# Experience with EFT fits to Higgs data

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# Overview



- Motivation
- ATLAS STXS measurement
- EFT models
- Procedure to relate EFT to measurements
- Fits using HEL and SMEFTsim models
- STXS prospects

# Overview map

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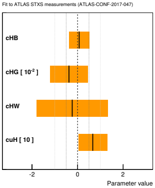
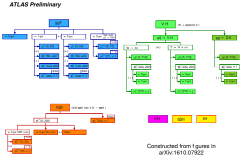
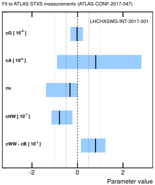



SMEFT

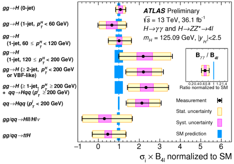
ATLAS EXPERIMENT

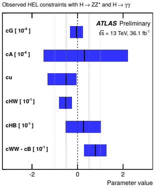



HEL




HEL




LHCHXSWG-INT-2017-001 ATLAS-CONF-2017-047 ATL-PHYS-PUB-2017-018

# Motivation



- Prepare experiments for EFT fits by designing strategies and providing tools for fitting Higgs measurements.
  - Working within the LHC Higgs WG
- Use public EFT implementations to develop parameterizations
- Apply fit procedures to an example set of STXS measurements

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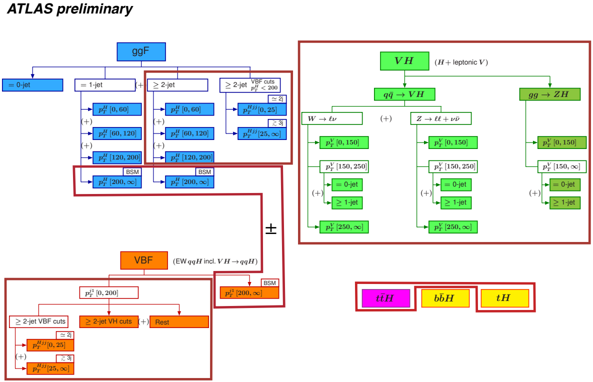
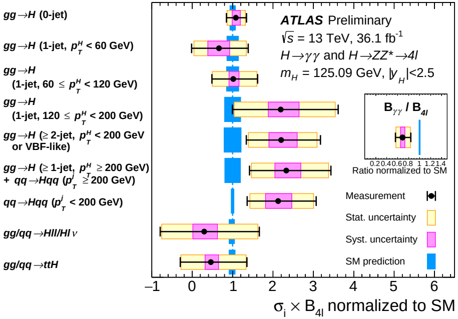
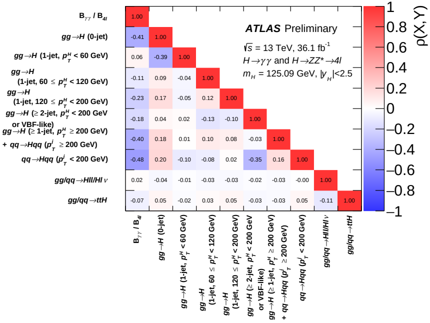
- The STXS are an evolution from inclusive production cross section measurements to production cross sections split into a few kinematic regions, which are most sensitive to new physics.

- Measured at the generator level.
- STXS stage 1 binning is on the right. Red boxes show how ATLAS merged the bins in ATLAS-CONF-2017-047.



# ATLAS STXS results




- The value of the difference between $qq \to Hqq\ p_{\mathrm{T}}^{j} \geq 200\ GeV$ and $gg \to H\ p_{\mathrm{T}}^{H} \geq 200$ GeV is not shown due to the low experimental sensitivity: the fit result is $1.7^{+1.7}_{-1.5}$ pb while SM prediction is $0.4$ pb.

# EFT models

- Use Madgraph with Feynrules models HEL and SMEFTsim
- Dimension 6 operators, at LO.
- HEL - used as effective Lagrangian:
  - SILH basis with no four-fermion operators and assuming flavour-universal couplings

*A. Alloul, B. Fuks, V. Sanz*

- SMEFTsim - complete Warsaw basis implementation:
  - includes all four-fermion couplings and flavour dependence: 2499 parameters
  - use $U(3)^5$ symmetry assumption: 76 parameters
  - two sets of equivalent models for validation

*I. Brivio, Y. Jiang, M. Trott*

# Relating STXS bins to EFT

- Parameterize each STXS production bin, partial decay width, and total width:
  - Derive interference-only and quadratic-only terms with dedicated MadGraph options:

$$\frac{\sigma}{\sigma_{\rm SM}} = 1 + \sum_i A_i \bar{c}_i + \sum_{ij} B_{ij} \bar{c}_i \bar{c}_j \qquad (1)$$

  - Include dependence on width:

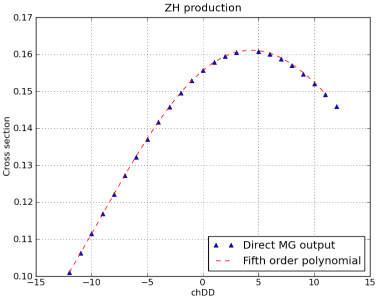
$$\sigma = \sigma_{SM}(\Delta w_p) + A_i(\Delta w_p) c_i \qquad (2)$$

$$A(\Delta w) = A(0) + a_p \Delta w_p + b_{pq} \Delta w_p \Delta w_q + .. \qquad (3)$$

$$w = w_{SM} + k_i c_i + t_{ij} c_i c_j \qquad (4)$$

$$\Rightarrow \ \sigma = \sigma_{SM}(0) + a_p k_i^p c_i + A_i(0) c_i \qquad (5)$$

Left: derivation of 5th-order dependence on Wilson coefficients, and the linearized dependence [5].



# HEL fits

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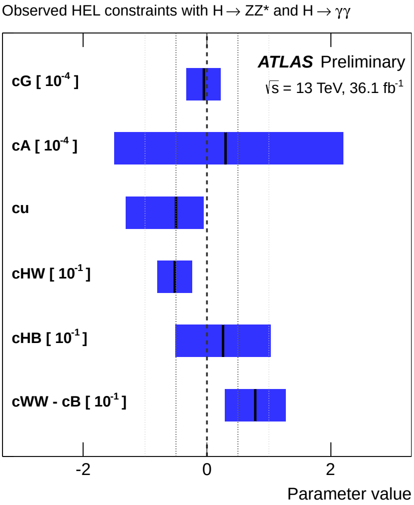
- Fit to an effective Lagrangian (includes quadratic dependence on Wilson coefficients)
- ATLAS: fit to STXS full stage 1 binning, external to ATLAS: fit to merged version of stage 1.
- Operators aimed to be constrained:

| Operator | Expression | HEL coefficient | Vertices |
|---|---|---|---|
| $\mathcal{O}_g$ | $\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$ | $\texttt{cG} = \frac{m_W^2}{g_s^2}\bar{c}_g$ | $Hgg$ |
| $\mathcal{O}_\gamma$ | $\|H\|^2 B_{\mu\nu} B^{\mu\nu}$ | $\texttt{cA} = \frac{m_W^2}{g'^2}\bar{c}_\gamma$ | $H\gamma\gamma, HZZ$ |
| $\mathcal{O}_u$ | $y_u \|H\|^2 \bar{u}_l H u_R +$ h.c. | $\texttt{cu} = v^2 \bar{c}_u$ | $Ht\bar{t}$ |
| $\mathcal{O}_{HW}$ | $i\,(D^\mu H)^\dagger\, \sigma^a\, (D^\nu H)\, W^a_{\mu\nu}$ | $\texttt{cHW} = \frac{m_W^2}{g}\bar{c}_{HW}$ | $HWW, HZZ$ |
| $\mathcal{O}_{HB}$ | $i\,(D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu}$ | $\texttt{cHB} = \frac{m_W^2}{g'}\bar{c}_{HB}$ | $HZZ$ |
| $\mathcal{O}_W$ | $i\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$ | $\texttt{cWW} = \frac{m_W^2}{g}\bar{c}_W$ | $HWW, HZZ$ |
| $\mathcal{O}_B$ | $i\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$ | $\texttt{cB} = \frac{m_W^2}{g'}\bar{c}_B$ | $HZZ$ |

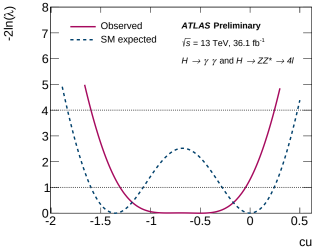
- Other parameters are set to zero based on their constraints from other measurements.
- Full HEL equations documented in LHCHXSWG-INT-2017-001, WG2 twiki

# ATLAS EFT results



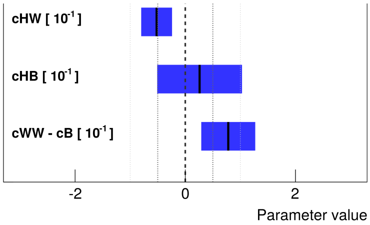


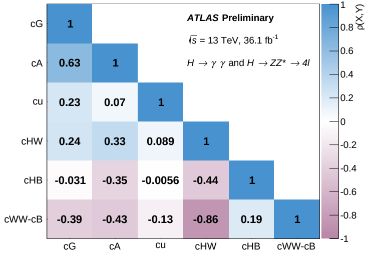

- Quoted central values are those closest to the SM predictions.
- cu's observed likelihood has a small local maximum between the two solutions, leading to an asymmetric uncertainty.




Profiled likelihood scan of cu parameter.

# Results: cHW and cWW-cB

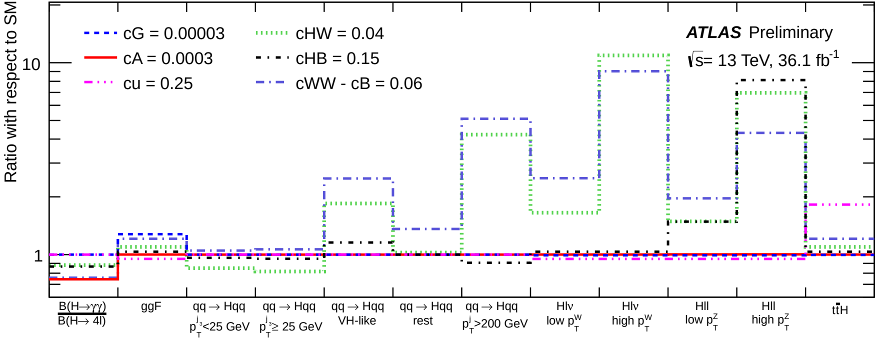



- cHW and cWW-cB are strongly anticorrelated.
- Part of the reason - similar impact on STXS bins.

# Results: impact plot

- Impact plot: values of STXS regions relative to the SM, for $\approx +1\sigma$ expected SM values.
- cHW and cWW-cB have similar impact.
- Different WH and ZH profile show sensitivity to cHB.



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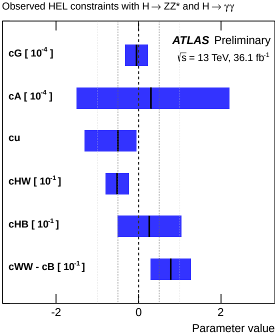
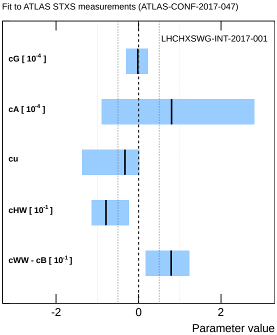
# Study using STXS measurements

- Later replicated study using STXS measurements.
- Fit to public results loses sensitivity to one parameter (cHB, cHW or cWW-cB) due to WH and ZH merging.
- Other parameters have similar constraints in both studies.




Left: ATLAS-CONF-2017-047
*ATLAS*

Right: LHCHXSWG-INT-2017-001
*C. Hays, V. Sanz, G. Žemaitytė*

# SMEFTsim fits



- Warsaw basis, with $\Lambda = 1$ TeV.
- Use linear interference terms only.
- External to ATLAS: fit to merged version of STXS stage 1.
- Operators aimed to be constrained:

| Operator | Expression | SMEFT coefficient | Production/ decay |
|---|---|---|---|
| $\mathcal{O}_{HG}$ | $H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$ | *cHG* | *ggf,* |
| $\mathcal{O}_{HW}$ | $H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$ | *cHW* | $H\gamma\gamma$, *HZZ, WH, ZH, VBF* |
| $\mathcal{O}_{HB}$ | $H^\dagger H B_{\mu\nu} B^{\mu\nu}$ | *cHB* | $H\gamma\gamma$, *HZZ, ZH, VBF* |
| $\mathcal{O}_{HWB}$ | $H^\dagger H \tau^I W^I_{\mu\nu} B^{\mu\nu}$ | *cHWB* | $H\gamma\gamma$, *HZZ, ZH, VBF* |
| $\mathcal{O}_{uH}$ | $H^\dagger H \bar{q}_p u_r \widetilde{H}$ | *cuH* | *ttH, ggf* |

# SMEFTsim four parameter fit

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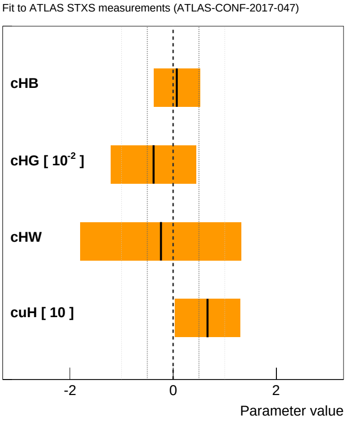
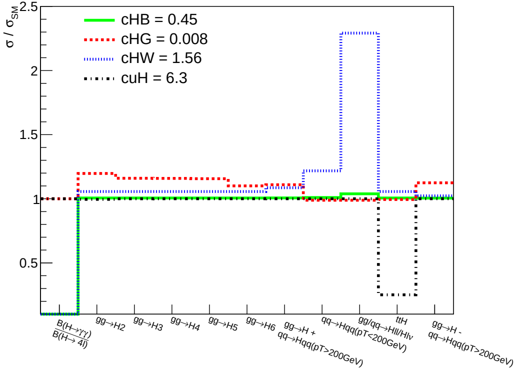
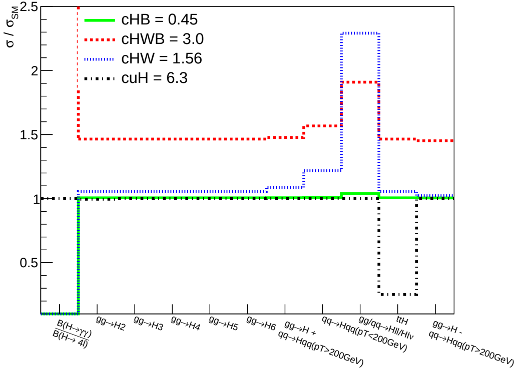
- Fit to ATLAS public STXS measurements using SMEFTsim.
- Right: values of merged STXS regions for $\approx +1\sigma$ data values. Each parameter has a distinct profile.



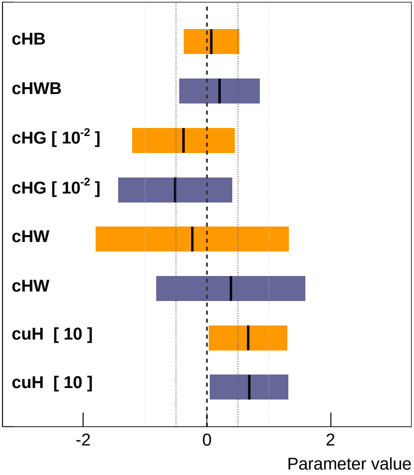
# Alternative fits

- Based on impact plot that includes cHWB(=3.0), we can see what other four parameter subsets can be fitted.



# Replacing cHB by cHWB

Fit to ATLAS STXS measurements (ATLAS-CONF-2017-047)




- The plot shows two different four parameter fits:
  - Orange: cG, cHW, cuH, cHB
  - Violet: cG, cHW, cuH, cHWB
- Similar constraints on cHG and cuH.

# Extending to an SMEFT fit

- Individual experimental measurements sensitive to isolated parameter set at LO.
- Ideally: each measurement provides the multidimensional likelihood for this parameter set.
- To a good approximation: parameters highly constrained by external measurements can be fixed.
  - Not a replacement for a rigorous fit but can be useful for studies.
- Fits that constrain the reduced parameter set could quote the dependence on the other parameter values.

# Dependence on unfit parameters

The likelihood L is expressed as:

$$-2\log L = (Ac - D)^T M (Ac - D) \tag{6}$$

*where A is the EFT equation matrix, c is the Wilson coefficient vector, D is the vector of data deviation from SM, M - the inverse of covariance matrix.*

Let A'c' be EFT matrix and (externally determined) Wilson vector of not fitted Wilson parameters (i.e. the ones that we usually set to 0), then likelihood is:

$$-2\log L = (Ac + A'c' - D)^T M (Ac + A'c' - D) \tag{7}$$

When we assume that c' is constant vector, then A'c' can be interpreted as corrections to data deviations from SM:

$$D \longrightarrow D - A'c' \tag{8}$$

then solution to (7):

$$c = (A^T M A)^{-1} A^T M (D - A'c') = (A^T M A)^{-1} A^T M D - (A^T M A)^{-1} A^T M A' c' \tag{9}$$

$(A^T M A)^{-1} A^T M D$ - central value, $-(A^T M A)^{-1} A^T M A'$ - prefactors for unfitted coefficients.

# Unfitted Wilsons: example

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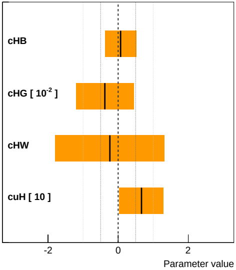
Fit to ATLAS STXS measurements (ATLAS-CONF-2017-047)



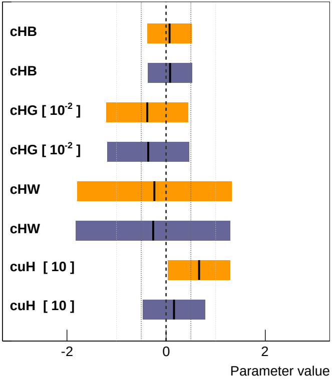

$$\text{cHB} = 0.071 + 0.68 \cdot cHWB - 1.5 \cdot cHl3 + ..$$

$$\text{cHG} = -0.0038 + 0.1 \cdot cHl3 - 0.1 \cdot cHq3 + ..$$

$$\text{cHW} = -0.24 - 0.19 \cdot cHbox - 0.16 \cdot cHDD + ..$$

$$\text{cuHAbs} = 6.7 + 0.84 \cdot cHbox + 0.5 \cdot cHDD + ..$$

Fit to ATLAS STXS measurements (ATLAS-CONF-2017-047)

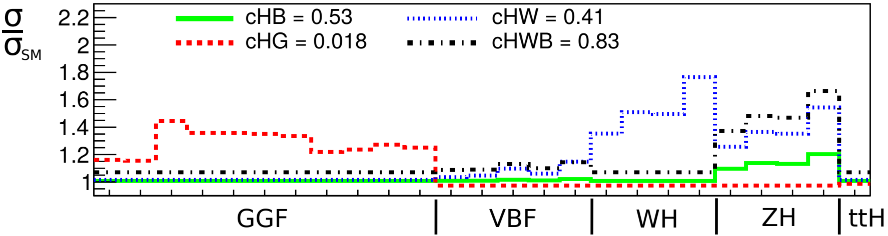



- External constraints give an indication of uncertainties:
  - Orange: other parameters set to 0 vs violet: not fitted parameters set to values from a global fit from *1803.03252, J. Ellis, C.W. Murphy, V. Sanz, T. You*.
  - Central values shift unsignificantly.

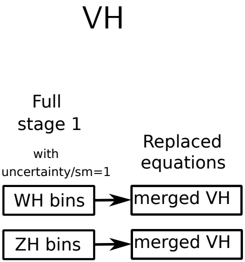
| Wilson | $c_i' = 0$ | Best-fit $c_i'$ | $c_i' \pm 1\sigma$ ($c_i$ furthest from SM) |
|---|---|---|---|
| cHB | 0.071 | 0.081 | 0.089 |
| cHW | -0.24 | -0.26 | -0.28 |
| cHG | -0.0038 | -0.0036 | -0.0035 |
| cuH | 6.7 | 4.2 | 1.6 |

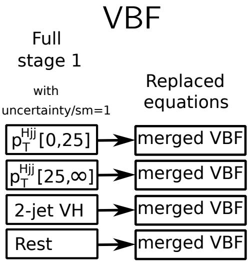
# STXS stage 1 prospects

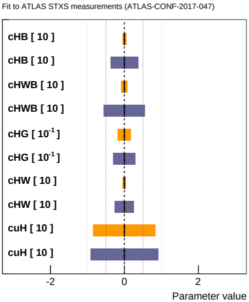
- Let's assume that having full STXS stage 1 we measure bins with uncertainty/sm ≈1.
- ggf bins are not that interesting at LO, VH and VBF bins have potential to constrain 5 parameters (cHW, cHB, cHWB, cHG, cuH):

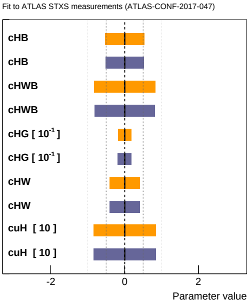


# VH and VBF bins




- Assuming uncertainty/sm ≈1.
- Plots: orange - full stage 1; left violet: WH, ZH equations replaced by merged VH; right violet: VBF equations are replaced by VBF merged.
- VBF granularity is not important - results have not changed much.
- Using VH merged equations give much larger uncertainties.

# Reproducing ATLAS data set

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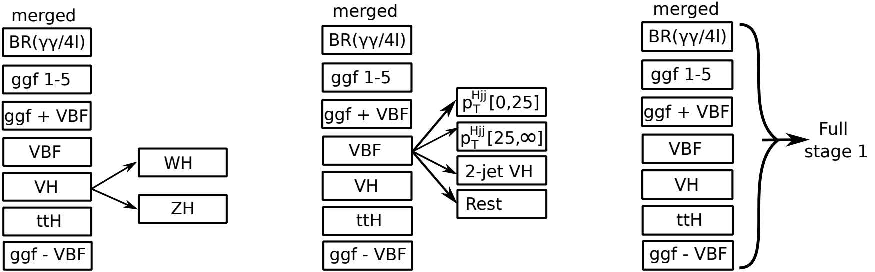
- ATLAS public STXS measurement is sensitive to 4 parameters from SMEFTsim, how can we recover the 5th?
- To predict what ATLAS internal would give - split bins assuming uncertainties are $\sim \frac{1}{\sqrt{N}}$.
- None of the splittings below gave sensitivity to the 5th parameter - full granularity in ATLAS probably would not be sensitive.



# Summary

- With current ATLAS STXS measurement we can constrain:
  - 6 HEL parameters inside ATLAS, 5 - external to ATLAS.
  - 4 SMEFTsim parameters external to ATLAS.
- Equations with unfit parameters can be used to estimate their impact.
- Full Higgs STXS stage 1 $H \to 4l$ and $H \to \gamma\gamma$ measurements have the capacity to constrain 5 SMEFT coefficients, and for the improvement the most important productions are WH and ZH.

# THANK YOU

# BACKUP

# Presenting as a function

$$\text{cHB} = 0.071 + 1.8e-08 \cdot cH + 0.053 \cdot cHbox + 0.045 \cdot cHDD + 0.68 \cdot cHWB + 9.4e-10 \cdot ceHAbs - 0.0001 \cdot ceWAbs - 3.1e-07 \cdot ceBAbs + 0.039 \cdot cHl1 - 1.5 \cdot cHl3 - 0.015 \cdot cHe + 0.062 \cdot cll + 1.2 \cdot cll1 - 0.00016 \cdot cuWAbs + 2.6e-06 \cdot cuBAbs - 8.3e-05 \cdot cdWAbs - 4.5e-05 \cdot cdBAbs + 0.01 \cdot cHq1 + 2 \cdot cHq3 + 0.075 \cdot cHu - 0.034 \cdot cHd + 3.1e-08 \cdot cdHAbs - 3e-05 \cdot cuGAbs - 2.9e-09 \cdot cdGAbs - 6.3e-13 \cdot cHudAbs + 0.0022 \cdot cG + 4.1e-17 \cdot cquqd1Abs - 1.4e-17 \cdot cquqd8Abs$$

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$$\text{cHW} = -0.24 - 6.4e-08 \cdot cH - 0.19 \cdot cHbox - 0.16 \cdot cHDD - 0.51 \cdot cHWB - 3.4e-09 \cdot ceHAbs + 0.00036 \cdot ceWAbs + 1e-06 \cdot ceBAbs - 0.15 \cdot cHl1 + 5.1 \cdot cHl3 + 0.051 \cdot cHe - 0.22 \cdot cll - 4 \cdot cll1 + 0.00056 \cdot cuWAbs - 9e-06 \cdot cuBAbs + 0.00029 \cdot cdWAbs + 0.00015 \cdot cdBAbs - 0.036 \cdot cHq1 - 7 \cdot cHq3 - 0.26 \cdot cHu + 0.12 \cdot cHd - 8.8e-08 \cdot cdHAbs + 8.5e-05 \cdot cuGAbs + 1e-08 \cdot cdGAbs + 2.2e-12 \cdot cHudAbs - 0.0072 \cdot cG - 1.2e-16 \cdot cquqd1Abs + 4e-17 \cdot cquqd8Abs$$

# Presenting as a function

cHG $=$

$$-0.0038-1.4e-09\cdot cH+0.00033\cdot cHbox-0.0041\cdot cHDD-0.0057\cdot cHWB-7.5e-11\cdot ceHAbs+7.9e-06\cdot ceWAbs+2.5e-08\cdot ceBAbs-0.0038\cdot cHl1+0.1\cdot cHl3+0.0009\cdot cHe-0.0034\cdot cll-0.083\cdot cll1+1.2e-05\cdot cuWAbs-1.9e-07\cdot cuBAbs+6.7e-06\cdot cdWAbs+3.6e-06\cdot cdBAbs-0.0027\cdot cHq1-0.1\cdot cHq3-0.0012\cdot cHu+0.00095\cdot cHd+2e-07\cdot cdHAbs-0.00019\cdot cuGAbs+3.2e-10\cdot cdGAbs+1.4e-14\cdot cHudAbs-0.00029\cdot cG+2.6e-16\cdot cquqd1Abs-8.8e-17\cdot cquqd8Abs$$

# Presenting as a function

cuHAbs $=$

$$6.7+2.6e-07\cdot cH+0.84\cdot cHbox+0.5\cdot cHDD+1\cdot cHWB+1.4e-08\cdot ceHAbs-0.0014\cdot ceWAbs-4.5e-06\cdot ceBAbs+0.68\cdot cHl1-20\cdot cHl3-0.16\cdot cHe+0.89\cdot cll+15\cdot cll1-0.0022\cdot cuWAbs+3.4e-05\cdot cuBAbs-0.0012\cdot cdWAbs-0.00066\cdot cdBAbs+0.49\cdot cHq1+19\cdot cHq3+0.22\cdot cHu-0.18\cdot cHd-1.7e-06\cdot cdHAbs-7.1\cdot cuGAbs-4.1e-08\cdot cdGAbs-1.6e-12\cdot cHudAbs+1.3\cdot cG+9.9e-12\cdot cquqd1Abs-3.4e-12\cdot cquqd8Abs$$

# Presenting as a function

Correlation matrix:

| | cHB | cHW | cHG | cuHAbs |
|---|---|---|---|---|
| cHB | 1 | -1 | 0.05 | 0.01 |
| cHW | -1 | 1 | -0.04 | -0.01 |
| cHG | 0.05 | -0.04 | 1 | -0.21 |
| cuHAbs | 0.01 | -0.01 | -0.21 | 1 |

# Dependence on width

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- Most efficient derivation of equation is using substitution:

$$\sigma = \sigma_{SM}(\Delta w_p) + A_i(\Delta w_p)c_i + B_{ij}(\Delta w_p)c_i c_j \tag{10}$$

$$A(\Delta w) = A(0) + a_p \Delta w_p + b_{pq}\Delta w_p \Delta w_q \tag{11}$$

$$w = w_{SM} + k_i c_i + t_{ij} c_i c_j \tag{12}$$

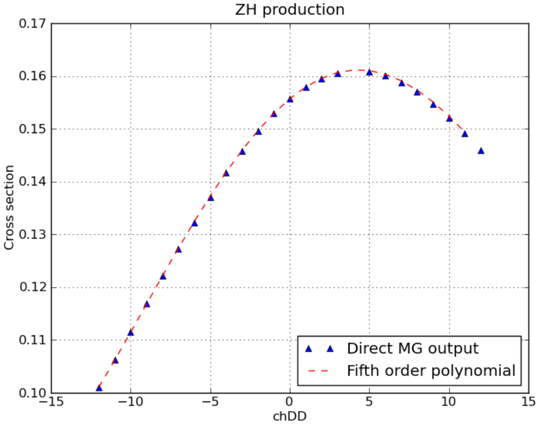
$$\sigma_{SM}(\Delta w) = \sigma_{SM}(0) + r_p \Delta w_p + s_{pq}\Delta w_p \Delta w_q \tag{13}$$

Then 10 becomes:

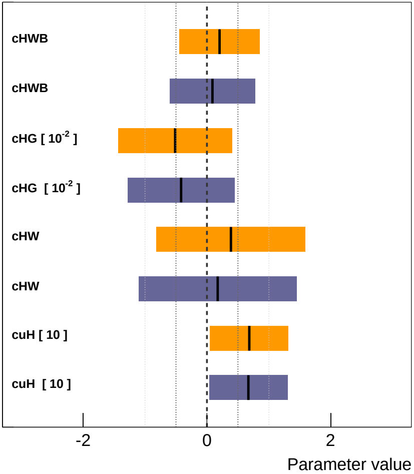
$$\begin{aligned}
\sigma &= \sigma_{SM}(0)\left(1 + \frac{r_p}{\sigma_{SM}(0)}\Delta w_p\right) + A_i(0)c_i \\
&= \sigma_{SM}(0)\left(1 + \frac{r_p}{\sigma_{SM}(0)}k_i^p c_i\right) + A_i(0)c_i \\
&= \sigma_{SM}(0) + r_p k_i^p c_i + A_i(0)c_i
\end{aligned} \tag{14}$$

# Dependence on width uncertainties

- Validation for ZH production for cHDD coefficient. Red dashed - from the equations.
- Advantage: we have only four widhts which need to be calculated once.



Fit to ATLAS STXS measurements (ATLAS-CONF-2017-047)




- Only cHWB (from our 5 param set) affects particle widhts.
- Orange: width width non constant, violet: width constant SM value.

# Sanity check

- Substituted results from 1803.03252 (Ellis et al.)
- There Higgs STXS measurement were included, so substituted results should be consistent.

| Wilson | Other=0 | $1\sigma$ closer to SM | Central values | $1\sigma$ further from SM | Other=1 |
|---|---|---|---|---|---|
| cHB | 0.071 | 0.073 | 0.081 | 0.089 | 2.7 |
| cHW | -0.24 | -0.24 | -0.26 | -0.28 | -7.5 |
| cHG | -0.0038 | -0.0038 | -0.0036 | -0.0035 | -0.11 |
| cuH | 6.7 | 6.8 | 4.2 | 1.6 | 19 |