Probing high-scale physics using ATLAS Higgs boson measurements and SM effective field theory

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Motivation

- A program of precise measurements and the EFT interpretation constrains coupling/mass^2 factors for new particles such as dark matter. This bottom-up approach is complementary to the top-down approach of searching directly for new particles.
- Discovery in the top-down approach is through observation of specific new particles in classes of models, while discovery in the bottom-up approach is through deviations observed in precise SM measurements.

Overview

- We use a simplified set of six operators from the SM EFT to constrain new Higgs boson interactions, which are a promising source of new physics.
- The operator coefficients are fit using the combined ATLAS $\mathbf{H} \rightarrow \gamma\gamma$ and $\mathbf{H} \rightarrow \mathbf{ZZ}^{(*)} \rightarrow \mathbf{4l}$ measurements with the 2015-2016 dataset, corresponding to an integrated luminosity of 36.1 $\mathbf{fb}^{-1}$.

EFT Lagrangian

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

$$\mathcal{L} = \mathcal{L}_{\rm SM} + c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$$

- To determine the relationship between STXS measurements and EFT parameters, we separate the cross section into SM, SM-BSM interference, and BSM components: $\sigma = \sigma_{\rm SM} + \sigma_{\rm int} + \sigma_{\rm BSM}$.
- Then the cross section dependence on the couplings can be expressed as:

$$\frac{\sigma}{\sigma_{\rm SM}} = 1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j$$

EFT at LO dimension-6 and selected Wilson coefficients

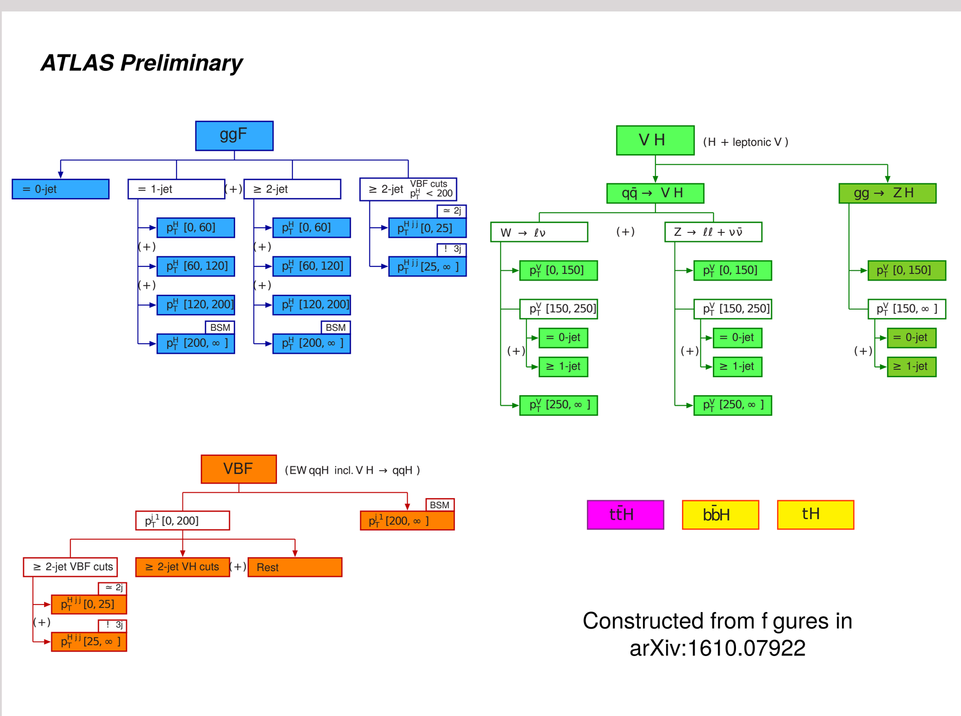
- The SM EFT has 59 operators. The majority of these operators do not affect Higgs physics at LO.
- We used the 'Higgs effective Lagrangian' model, which is implemented in the Madgraph generator.

We selected the following Wilson coefficients to constrain, based on the expected sensitivity of the measurements:

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

Simplified template cross sections (STXS)

- 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.
- Cross sections are measured in each STXS region at the generator level, with correlations.
- The regions are: $\sigma_i \times B_{4l}$ and B_i/B_{4l}.
- The STXS measurement regions on which the fit is based are shown in the figure on the right [1] [2].



Example equations and validation

The fit uses equations expressing the STXS regions in terms of EFT parameters, for example:

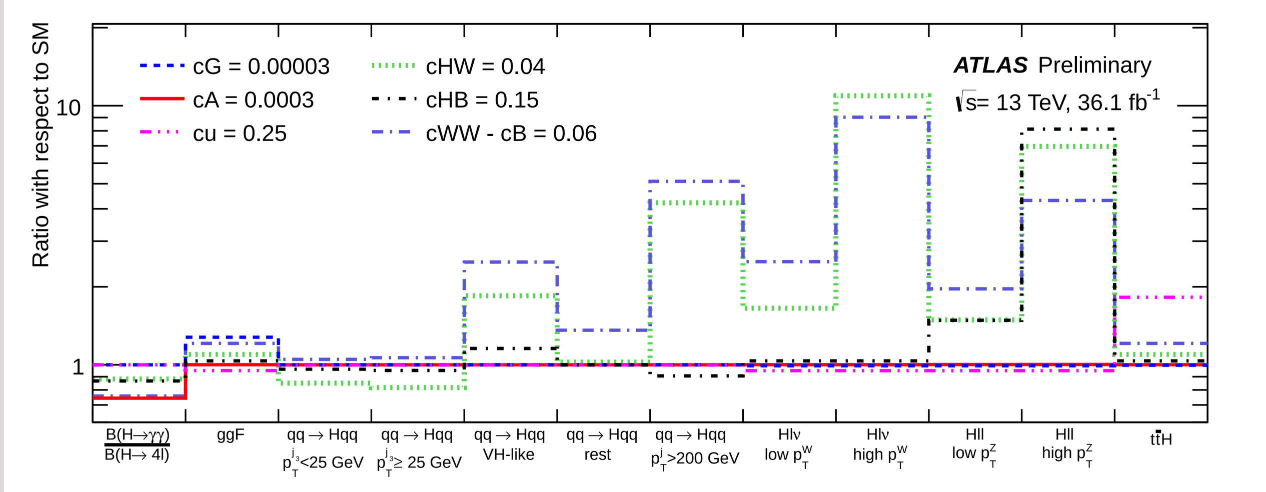
$$\sigma_{BSM}/\sigma_{SM} = 1 + 1.546 \cdot cWW - 3.631 \cdot cHW - 0.2361 \cdot cHB + 11.11 \cdot cWW \cdot cWW + 0.2245 \cdot cB \cdot cB + 12.54 \cdot cHW \cdot cHW + 0.2189 \cdot cHB \cdot cHB + 0.9 \cdot cWW \cdot cB + 3.43 \cdot cWW \cdot cHW + 0.43 \cdot cB \cdot cHW + 1.52 \cdot cHW \cdot cHB$$

MC samples were generated with a variety of c_i values and a statistical precision <1%. Example validation samples show consistency with the equations (right).

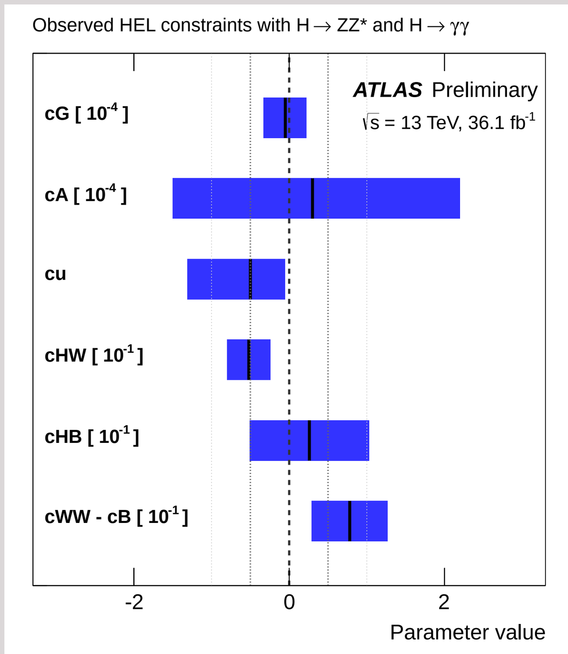
STXS region	σ_{MG}/σ_{SM}	σ_{eq}/σ_{SM}	δ^{stat}_{MG}
$gg \rightarrow H$ (≥ 2 jets, $p_T^H \geq 200$ GeV)	0.859	0.851	0.006
$gg \rightarrow H$ (≥ 2 jets, $p_T^H \geq 200$ GeV)	0.948	0.945	0.006
$q\bar{q} \rightarrow Hl\nu$ ($p_T^V \geq 250$ GeV)	1.112	1.110	0.002
$q\bar{q} \rightarrow Hl\nu$ ($p_T^V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

EFT impact plot on STXS measurements

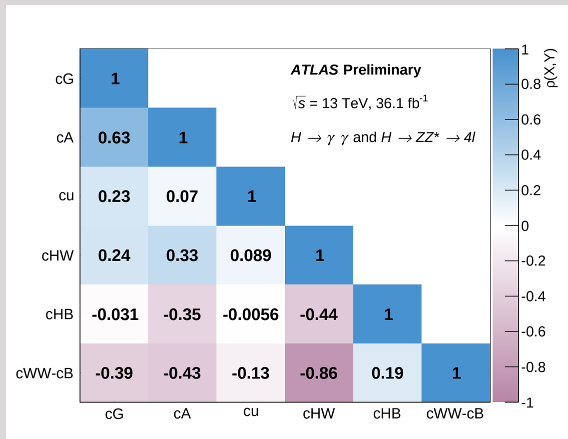
The impact plot shows how various STXS regions are affected by parameters corresponding to $+1\sigma$ expected sensitivity [2].

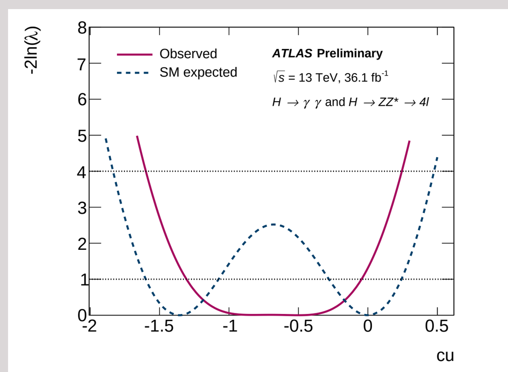


Results of fit to ATLAS measurements



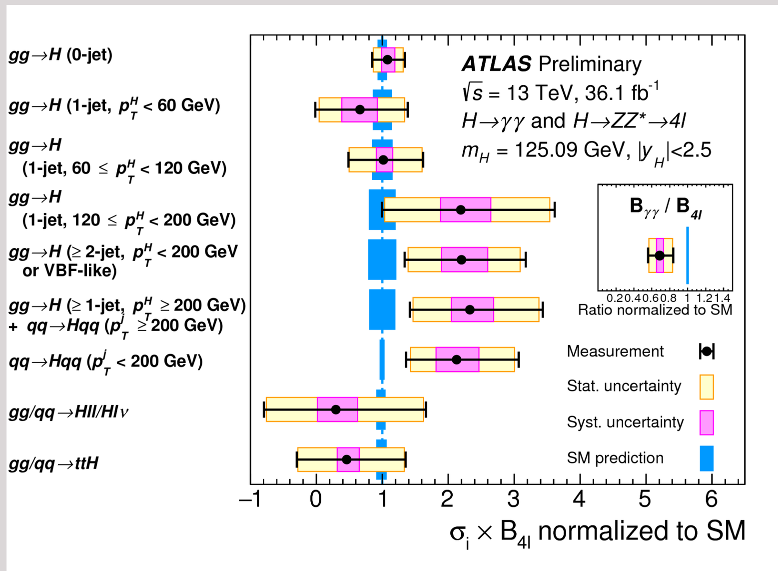
For O(1) couplings of new particles to the SM, the constraints extend to new-physics scales of 10 TeV for ggH vertex, 5 TeV for $H\gamma\gamma$ vertex, and 500 GeV for HVV and ttH vertices. [2]

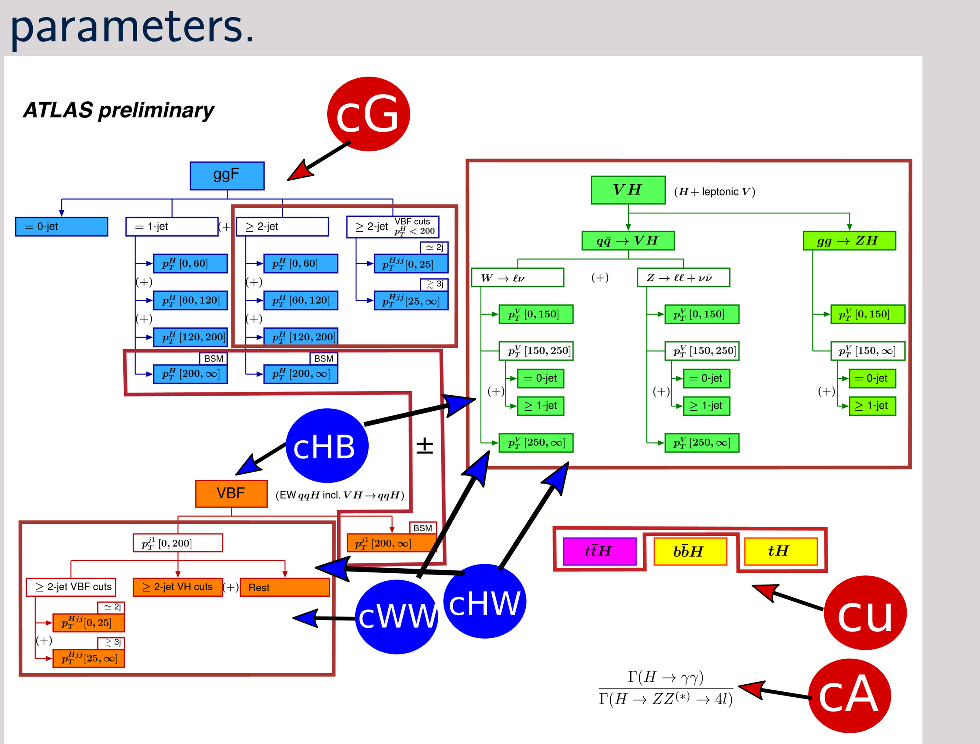


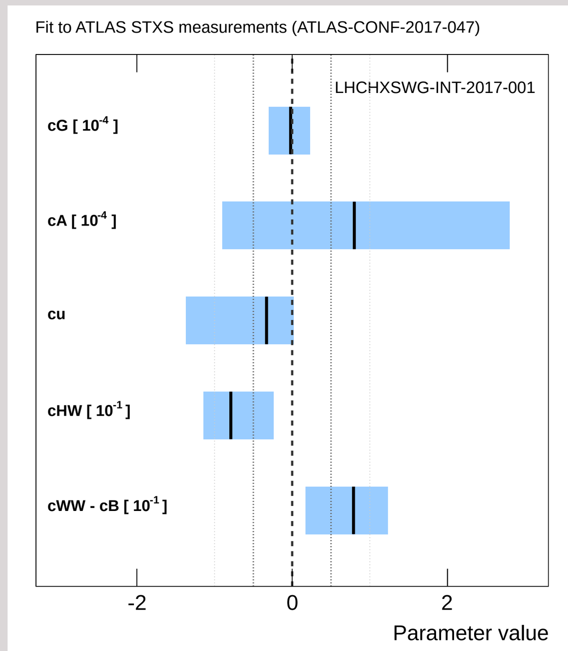


Alternative fit to a reduced set of STXS regions

- ATLAS previously used the same data to directly measure a reduced set of 11 STXS [3]. This reduced set can also be used to fit for EFT parameters to investigate the reduction in sensitivity to the parameters [4].
- The ATLAS measurements merged regions most sensitive to cWW-cB, cHW, and cHB. In the fit to these regions we remove cHB, leaving five parameters.







Summary

- These results represent the first step towards a full EFT fit to Higgs boson measurements by the LHC experiments, whose results will provide important information about the possible couplings and mass scales of new physics.
- The six-parameter fit demonstrates the general procedure for transitioning from constraints on coefficients of dimension-4 operators to those of dimension-6 operators in a general EFT framework for combined Higgs measurements.
- As more measurements are included and more robust theoretical tools become available, the fits will expand to larger operator sets and more deeply probe distributions and individual couplings.

References

[1] D. de Florian et al. Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector. 2016.

[2] ATLAS Collaboration. Constraints on an effective Lagrangian from the combined $\mathbf{H} \rightarrow \mathbf{ZZ}^* \rightarrow 4\ell$ and $\mathbf{H} \rightarrow \gamma\gamma$ channels using 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data collected with the ATLAS detector. *ATL-PHYS-PUB-2017-018*, 2017.

[3] ATLAS Collaboration. Combined measurements of Higgs boson production and decay in the $\mathbf{H} \rightarrow \mathbf{ZZ}^* \rightarrow 4\ell$ and $\mathbf{H} \rightarrow \gamma\gamma$ channels using $\sqrt{s} = 13$ TeV pp collision data collected with the ATLAS experiment. *ATLAS-CONF-2017-047*, 2017.

[4] Chris Hays, Veronica Sanz, and Gabija Zemaityte. Constraining eft parameters using simplified template cross sections. *LHCHXSWG-INT-2017-001*, Oct 2017.

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