p > h j QED=1 add process p p > h j j QED=1 add process p p > h b b~QED=1
VBF+VHhad	generate p p > h j j QCD=0
ZHlep	generate p p > h l+ l- add process p p > h ta+ ta- add process p p > h vl vl~ add process p p > h vt vt~
WHlep	generate p p > h l+ vl add process p p > h l- vl~
ttH	generate p p > h t t~
tHjb	generate p p > h t b~j add process p p > h t~b j
tHW	define p = p b b~ generate p p > h t w- add process p p > h t~w+
$H \to 4\ell$	generate h > l+ l- l+ l-
$H \to b\bar{b}$	generate h > b b~
$H \to \gamma\gamma$	generate h > a a
+ Additional channels (2-&3-body decays) entering total width	

EFT parametrisation

- EFT parametrisation is multiplicative correction to best-knowledge STXS and BR predictions in each bin
  - assume / hope that higher order effects cancel in ratio EFT / SM
  - no additional uncertainties, except full SM uncertainty at SM-MC order taken into account
- Parametrisation of each process at its leading order:
  - ggF, $ggZ(\to \ell\ell)H$, $H \to gg$: NLO QCD with SMEFTatNLO
  - $H \to \gamma\gamma$: NLO QED from this paper
  - rest: LO with SMEFTsim
- Factorisation of production and decay (+ Higgs decays simulated at rest)
- In this step, consider all operators in each bin with interference term impact $> 0.1\%$:
  - does not reject operators, but avoid contributions from stat. fluctuations in some bins
  - 0.1% is far below uncertainty on measurement in each bin within validity regime of EFT

Power in Λ^{-2}

$$\frac{\sigma_{EFT}}{\sigma_{SM}} = 1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_{ij}$$

2 fit scenarios considered:

- "Linear": Taylor expansion, truncation at $\frac{1}{\Lambda^2}$

$$(\sigma \times BR)_{\mathrm{EFT}} = (\sigma \times BR)_{\mathrm{SM}} \cdot \left(1 + \sum_i A_i^{\mathrm{STXS}} c_i + \sum_i (A_i^{H\to X} - A_i^H) \cdot c_i \right)$$

- "Linear + quadratic": full parametrisation, including pure BSM terms and mixed terms with higher orders

$$\sigma_i^{H\to X} = \sigma_i \cdot \mathcal{BR}_{H\to X} = \left(\sigma^i_{\mathrm{SM}} + \sigma^i_{\mathrm{int}} + \sigma^i_{\mathrm{BSM}}\right) \cdot \frac{\Gamma^{H\to X}_{\mathrm{SM}} + \Gamma^{H\to X}_{\mathrm{int}} + \Gamma^{H\to X}_{\mathrm{BSM}}}{\Gamma^{H}_{\mathrm{SM}} + \Gamma^{H}_{\mathrm{int}} + \Gamma^{H}_{\mathrm{BSM}}}$$

Only dimension 6 operators are considered!

Sensitivity study

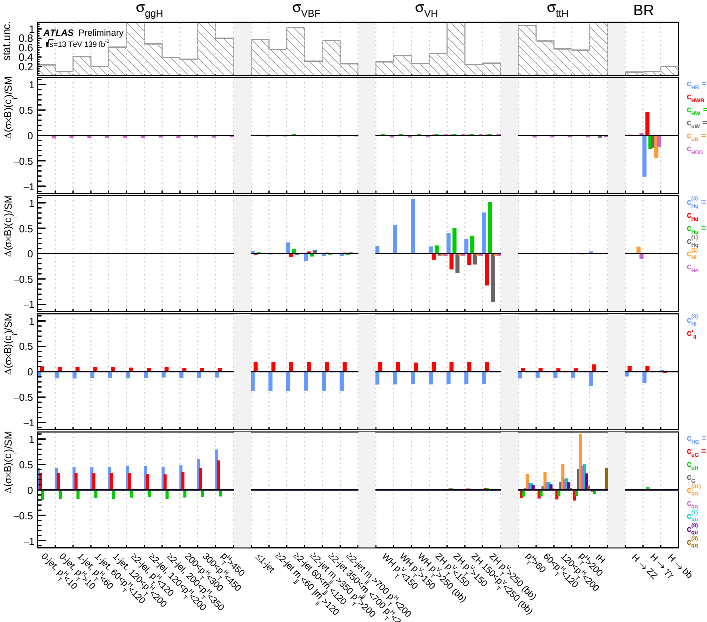
- Fit with all Wilson coefficients does not converge and correlations are making results somewhat arbitrary
- Study sensitivity from covariance matrix: set only parameters to 0 to which there is no sensitivity
- Build full EFT covariance matrix fron STXSxBR covariance matrix, propagate linear EFT parametrisation:

$$C_{\mathrm{EFT}}^{-1} = P^T \, C_{\mathrm{STXS}}^{-1} \, P$$

- Eigenvector decomposition gives hints on sensitive directions: large eigenvalues $\leftrightarrow$ good sensitivity

- Do not use full eigenvector decomposition: difficult to interpret intuitively and validate results
  - group only operators with similar impact on specific physics processes
  - no aim to reduce "experimental" correlations (e.g. between ggF and $H \to \gamma\gamma$)

Parameter rotations



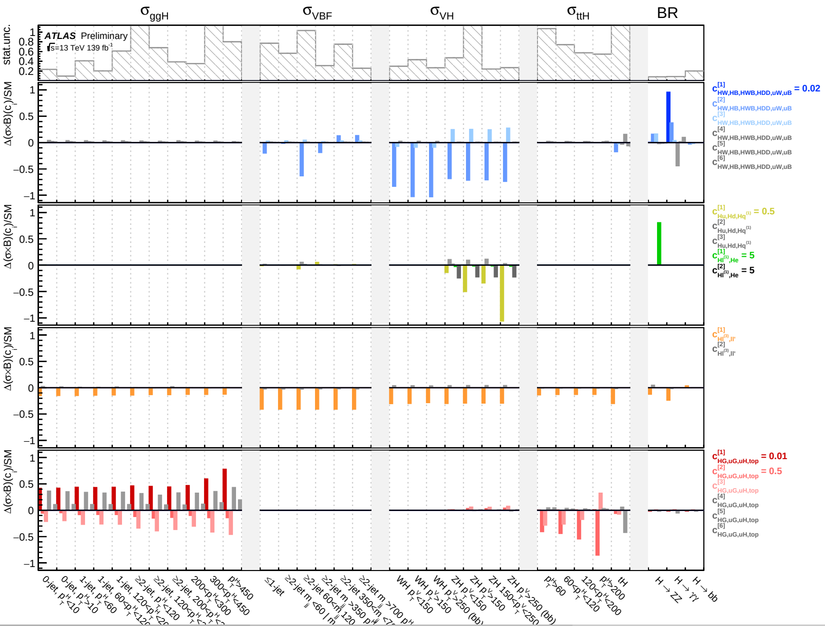
Parameter rotations

- Group parameter with similar impact in specific processes
- Eigenvector of sub-covariance matrix with these operators
- Keep the ones with "large" eigenvalue, set the others to 0
- Will be validated later on!

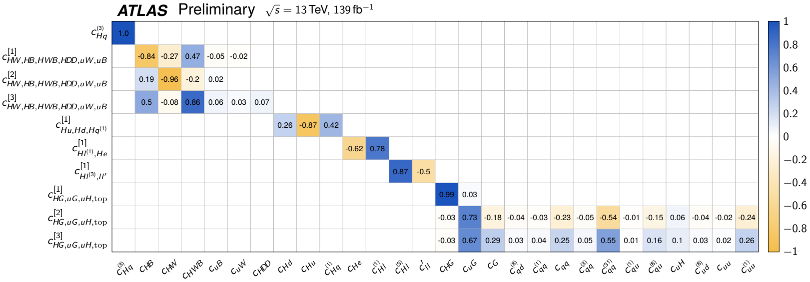
- Set operators impacting overall normalisation to zero; in future: would compute impact on fitted directions

Parameter		Definition	Eigenvalue	Fit Parameter	
$c_{Hq}^{(3)}$		$c_{Hq}^{(3)}$	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	✓	$H \to \gamma\gamma$, VBF/VH
	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		
$c^{[i]}_{HG,uG,uH,\mathrm{top}}$	1	$+0.999c_{HG} + 0.038c_{uG}$	176000	✓	ggF, ttH
	2	$-0.03c_{HG} + 0.73c_{uG} - 0.03c_{qq}^{(1)} - 0.23c_{qq} - 0.05c_{qq}^{(3)} - 0.54c_{qq}^{(31)} - 0.02c_{uu} - 0.24c_{uu}^{(1)} - 0.04c_{ud}^{(8)} - 0.01c_{qu}^{(1)} - 0.15c_{qu}^{(8)} - 0.04c_{qd}^{(8)} - 0.18c_{G} + 0.06c_{uH}$	20	✓	
	3	$-0.03c_{HG} + 0.67c_{uG} + 0.04c_{qq}^{(1)} + 0.25c_{qq} + 0.05c_{qq}^{(3)} + 0.55c_{qq}^{(31)} + 0.02c_{uu} + 0.26c_{uu}^{(1)} + 0.03c_{ud}^{(8)} + 0.01c_{qu}^{(1)} + 0.16c_{qu}^{(8)} + 0.03c_{qd}^{(8)} + 0.29c_{G} + 0.1c_{uH}$	1.3	✓	
	4	$+0.11c_{uG} + 0.01c_{qq} - 0.018c_{qq}^{(3)} + 0.029c_{qq}^{(31)} + 0.012c_{uu}^{(1)} - 0.993c_{uH}$	0.14		
	5	$+0.02c_{qq} - 1.0c_{qq}^{(3)} + 0.06c_{qq}^{(31)} + 0.03c_{uu}^{(1)} + 0.02c_{qu}^{(8)} + 0.02c_{uH}$	0.02		
	6	$+0.07c_{uG} - 0.02c_{qq}^{(1)} + 0.07c_{qq} + 0.03c_{qq}^{(3)} + 0.32c_{qq}^{(31)} + 0.06c_{uu}^{(1)} + 0.04c_{ud}^{(8)} + 0.08c_{qu}^{(8)} + 0.04c_{qd}^{(8)} - 0.94c_{G} + 0.02c_{uH}$	0.0092		
$c^{[1]}_{Hl^{(1)},He}$		$+0.78c_{Hl}^{(1)} - 0.62c_{He}$	2.6	✓	$H \to 4\ell$
$c^{[2]}_{Hl^{(1)},He}$		$+0.62c_{Hl}^{(1)} + 0.78c_{He}$	0.056		
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$		$-0.87c_{Hu} + 0.26c_{Hd} + 0.42c_{Hq}^{(1)}$	59	✓	VH
$c^{[2]}_{Hu,Hd,Hq^{(1)}}$		$+0.41c_{Hu} - 0.09c_{Hd} + 0.91c_{Hq}^{(1)}$	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	✓	field redefinition
$c^{[2]}_{Hl^{(3)},ll'}$		$0.50c_{Hl}^{(3)} + 0.87c'_{ll}$	0.33		

Parameter rotations



Choice of fitted directions

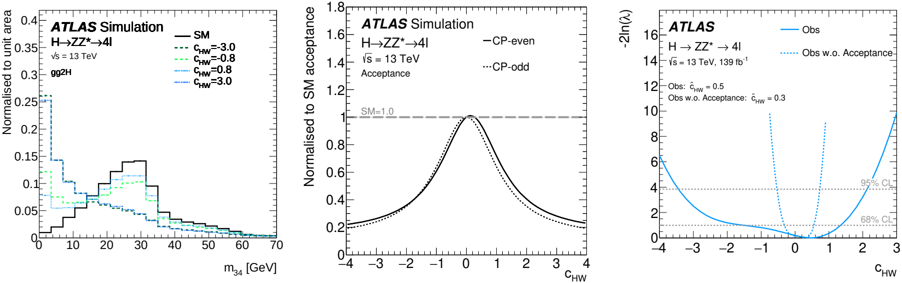


- 10 directions fitted simultaneously
- Used for both fit scenarios (choice of sensitive directions not re-optimised including quadratic terms)

EFT parametrisation of acceptance

No definition of decay-side binning in STXS:

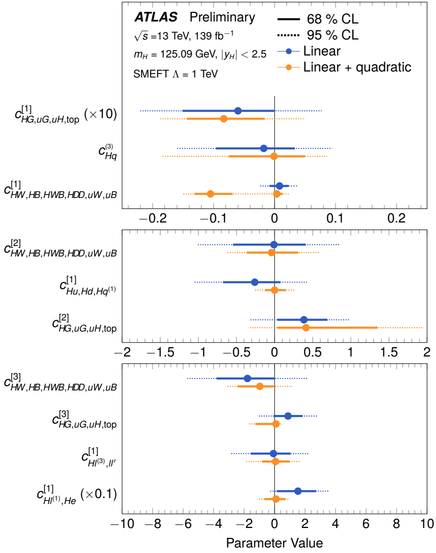
- Experimental requirements on m_{12} and m_{34} to target $H \to ZZ^*$ decay
- Wilson coefficients might cause diff. kinematics or contact terms with Higgs, Z and leptons

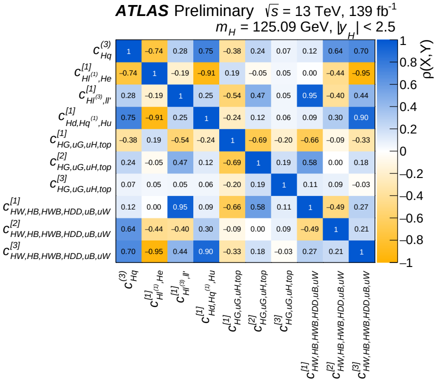


Use acceptance parametrisation from Eur.Phys.J C 80 (2020) 957:

- ad-hoc parametrisation with 3D Lorenzian
- includes c_{HW}, c_{HB}, c_{HWB}: neglect other operators
- multiplicative factor: non-linear component in the fit, even for "linear" model

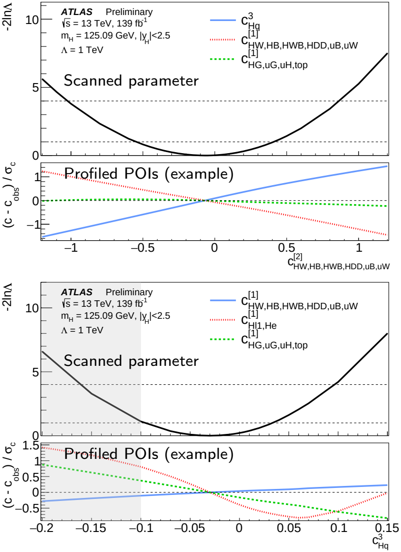
Fit results





- Excellent sensitivity from simultaneous fit to 10 POIs
- No reduction of "experimental" correlations

About correlations (linear model)



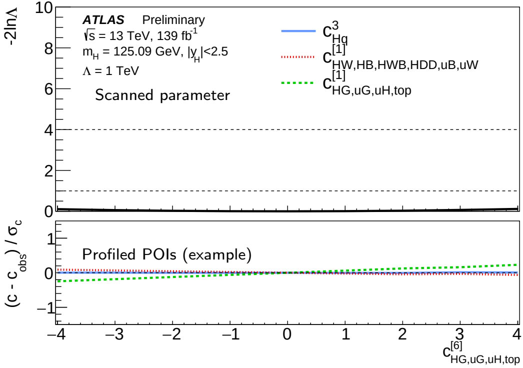
Correlations should be linear to keep generality of results when quoting central values and covariance matrix

- variation of profiled directions in likelihood scans show mostly linear correlations
- exception: parameters relevant mostly in $H \to 4\ell$ and correlated with operators included in acceptance correction (this is not a fundamental problem and can be fixed for next round)

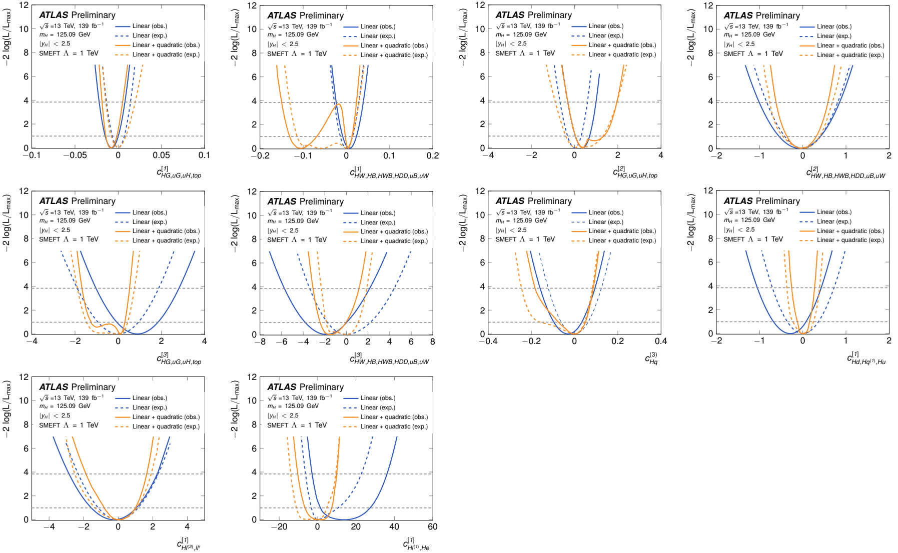
Only valid in linear model; more difficult to handle including quadratic terms!

Neglected directions

- Setting parameters to SM (zero) can be strong model assumption
- To keep generality of results, show that impact on fitted directions is negligible within EFT validity range



Impact of quadratic terms



Non-negligible impact from quadratic terms; should study dim-8 terms...

MSSM interpretation