Experience with EFT fits to combined Higgs data

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Overview

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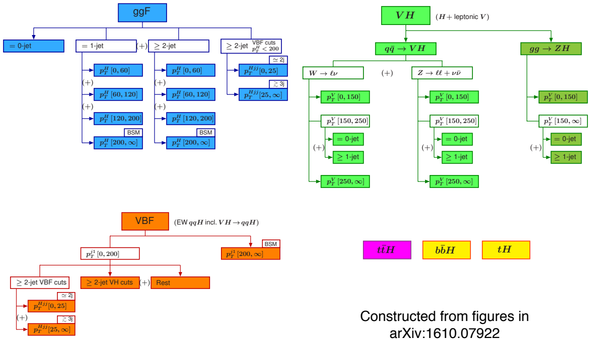
- In this talk I will share experience of EFT fits to combined ATLAS $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4l$ full 2015-2016 dataset and an integrated luminosity of 36.1 fb^{-1}.
- I will discuss:
  - Gains from distinguishing processes.
  - Fitting different EFT bases.
  - 1 + 1' approaches to motivate a subset of Wilson coefficients.
  - Some other observations.

- Simplified template cross sections (STXS) - fixed predefined kinematic regions of Higgs production and decay.
- Measured at the generator level.
- STXS vs differential cross sections (diffXS):
  - STXS extrapolate to bigger phase space regions using SM templates
  - diffXS: unfold (i.e. take migration between bins into account)

ATLAS Preliminary



Constructed from figures in arXiv:1610.07922

EFT models

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- 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:
  - use $U(3)^5$ symmetry assumption

I. Brivio, Y. Jiang, M. Trott

Relating STXS bins to EFT

- Usual EFT paramterization is based on: $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$, which leads to:

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

- The above is not exact since cross section also depends on particle widths which have EFT dependence. May be relevant to dibosons.
- Picture below: we expect linear dependence, while 5th order polynomial is a better modelling.
- I validated that substituting widths works well to model this deviation (HEFT):

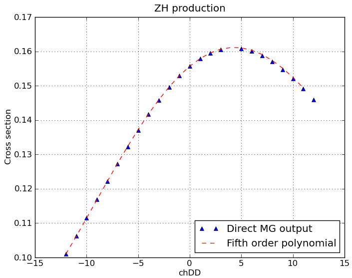
$$\sigma = \sigma_{SM}(\Delta w_p) + A_i(\Delta w_p) c_i \quad (2)$$

Prefactor dependence on width w:

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

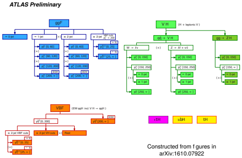
$$w = w_{SM} + k_i c_i + t_{ij} c_i c_j \quad (4)$$

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



- Equation 5 is a polynomial and we may take linear or quadratic terms as usual.
- This approach is efficient in linear equation case.

- Choose truth level measurement framework: STXS.



Road to EFT results

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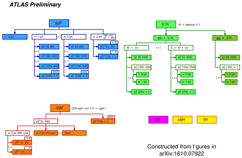
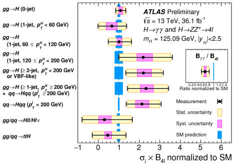
- ATLAS measures STXS.

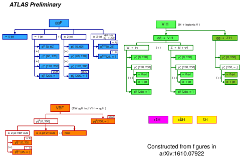




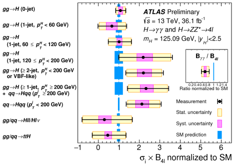
ATLAS-CONF-2017-047

Road to EFT results

- ATLAS fit to the HEL model parameters using the full granularity of STXS.



HEL



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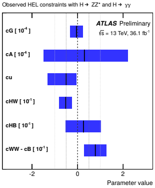

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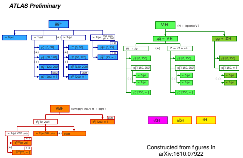
Road to EFT results

- Our EFT fit with HEL model on ATLAS public measurement.



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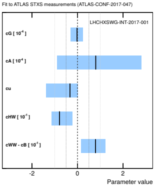
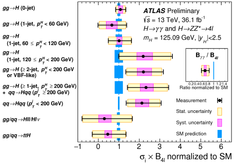
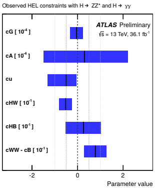


HEL



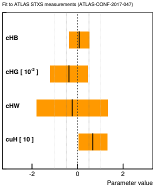


LHCHXSWG-INT-2017-001 ATLAS-CONF-2017-047 ATL-PHYS-PUB-2017-018

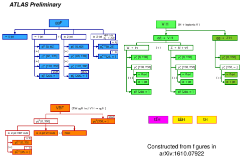
C. Hays, V. Sanz, G. Žemaitytė

Road to EFT results

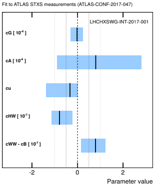
- We perform SMEFTsim model fit on ATLAS public data.



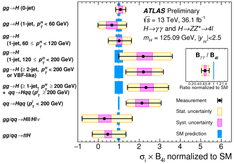
SMEFT

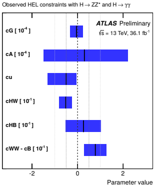


HEL



HEL





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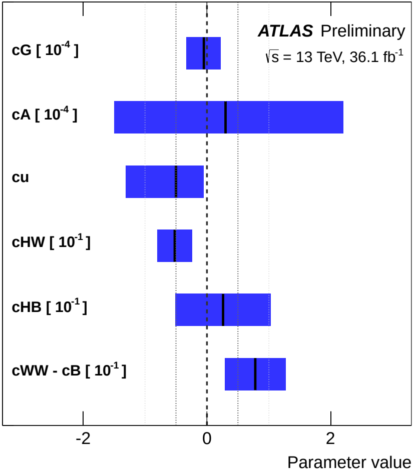
Setting parameters to zero

- Setting parameters to zero reduces EFT applicability to subset of models.
- For HEL model fit, we removed externally constrained parameters to minimize model dependence:
  - At leading order, 15 dimension-6 operators reduce to SM Higgs interactions through $H \to vev$ and are not directly constrained by electroweak data
  - We reduce the operator set as follows:
    - one coefficient combination (cWW+cB) is constrained by the S parameter
    - four operators are CP-odd and do not have any interference contribution to STXS
    - two operators correspond to lepton and down-type Yukawas and are not directly constrained by the $H \to ZZ$ and $H \to \gamma\gamma$ measurements
    - one operator corresponds to di-Higgs production
    - one operator renormalizes the Higgs field and produces a small global change in the rate
  - This leaves six operator combinations to constrain

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

ATLAS fit to full STXS granularity

Observed HEL constraints with H → ZZ* and H → γγ



Operators of interest:

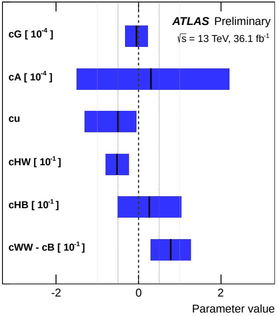
Operator	Expression
$\mathcal{O}_g$	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_\gamma$	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_u$	$y_u \lvert H\rvert^2 \bar{u}_l H u_R +$ h.c.
$\mathcal{O}_{HW}$	$i\,(D^\mu H)^\dagger\, \sigma^a\, (D^\nu H)\, W^a_{\mu\nu}$
$\mathcal{O}_{HB}$	$i\,(D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu}$
$\mathcal{O}_W$	$i\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$
$\mathcal{O}_B$	$i\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$

ATLAS-CONF-2017-047

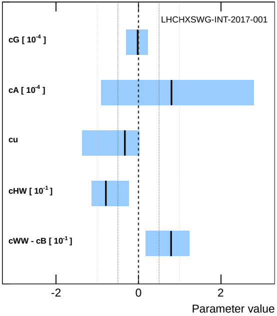
Study using STXS measurements

- 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
  $\Rightarrow$ if measurements are well represented by Gaussian, we do not win much doing in ATLAS.

Observed HEL constraints with $H \to ZZ^*$ and $H \to \gamma\gamma$



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

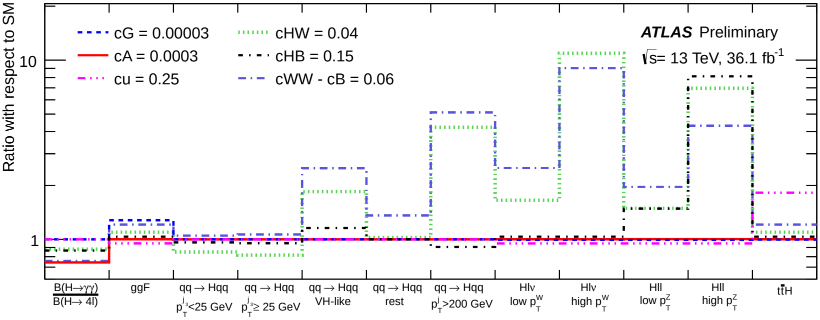


Left: ATLAS-CONF-2017-047

Right: LHCHXSWG-INT-2017-001

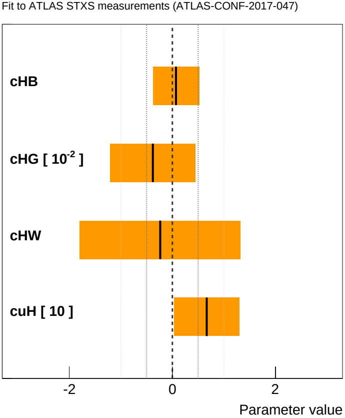
Impact plot

- It is worth looking at impact plot of high granularity pre-merged measurements:
  - 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.



SMEFTsim basis result

- Fit to ATLAS public measurement.



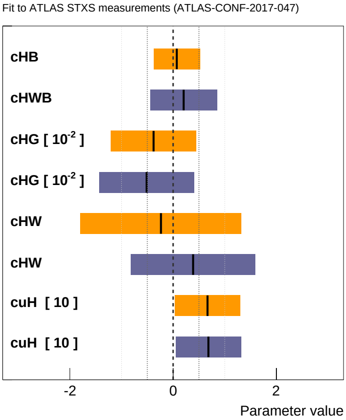
Aimed to constrain 5 parameters:

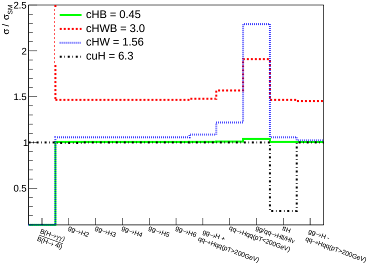
Operator	Expression
$\mathcal{O}_{HG}$	$H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_{HW}$	$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{HB}$	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HWB}$	$H^\dagger H \tau^I W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{uH}$	$H^\dagger H \bar{q}_p u_r \widetilde{H}$

... but were sensitive to four only.

Replacing cHB by cHWB

- Based on impact plot (right): other four parameter subsets can be fitted.





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

Wilsons as function

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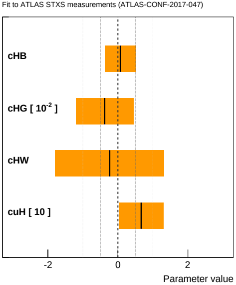
- This is unconventional approach to account for Wilson coefficients otherwise set to zero.
  - Let's assume we have a subset that we can constrain with our data and call it "orange" and the remaining subset call "black".
  - Let's assume that after ATLAS publishes EFT study, there is a new measurement that constrains very well some Wilsons from a black subset and we would like to know how this new knowledge affects our EFT measurement.
  - I proposed to treat black subset as constant unknown values. They can be understood as an unknown correction to ATLAS data.

Wilsons as function

- This is how the previous result would look like:



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

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

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

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

Derive dependence on "black subset"

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:

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

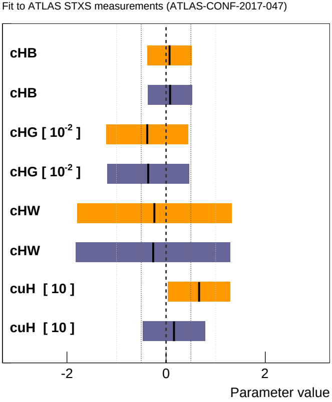
then solution to (7):

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

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

Sketch study: potential applications

- We can use this approach to estimate uncertainties due to ignored “black subset” Wilsons constrained elsewhere.



- Orange: “black subset“ set to 0 vs violet: ”black subset“ set to values from a global fit in *1803.03252, J. Ellis, C.W. Murphy, V. Sanz, T. You*.
- Central values of ”orange subset“ shift unsignificantly for different values of ”black subset“ (c_i'):

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

Summary

- We looked at variations of EFT studies using ATLAS combined measurements.
- Discussed two options to deal with unconstrained Wilson coefficients.
- Discussed subtleties that improve EFT studies.

THANK YOU

Relating STXS bins to EFT parameters

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + c_i \mathcal{O}_i / \Lambda^2$$

- To determine the relationship between STXS measurements and EFT parameters, we separate the cross section into SM, SM-BSM interference, and BSM components:

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

- σ_{BSM} is a subleading term (suppressed by $1/\Lambda^4$).
- The dependence of the cross section on the couplings can then be expressed as (we define $\bar{c}_i = c_i/\Lambda^2$):

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

Extraction of the equation

$$\sigma = SM + A_1 c_1 + B_{11} c_1^2 + A_2 c_2 + B_{22} c_2^2 + B_{12} c_1 c_2$$

- There are several technical ways to extract equations.
- It is just linear algebra - we produce MC samples s.t. system of equations is close to diagonal.
- We use 'NP^2==' syntax in MadGraph:
  - SM, A_i and B_{ij} for $i = j$ are obtained directly:

$$\begin{cases} NP\hat{}2 == 0 : \sigma_1 = SM \\ NP\hat{}2 == 1 : \sigma_{A1} = A_1 c_1, \ \sigma_{A2} = A_2 c_2 \\ NP\hat{}2 == 2 : \sigma_{B11} = B_{11} c_1^2, \ \sigma_{B22} = B_{22} c_2^2 \end{cases}$$

  - Extracting B_{ij} for $i \neq j$: generate a sample with NP^2==2, then $\sigma = B_{11} c_1^2 + B_{22} c_2^2 + B_{12} c_1 c_2$.
- Technical advantage: precision can be customised for individual prefactors.