IMPERIAL

SMEFT, Anomalous Couplings and CPV results from CMS and ATLAS

Daniel Winterbottom
d.winterbottom15@imperial.ac.uk

Overview

- **SMEFT** a framework adding higher-dimensional operators to capture possible BSM effects from heavy new physics
- **Anomalous Couplings:** express an interaction amplitude as a sum of all Lorentz allowed tensor structures, each multiplied by a coefficient that defines the corresponding coupling
- Both approaches translate LHC precision measurements into model-independent constraints on new physics
- CP-violating terms in SMEFT and ACs provide clean handles to search for sources of new CP violation (CPV)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d}^{N} \sum_{j \in \mathcal{O}^{(d)}} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{O}_j^{(d)}$$

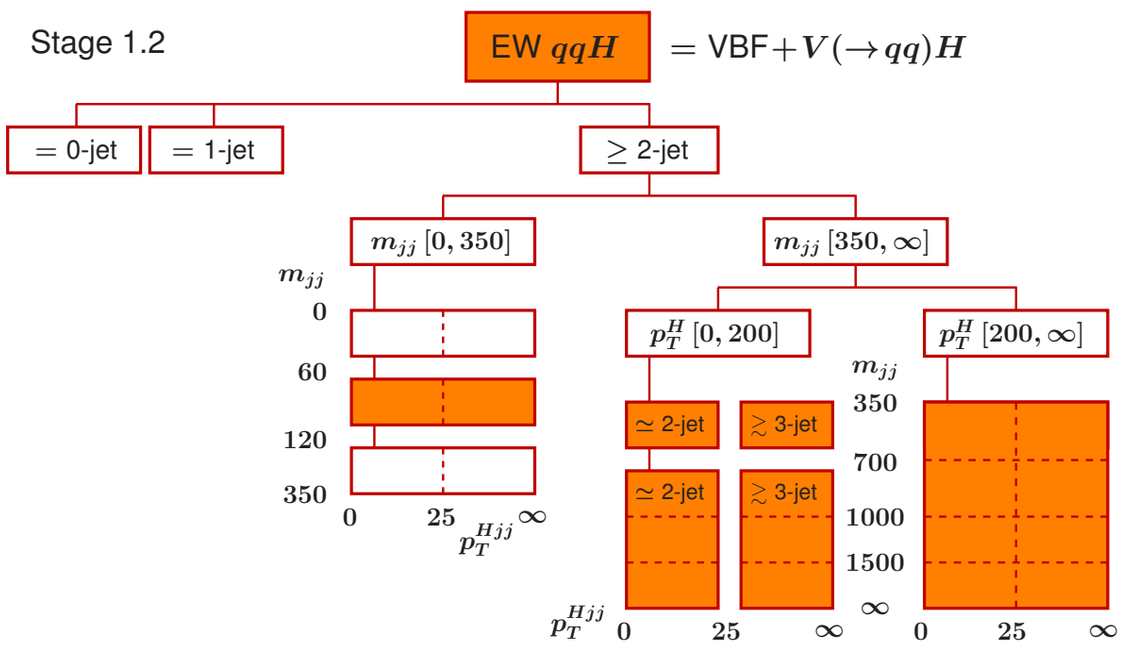
$$\mathcal{A}(\text{HV}_1\text{V}_2) \sim \left[a_1^{\text{VV}} + \frac{\kappa_1^{\text{VV}} q_{V1}^2 + \kappa_2^{\text{VV}} q_{\text{V2}}^2}{\left(\Lambda_1^{\text{VV}}\right)^2} \right] m_{\text{V1}}^2 \epsilon_{\text{V1}}^* \epsilon_{\text{V2}}^* + a_2^{\text{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\text{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

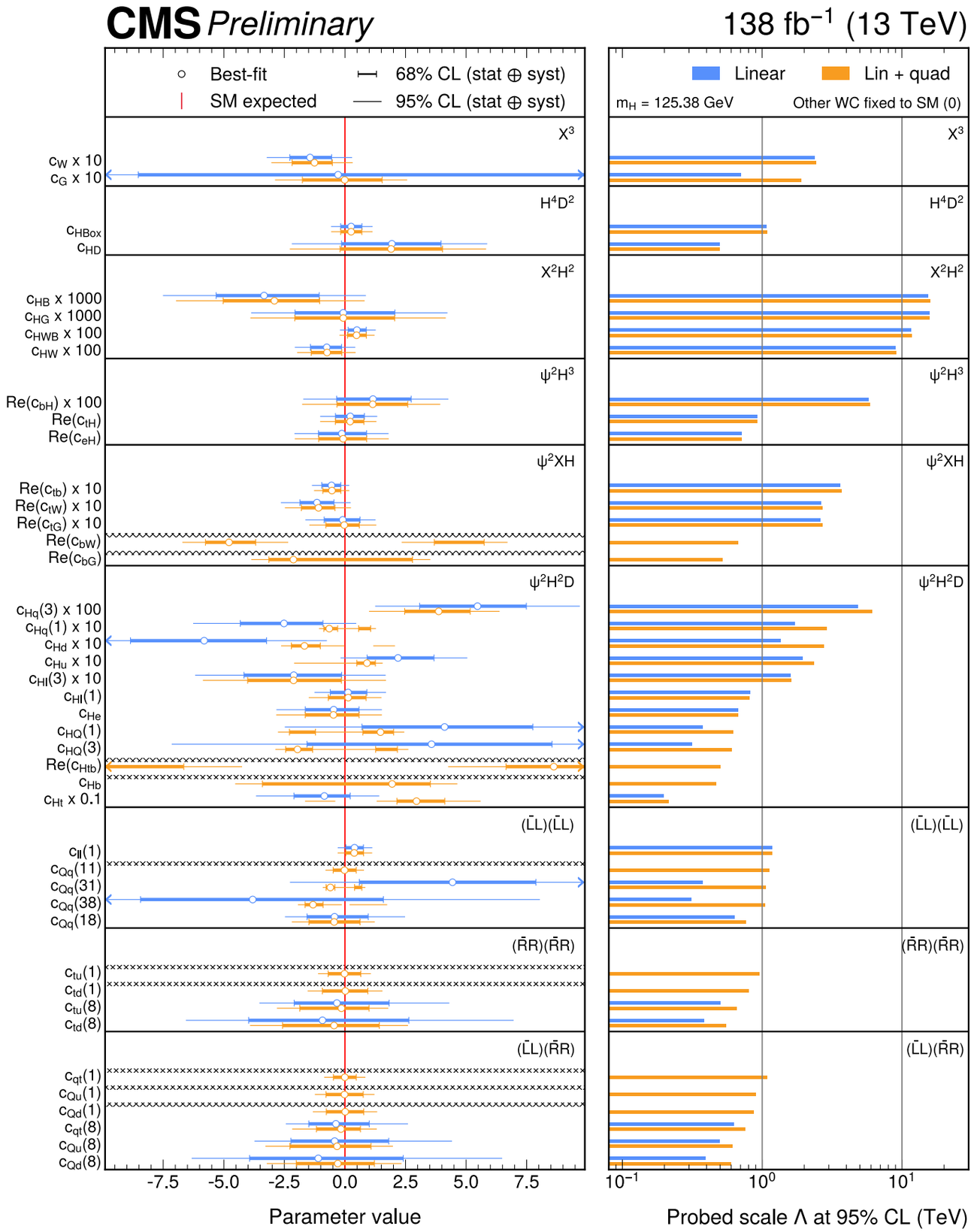
STXS

- Reinterpret STXS cross-section measurements to set limits on SMEFT

- E.g CMS Run-2 Higgs combination: CMS-PAS-HIG-21-018

- Limitations: no sensitivity to CPV operators for stage 1.2

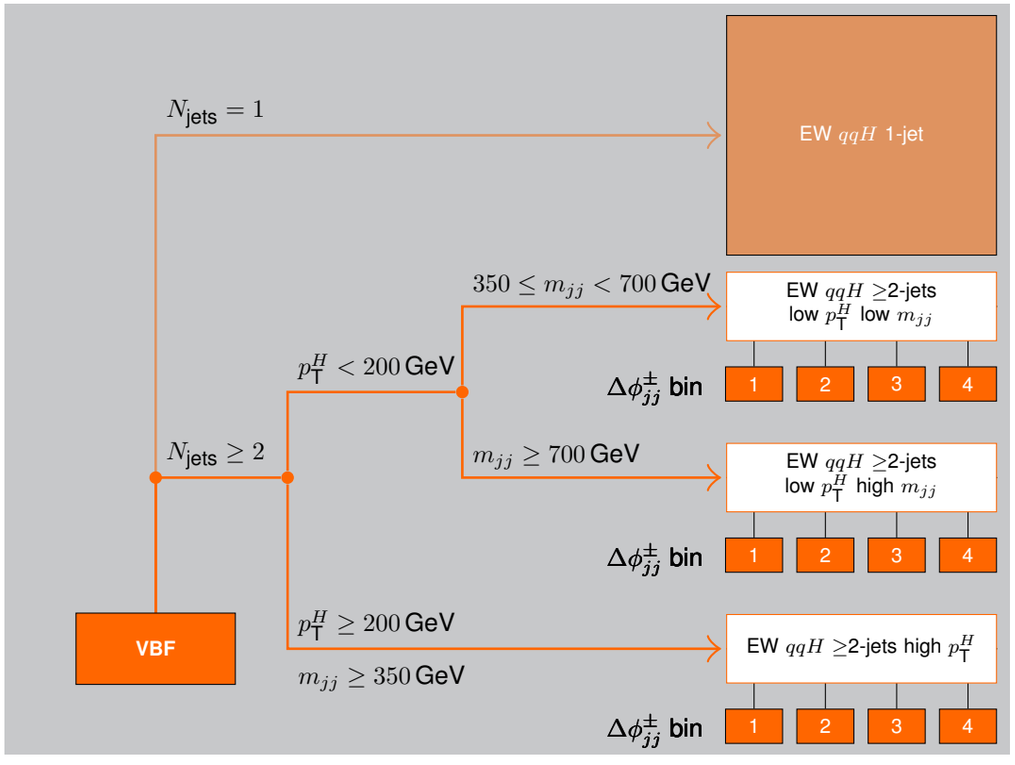


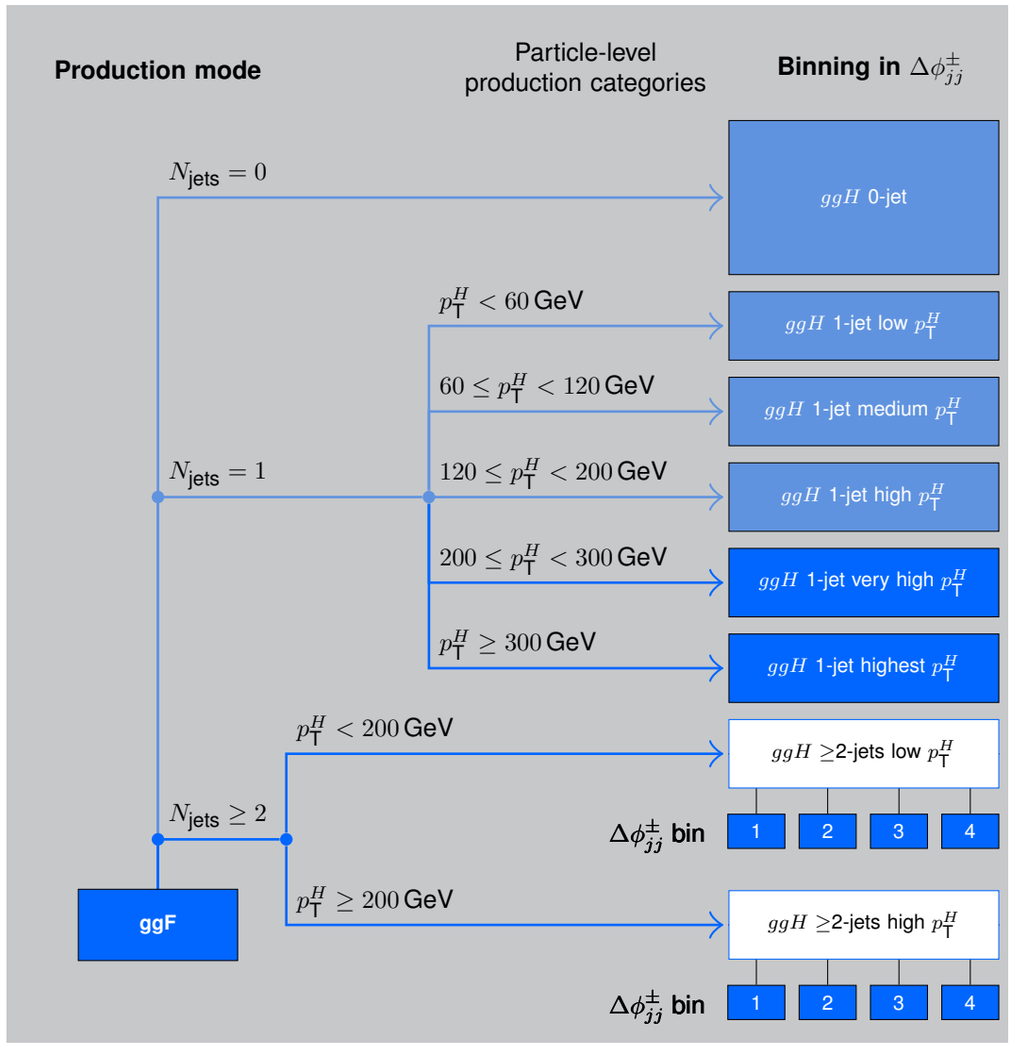


ATLAS H→WW CPV measurements

- ATLAS-HIGP-2024-07

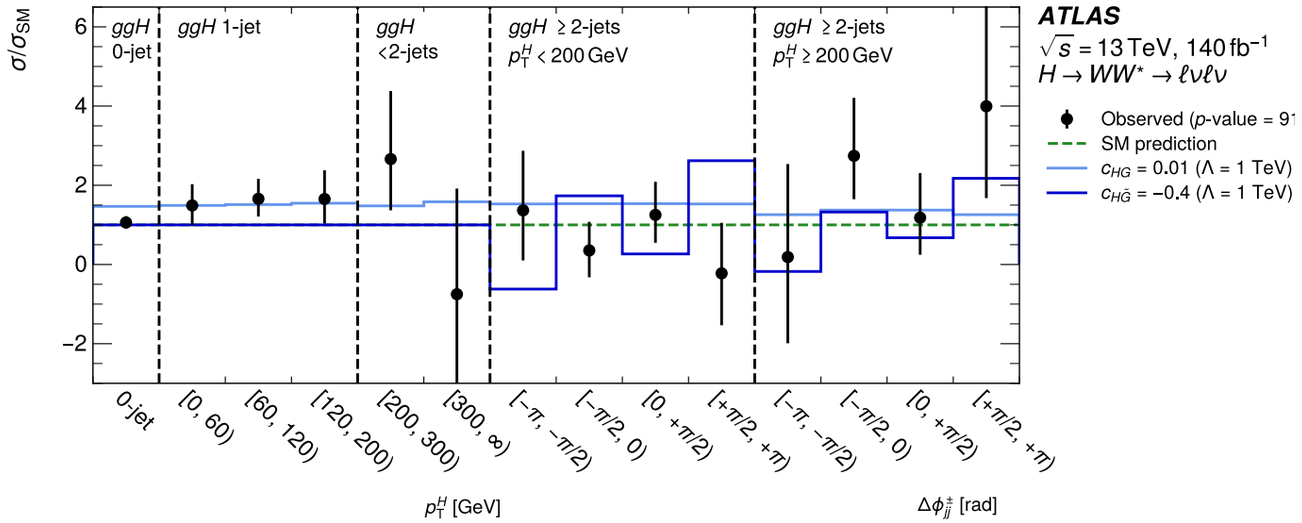
- STXS binning adjusted with introduction of additional $\Delta\phi_{jj}$ bins to give sensitivity to CPV (+ merging of m_{jj} bins)

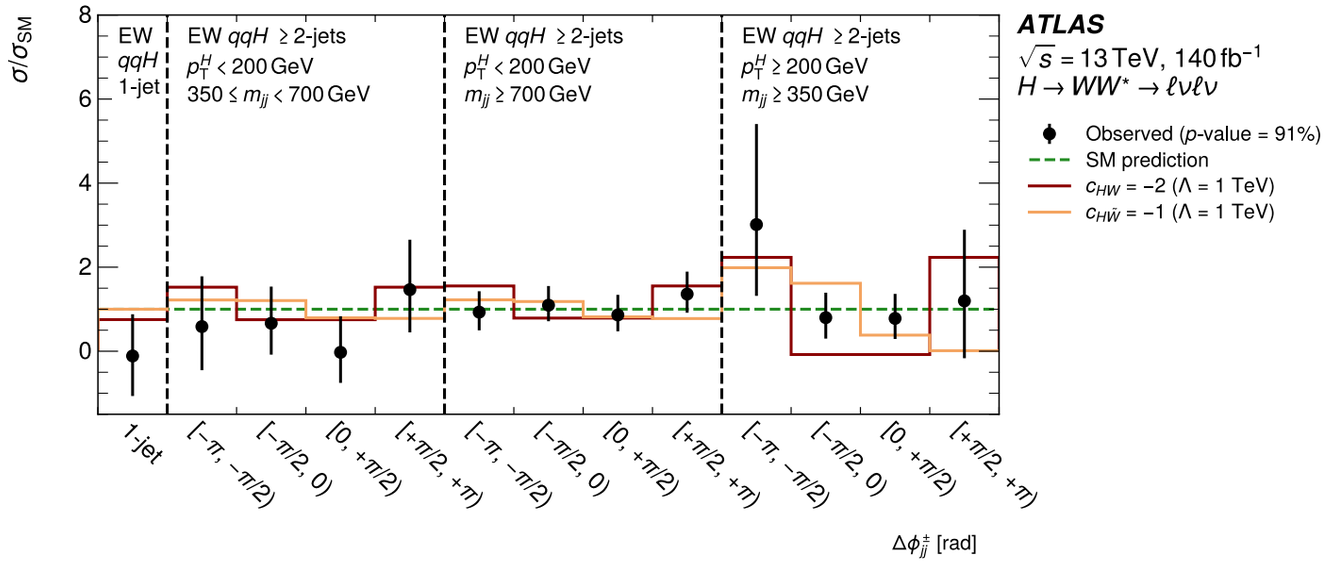


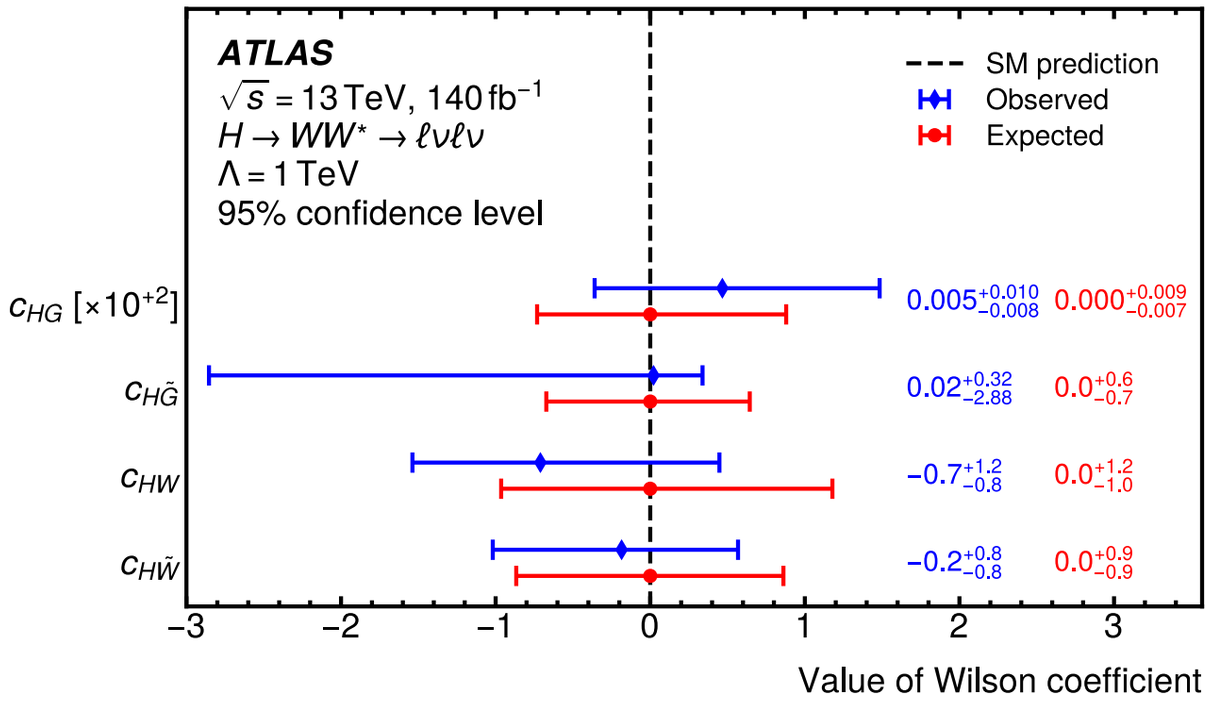


ATLAS H→WW CPV measurements

- Simultaneous fit to determine c_{HW}, $c_{\mathrm{H\tilde{W}}}$, c_{HG}, $c_{\mathrm{H\tilde{G}}}$
  - Considering only the linear terms





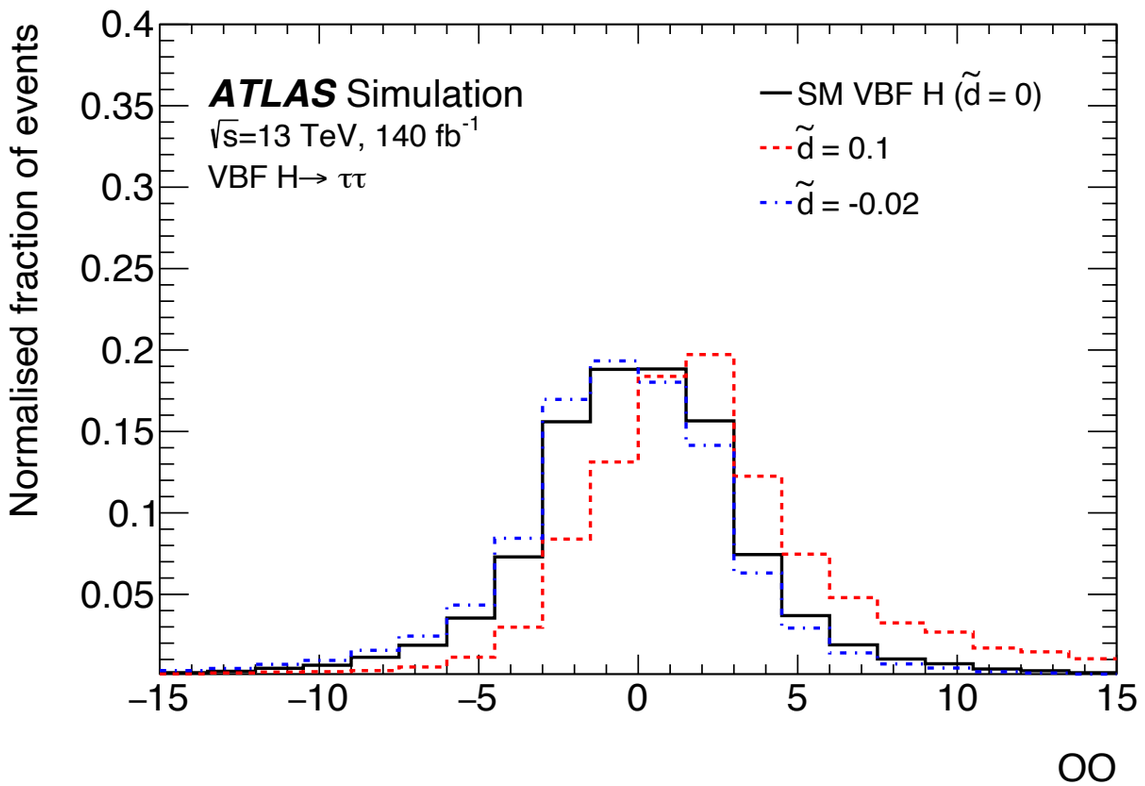


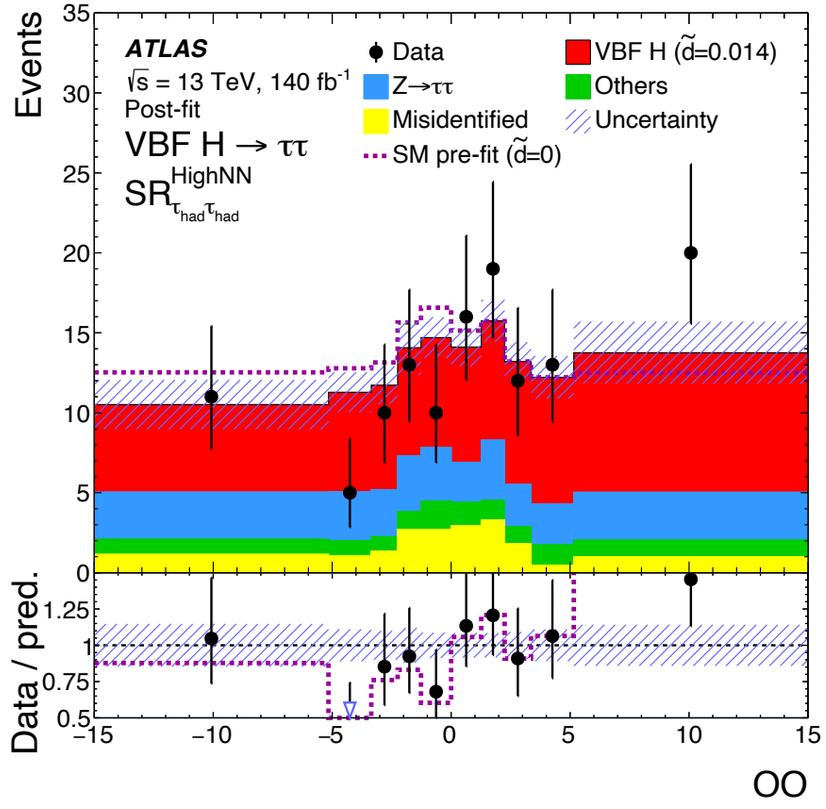
ATLAS VBF CP measurements in H→ττ

- Measurements of the CPV for VBF process in H→ττ channel ATLAS-HIGP-2024-09

- NN to separate signal from background, then fit optimal-observable to extract CP information

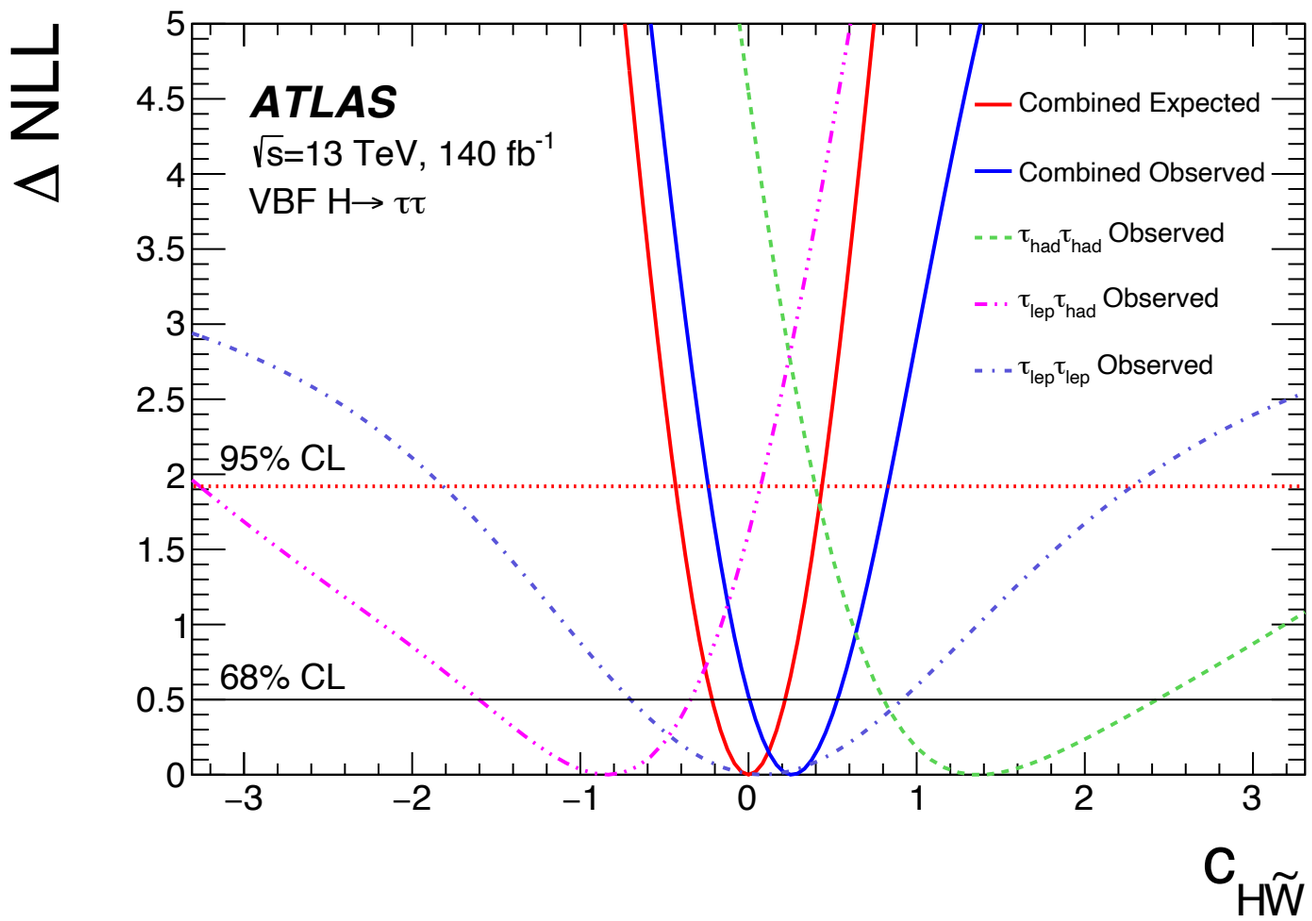
$$OO = \frac{2\Re(\mathcal{M}^{*}_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$





ATLAS VBF CP measurements in H→ττ

- SMEFT results in Warsaw basis measuring $c_{H\tilde{W}}$ only (as sensitivity to other parameters 10-20 times worse)

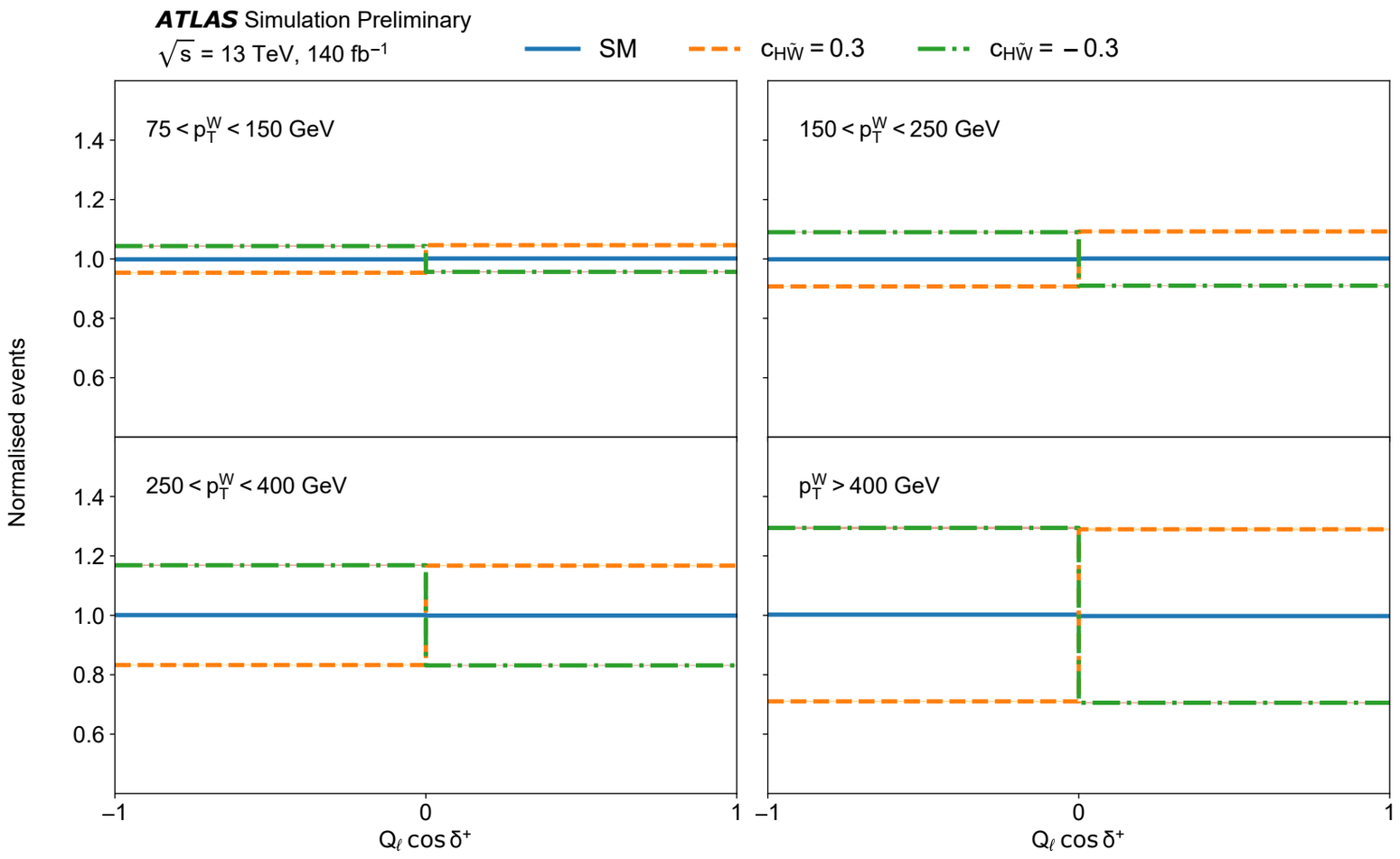


ATLAS CPV measurements using WH production

- Search for CPV using WH production mode (H→bb) ATL-PHYS-PUB-2025-022

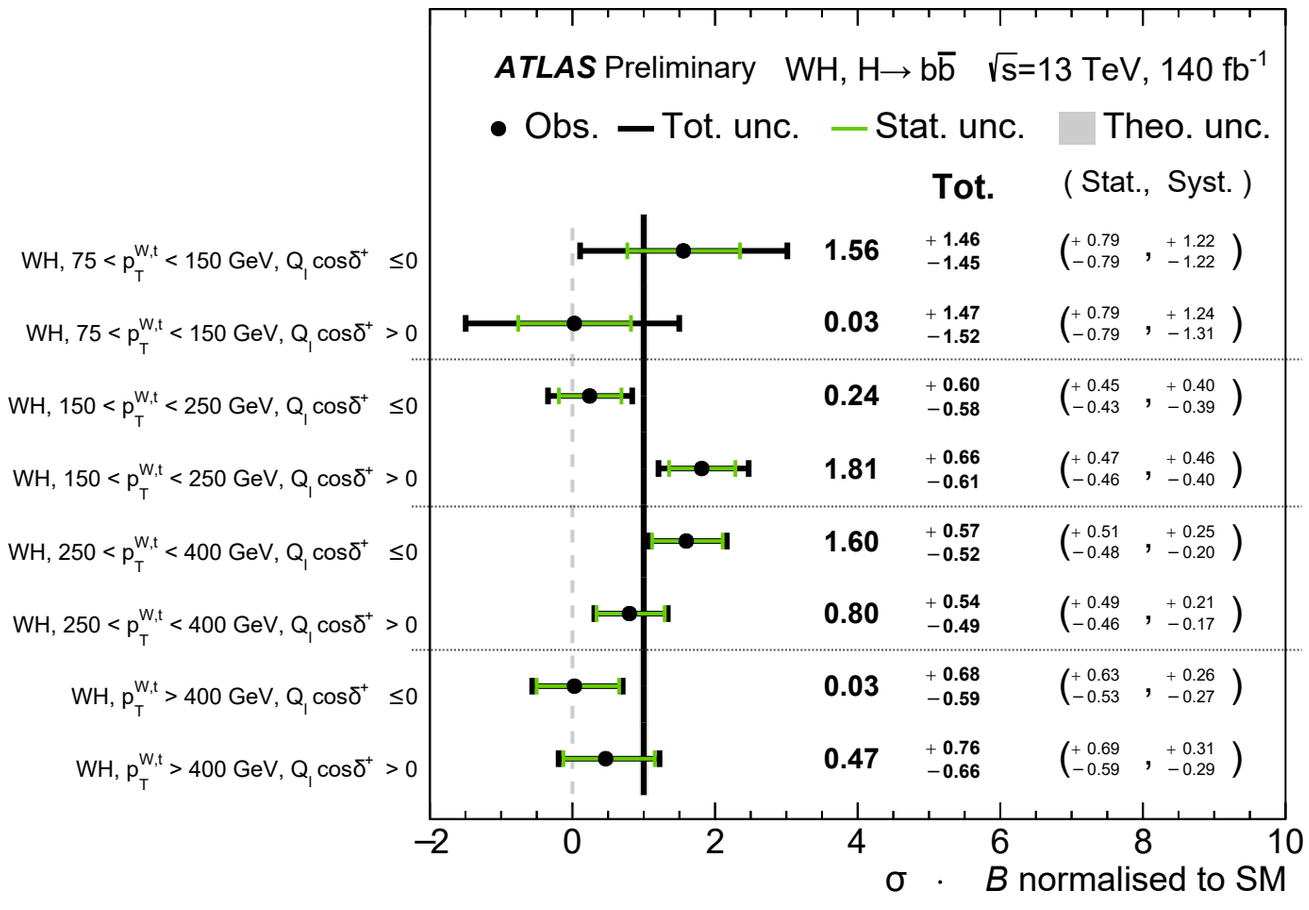
- STXS measurements (W p_T splitting) with additional splitting using using dedicated angular observable: $Q_{l\cos\delta+}$

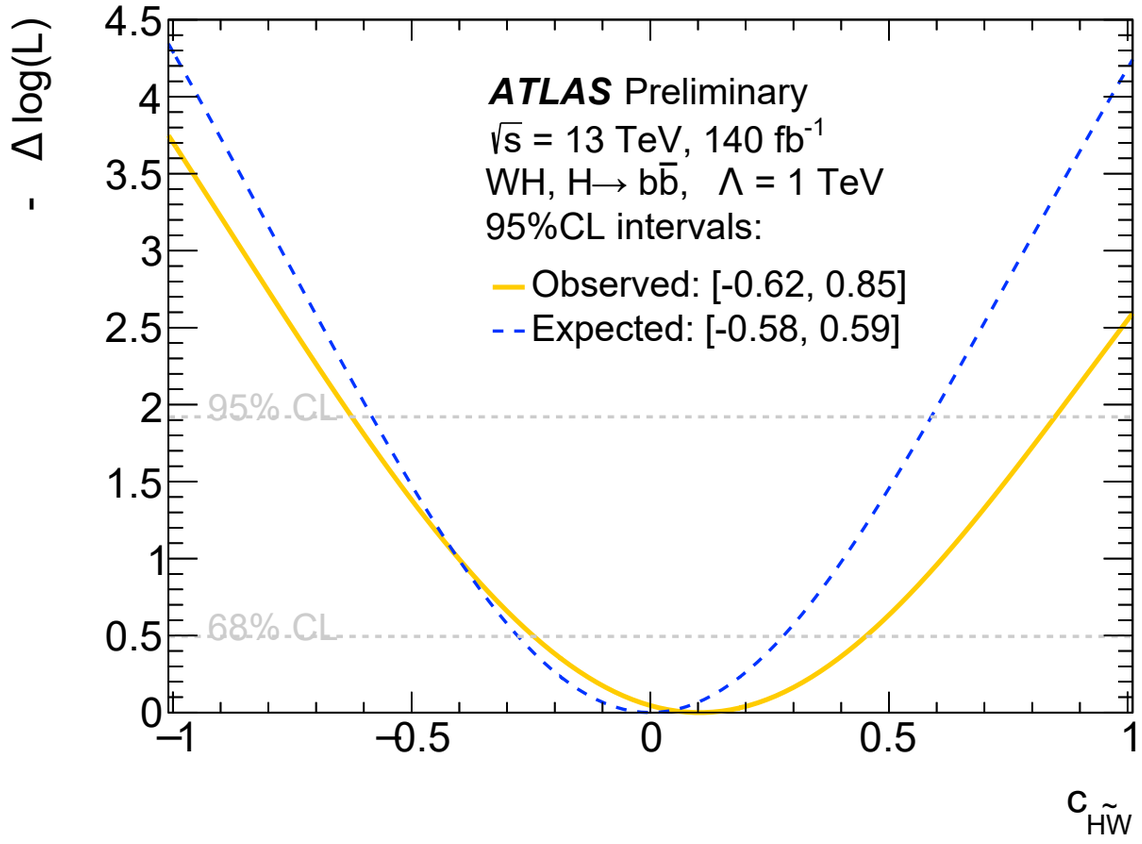
$$\cos\delta^{+} = \frac{\mathbf{p}_{\ell}^{(W)} \cdot (\mathbf{p}_H \times \mathbf{p}_W)}{|\mathbf{p}_{\ell}^{(W)}| \cdot |\mathbf{p}_H \times \mathbf{p}_W|}$$



ATLAS CPV measurements using WH production

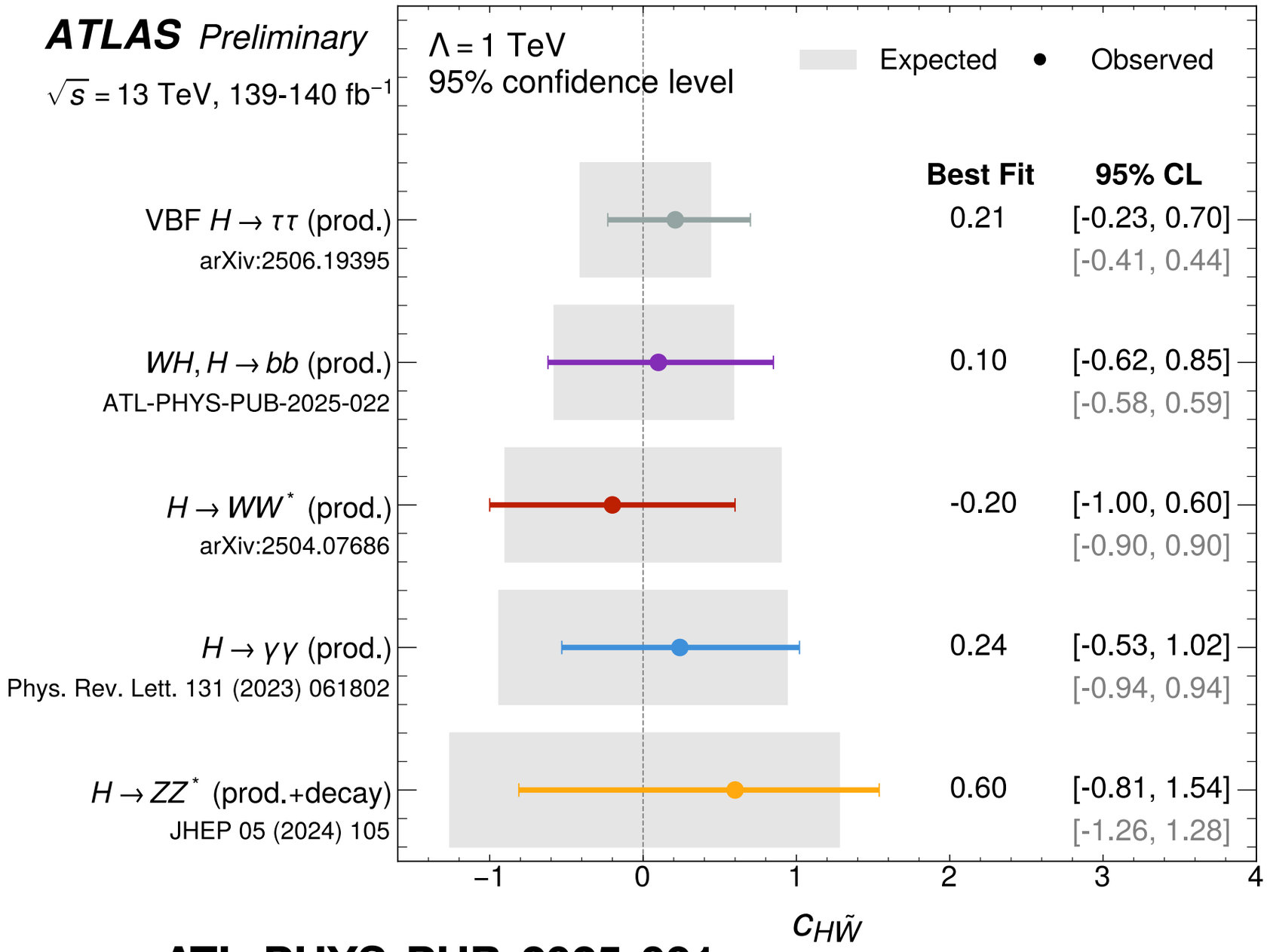
- Cross-section measurement reinterpreted to set limits on $c_{\mathrm{H\tilde{W}}}$
  - Considering only the linear term
- Separate signal scalings parameters are used for each p_T region to ensure analysis is only sensitive to CP-odd effects





Comparison between ATLAS measurements

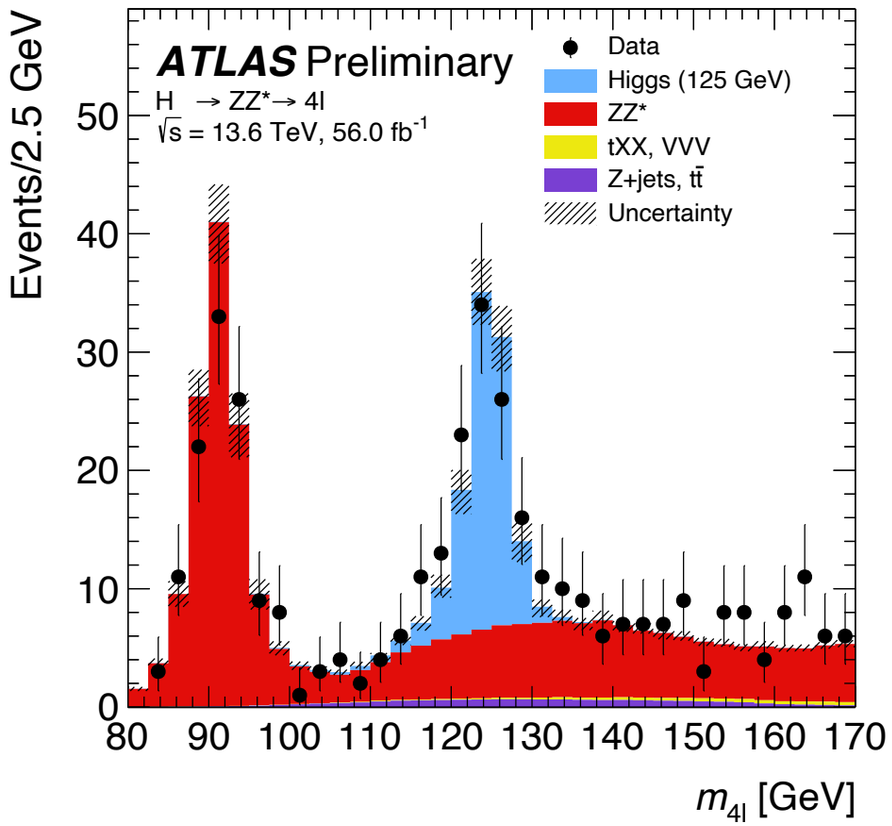
- Comparison new ATLAS measurements with previous results in H→ɣɣ and H→ZZ channels

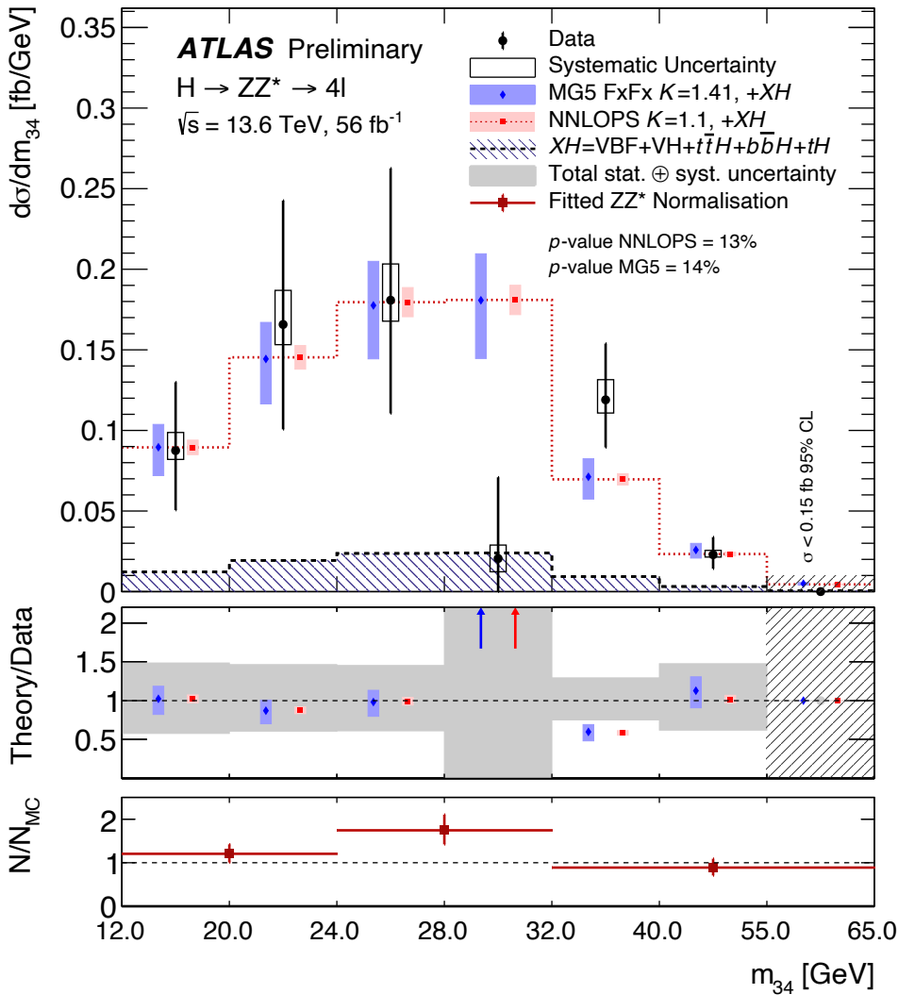


ATL-PHYS-PUB-2025-031

ATLAS H→ZZ SMEFT measurements at 13.6 TeV

- SMEFT measurements using H→ZZ channel at 13.6 TeV ATLAS-CONF-2025-002
- Differential measurements of cross-sections are performed for several variables
- Differential measurements for the m_{34} observable (off-shell Z mass) interpreted in EFT framework

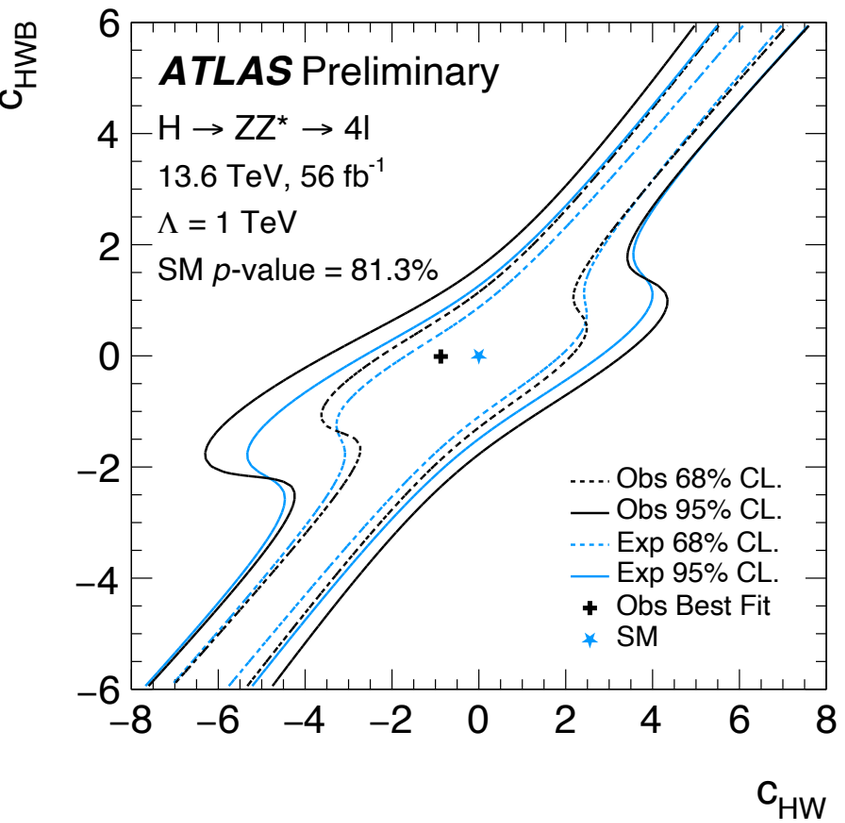


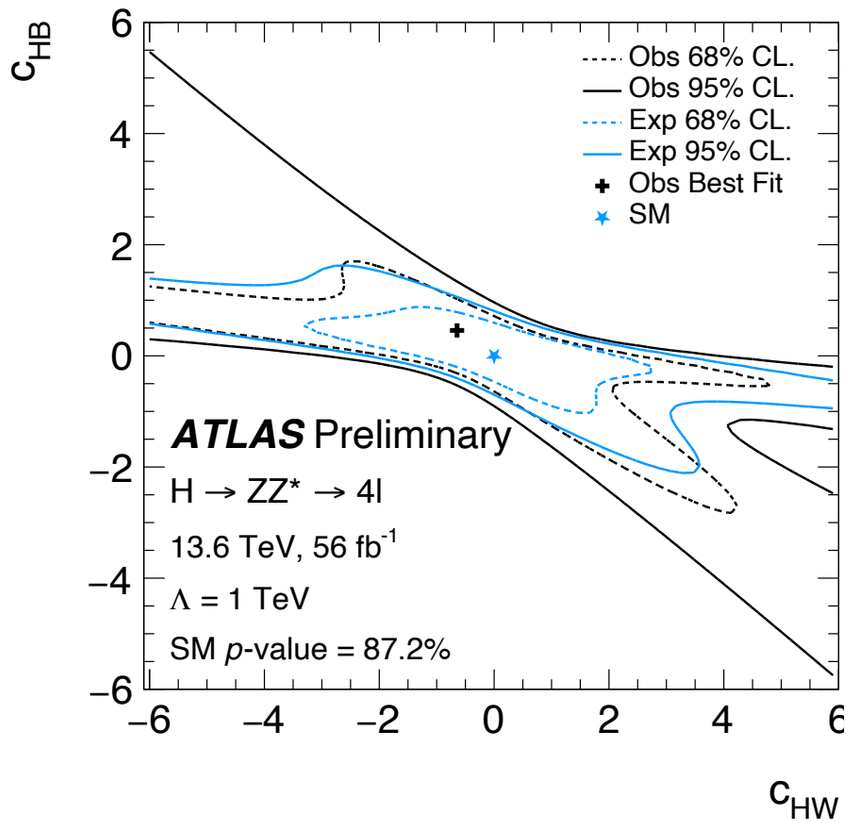


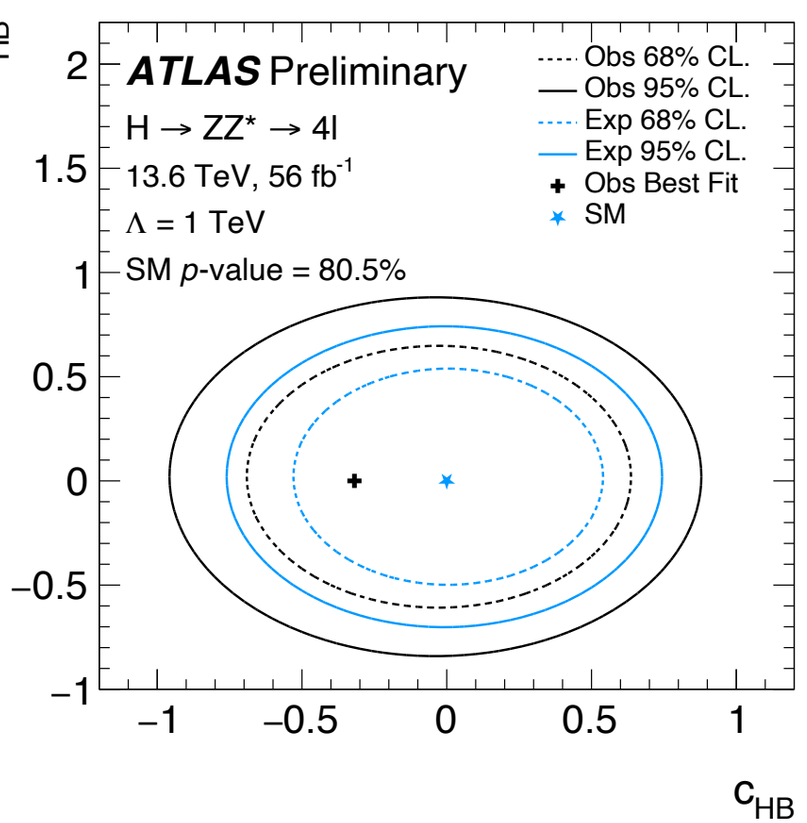
ATLAS H→ZZ SMEFT measurements at 13.6 TeV

- Coefficients measured: c_{HWB}, c_{HW}, c_{HB} [+ corresponding CP odd terms]

- Note that m_{34} observable cannot distinguish CP-even and CP-odd



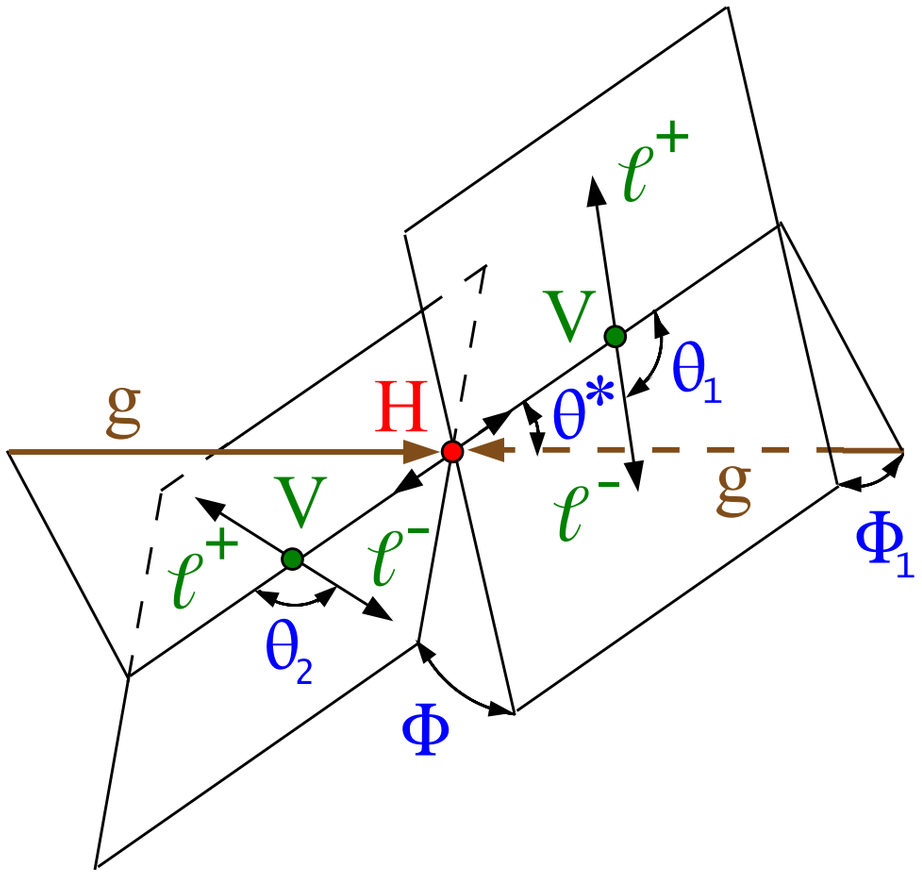


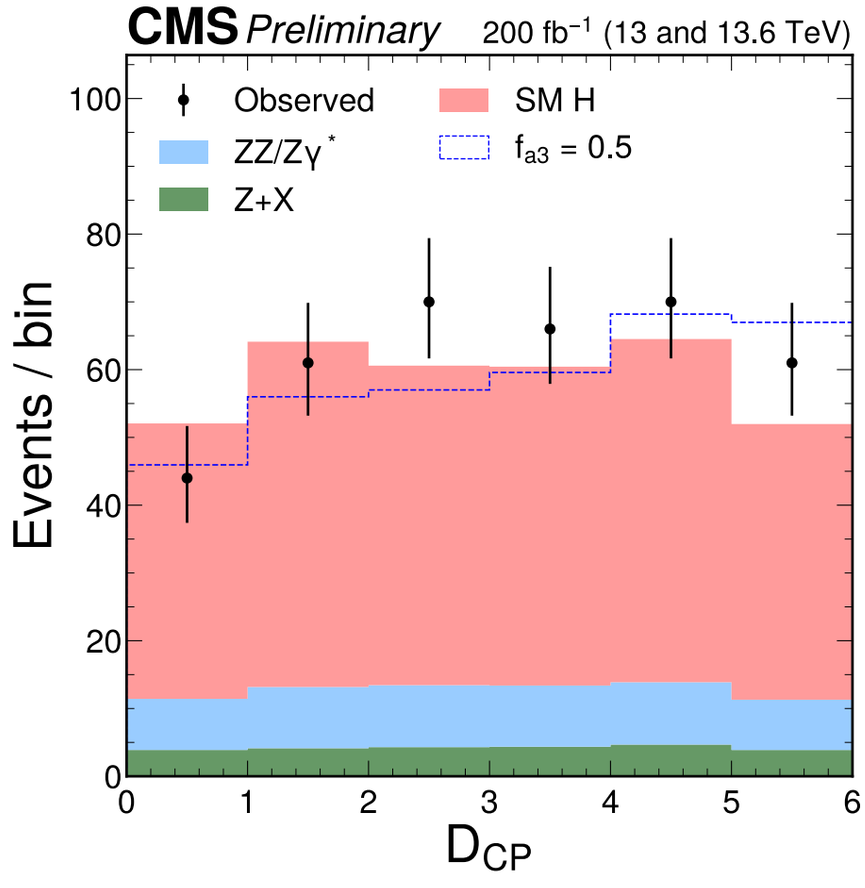


CMS CPV and anomalous couplings using H→ZZ

- Measurements of anomalous couplings and CPV using H→ZZ channel using 13 and 13.6 TeV data: CMS-PAS-HIG-25-011

- Matrix elements used to construct optimal observables using MELA





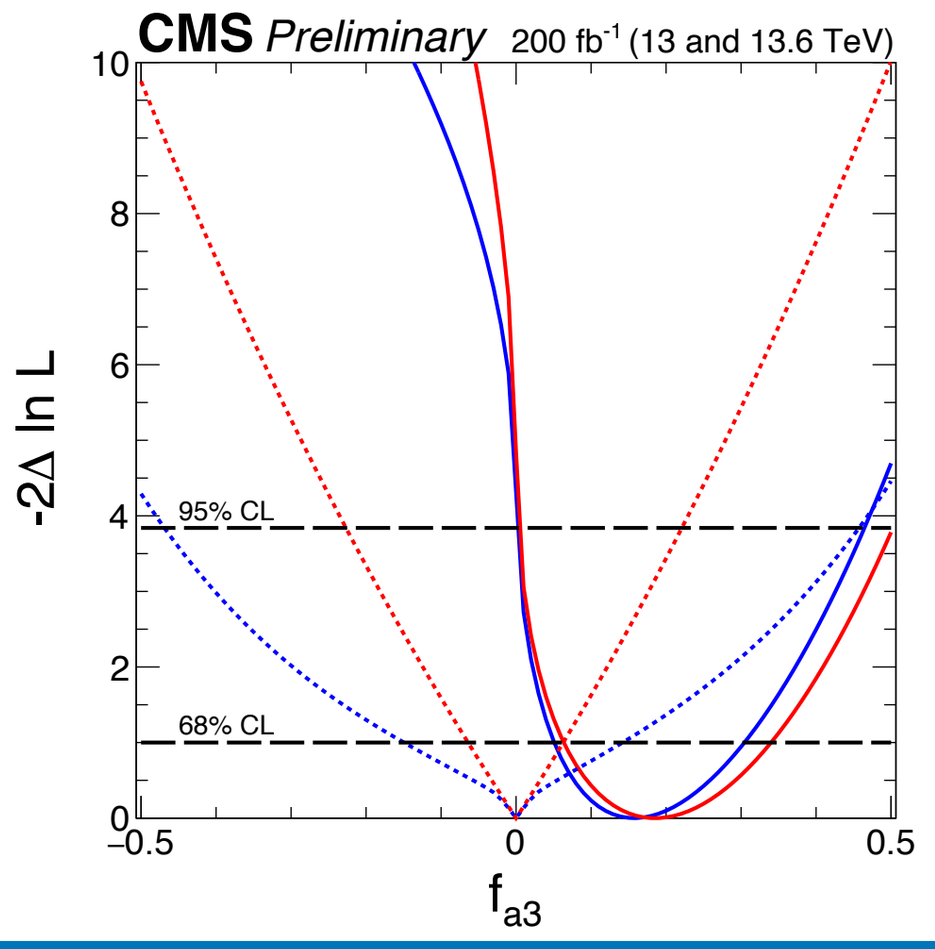
CMS CPV and anomalous couplings using H→ZZ

$$\mathcal{A}(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q^2_{V1} + \kappa_2^{\mathrm{VV}} q^2_{\mathrm{V2}}}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m^2_{\mathrm{V1}} \epsilon^*_{\mathrm{V1}} \epsilon^*_{\mathrm{V2}} + a_2^{\mathrm{VV}} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2)\mu\nu},$$

- SM tree level (+ kinematic terms), CP-even Dim-6, CP-odd Dim-6

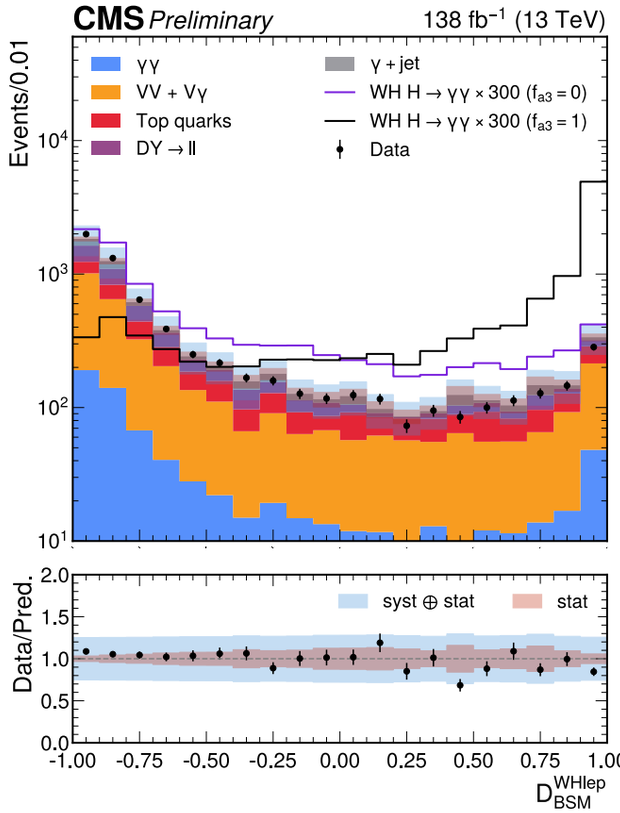
- Parameterise using fractional XS:

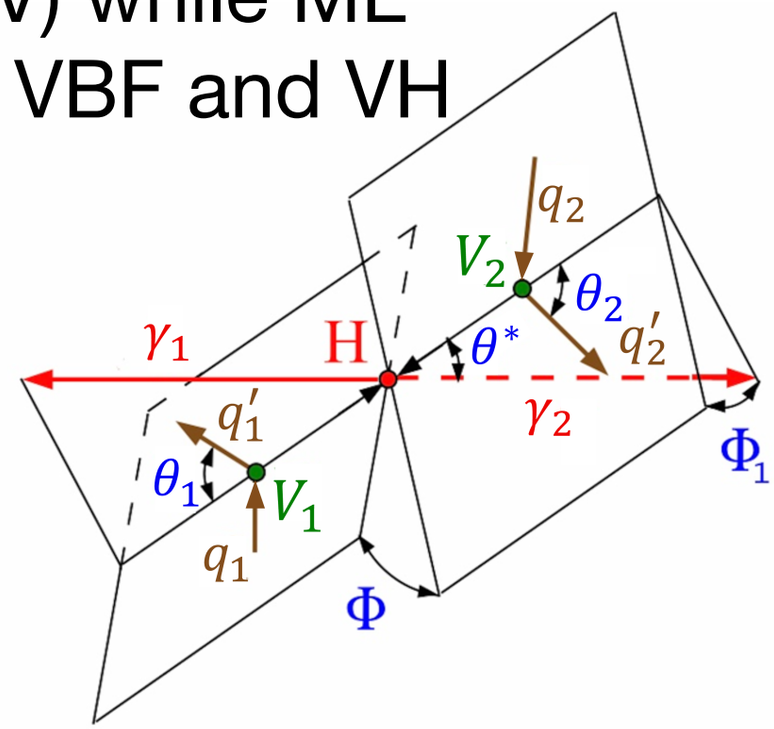
$$f_{ai} = \frac{|c_i'|^2 \sigma_i / \sigma_0}{1 + \sum_j |c_j'|^2 \sigma_j / \sigma_0} \mathrm{sign}\,(c_i')$$

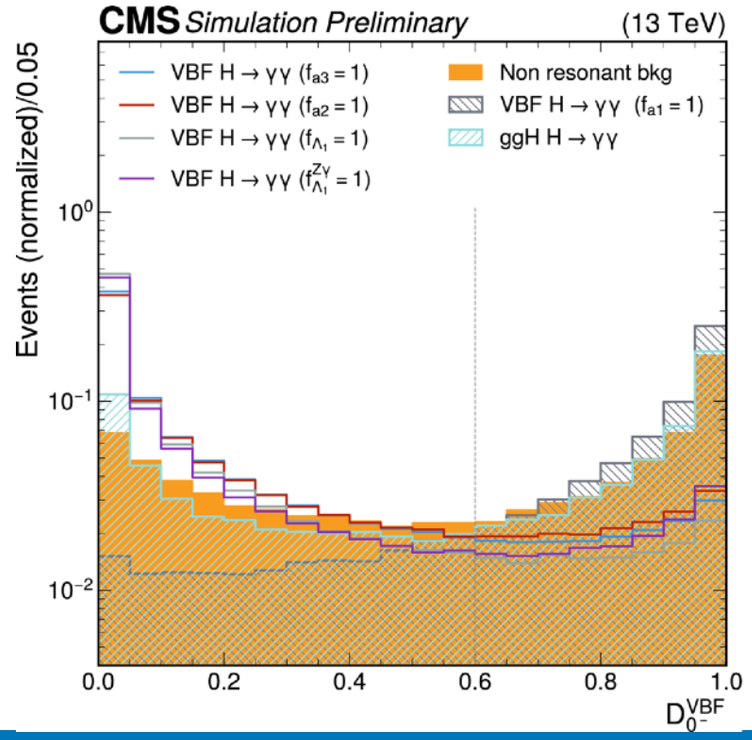


CMS CPV and anomalous couplings using H→γγ

- Measurements of anomalous couplings including CPV couplings using the H→γγ channel CMS-PAS-HIG-24-006
- Explores ACs impacting VBF, ggH (+ 2j), and VH production vertices
- Matrix element variables from MELA used for ggH (and VBF CPV) while ML observables used for VBF and VH



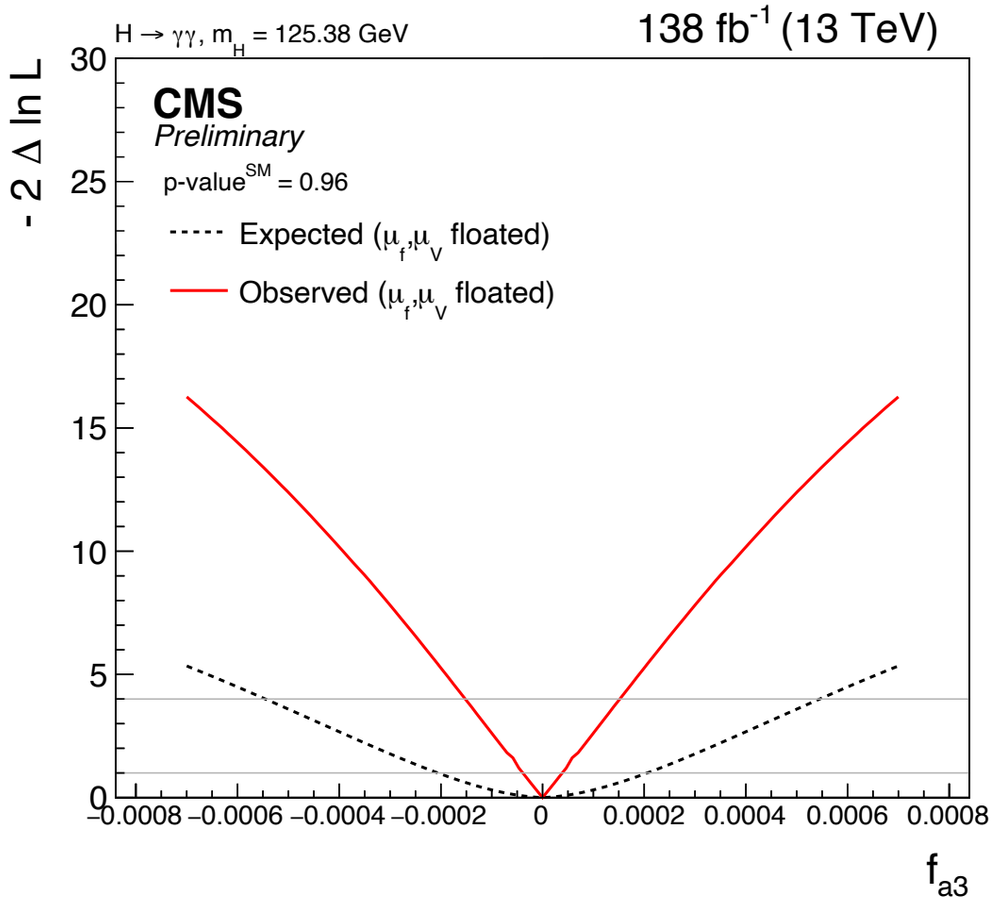


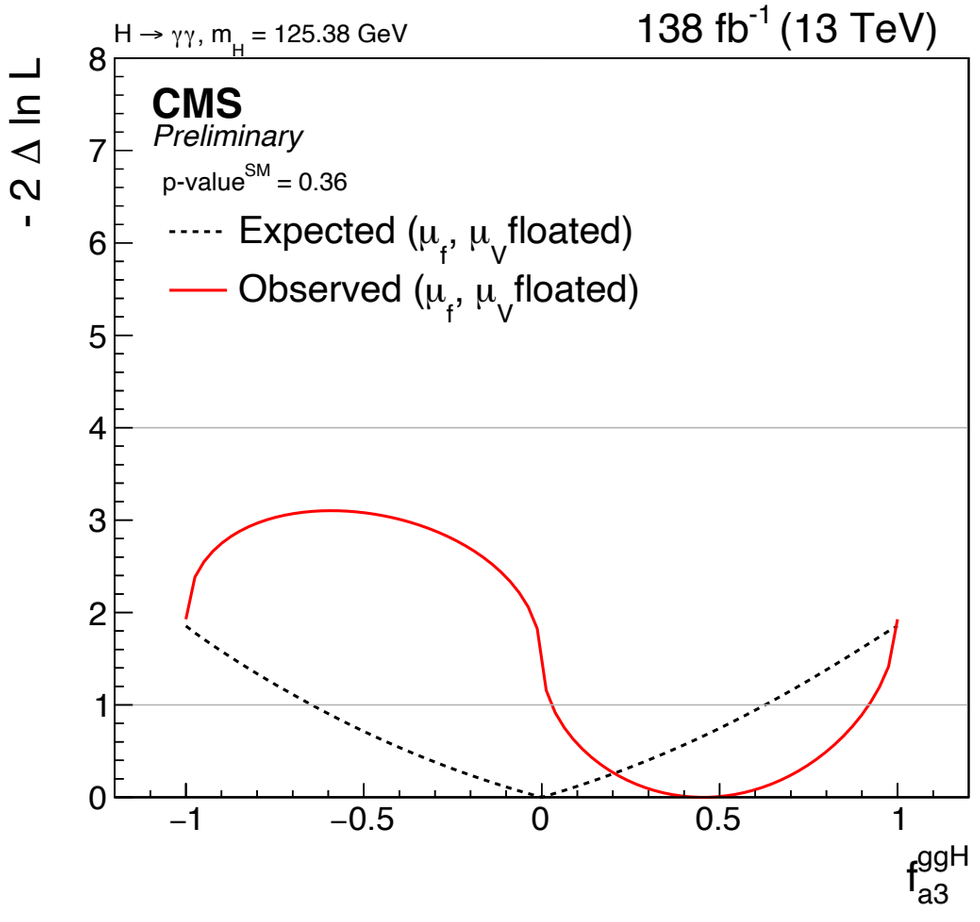


CMS CPV and anomalous couplings using H→γγ

$$\mathcal{A}(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q^2_{V1} + \kappa_2^{\mathrm{VV}} q^2_{\mathrm{V2}}}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m^2_{\mathrm{V1}} \epsilon^*_{\mathrm{V1}} \epsilon^*_{\mathrm{V2}} + a_2^{\mathrm{VV}} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2)\mu\nu},$$

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^2 + \tilde{\sigma}^{Z\gamma}_{\Lambda_1}/(\Lambda_1{}^{Z\gamma})^2} \times \mathrm{sgn}\left(\frac{a_i}{a_1}\right) \qquad f^{\mathrm{ggH}}_{a3} = \frac{|a_3^{\mathrm{gg}}|^2}{|a_2^{\mathrm{gg}}|^2 + |a_3^{\mathrm{gg}}|^2} \times \mathrm{sgn}\left(\frac{a_3^{\mathrm{gg}}}{a_2^{\mathrm{gg}}}\right)$$



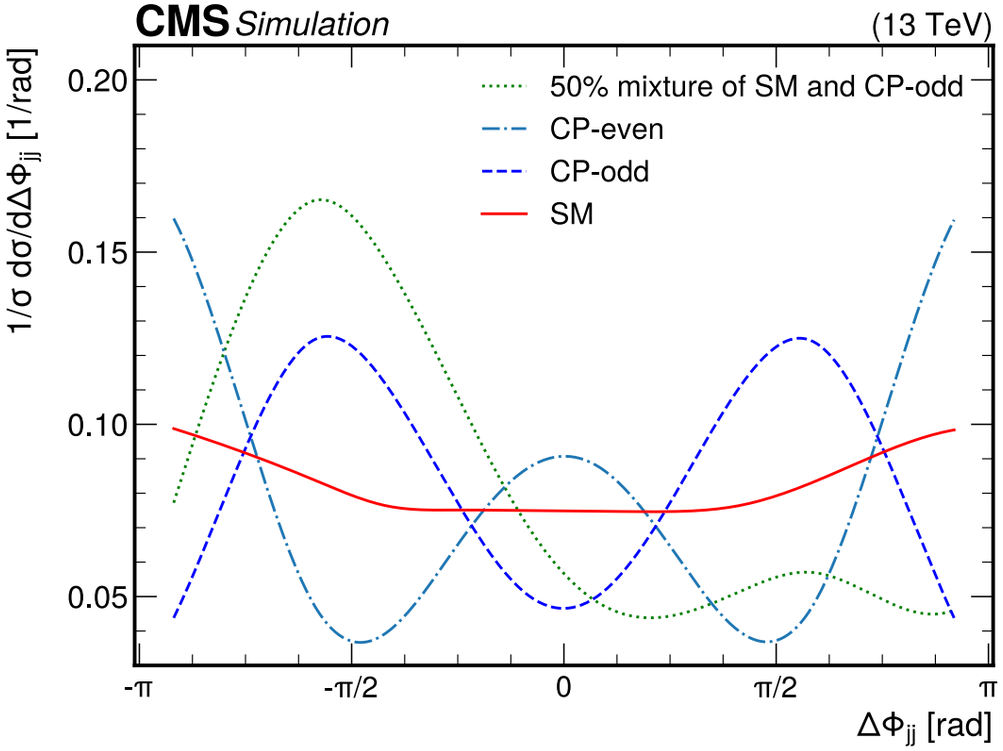


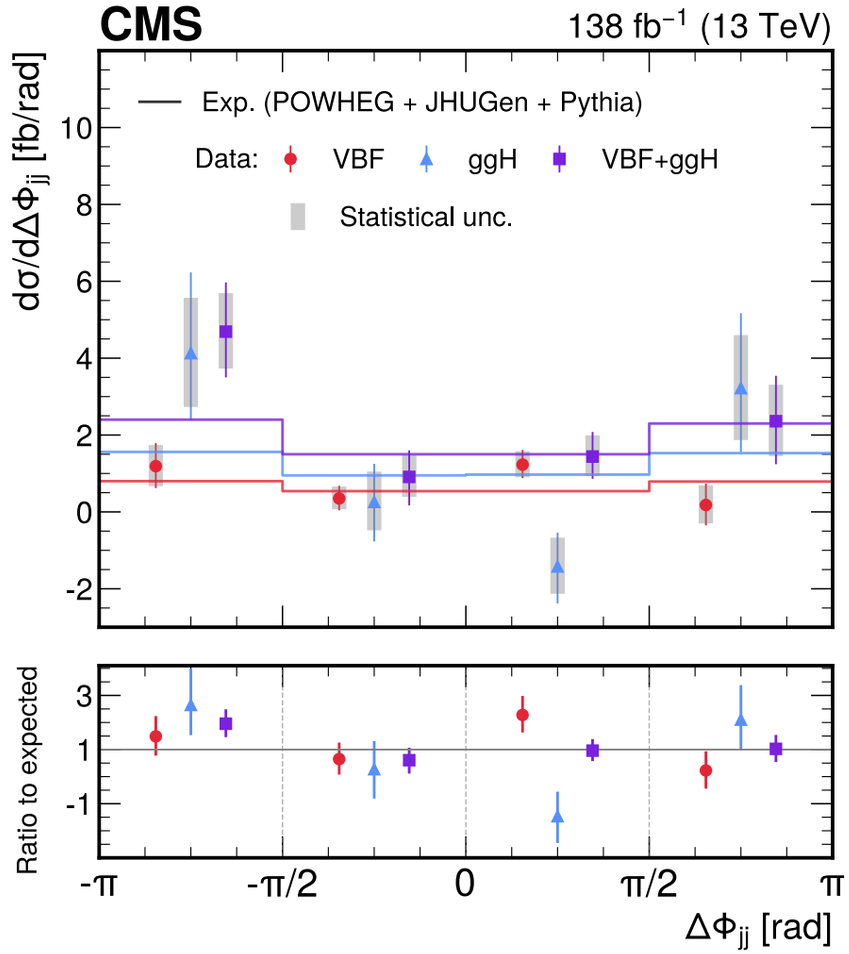
CMS SMEFT measurements using H+2j events using the H→WW

- Model-independent analysis of H+2j events using the H→WW channel: CMS-HIG-24-004

- Differential measurement as a function of $\Delta\phi_{jj}$

- Signal vs background extraction designed to be signal agnostic using NN with domain adaptation - output of NN fitted in bins of $\Delta\phi_{jj}$

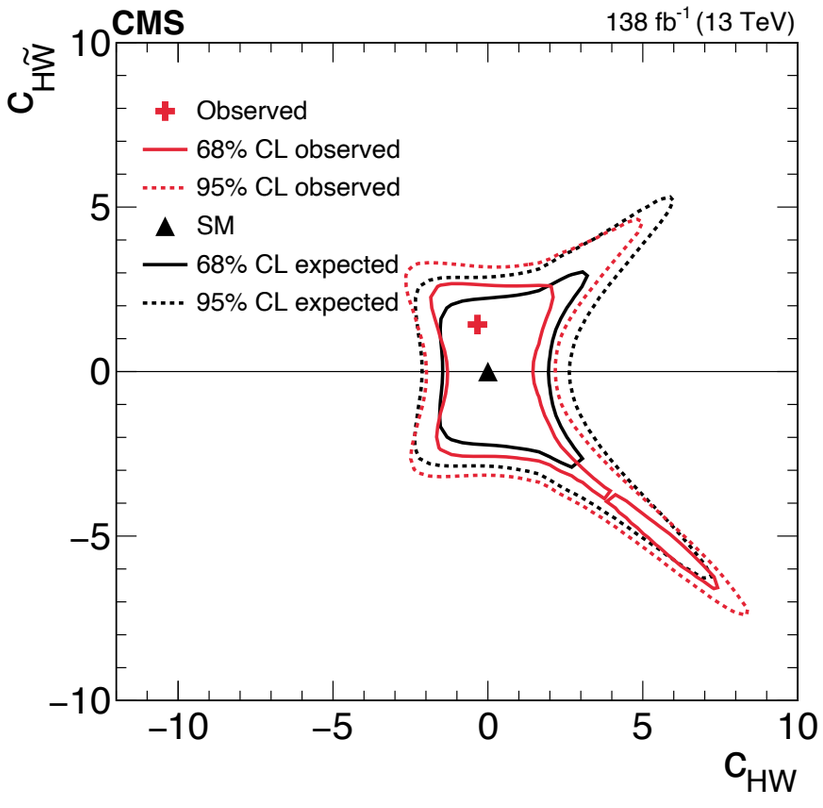


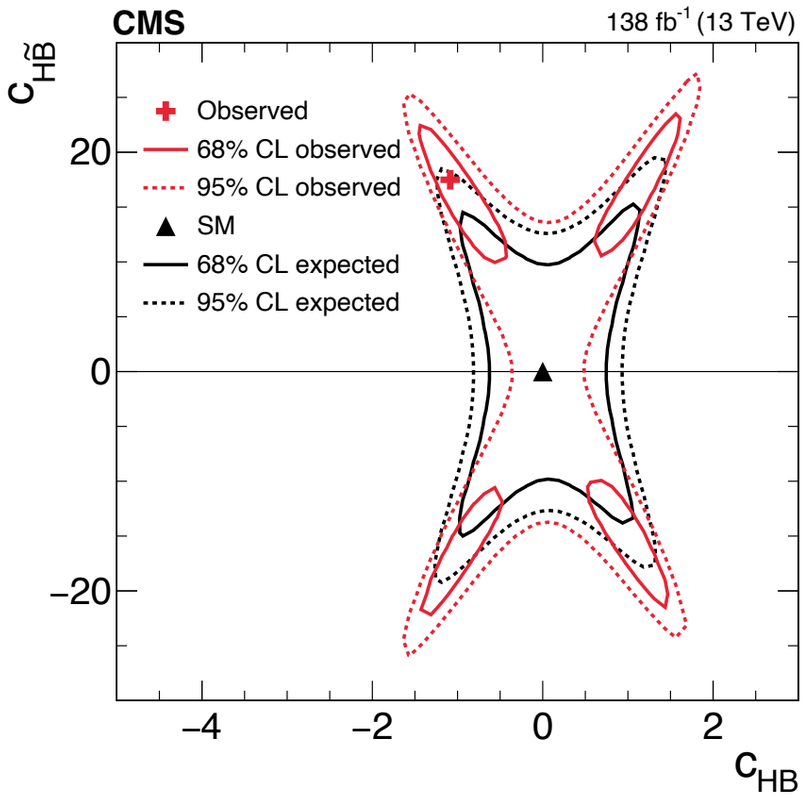


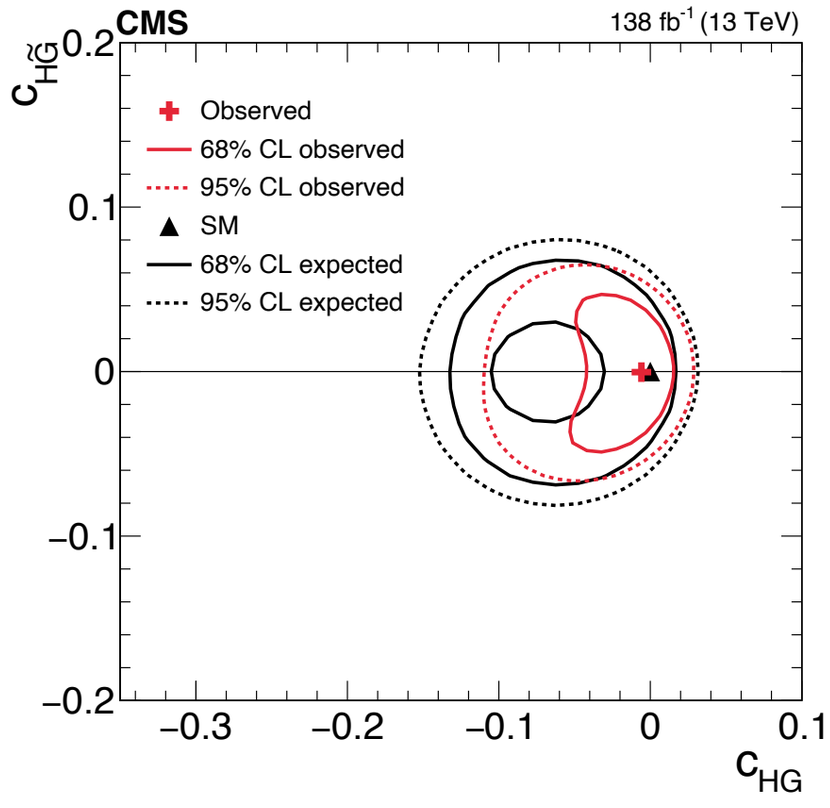
CMS SMEFT measurements using H+2j events using the H→WW

- Results interpreted in SMEFT framework to set limits on several Wilson coefficients in Warsaw basis

- Coefficients measured: c_{HWB}, c_{HW}, c_{HB}, c_{HG} [+ corresponding CP odd terms] and c_{Hu}, c_{Hd}, c_{Hj3}, c_{Hj1}, c_{HD}, $c_{\mathrm{H}\Box}$

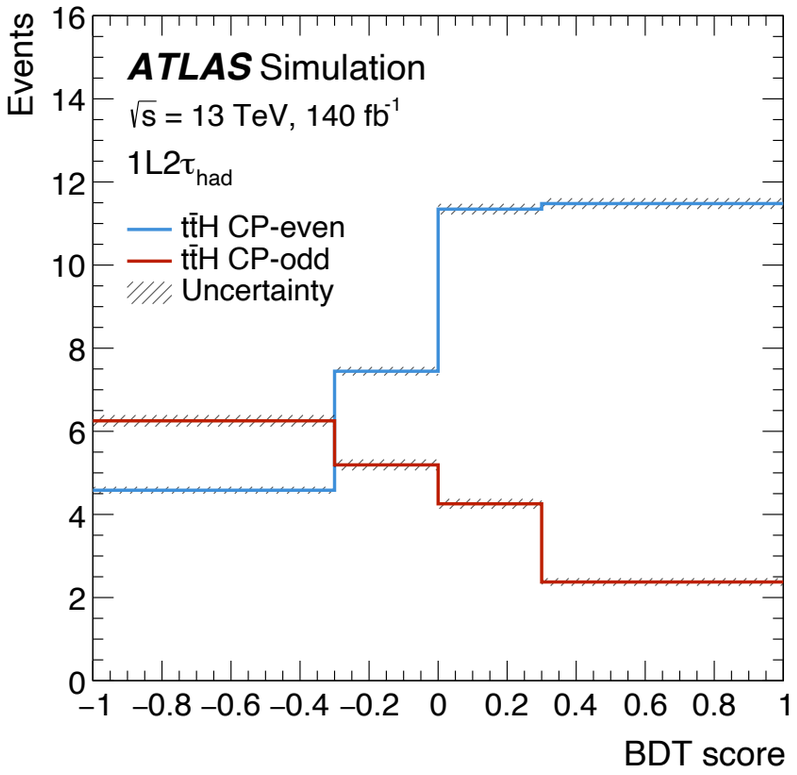


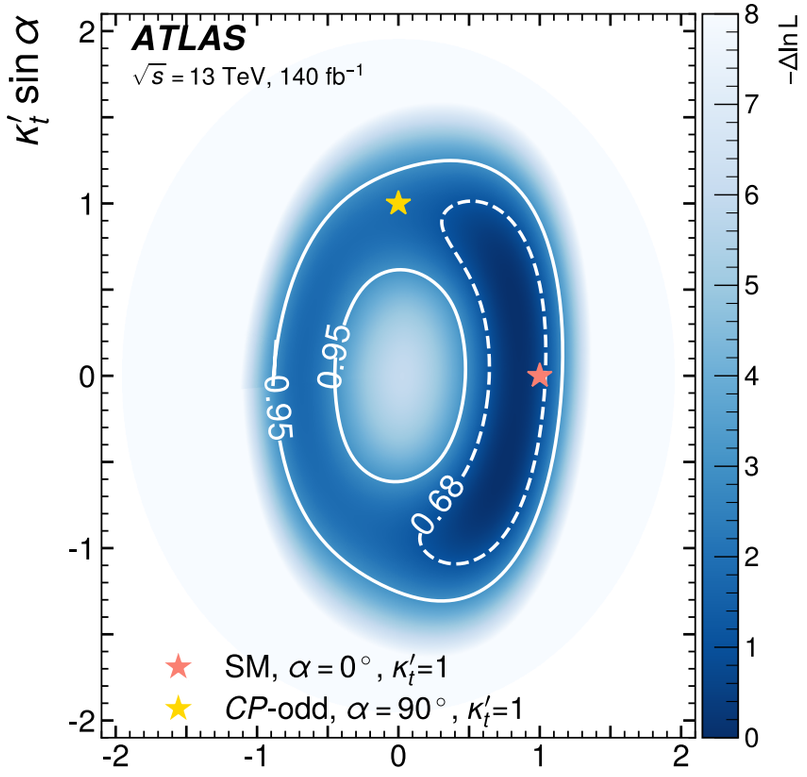




ATLAS ttH+tH multi lepton CP measurements

- ttH+tH CP measurements in the multi lepton final state: ATLAS-HIGP-2024-08
- Multilepton = H→WW, H→ττ, and partially H→ZZ (except the 4l)
- BDT to separate CP-even and CP-odd in channels with two hadronic taus
  - Most important features are angular separation between jets and taus, jets and leptons, and taus and leptons
- STXS p_T binning sensitive to CP in other channels





α>62° excluded at 68% CL

Summary

- I have shown several new results from both CMS and ATLAS in the last year
- Several of these analyses still exploiting the Run-2 data
- We have also started to see the first measurements using Run-3 data with more Run-3 analyses expected soon
- SMEFT and AC frameworks continue to provide powerful, model-independent interpretations of LHC measurements

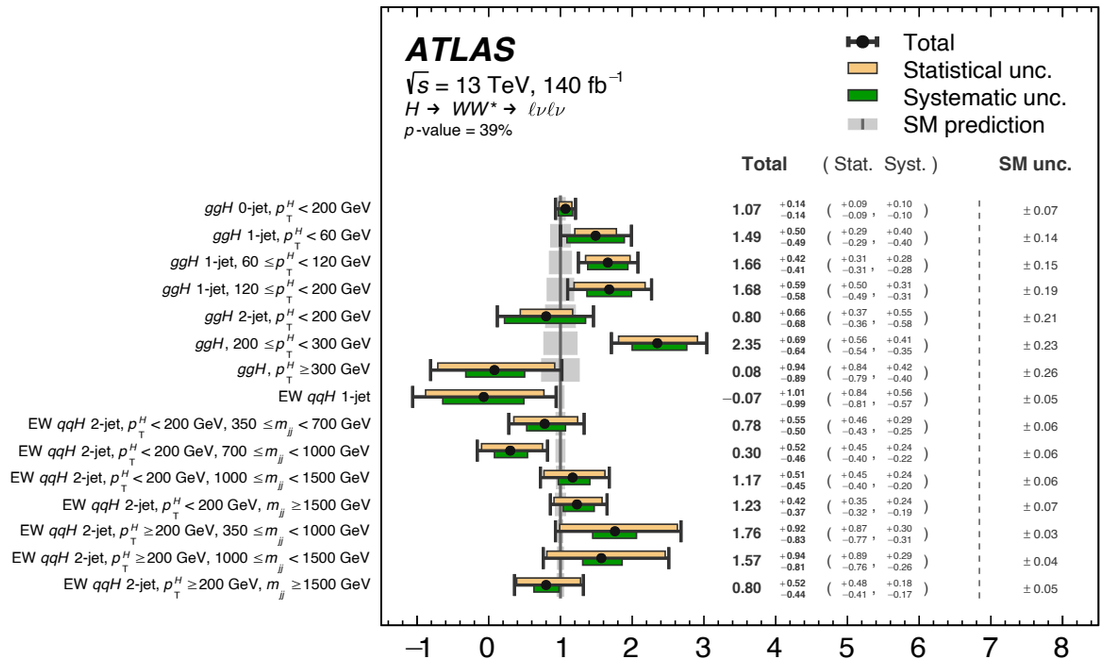
Backup

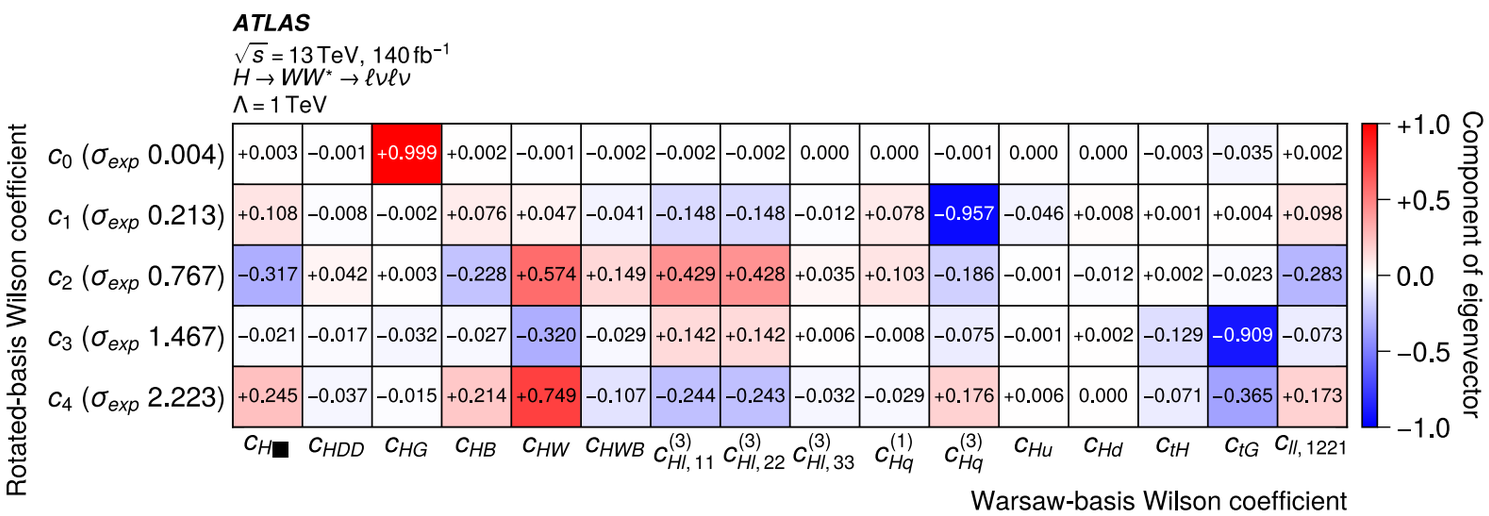
ATLAS H→WW SMEFT measurements

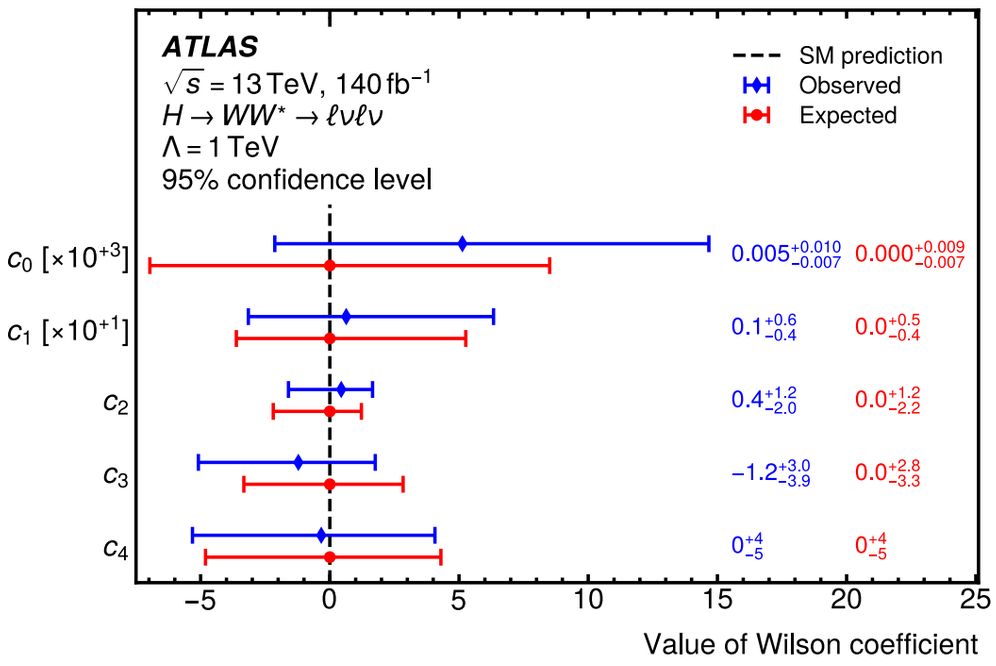
- ATLAS-HIGP-2024-07

- STXS binning (Stage 1.2) used to extract Wilson coefficients

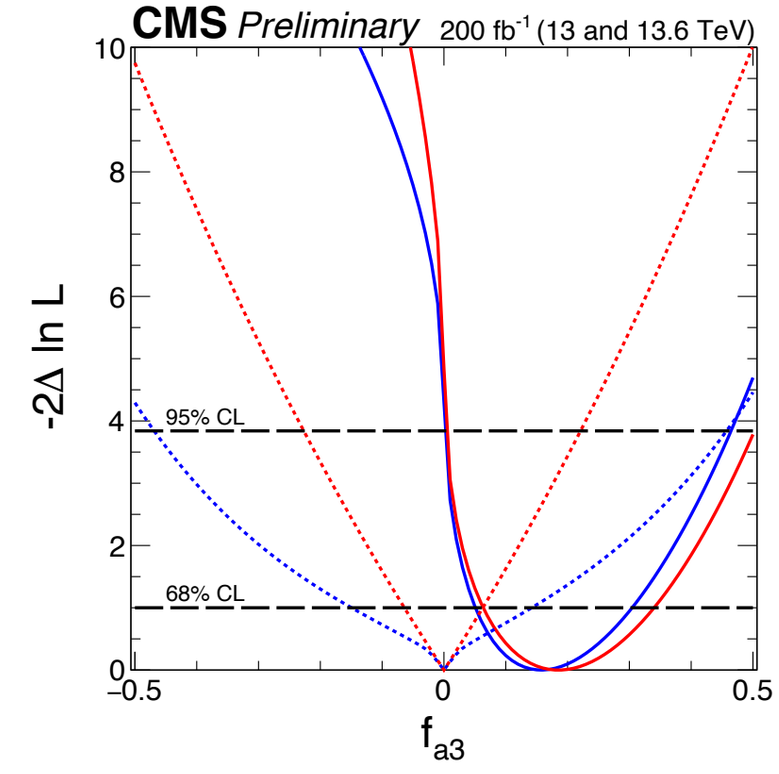
- Use PCA to obtain a rotated, orthogonal basis of the most sensitive directions in the Wilson-coefficient space

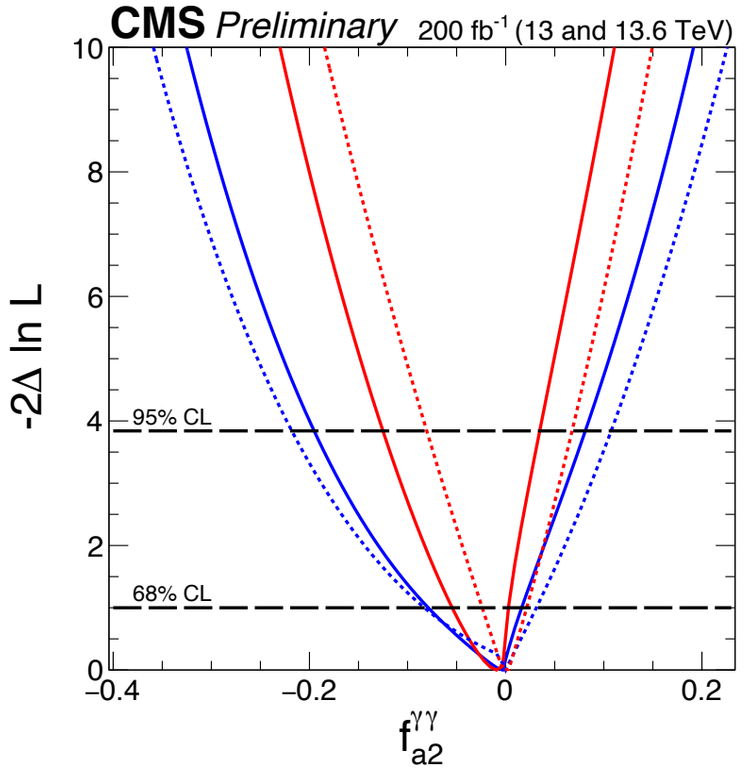


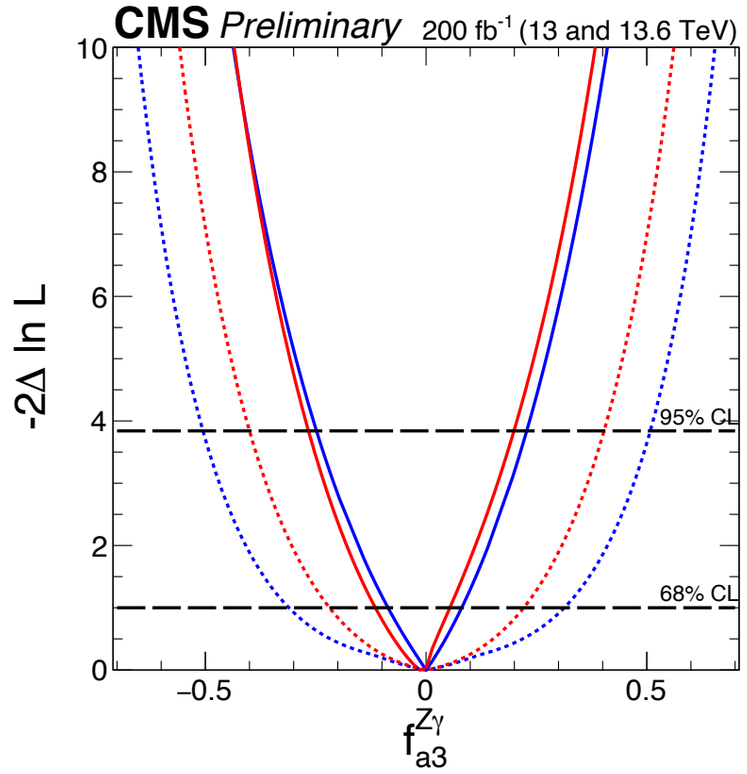


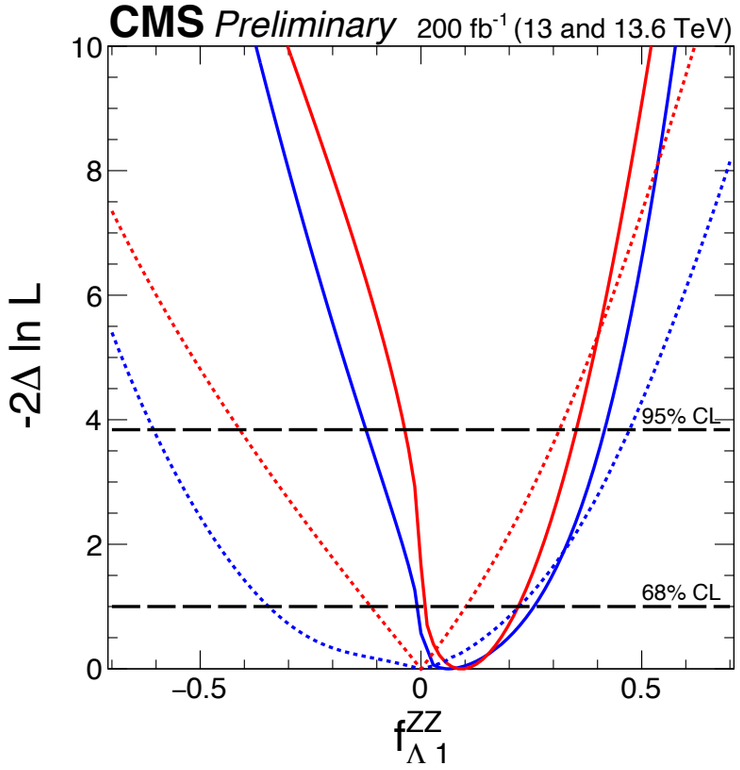


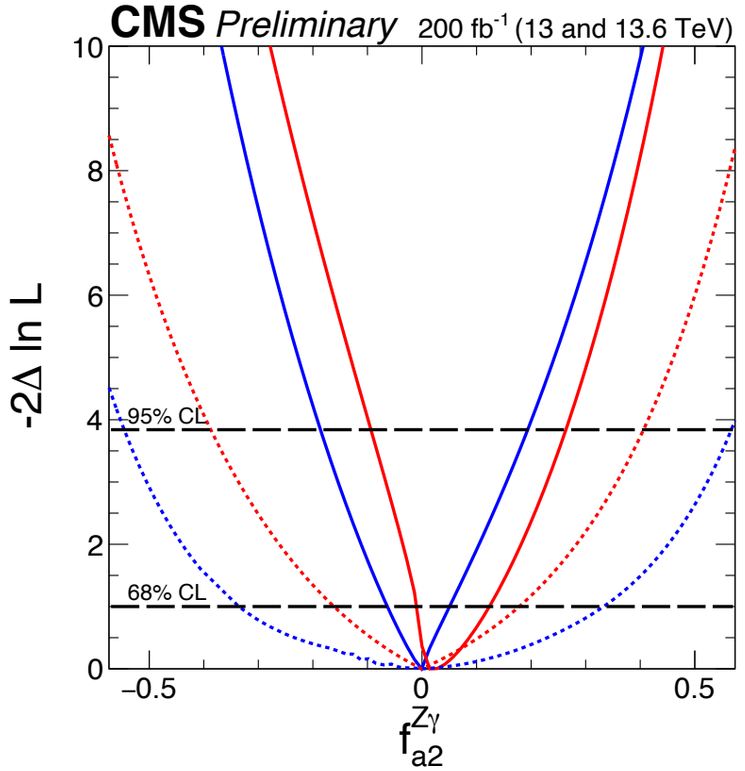
CMS CPV and anomalous couplings using H→ZZ

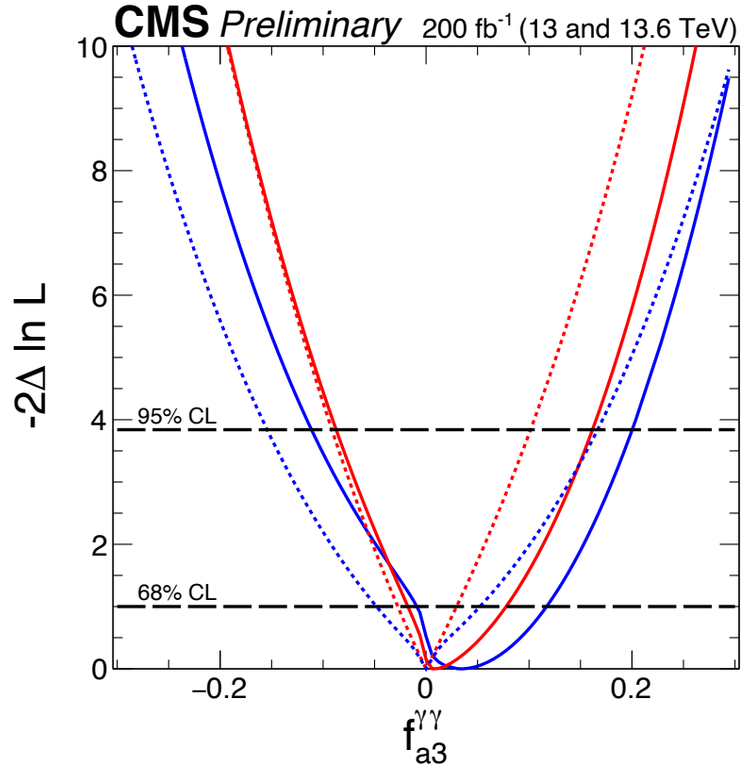




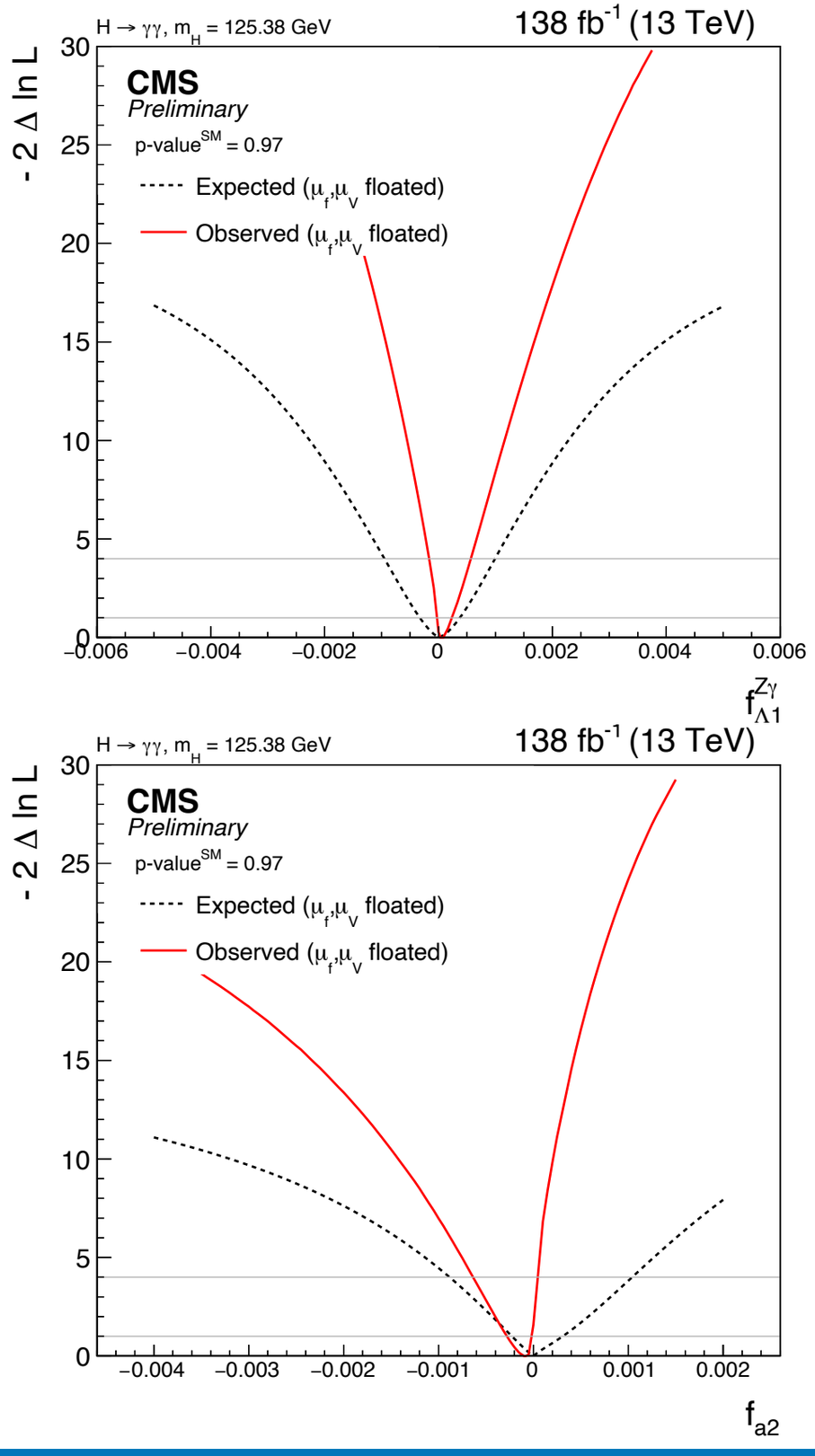


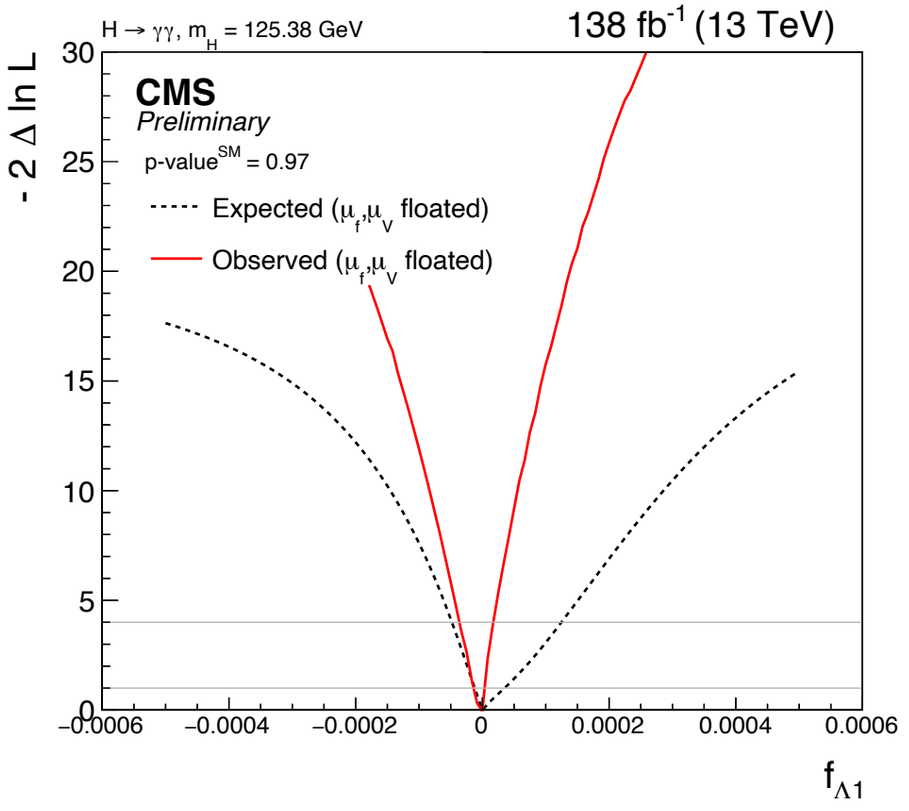




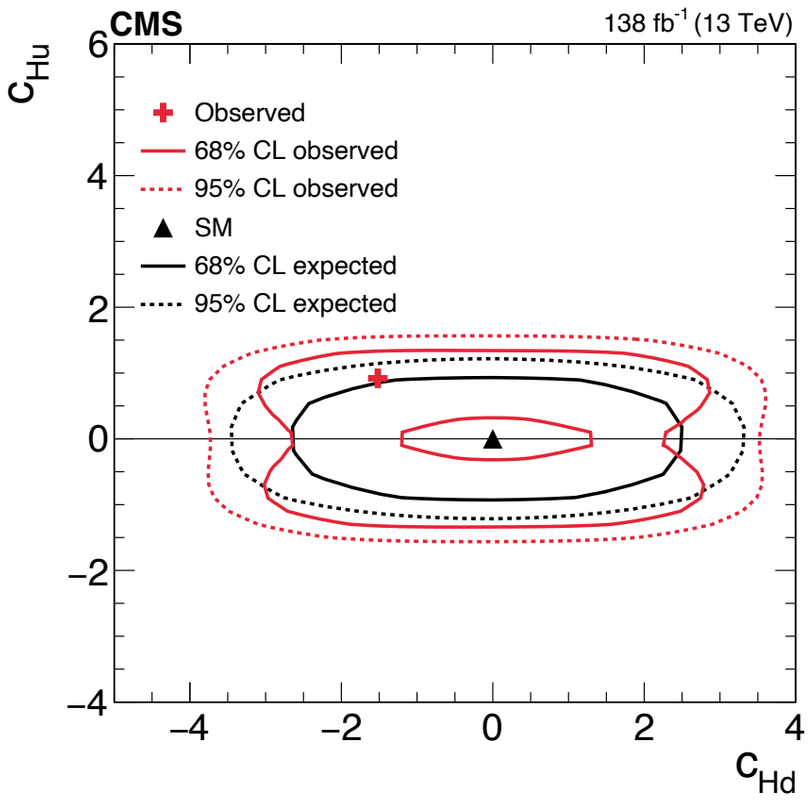


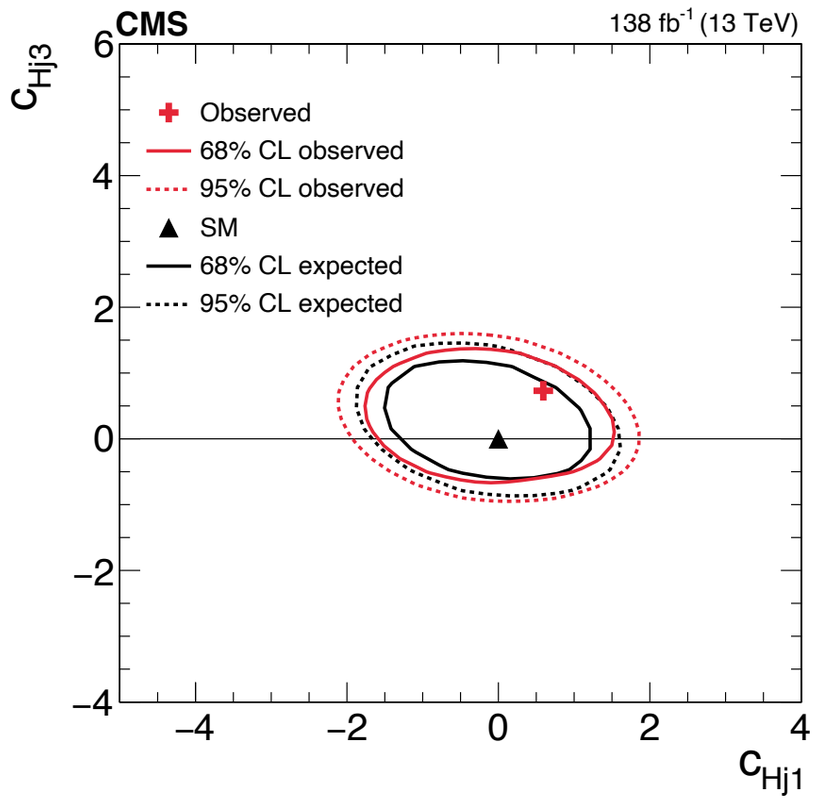
Additional CMS H→γγ AC scans

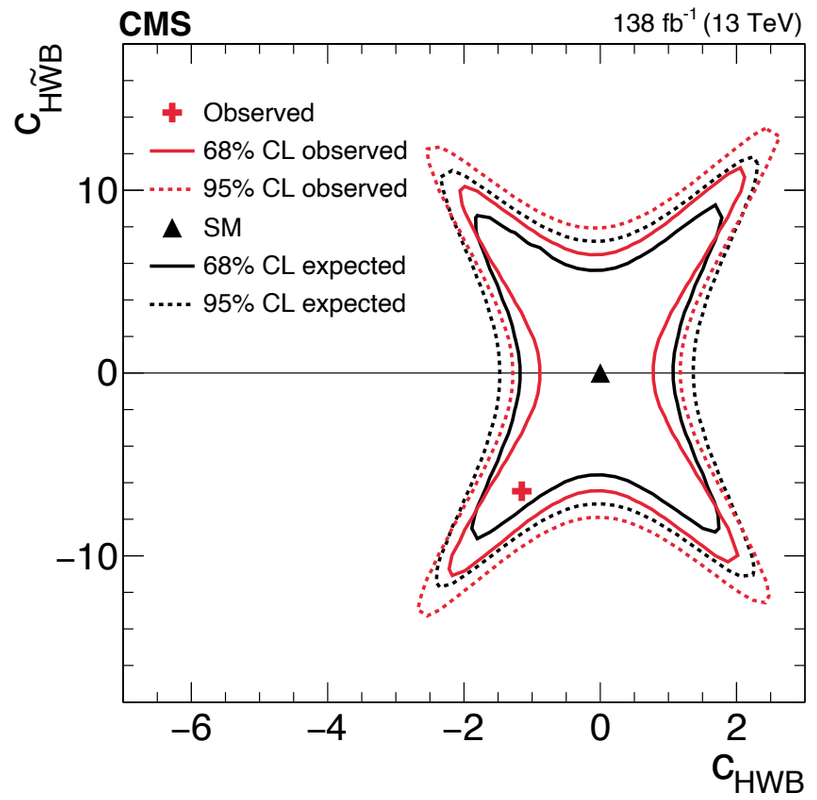




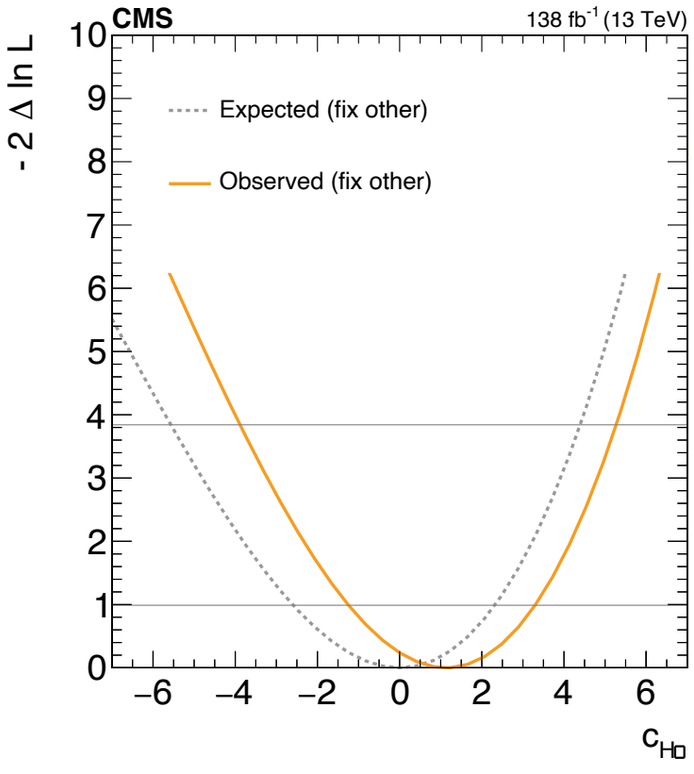
Additional CMS H→WW scans



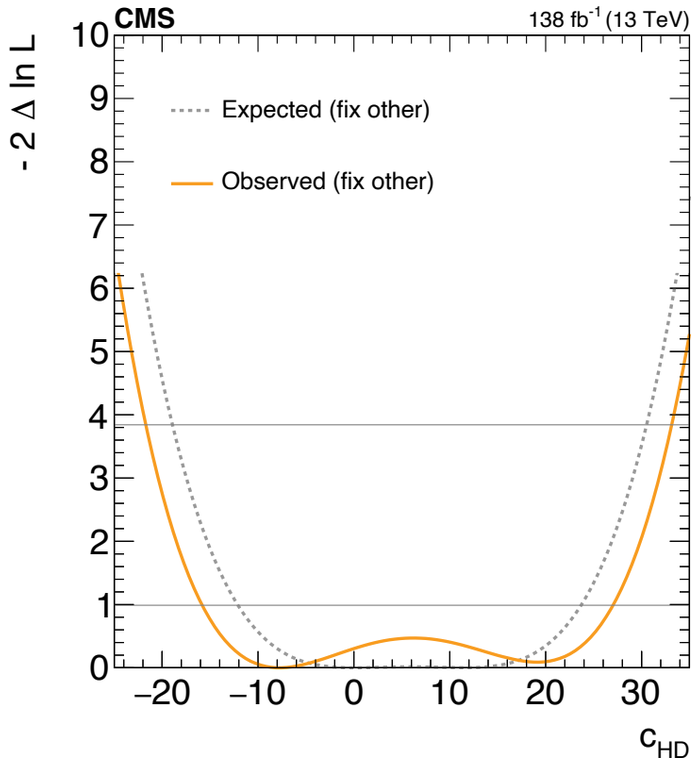




c_{Hd}

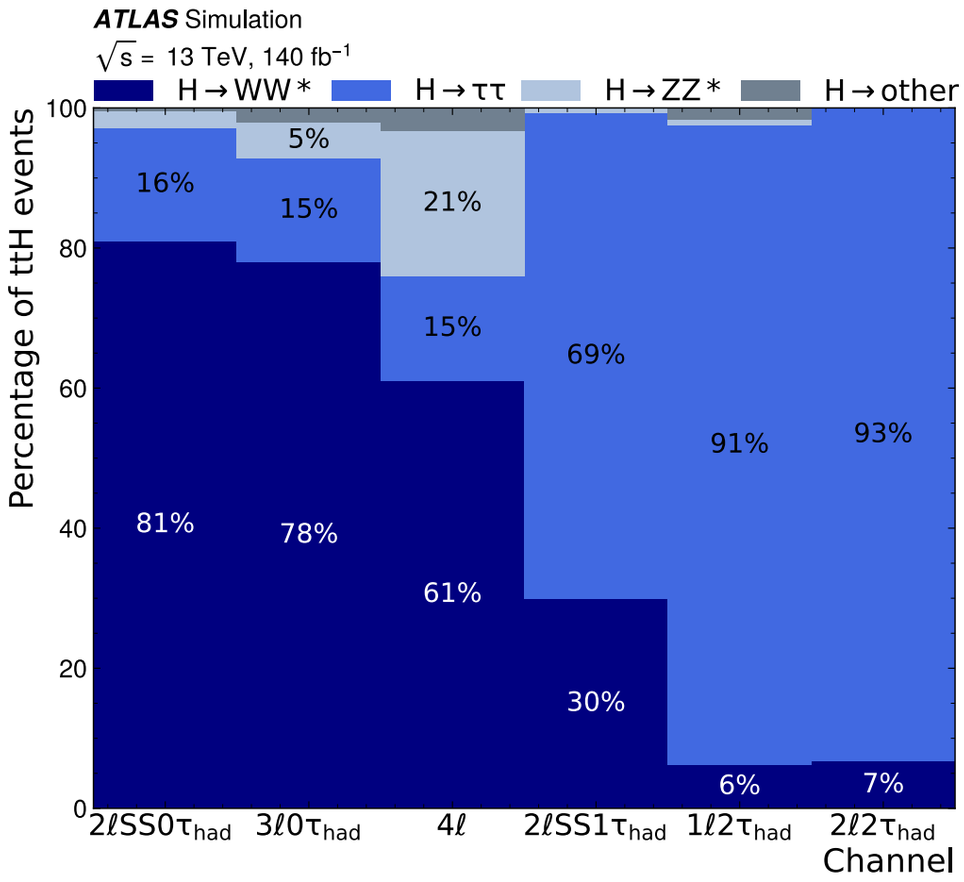


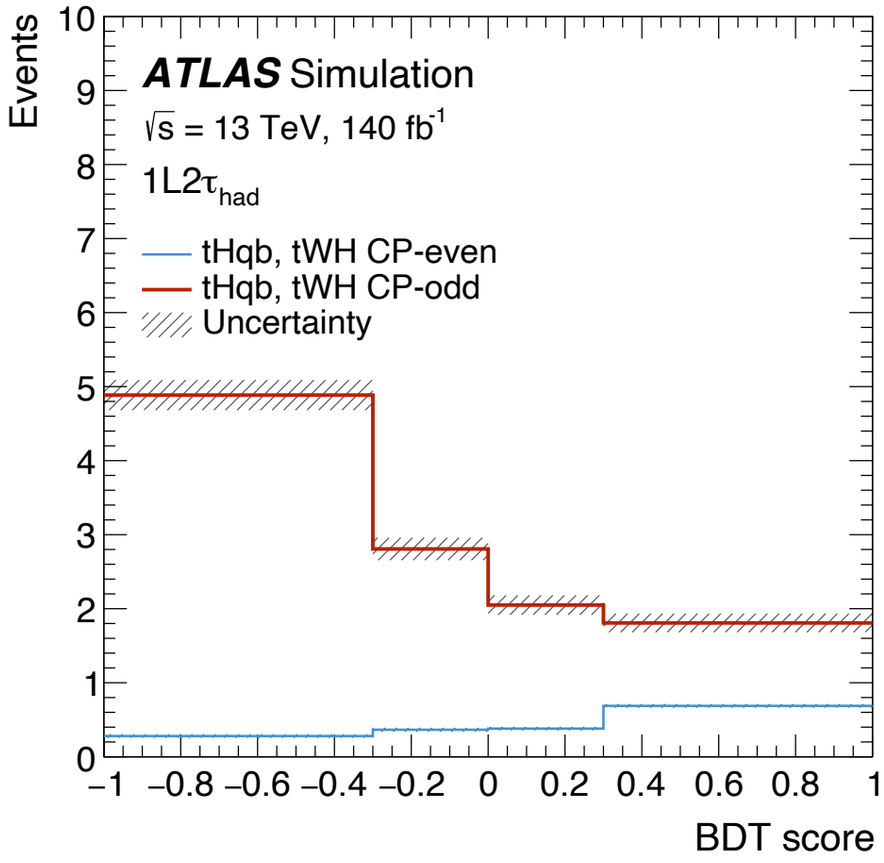
c_{Hj1}

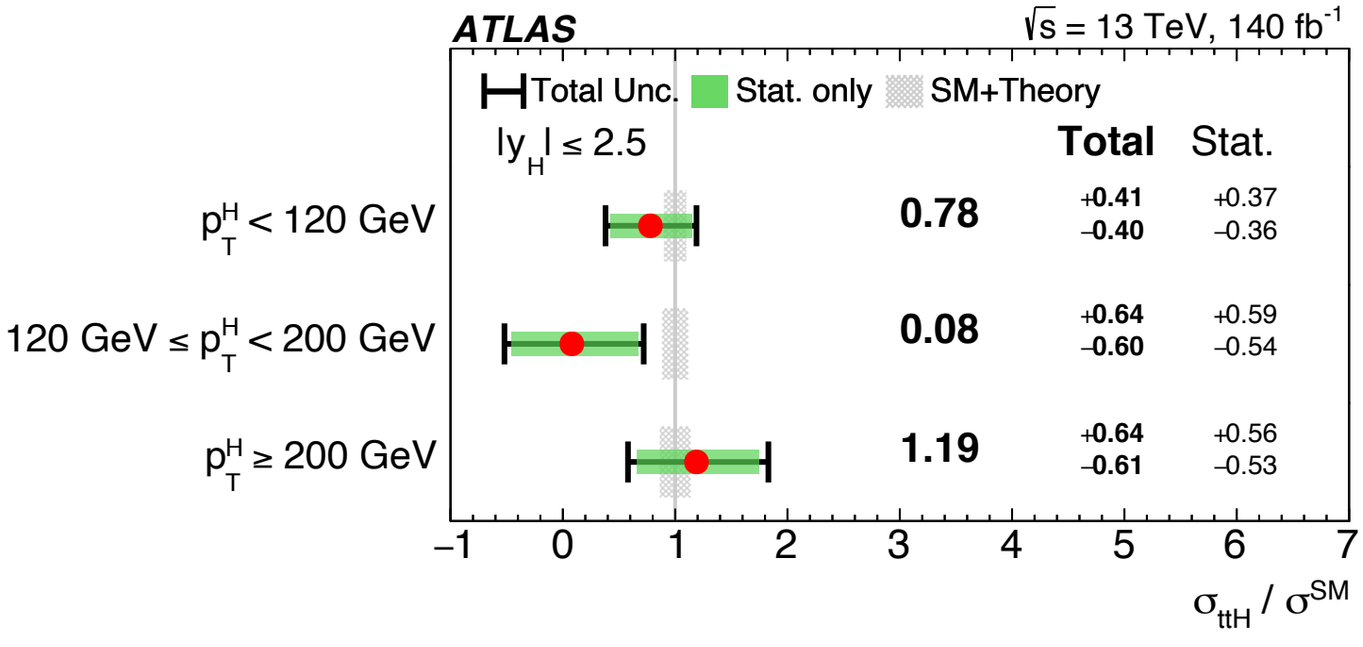


c_{HWB}

ATLAS ttH+tH multi lepton CP measurements

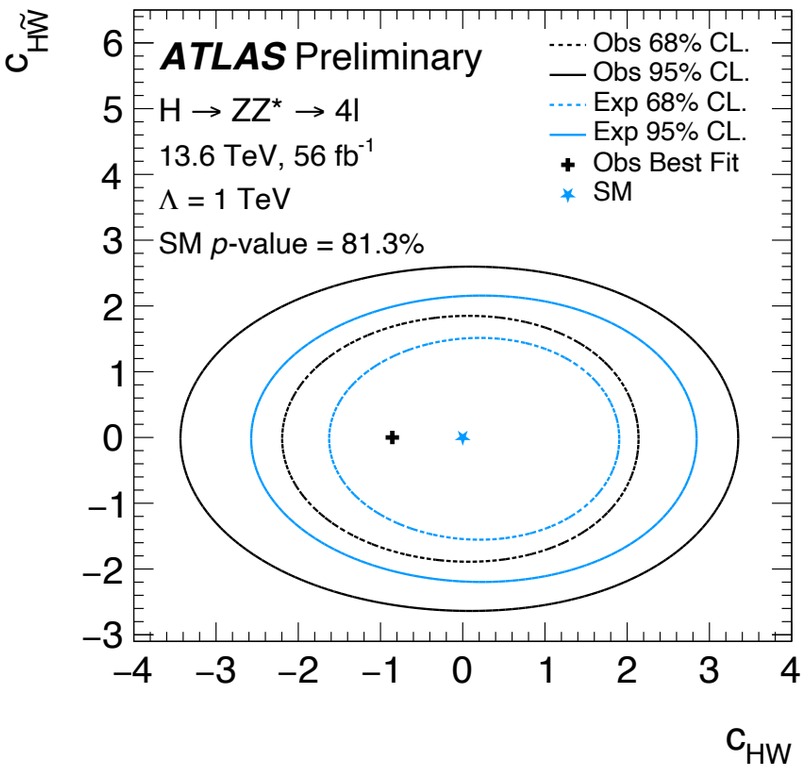


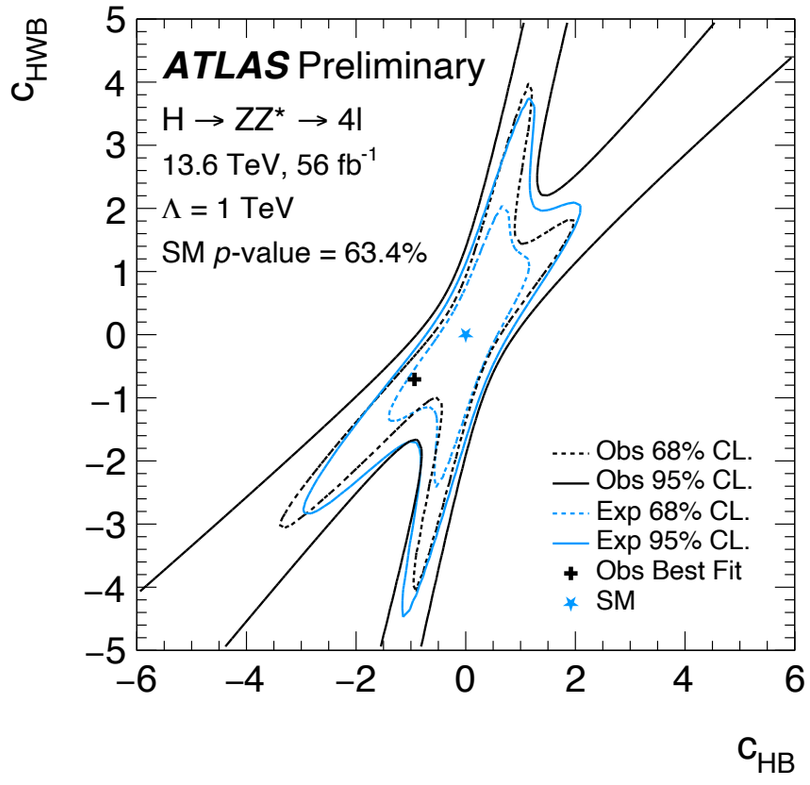


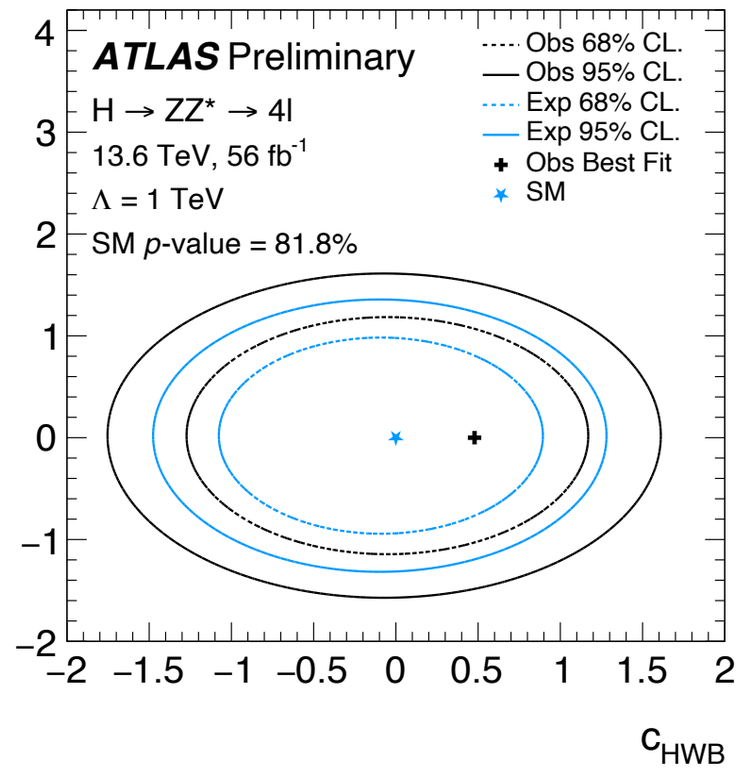


ATLAS H→ZZ SMEFT measurements: extra scans

- Coefficients measured: c_{HWB}, c_{HW}, c_{HB} [+ corresponding CP odd terms]

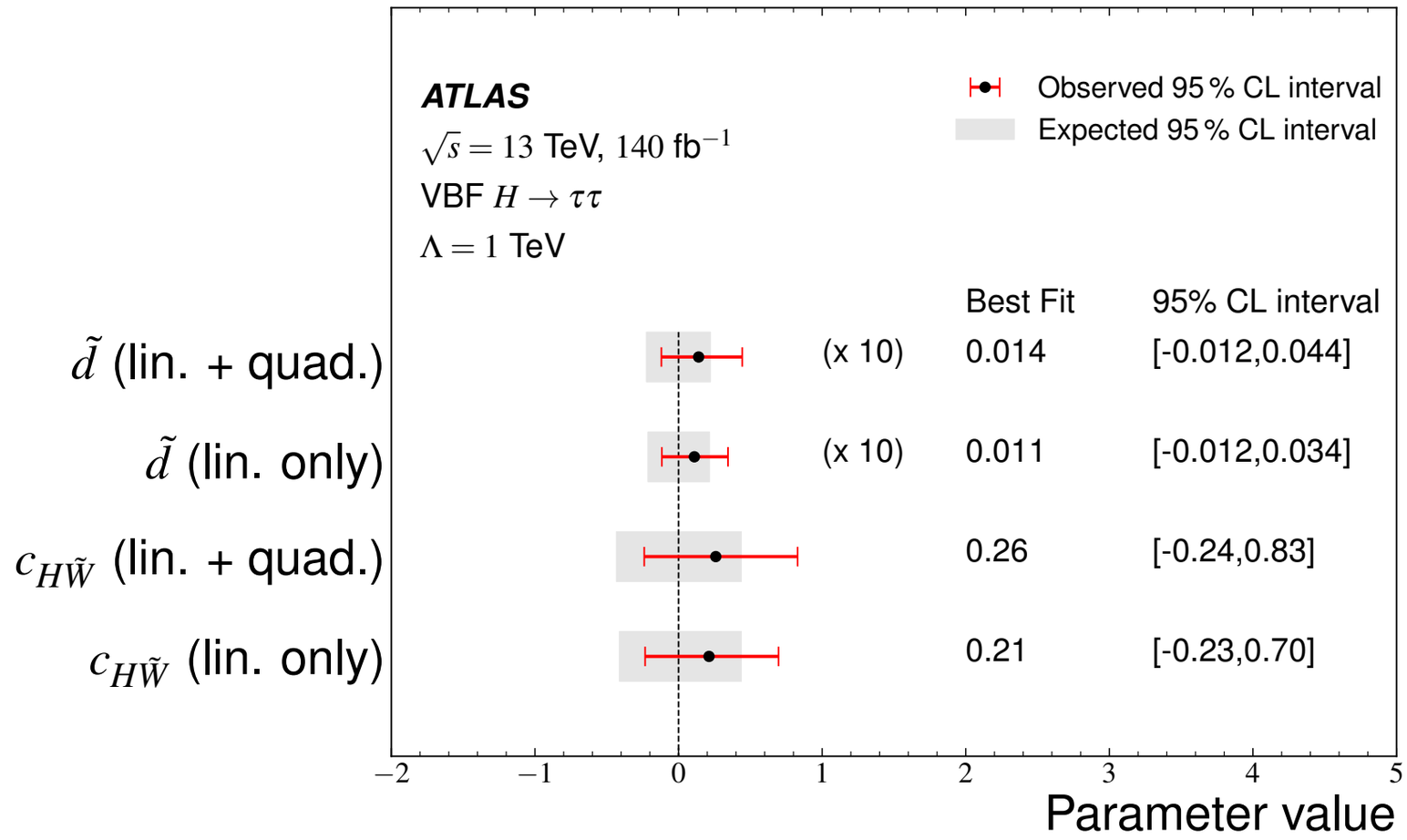






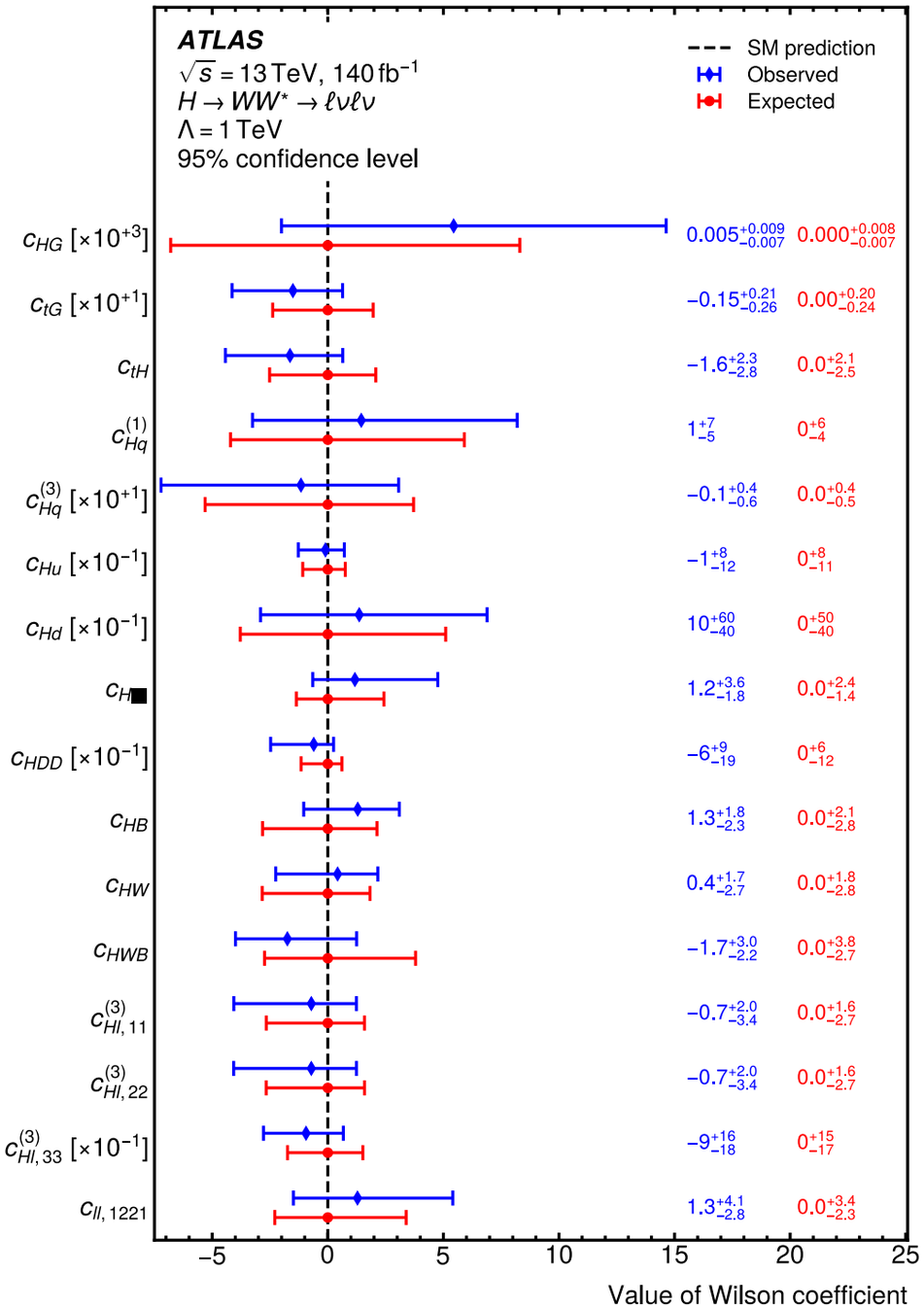
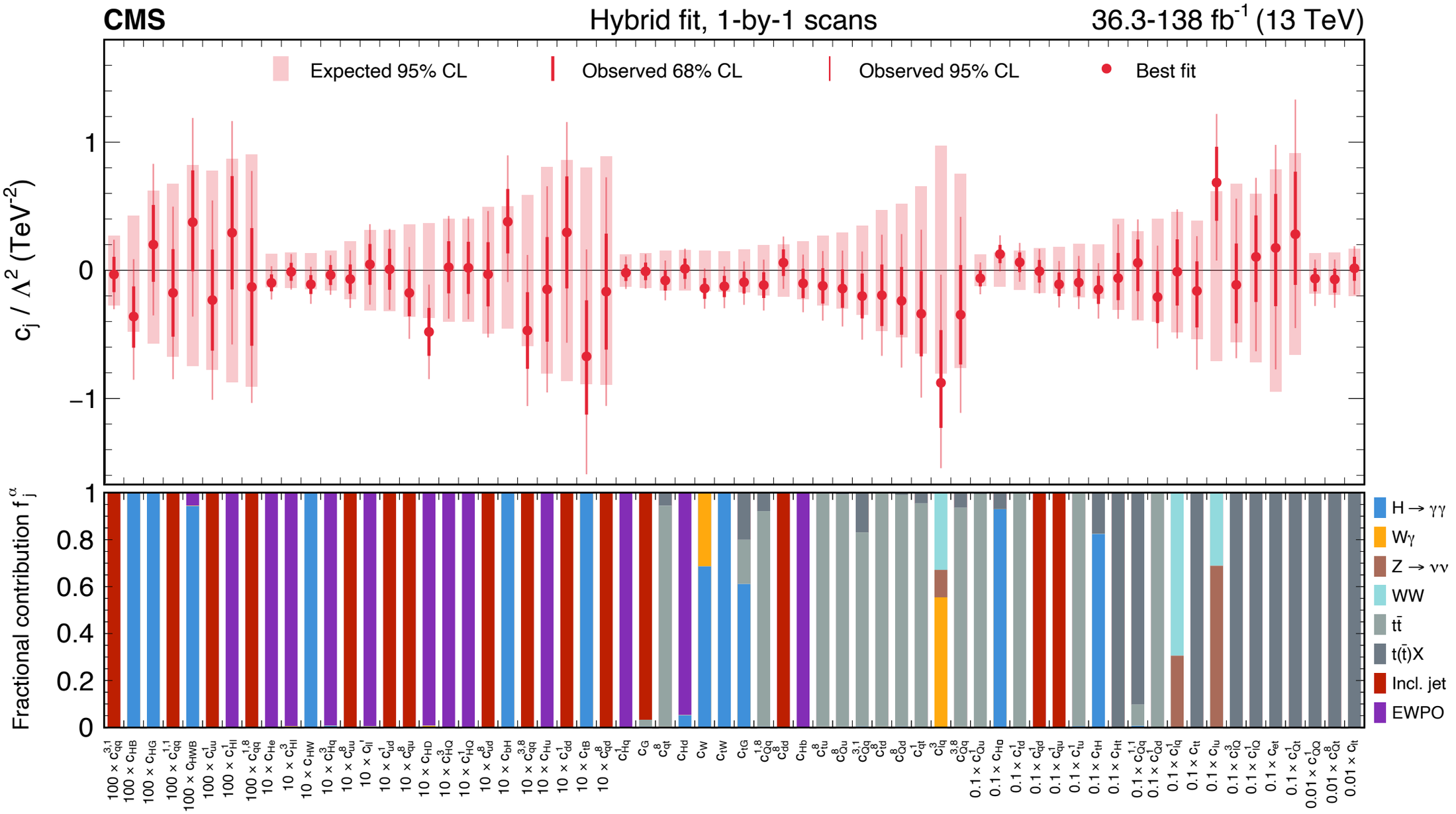
ATLAS VBF CP measurements in H→ττ

- Comparison considering linear+quadratic terms or linear terms only



ATLAS H→WW SMEFT measurements

- SMEFT results for un-rotated basis
- Parameters fitted individually



- Combining Higgs measurements with measurements of other processes: CMS-SMP-24-003