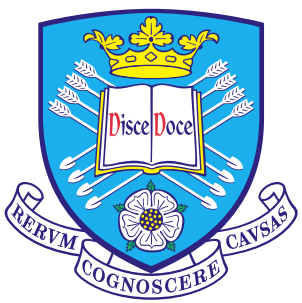
CP-odd EFT constraints from ggH + VBF + H4l

LHCHXS WG2 meeting on EFT & CP



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13.11.2018

Introduction

Presenting results of

Bernlochner, Englert, Hays, Lohwasser, Mildner, Pilkington, Price and Spannowsky
Signs of CP-violation in Higgs boson interactions, arXiv:1808.06577 [hep-ph]

Strategy

- Constrain CP-odd dimension-six SM EFT operators
- By re-interpreting model-independent Higgs measurements
- Capture leading effect of operators ($\propto \Lambda^{-2}$) with CP-odd observables

Outline

- One usable observable measured ($\Delta\phi_{jj}$), by ATLAS, in two channels
- Observe asymmetry in this CP-odd observable – but unable to distinguish between CP-violating sources with available measurements
- Demonstrate: split by production mode would reduce ambiguity
- Addition of additional H→4l observable allows constraining multiple operators, additionally extrapolate to 300 and 3000 fb^{-1}

Analysis Framework

- Analysing dimension-six operators of SM EFT in Warsaw basis

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

- Considering four CP-odd operators affecting Higgs interactions

$$O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \qquad O_{H\tilde{B}} = H^\dagger H B^{\mu\nu} \tilde{B}_{\mu\nu}$$
$$O_{H\tilde{W}} = H^\dagger H W^{a\mu\nu} \tilde{W}^a_{\mu\nu} \qquad O_{H\tilde{W}B} = H^\dagger \tau^a H B_{\mu\nu} \tilde{W}^{a\mu\nu}$$

  and corresponding CP-even operators $O_{HG}, O_{HW}, O_{HB}, O_{HWB}$
- Technical details
  - SMEFTsim code used [arXiv:1709.06492]
  - Simulate dim-6 operator contribution with Madgraph5+Pythia8, analysed with Rivet
  - Measurement, uncertainty, and SM prediction are taken from experimental publications
  - Effect (of CP-even operators) on branching ratios considered, too

Linearisation

Considering only leading ($\propto \Lambda^{-2}$) effect in EFT expansion: interference (of $c_i/\Lambda^2 O_i$ contribution) with SM

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\text{Re}\left(\mathcal{M}^{\star}_{\text{SM}}\mathcal{M}_{\text{d6}}\right) + \mathcal{O}(\Lambda^{-4})$$

Terms quadratic in CP-odd operators:

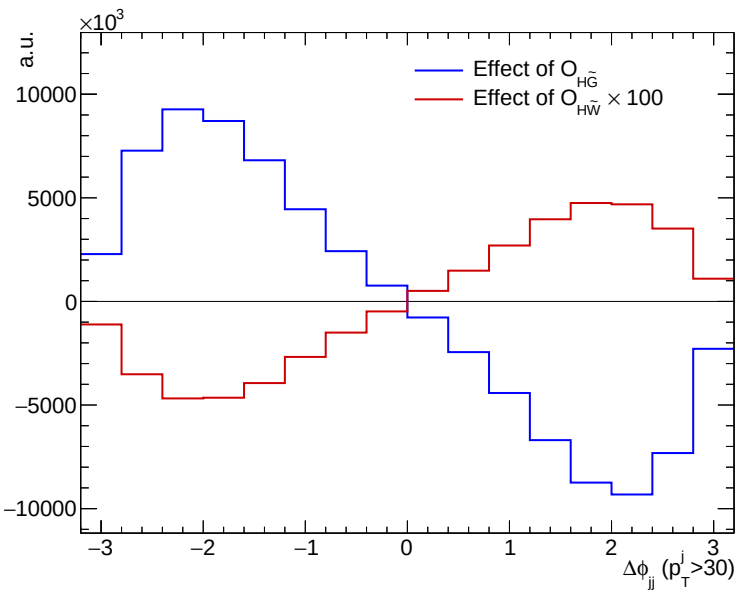
- Generate no genuine CP-odd effects
- Introduce more model-dependence (would need to consider all effects at $\mathcal{O}(\Lambda^{-4})$, including dim-8 operator interference)
- Will only improve our constraints when included

CP-odd operators in linearised approach:

- Integration over interference term vanishes for CP-odd operators
- They have no linear contributions to CP-even observables
- *Require construction of CP-odd observables to capture* $\propto \Lambda^{-2}$ *effect*

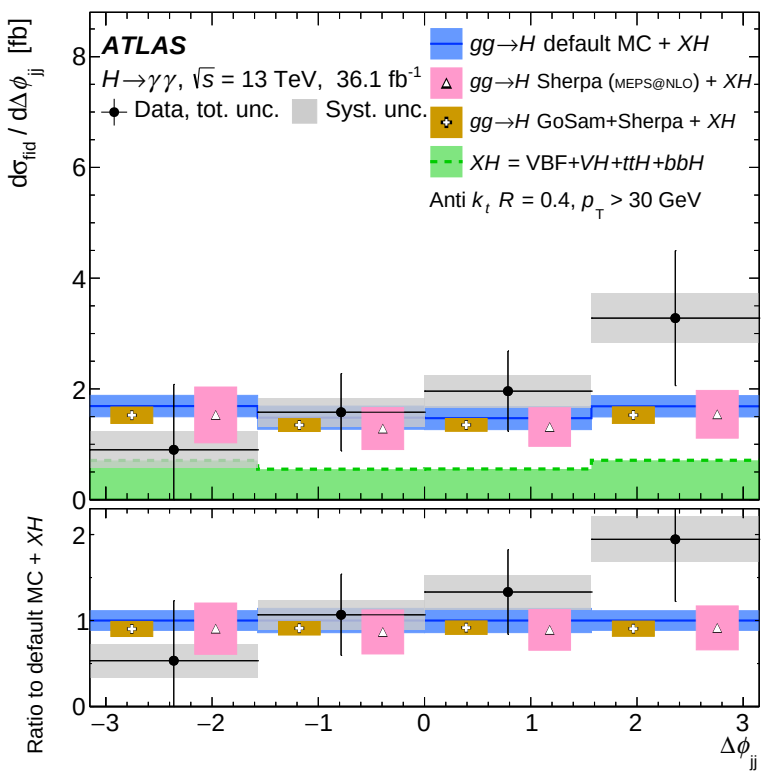
CP-odd observables

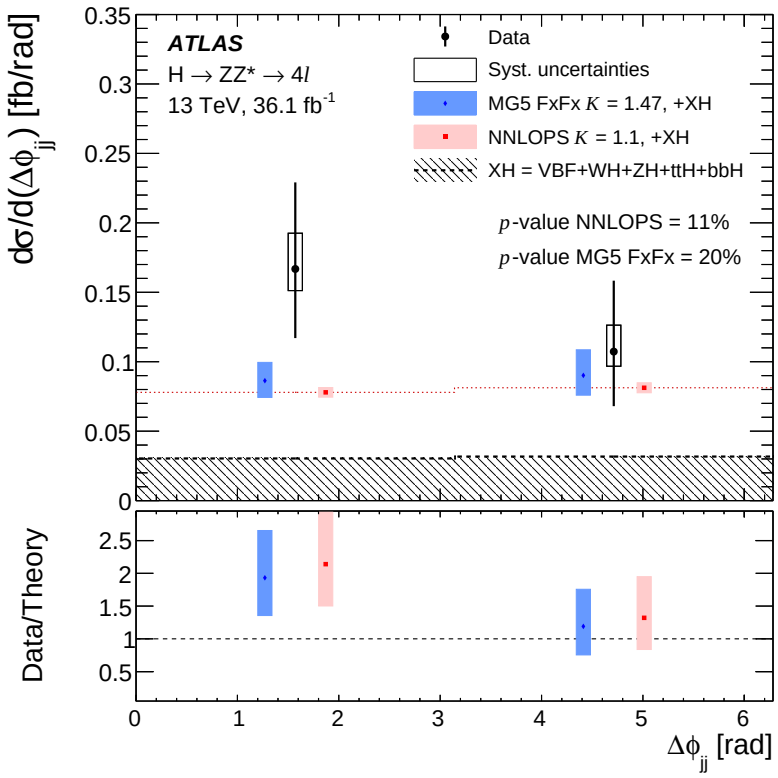
- CP-odd observables:
  - Can be constructed for large number of processes
  - Asymmetry can be indication of CP-violation
  - Affected symmetrically by CP-even operators
    $\Rightarrow$ in linearised approach, CP-odd fit largely decoupled from CP-even
  - Also affected symmetrically by most experimental uncertainties, small uncertainty of asymmetry
- Only CP-odd observable unfolded in LHC Higgs measurements so far: $\Delta\phi_{jj}$
  - Measured by ATLAS in H(ZZ) and H($\gamma\gamma$) decays
  - Sign determined by direction of jet with larger rapidity



- No CP-odd observables measured by CMS or in ATLAS WW, unable to re-interpreted ATLAS optimal observable analysis in VBF H($\tau\tau$)

$\Delta\phi_{jj}$ measurements



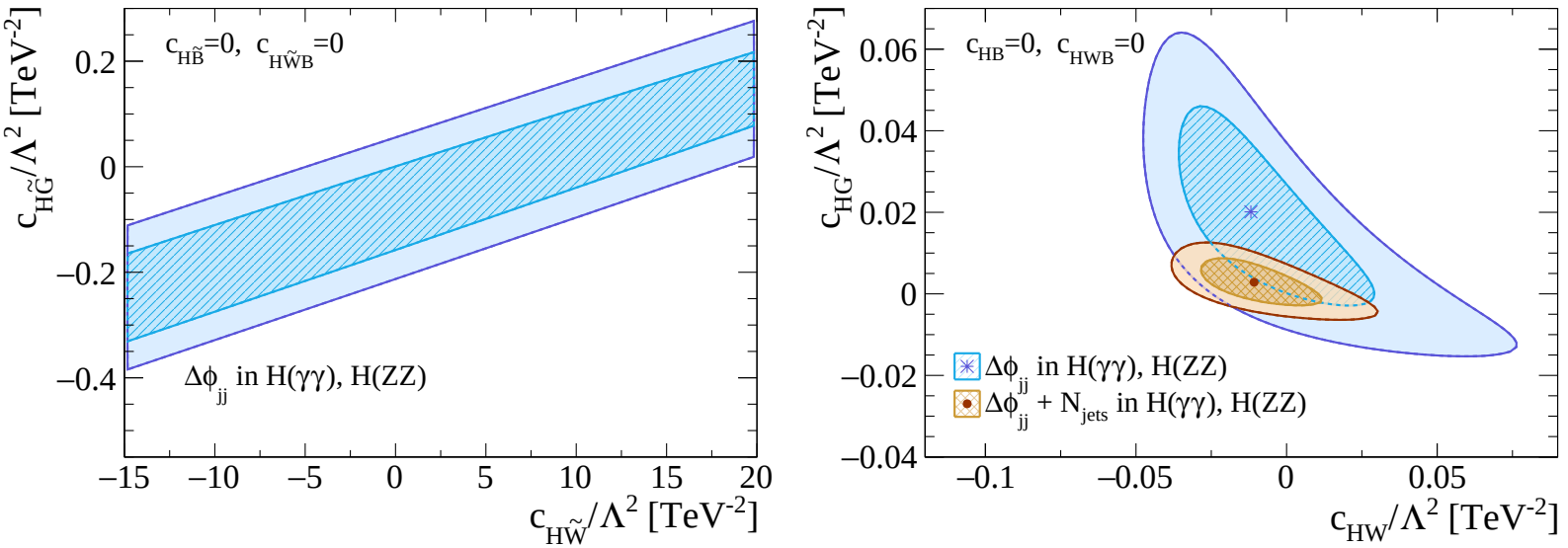


- $\Delta\phi_{jj}$ measured by ATLAS in $H(\gamma\gamma)$ and H(ZZ) with 36.1 fb^{-1}
- Both measurement exhibit similar asymmetry, combined:

$$A = \frac{\sigma(0<\Delta\phi_{jj}<\pi)-\sigma(-\pi<\Delta\phi_{jj}<0)}{\sigma(0<\Delta\phi_{jj}<\pi)+\sigma(-\pi<\Delta\phi_{jj}<0)} = 0.3 \pm 0.2,$$

could be sign of CP-violation in Higgs sector, if persistent

Fit results for $\Delta\phi_{jj}$



Constraints on CP-odd operators from $\Delta\phi_{jj}$ measurements

- Can constrain one of $O_{H\tilde{G}}$, $O_{H\tilde{W}}$, $O_{H\tilde{B}}$, $O_{H\tilde{W}B}$
- Blind directions: cannot distinguish between, e.g., $O_{H\tilde{G}}$ and $O_{H\tilde{W}}$

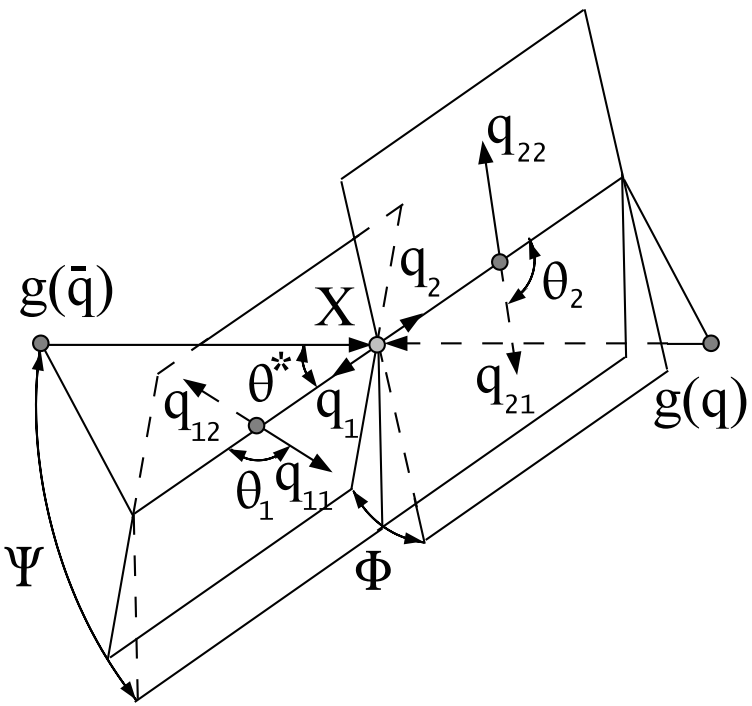
Constraints on CP-even operators

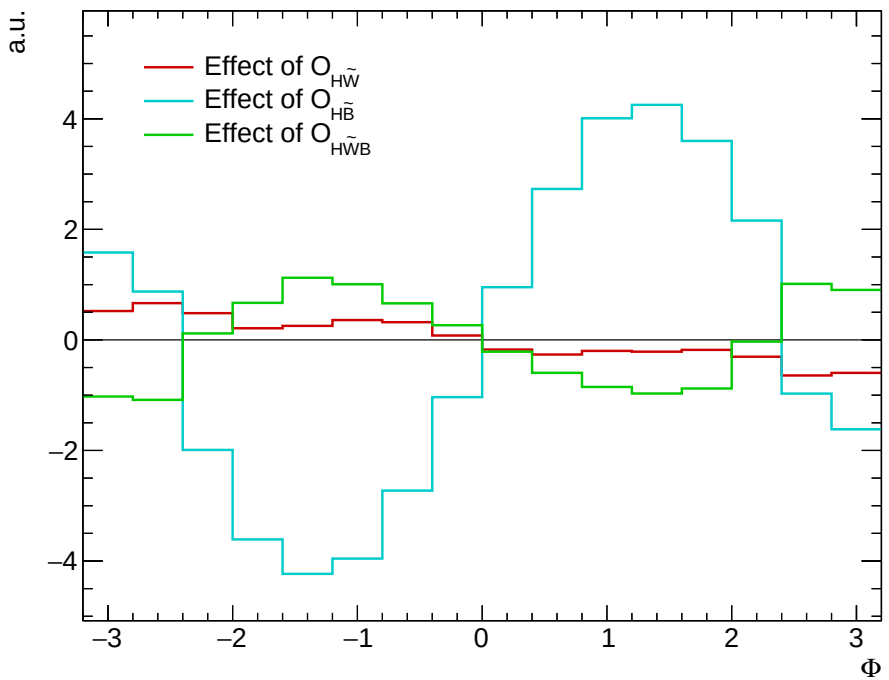
- Tightly constrained by integrated cross section and branching ratios
- Further improved by including 0 and 1 jet rate ("N_{jets}")
- With limited experimental inputs: blind directions exist for CP-even – but do not affect CP-odd operator constraints

VBF split & additional observable Φ_{ZZ}

Possible improvements to existing measurements

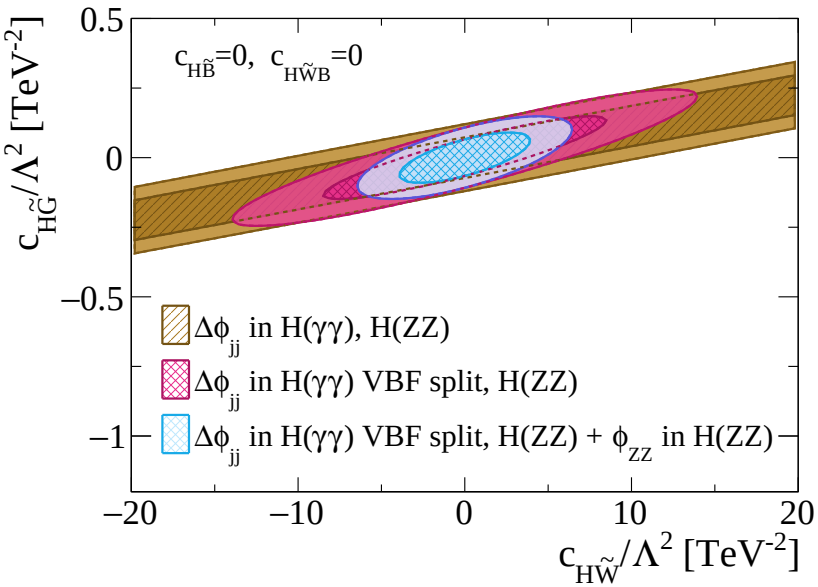
- Measure $\Delta\phi_{jj}$ in VBF enhanced/suppressed phase space
  $\rightarrow$ allows distinguishing gluon and vector boson operators
- Analyse angle Φ between Z-decay planes – a CP-odd observable
  - Already utilised in ATLAS and CMS Higgs characterisation studies
  - Can further help separating effect of $\tilde{O}_{HW}$, $\tilde{O}_{HB}, \tilde{O}_{HWB}$

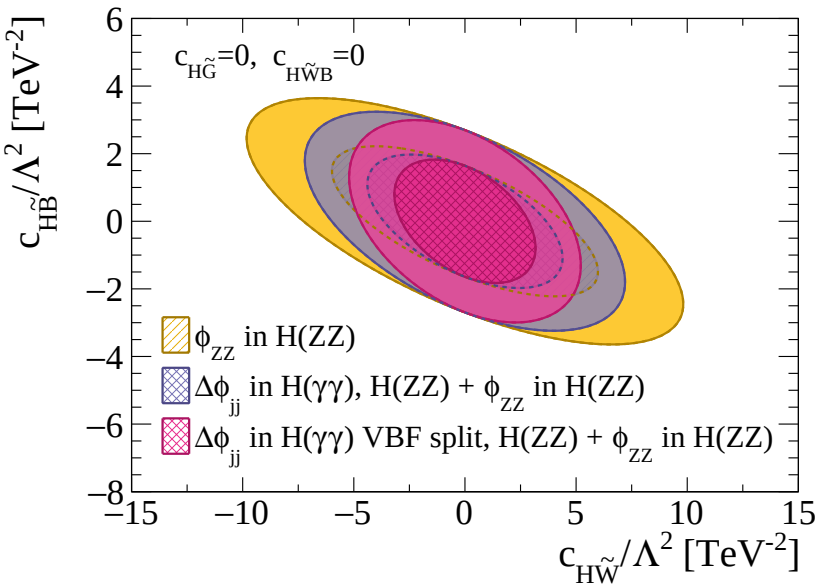




Results with pseudo data

- Now: pseudodata corresponding to SM and 36 fb^{-1}

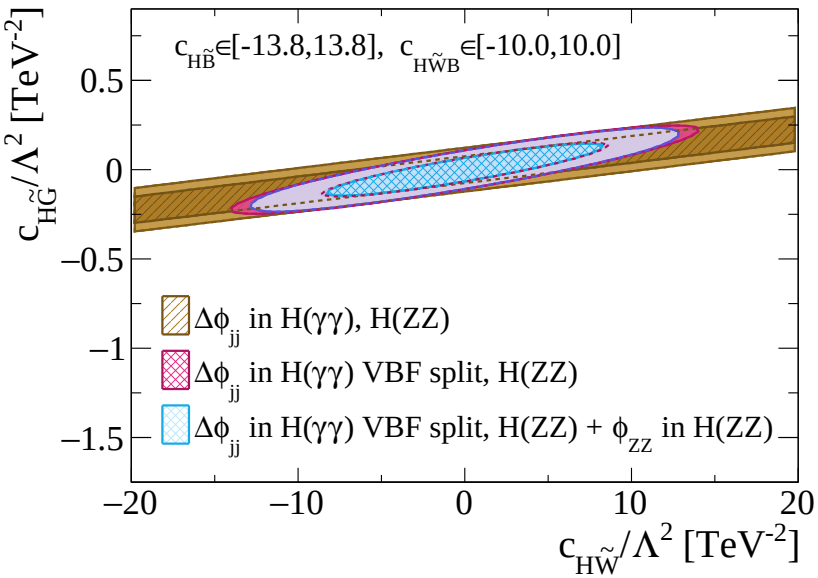


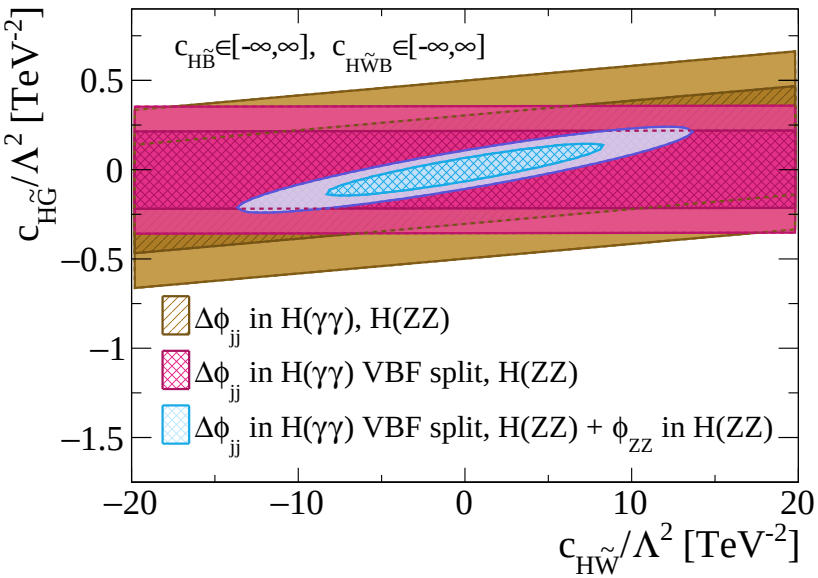


- As before: blind direction in existing $\Delta\phi_{jj}$ measurement
- Can be resolved by introduction of VBF split
- Adding Φ_{ZZ} improves constraints (significantly so for $c_{H\tilde{B}}, c_{H\tilde{W}B}$)

Results with pseudo data – marginalisation

- Now marginalising over $c_{H\tilde{B}}, c_{H\tilde{W}B} \rightarrow$ all operators potentially affected by new physics

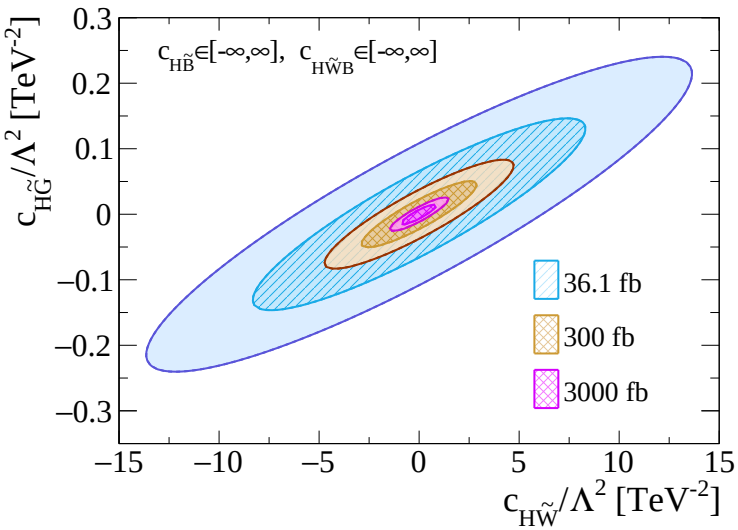




- Left: When restricting range of marginalisation to reasonably small values (respecting a perturbative constraint of $\sum_i |\sigma^i_{\text{BSM}\times\text{SM}}|/\sigma_{\text{SM}} < 0.5$) CP-odd constraints only slightly weakened
- Right: Without restriction, VBF-split not enough to resolve blind direction $\rightarrow$ but combination with Φ_{ZZ} still allows constraining all four CP-odd operators

Extrapolation of pseudodata results

- Extrapolation of Φ_{ZZ} and VBF-split ϕ_{jj} measurement, assuming relevant uncertainties are statistically dominated



Coefficient $\left[\text{TeV}^{-2}\right]$	36.1 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
$c_{H\tilde{G}}/\Lambda^2$	$[-0.19, 0.19]$	$[-0.067, 0.067]$	$[-0.021, 0.021]$
$c_{H\tilde{W}}/\Lambda^2$	$[-11, 11]$	$[-3.8, 3.8]$	$[-1.2, 1.2]$
$c_{H\tilde{B}}/\Lambda^2$	$[-5.9, 5.9]$	$[-2.1, 2.1]$	$[-0.65, 0.65]$
$c_{H\tilde{W}B}/\Lambda^2$	$[-14, 14]$	$[-4.9, 4.9]$	$[-1.5, 1.5]$

- Constrains of $\mathcal{O}(1/\text{TeV}^2)$, even $0.02/\text{TeV}^2$ for $c_{H\tilde{G}}$ with 3000 fb^{-1} (all while profiling remaining coefficients)
- Note: with higher sensitivity, quadratic terms also less relevant
- Addition of more measurements – ATLAS+CMS, WW/$\tau\tau$ channels, more observables (e.g. in WW decay) – would clearly further improve constraints

Conclusion

- Re-interpretation of Higgs measurements in linearised fit of multiple CP-odd SMEFT operators
  - Well-motivated, interesting, and useful approach
  - Modest excess in CP-odd observable found, cannot be characterised further using current measurements
  - Demonstrated: much more information on CP-odd operators could be gathered with a few simple additional measurements
- Measurement of CP-odd observables important task
  - Easy to measure but often blind spot of experimental analyses
  - One simple CP-odd observable per channel would already allow constraining multiple CP-odd operators in combined fit
  - Where possible, split by production mode useful
  - Constraints from experimental collaborations (with specific models and assumptions) of course also valuable
    $\rightarrow$ additional publication of model-independent measurement important for re-interpretation with new assumptions
  - Asymmetries in signed quantities could be sign of CP violation ☺