Constraining EFT parameters with simplified template cross sections

Chris Hays[1], Veronica Sanz[2], **Gabija Žemaitytė**[1]

[1]University of Oxford, [2]University of Sussex

LHCHXSWG-INT-2017-001
https://cds.cern.ch/record/2290628

Higgs Couplings
8 November 2017

Overview

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- In LHCHXSWG-INT-2017-001 we outline a procedure for fitting a set of dimension-6 EFT parameters using simplified template cross section (STXS) measurements.
- Steps:
  - choose a basis implementation
  - identify Higgs-sensitive operators and existing constraints
  - determine operators' effect on the STXS regions
  - perform the fit

EFT at LO dimension-6

EFT at LO, dimension-6 operators:

- The general form of the Lagrangian including dimension-6 operators

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

- Assuming flavour universality, the SM EFT has 59 operators. The majority of these operators do not affect Higgs physics at LO.
- Several operator bases have been defined, we chose to use the HEL implementation of the SILH basis since it was the most complete public implementation at the start of this work.

Higgs-sensitive operators

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HEL operator	Coefficient
$\mathcal{O}_g = \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{c_g}{\Lambda^2} = \frac{g_s^2}{m_W^2}\,\texttt{cG}$
$\tilde{\mathcal{O}}_g = \lvert H\rvert^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$	$\frac{\tilde{c}_g}{\Lambda^2} = \frac{g_s^2}{m_W^2}\,\texttt{tcG}$
$\mathcal{O}_\gamma = \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{c_\gamma}{\Lambda^2} = \frac{g'^2}{m_W^2}\,\texttt{cA}$
$\tilde{\mathcal{O}}_\gamma = \lvert H\rvert^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$	$\frac{\tilde{c}_\gamma}{\Lambda^2} = \frac{g'^2}{m_W^2}\,\texttt{tcA}$
$\mathcal{O}_u = y_u \lvert H\rvert^2 \bar{Q}_L H^\dagger u_R + \text{h.c.}$	$\frac{c_u}{\Lambda^2} = \frac{\texttt{cu}}{v^2}$
$\mathcal{O}_d = y_d \lvert H\rvert^2 \bar{Q}_L H d_R + \text{h.c.}$	$\frac{c_d}{\Lambda^2} = \frac{\texttt{cd}}{v^2}$
$\mathcal{O}_\ell = y_\ell \lvert H\rvert^2 \bar{L}_L H \ell_R + \text{h.c.}$	$\frac{c_\ell}{\Lambda^2} = \frac{\texttt{cl}}{v^2}$
$\mathcal{O}_H = \frac{1}{2}\left(\partial^\mu \lvert H\rvert^2\right)^2$	$\frac{c_H}{\Lambda^2} = \frac{\texttt{cH}}{v^2}$
$\mathcal{O}_6 = \left(H^\dagger H\right)^3$	$\frac{c_6}{\Lambda^2} = \frac{\lambda}{v^2}\,\texttt{c6}$
$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger\,\sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{c_{HW}}{\Lambda^2} = \frac{g}{m_W^2}\,\texttt{cHW}$
$\tilde{\mathcal{O}}_{HW} = i\,(D^\mu H)^\dagger\,\sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$	$\frac{\tilde{c}_{HW}}{\Lambda^2} = \frac{g}{m_W^2}\,\texttt{tcHW}$
$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger\,(D^\nu H) B_{\mu\nu}$	$\frac{c_{HB}}{\Lambda^2} = \frac{g'}{m_W^2}\,\texttt{cHB}$
$\tilde{\mathcal{O}}_{HB} = i\,(D^\mu H)^\dagger\,(D^\nu H) \tilde{B}_{\mu\nu}$	$\frac{\tilde{c}_{HB}}{\Lambda^2} = \frac{g'}{m_W^2}\,\texttt{tcHB}$
$\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$	$\frac{c_W}{\Lambda^2} = \frac{g}{m_W^2}\,\texttt{cWW}$
$\mathcal{O}_B = \frac{i}{2}\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{c_B}{\Lambda^2} = \frac{g'}{m_W^2}\,\texttt{cB}$

- At LO, 15 dimension-6 operators reduce to SM Higgs interactions through $H \to vev$ and are not directly constrained by precision electroweak data.

Equations derived for STXS bins

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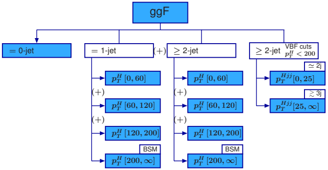
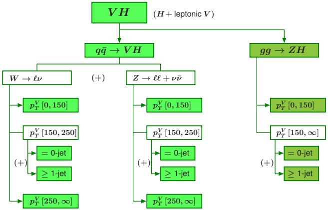
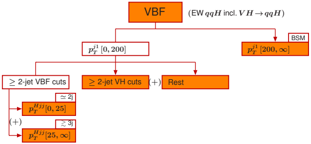
- Cross sections are measured in each STXS truth bin, with correlations.
- Bins include: $\sigma_i \times B_{4l}$ and B_i/B_{4l}







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

- 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 $1/\Lambda^4$) but can be included to avoid negative cross sections and improve fit convergence.
- 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.

MadGraph validation

- The equations have been validated to check any assumptions and approximations
  - Madgraph+Pythia samples were generated with a variety of c_i values and a statistical precision of $<1\%$
  - The difference between the generated cross section and that calculated with the equations is found to be approximately Gaussian-distributed according to the generator uncertainty
- A few examples are shown below:

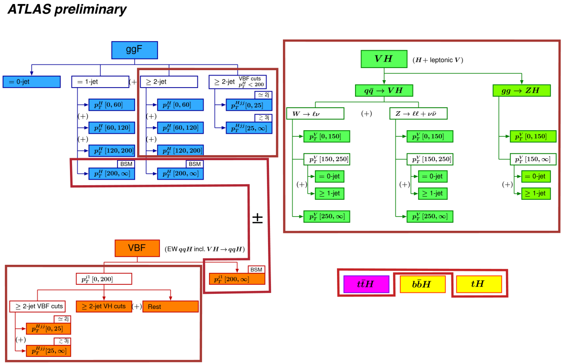
STXS region	σ_{MG}/σ_{SM}	σ_{eq}/σ_{SM}	δ^{stat}_{MG}
$gg \to H$ ($\geq$ 2 jets, $p_T^H \geq$ 200 GeV)	0.859	0.851	0.006
$gg \to H$ ($\geq$ 2 jets, $p_T^H \geq$ 200 GeV)	0.948	0.945	0.006
$q\bar{q} \to Hl\nu$ ($p_T^V \geq$ 250 GeV)	1.112	1.110	0.002
$q\bar{q} \to Hl\nu$ ($p_T^V \geq$ 250 GeV)	1.277	1.276	0.002
$q\bar{q} \to Hl\nu$ ($p_T^V \geq$ 250 GeV)	1.420	1.419	0.002
$gg/q\bar{q} \to ttH$	0.848	0.848	0.001
$gg/q\bar{q} \to ttH$	1.653	1.653	0.002

Equations of the interference terms for ggF, qq→Hqq and ttH production. The equations with all terms will be available on the LHC Working Group 2 twiki.

Cross-section region	$\sum_i A_i c_i$
$gg \to H$ (0-jet) $gg \to H$ (1-jet, $p_T^H < 60$ GeV) $gg \to H$ (1-jet, $60 \leq p_T^H < 120$ GeV)	$56c_g'$
$gg \to H$ (1-jet, $120 \leq p_T^H < 200$ GeV)	$56c_g' + 18\mathtt{c3G} + 11\mathtt{c2G}$
$gg \to H$ (1-jet, $p_T^H \geq 200$ GeV)	$56c_g' + 52\mathtt{c3G} + 34\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H < 60$ GeV)	$56c_g'$
$gg \to H$ ($\geq$ 2-jet, $60 \leq p_T^H < 120$ GeV)	$56c_g' + 8\mathtt{c3G} + 7\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $120 \leq p_T^H < 200$ GeV)	$56c_g' + 23\mathtt{c3G} + 18\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H \geq 200$ GeV)	$56c_g' + 90\mathtt{c3G} + 68\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j3} < 25$ GeV)	$56c_g'$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j3} \geq 25$ GeV)	$56c_g' + 9\mathtt{c3G} + 8\mathtt{c2G}$
$qq \to Hqq$ (VBF-like, $p_T^{j3} < 25$ GeV)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.3\mathtt{cWW} - 0.023\mathtt{cB} - 4.3\mathtt{cHW}$ $-0.29\mathtt{cHB} + 0.092\mathtt{cHQ} - 5.3\mathtt{cpHQ} - 0.33\mathtt{cHu} + 0.12\mathtt{cHd}$
$qq \to Hqq$ (VBF-like, $p_T^{j3} \geq 25$ GeV)	$-1.0\mathtt{cH} - 1.1\mathtt{cT} + 1.2\mathtt{cWW} - 0.027\mathtt{cB} - 5.8\mathtt{cHW}$ $-0.41\mathtt{cHB} + 0.13\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.45\mathtt{cHu} + 0.15\mathtt{cHd}$
$qq \to Hqq$ ($p_T^j \geq 200$ GeV)	$-1.0\mathtt{cH} - 0.95\mathtt{cT} + 1.5\mathtt{cWW} - 0.025\mathtt{cB} - 3.6\mathtt{cHW}$ $-0.24\mathtt{cHB} + 0.084\mathtt{cHQ} - 4.5\mathtt{cpHQ} - 0.25\mathtt{cHu} + 0.1\mathtt{cHd}$
$qq \to Hqq$ ($60 \leq m_{jj} < 120$ GeV)	$-0.99\mathtt{cH} - 1.2\mathtt{cT} + 7.8\mathtt{cWW} - 0.19\mathtt{cB} - 31\mathtt{cHW}$ $-2.4\mathtt{cHB} + 0.9\mathtt{cHQ} - 38\mathtt{cpHQ} - 2.8\mathtt{cHu} + 0.9\mathtt{cHd}$
$qq \to Hqq$ (rest)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.4\mathtt{cWW} - 0.028\mathtt{cB} - 6.2\mathtt{cHW}$ $-0.42\mathtt{cHB} + 0.14\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.42\mathtt{cHu} + 0.16\mathtt{cHd}$
$gg/q\bar{q} \to ttH$	$-0.98\mathtt{cH} + 2.9\mathtt{cu} + 0.93\mathtt{cG} + 310\mathtt{cuG} + 27\mathtt{c3G} - 13\mathtt{c2G}$

Example fit

- To demonstrate the procedure we use the equations to perform a fit to the ATLAS STXS measurements in the $H \to \gamma\gamma$ and H→ZZ*→4l channels (ATLAS-CONF-2017-047).
- The measurement merges STXS regions as follows:



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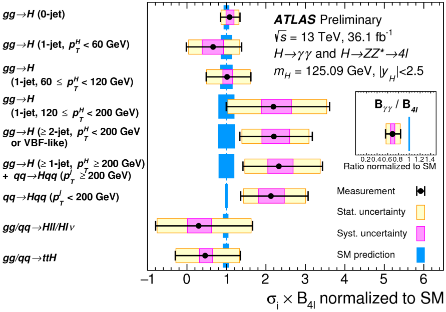
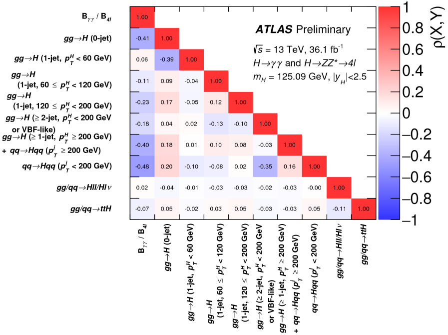
- ATLAS results of merged STXS bins (ATLAS-CONF-2017-047) used for the example fit.



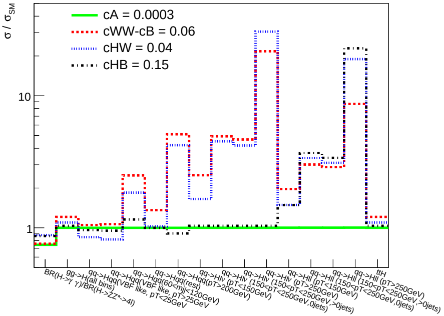


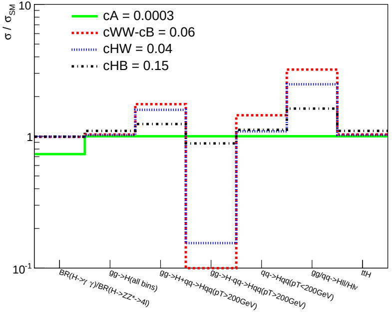
Physics of Wilson coefficients

- To allow a convergent fit we fit only the leading coefficients affecting the measurements, so we reduce the EFT to an effective Lagrangian containing five parameters
- We thus neglect the following Higgs-sensitive operators:
  - 4 CP-odd operators that do not have any interference contribution to STXS
  - 2 operators corresponding to lepton and down-type Yukawas not directly constrained by the H$\rightarrow$ZZ*$\rightarrow$4l and H$\rightarrow \gamma\gamma$ measurements
  - 1 operator corresponding to di-Higgs production
  - 1 operator that normalizes the Higgs field and produces a small global change in the rate
  - 1 coefficient combination (cWW+cB) constrained by the S parameter
- This leaves six operator combinations

Impact of coefficients on STXS

- The ATLAS merged regions provide little sensitivity to cHB
  - We therefore also remove this parameter from the fit, leaving five parameters.
- Left: STXS stage 1. Right: merged version as in ATLAS-CONF-2017-047.





Fit procedure

- Fit procedure:
  - likelihood minimization with RooFit
  - assume Gaussian uncertainties
  - apply the ATLAS correlation matrix
- The correlation coefficients with $gg \to H$ ($\geqslant 1$-jet$p_T^H \geqslant 200 GeV$) $- qq \to Hqq$ ($p_t^j \geqslant 200 GeV$) bin were not quoted in the ATLAS note due to low experimental sensitivity, so we assumed correlations are 0 with other bins.

Results

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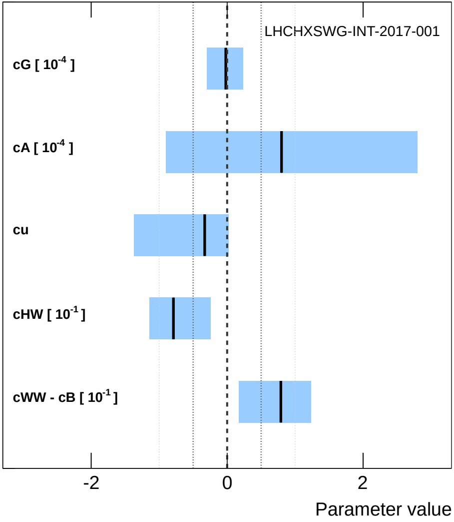
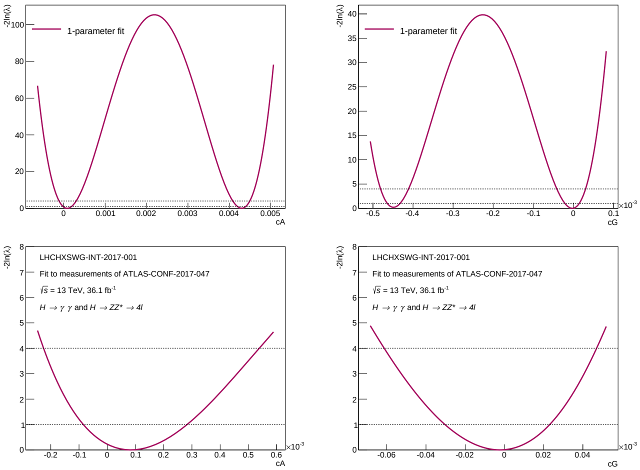
Fit to ATLAS STXS measurements (ATLAS-CONF-2017-047)



- 5-parameter fit.
- Uncertainties from likelihood scan.
- For well separated double minima used solution closest to SM.

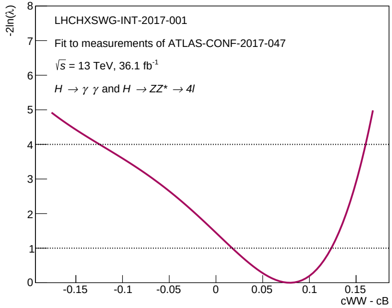
Likelihood scan

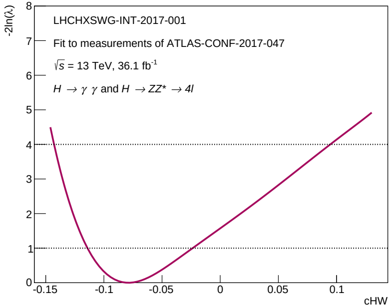
- cA and cG have well separated double minima - chose solution closest to SM.



Likelihood scan

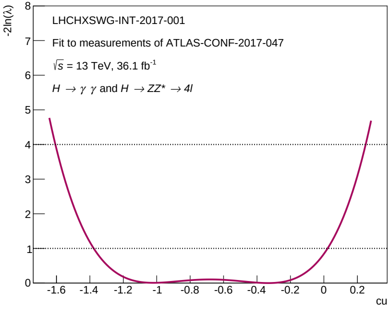
- cHW and cWW do not have a clear second minimum or it is outside fit convergence range.





Likelihood scan

- cu has two minima which are not well separated.



Improvements

- Possible improvements with the currently available tools and calculations:
  - similar equations can be derived using the recent SMEFT Feynrules implementation that uses the Warsaw basis
  - the theoretical predictions and simulation of kinematic distributions of some Higgs operators could be performed at NLO in QCD using public implementations of the HEL Lagrangian in aMC@NLO and POWHEG-BOX
  - NLO Electroweak corrections in decays could be included by interfacing with eHDECAY, with the use of Rosetta
  - a combination with electroweak diboson production (and other measurements) could be incorporated within the same framework

Summary

- We have described a general procedure for using the STXS framework to constrain EFT parameters, providing a first step towards the use of STXS in the context of the EFT approach.
- We applied the procedure to ATLAS results and obtained constraints on 5 EFT parameters.
- The procedure is described in LHCHXSWG-INT-2017-001.