Update on EFT fits for LHC run II

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Outline

Introduction

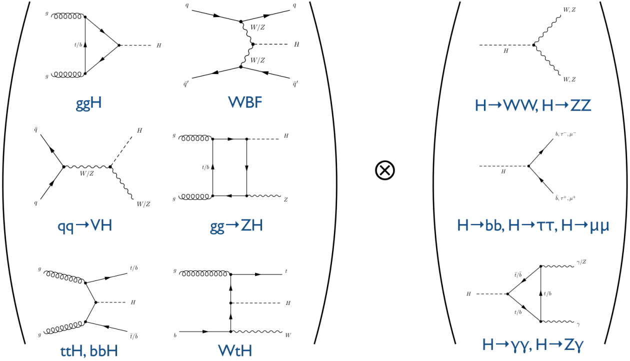
- Recap on signal strengths and EFT parametrisations
- Discussion on differential distributions and STXS
- Summary of available measurements
- Fit technology: EFT implementation for Gfitter

Results

- Update from Run-I EFT fits
- Run-II fit
- Ongoing work:
  Run I+II combination, p_T distributions, additional EFT basis

Signal Strengths

Focus on Higgs measurements at LHC (assuming $M_H \sim 125$GeV, narrow resonance)



Signal Strengths

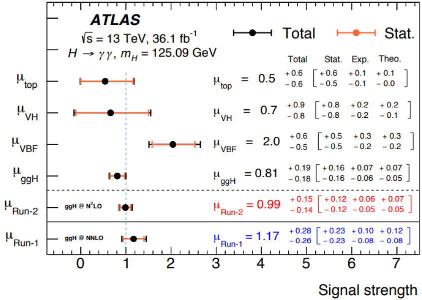
- Assuming NWA:

$$\mu = \frac{\sigma \times \mathrm{BR}}{\sigma_{SM} \times \mathrm{BR}_{\mathrm{SM}}}$$

- In particular:

$$\sigma(i \to h \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H}$$

- Can be used in combination with off-shell measurements to extract information on Γ_H
- Hard to disentangle measurement from theory uncertainty (numerator and denominator respectively)



ATLAS 1802.04146 (run II):
Signal strengths for different production modes and H decaying to diphoton

EFT parametrisations

Parametrise New Physics (NP) in a model independent way

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \dots$$

Choice of basis

- SILH basis $\Rightarrow$ phenomenologically intuitive, maps directly to several BSM models
- Warsaw basis $\Rightarrow$ maps to a larger class of BSM scenarios, also has the NP scale as an independent parameter
- The natural progression for a global fit is:
  - SILH (8ops) $\Rightarrow$ Warsaw (8ops) $\Rightarrow$ Warsaw (59 Ops) $\underbrace{\Rightarrow}_{?}$ $\begin{cases} \text{Warsaw 2599 Ops ?} \\ \text{Dim 8 operatos ?} \end{cases}$

SILH basis

$$\mathcal{L}_{SILH} = \frac{\bar{c}_H}{2v^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H) - \frac{\bar{c}_6\lambda}{v^2}(H^\dagger H)^3 +$$
$$\left(\frac{c_{u,i}y_{u,i}}{v^2}H^\dagger H \bar{u}_L^{(i)} H^c u_R^{(i)} + h.c.\right) + \left(\frac{c_{d,i}y_{d,i}}{v^2}H^\dagger H \bar{d}_L^{(i)} H^c d_R^{(i)} + h.c.\right)$$
$$+ \frac{i\bar{c}_W \mathrm{g}}{2\mathrm{M_W}^2}(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H)(D^\mu W_{\mu\nu})^i + \frac{i\bar{c}_B \mathrm{g}'}{2\mathrm{M_W}^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\partial^\mu B_{\mu\nu})$$
$$+ \frac{i\bar{c}_{HW}\mathrm{g}}{\mathrm{M_W}^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\mathrm{g}'}{\mathrm{M_W}^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+ \frac{\bar{c}_\gamma \mathrm{g}'^2}{\mathrm{M_W}^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g \mathrm{g_s}}{\mathrm{M_W}^2}H^\dagger H G^a_{\mu\nu}G^{\mu\nu a}$$

If we look at the main LHC channels, there are 8 main operators contributing: $\{C_H, C_{u3}, C_{d3}, C_W, C_{HW}, C_{HB}, C_\gamma, C_g\}$

(minimal) Warsaw basis

$$
\begin{aligned}
\mathcal{L}_{Warsaw} =& \frac{C_{H\Box}}{\Lambda^2}(H^\dagger H)\Box(H^\dagger H) + \frac{C_{eH}}{\Lambda^2} y_e (H^\dagger H)(\bar{\ell} e H) + \frac{C_{uH}}{\Lambda^2} y_u (H^\dagger H)(\bar{q} u H) + \\
& \frac{C_{dH}}{\Lambda^2} y_d (H^\dagger H)(\bar{q} d H) + \frac{C_G}{\Lambda^2} f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu} + \frac{C_{HW}}{\Lambda^2} H^\dagger H W^I_{\mu\nu} W^{\mu\nu I} \\
& + \frac{C_{HB}}{\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{C_{HG}}{\Lambda^2} H^\dagger H G^A_{\mu\nu} G^{\mu\nu A}
\end{aligned}
$$

Assumptions:

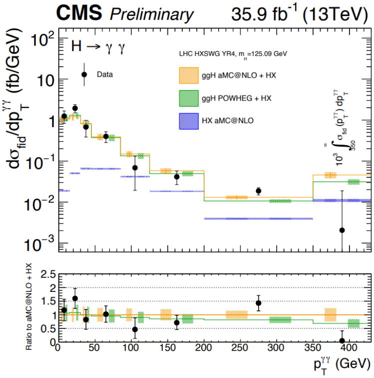
- Only operators affecting the Higgs vertices
- Don't fit $C_H \sim (H^\dagger H)^3 \Rightarrow$ only accessible through the triple Higgs coupling
- Don't fit operators that can be constrained better with LEP data (postpone for higher LHC lumi)
- The minimal Warsaw-run-II set is then:
  $\{C_{H\Box}, C_{eH}, C_{dH}, C_{uH}, C_G, C_{HW}, C_{HB}, C_{HG}\}$

Differential Distributions

- EFT effects are expected to be larger in the tails of p_T distributions
- The Higgs width can be accessed mainly through off-shell measurements
- Unfolded p_T distributions (or STXS) allow for a bin-per-bin fit of the EFT effects:

$$\mathcal{M} = \mathcal{M}_{SM} + \frac{c_i}{\Lambda^2}\mathcal{M}_{dim=6} + \frac{d_i}{\Lambda^4}\mathcal{M}_{dim=8}$$

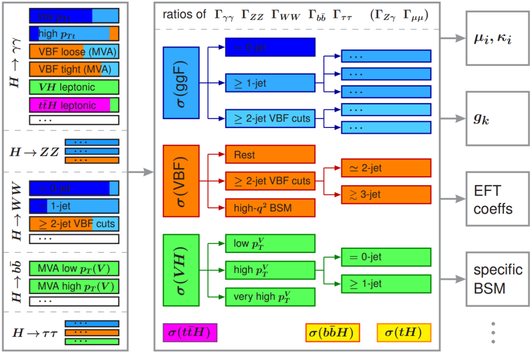
- The terms $\sim \frac{c_i}{\Lambda^2}$ can be added operator-by-operator and bin-by-bin to the SM predictions



(from H.BRUN's talk)

Simplified and Template Cross Sections (STXS)

- Easier to match with theoretical predictions:
  - delivered bin-per-bin (interesting for high p_T studies)
  - staged for specific sets of cuts and final states.
  - minimize contamination across channels.
- Limited resolution (large uncertainty introduced by the extrapolation)



EFT predictions and Theoretical Uncertainties

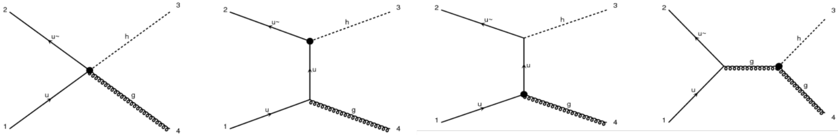
The EFT amplitude can be parametrised as

$$\mathcal{M} = \mathcal{M}_{SM} + \frac{c_i}{\Lambda^2}\mathcal{M}_{dim=6} + \frac{d_i}{\Lambda^4}\mathcal{M}_{dim=8}$$

and hence, the inclusive cross-section:

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\mathcal{R}e\left[\frac{c_i}{\Lambda^2}\mathcal{M}^*_{dim=6}\mathcal{M}_{SM}\right] + \underbrace{2\mathcal{R}e\left[\frac{d_i}{\Lambda^4}\mathcal{M}^*_{dim=8}\mathcal{M}_{SM} + \frac{c_i^2}{\Lambda^4}\mathcal{M}^2_{dim=6}\right]}_{Theoretical\ \ Uncertainty} + \ldots$$

We expect that the inclusive cross sections, STXS and the (bins of) differential distributions scale linearly on each of the Wilson Coefficients (as long as we only allow one operator insertion per diagram). Example: some $qq \to hg$ diagrams



Fit Technology

Predictions

- SILH basis: VBFNLO + eHDECAY + Professor[1]
- Warsaw basis: SMEFTsim + Madgraph[2]
- Results normalized (and uncertainties) to HXSWG predictions [3]

Fit

- Gfitter[4] + ROOT (minuit + roofit)
- Chi-squared analysis:

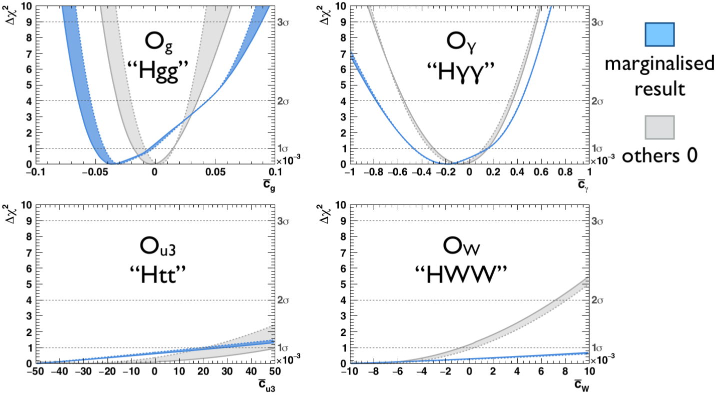
$$\chi^2 = (x - \underbrace{t(c_i, \delta_k)}_{prediction})^T V^{-1} (x - t(c_i, \delta_k)) \begin{cases} c_i = \text{Wilson coeffs.} \\ \delta_k = \text{nuisance params. (th.unc).} \\ V = V_{stat} + V_{syst} \end{cases}$$

- Fit over: 8TeV(μ), 13 TeV(μ)
- Two fit-modes: setting all operators but one to zero at a time, or marginalising.
- Th. Uncertainties from SM higher order calculations $\Rightarrow$ 2 nuisance parameters per channel: $(\delta_{SM}, \delta_{EFT}) \Rightarrow$ 26 nuisances $\Rightarrow$ 34 total free parameters

[1] Arnold et al., 1207.4975 7 Contino et al., 1403.3381 / Buckley et al., 0907.2973
[2] Brivio et.al.1709.06492 / Alwall et. al. 1405.0301
[3] Passarino et. al., 1101.0593
[4] Gfitter group, 0811.0009

Reminisce....SILH basis, results from RUN-I

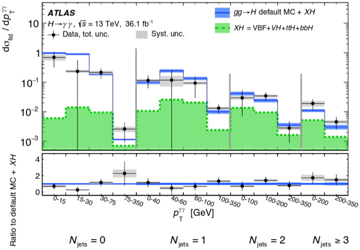
From Roman Kogler's talk at HEFT 2017



No noteworthy constraints on other 4 operators (within region of validity)

Signal Strengths

- Update from Run-I:
  - 20 μ from CMS+ATLAS combination
  - Including correlations
- From Run-II:
  - 18 μ from CMS
  - 14 μ from ATLAS
  - No correlations available
  - NB: Some of these μ have extreme values (e.g. ATLAS $VBF \to H \to \bar{b}b$, $\mu = -3.9 + 2.8 - 2.7$, $GGF \to H \to \bar{b}b$, $\mu = 2.51 + 2.44 - 2.01$)



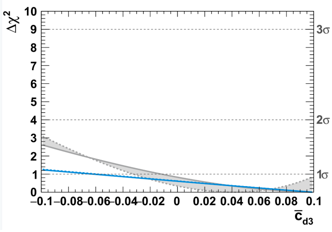
ATLAS 1802.04146

Ongoing:

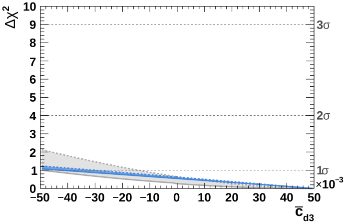
- Differential p_T distributions
- STXS

“Quark Operators” slight improvement on 8TeV, no improvement at 13TeV

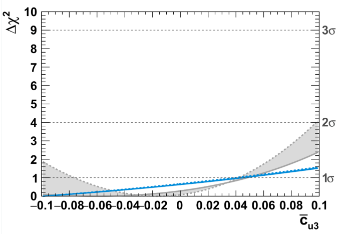
(C_{d3}, 8TeV updated)



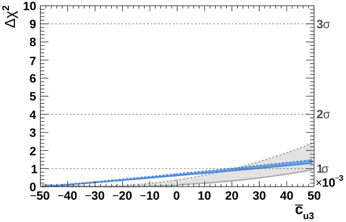
(C_{d3}, 8TeV, ArXiv:1511.05170)



(C_{u3}, 8TeV, updated)

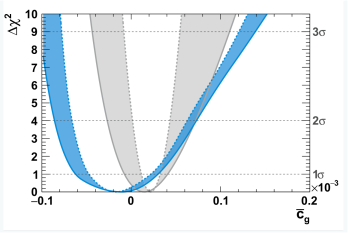


(C_{u3}, 8TeV, ArXiv:1511.05170)

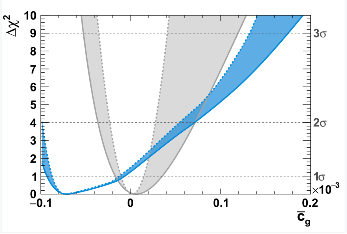


Slight improvement in C_W and G_g, both at 8TeV and 13TeV

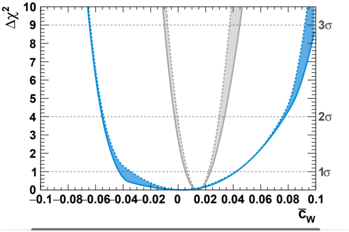
(C_g, 13TeV)



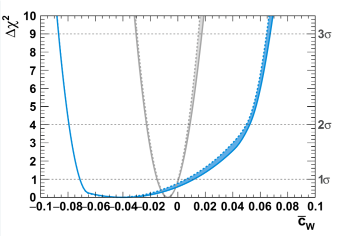
(C_g, 8TeV, updated)



(C_W, 13TeV)

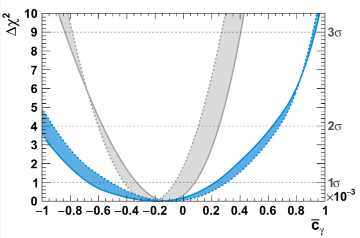


(C_W, 8TeV, updated)

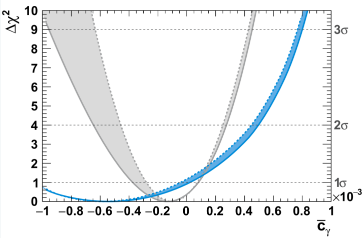


Slight improvement in C_{HW} and G_γ, both at 8TeV and 13TeV

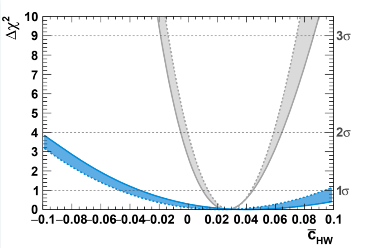
(C_γ, 13TeV)



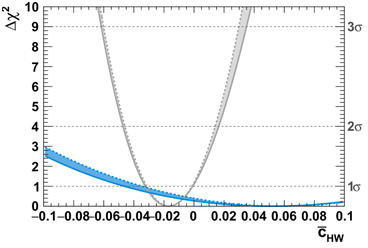
(C_γ, 8TeV, updated)



(C_{HW}, 13TeV)

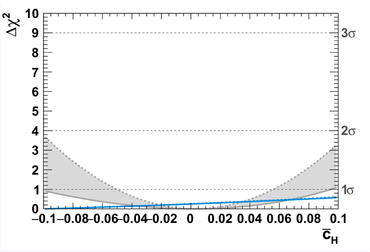


(C_{HW}, 8TeV, updated)

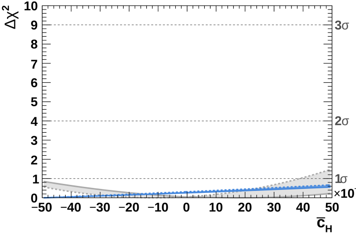


No improvement in “Higgs” operators

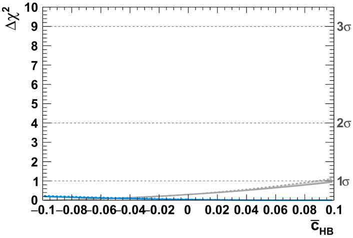
(C_H, 8TeV, updated)



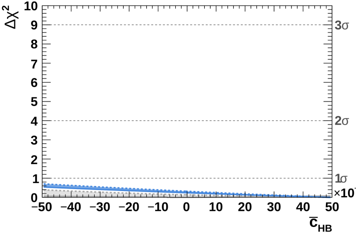
(C_H, 8TeV, ArXiv:1511.05170)



(C_{HB}, 8TeV, updated)



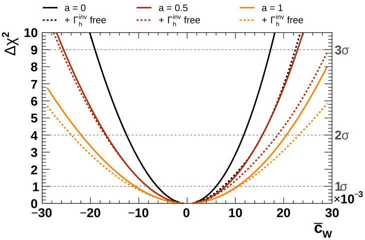
(C_{HB}, 8TeV, ArXiv:1511.05170)



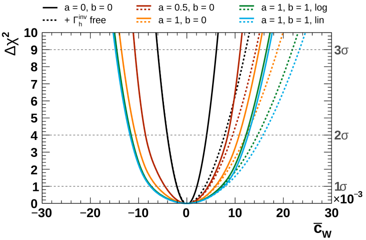
Extrapolation to HL-LHC

from arXiv:1708.06355

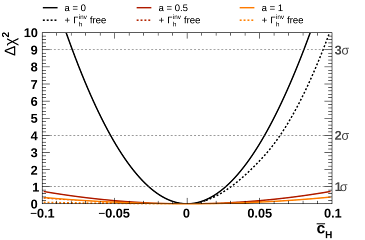
C_W, 14TeV μ only



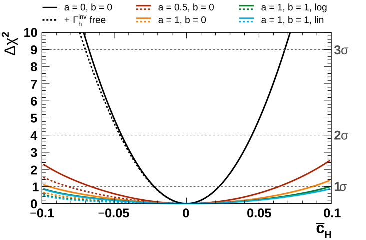
C_W, 14TeV μ and p_T



C_H, 14TeV μ only



C_H, 14TeV μ and p_T



Conclusions and future prospects

Conclusions

- Results from 8TeV improve when using combined results for signal strengths with correlations.
- Results for 13TeV similar to those for run I. Agreement with a recent publication on the topic (Ellis et. al. arXiv:1803.03252)
- Lack of sensitivity in C_H propagates to the rest of the Wilson coefficients
- Prospects for improved constraints with 8 and 13TeV data (need correlations)
- Studies show that unfolded p_T distributions will improve precision of all EFT fits.

Ongoing Work/ Future Prospects

- Transition to the Warsaw basis: fit over larger sets of operators
  $\Rightarrow$ accommodate EWPD
- Implementation for differential distributions and STXS is ready
  $\Rightarrow$ currently under scrutiny
- Hope for more combinations, correlations and p_T distributions from the collaborations soon.

Thank you for your attention!

BACKUP

STXS for ggF/H+j : Definitions

Process	Measurement region	Stage 1 region
ggH + $gg \to Z(\to qq)H$	0-jet	0-jet
	1-jet, $p_T^H < 60$ GeV	1-jet, $p_T^H < 60$ GeV
	1-jet, $60 \le p_T^H < 120$ GeV	1-jet, $60 \le p_T^H < 120$ GeV
	1-jet, $120 \le p_T^H < 200$ GeV	1-jet, $120 \le p_T^H < 200$ GeV
	1-jet, $p_T^H > 200$ GeV	1-jet, $p_T^H > 200$ GeV
	$\ge$ 2-jet, $p_T^H < 60$ GeV	$\ge$ 2-jet, $p_T^H < 60$ GeV
	$\ge$ 2-jet, $60 \le p_T^H < 120$ GeV	$\ge$ 2-jet, $60 \le p_T^H < 120$ GeV
	$\ge$ 2-jet, $120 \le p_T^H < 200$ GeV	$\ge$ 2-jet, $120 \le p_T^H < 200$ GeV
	$\ge$ 2-jet, $p_T^H > 200$ GeV	$\ge$ 2-jet, $p_T^H > 200$ GeV
	VBF-like	VBF-like, $p_T^{Hjj} < 25$ GeV
		VBF-like, $p_T^{Hjj} \ge 25$ GeV
$qq' \to Hqq'$ (VBF + VH)	$p_T^j < 200$ GeV, VBF-like	$p_T^j < 200$ GeV, VBF-like, $p_T^{Hjj} < 25$ GeV
		$p_T^j < 200$ GeV, VBF-like, $p_T^{Hjj} \ge 25$ GeV
	$p_T^j < 200$ GeV, VH+Rest	$p_T^j < 200$ GeV, VH-like
		$p_T^j < 200$ GeV, Rest
	$p_T^j > 200$ GeV, BSM-like	$p_T^j > 200$ GeV
VH (leptonic decays)	VH leptonic	$q\bar{q} \to ZH$, $p_T^Z < 150$ GeV
		$q\bar{q} \to ZH$, $150 < p_T^Z < 250$ GeV, 0-jet
		$q\bar{q} \to ZH$, $150 < p_T^Z < 250$ GeV, $\ge$ 1-jet
		$q\bar{q} \to ZH$, $p_T^Z > 250$ GeV
		$q\bar{q} \to WH$, $p_T^W < 150$ GeV
		$q\bar{q} \to WH$, $150 < p_T^W < 250$ GeV, 0-jet
		$q\bar{q} \to WH$, $150 < p_T^W < 250$ GeV, $\ge$ 1-jet
		$q\bar{q} \to WH$, $p_T^W > 250$ GeV
		$gg \to ZH$, $p_T^Z < 150$ GeV
		$gg \to ZH$, $p_T^Z > 150$ GeV, 0-jet
		$gg \to ZH$, $p_T^Z > 150$ GeV, $\ge$ 1-jet
Top-associated production	top	$t\bar{t}H$
		tHW
		tHq
bbH	merged w/ ggH	bbH

STXS for ggF/H+j : Measurements

Measurement region ($\|y_H\| < 2.5$)	Result	Uncertainty Total	Stat.	Syst.		SM prediction
ggH, 0 jet	38	$^{+16}_{-15}$	(± 14	$^{+6}_{-5}$)	fb	63 ± 5 fb
ggH, 1 jet, $p_T^H < 60$ GeV	23	$^{+14}_{-13}$	(± 13	$^{+5}_{-4}$)	fb	15 ± 2 fb
ggH, 1 jet, $60 \leq p_T^H < 120$ GeV	11	± 8	(± 7	$^{+3}_{-2}$)	fb	10 ± 2 fb
ggH, 1 jet, $120 \leq p_T^H < 200$ GeV	4.0	$^{+2.1}_{-1.9}$	(± 1.8	$^{+0.9}_{-0.6}$)	fb	1.7 ± 0.3 fb
ggH, 1 jet, $p_T^H \geq 200$ GeV	2.6	$^{+1.6}_{-1.2}$	($^{+1.3}_{-1.1}$	$^{+0.8}_{-0.5}$)	fb	0.4 ± 0.1 fb
ggH, ≥ 2 jet, $p_T^H < 60$ GeV	0	± 8	(± 8	$^{+3}_{-2}$)	fb	3 ± 1 fb
ggH, ≥ 2 jet, $60 \leq p_T^H < 120$ GeV	12	$^{+8}_{-7}$	(± 7	$^{+3}_{-2}$)	fb	4 ± 1 fb
ggH, ≥ 2 jet, $120 \leq p_T^H < 200$ GeV	7.9	$^{+3.5}_{-3.4}$	(± 3.3	$^{+1.1}_{-0.9}$)	fb	2.3 ± 0.6 fb
ggH, ≥ 2 jet, $p_T^H \geq 200$ GeV	2.6	$^{+1.6}_{-1.4}$	($^{+1.5}_{-1.4}$	$^{+0.6}_{-0.5}$)	fb	1.0 ± 0.3 fb
ggH, VBF – like	6.2	$^{+5.0}_{-4.5}$	(± 4.1	± 1.2)	fb	1.5 ± 0.3 fb
$qq \to Hqq$, VBF – like	3.8	$^{+2.5}_{-2.3}$	($^{+2.2}_{-2.0}$	± 1.2)	fb	2.7 ± 0.2 fb
$qq \to Hqq$, VH + Rest	-19	± 22	($^{+21}_{-20}$	$^{+6}_{-7}$)	fb	7.7 ± 0.4 fb
$qq \to Hqq$, $p_T^j > 200$ GeV	-3.2	$^{+1.9}_{-2.0}$	(± 1.7	$^{+0.7}_{-0.9}$)	fb	0.5 ± 0.1 fb
VH, leptonic	0.7	$^{+1.4}_{-1.2}$	($^{+1.4}_{-1.2}$	$^{+0.4}_{-0.3}$)	fb	1.4 ± 0.1 fb
Top	0.7	$^{+0.8}_{-0.7}$	($^{+0.8}_{-0.7}$	$^{+0.2}_{-0.1}$)	fb	1.3 ± 0.1 fb