# EFT Acceptance studies in VHbb process.

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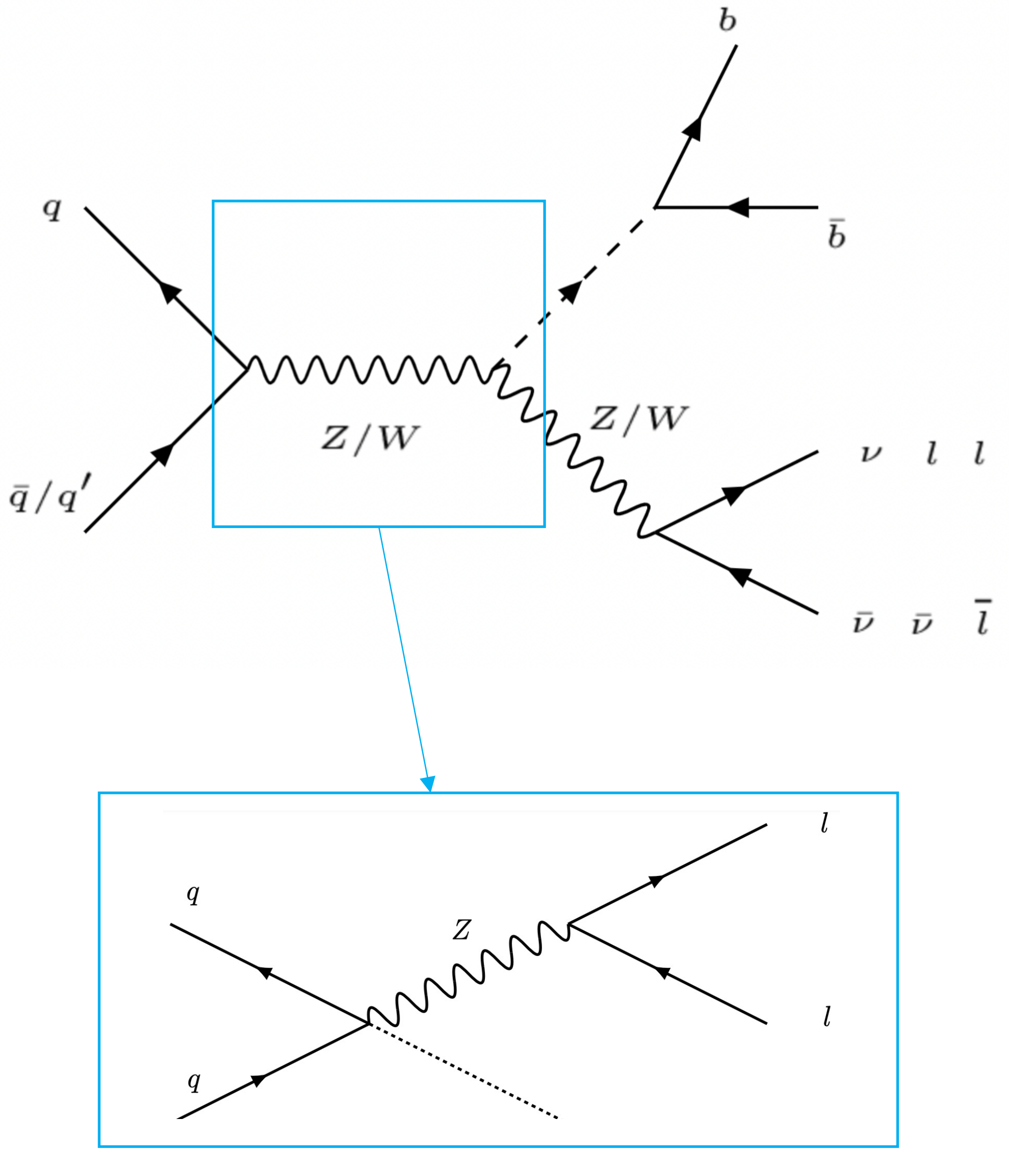
# Overview

- (VHbb) Associated vector Boson production and H to bb decay, using Effective Field Theory (EFT)
- Use Full Run-2 CMS data.
- Channel studied:
  - $Z \rightarrow \mu\mu/ee$
- Use contact interactions to replace NP interactions.



# Aim

- Compare EFT effects in Reconstructed(RECO)-level with Generator(GEN)-level.
- Obtain cross-sections in terms of EFT observables.
- Look for difference between the two caused by acceptance effect.

# EFT(Effective Field Theory)

- SMEFT(Standard Model Effective Field Theory): expansion from the standard model Higgs

$\Lambda$: set to equal 1 TeV

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots$$

- Dimension 5 and 7 violates conservation of lepton or baryon numbers
- Leading order – dimension 6
- Full set of operators generated in Warsaw Basis
- Looking for deviations of Wilson Coefficients $c_i$ from zero

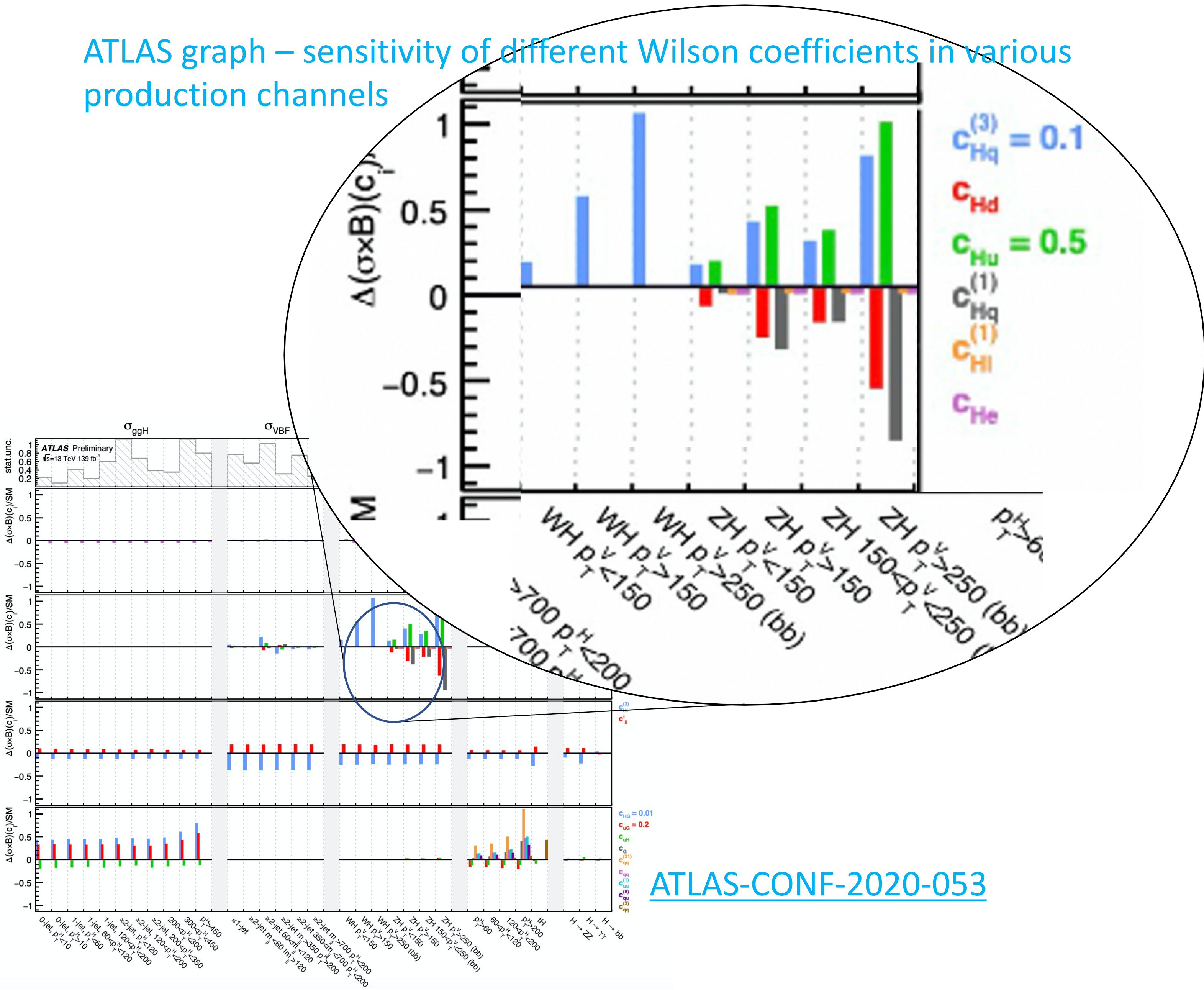
# SMEFT

- Using SMEFTsim for the leading order generation

- Most relevant Wilson Coefficients for production :
  - $c_{Hq}^{(1)}$ , $c_{Hq}^{(3)}$ , $c_{Hu}$ , $c_{Hd}$

- Different coefficients for decay

ATLAS graph – sensitivity of different Wilson coefficients in various production channels

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# STXS Framework

STXS 1.2 bin:

- 0-75 GeV
- 75-150 GeV
- 150-250 GeV 0j
- 150-250 GeV >0j
- >250 GeV

- Events are Classified according to their STXS bin
  - More fine-grained measurements
  - reduce the folded theoretical uncertainties
- Parameterize signal bins with Wilson coefficients.

arXiv:1906.02754

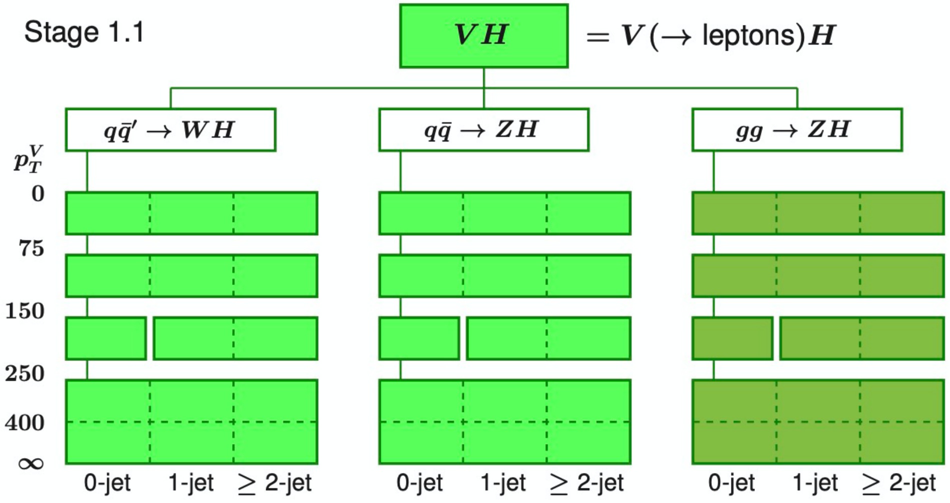


**Figure 3.** Stage 1.1 bins for $VH$ production, $V(\to \text{leptons})H$.

# STXS Parametrisation - Production

- STXS Prodution cross-section simulated in three parts:

$$\sigma_{\mathrm{STXS}} = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{int}} + \sigma_{\mathrm{BSM}}$$

- $\sigma_{int}$ : interference term, involve a single SMEFT operator, $\Lambda^{-2}$ suppression
- $\sigma_{BSM}$: pure SMEFT term, product of two SMEFT operators, $\Lambda^{-4}$ suppression

$$\frac{\sigma^i_{\mathrm{int}}}{\sigma^i_{\mathrm{SM}}} = \sum_j A_j^{\sigma_i} c_j \qquad \frac{\sigma^i_{\mathrm{BSM}}}{\sigma^i_{\mathrm{SM}}} = \sum_{jk} B_{jk}^{\sigma_i} c_j c_k$$

$$\mu_i(c_j) = \frac{\sigma_{STXS}}{\sigma_{SM}} = 1 + \sum_j A_j^i c_j + \sum_{jk} B_{jk}^i c_j c_k$$

- Assume $\Lambda^{-4}$ terms are negligible, signal event count can be expressed as linear function of the Wilson coefficients($c_j$)

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# STXS Parametrisation - Decay

- Working with SM Higgs.
- SM Higgs Boson is a scalar particle with a narrow width.
- Expect production cross section and decay width factorise:

$$(\sigma\times B)^{i,H\to X} = \sigma^i \times B^{H\to X} = \left(\sigma^i_{\rm SM} + \sigma^i_{\rm int} + \sigma^i_{\rm BSM}\right) \times \left(\frac{\Gamma^{H\to X}_{\rm SM} + \Gamma^{H\to X}_{\rm int} + \Gamma^{H\to X}_{\rm BSM}}{\Gamma^{H}_{\rm SM} + \Gamma^{H}_{\rm int} + \Gamma^{H}_{\rm BSM}}\right).$$

$$= (\sigma\times B)^{i,H\to X}_{\rm SM,((N)N)LO} \times \left(1 + \sum_j A_j^{\sigma_i} c_j\right) \times \left(\frac{1 + \sum_j A_j^{\Gamma^{H\to X}} c_j}{1 + \sum_j A_j^{\Gamma^{H}} c_j}\right)$$

$$\frac{\Gamma^{H\to X}_{\rm int}}{\Gamma^{H\to X}_{\rm SM}} = \sum_j A_j^{\Gamma^{H\to X}} c_j$$

$$\frac{\Gamma^{H}_{\rm int}}{\Gamma^{H}_{\rm SM}} = \sum_j A_j^{\Gamma^{H}} c_j$$

- Different Wilson Coefficients derived separately for the H→bb decay process
- Bins are merged because decay width doesn't depend on kinematics

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# Reweighting

- Reweight the existing Monte-Carlo samples, not generating new samples
- Separate for decay and production
- Working in the LO.
- Multiply the original Monte-Carlo weight with the ratio of the matrix-elements estimated on that event

$$W_{new} = \frac{|M_{new}|^2}{|M_{orig}|^2} W_{orig}.$$

arXiv:1607.00763

- Feynman diagrams with different Wilson coefficients embedded in the Matrix element are generated using EFT2Obs

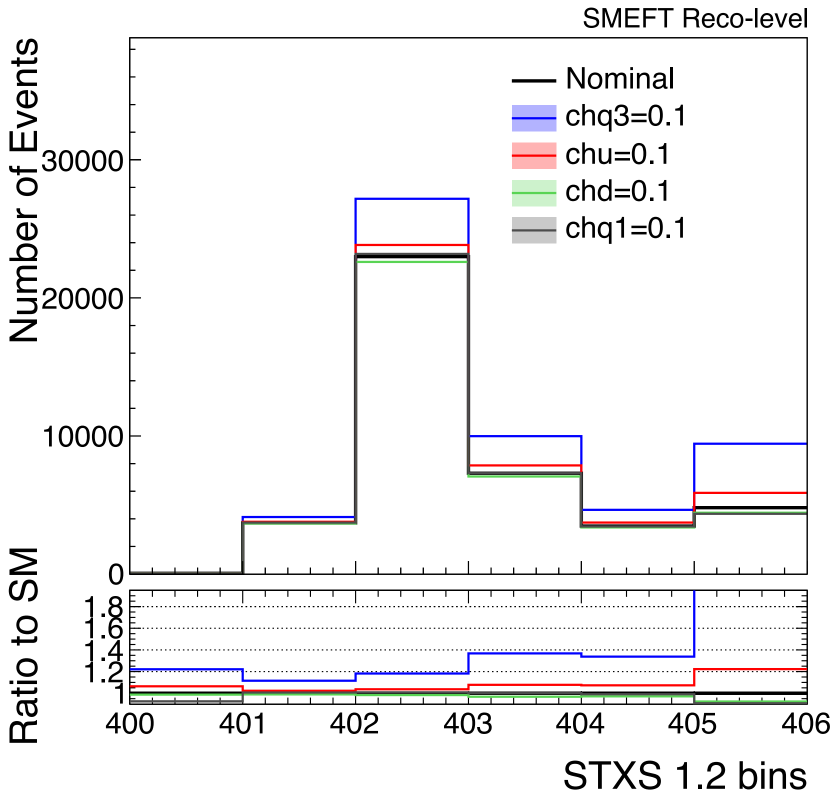
# Reweighting - Production

STXS 1.2 bin:

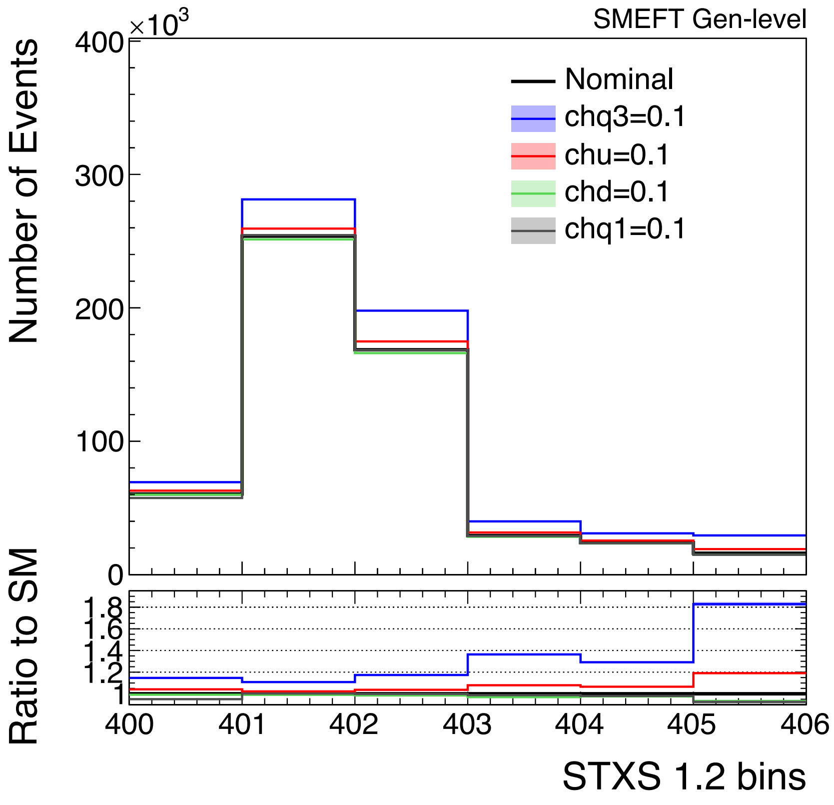
- 400 : FWD
- 401 : 0-75 GeV
- 402 : 75-150 GeV
- 403 : 150-250 GeV 0j
- 404 : 150-250 GeV >0j
- 405: >250 GeV

- Trying to see the effect if we set Wilson coefficients to be none-zero.
- Deviations from standard model is seen – so some of them must have non-zero parameters.

Reco-level




Gen-level



# Parameter Table – Production

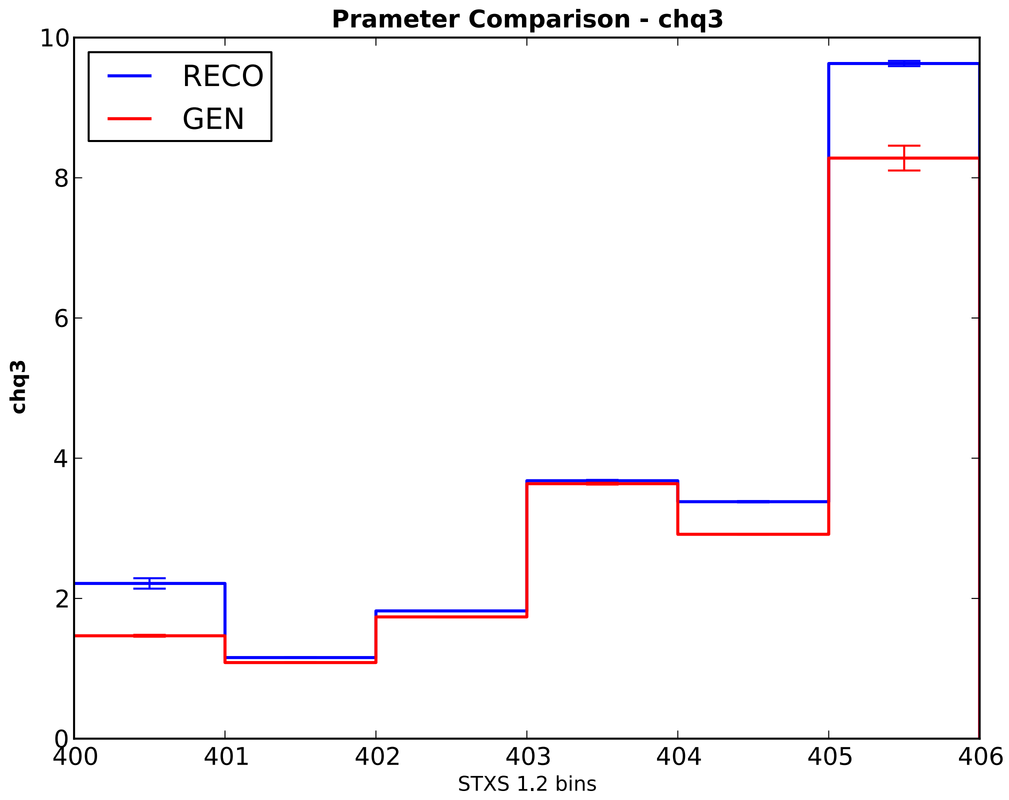
| STXS Bins | Parametrisation: RECO-level |
|---|---|
| 400–401 | $1-0.75\ c_{Hq}^{(1)}+2.21\ c_{Hq}^{(3)}+0.64\ c_{Hu}-0.13\ c_{Hd}+0.82\ c_{HW}+0.37\ c_{HWB}$ |
| 401–402 | $1+0.07\ c_{Hq}^{(1)}+1.16\ c_{Hq}^{(3)}+0.23\ c_{Hu}-0.11\ c_{Hd}+0.67\ c_{HW}+0.32\ c_{HWB}$ |
| 402–403 | $1+0.09\ c_{Hq}^{(1)}+1.82\ c_{Hq}^{(3)}+0.37\ c_{Hu}-0.17\ c_{Hd}+0.75\ c_{HW}+0.34\ c_{HWB}$ |
| 403–404 | $1+0.01\ c_{Hq}^{(1)}+3.68\ c_{Hq}^{(3)}+0.78\ c_{Hu}-0.32\ c_{Hd}+0.87\ c_{HW}+0.38\ c_{HWB}$ |
| 404–405 | $1-0.09\ c_{Hq}^{(1)}+3.38\ c_{Hq}^{(3)}+0.73\ c_{Hu}-0.29\ c_{Hd}+0.85\ c_{HW}+0.37\ c_{HWB}$ |
| 405–406 | $1-0.92\ c_{Hq}^{(1)}+9.63\ c_{Hq}^{(3)}+2.23\ c_{Hu}-0.76\ c_{Hd}+0.94\ c_{HW}+0.40\ c_{HWB}$ |

| STXS Bins | Parametrisation: GEN-level |
|---|---|
| 400–401 | $1-0.49\ c_{Hq}^{(1)}+1.47\ c_{Hq}^{(3)}+0.42\ c_{Hu}-0.08\ c_{Hd}+0.72\ c_{HW}+0.33\ c_{HWB}$ |
| 401–402 | $1+0.03\ c_{Hq}^{(1)}+1.09\ c_{Hq}^{(3)}+0.22\ c_{Hu}-0.10\ c_{Hd}+0.64\ c_{HW}+0.30\ c_{HWB}$ |
| 402–403 | $1-0.01\ c_{Hq}^{(1)}+1.74\ c_{Hq}^{(3)}+0.37\ c_{Hu}-0.15\ c_{Hd}+0.75\ c_{HW}+0.34\ c_{HWB}$ |
| 403–404 | $1-0.12\ c_{Hq}^{(1)}+3.64\ c_{Hq}^{(3)}+0.79\ c_{Hu}-0.31\ c_{Hd}+0.89\ c_{HW}+0.38\ c_{HWB}$ |
| 404–405 | $1-0.19\ c_{Hq}^{(1)}+2.91\ c_{Hq}^{(3)}+0.66\ c_{Hu}+-0.24\ c_{Hd}+0.83\ c_{HW}+0.36\ c_{HWB}$ |
| 405–406 | $1-0.74\ c_{Hq}^{(1)}+8.28\ c_{Hq}^{(3)}+1.91\ c_{Hu}-0.66\ c_{Hd}+0.94\ c_{HW}+0.39\ c_{HWB}$ |

STXS 1.2 bin:

- 400 : FWD
- 401 : 0-75 GeV
- 402 : 75-150 GeV
- 403 : 150-250 GeV 0j
- 404 : 150-250 GeV >0j
- 405: >250 GeV

# Parameter Comparison – Production




- Quite Consistent
- Deviation observed– acceptance effect

STXS 1.2 bin:

400 : FWD

401 : 0-75 GeV

402 : 75-150 GeV

403 : 150-250 GeV 0j

404 : 150-250 GeV >0j

405: >250 GeV

# Parameter Table - Production

- Compared with ATLAS results of parametrization at RECO-level
- Slight difference due to different acceptances and ATLAS study included more Wilson coeffients
- We are only comparing the most important ones$(c_{Hq}^{(1)}, c_{Hq}^{(3)}, c_{Hu}, c_{Hd})$
- Overall quite consistent

Comparison graph in appendix

Our Measurement

| STXS Bins | Parametrisation: RECO-level |
|---|---|
| 400–401 | $1 - 0.75\ c_{Hq}^{(1)} + 2.21\ c_{Hq}^{(3)} + 0.64\ c_{Hu} - 0.13\ c_{Hd} + 0.82\ c_{HW} + 0.37\ c_{HWB}$ |
| 401–402 | $1 + 0.07\ c_{Hq}^{(1)} + 1.16\ c_{Hq}^{(3)} + 0.23\ c_{Hu} - 0.11\ c_{Hd} + 0.67\ c_{HW} + 0.32\ c_{HWB}$ |
| 402–403 | $1 + 0.09\ c_{Hq}^{(1)} + 1.82\ c_{Hq}^{(3)} + 0.37\ c_{Hu} - 0.17\ c_{Hd} + 0.75\ c_{HW} + 0.34\ c_{HWB}$ |
| 403–404 | $1 + 0.01\ c_{Hq}^{(1)} + 3.68\ c_{Hq}^{(3)} + 0.78\ c_{Hu} - 0.32\ c_{Hd} + 0.87\ c_{HW} + 0.38\ c_{HWB}$ |
| 404–405 | $1 - 0.09\ c_{Hq}^{(1)} + 3.38\ c_{Hq}^{(3)} + 0.73\ c_{Hu} - 0.29\ c_{Hd} + 0.85\ c_{HW} + 0.37\ c_{HWB}$ |
| 405–406 | $1 - 0.92\ c_{Hq}^{(1)} + 9.63\ c_{Hq}^{(3)} + 2.23\ c_{Hu} - 0.76\ c_{Hd} + 0.94\ c_{HW} + 0.40\ c_{HWB}$ |

ATLAS Measurement

| Category in $qq \to H\ell\ell$ | Parametrisation |
|---|---|
| $p_T^V$<75 | $0.12c_{H\Box} + 0.0129c_{HDD} + 0.665c_{HW} + 0.0835c_{HB} + 0.303c_{HWB} - 0.0362c_{Hl}^{(1)} - 0.241c_{Hl}^{(3)} - 0.0359c_{He} + 0.029c_{Hq}^{(1)} + 1.27c_{Hq}^{(3)} + 0.245c_{Hu} - 0.1064c_{Hd} + 0.183c'_{ll}$ |
| $p_T^V$<150 | $0.12c_{H\Box} + 0.0128c_{HDD} + 0.771c_{HW} + 0.092c_{HB} + 0.341c_{HWB} - 0.0360c_{Hl}^{(1)} - 0.238c_{Hl}^{(3)} - 0.0362c_{He} + 0.01c_{Hq}^{(1)} + 1.80c_{Hq}^{(3)} + 0.403c_{Hu} - 0.166c_{Hd} + 0.182c'_{ll}$ |
| $p_T^V$<250, $N_{\text{jets}}$=0 | $0.12c_{H\Box} + 0.013c_{HDD} + 0.86c_{HW} + 0.103c_{HB} + 0.366c_{HWB} - 0.035c_{Hl}^{(1)} - 0.232c_{Hl}^{(3)} - 0.0358c_{He} - 0.12c_{Hq}^{(1)} + 3.63c_{Hq}^{(3)} + 0.87c_{Hu} - 0.323c_{Hd} + 0.177c'_{ll}$ |
| $p_T^V$<250, $N_{\text{jets}}\geq$1 | $0.12c_{H\Box} + 0.013c_{HDD} + 0.85c_{HW} + 0.102c_{HB} + 0.373c_{HWB} - 0.036c_{Hl}^{(1)} - 0.230c_{Hl}^{(3)} - 0.0367c_{He} - 0.10c_{Hq}^{(1)} + 3.19c_{Hq}^{(3)} + 0.77c_{Hu} - 0.282c_{Hd} + 0.177c'_{ll}$ |
| $p_T^V$>250 | $0.12c_{H\Box} + 0.010c_{HDD} + 0.88c_{HW} + 0.135c_{HB} + 0.41c_{HWB} - 0.037c_{Hl}^{(1)} - 0.234c_{Hl}^{(3)} - 0.036c_{He} - 1.12c_{Hq}^{(1)} + 9.9c_{Hq}^{(3)} + 2.51c_{Hu} - 0.81c_{Hd} + 0.181c'_{ll}$ |

# Parameter Table - Decay

Our Measurement

| STXS Bins | Parametrisation: RECO-level |
|---|---|
| 400–406 | $1 + 0.12\ c_{H\Box} + -0.03\ c_{HDD} + -0.12\ c_{dH} + -0.12\ c^{(3)}_{Hl} + 0.06\ c'_{ll}$ |

ATLAS Measurement

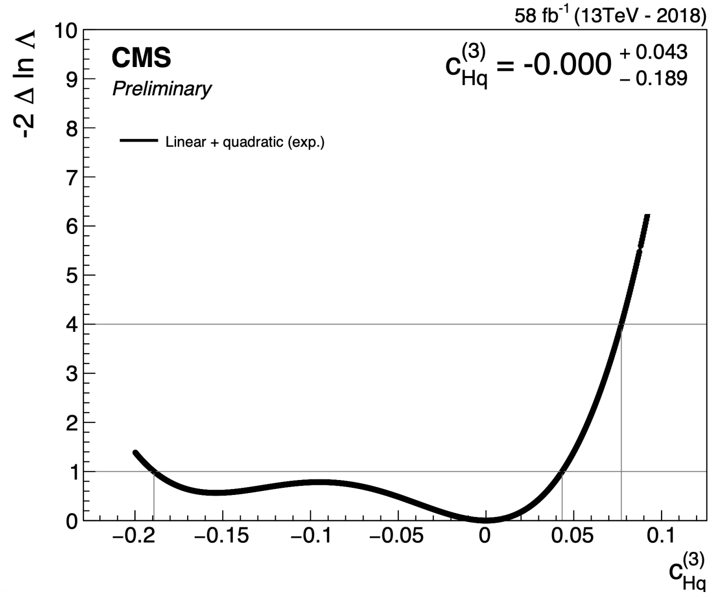
| Channel | $\Gamma_{\mathrm{int}}/\Gamma_{\mathrm{SM}}$ |
|---|---|
| $H \to \gamma\gamma$ | $-40.15c_{HB} - 13.08c_{HW} + 22.4c_{HWB} - 0.9463c_{W} + 0.12c_{H\Box} - 0.2417c_{HDD} + 0.03447c_{uH} - 1.151c_{uW} - 2.150c_{uB} - 0.3637c^{(3)}_{Hl} + 0.1819c'_{ll}$ |
| $H \to ZZ^* \to 4\ell$ | $0.12c_{H\Box} + 0.005c_{HDD} - 0.296c_{HW} - 0.197c_{HB} + 0.296c_{HWB} + 0.126c^{(1)}_{Hl} - 0.234c^{(3)}_{Hl} - 0.101c_{He} + 0.181c'_{ll}$ |
| $H \to b\bar{b}$ (VH) | $0.12c_{H\Box} - 0.030c_{HDD} - 0.121c_{dH} - 0.121c^{(3)}_{Hl} + 0.061c'_{ll}$ |
| Total | $-0.001c_{W} + 0.12c_{H\Box} - 0.030c_{HDD} + 1.362c_{HG} - 0.048c_{HW} - 0.049c_{HB} + 0.046c_{HWB} - 0.005c_{eH} - 0.012c_{uH} - 0.085c_{dH} + 0.051c_{uG} - 0.002c_{uW} - 0.003c_{uB} - 0.150c^{(3)}_{Hl} + 0.013c^{(3)}_{Hq} + 0.079c'_{ll}$ |

- Different Wilson Coefficients due to different interaction.
- Very Consistent with ATLAS measurement – bins are merged, so less deviation.

Reminder: bins are merged because decay width has no dependence on P_t

# SUMMARY

- Ran selection on GEN-level data – obtain RECO data
- Reweighted the Monte Carlo samples in both GEN and RECO level
- Parametrised Wilson Coefficients in both cases
- Compared to see difference caused by acceptance effect.
- Small deviation observed, but generally consistent
- Possible next step:
  - Do a linear likelihood fit on the Wilson Coefficients



# Thank you!

# APPENDIX

- Parameter table - RECO

Bin 0 numEntries: 694 mean: 0.0804 stderr: 0.00096
edges: [400.0, 401.0]

| Term | Val | Uncert | Rel. uncert. |
|---|---|---|---|
| chq1 | -0.7516 | 0.1085 | 0.1444 |
| chq3 | 2.2140 | 0.0744 | 0.0336 |
| chu | 0.6421 | 0.0381 | 0.0593 |
| chd | -0.1275 | 0.0091 | 0.0710 |
| chw | 0.8211 | 0.0222 | 0.0270 |
| chwb | 0.3660 | 0.0105 | 0.0288 |

Bin 1 numEntries: 46362 mean: 0.0799 stderr: 0.000125
edges: [401.0, 402.0]

| Term | Val | Uncert | Rel. uncert. |
|---|---|---|---|
| chq1 | 0.0671 | 0.0060 | 0.0901 |
| chq3 | 1.1566 | 0.0028 | 0.0024 |
| chu | 0.2305 | 0.0015 | 0.0067 |
| chd | -0.1071 | 0.0006 | 0.0058 |
| chw | 0.6730 | 0.0017 | 0.0025 |
| chwb | 0.3153 | 0.0012 | 0.0037 |

Bin 2 numEntries: 286102 mean: 0.0803 stderr: 4.75e-05
edges: [402.0, 403.0]

| Term | Val | Uncert | Rel. uncert. |
|---|---|---|---|
| chq1 | 0.0858 | 0.0042 | 0.0494 |
| chq3 | 1.8224 | 0.0025 | 0.0014 |
| chu | 0.3676 | 0.0010 | 0.0027 |
| chd | -0.1667 | 0.0005 | 0.0031 |
| chw | 0.7530 | 0.0008 | 0.0010 |
| chwb | 0.3394 | 0.0004 | 0.0012 |

Bin 5 numEntries: 60062 mean: 0.0801 stderr: 0.000107
edges: [405.0, 406.0]

| Term | Val | Uncert | Rel. uncert. |
|---|---|---|---|
| chq1 | -0.9244 | 0.0541 | 0.0585 |
| chq3 | 9.6298 | 0.0373 | 0.0039 |
| chu | 2.2291 | 0.0152 | 0.0068 |
| chd | -0.7609 | 0.0053 | 0.0070 |
| chw | 0.9422 | 0.0043 | 0.0045 |
| chwb | 0.3990 | 0.0019 | 0.0046 |

Bin 4 numEntries: 41337 mean: 0.0841 stderr: 2.51e-05
edges: [404.0, 405.0]

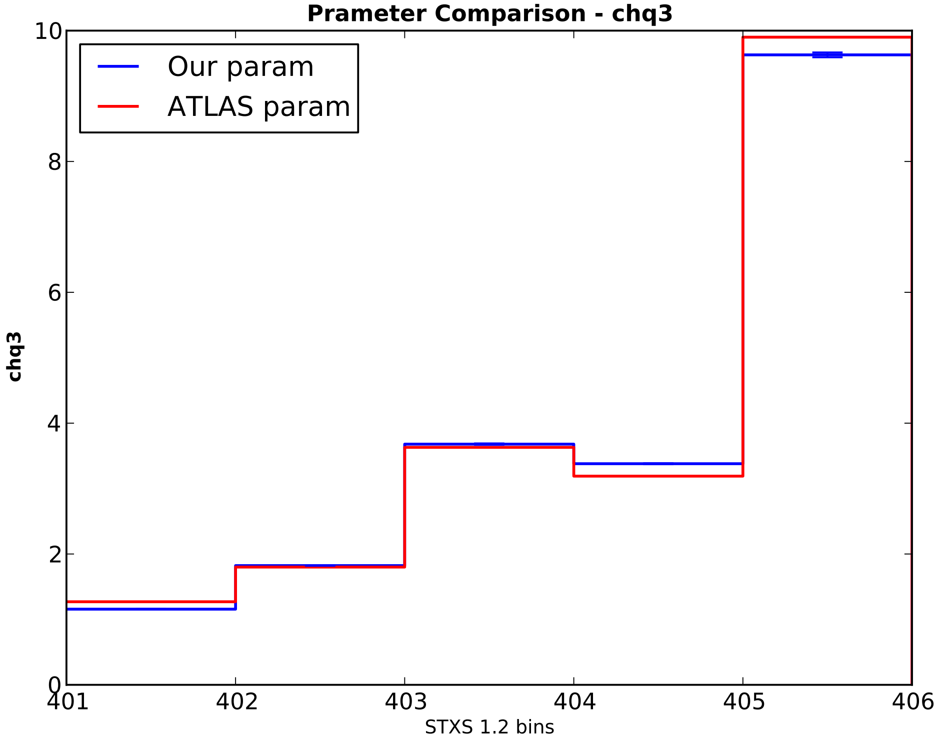
| Term | Val | Uncert | Rel. uncert. |
|---|---|---|---|
| chq1 | -0.0902 | 0.0186 | 0.2065 |
| chq3 | 3.3800 | 0.0084 | 0.0025 |
| chu | 0.7320 | 0.0046 | 0.0063 |
| chd | -0.2855 | 0.0018 | 0.0063 |
| chw | 0.8477 | 0.0025 | 0.0030 |

Bin 3 numEntries: 92882 mean: 0.0786 stderr: 9.96e-05
edges: [403.0, 404.0]

| Term | Val | Uncert | Rel. uncert. |
|---|---|---|---|
| chq1 | 0.0057 | 0.0166 | 2.9139 |
| chq3 | 3.6793 | 0.0114 | 0.0031 |
| chu | 0.7772 | 0.0055 | 0.0071 |
| chd | -0.3216 | 0.0015 | 0.0048 |
| chw | 0.8713 | 0.0021 | 0.0024 |
| chwb | 0.3777 | 0.0010 | 0.0025 |

# APPENDIX

- Parameter comparison with ATLAS



# APPENDIX

- Decay Width formula – no dependence on kinematics:

$$\Gamma^{(4,0)} = \frac{N_c m_H m_b^2}{8\pi \hat{v}_T^2} ,$$

$$\hat{v}_T \equiv \frac{2 M_W \hat{s}_w}{e}, \qquad \hat{c}_w^2 \equiv \frac{M_W^2}{M_Z^2}, \qquad \hat{s}_w^2 \equiv 1 - \hat{c}_w^2 .$$

$$\Gamma^{(6,0)} = 2\Gamma^{(4,0)} \left[ C_{H\Box} - \frac{C_{HD}}{4} \left( 1 - \frac{\hat{c}_w^2}{\hat{s}_w^2} \right) + \frac{\hat{c}_w}{\hat{s}_w} C_{HWB} - \frac{\hat{v}_T}{m_b} \frac{C_{bH}}{\sqrt{2}} \right] \hat{v}_T^2 .$$

arXiv:1904.06358

- STXS bins are classified according to their P_t.