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EFT fits in Higgs @ ATLAS & CMS

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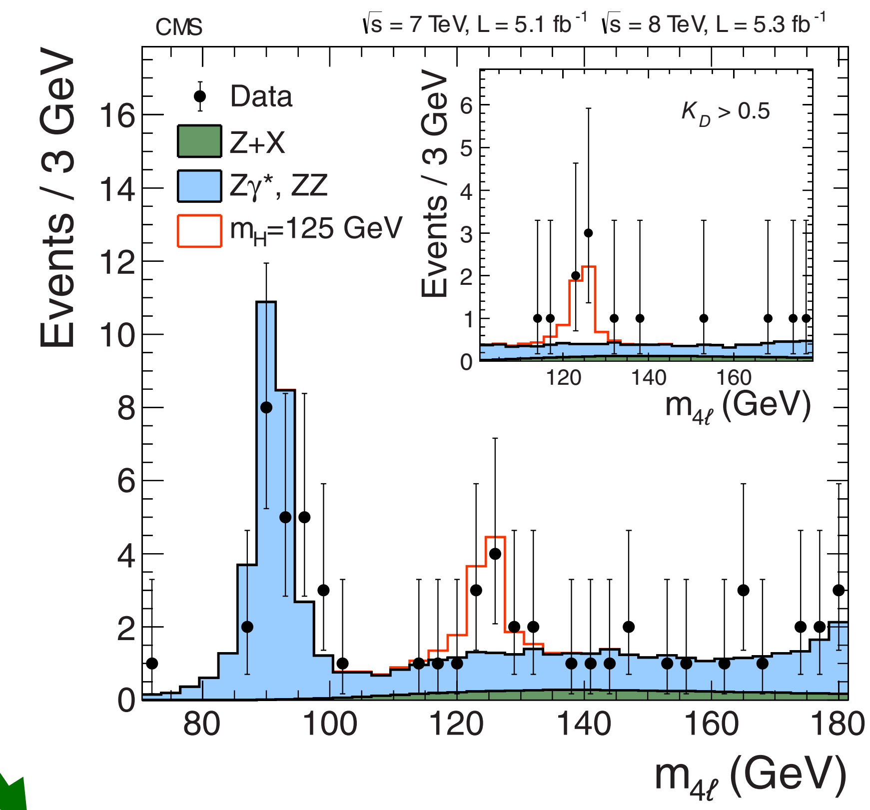
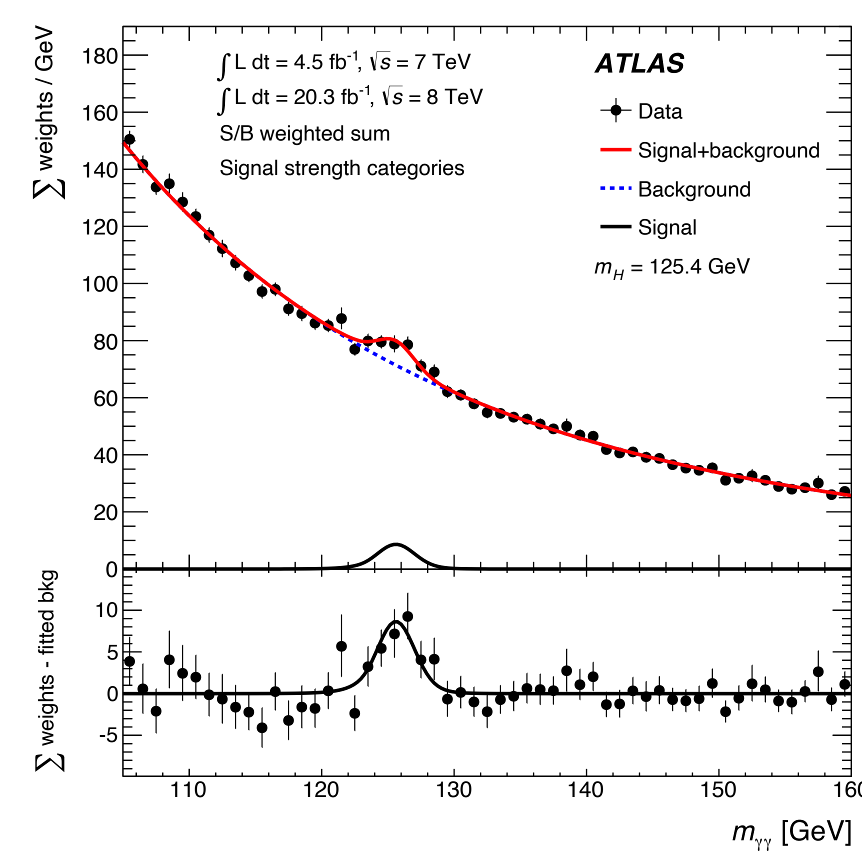
Introduction

- Run 1 focus: Higgs discovery; establish bosonic couplings
- Run 2 focus: Establish Yukawa couplings; **precision; going beyond incl measurements**

➔ constraining BSM effects with more granular Higgs measurements (e.g. **EFT**)

- Dedicated analyses
- Interpretations of cross section measurements (simplified template cross sections; differential fiducial cross sections)

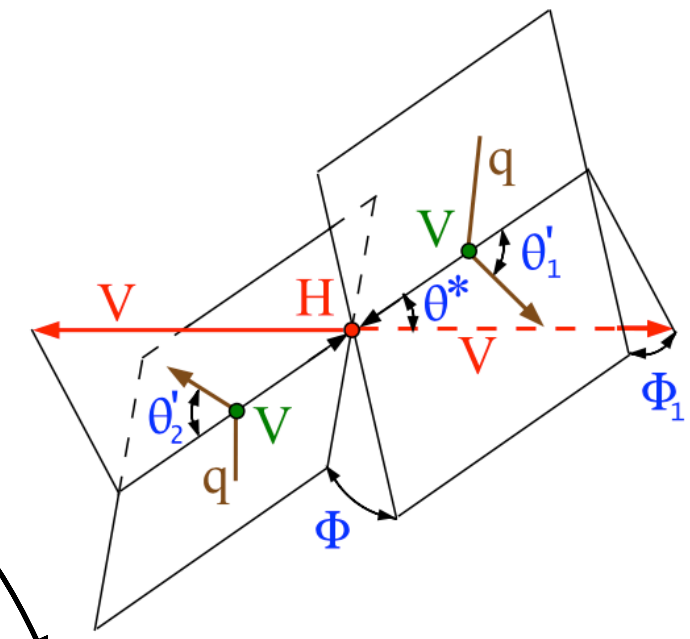




Dedicated analyses

H➔ZZ➔4l

- Target specific couplings/operators
  - Using ME information
  - Exploits full kinematic information of the event ➔ optimised sensitivity (to specific operators)
- General parameterisation of anomalous HVV/Hff interactions, e.g.



$$\mathcal{D}_{\rm alt}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\rm sig}(\mathbf{\Omega})}{\mathcal{P}_{\rm sig}(\mathbf{\Omega}) + \mathcal{P}_{\rm alt}(\mathbf{\Omega})}$$

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

$$c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_2$$

Can translate to EFT coefficients in the Higgs basis

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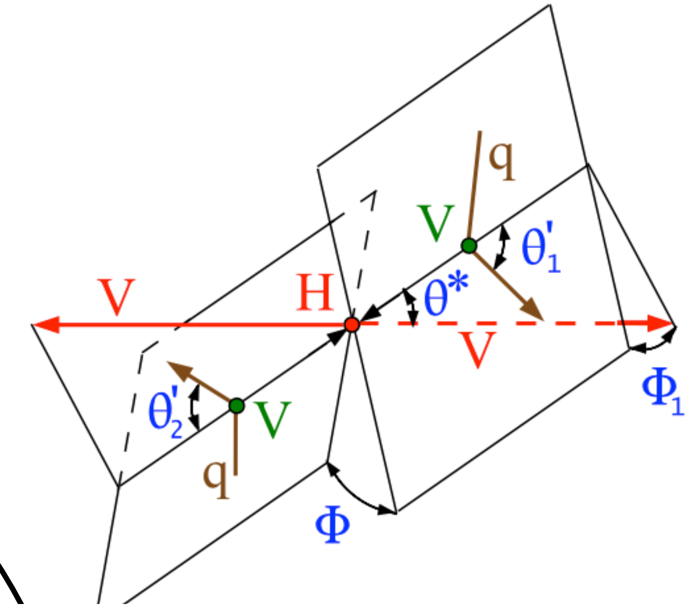

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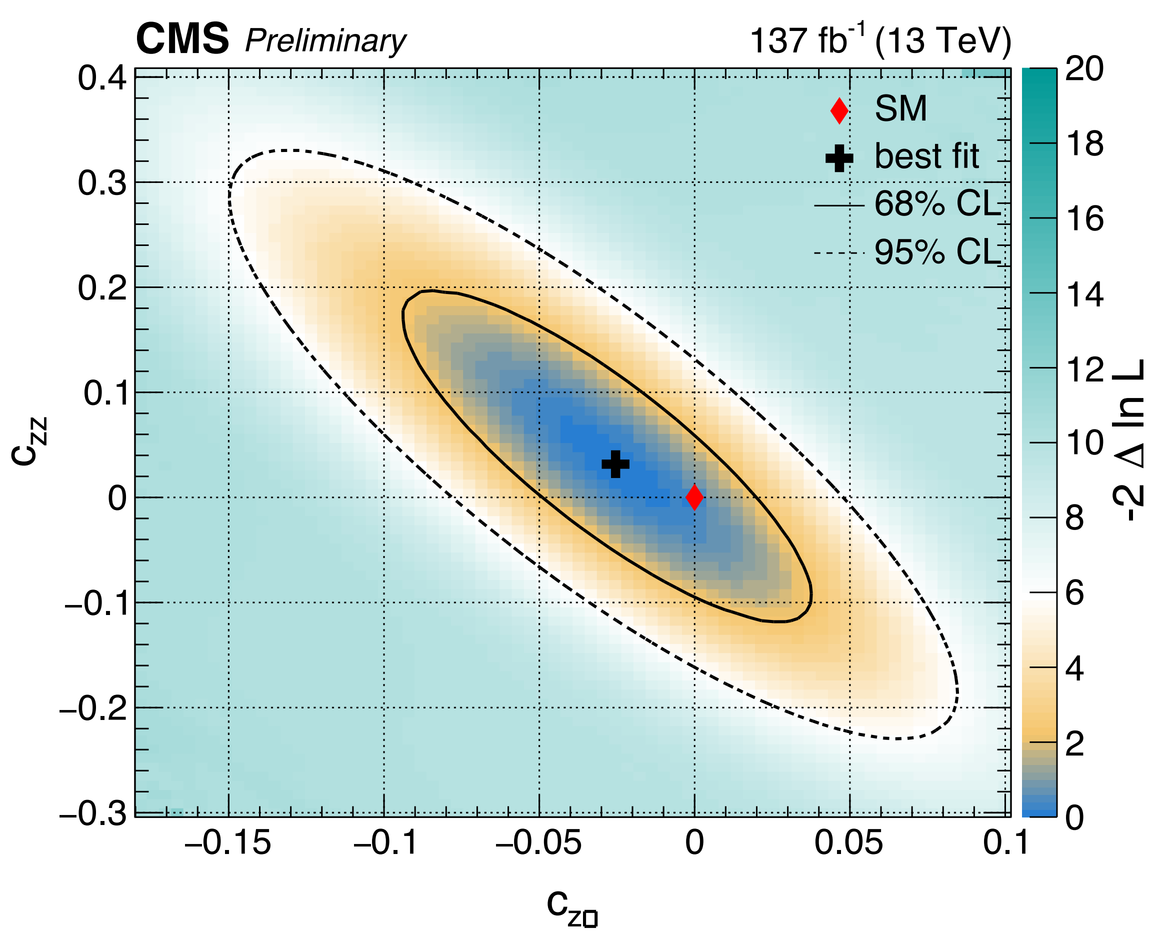
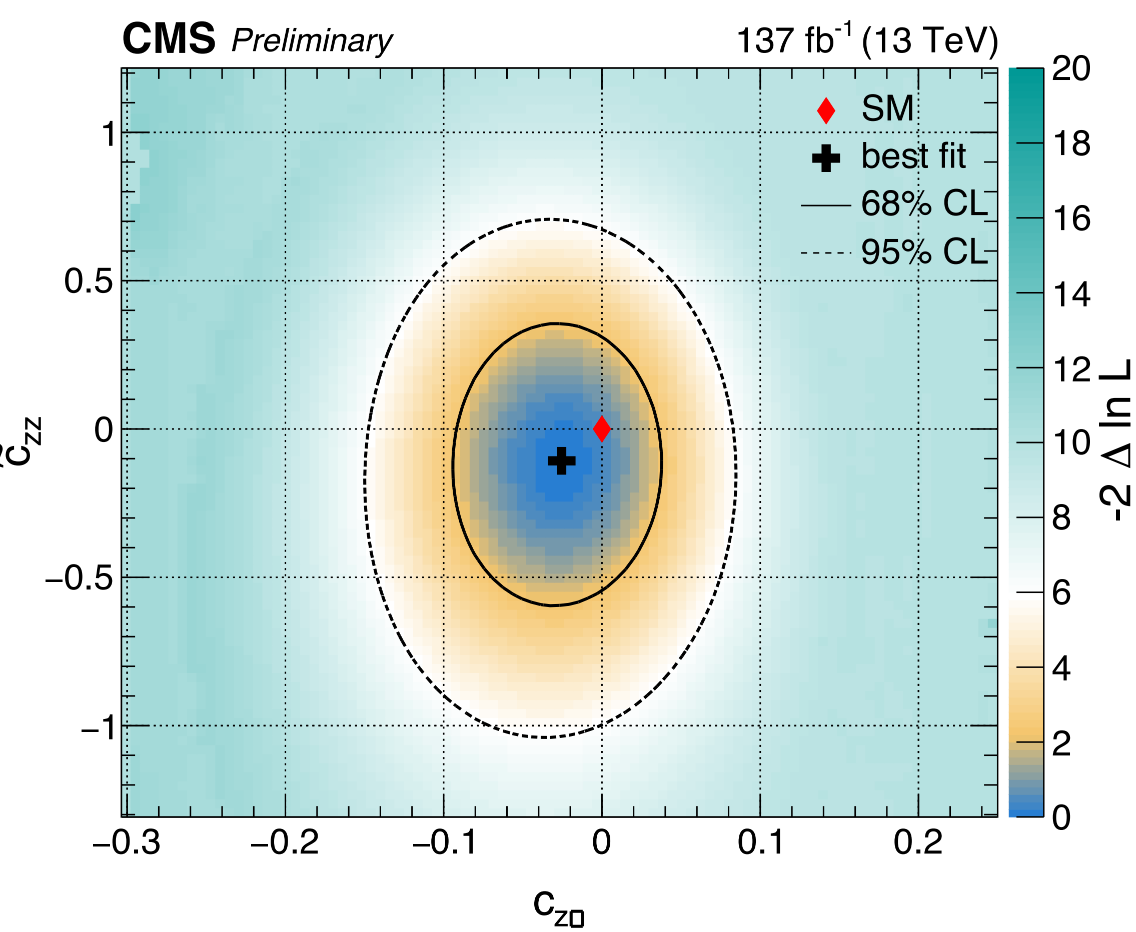
EFT





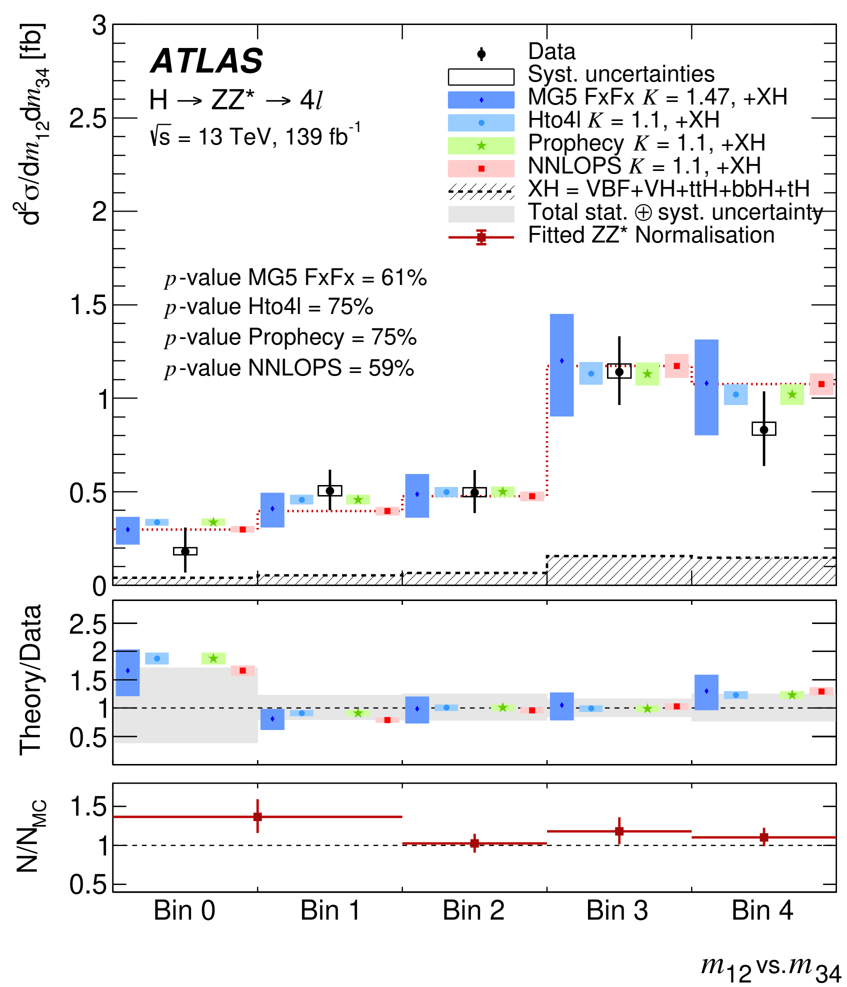
Constraints in the Higgs basis on 2 EFT coefficients at a time

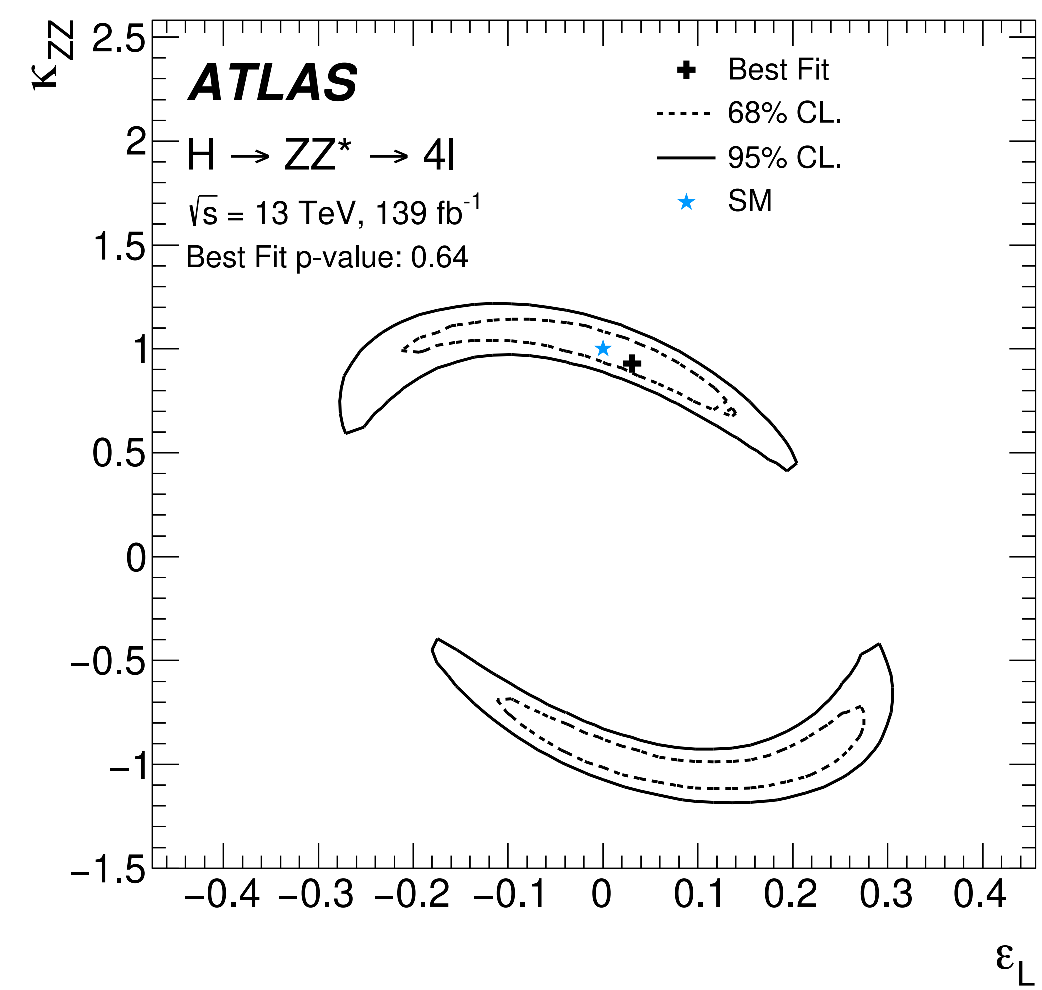
Eur. Phys. J. C80 (2020) 941

Fid/Diff cross section measurements

H→ZZ→4l

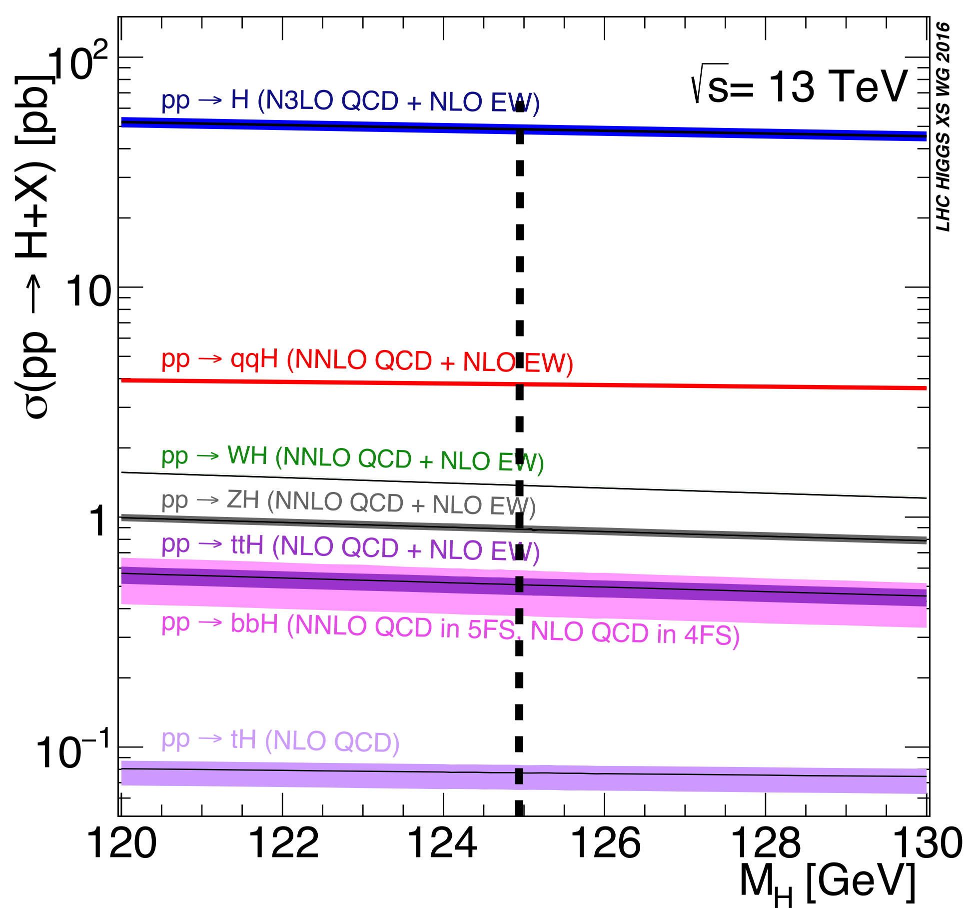
- Use double-differential cross section measurement in m_{Z1} and m_{Z2} to constrain BSM
  - Pseudo-observables: framework that introduces modified interactions between H, Z & left-handed/right-handed leptons
  - Can be mapped to EFT e.g. see [EPJC 75 (2015) 128]

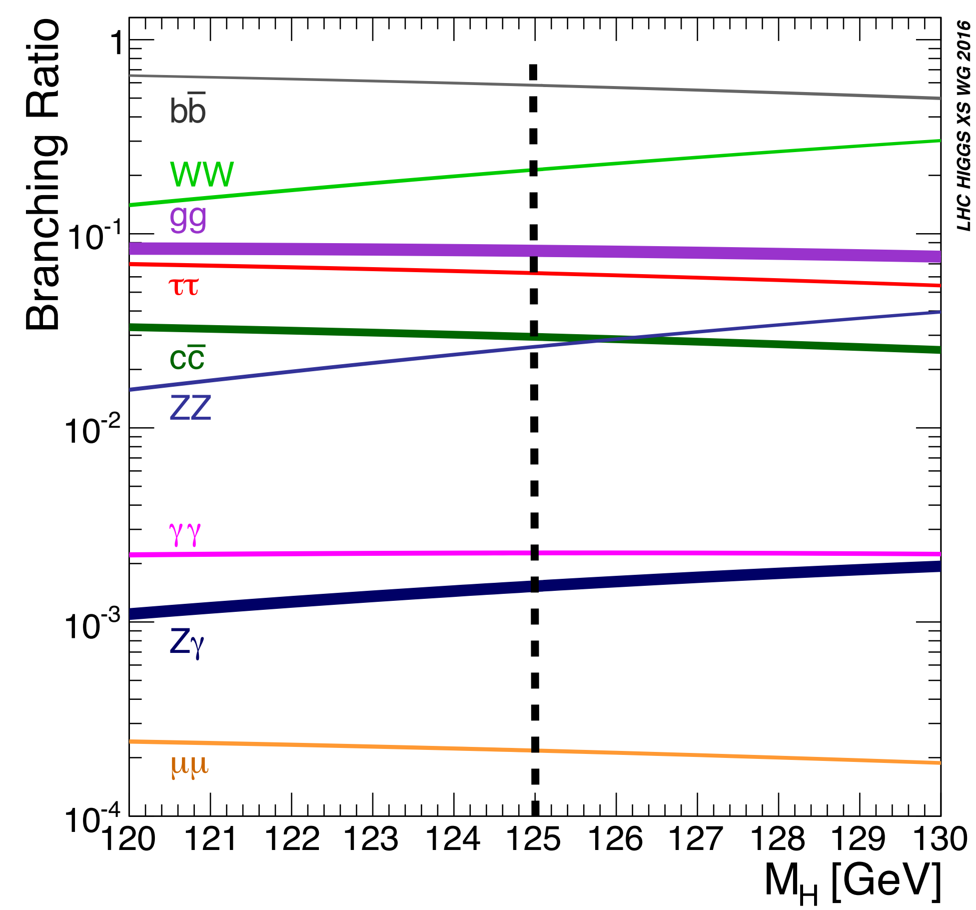




Beyond 4l

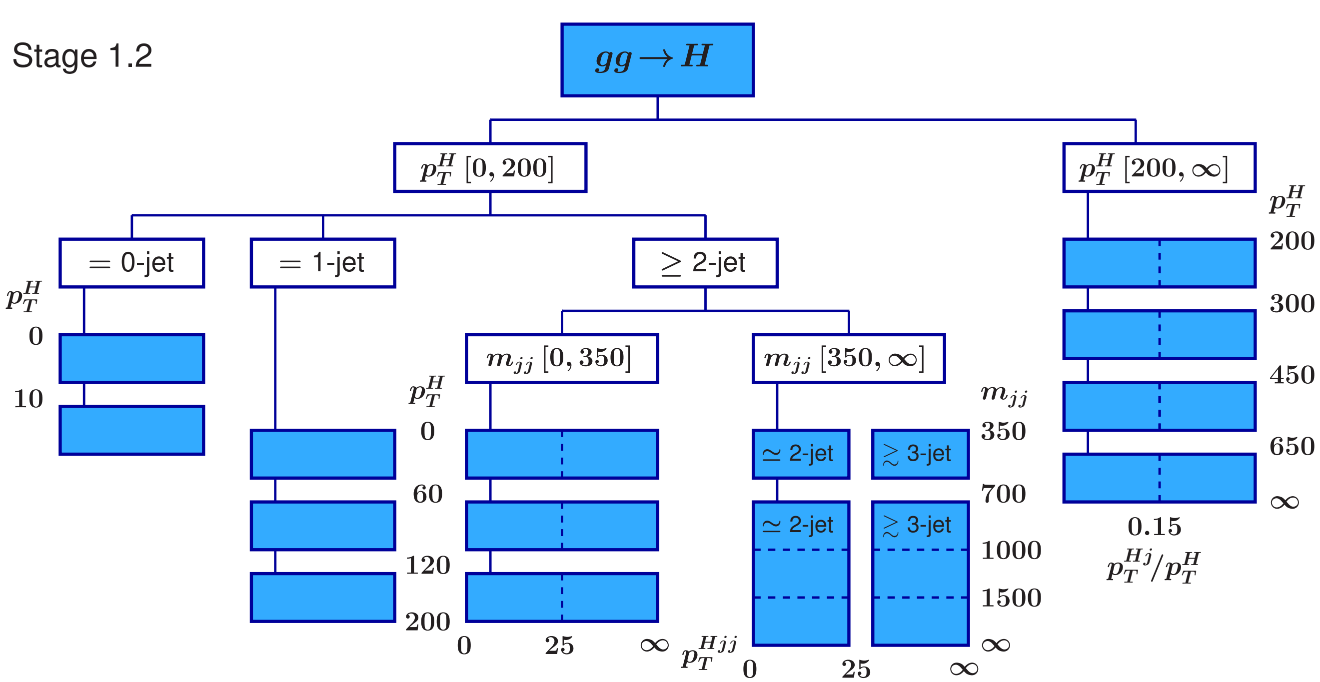
- Results shown so far use H➔ZZ➔4l channel
  - EFT interpretations based on differential measurements exist e.g. in H➔γγ [ATLAS-CONF-2019-029]
  - **How to benefit from all the different channels?**

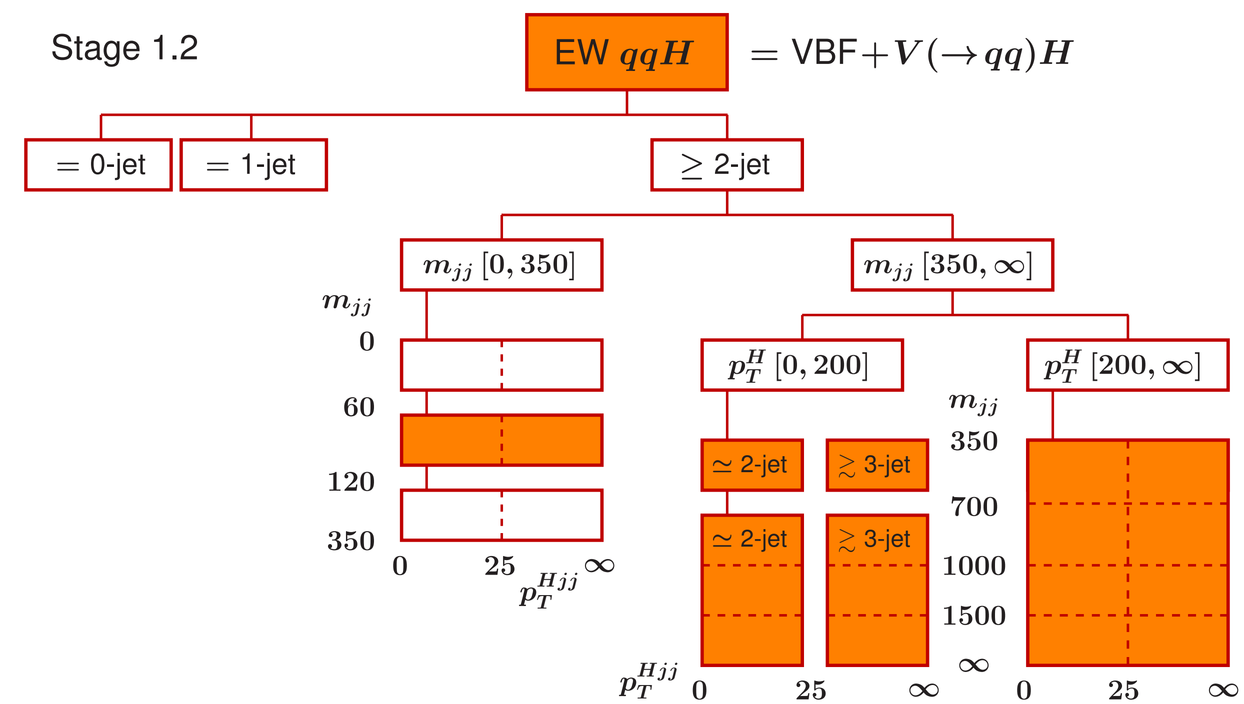




Simplified template cross sections

- Higgs analyses measure **Simplified template cross sections (STXS)**
  - Divide production modes in different kinematic regions
  - Aim to minimise theory dependence while maximising experimental sensitivity to BSM effects
  - Note: still unfolding to particle level!
- Different ‘stages’ evolving with available statistical precision
  - With Run 2 dataset: stage 1.2
- Decay channels considered inclusively
- Measurements performed in main production & decay modes

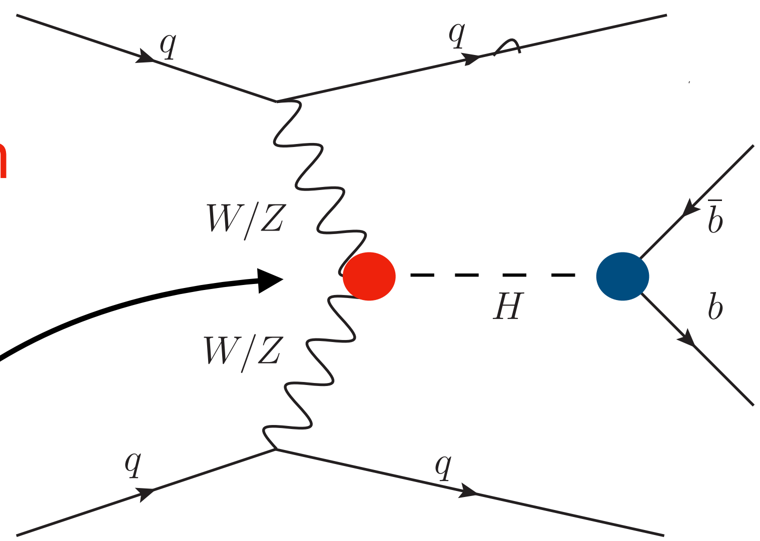




EFT parameterisation

NP considered in production & decay and this factorizes

Considering dimension-6 operators



i: production mode

$$\sigma_i^{\text{EFT}} = \sigma_i^{\text{SM}} + \sigma_i^{\text{int}} + \sigma_i^{\text{BSM}}$$

x

f: decay channel

$$\mathscr{B}_f^{\text{EFT}} = \frac{\Gamma_f^{\text{SM}} + \Gamma_f^{\text{int}} + \Gamma_f^{\text{BSM}}}{\Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{tot}}^{\text{int}} + \Gamma_{\text{tot}}^{\text{BSM}}}$$

EFT parameterisation

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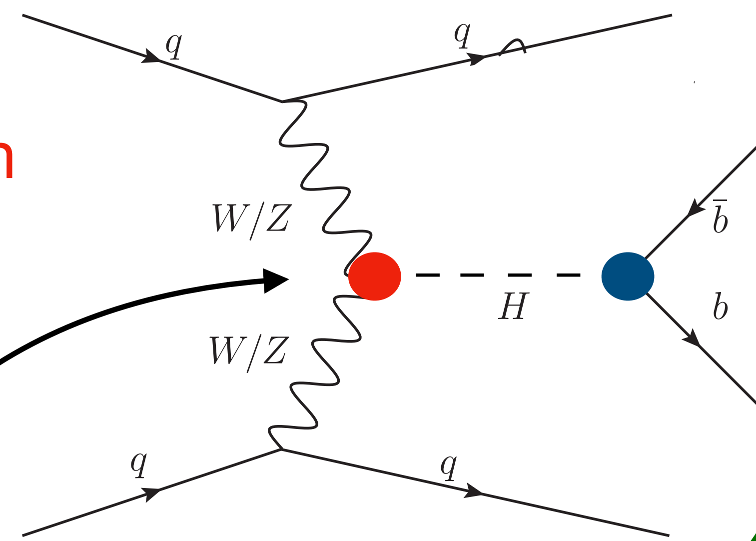

i: production mode

f: decay channel

$$\sigma_i^{\text{EFT}} = \sigma_i^{\text{SM}} + \sigma_i^{\text{int}} + \sigma_i^{\text{BSM}} \quad \times \quad \mathscr{B}_f^{\text{EFT}} = \frac{\Gamma_f^{\text{SM}} + \Gamma_f^{\text{int}} + \Gamma_f^{\text{BSM}}}{\Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{tot}}^{\text{int}} + \Gamma_{\text{tot}}^{\text{BSM}}}$$

$$\propto \frac{1}{\Lambda^2}$$

$$\propto \frac{1}{\Lambda^4}$$

EFT parameterisation

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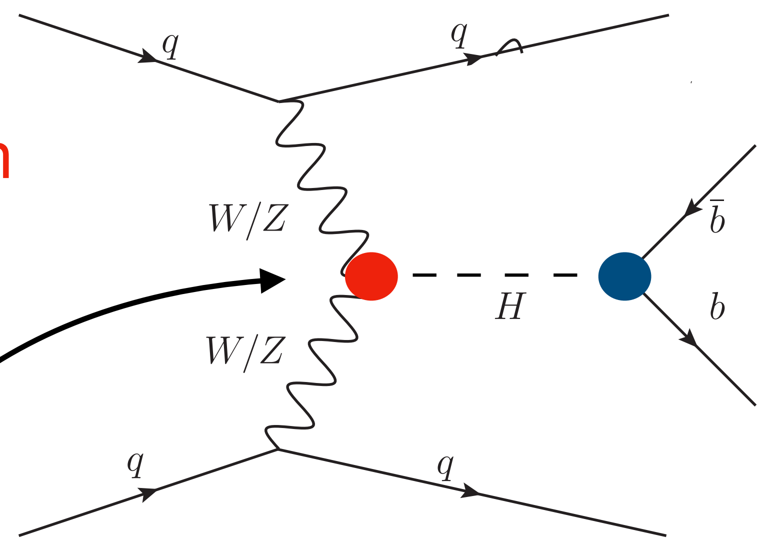
Considering dimension-6 operators



i: production mode

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$$\sigma_i^{\mathrm{EFT}} = \sigma_i^{\mathrm{SM}} + \sigma_i^{\mathrm{int}} + \sigma_i^{\mathrm{BSM}} \quad \mathrm{x} \quad \mathscr{B}_f^{\mathrm{EFT}} = \frac{\Gamma_f^{\mathrm{SM}} + \Gamma_f^{\mathrm{int}} + \Gamma_f^{\mathrm{BSM}}}{\Gamma_{\mathrm{tot}}^{\mathrm{SM}} + \Gamma_{\mathrm{tot}}^{\mathrm{int}} + \Gamma_{\mathrm{tot}}^{\mathrm{BSM}}}$$

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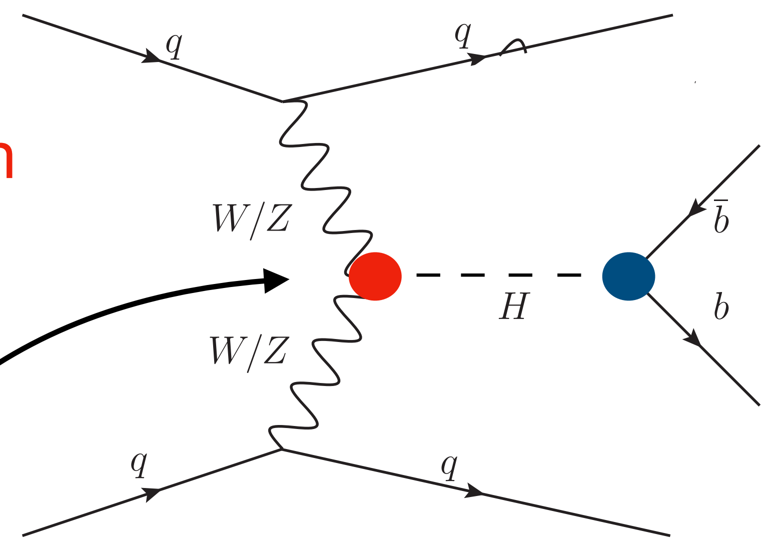

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Input analyses consider SM-expected cross sections ➔ scaling per (production x decay bin) becomes:

$$\text{scaling} = \left(1 + \frac{\sigma_i^{\text{int}}}{\sigma_i^{\text{SM}}} + \frac{\sigma_i^{\text{BSM}}}{\sigma_i^{\text{SM}}}\right)\left(\frac{1 + \frac{\Gamma_f^{\text{int}}}{\Gamma_f^{\text{SM}}} + \frac{\Gamma_f^{\text{BSM}}}{\Gamma_f^{\text{SM}}}}{1 + \frac{\Gamma_{\text{tot}}^{\text{int}}}{\Gamma_{\text{tot}}^{\text{SM}}} + \frac{\Gamma_{\text{tot}}^{\text{BSM}}}{\Gamma_{\text{tot}}^{\text{SM}}}}\right)$$

EFT parameterisation

$$\text{scaling} = \left(1 + \frac{\sigma_i^{\text{int}}}{\sigma_i^{\text{SM}}} + \frac{\sigma_i^{\text{BSM}}}{\sigma_i^{\text{SM}}}\right)\left(\frac{1 + \frac{\Gamma_f^{\text{int}}}{\Gamma_f^{\text{SM}}} + \frac{\Gamma_f^{\text{BSM}}}{\Gamma_f^{\text{SM}}}}{1 + \frac{\Gamma_{\text{tot}}^{\text{int}}}{\Gamma_{\text{tot}}^{\text{SM}}} + \frac{\Gamma_{\text{tot}}^{\text{BSM}}}{\Gamma_{\text{tot}}^{\text{SM}}}}\right)$$

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$$\frac{\sigma_i^{\text{int}}}{\sigma_i^{\text{SM}}} = \Sigma_j A_j^i c_j$$

EFT parameterisation

$$\text{scaling} = \left(1 + \frac{\sigma_i^{\text{int}}}{\sigma_i^{\text{SM}}} + \frac{\sigma_i^{\text{BSM}}}{\sigma_i^{\text{SM}}}\right)\left(\frac{1 + \frac{\Gamma_f^{\text{int}}}{\Gamma_f^{\text{SM}}} + \frac{\Gamma_f^{\text{BSM}}}{\Gamma_f^{\text{SM}}}}{1 + \frac{\Gamma_{\text{tot}}^{\text{int}}}{\Gamma_{\text{tot}}^{\text{SM}}} + \frac{\Gamma_{\text{tot}}^{\text{BSM}}}{\Gamma_{\text{tot}}^{\text{SM}}}}\right)$$

$$\frac{\sigma_i^{\text{int}}}{\sigma_i^{\text{SM}}} = \Sigma_j A_j^i c_j$$

$$\frac{\sigma_i^{\text{BSM}}}{\sigma_i^{\text{SM}}} = \Sigma_j \Sigma_k B_{jk}^i c_j c_k$$

EFT parameterisation

$$\text{scaling} = \left(1 + \frac{\sigma_i^{\text{int}}}{\sigma_i^{\text{SM}}} + \frac{\sigma_i^{\text{BSM}}}{\sigma_i^{\text{SM}}}\right)\left(\frac{1 + \frac{\Gamma_f^{\text{int}}}{\Gamma_f^{\text{SM}}} + \frac{\Gamma_f^{\text{BSM}}}{\Gamma_f^{\text{SM}}}}{1 + \frac{\Gamma_{\text{tot}}^{\text{int}}}{\Gamma_{\text{tot}}^{\text{SM}}} + \frac{\Gamma_{\text{tot}}^{\text{BSM}}}{\Gamma_{\text{tot}}^{\text{SM}}}}\right)$$

$$= \Sigma_j A_j^i c_j$$

$$= \Sigma_j \Sigma_k B_{jk}^i c_j c_k$$

Extracted from simulation

EFT parameterisation

$$\text{scaling} = \left(1 + \frac{\sigma_i^{\text{int}}}{\sigma_i^{\text{SM}}} + \frac{\sigma_i^{\text{BSM}}}{\sigma_i^{\text{SM}}}\right)\left(\frac{1 + \frac{\Gamma_f^{\text{int}}}{\Gamma_f^{\text{SM}}} + \frac{\Gamma_f^{\text{BSM}}}{\Gamma_f^{\text{SM}}}}{1 + \frac{\Gamma_{\text{tot}}^{\text{int}}}{\Gamma_{\text{tot}}^{\text{SM}}} + \frac{\Gamma_{\text{tot}}^{\text{BSM}}}{\Gamma_{\text{tot}}^{\text{SM}}}}\right)$$

$$= \Sigma_j A_j^i c_j$$

$$= \Sigma_j \Sigma_k B_{jk}^i c_j c_k$$

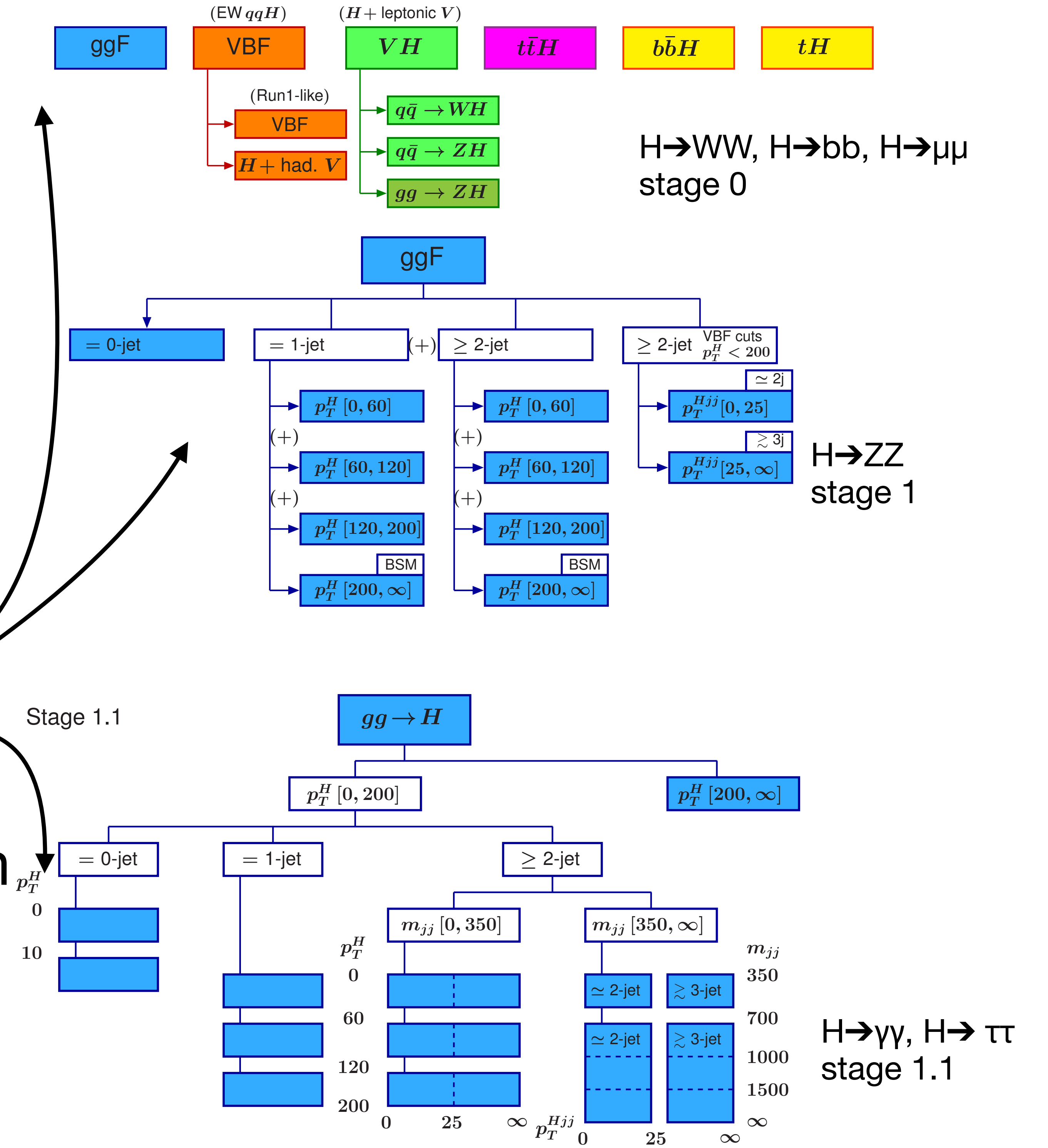
Extracted from simulation

& equivalent for the decay parameterisation

Recall: production split into STXS bins, full phase space considered for decays

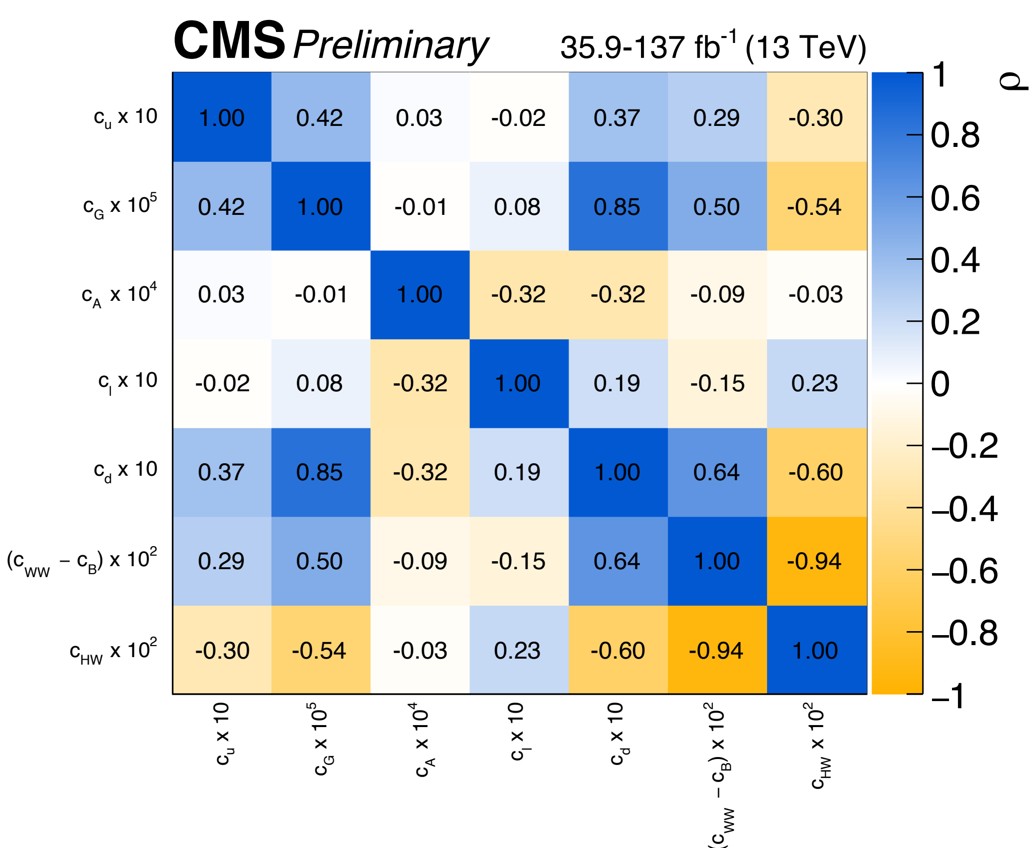
CMS: Higgs Effective Lagrangian (SILH)

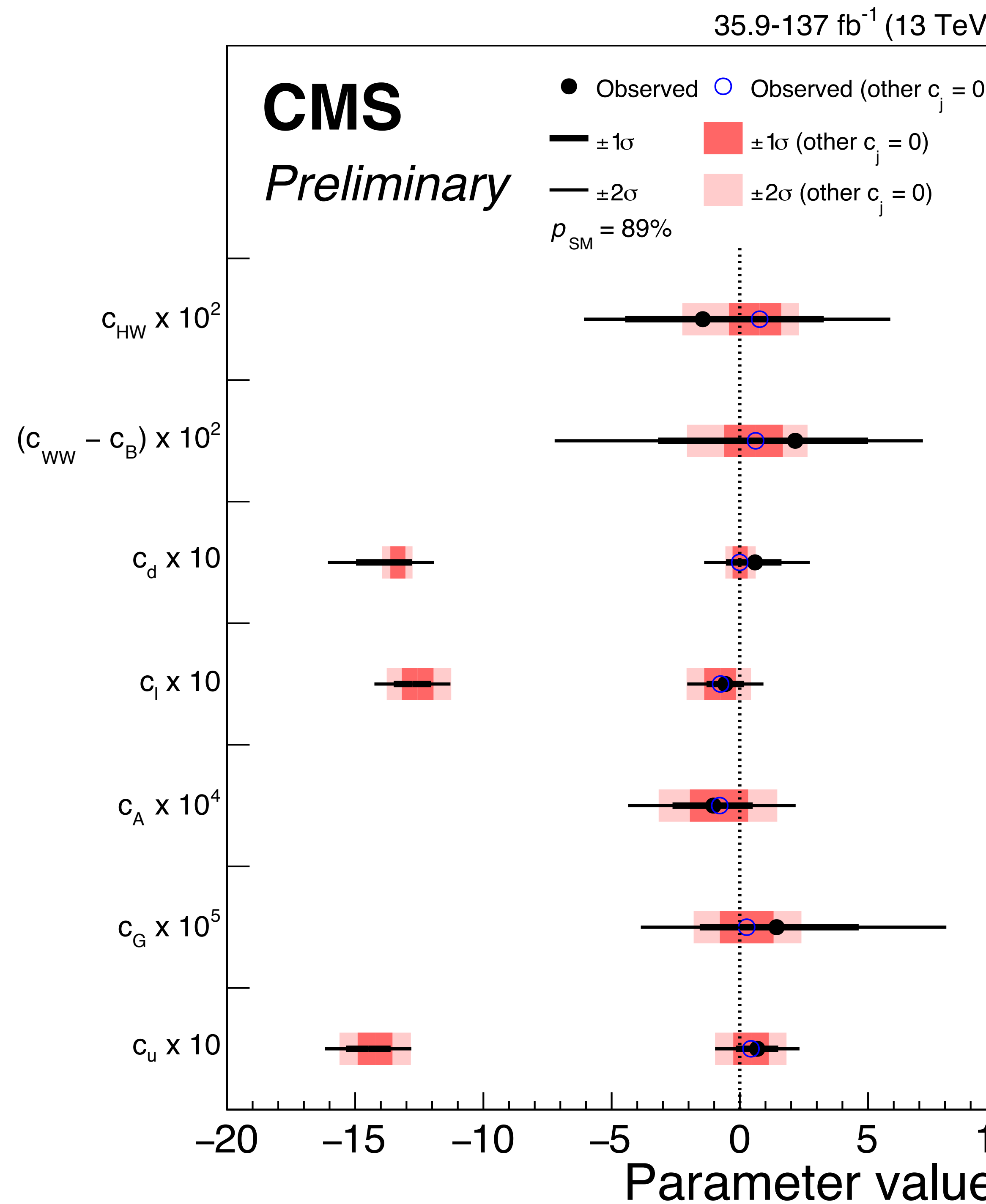
- Partial run 2 dataset analyses with different stages of STXS classification available
- No STXS combination performed ➔ directly to EFT interpretation
  - Derive parameterisation for each stage of STXS considered
- Use Higgs Effective Lagrangian (HEL) model ➔ ~ SILH basis
- LO parameterization



Results in HEL model

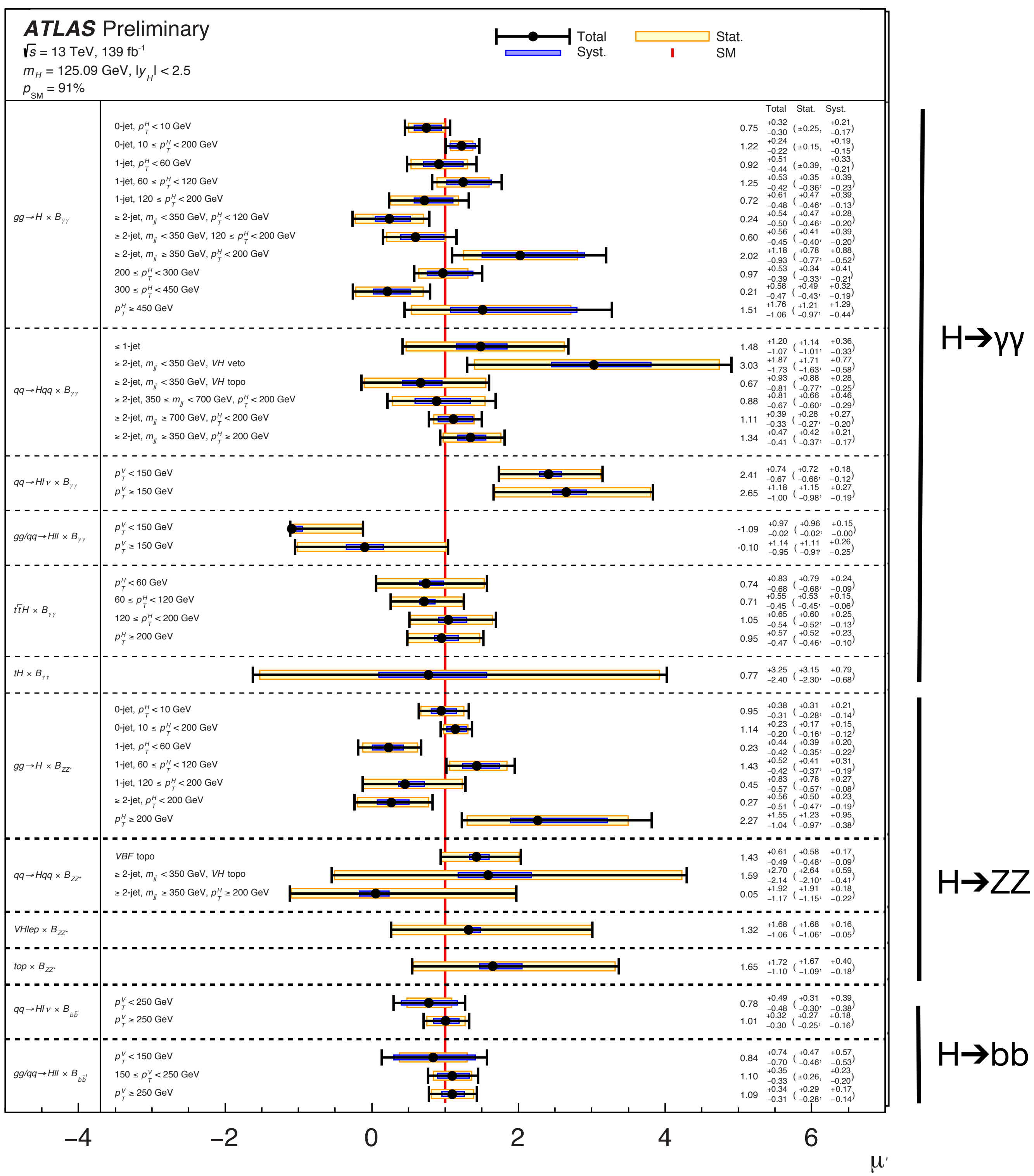
- Consider 7 coefficients affecting the Higgs sector
  - Use interference + BSM terms
  - CP-violating operators ignored
- Sizeable correlations between some of the parameters





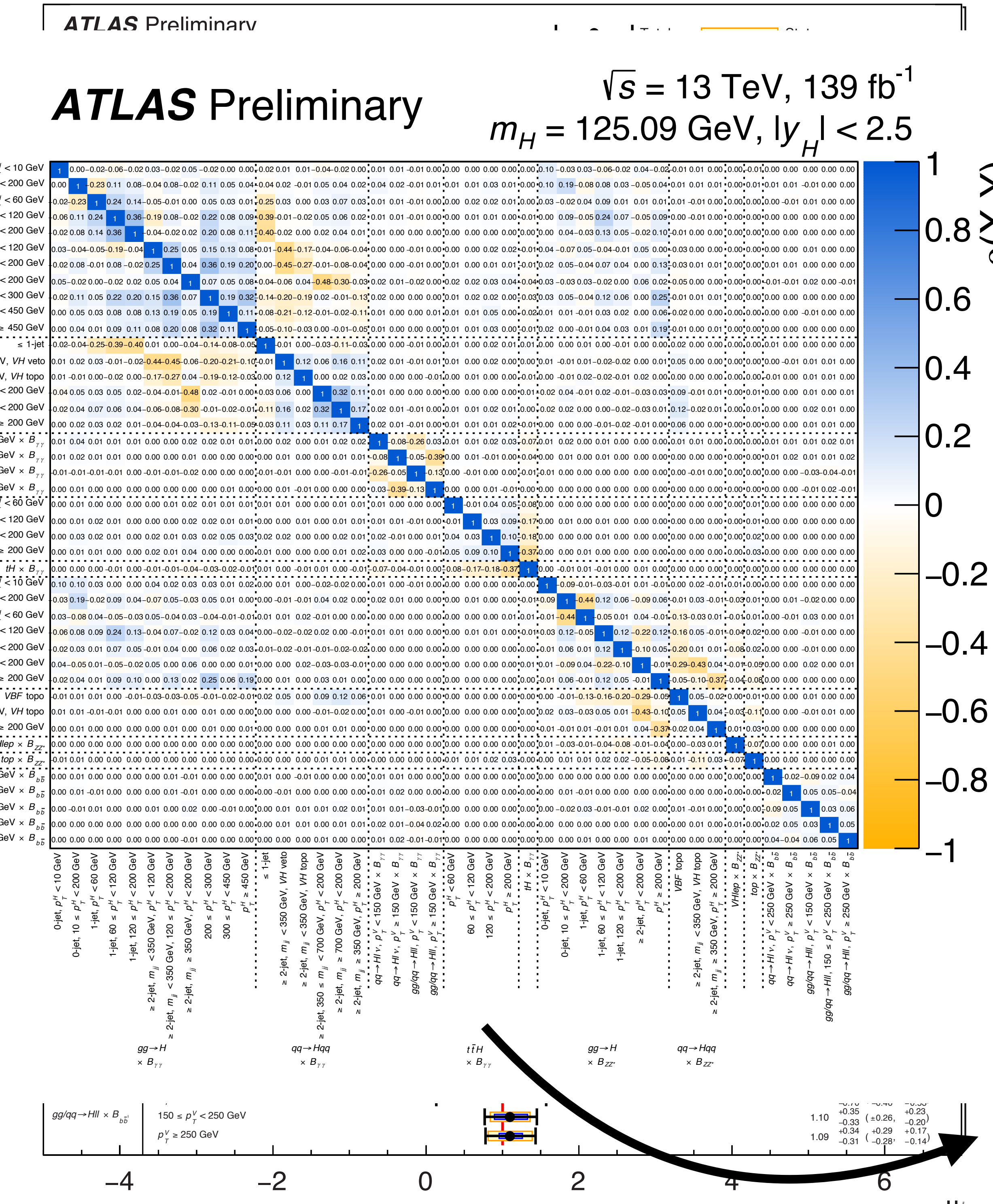
ATLAS-CONF-2020-053

ATLAS: in Warsaw basis



- Using STXS stage 1.2 measurements in H➔γγ, H➔ZZ , V(lep)H➔bb
- Parameterisation in Warsaw basis with SMEFTsim / SMEFT@NLO
  - Don’t **just** have Higgs related operators / how to deal with blind directions?
  - Use linearised EFT parameterisation to rotate STXS hessian matrix to EFT basis
  - Eigenvector decomposition to identify groups of parameters

ATLAS: in Warsaw basis



H➔γγ

- Using STXS stage 1.2 measurements in H➔γγ, H➔ZZ , V(lep)H➔bb
- Parameterisation in Warsaw basis with SMEFTsim / SMEFT@NLO
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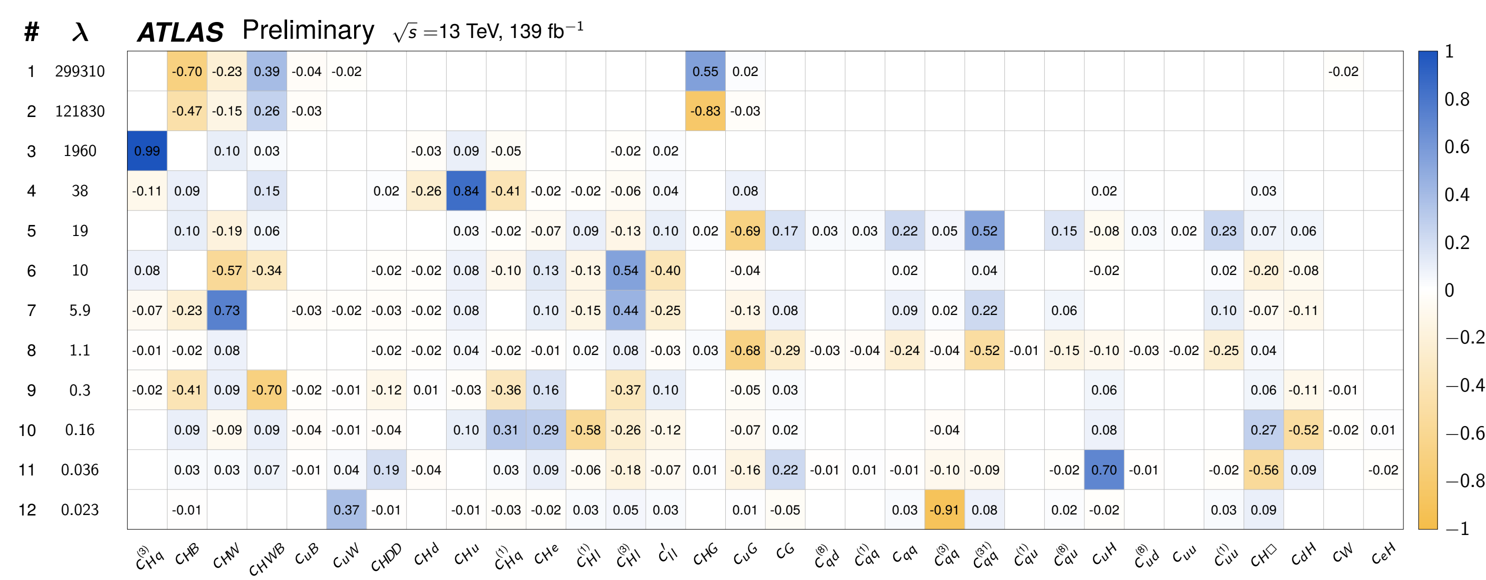
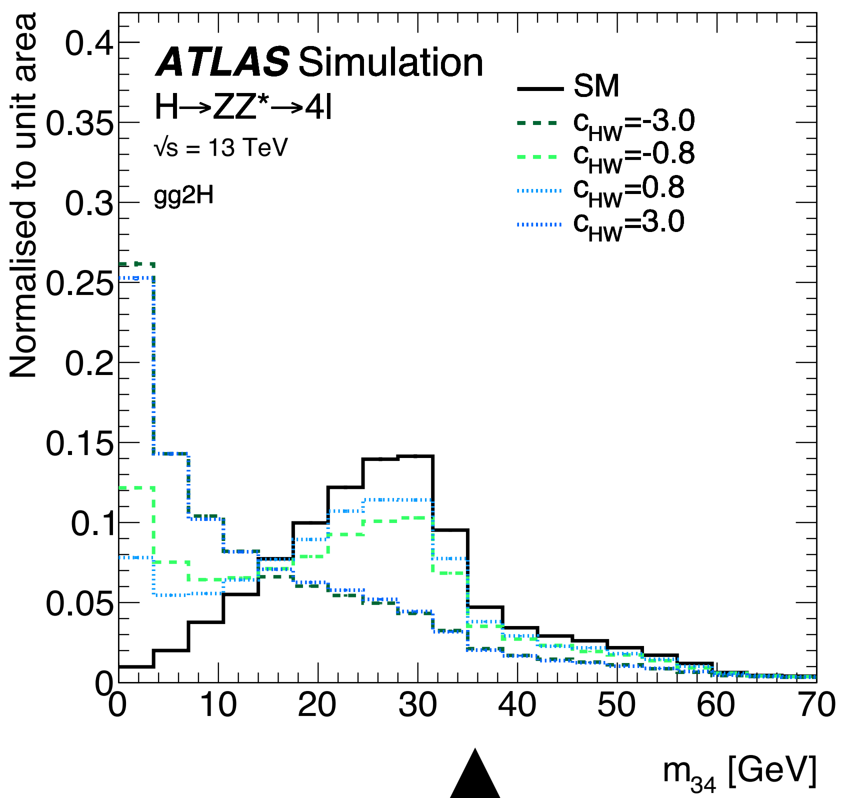
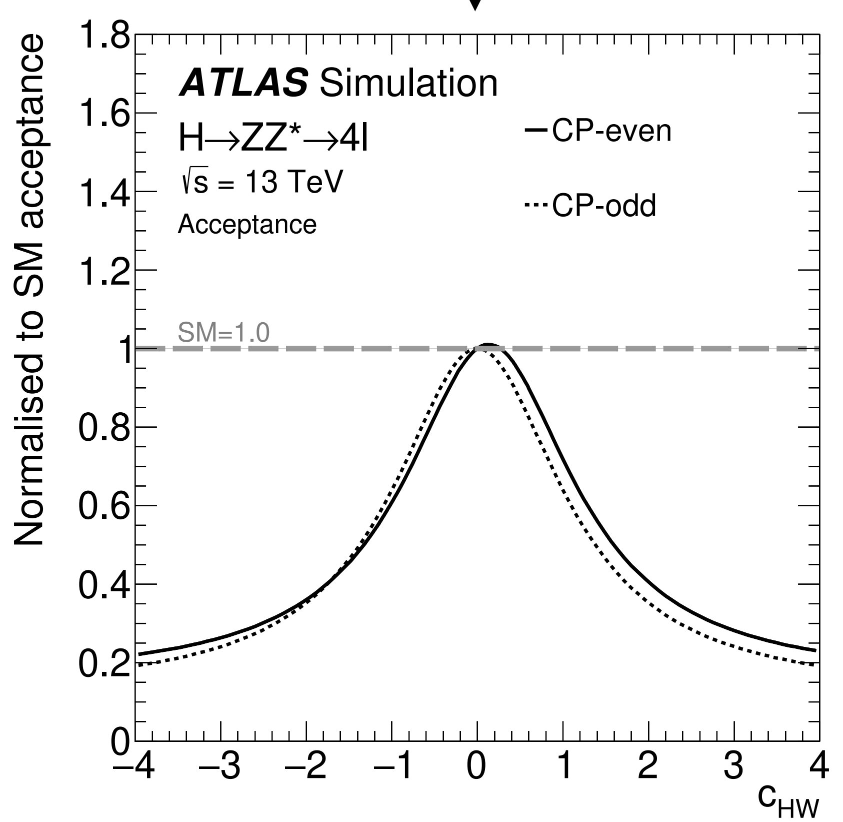


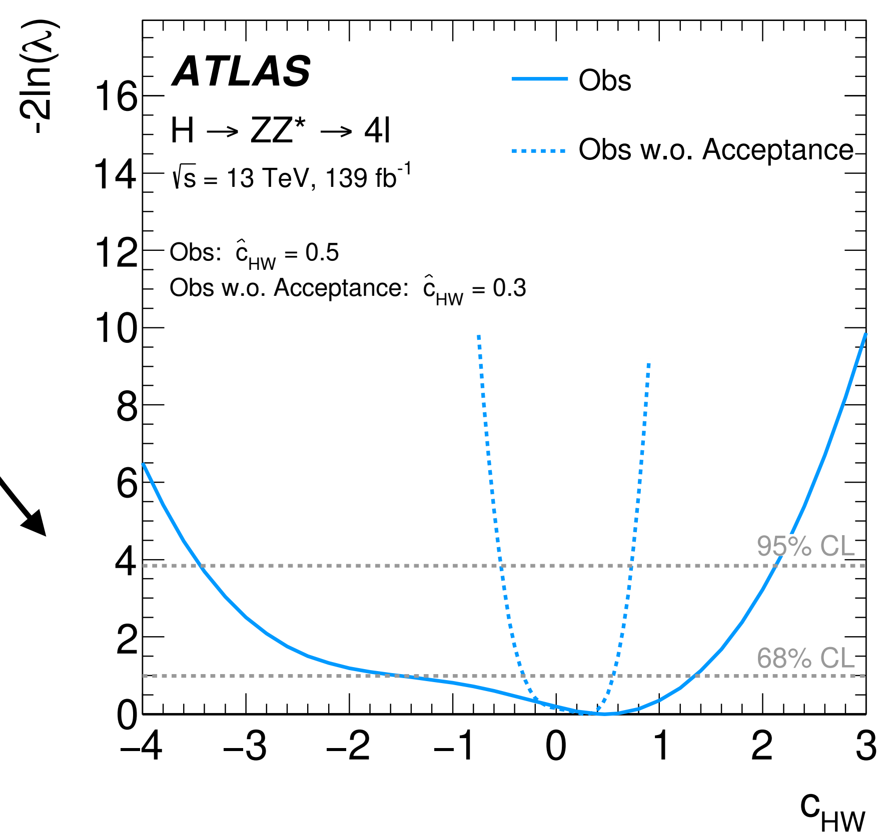
Eur. Phys. J. C 80 (2020) 957

Acceptance effects

- In H➔ZZ➔4l, sizeable differences in acceptance depending on value of EFT coefficients
  - Particularly due to m_{Z2} requirements in the analysis
  - Ad-hoc acceptance correction derived and applied to decay parameterization
- Acceptance effects ignored for other decay channels.

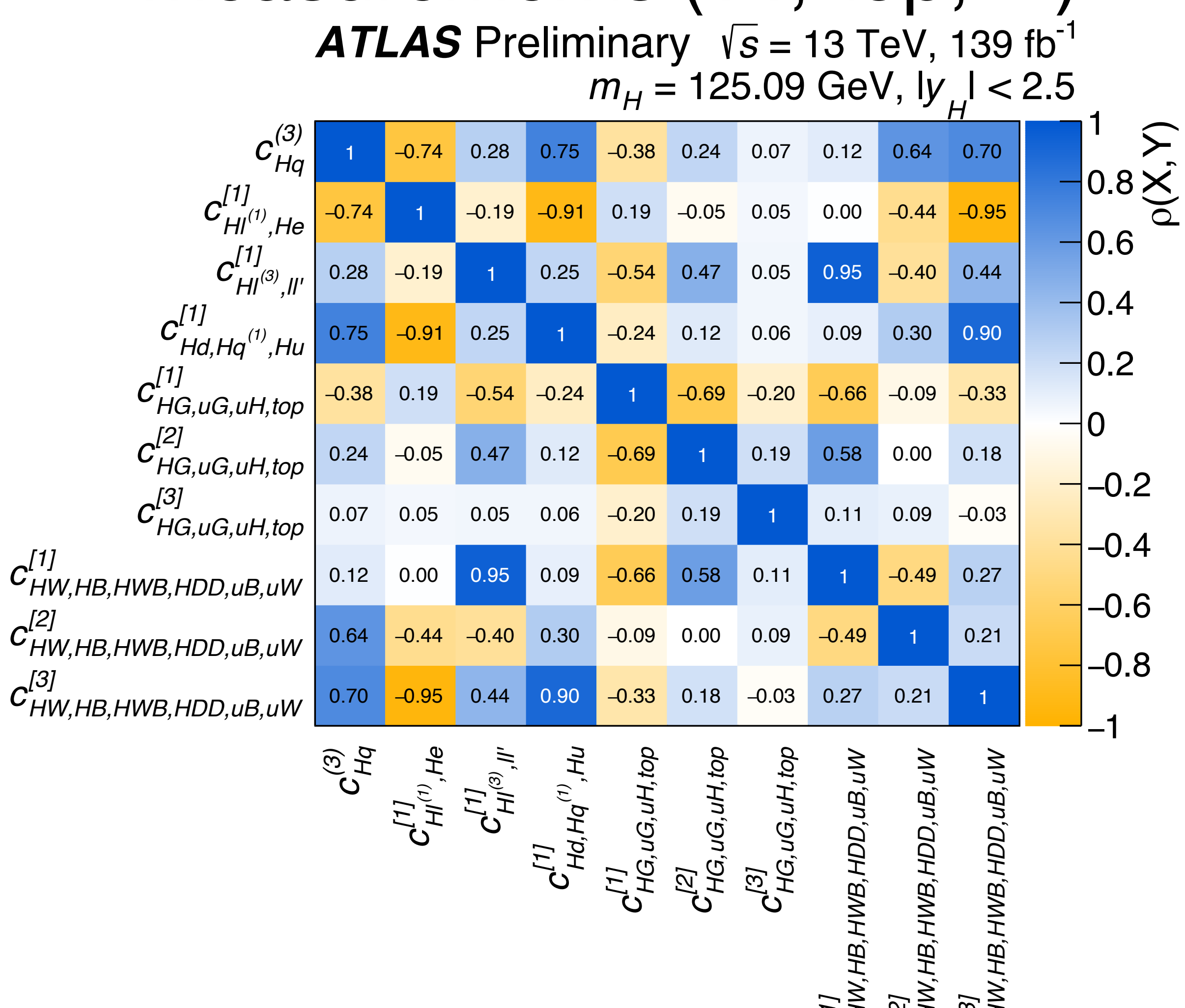


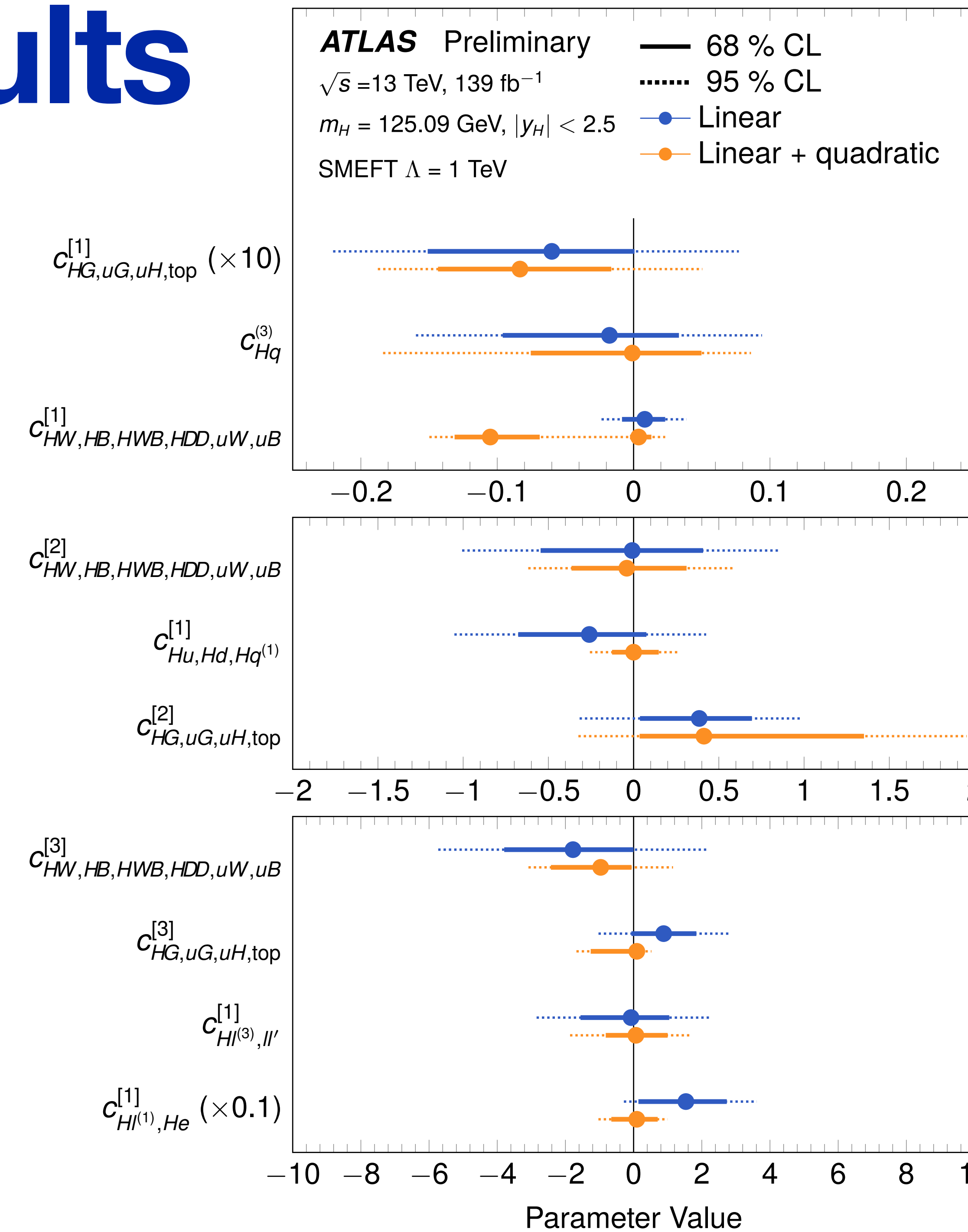




Warsaw basis results

- Group correlated coefficients and set constraints on linear combinations of coefficients
  - Fit 10 directions
- Degeneracy could be broken with information from other measurements (VV, top, ...)





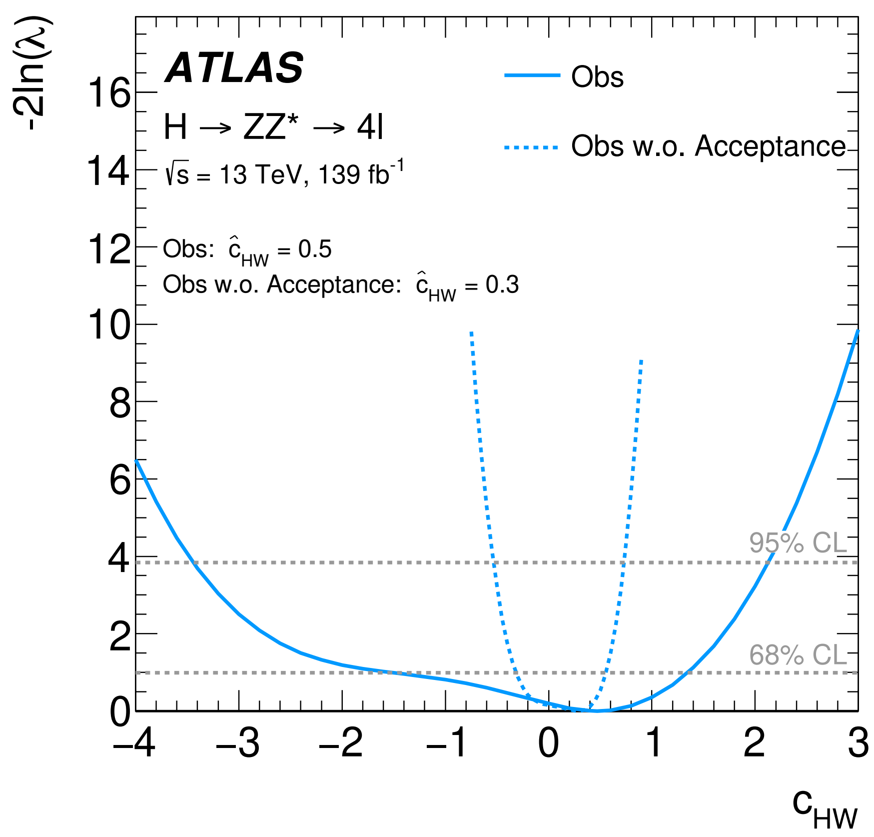
Linearised (No BSM-only terms)
Linear+ quadratic (~interference +BSM)

Lessons learned

- Measurement ➔ interpretation cycle decouples interpretation from the analysis itself
  - If the theory changes, or parameterisations at higher oder become available, several years down the line interpretation can always be re-done
  - Straightforward to present results in multiple models
  - Can be re-interpreted by theory colleagues
    - Input measurements + correlations & uncertainties
  - Trade in some sensitivity
  - Acceptance...

Lessons learned - II

- Careful with acceptance effects
  - Ignored at our peril!
  - In STXS, fiducial regions only defined for production ➔ more sensitive to differences in acceptance across inclusive region
  - Ad-hoc corrections can be derived - these can have a large effect
  - ➔ think about defining fiducial regions in the decay
- Can be relevant in production too (e.g. using non-fid-region defining variables)
- Direct-to-EFT results don't have this caveat, but also not the same advantages as decoupled interpretation



Summary

- Showed results from ATLAS & CMS Higgs EFT fits
- Approach from combined measurements ➔ interpretation decoupled from analysis
    - Relatively recent effort in Higgs (O(few years)) ➔ already have interesting results and some lessons for the future