Precision Higgs boson measurements

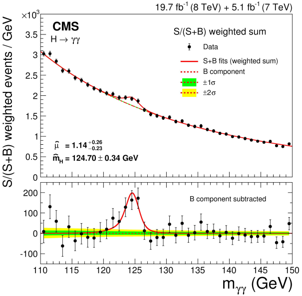
Andy Pilkington, University of Manchester

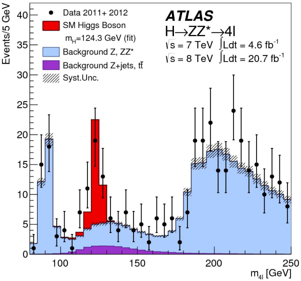
LHC Precision Programme, Benasque, Spain, 2nd October 2023

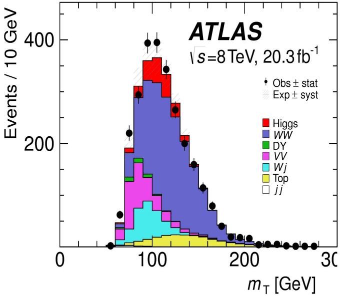
Outline:

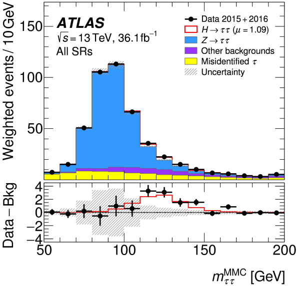
1) Higgs mass and width
2) Fiducial, differential and simplified-template cross sections
3) Spin-CP
4) HL-LHC outlook

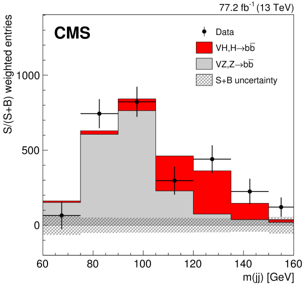
Higgs observations in different decay channels



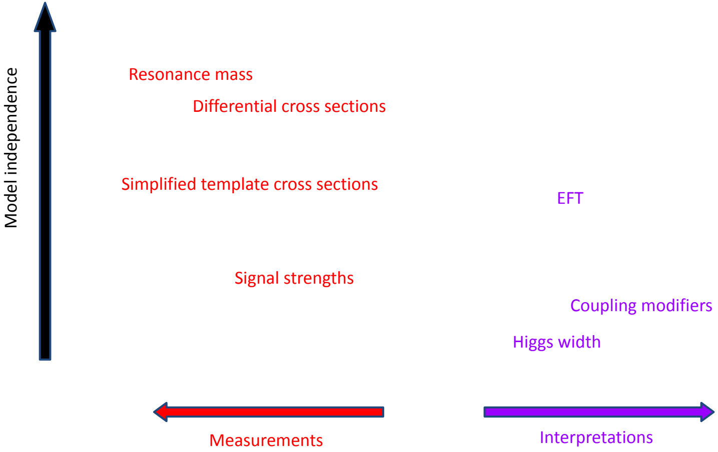




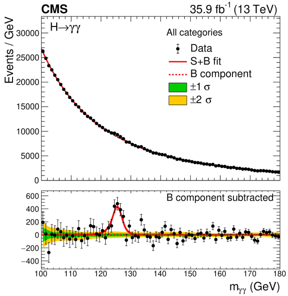




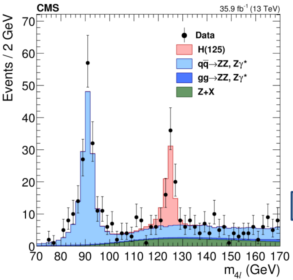
Measurements vs Interpretations



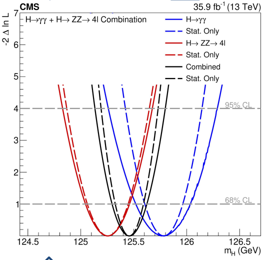
Higgs mass



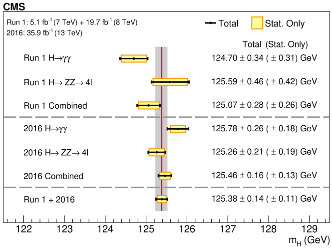
CMS
35.9 fb-1 (13 TeV)
H→γγ
All categories
Data
S+B fit
B component
±1 σ
±2 σ
B component subtracted
Events / GeV
mγγ (GeV)



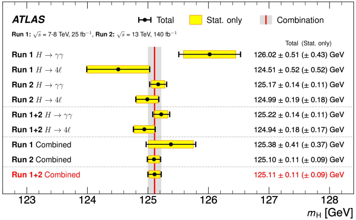
CMS
35.9 fb-1 (13 TeV)
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
Events / 2 GeV
m4l (GeV)



CMS
35.9 fb-1 (13 TeV)
H→γγ + H→ ZZ→ 4l Combination
H→γγ
Stat. Only
H→ ZZ→ 4l
Stat. Only
Combined
Stat. Only
95% CL
68% CL
-2 Δ ln L
mH (GeV)



CMS
Run 1: 5.1 fb-1 (7 TeV) + 19.7 fb-1 (8 TeV)
2016: 35.9 fb-1 (13 TeV)
Total
Stat. Only
Total (Stat. Only)
Run 1 H→γγ 124.70 ± 0.34 (± 0.31) GeV
Run 1 H→ ZZ→ 4l 125.59 ± 0.46 (± 0.42) GeV
Run 1 Combined 125.07 ± 0.28 (± 0.26) GeV
2016 H→γγ 125.78 ± 0.26 (± 0.18) GeV
2016 H→ ZZ→ 4l 125.26 ± 0.21 (± 0.19) GeV
2016 Combined 125.46 ± 0.16 (± 0.13) GeV
Run 1 + 2016 125.38 ± 0.14 (± 0.11) GeV
mH (GeV)



ATLAS
Total
Stat. only
Combination
Run 1: √s = 7-8 TeV, 25 fb−1, Run 2: √s = 13 TeV, 140 fb−1
Total (Stat. only)
Run 1 H → γγ 126.02 ± 0.51 (± 0.43) GeV
Run 1 H → 4ℓ 124.51 ± 0.52 (± 0.52) GeV
Run 2 H → γγ 125.17 ± 0.14 (± 0.11) GeV
Run 2 H → 4ℓ 124.99 ± 0.19 (± 0.18) GeV
Run 1+2 H → γγ 125.22 ± 0.14 (± 0.11) GeV
Run 1+2 H → 4ℓ 124.94 ± 0.18 (± 0.17) GeV
Run 1 Combined 125.38 ± 0.41 (± 0.37) GeV
Run 2 Combined 125.10 ± 0.11 (± 0.09) GeV
Run 1+2 Combined 125.11 ± 0.11 (± 0.09) GeV
mH [GeV]

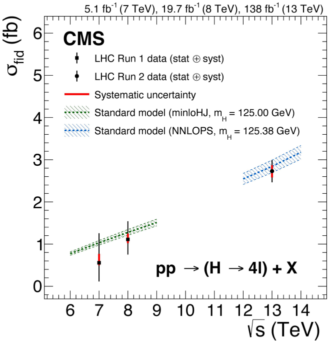
Fiducial and total cross section

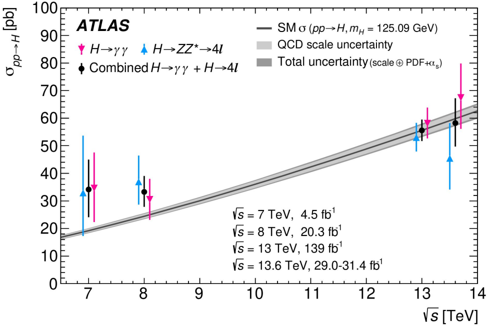
Fiducial cross sections extracted by correcting the observed signal yield for detector inefficiency and resolution, and accounting for the dataset size

$$N_S = \sigma_{\text{fid}} \times \mathcal{L} \times C_{\mathcal{F}}$$

Total cross sections then obtained by correcting for the branching ratio and fiducial acceptance

$$\sigma_{\text{fid}} = \sigma_{\text{tot}} \times \mathcal{B}_{\gamma\gamma} \times \mathcal{A}$$





Differential cross sections

Extend the detector-corrected measurements to differential spectra by unfolding.

Three approaches to unfolding taken by Higgs/SM/Top precision measurements:

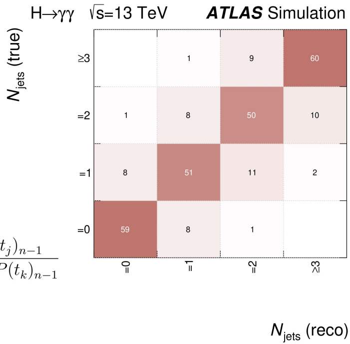
- Simple bin-by-bin corrections (similar to fiducial cross section measurement)
- Inverting the response matrix using the likelihood fit:

$$N_r^{(H)} = \frac{1}{C_r^{\text{fid}}} \left[\sum_t L \times (\sigma_t \times B_{\gamma\gamma}) \times R_{t,r} \right]$$

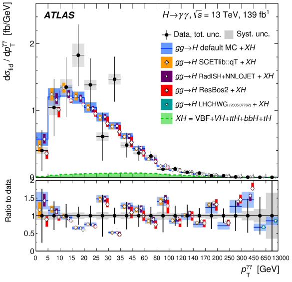
- Regularised unfolding (e.g. D'Agostini).

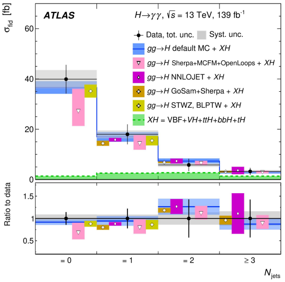
$$N(t_j) = \frac{1}{\varepsilon_j} \sum_i f_i \cdot N(r_i)_{\text{obs}} \cdot P(t_j|r_i)_{n_f}$$

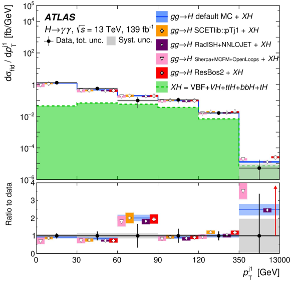
$$P(t_j|r_i)_n = \frac{P(r_i|t_j) \cdot P(t_j)_{n-1}}{\sum_k P(r_i|t_k) \cdot P(t_k)_{n-1}}$$

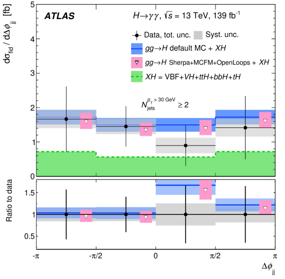


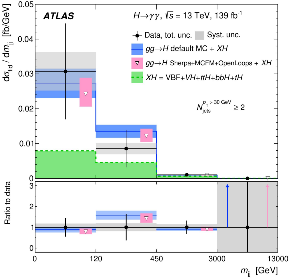
Differential cross sections







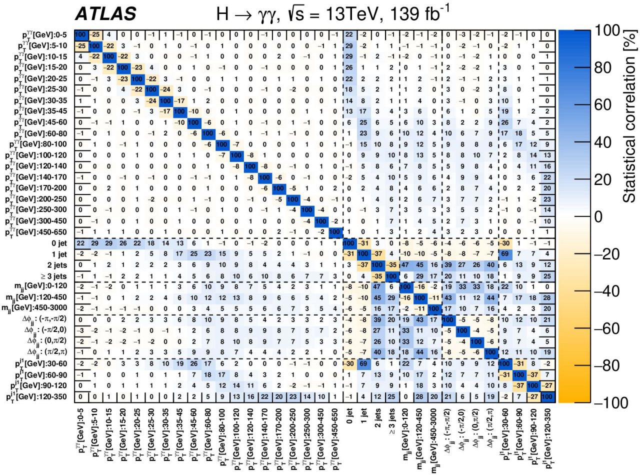




Example from $H\rightarrow\gamma\gamma$

Can measure any/all kinematic variables that experiment has sensitivity to.

Fiducial and differential cross sections



All measurements, and correlations between measurements, available in HEPDATA.

Rivet routine provided to allow comparison between theory and data

Differential cross sections: reinterpreted with EFT

- The differential cross sections (and their correlations) can be used for reinterpretations.

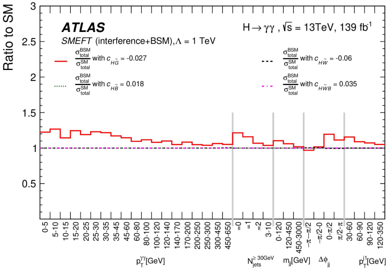
- EFT approach: augment the SM lagrangian with dimension-6 operators that induce anomalous Higgs boson interactions:

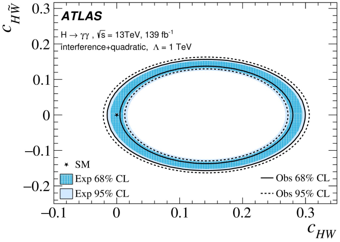
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)}$$

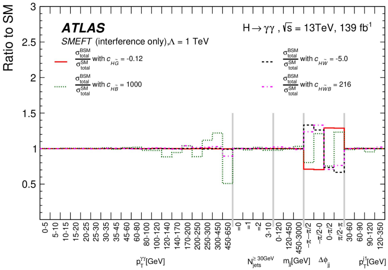
- The anomalous interactions lead to deviations in shape and normalisation of the squared scattering amplitude (and therefore the differential cross sections):

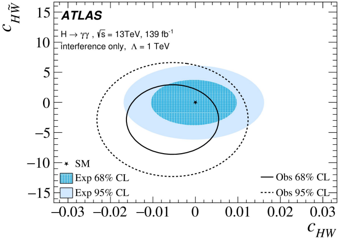
$$|\mathcal{M}_{\mathrm{BSM}}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{\mathrm{d6}}\} + |\mathcal{M}_{\mathrm{d6}}|^2$$

Differential cross sections: reinterpreted with EFT





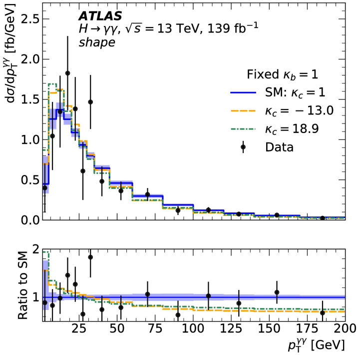


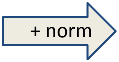


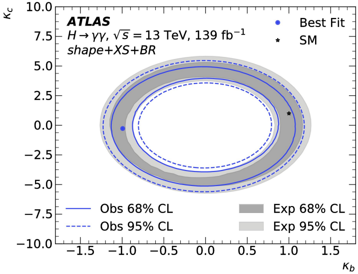
Differential cross sections: reinterpreted with K-framework

- Kappa-framework approach: modify the strength of the Higgs boson couplings, do not allow new Lorentz structures

$$\sigma \cdot \mathcal{B}\,(i \to H \to f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma_i^{\mathrm{SM}} \cdot \frac{\Gamma_f^{\mathrm{SM}}}{\Gamma_H(\kappa_i^2, \kappa_f^2)}$$



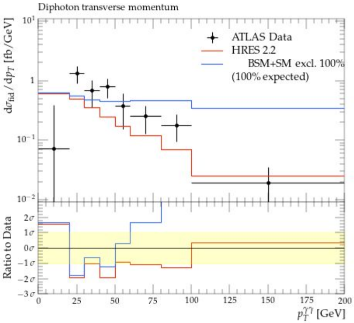




Differential cross sections: reinterpreted by anyone

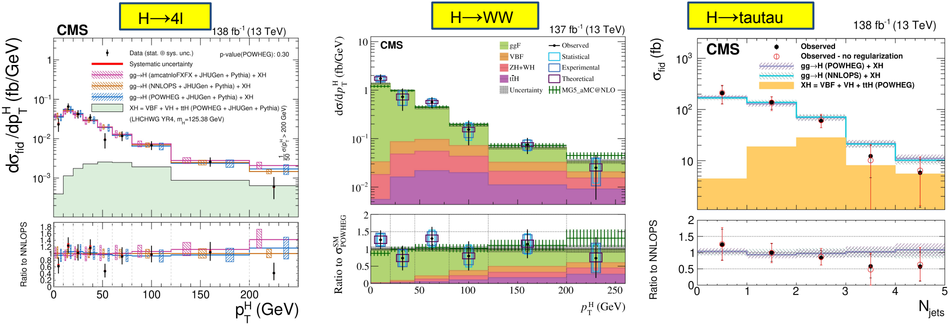
- Data and correlations typically made available in HEPDATA, analysis routines provided in Rivet.
- Allows fast/easy comparisons with any current or future theoretical model.

- Example below, showing exclusion of parameters in a custodial symmetry breaking model (https://arxiv.org/abs/2309.10027).



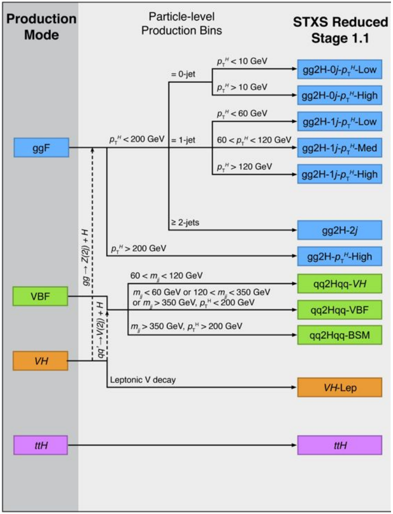
(plot made by Jon Butterworth in T2A of Barcelona airport whilst waiting for the Benasque Bus……)

Differential cross sections: many decay channels

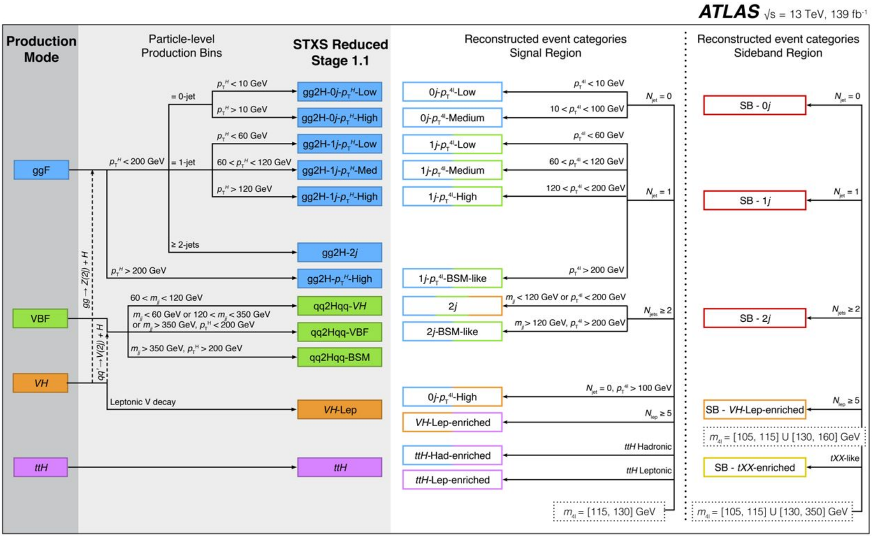


- Differential cross sections can be measured for any Higgs decay channel, within the fiducial volume used for the observation
    - Measured for the $\gamma\gamma$, ZZ and WW decay channels by both ATLAS and CMS
    - Also for the tau tau decay channel by CMS

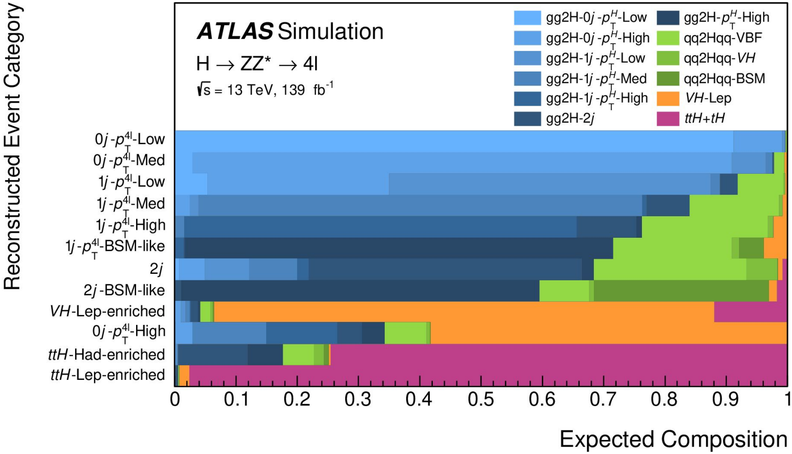
Simplified Template Cross Sections



Simplified Template Cross Sections



Simplified Template Cross Sections



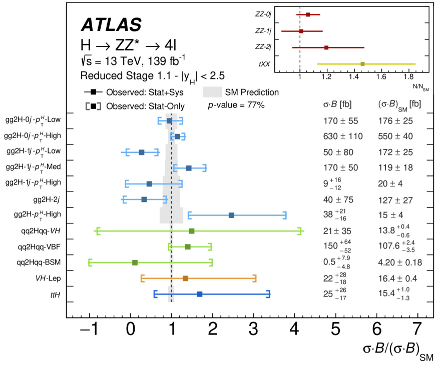
Simplified Template Cross Sections

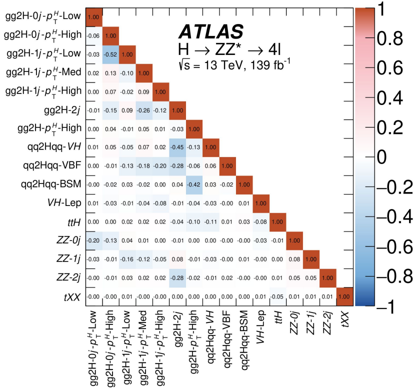
- Event yields in each *reconstuction-level event category* can be further subdivided into bins of a kinematic quantity that can distinguish between different production mechanisms.
  - e.g. use an dijet-invariant mass discriminant in the 2j category to separate gluon fusion and VBF contributions
  - more commonly: use multivariate discriminates (BDT or NN).

- Once background contributions have been determined for each event category, the *production bin cross sections* can be extracted with a likelihood fit:

$$\mathcal{L}(\vec{\sigma},\vec{\theta}) = \prod_{j}^{N_{\text{categories}}} \prod_{i}^{N_{\text{bins}}} P\left(N_{i,j} \mid L \cdot \vec{\sigma} \cdot \mathcal{B} \cdot \vec{A}_{i,j}(\vec{\theta}) + B_{i,j}(\vec{\theta})\right) \times \prod_{m}^{N_{\text{nuisance}}} C_m(\vec{\theta})$$

Simplified Template Cross Sections

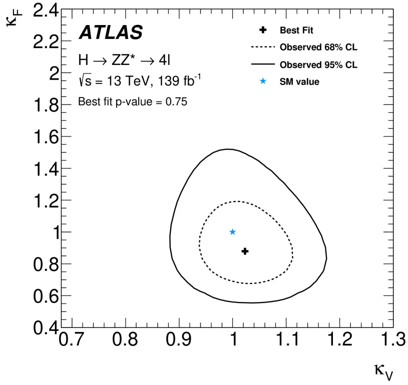


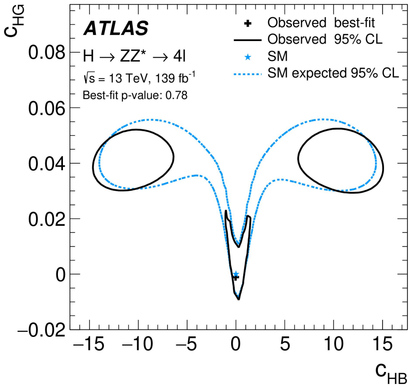


- For this channel, unsurprising that gluon fusion categories are measured most accurately.
- Large correlations between some production bin cross sections.

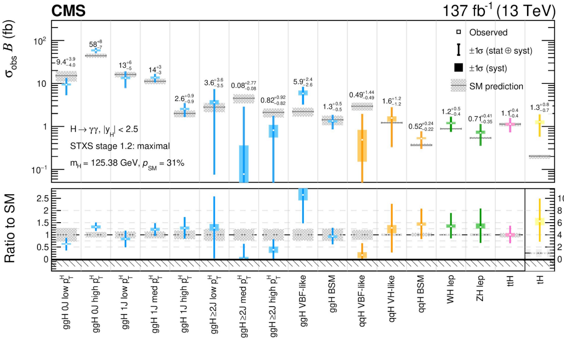
Simplified Template Cross Sections: reinterpreted

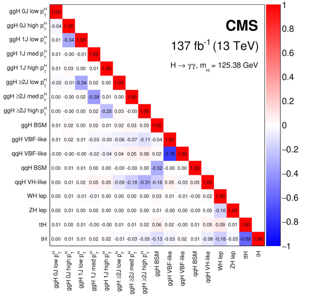
- The production bin cross sections and the associated correlations can be used for reinterpretations, again in EFT or coupling-modifier frameworks

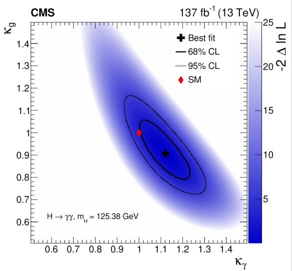




Simplified Template Cross Sections



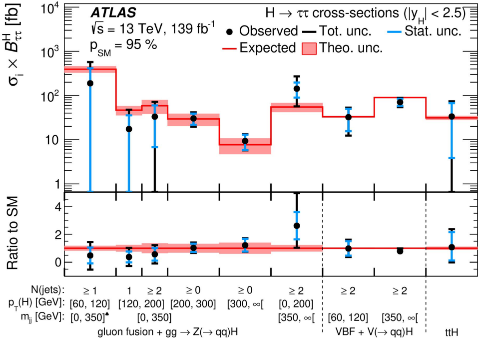


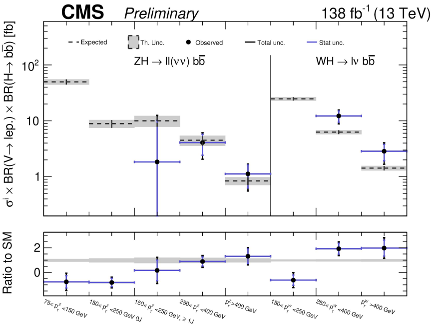


STXS implemented across many channels.

The ZZ, WW and $\gamma\gamma$ decay channels have similar characteristics; sensitivity mainly to gluon fusion categories.

Simplified Template Cross Sections





STXS now being rolled out across fermion decay channels (tau tau, bb).

—> Increased sensitivity to the VH and VBF production cross sections.

—> Generally stats-limited, but systematics affect the gluon fusion categories

Probing the CP-structure of Higgs interactions

CP-violation in the Higgs boson interactions manifest as asymmetries in appropriately constructed CP-sensitive observables.

Two types of CP-sensitive observable typically measured:

- angular observables that probe the production or decay of the Higgs boson.
- so-called ‘optimal observables’ constructed from matrix elements

Matrix-element-based observables target the interference between the CP-even SM amplitude and a CP-odd amplitude (typically estimated using dimension-6 EFT)

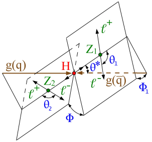
$$OO = \frac{2\Re\left(\mathcal{M}_{\mathrm{SM}}\mathcal{M}^{*}_{\mathrm{d6}}\right)}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

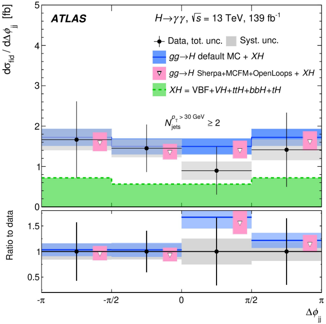
$$\mathcal{D}_{\mathrm{int}}\left(\vec{\Omega}\right) = \frac{\mathcal{P}_{\mathrm{int}}\left(\vec{\Omega}\right)}{2\sqrt{\mathcal{P}_{\mathrm{sig}}\left(\vec{\Omega}\right)\,\mathcal{P}_{\mathrm{alt}}\left(\vec{\Omega}\right)}}$$

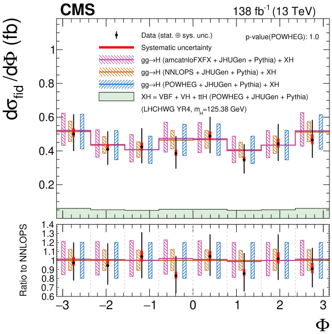
$$|\mathcal{M}_{\mathrm{BSM}}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^{*}_{\mathrm{d6}}\} + |\mathcal{M}_{\mathrm{d6}}|^2$$

CP-structure of Higgs interactions: angular observables

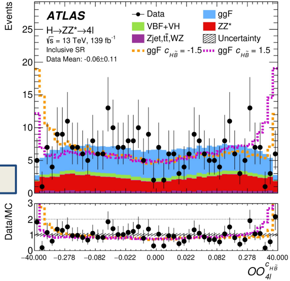
Angular observables routinely measured as part of the differential cross section programme.





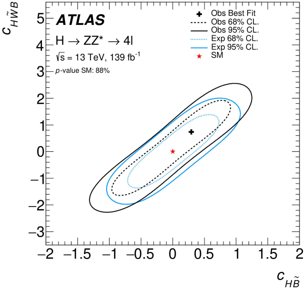


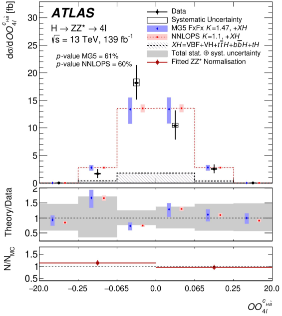
CP-structure of Higgs interactions: ME-based observables

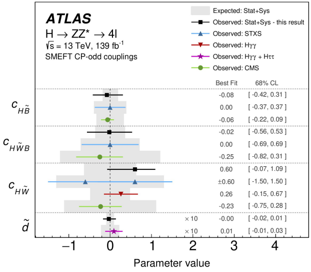


optimal observables exploit the full kinematic information in the scattering amplitude

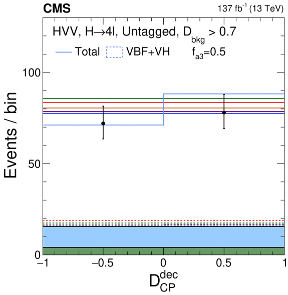
= increased sensitivity

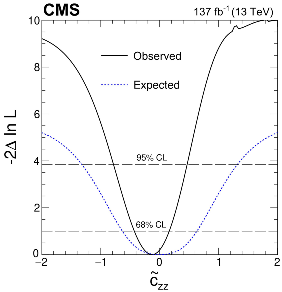


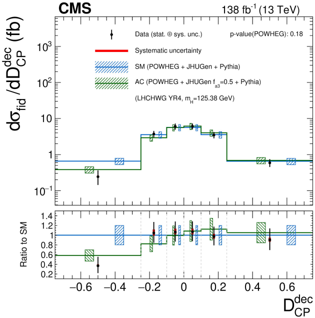




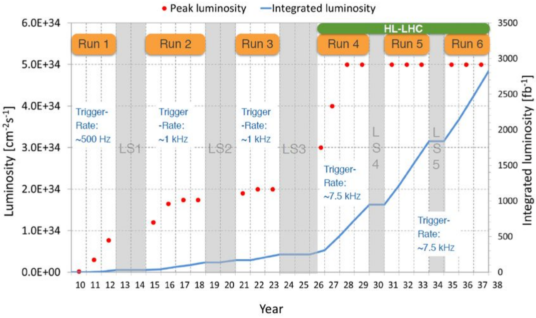
CP-structure of Higgs interactions: ME-based observables







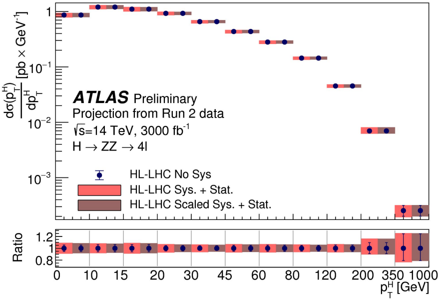
HL-LHC projections



Differential cross sections at HL-LHC

Current approach with more data

- Inclusive measurements become limited by systematics
- Increased statistical precision in more extreme phase space regions



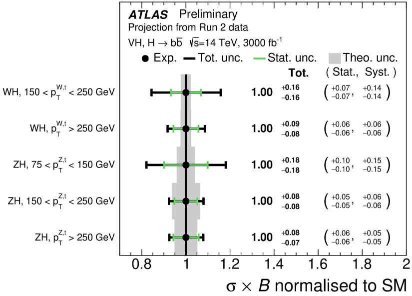
New measurements possible

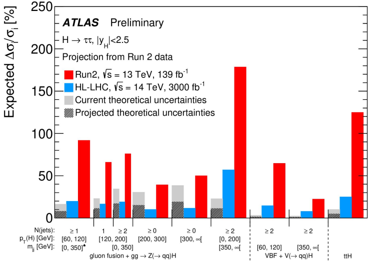
- Polarisation of the vector boson in VH production?
- ttH differential cross sections?
- Angular moments/coefficients?
- CP-sensitive observables for different decay channels and production mechanisms

Simplified Template Cross Sections at HL-LHC

Similar outlook as to differential cross sections:

- Current production bin measurements would become systematics dominated.
- Likely to further split the production bins for finer granularity

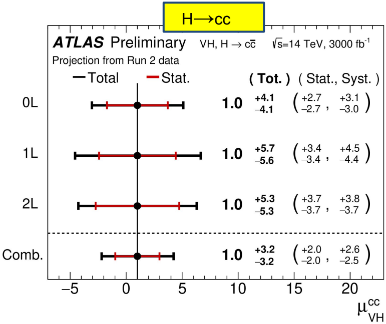


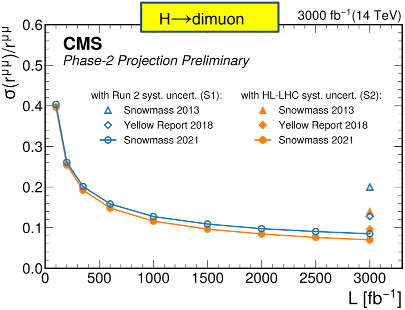


Second-generation couplings at HL-LHC

With more data, open up new decay channels

Improvements needed if H→cc is going to be possible





Thoughts…..

In the 11 years since the Higgs discovery, we have started to enter the precision realm:

- Moved away from signal strengths to more model-independent measurements
- Unfolded measurements for optimised observables targeting specific BSM scenarios (e.g. CPV).
- We will gain in sensitivity for all existing measurements, from the luminosity increase. Some measurements start to become systematics dominated.

A good time to evaluate if we are on the right track for HL-LHC:

- Do we need to measure both STXS and differential cross sections?
- Have we missed observables that we should have measured?
- Can we improve charm-tagging to bring observation and precision to $H \to cc$?