Toward global fits using Higgs STXS data with Lilith

Le Duc Ninh

Phenikaa University, Hanoi, Vietnam

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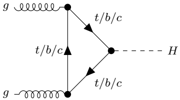
collaborators: Le Van Dung, Sabine Kraml, Tran Quang Loc, Nguyen Dang Bao Nhi

PHENIKAA UNIVERSITY

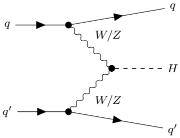
NAFOSTED National Foundation for Science & Technology Development

Higgs production processes at the LHC

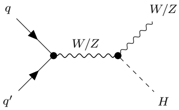
a) ggF (87%)



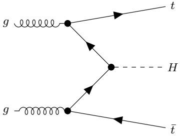
b) VBF (7%)



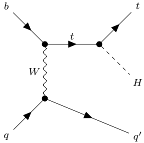
c) VH (4%)

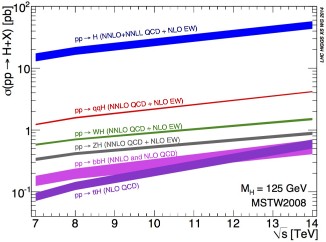


d) ttH (1%)



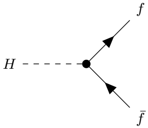
e) tH ($< 0.1\%$)



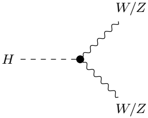


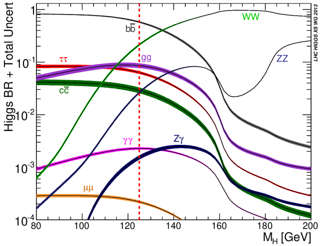
Higgs decays & signal strength (SS)

a) $H \to f\bar{f}$

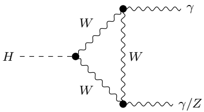


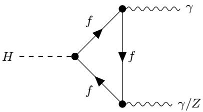
b) $H \to WW^*/ZZ^*$





c) $H \to \gamma\gamma/Z\gamma$





Mean lifetime:
$\approx 2 \times 10^{-22}$ s

Signal strength:

$$\mu_i^f = \frac{(\sigma_i \times \mathcal{B}^f)_{\text{experiment}}}{(\sigma_i \times \mathcal{B}^f)_{\text{SM}}}$$

Simplified Template Cross Section (STXS)

STXS data is available from Run 2:

- Better control on errors and their correlation
- Separate bins for new physics searches
- Binning evolves in stages: stage 0, 1.0, 1.1, 1.2, ...

	Production bin	Cross-section $(\sigma \cdot \mathcal{B})$ [pb]		$(\sigma \cdot \mathcal{B})/(\sigma \cdot \mathcal{B})_{\mathrm{SM}}$
		SM expected	Observed	Observed
SS	Production Mode Stage bins, $\lvert y_H \rvert < 2.5$			
	ggF	1.17 ± 0.08	$1.12 \pm 0.12 \pm 0.04 \pm 0.03$	$0.96 \pm 0.10 \pm 0.03 \pm 0.03$
	VBF	0.0920 ± 0.0020	$0.11 \pm 0.04 \pm 0.01 \pm 0.01$	$1.21 \pm 0.44\,{}^{+0.13}_{-0.08}\,{}^{+0.07}_{-0.05}$
	VH	$0.0524^{+0.0027}_{-0.0049}$	$0.075^{+0.059}_{-0.047}\,{}^{+0.011}_{-0.007}\,{}^{+0.013}_{-0.009}$	$1.44^{+1.13}_{-0.90}\,{}^{+0.21}_{-0.14}\,{}^{+0.24}_{-0.17}$
	ttH	$0.0154^{+0.0010}_{-0.0013}$	$0.026^{+0.026}_{-0.017} \pm 0.002 \pm 0.002$	$1.7^{+1.7}_{-1.2} \pm 0.2 \pm 0.2$
STXS	Reduced Stage-1.1 bins, $\lvert y_H \rvert < 2.5$			
	gg2H-0j-p_{T}^{H}-Low	0.176 ± 0.025	$0.17 \pm 0.05 \pm 0.02$	$0.96 \pm 0.30 \pm 0.09$
	gg2H-0j-p_{T}^{H}-High	0.55 ± 0.04	$0.63 \pm 0.09 \pm 0.06$	$1.15 \pm 0.17 \pm 0.11$
	gg2H-1j-p_{T}^{H}-Low	0.172 ± 0.025	$0.05 \pm 0.07\,{}^{+0.04}_{-0.06}$	$0.3 \pm 0.4\,{}^{+0.2}_{-0.3}$
	gg2H-1j-p_{T}^{H}-Med	0.119 ± 0.018	$0.17 \pm 0.05\,{}^{+0.02}_{-0.01}$	$1.4 \pm 0.4 \pm 0.1$
	gg2H-1j-p_{T}^{H}-High	0.020 ± 0.004	$0.009^{+0.016}_{-0.011} \pm 0.002$	$0.5^{+0.8}_{-0.6} \pm 0.1$
	gg2H-2j	0.127 ± 0.027	$0.04 \pm 0.07 \pm 0.04$	$0.3 \pm 0.5 \pm 0.3$
	gg2H-p_{T}^{H}-High	0.015 ± 0.004	$0.038^{+0.021}_{-0.016}\,{}^{+0.003}_{-0.002}$	$2.5^{+1.3}_{-1.0}\,{}^{+0.2}_{-0.1}$
	qq2Hqq-VH	$0.0138^{+0.0004}_{-0.0006}$	$0.021^{+0.037}_{-0.029}\,{}^{+0.009}_{-0.006}$	$1.5^{+2.7}_{-2.1}\,{}^{+0.6}_{-0.4}$
	qq2Hqq-VBF	$0.1076^{+0.0024}_{-0.0035}$	$0.15 \pm 0.05\,{}^{+0.02}_{-0.01}$	$1.4 \pm 0.5\,{}^{+0.2}_{-0.1}$
	qq2Hqq-BSM	0.00420 ± 0.00018	$0.0005^{+0.0079}_{-0.0047} \pm 0.008$	$0.1^{+1.9}_{-1.1} \pm 0.2$
	VH-Lep	0.0164 ± 0.0004	$0.022^{+0.028}_{-0.018}\,{}^{+0.003}_{-0.001}$	$1.3^{+1.7}_{-1.1}\,{}^{+0.2}_{-0.1}$
	ttH	$0.0154^{+0.0010}_{-0.0013}$	$0.025^{+0.026}_{-0.017}\,{}^{+0.005}_{-0.003}$	$1.6^{+1.7}_{-1.1}\,{}^{+0.3}_{-0.2}$

Credit: ATLAS HIGG-2018-28

Lilith

Lilith

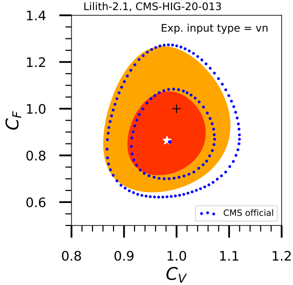
Light Likelihood Fit for the Higgs[1,2]

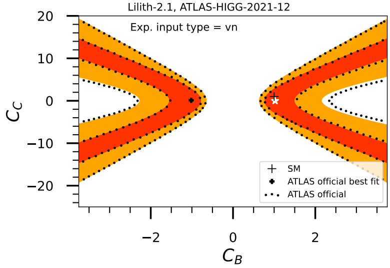
- A python package for constraining Higgs-coupling parameters of a BSM model (Kappa, SMEFT, 2HDM, ...).
- Current database: SS from publications of ATLAS, CMS, Tevatron.
- Statistical method: maximal likelihood using variable Gaussian distributions.
- On-going work:
  - Extended the database to include STXS data.
  - Include correlations of theoretical errors.
  - Implement SMEFT parametrizations.

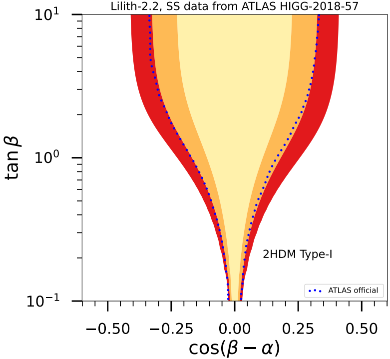
[1] Bernon and Dumont *Eur. Phys. J. C* 75 (2015) 440. **[Lilith-1.1]**

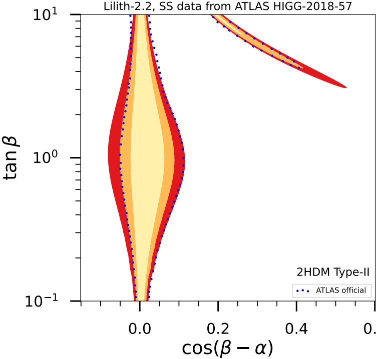
[2] S. Kraml, T.Q. Loc, D.T. Nhung, and L.D. Ninh *SciPost Phys.* 7 (2019) 052. **[Lilith-2.0]**

Results using SS data









STXS data

Measurement region $\left((\sigma_i \times B_{ZZ})/B_{ZZ}^{\mathrm{SM}}\right)$	Value [pb]	Uncertainty [pb] Total	Stat.	Syst.	SM prediction [pb]
$gg \to H$, 0-jet	35.5	$^{+5.0}_{-4.7}$	$^{+4.4}_{-4.1}$	$^{+2.5}_{-2.2}$	27.5 ± 1.8
$gg \to H$, 1-jet, $p_T^H < 60$ GeV	3.7	$^{+2.8}_{-2.7}$	$^{+2.4}_{-2.3}$	$^{+1.5}_{-1.4}$	6.6 ± 0.9
$gg \to H$, 1-jet, $60 \leq p_T^H < 120$ GeV	4.0	$^{+1.7}_{-1.5}$	$^{+1.5}_{-1.4}$	$^{+0.8}_{-0.7}$	4.6 ± 0.6
$gg \to H$, 1-jet, $120 \leq p_T^H < 200$ GeV	1.0	$^{+0.6}_{-0.5}$	± 0.5	$^{+0.3}_{-0.2}$	0.75 ± 0.15
$gg \to H$, $\geq$ 1-jet, $p_T^H \geq 200$ GeV	1.2	$^{+0.5}_{-0.4}$	± 0.4	$^{+0.3}_{-0.2}$	0.59 ± 0.16
$gg \to H$, $\geq$ 2-jet, $p_T^H < 200$ GeV	5.4	$^{+2.7}_{-2.5}$	$^{+2.2}_{-2.1}$	$^{+1.5}_{-1.3}$	4.8 ± 1.0
$qq \to Hqq$, VBF topo + Rest	6.4	$^{+1.8}_{-1.5}$	$^{+1.5}_{-1.3}$	$^{+1.1}_{-0.9}$	4.07 ± 0.09
$qq \to Hqq$, VH topo	−0.06	$^{+0.70}_{-0.58}$	$^{+0.68}_{-0.57}$	$^{+0.16}_{-0.12}$	0.515 ± 0.019
$qq \to Hqq$, $p_T^j \geq 200$ GeV	−0.21	± 0.33	$^{+0.29}_{-0.28}$	$^{+0.15}_{-0.16}$	0.220 ± 0.005
$qq \to H\ell\nu$, $p_T^V < 250$ GeV	0.90	$^{+0.49}_{-0.40}$	$^{+0.40}_{-0.33}$	$^{+0.28}_{-0.22}$	0.393 ± 0.009
$qq \to H\ell\nu$, $p_T^V \geq 250$ GeV	0.023	$^{+0.028}_{-0.015}$	$^{+0.018}_{-0.012}$	$^{+0.022}_{-0.008}$	0.0122 ± 0.0006
$gg/qq \to H\ell\ell$, $p_T^V < 150$ GeV	0.17	$^{+0.25}_{-0.31}$	± 0.20	$^{+0.15}_{-0.24}$	0.200 ± 0.008
$gg/qq \to H\ell\ell$, $150 \leq p_T^V < 250$ GeV	0.028	$^{+0.042}_{-0.037}$	$^{+0.033}_{-0.029}$	$^{+0.026}_{-0.023}$	0.0324 ± 0.0041
$gg/qq \to H\ell\ell$, $p_T^V \geq 250$ GeV	0.024	$^{+0.025}_{-0.013}$	$^{+0.016}_{-0.011}$	$^{+0.020}_{-0.006}$	0.0083 ± 0.0009
$t\bar{t}H$+tH	0.84	$^{+0.23}_{-0.19}$	$^{+0.18}_{-0.16}$	$^{+0.14}_{-0.11}$	$0.59\ ^{+0.04}_{-0.05}$
Branching fraction ratio	**Value**	**Uncertainty Total**	**Stat.**	**Syst.**	**SM prediction**
$B_{\gamma\gamma}/B_{ZZ}$	0.074	$^{+0.012}_{-0.010}$	$^{+0.010}_{-0.009}$	$^{+0.006}_{-0.005}$	0.0860 ± 0.0010
$B_{b\bar{b}}/B_{ZZ}$	14	$^{+8}_{-6}$	$^{+5}_{-4}$	$^{+6}_{-5}$	22.0 ± 0.5
B_{WW}/B_{ZZ}	7.0	$^{+1.5}_{-1.3}$	$^{+1.1}_{-0.9}$	$^{+1.0}_{-0.9}$	$8.15 \pm\ < 0.01$
$B_{\tau\tau}/B_{ZZ}$	2.1	$^{+0.7}_{-0.6}$	± 0.5	$^{+0.5}_{-0.3}$	2.37 ± 0.02

Source: ATLAS HIGG-2018-57

Likelihood:

$$-2\log L = (\hat{x}-x)^T \cdot C^{-1} \cdot (\hat{x}-x),$$

where:

- $\hat{x}^p = (\sigma_i^p \times \mathcal{B}_Y)_{\text{exp}}$ [best fits],
- $x^p = \mu_i^Y \times (\sigma^p \times \mathcal{B}_Y)_{\text{SM}}$ [model prediction],
- $C = C_{\text{ex}} + C_{\text{th}}$ [covariance].

Covariances:

$$C_{\text{ex}} = \Sigma_{\text{ex}} \cdot \rho_{\text{ex}} \cdot \Sigma_{\text{ex}},$$

$$C_{\text{th}} = \Sigma_{\text{th}} \cdot \rho_{\text{th}} \cdot \Sigma_{\text{th}}$$

STXS data

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$gg \to H$, 1-jet, $120 \le p_{\mathrm{T}}^{H} < 200$ GeV	1.0	$^{+0.6}_{-0.5}$	± 0.5	$^{+0.3}_{-0.2}$	0.75 ± 0.15
$gg \to H$, $\ge$ 1-jet, $p_{\mathrm{T}}^{H} \ge 200$ GeV	1.2	$^{+0.5}_{-0.4}$	± 0.4	$^{+0.3}_{-0.2}$	0.59 ± 0.16
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B_{WW}/B_{ZZ}	7.0	$^{+1.5}_{-1.3}$	$^{+1.1}_{-0.9}$	$^{+1.0}_{-0.9}$	$8.15 \pm\ < 0.01$
$B_{\tau\tau}/B_{ZZ}$	2.1	$^{+0.7}_{-0.6}$	± 0.5	$^{+0.5}_{-0.3}$	2.37 ± 0.02

Source: ATLAS HIGG-2018-57

Likelihood:

$$-2\log L = (\hat{x}-x)^T \cdot C^{-1} \cdot (\hat{x}-x),$$

where:

- $\hat{x}^p = (\sigma_i^p \times \mathcal{B}_Y)_{\text{exp}}$ [best fits],
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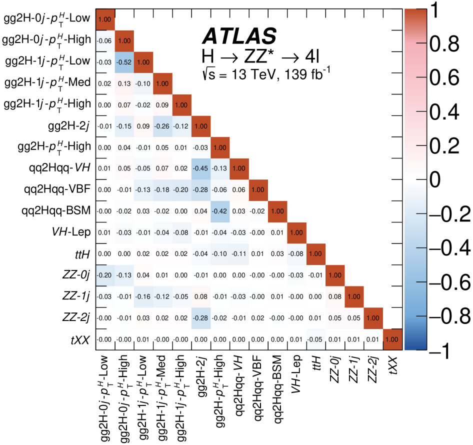
- $C = C_{\text{ex}} + C_{\text{th}}$ [covariance].

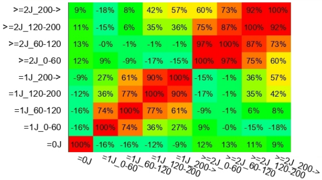
Covariances:

$$C_{\text{ex}} = \Sigma_{\text{ex}} \cdot \rho_{\text{ex}} \cdot \Sigma_{\text{ex}},$$
$$C_{\text{th}} = \Sigma_{\text{th}} \cdot \rho_{\text{th}} \cdot \Sigma_{\text{th}}$$

Experiment and theory correlations

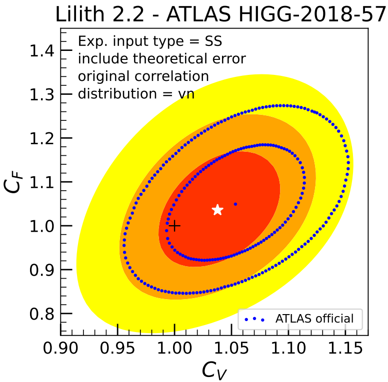
correlation of exp. errors

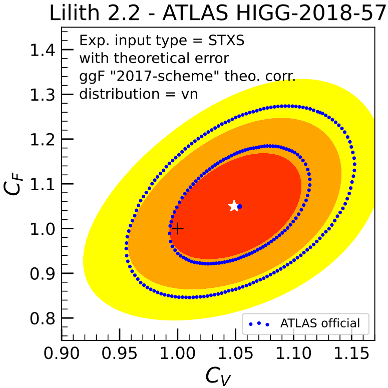




- ATLAS and CMS dont provide the theoretical correlations with their papers.
- It's not easy, if not impossible, for theorists to calculate them.

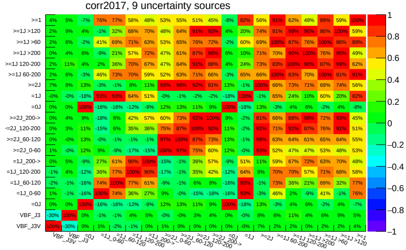
STXS vs. SS

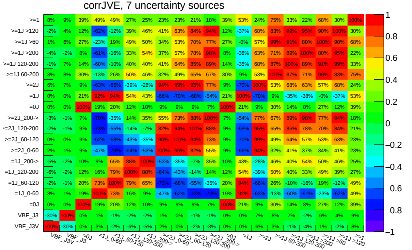


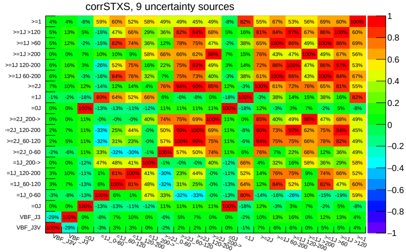


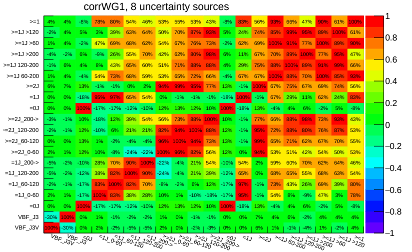
- STXS data gives better results than SS data, as expected!

Theoretical correlations (ggF only)



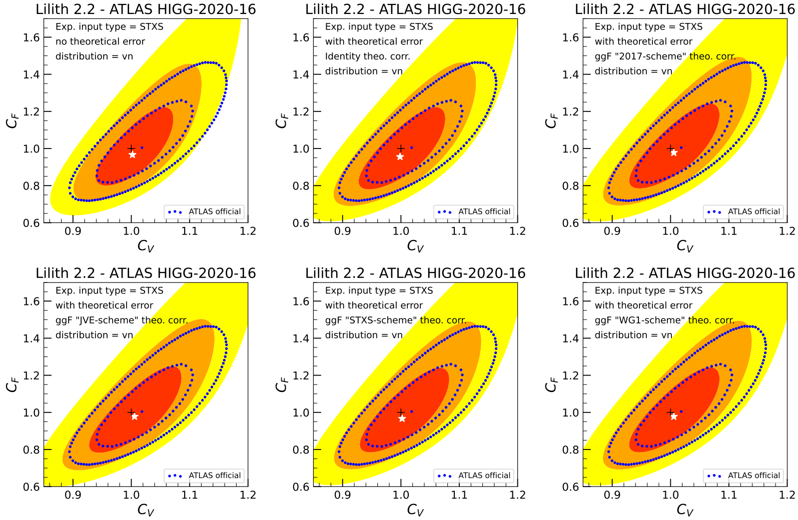






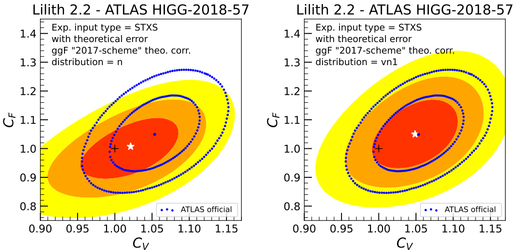
Need also corr. between ggF and VBF, ttH, ...

Effects of theoretical correlations (ggF only)



Discrepancies due to missing theoretical correlations? Need help from exp colleagues!

Variable Gaussian vs. Gaussian



(a) Gaussian (b) variable Gaussian

Likelihood

$$-2\log L = (\hat{x}-x)^T \cdot C^{-1} \cdot (\hat{x}-x)$$
$$C = \Sigma \cdot \rho \cdot \Sigma,$$
$$\Sigma = \text{diag}(\sigma_1, \sigma_2, \ldots)$$

Gaussian:

$$\sigma_i = (\sigma_i^+ + \sigma_i^-)/2$$

Variable Gaussian [Barlow (2004)]:

$$\sigma_i = \sqrt{\sigma_i^+\sigma_i^- + (\sigma_i^+ - \sigma_i^-)(\hat{x}-x)}$$
$$= f(C_V, C_F)$$

- Variable Gaussian is better for asymmetric errors !

SMEFT

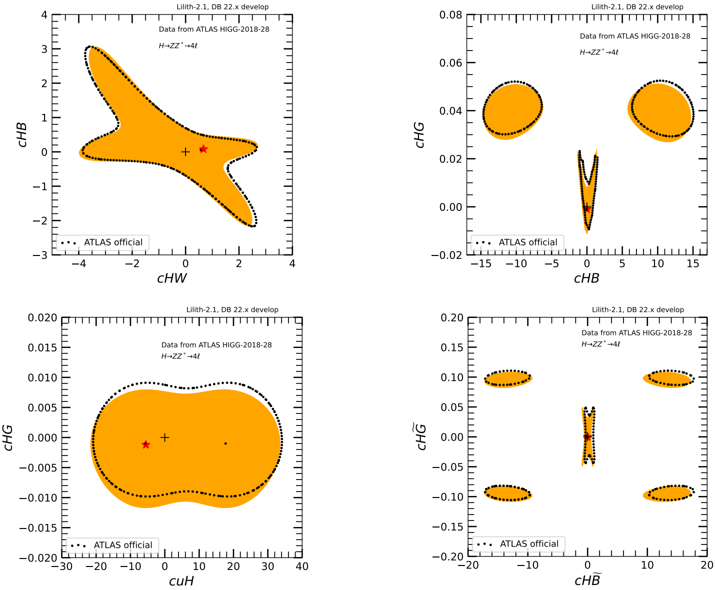
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(D=6)}}{\Lambda^2} Q_i^{(D=6)} + \sum_i \frac{c_i^{(D=8)}}{\Lambda^4} Q_i^{(D=8)} + \ldots ,$$

$$\sigma^p \propto \left|\mathcal{M}^p_{\text{SMEFT}}\right|^2 = \left|\mathcal{M}^p_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}^p_i\right|^2$$
$$\Rightarrow \sigma^p_{\text{SM}} \left(1 + \sum_i A^p_i c_i + \sum_{ij} B^p_{ij} c_i c_j\right) ,$$

$$\mathcal{B}^f = \frac{\Gamma^f}{\Gamma^{\text{total}}} = \mathcal{B}^f_{\text{SM}} \cdot \frac{1 + \sum_i A^f_i c_i + \sum_{ij} B^f_{ij} c_i c_j}{1 + \sum_f \left(\sum_i A^f_i c_i + \sum_{ij} B^f_{ij} c_i c_j\right)} .$$

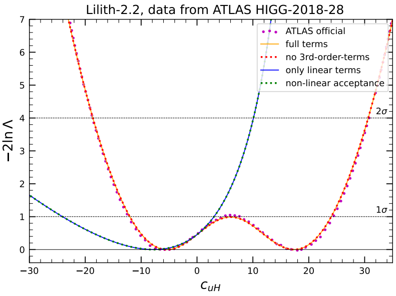
$$\frac{A}{A_{\text{SM}}} = \alpha_0 + (\alpha_1)^2 \cdot \left[\alpha_2 + \sum_i \delta_i \cdot (c_i + \beta_i)^2 + \sum_{\substack{ij \\ i \neq j}} \delta_{(i,j)} \cdot c_i c_j + \delta_{\substack{(i,j,k) \\ i \neq j \neq k}} \cdot c_i c_j c_k\right]^{-1}$$

SMEFT fit results



Lilith application: $1/\Lambda^4$ effects

$$\sigma^p = \left| \mathcal{M}^p_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i^{(D6)}\mathcal{M}_i^{D6,p} + \frac{1}{\Lambda^4}\sum_j c_j^{(D8)}\mathcal{M}_j^{D8,p} + \ldots \right|^2$$



ATLAS HIGG-2018-28: only $D6^2$

Large $1/\Lambda^4$ effects !
$\longrightarrow$ need D8 operators.

Summary

- Lilith: a python tool to use ATLAS and CMS Higgs SS and STXS data to constrain Higgs-coupling parameters.
- Information on the correlation of SM errors between different processes is still lacking.
- SMEFT: Parametrizations are crucial. ATLAS and CMS, please provide this information in your papers. We need this to validate our results.

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Thank you for your attention!