Experimental results on the EFT interpretations of Higgs boson measurements

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Outline

- Summary of the Higgs measurements
- How to extract info on EFT
- Global fit & Extrapolation to HL-HE LHC
- Future Colliders

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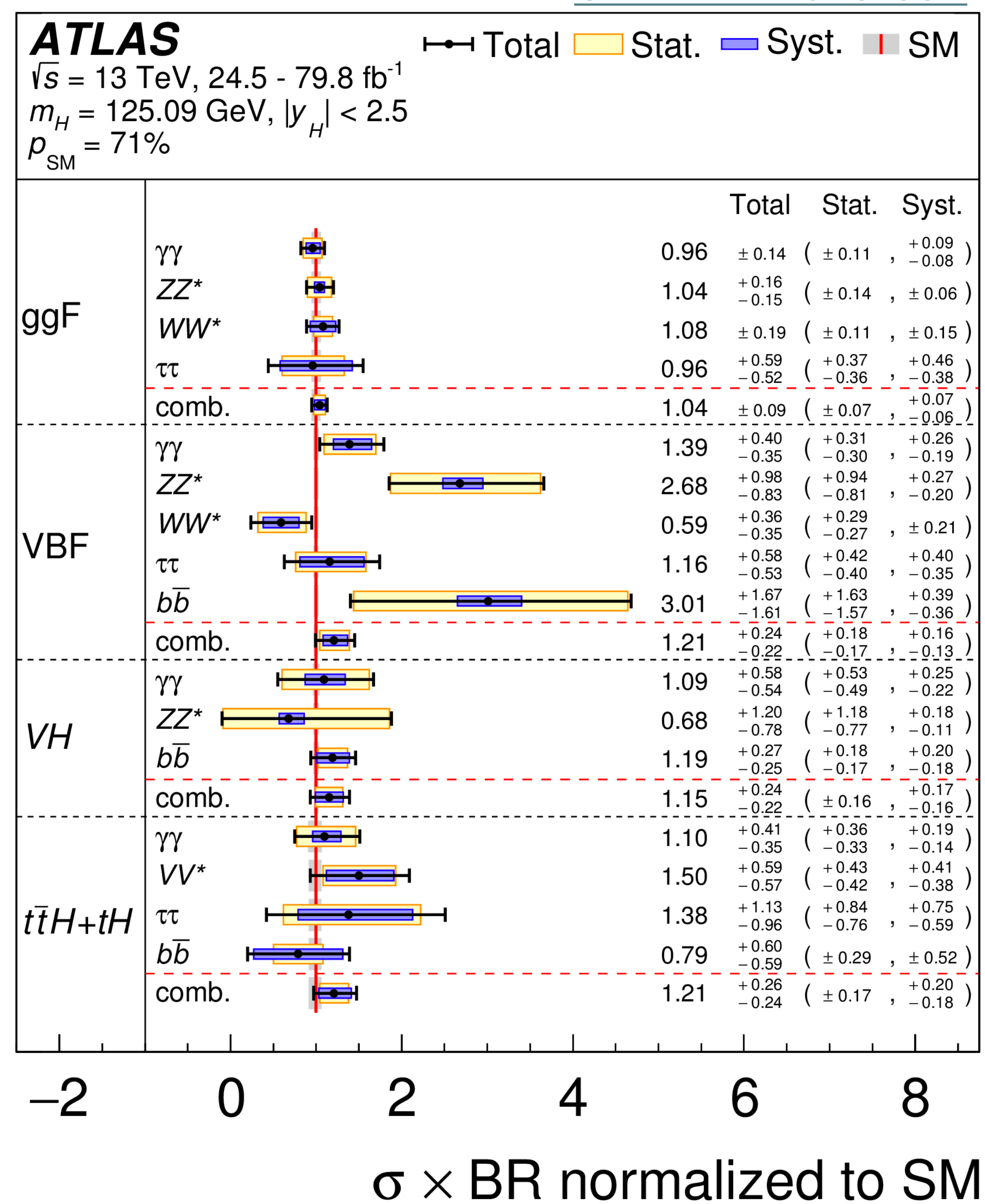
Higgs measurements (I)
XS times BR

- Higgs boson measurements reached unprecedented precision…

  …and analyses of full Run2 dataset are ongoing

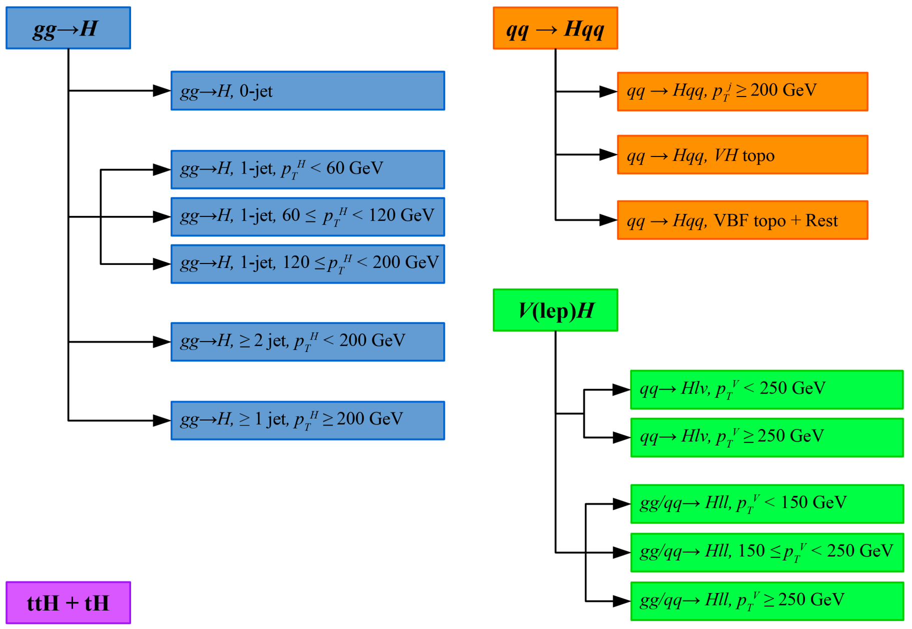
- Already
  ~10% precision on ggF
  ~25% precision on VBF, VH, ttH

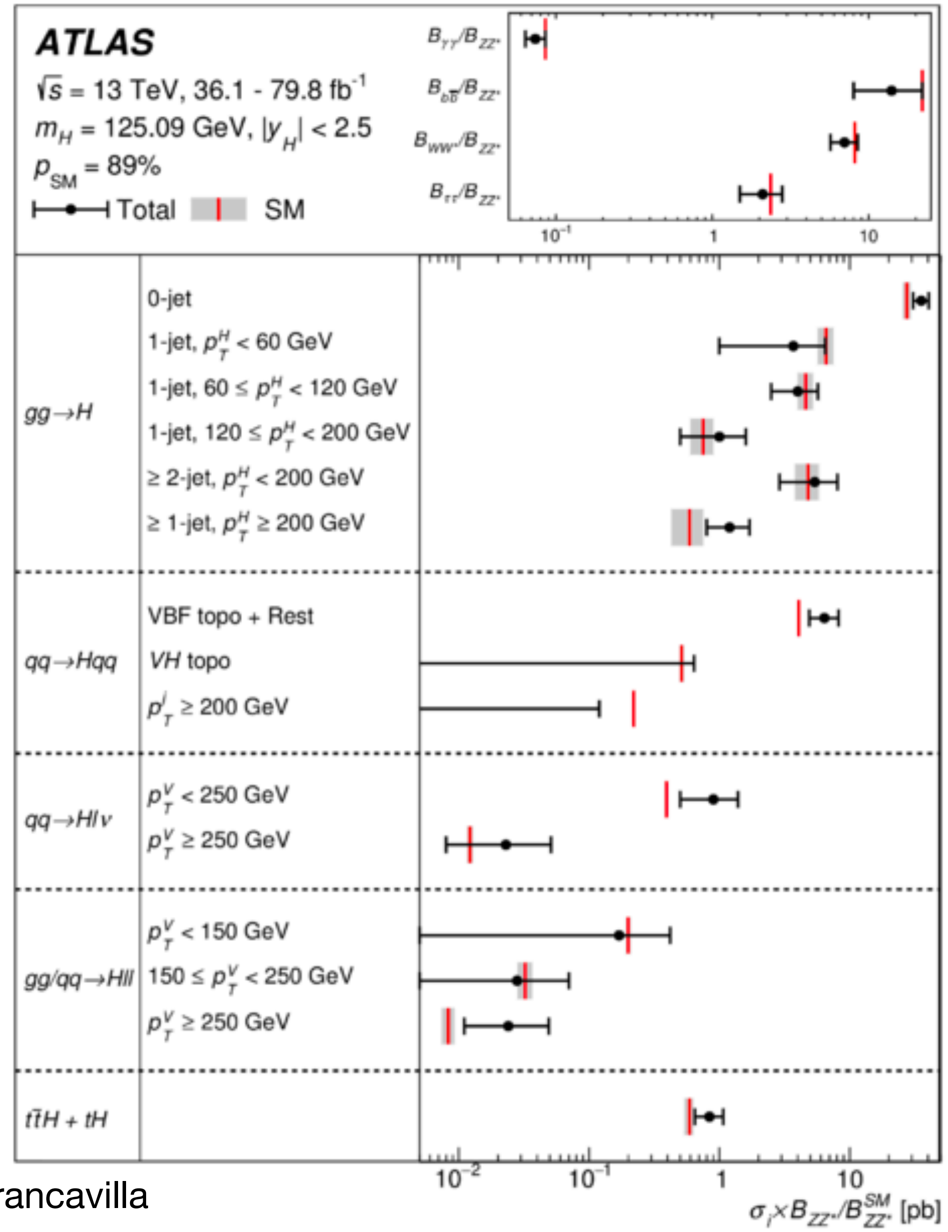
CERN-EP-2019-097

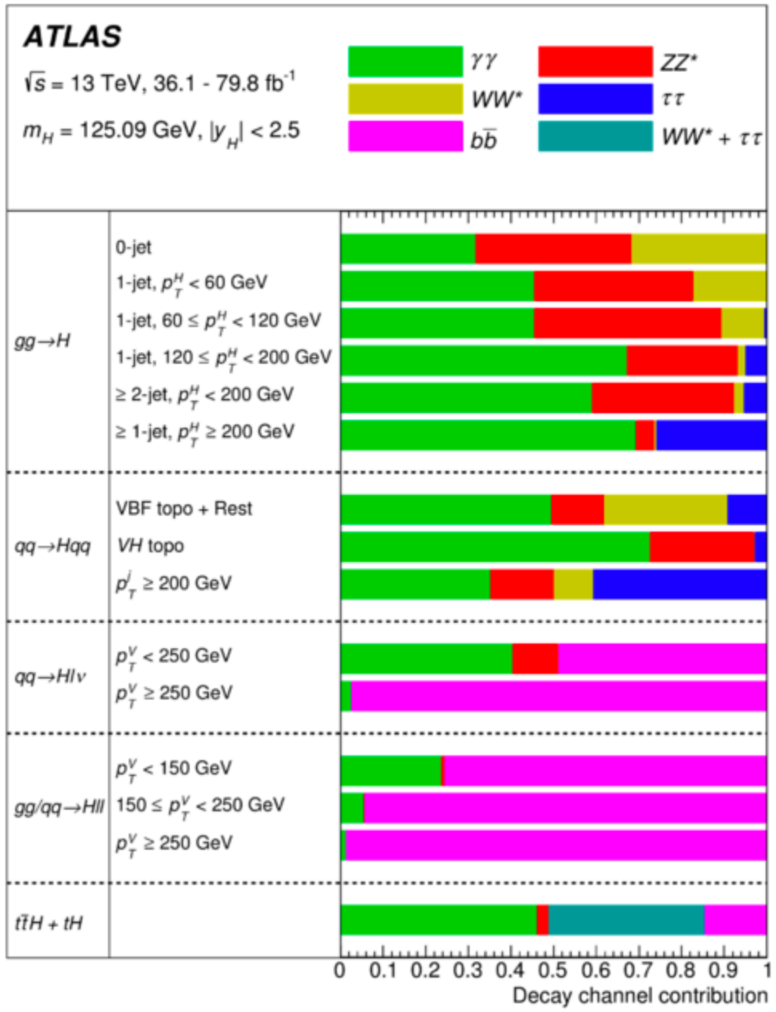


Higgs measurements (II)
Simplified Template XS

- **STXS** [LHC Higgs XS Yellow Report 4] **implemented in all the major channels**
- Different channels contribute to determine the final measurement







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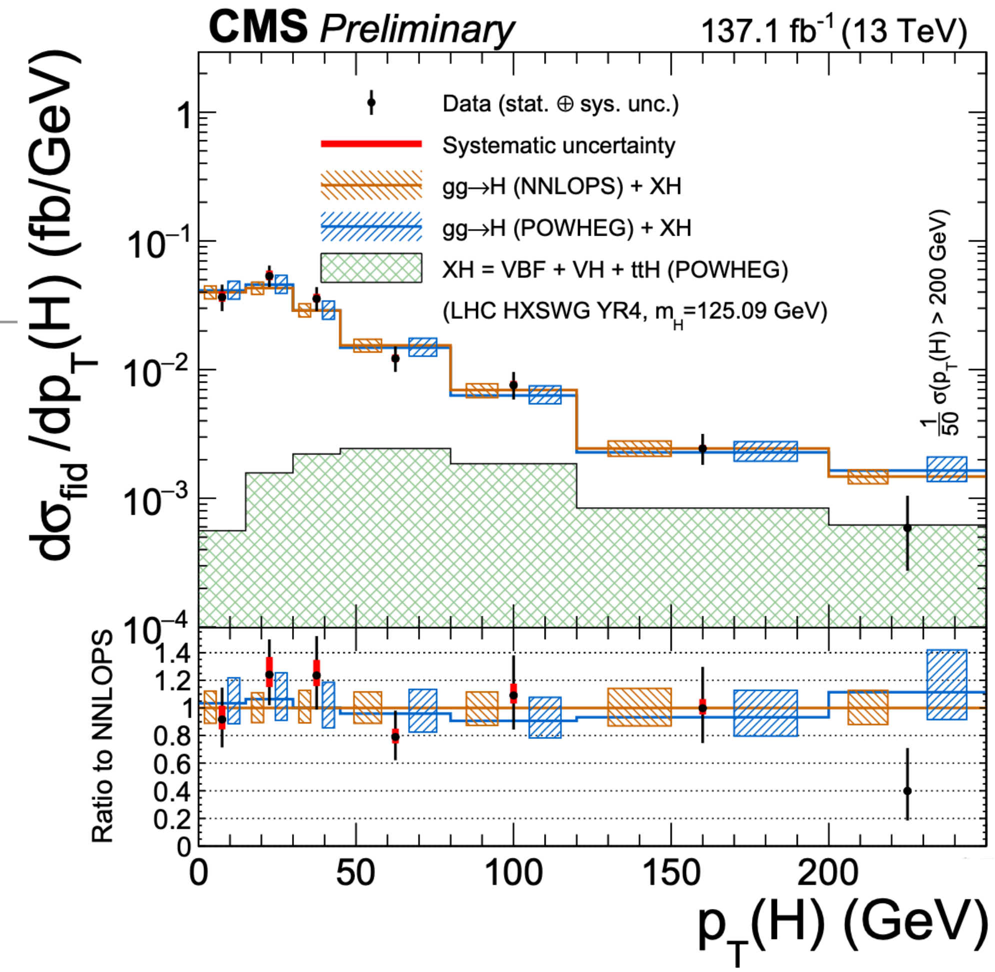
Higgs measurements (III)
Differential measurements

- Measurement of differential cross sections are available
  - H→γγ,H→ZZ, H→WW (in CMS)
- Usually uncertainties still large and in most of the cases statistical limited.



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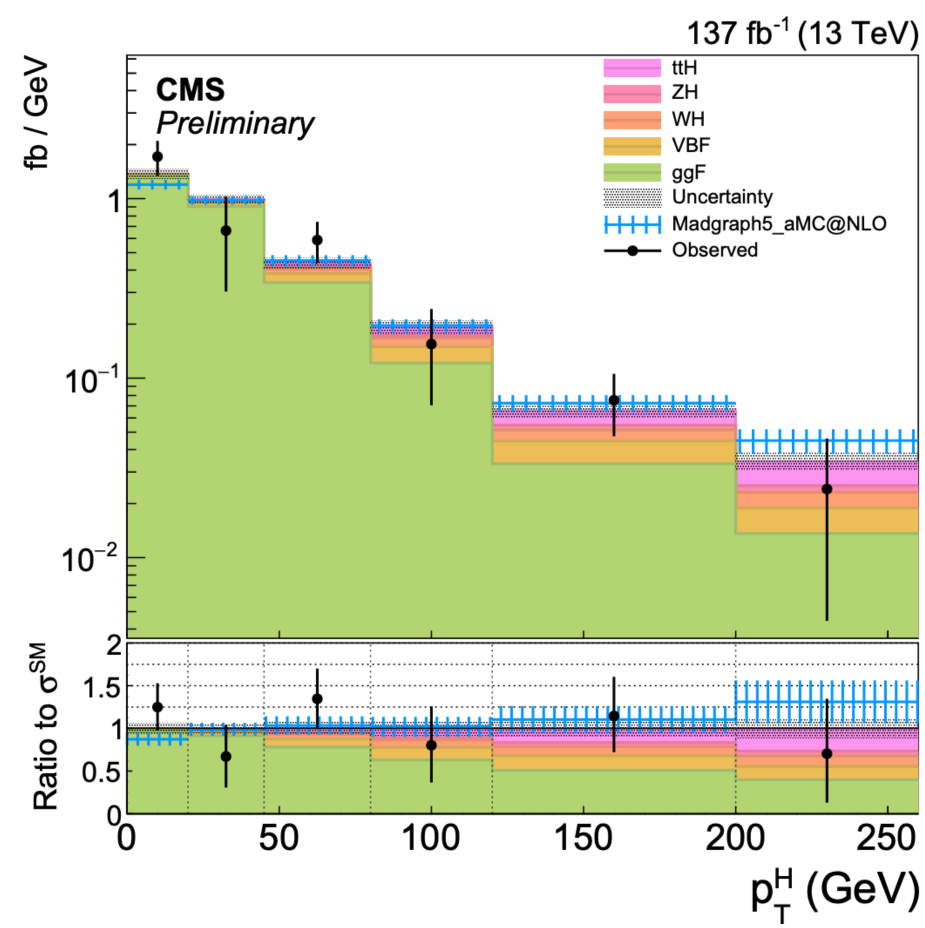

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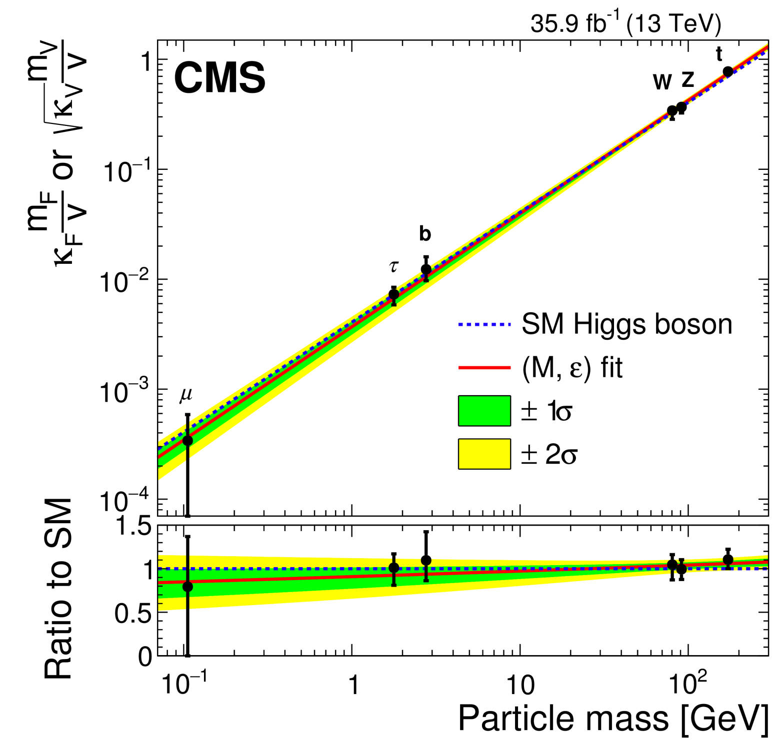
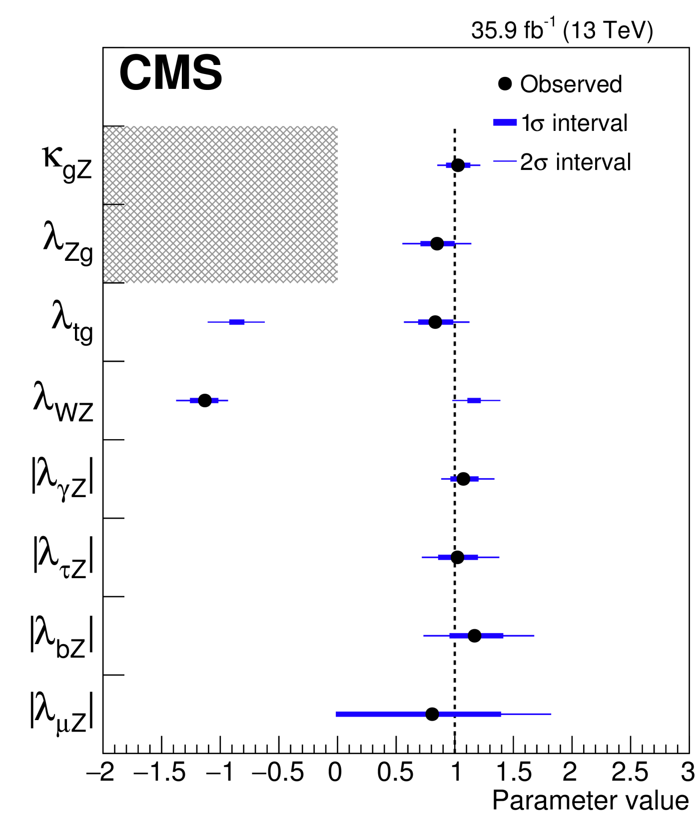
Higgs measurement interpretation (I)
***κ*-formalism**

$$\sigma_i \cdot \mathrm{B}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma_{\mathrm{SM}}^j$$

- Extracting coupling constants in the ***κ*-framework**
- Under the assumption of no new particles in loop and decays:
  - **~10-20% for fermions**
  - **8% for vector bosons**
- More generic parameterisations used already





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Higgs measurement interpretation (II)
Effective Field Theory

- k-model not consistent beyond LO (not suited to precision measurements)
- **Effective Fields Theory natural way to extend SM**

$$L = L_{SM}^{(d\leq 4)} + \boxed{\frac{1}{\Lambda^2}\sum_i c_i^{(d=6)} O_i^{(d=6)}} + \frac{1}{\Lambda^4}\sum_i c_i^{(d=8)} O_i^{(d=8)} + \dots^{(*)}$$

- **EFT allows modifications of rate and of kinematic**
  - **STXS and Differential measurements** are particularly interesting for this interpretation
  - **Different EFT approaches** used in different analyses (AC, HC, SMEFT, SILH …),
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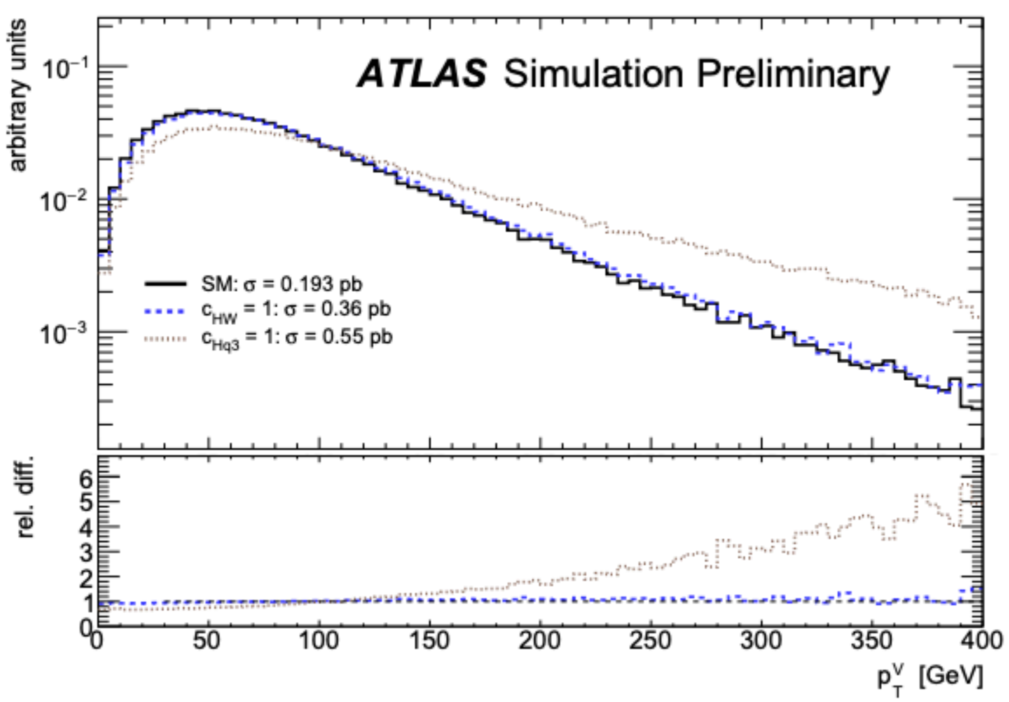
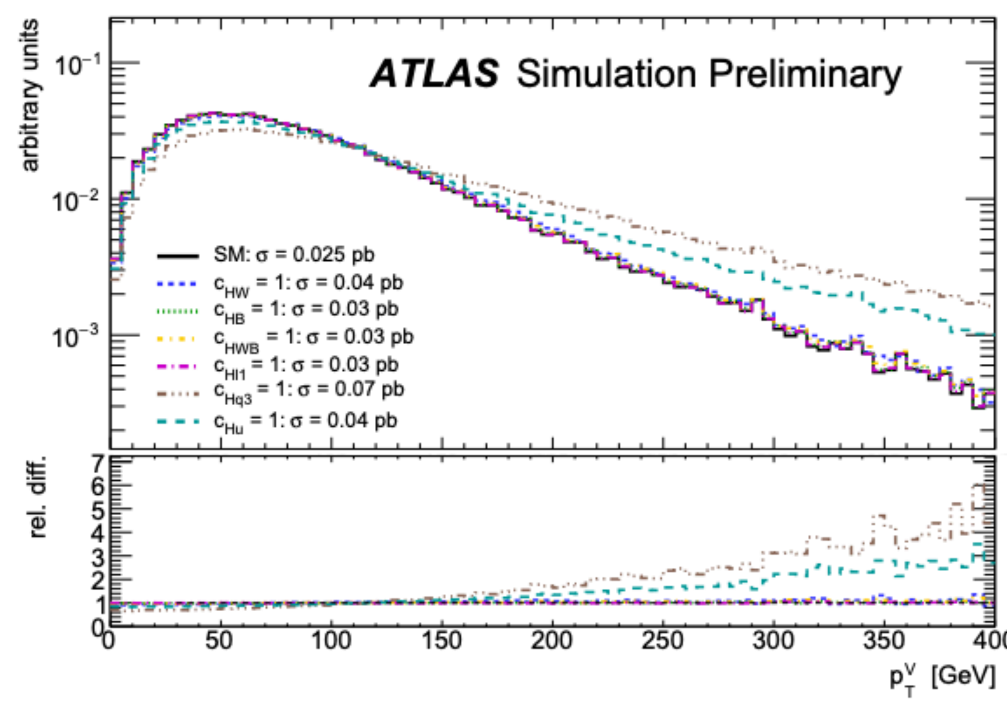


(c) leptonic WH



(d) leptonic ZH

ATL-PHYS-PUB-2019-042

(*) *d=5 (violate lepton number) and d=7(violate B-L) terms are not shown*

Outline

- Summary of the Higgs measurements
- **How to extract info on EFT**
- Global fit & Extrapolation to HL-HE LHC
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How to extract info on EFT

- Requirement: Want to be able to fit for the c_j coefficients:
  - ➡ Need a continuous signal model (not just testing single points in the EFT space);
  - ➡ For the statistical analysis we need to know the pdf for the signal (and in some cases for the background) as a function of the parameters:

$$P_s(\vec{x}\,|\,\vec{c})$$

Sum of full-sim. signal PDFs [1]

- Generate full-sim $p_i(\vec{x})$ for fixed points i in the parameter space
- Calculate the weighted sum of $p_i(\vec{x})$ with the appropriate dependence on $\vec{c}$

$$P_s(\vec{x}|\vec{c}) = \sum_i a_i(\vec{c})p_i(\vec{x})$$

Parametrise in gen-level fiducial bins(*)[2]

- Split the gen-level in bins k
- Get the appropriate scaling μ_k factor for the effect of $\vec{c}$ on the bin k
  (usually 1st of 2nd order polynomials)
- Use the SM pdf for x in each bin k: $p^{SM}_k(\vec{x})$

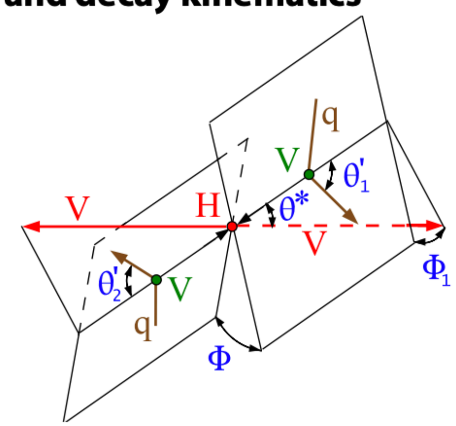
$$P_s(\vec{x}|\vec{c}) = \sum_k \mu_k(\vec{c})p_k^{\mathrm{SM}}(\vec{x})$$

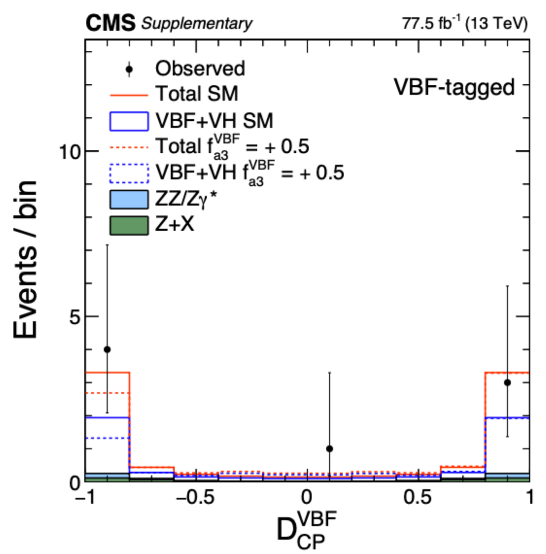
(*) It assumes that effects on acceptance and shape inside the bin k are subdominant and can be neglected. If this is not negligible, you can split the bin k again

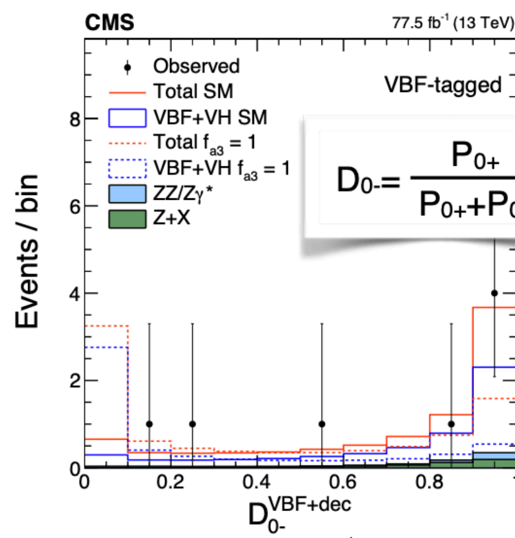
Strategy [1] at work:
HVV anomalous couplings

- An example using AC in CMS. NOTE: Straightforward mapping between AC formalism and linear EFT (bkp)
- Construct optimal observables using MELA
- Simulation using JHU generator and POWHEG, re-weighting to different AC using MELA
- Signal model construction follows flexible and extensible approach

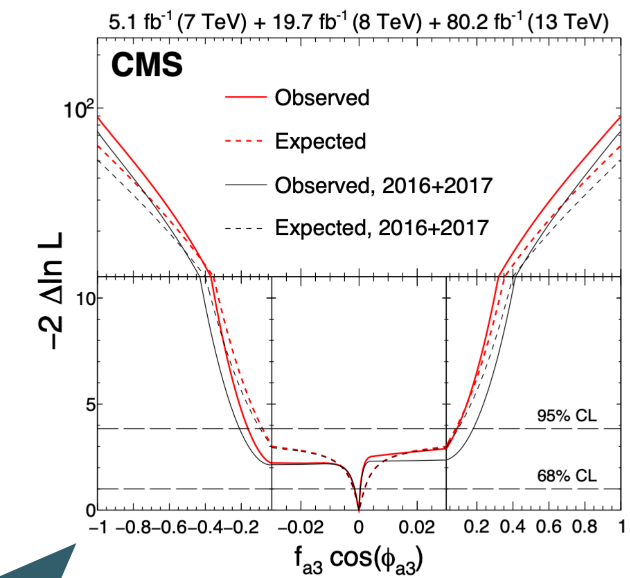
Contains both production and decay kinematics







$$D_{0-} = \frac{P_{0+}}{P_{0+} + P_{0-}}$$



PDFs for each component **Normalisation**

$$\mathcal{P}^{\mathrm{sig/int}}_{jk}\left(\vec{x};\vec{\xi}_{jk},f_{ai},\phi_{ai}\right) = \sum_{m=0}^{M} \mathcal{P}^{\mathrm{sig/int}}_{jk,m}\left(\vec{x};\vec{\xi}_{jk}\right) f_{ai}^{\frac{m}{2}}\left(1-f_{ai}\right)^{\frac{M-m}{2}} \cos^{m}(\phi_{ai}),$$

M up to 4

CMS-HIG-17-034

heavily inspired by the talk of A. Gilbert in link

Strategy [1] at work:
HVV anomalous couplings

- An example using AC in CMS. NOTE: Straight
- Construct **optimal observables** using MELA
- Simulation using JHU generator and POWHEG
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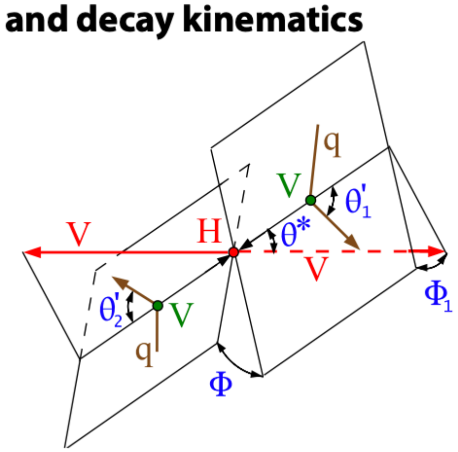
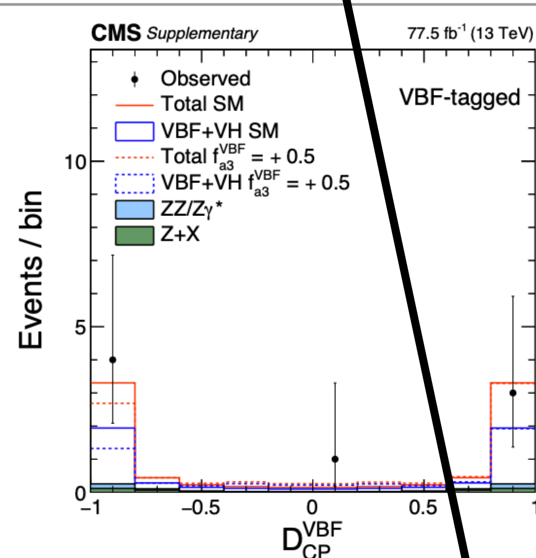




$$\mathcal{P}^{\mathrm{sig/int}}_{jk}\left(\vec{x};\vec{\xi}_{jk},f_{ai},\phi_{a}\right.$$

CMS-HIG-17-034

Which observable? Optimal!

We are testing two hypothesis: c=0 VS c!=0

Which is the best test statistics for the test?
Likelihood ratio ⇒ Optimal Observable:

$$\mathcal{D}_{\mathrm{BSM}} = \frac{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})+\mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})}, \qquad \mathcal{D}_{\mathrm{int}} = \frac{\mathcal{P}^{\mathrm{int}}_{\mathrm{SM-BSM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})+\mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})},$$

or ratio of or matrix elements $\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d}\cdot\mathcal{M}_{\mathrm{CP\text{-}odd}}.$

$$OO_2 := \frac{|\mathcal{M}_{\mathrm{CP\text{-}odd}}|^2}{|\mathcal{M}_{\mathrm{SM}}|^2} \qquad \boxed{OO_1 := \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}}$$

(used in ATLAS used for CP studies in H→ττ [ATLAS-CONF-2019-050])
Maximum sensitivity, but don't separate measurement and interpretation
Usually one needs one observable for each c.

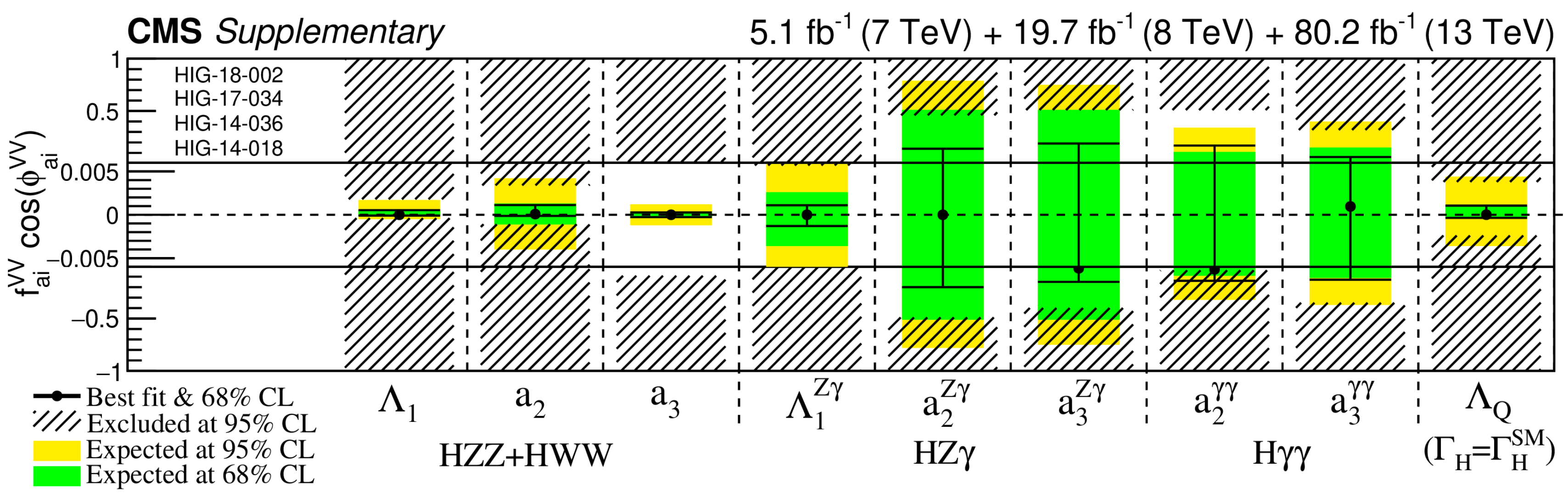
General measurements could loose a bit of information, but more suitable for reinterpretation

Strategy [1] at work:
HVV anomalous couplings

- An exam
- Constru
- Simulati
- Signal m

EFT (bkp)

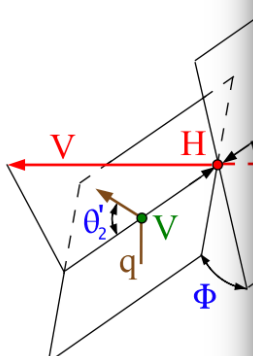
$$A = \frac{1}{v}\left(\left[a_1 - e^{i\phi_{\Lambda Q}}\frac{(q_1+q_2)^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}}\frac{q_1^2+q_2^2}{(\Lambda_1)^2}\right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}\right)$$

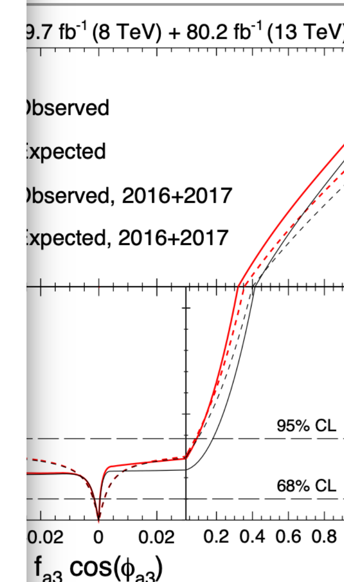


Parameter	Observed / (10^{-3}) 68% CL	Observed / (10^{-3}) 95% CL	Expected / (10^{-3}) 68% CL	Expected / (10^{-3}) 95% CL
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$	$[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$	$[-4.0, 4.2]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.53}_{-0.09}$	$[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$	$[-0.5, 1.7]$
$f^{Z\gamma}_{\Lambda 1}\cos(\phi^{Z\gamma}_{\Lambda 1})$	$0.0^{+1.1}_{-1.3}$	$[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$	$[-11, 8.0]$

Parameter	Observed	Expected
a_3/a_1	$[-0.81, 0.31]$	$[-0.090, 0.090]$
a_2/a_1	$[-0.055, 0.097]$	$[-0.11, 0.11]$
$(\Lambda_1\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda 1})$ (GeV)	$[-\infty, -650] \cup [440, \infty]$	$[-\infty, -610] \cup [450, \infty]$
$(\Lambda_1^{Z\gamma}\sqrt{\lvert a_1\rvert})\cos(\phi^{Z\gamma}_{\Lambda 1})$ (GeV)	$[-\infty, -400] \cup [420, \infty]$	$[-\infty, -360] \cup [390, \infty]$

Contains both pro
and decay kine





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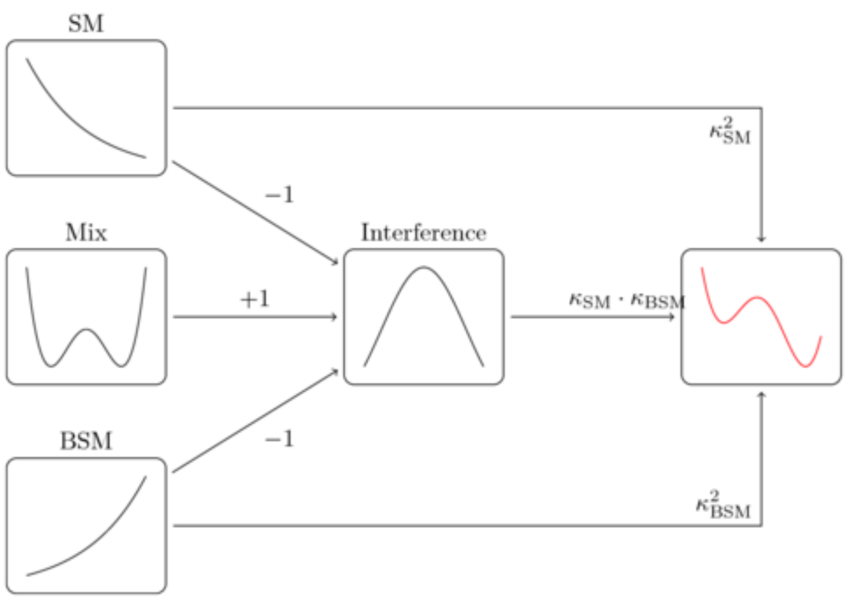
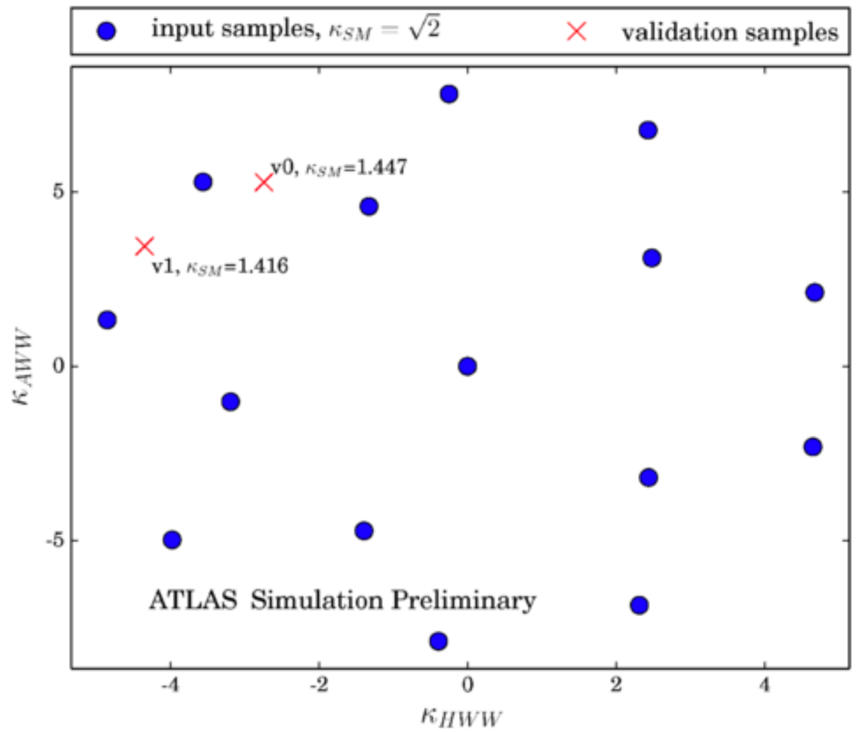
M up to 4

Strategy [1] at work:
Morphing in multidimensional space

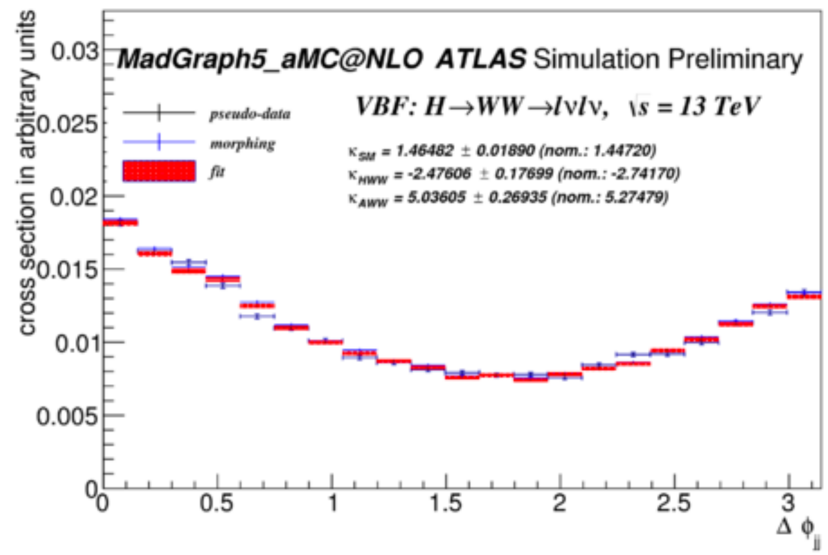
- An example using Higgs Characterisation Model (SMEFTsim also supported) in ATLAS Run2 HZZ analysis
- Given a set of input templates/PDFs and the corresponding EFT parameter points generates a morphing function to model any point in parameter space
- NOTE that this can be used in both approaches [1] and [2].



Simple showcase



Generated samples



Closure

ATL-PHYS-PUB-2015-047

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- An example using Higgs Characterisation Model (SMEFTsim also supported) in ATLAS Run2 HZZ analysis
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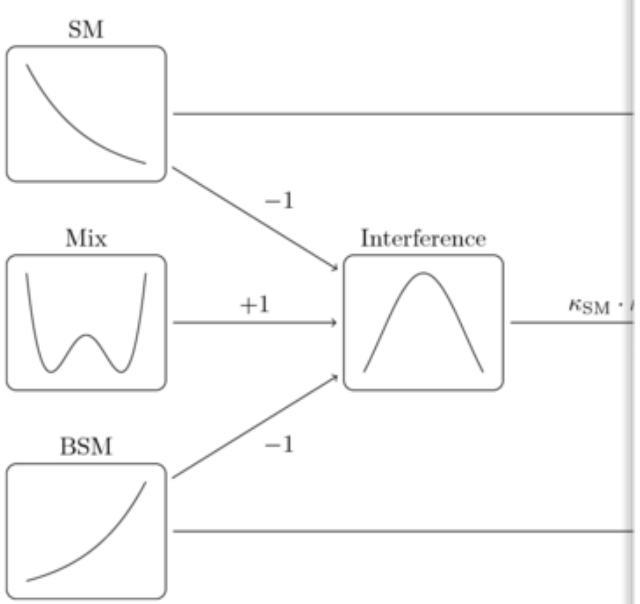
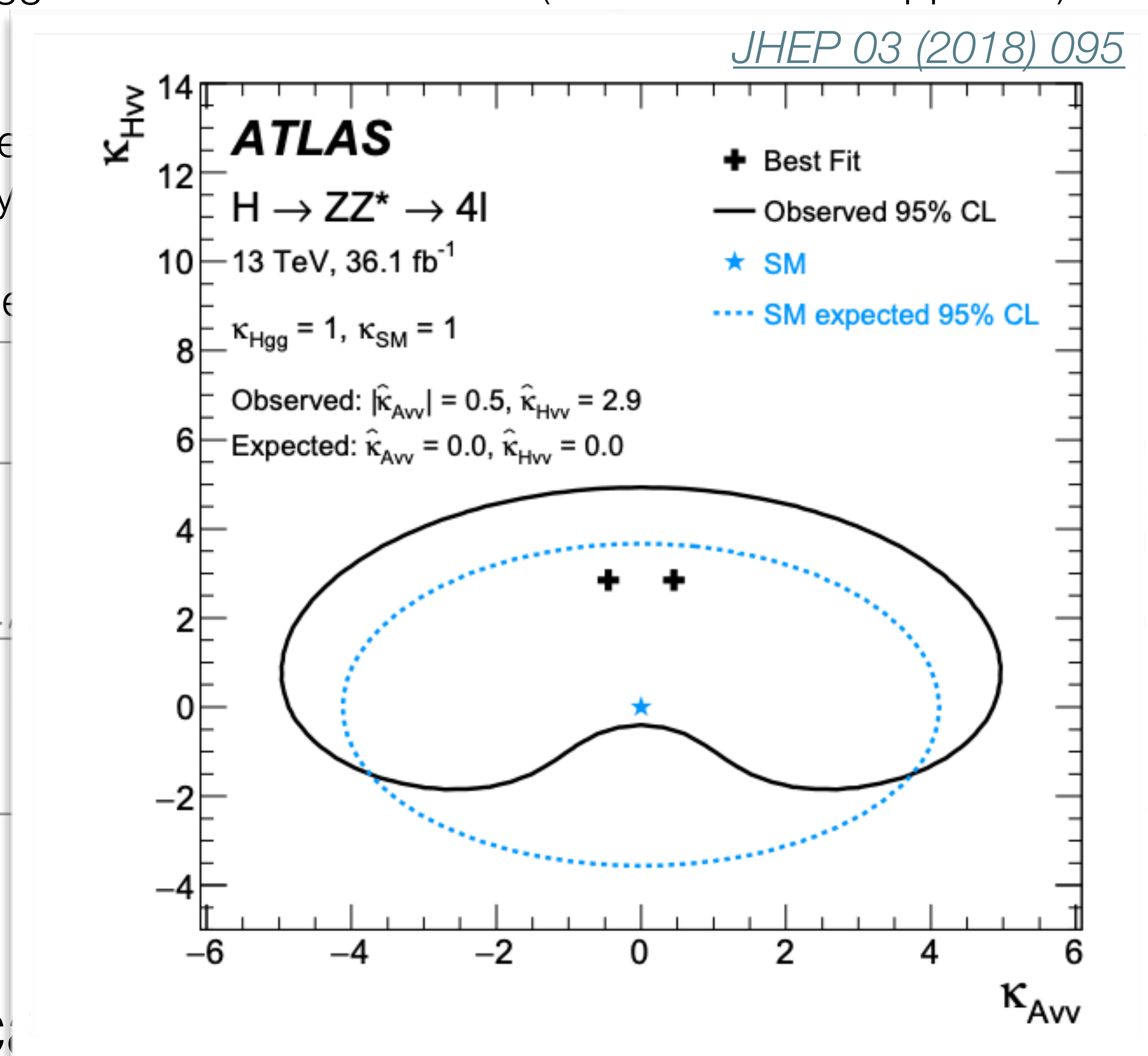
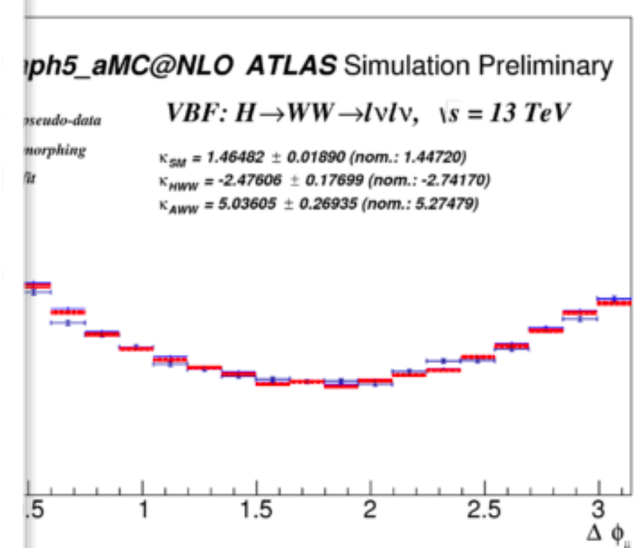


Simple showca…



Generated samples



Closure

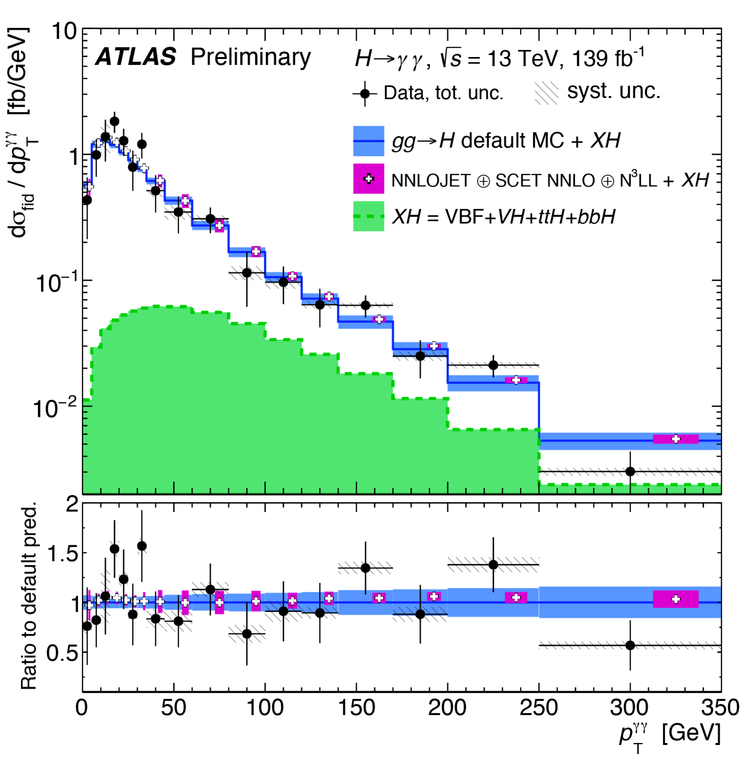
ATL-PHYS-PUB-2015-047

Strategy [2] at work:
Differential cross sections

- Measured fiducial differential cross sections can be used to measure EFT coefficients.
- In ATLAS, use unfolded distribution of $p_T^{\gamma\gamma}$, N_{jets}, m_{jj}, $\Delta\varphi_{jj}$ and p_T^{j1}
- Correlation between observables obtained by bootstrap
- Need to know how $\boldsymbol{\sigma_{pred}}$ depends on $\boldsymbol{c_j}$

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp\left(-\frac{1}{2}\left(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{pred}}\right)^T C^{-1} \left(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{pred}}\right)\right)$$

ATLAS-CONF-2019-029



Need to know:

- $\sigma_i = \sigma_i^{\text{SM}} + \sum_j c_j \sigma_{i,j}^{\text{int}} + \sum_{jk} c_j c_k \sigma_{i,jk}^{\text{BSM}}$, where j and k run over all relevant operators
- $\mu_i = 1 + \sum_j c_j A_{i,j} + \sum_{jk} c_j c_k B_{i,jk}$, relative to the SM prediction ⇒ need to find A_j, B_{jk}

- **A and B are calculated from MC**
- **For specific observables (see later) given by LHC-HXSWG**
- **General use tools start to appear (i.e. EFT2Obs) (*)**

(*) This is great! And it is great to see their cross checks and validations. A preferable direction (imo) for the future would be to converge in a (few?) common validated set among experiments/channels, avoiding a proliferation.

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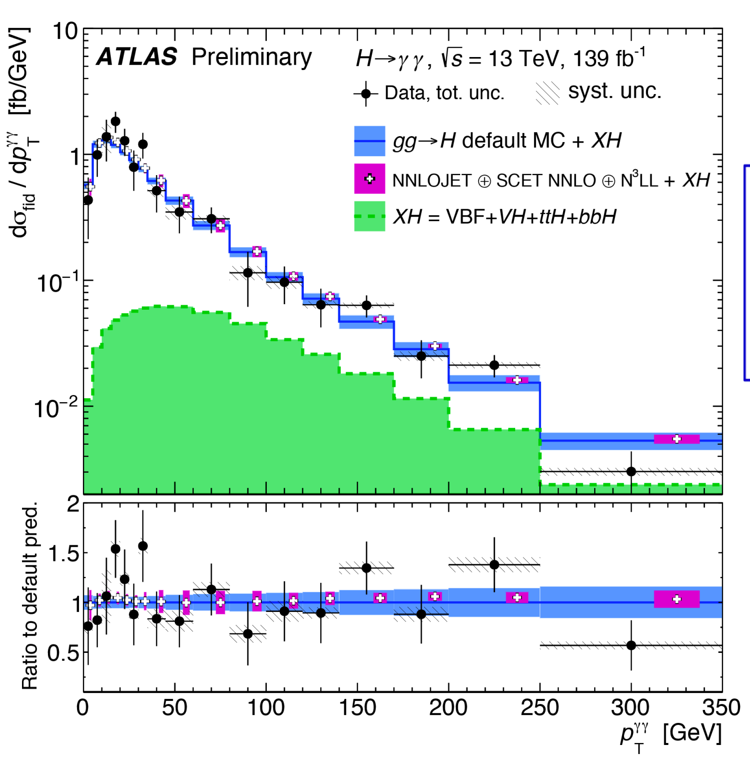
ATLAS-CONF-2019-029

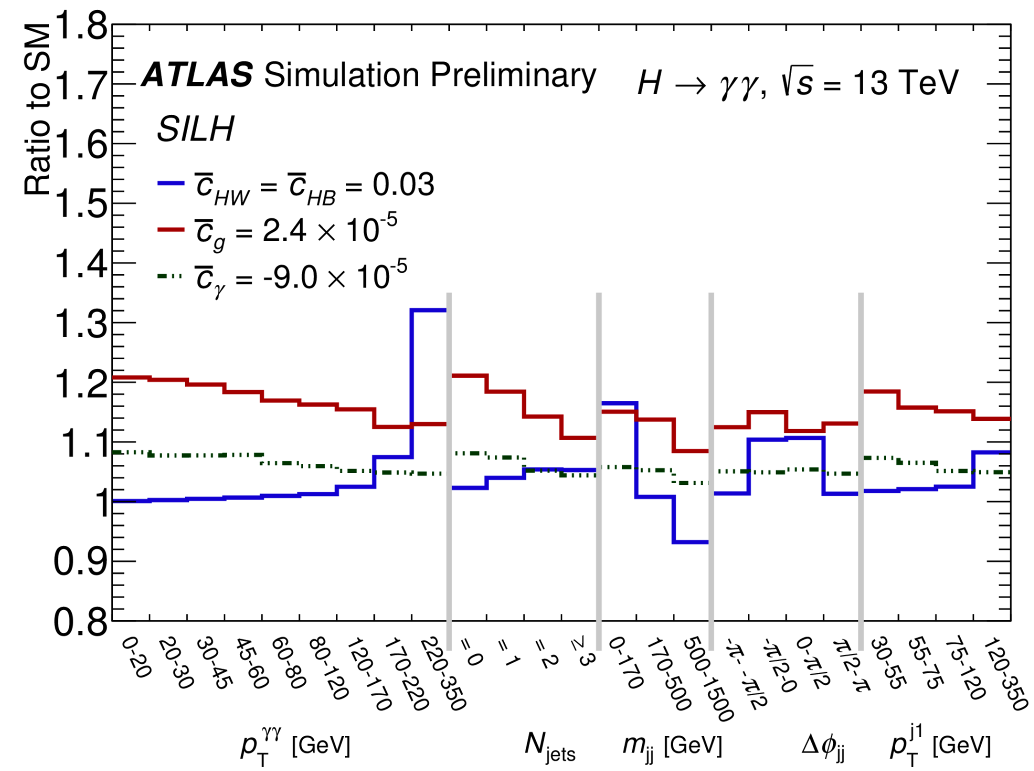


HEL operators of the SILH basis considered

(results provided in SMEFT-Warsaw basis too)

$O_g = H^\dagger H G_{\mu\nu} G^{\mu\nu}$	$\bar{c}_g$		$\bar{c}_g$
$O_\gamma = H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$\bar{c}_\gamma$	+ CP-odd operators →	$\bar{c}_\gamma$
$O_{HW} = i(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$	$\bar{c}_{HW}$		$\bar{c}_{HW}$
$O_{HB} = i(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\bar{c}_{HB}$		$\bar{c}_{HB}$

Consider $\bar{c}_{HW}=\bar{c}_{HB}$ and $\bar{c}_{HW}=\bar{c}_{HB}$



Strategy [2] at work:
Differential cross sections

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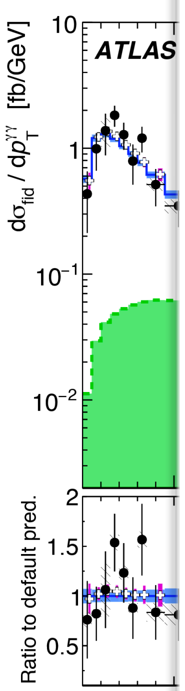

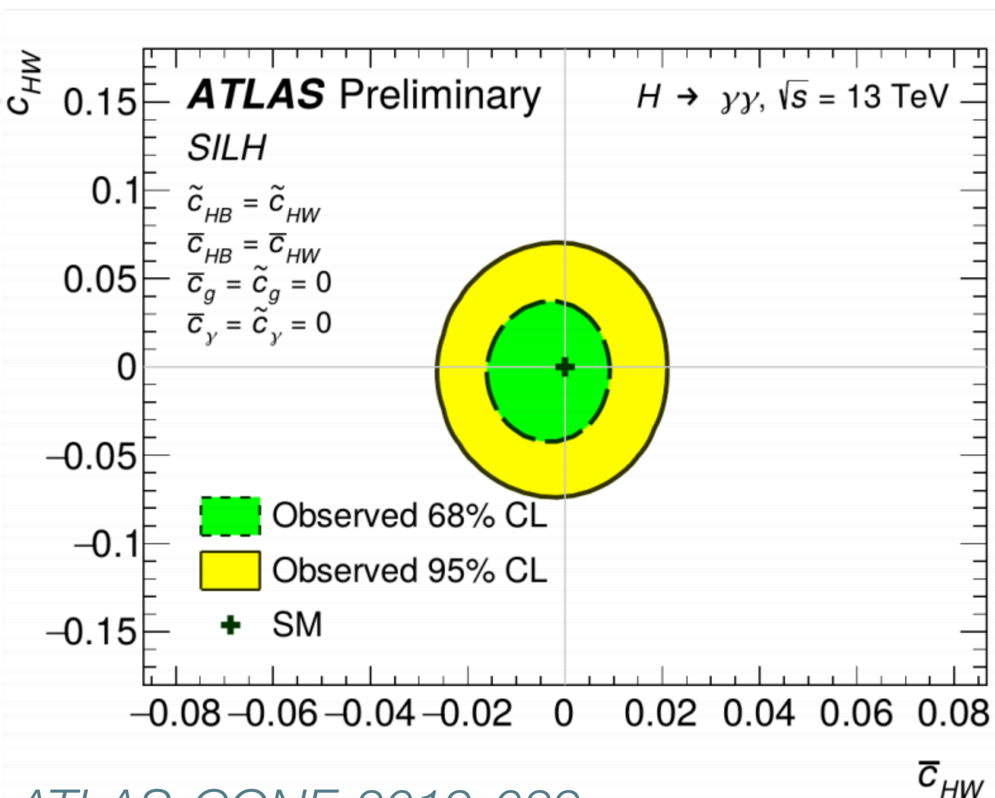

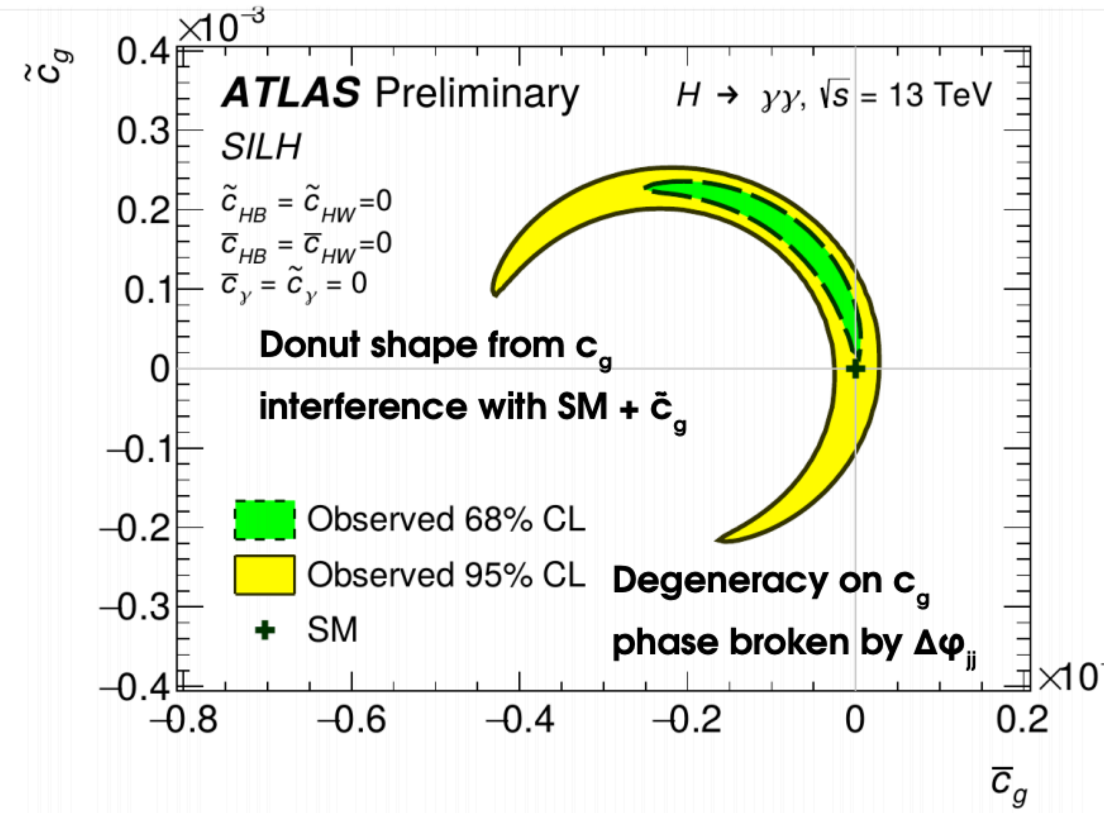

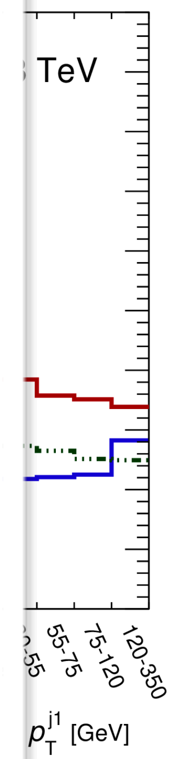

ATLAS-CONF-2019-029

Coefficient	Observed 95% CL limit	Expected 95% CL limit
$\bar{c}_g$	$[-0.26, 0.26] \times 10^{-4}$	$[-0.25, 0.25] \cup [-4.7, -4.3] \times 10^{-4}$
$\tilde{c}_g$	$[-1.3, 1.1] \times 10^{-4}$	$[-1.1, 1.1] \times 10^{-4}$
$\bar{c}_{HW}$	$[-2.5, 2.2] \times 10^{-2}$	$[-3.0, 3.0] \times 10^{-2}$
$\tilde{c}_{HW}$	$[-6.5, 6.3] \times 10^{-2}$	$[-7.0, 7.0] \times 10^{-2}$
$\bar{c}_\gamma$	$[-1.1, 1.1] \times 10^{-4}$	$[-1.0, 1.2] \times 10^{-4}$
$\tilde{c}_\gamma$	$[-2.8, 4.3] \times 10^{-4}$	$[-2.9, 3.8] \times 10^{-4}$

Strategy [2] at work:
Simplified Template Cross Sections

- Adopt the Simplified Template cross section to extract EFT information.
- The bins at gen-level are pre-defined, and anyone can calculate the dependence for its favorite basis.
- Parameterisations already exist for for **HEL-SILH** [LHCHXSWG-2019-004, STXStoEFT] and **SMEFT-Warsaw** basis [ATL-PHYS-PUB-2019-042]

$$O_{HW} = i\,(D^{\mu}H)^{\dagger}\,\sigma^{a}\,(D^{\nu}H)\,W^{a}_{\mu\nu},$$
$$O_{HB} = i\,(D^{\mu}H)^{\dagger}\,(D^{\nu}H)\,B_{\mu\nu},$$
$$O_{W} = \frac{i}{2}\left(H^{\dagger}\sigma^{a}\overleftrightarrow{D}^{\mu}H\right)D^{\nu}W^{a}_{\mu\nu},$$
$$O_{B} = \frac{i}{2}\left(H^{\dagger}\overleftrightarrow{D}^{\mu}H\right)\partial^{\nu}B_{\mu\nu},$$
$$O_{d} = y_{d}|H|^{2}\bar{Q}_{L}Hd_{R}$$

STXS for VH

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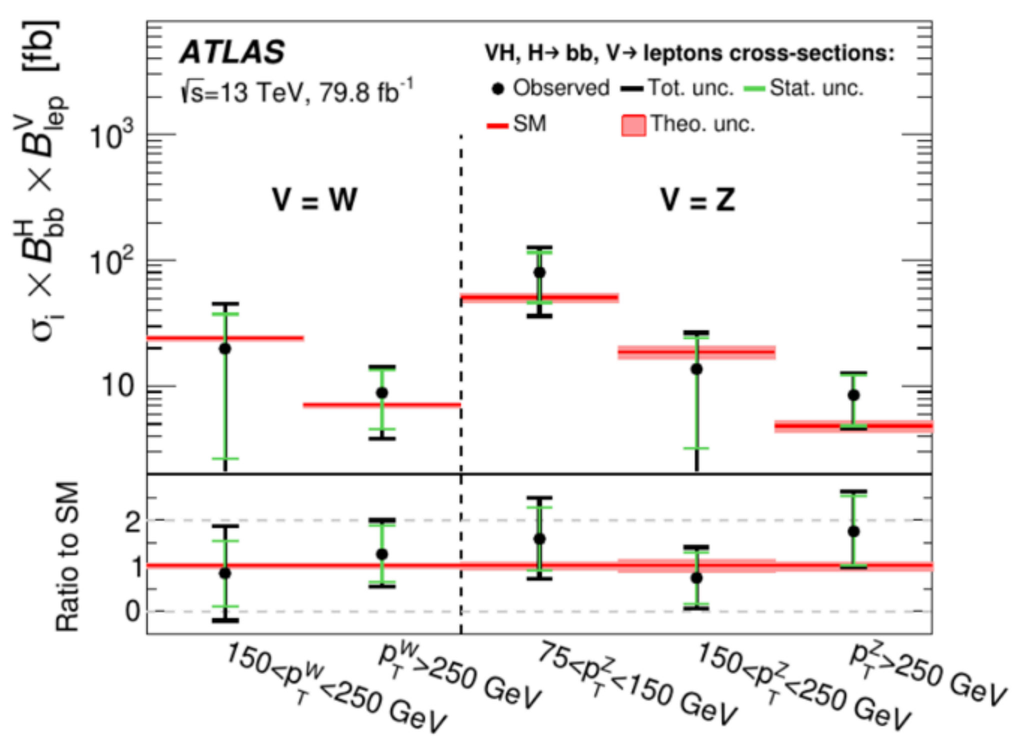
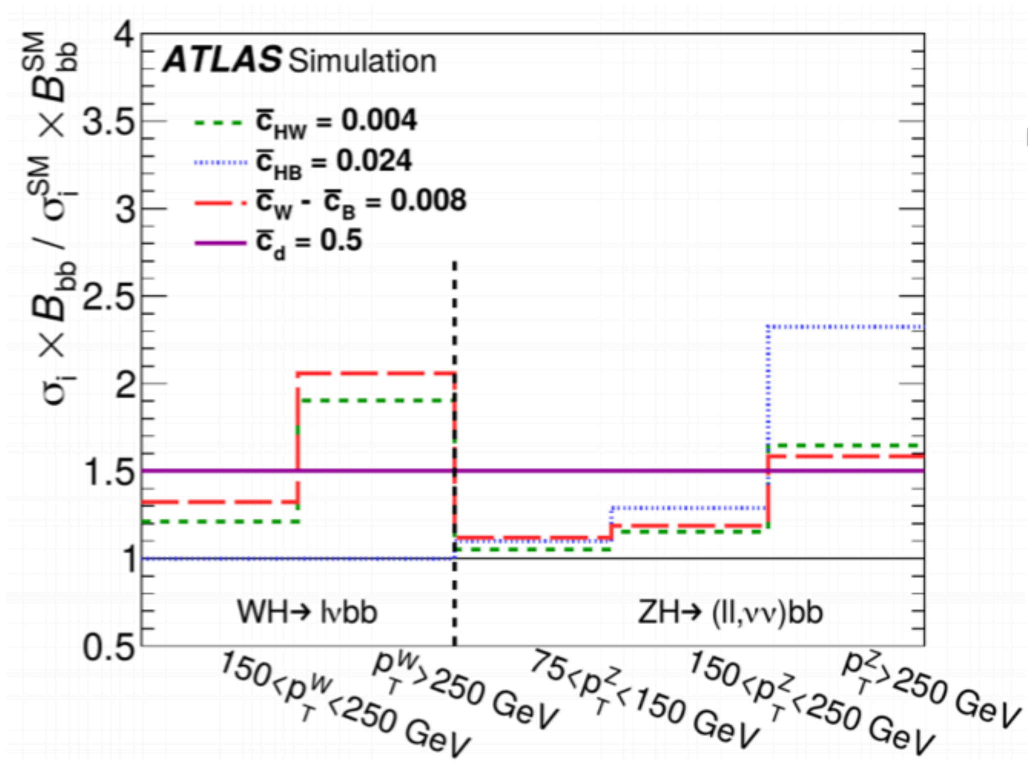


HEL operators of the SILH basis considered
Parameterisation from LHC HXSWG



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Simplifie

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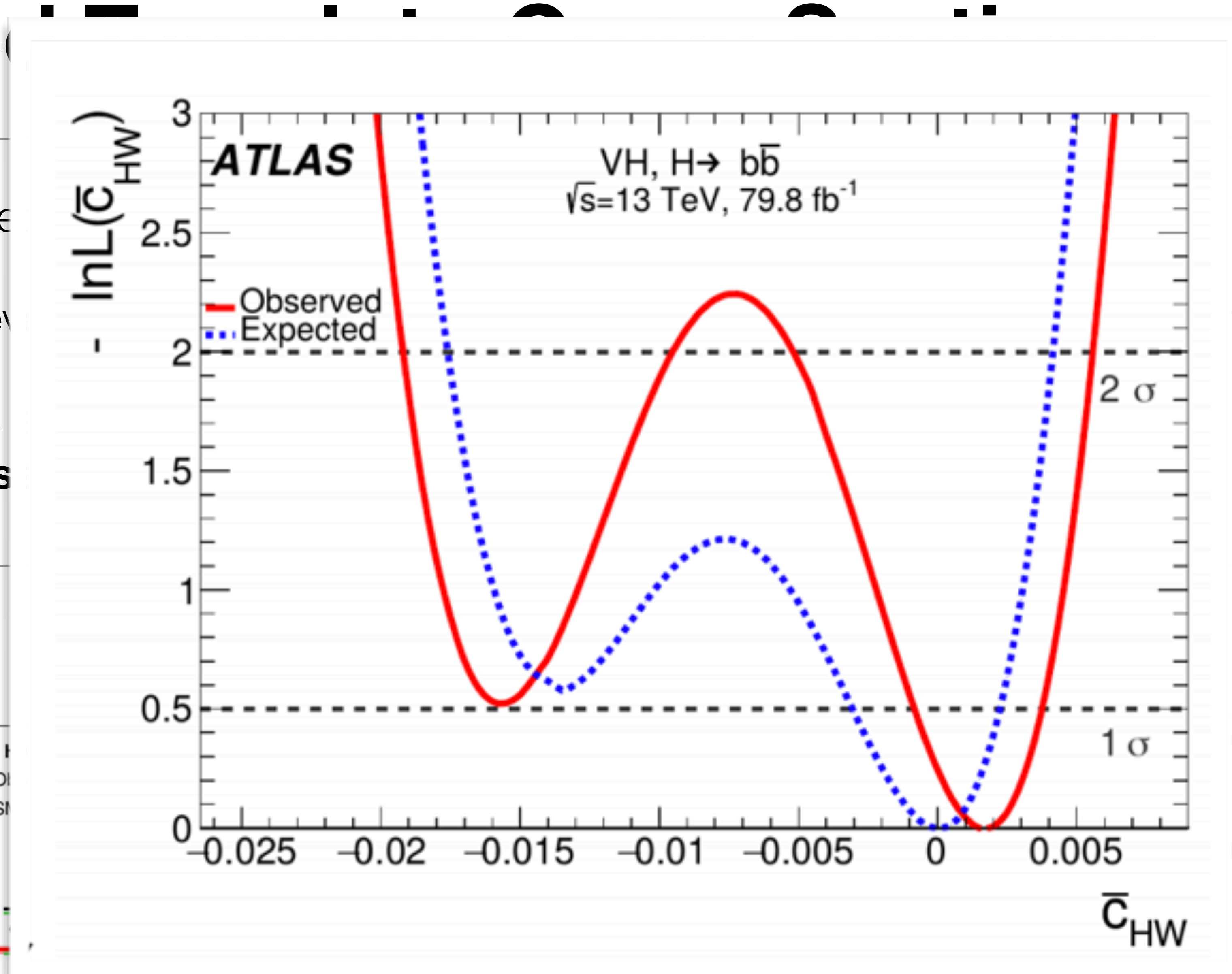
- The bins at gen-lev … s favorite basis.
- Parameterisations … and **SMEFT-Wars**



STXS for VH

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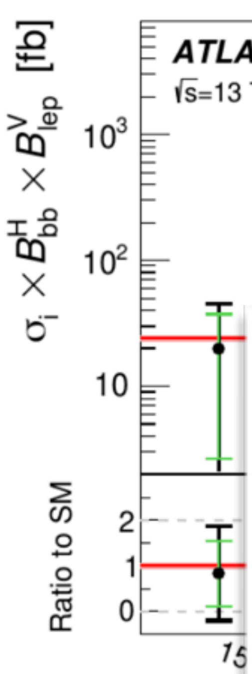
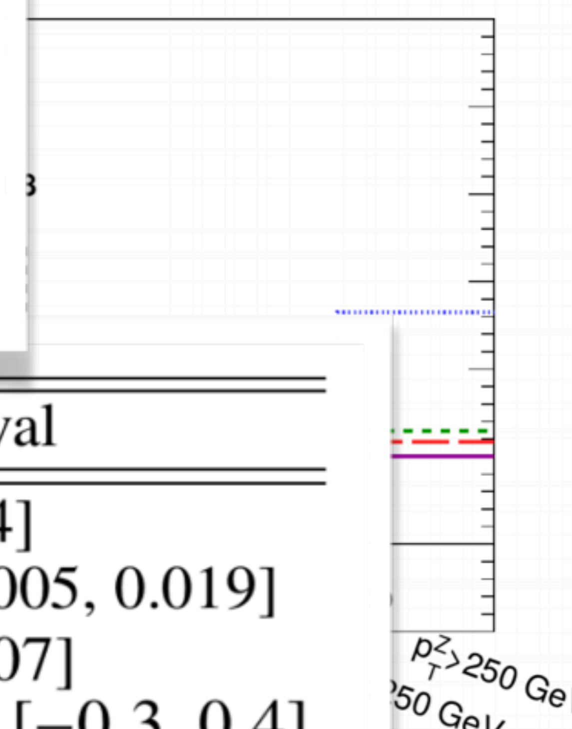




Coefficient	Expected interval	Observed interval
$\bar{c}_{HW}$	$[-0.003, 0.002]$	$[-0.001, 0.004]$
$\bar{c}_{HB}$	$[-0.066, 0.013]$	$[-0.078, -0.055] \cup [0.005, 0.019]$
$\bar{c}_W - \bar{c}_B$	$[-0.006, 0.005]$	$[-0.002, 0.007]$
$\bar{c}_d$	$[-1.5, 0.3]$	$[-1.6, -0.9] \cup [-0.3, 0.4]$

Strategy [2] at work:
Simplified Template Cross Sections

- Parameterisations for STXS already available:
- LHCHXSWG [*LHCHXSWG-2019-004*]

$$\sigma_{EFT} = \sigma_{SM} + \sigma_{int} + \sigma_{BSM},$$

$$\frac{\sigma_{int}}{\sigma_{SM}} = \sum_i A_i c_i,$$

$$\frac{\sigma_{BSM}}{\sigma_{SM}} = \sum_{ij} B_{ij} c_i c_j,$$

Parametrisation for both σ and B are provided

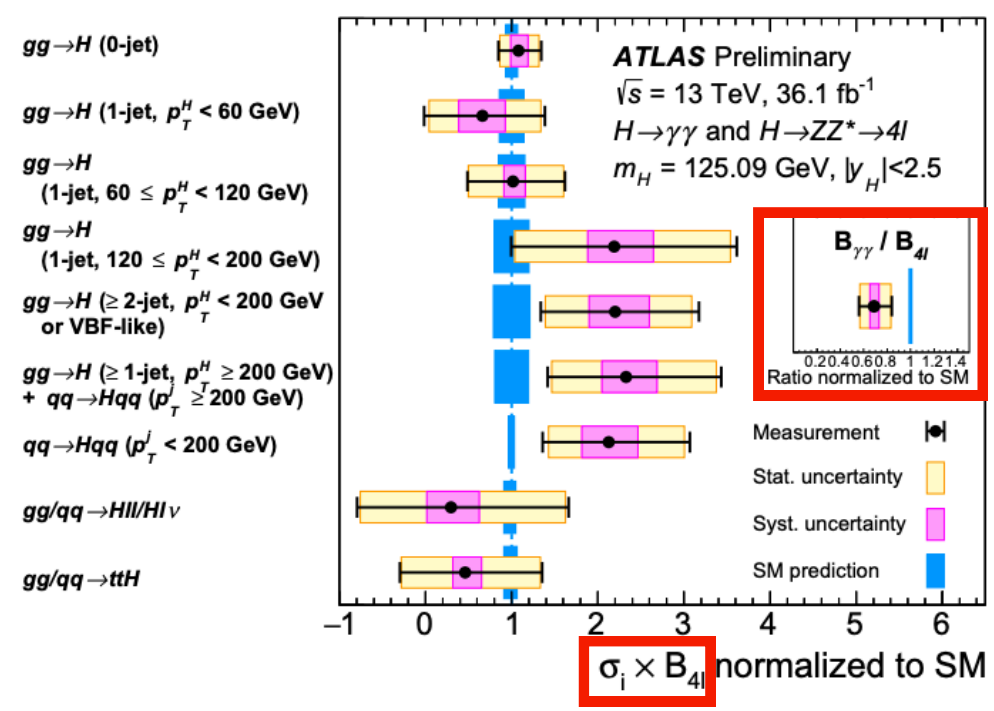
Cross-section region	$\sum_i A_i c_i$
$gg \to H$ (0-jet) $gg \to H$ (1-jet, $p_T^H < 60$ GeV) $gg \to H$ (1-jet, $60 \le p_T^H < 120$ GeV)	$56c'_g$
$gg \to H$ (1-jet, $120 \le p_T^H < 200$ GeV)	$56c'_g + 18\mathtt{c3G} + 11\mathtt{c2G}$
$gg \to H$ (1-jet, $p_T^H \ge 200$ GeV)	$56c'_g + 52\mathtt{c3G} + 34\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ ($\ge$ 2-jet, $60 \le p_T^H < 120$ GeV)	$56c'_g + 8\mathtt{c3G} + 7\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet, $120 \le p_T^H < 200$ GeV)	$56c'_g + 23\mathtt{c3G} + 18\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet, $p_T^H \ge 200$ GeV)	$56c'_g + 90\mathtt{c3G} + 68\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet VBF-like, $p_T^{j_3} < 25$ GeV)	$56c'_g$
$gg \to H$ ($\ge$ 2-jet VBF-like, $p_T^{j_3} \ge 25$ GeV)	$56c'_g + 9\mathtt{c3G} + 8\mathtt{c2G}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} < 25$ 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, $p_T^{j_3} \ge 25$ GeV)	$-1.0\mathtt{cH} - 1.1\mathtt{cT} + 1.2\mathtt{cWW} - 0.027\mathtt{cB} - 5.8\mathtt{cHW}$ $-0.41\mathtt{cHB} + 0.13\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.45\mathtt{cHu} + 0.15\mathtt{cHd}$
$qq \to Hqq$ ($p_T^j \ge 200$ GeV)	$-1.0\mathtt{cH} - 0.95\mathtt{cT} + 1.5\mathtt{cWW} - 0.025\mathtt{cB} - 3.6\mathtt{cHW}$ $-0.24\mathtt{cHB} + 0.084\mathtt{cHQ} - 4.5\mathtt{cpHQ} - 0.25\mathtt{cHu} + 0.1\mathtt{cHd}$
$qq \to Hqq$ ($60 \le m_{jj} < 120$ 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)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.4\mathtt{cWW} - 0.028\mathtt{cB} - 6.2\mathtt{cHW}$ $-0.42\mathtt{cHB} + 0.14\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.42\mathtt{cHu} + 0.16\mathtt{cHd}$
$gg/q\bar{q} \to ttH$	$-0.98\mathtt{cH} + 2.9\mathtt{cu} + 0.93c'_g + 310\mathtt{cuG}$ $+27\mathtt{c3G} - 13\mathtt{c2G}$

HEL

$$\mathcal{B}_{4\ell} = \frac{\Gamma_{4\ell}}{\sum_f \Gamma_f} \approx \frac{\Gamma_{4\ell}^{SM}}{\sum_f \Gamma_f^{SM}} \left[1 + \sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j - \sum_f \left(\sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j \right) \right],$$

$$\frac{\Gamma_f}{\Gamma_{4\ell}} \approx \frac{\Gamma_f^{SM}}{\Gamma_{4\ell}^{SM}} \left[1 + \sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j - \left(\sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j \right) \right]$$

- **NOTE 1** : Acceptance dependence on B are neglected so far. First attempts to go beyond for H->4l presented by C. Hays in LHC-HXSWG link.
- **NOTE 2**: EFT can change the decay topology. A summary for the options to make general measurement presented by M. Duehrssen and N. Berger in LHC-HXSWG link



ATLAS-CONF-2017-047

Strategy [2] at work:
Simplified Template Cross Sections

- Parameterisations for STXS already available:
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HEL

Cross-section region	$\sum_i A_i c_i$
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$gg \to H$ ($\ge$ 2-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ ($\ge$ 2-jet, $60 \le p_T^H < 120$ GeV)	$56c'_g + 8\mathtt{c3G} + 7\mathtt{c2G}$
$gg \to H$ ($\ge$ 2-jet, $120 \le p_T^H < 200$ GeV)	$56c'_g + 23\mathtt{c3G} + 18\mathtt{c2G}$
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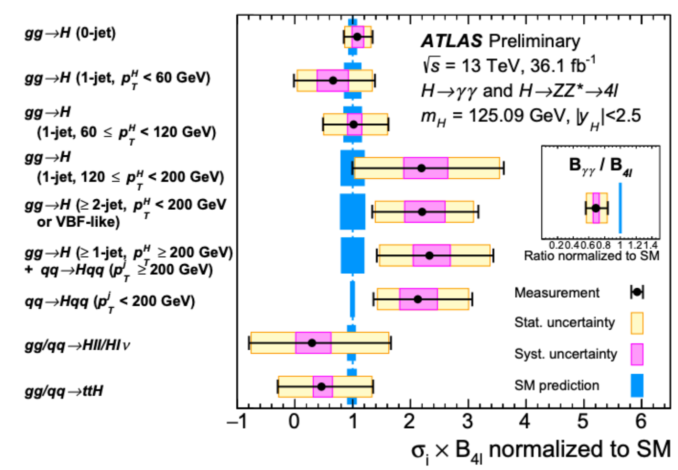
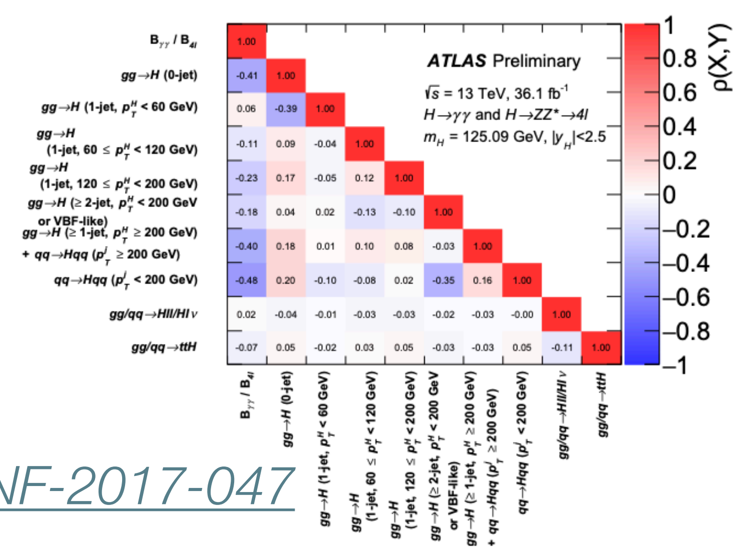
$gg \to H$ ($\ge$ 2-jet VBF-like, $p_T^{j_3} < 25$ GeV)	$56c'_g$
$gg \to H$ ($\ge$ 2-jet VBF-like, $p_T^{j_3} \ge 25$ GeV)	$56c'_g + 9\mathtt{c3G} + 8\mathtt{c2G}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} < 25$ GeV)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.3\mathtt{cWW} - 0.023\mathtt{cB} - 4.3\mathtt{cHW}$ $-0.29\mathtt{cHB} + 0.092\mathtt{cHQ} - 5.3\mathtt{cpHQ} - 0.33\mathtt{cHu} + 0.12\mathtt{cHd}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} \ge 25$ GeV)	$-1.0\mathtt{cH} - 1.1\mathtt{cT} + 1.2\mathtt{cWW} - 0.027\mathtt{cB} - 5.8\mathtt{cHW}$ $-0.41\mathtt{cHB} + 0.13\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.45\mathtt{cHu} + 0.15\mathtt{cHd}$
$qq \to Hqq$ ($p_T^j \ge 200$ GeV)	$-1.0\mathtt{cH} - 0.95\mathtt{cT} + 1.5\mathtt{cWW} - 0.025\mathtt{cB} - 3.6\mathtt{cHW}$ $-0.24\mathtt{cHB} + 0.084\mathtt{cHQ} - 4.5\mathtt{cpHQ} - 0.25\mathtt{cHu} + 0.1\mathtt{cHd}$
$qq \to Hqq$ ($60 \le m_{jj} < 120$ 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)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.4\mathtt{cWW} - 0.028\mathtt{cB} - 6.2\mathtt{cHW}$ $-0.42\mathtt{cHB} + 0.14\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.42\mathtt{cHu} + 0.16\mathtt{cHd}$
$gg/q\bar{q} \to ttH$	$-0.98\mathtt{cH} + 2.9\mathtt{cu} + 0.93c'_g + 310\mathtt{cuG}$ $+27\mathtt{c3G} - 13\mathtt{c2G}$





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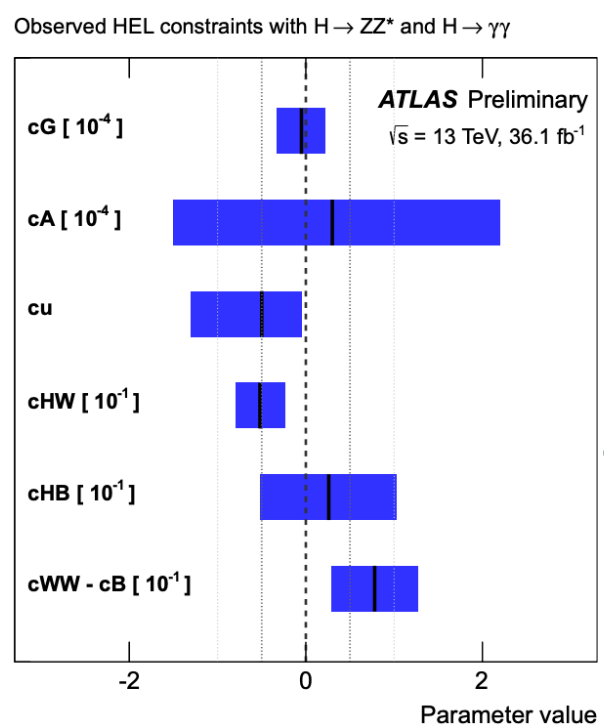

ATL-PHYS-PUB-2017-018

Results in ATLAS using STXS and HEL

Strategy [2] at work:
Simplified Template Cross Sections

- Parameterisations for STXS already available:
- LHCHXSWG [LHCHXSWG-2019-004]

HEL

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, $60 \le p_T^H < 120$ GeV)	$56c'_g$
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$gg \to H$ ($\ge$ 2-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ ($\ge$ 2-jet, $60 \le p_T^H < 120$ GeV)	$56c'_g + 8\text{c3G} + 7\text{c2G}$
$gg \to H$ ($\ge$ 2-jet, $120 \le p_T^H < 200$ GeV)	$56c'_g + 23\text{c3G} + 18\text{c2G}$
$gg \to H$ ($\ge$ 2-jet, $p_T^H \ge 200$ GeV)	$56c'_g + 90\text{c3G} + 68\text{c2G}$
$gg \to H$ ($\ge$ 2-jet VBF-like, $p_T^{j_3} < 25$ GeV)	$56c'_g$
$gg \to H$ ($\ge$ 2-jet VBF-like, $p_T^{j_3} \ge 25$ GeV)	$56c'_g + 9\text{c3G} + 8\text{c2G}$
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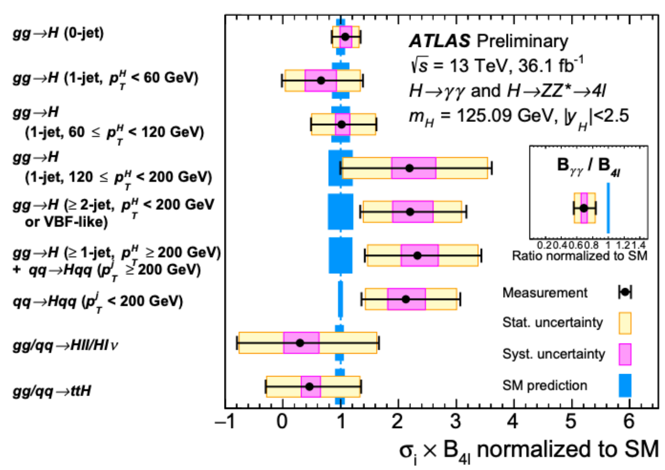
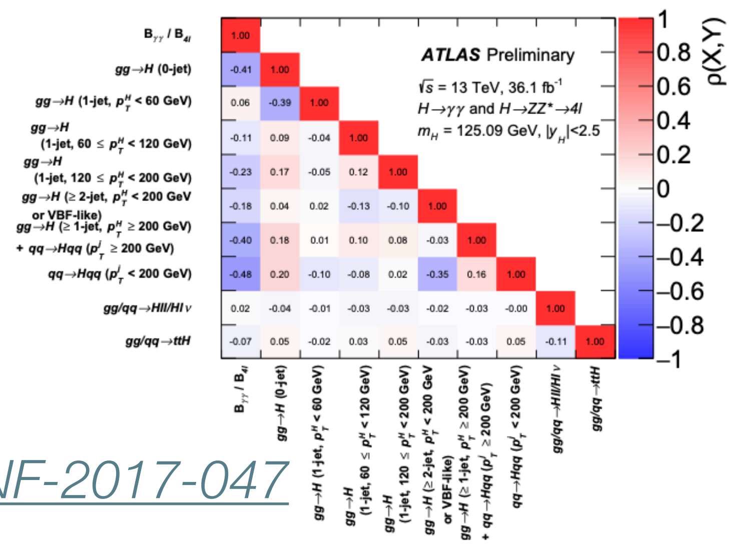
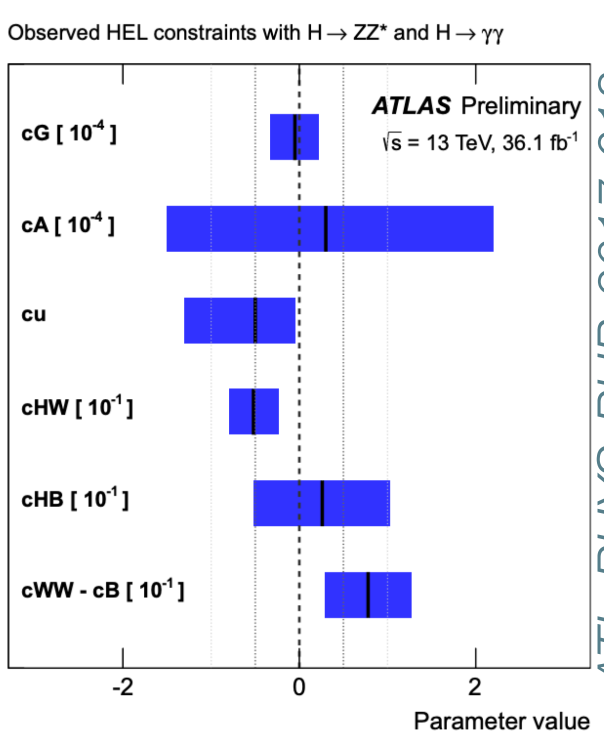
$qq \to Hqq$ (rest)	$-1.0\text{cH} - 1.0\text{cT} + 1.4\text{cWW} - 0.028\text{cB} - 6.2\text{cHW}$ $-0.42\text{cHB} + 0.14\text{cHQ} - 6.9\text{cpHQ} - 0.42\text{cHu} + 0.16\text{cHd}$
$gg/q\bar{q} \to ttH$	$-0.98\text{cH} + 2.9\text{cu} + 0.93c'_g + 310\text{cuG}$ $+27\text{c3G} - 13\text{c2G}$





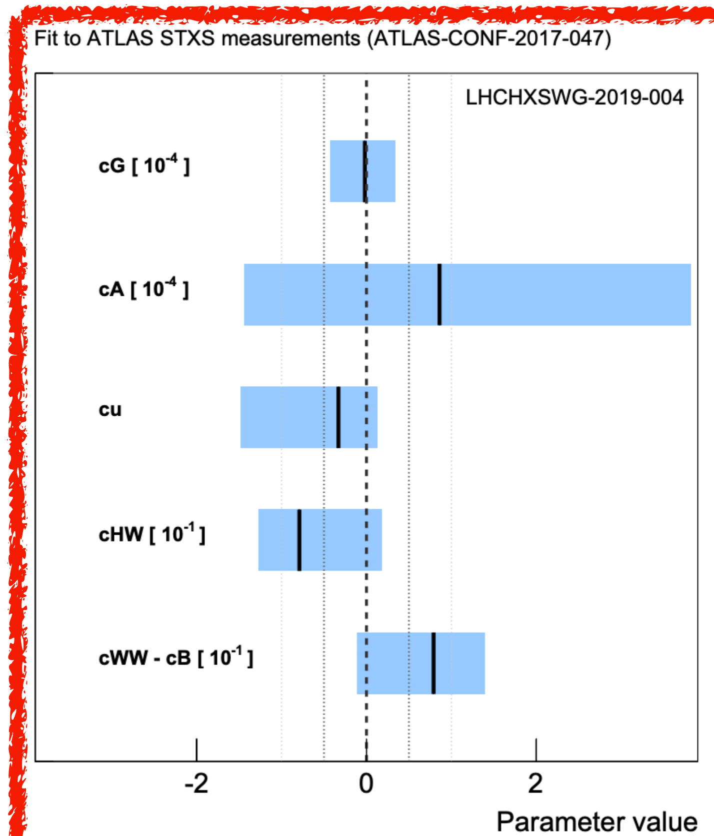
ATLAS-CONF-2017-047



ATL-PHYS-PUB-2017-018

Results in ATLAS using STXS and HEL

Reinterpreting ATLAS STXS in gaussian approximation



LHCHXSWG-2019-004

Strategy [2] at work:
Simplified Template Cross Sections

- Parameterisations for STXS already available:
- LHCHXSWG [*LHCHXSWG-2019-004*]
- CMS (based on EFT2Obs) [*STXStoEFT*]

HEL

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$gg \to H$ (1-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 18\mathtt{c3G} + 11\mathtt{c2G}$
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$gg \to H$ ($\geq$ 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)	$56c'_g + 23\mathtt{c3G} + 18\mathtt{c2G}$
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$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j_3} < 25$ GeV)	$56c'_g$
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$qq \to Hqq$ (VBF-like, $p_T^{j_3} \geq 25$ GeV)	$-1.0\mathtt{cH} - 1.1\mathtt{cT} + 1.2\mathtt{cWW} - 0.027\mathtt{cB} - 5.8\mathtt{cHW}$ $-0.41\mathtt{cHB} + 0.13\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.45\mathtt{cHu} + 0.15\mathtt{cHd}$
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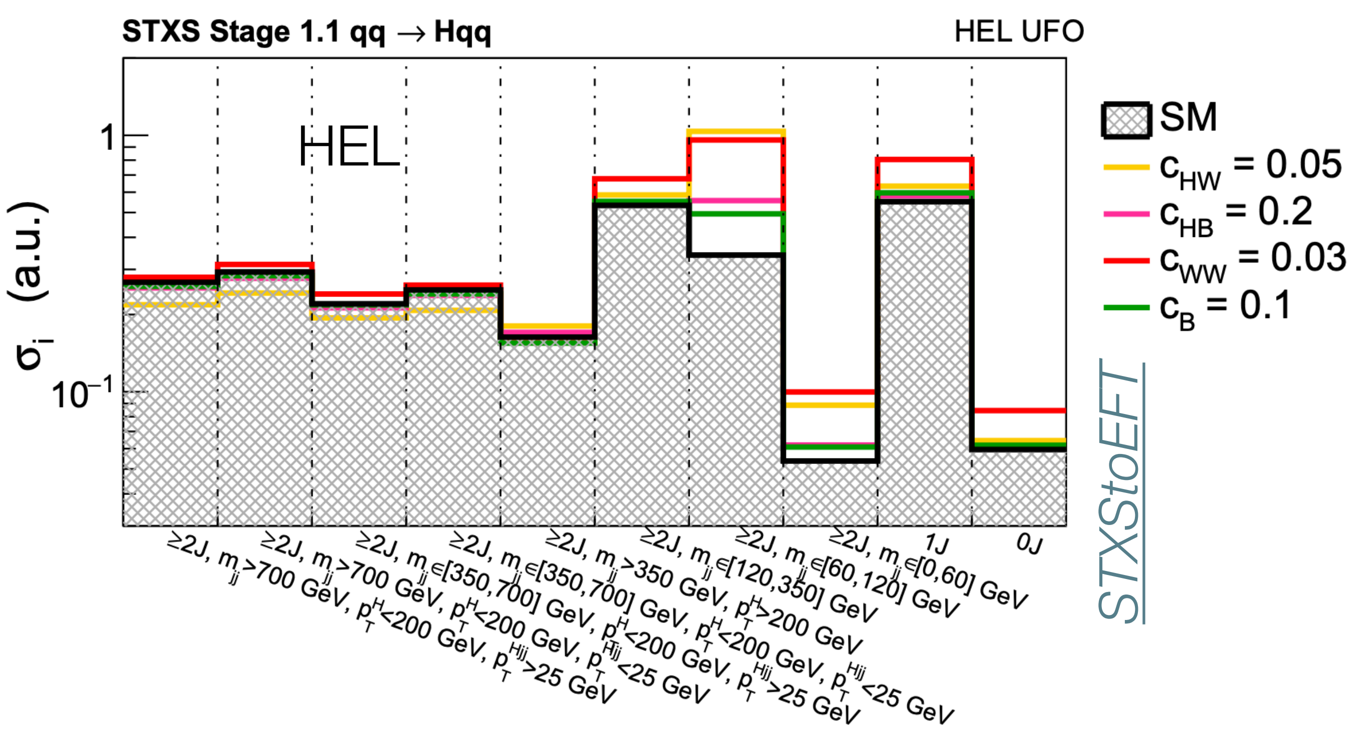

Strategy [2] at work:
Simplified Template Cross Sections

- Parameterisations for STXS already available:
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- CMS (based on EFT2Obs) [STXStoEFT]

HEL

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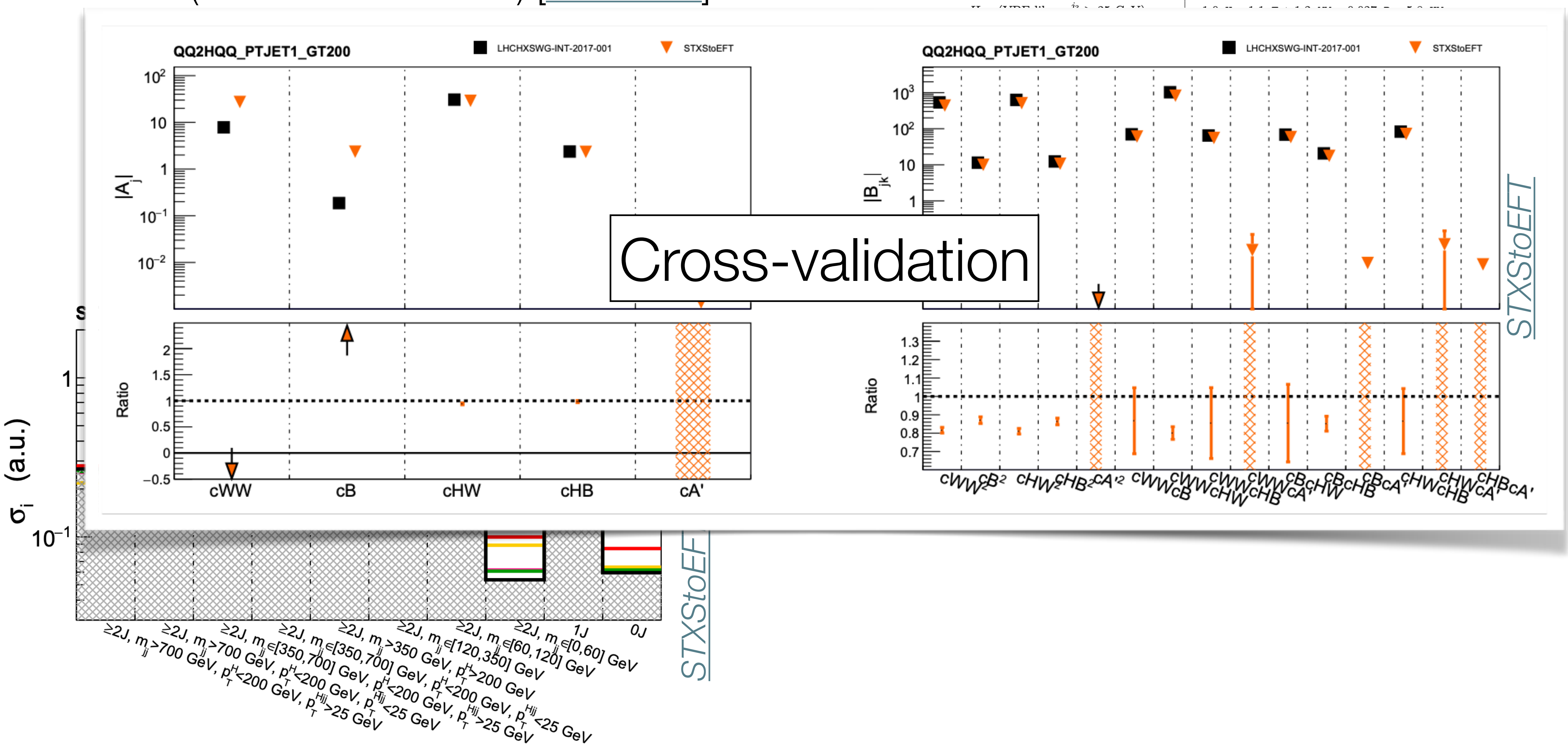

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Simplified Template Cross Sections

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- CMS (based on EFT2Obs) [STXStoEFT]
- ATLAS [ATL-PHYS-PUB-2019-042]

HEL

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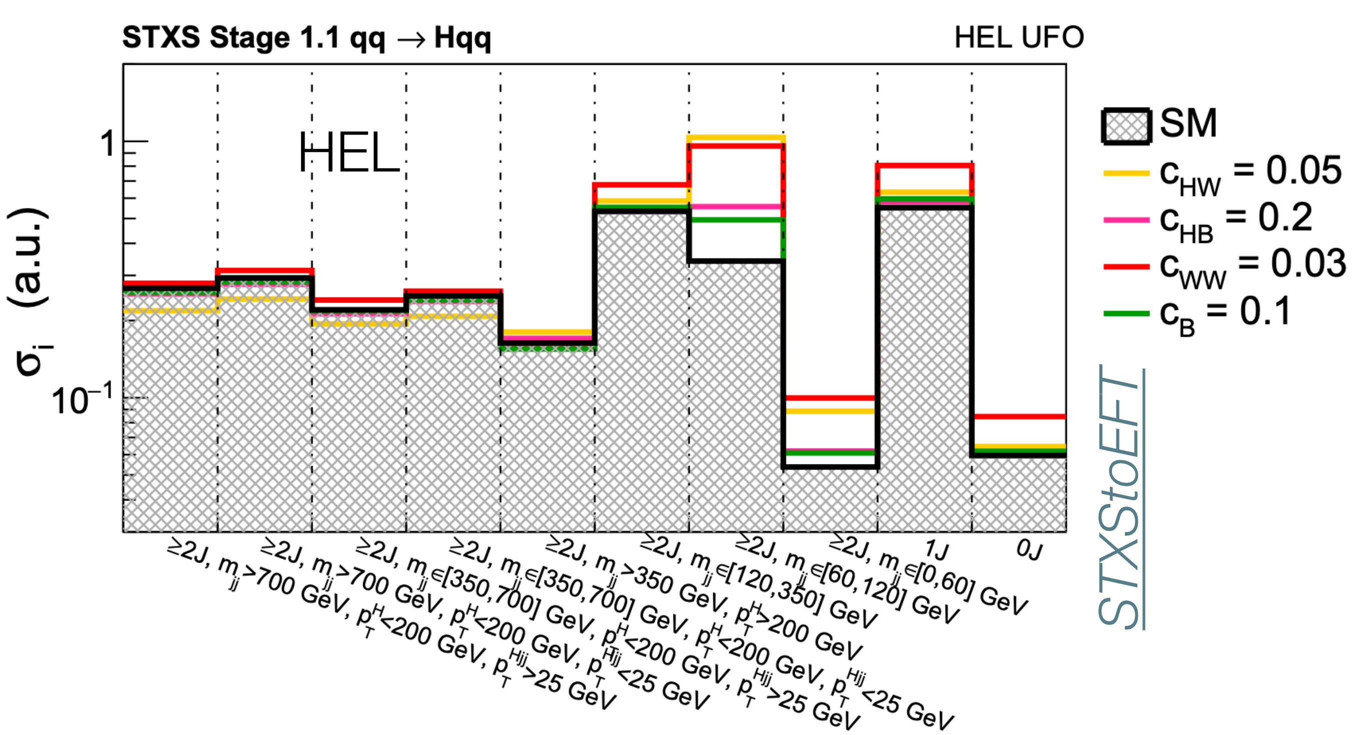
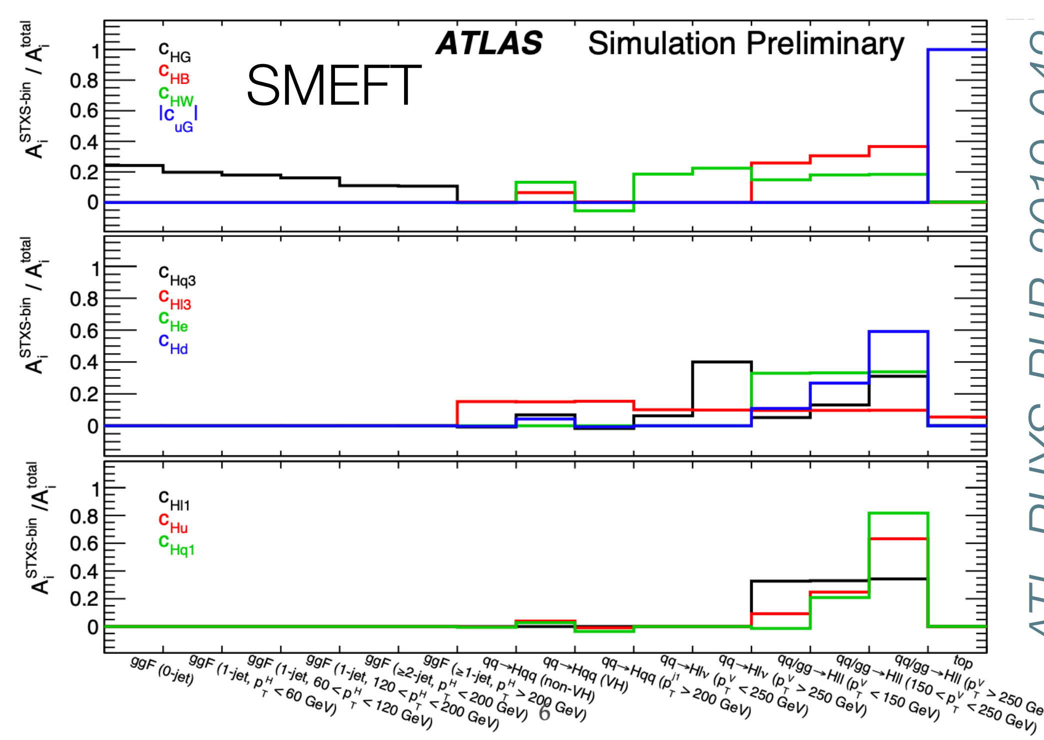
$gg \to H$ ($\geq$ 2-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 90\mathtt{c3G} + 68\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j_3} < 25$ GeV)	$56c'_g$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j_3} \geq 25$ GeV)	$56c'_g + 9\mathtt{c3G} + 8\mathtt{c2G}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} < 25$ GeV)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.3\mathtt{cWW} - 0.023\mathtt{cB} - 4.3\mathtt{cHW}$ $-0.29\mathtt{cHB} + 0.092\mathtt{cHQ} - 5.3\mathtt{cpHQ} - 0.33\mathtt{cHu} + 0.12\mathtt{cHd}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} \geq 25$ 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)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.4\mathtt{cWW} - 0.028\mathtt{cB} - 6.2\mathtt{cHW}$ $-0.42\mathtt{cHB} + 0.14\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.42\mathtt{cHu} + 0.16\mathtt{cHd}$
$gg/q\bar{q} \to ttH$	$-0.98\mathtt{cH} + 2.9\mathtt{cu} + 0.93c'_g + 310\mathtt{cuG}$ $+27\mathtt{c3G} - 13\mathtt{c2G}$



STXStoEFT



ATL-PHYS-PUB-2019-042

SMEFT

Wilson coefficient	Operator
c_{Hbox}	$(H^\dagger H)\Box(H^\dagger H)$
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
c_{Hl1}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
c_{Hl3}	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
c_{Hq1}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
c_{Hq3}	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$\lvert c_{uG}\rvert$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
c_{ll1}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

Towards global EFT fits

heavily inspired by the talk of A. Cueto in link

- Several operators can have very similar physics signature in the Higgs sector giving rise to high correlations in fits.
- Identify directions in the operators space for which the STXS measurement provides sensitivity and safely neglect “flat directions” (directions in the EFT parameters space to which the measurements are not sensitive), using Fisher information, and finding eigenvectors (sensitive directions) and eigenvalues

Combined measurement:

Eigenvalue	Eigenvector
241550	$0.24 \cdot c_{HG} - 0.23 \cdot c_{HW} - 0.83 \cdot c_{HB} + 0.45 \cdot c_{HWB}$
147981	$-0.97 \cdot c_{HG} - 0.21 \cdot c_{HB} + 0.11 \cdot c_{HWB}$
6090	$-0.12 \cdot c_{HW} - 0.98 \cdot c_{Hq3} - 0.11 \cdot c_{Hu}$
124	$-0.20 \cdot c_{HWB} + 0.30 \cdot c_{Hq1} + 0.14 \cdot c_{Hq3} - 0.85 \cdot c_{Hu} + 0.29 \cdot c_{Hd}$
34	$-0.21 \cdot c_{Hbox} - 0.56 \cdot c_{HW} - 0.24 \cdot c_{HWB} - 0.11 \cdot c_{Hl1} + 0.51 \cdot c_{Hl3} - 0.16 \cdot c_{Hq1} + 0.17 \cdot c_{Hu} - 0.37 \cdot c_{ll1} - 0.10 \cdot \lvert c_{dH}\rvert + 0.25 \cdot \lvert c_{uG}\rvert - 0.12 \cdot c_{qq3}1$
22	$-0.11 \cdot c_G + 0.60 \cdot c_{HW} - 0.12 \cdot c_{HB} + 0.18 \cdot c_{Hl3} + 0.63 \cdot \lvert c_{uG}\rvert - 0.13 \cdot c_{qq11} - 0.31 \cdot c_{qq31} - 0.13 \cdot c_{uu1}$
16	$-0.48 \cdot c_{HW} + 0.19 \cdot c_{HB} + 0.11 \cdot c_{HWB} + 0.13 \cdot c_{Hl1} - 0.47 \cdot c_{Hl3} - 0.11 \cdot c_{He} + 0.31 \cdot c_{ll1} + 0.14 \cdot \lvert c_{dH}\rvert + 0.49 \cdot \lvert c_{uG}\rvert - 0.24 \cdot c_{qq31} - 0.10 \cdot c_{uu1}$

***NOTE**: Sensitivity to C_{HW}, C_{HB}, C_{HWB} driven by $H\rightarrow\gamma\gamma$*

$$\frac{\Gamma(H \to \gamma\gamma)}{\Gamma_{SM}(H \to \gamma\gamma)} \approx \left|1 + \frac{8\pi^2 \bar{v}_T^2}{I^\gamma} C_{\gamma\gamma}\right|^2,$$

$$C_{\gamma\gamma} = \frac{1}{\bar{g}_2^2} c_{HW} + \frac{1}{\bar{g}_1^2} c_{HB} - \frac{1}{\bar{g}_1 \bar{g}_2} c_{HWB},$$

$\Rightarrow C_{HW}$, C_{HB}, C_{HWB} highly correlated

- Sensitivity to cHG, cHq3, |cuG|, cHW, cHu, cHl3 (potentially cHq1)
- Including the decay brings additional sensitivity to cHW, cHB and cHWB but also stronger correlations
- Sensitivity to cHl1, cHe and cHd (from VH(bb)). Also to |ceH| from H-> and |cdH| from H->bb

ATL-PHYS-PUB-2019-042

SMEFT

Wilson coefficient	Operator
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c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
c_{Hq1}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{H}\, G^A_{\mu\nu}$
	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

Towards global EFT fits

heavily inspired by the talk of A. Cueto in link

- Several operators can have very similar physics signature in the Higgs sector giving rise to high correlations in fits.
- Identify dire... measureme... directions" (... measureme... eigenvector...

Combined measu...

Eigenvalue	Eige...
241550	0.24
147981	−0.9
6090	−0.1
124	−0.2
34	−0.2 c_{Hu} ...
22	−0.1 c_{qq31} ...
16	−0.4 c_{ll1} + ...

Parameter	Appears in
cHG	ggH
cHq3	VBF, WH, ttH and W couplings
0.27cHW+0.96cHB 0.96cHW-0.27cHB	$\gamma\gamma$, $Z\gamma$ decays. VBF and VH (redefinition of EW fields)
| cuG |	Top
cHl3	VBF, WH, ttH, W couplings and δGf
cHl1-cHe	Z(lep)H, ZZ decay
| ceH |	$\tau\tau$ decay
| cdH |	bb decay
-0.3cHd + 0.9 cHu -0.3 cHq1	VBF and Z(lep)H, ZZ decay

... to C_{HW}, ... by $H\to\gamma\gamma$

$$\ldots 1 + \frac{8\pi^2 \bar{v}_T^2}{I^\gamma} C_{\gamma\gamma}\Big|^2,$$

$$\ldots_{HB} - \frac{1}{\bar{g}_1 \bar{g}_2} c_{HWB},$$

...$_{WB}$ highly

- Sensitivity t...
- Including th... correlations
- Sensitivity to cHl1, cHe and cHd (from VH(bb)). Also to |ceH| from H-> and |cdH| from H->bb

Outline

- Summary of the Higgs measurements
- How to extract info on EFT
- **Global fit & Extrapolation to HL-HE LHC**
- Future Colliders

Global fit: Current and future sensitivity

- Higgs sector give valuable information for the EFT, but global picture requires a fit with all the available information (EWPO, TGC, top sector,…)
- While in the ATLAS and CMS collaborations, work is ongoing, first global fits already exist.
- These are precious per se, and to inject information on which directions are less constraint to the experimental collaborations.
- Three examples reported here, on current sensitivity and projections to HL-HE LHC, based on the HL-HE LHC Yellow book [*CERN-LPCC-2018-04*] :
  - Prospective SMEFT Constraints from HL- and HE-LHC Data (*J. Ellis, C.W. Murphy, V. Sanz, T. You*)
  - Global constraints on universal new physics at the HL/HE-LHC (*J. de Blas, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, L. Silvestrini*)
  - Global analysis including the Higgs self-coupling (*A. Biekötter, D. Gonçalves, T. Plehn, M. Takeuchi, D. Zerwas*)

Global fit: Current and future sensitivity

J. Ellis, C.W. Murphy, V. Sanz, T. You

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{C_{HL}^{(3)}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar\ell\tau^I\gamma^\mu\ell) + \frac{C_{HL}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar\ell\gamma^\mu\ell) + \frac{C_{LL}}{\Lambda^2}(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)$$
$$+ \frac{C_{HD}}{\Lambda^2}\left|H^\dagger D_\mu H\right|^2 + \frac{C_{WB}}{\Lambda^2} g g' H^\dagger \tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$$
$$+ \frac{C_{He}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e\gamma^\mu e) + \frac{C_{Hu}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u\gamma^\mu u) + \frac{C_{Hd}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d\gamma^\mu d)$$
$$+ \frac{C_{HQ}^{(3)}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q\tau^I\gamma^\mu q) + \frac{C_{HQ}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q\gamma^\mu q) + \boxed{\frac{C_{3W}}{\Lambda^2}\frac{g}{3!}\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho}\,,$$

NLO

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{C_{y_e}}{\Lambda^2} y_e (H^\dagger H)(\bar\ell e H) + \frac{C_{y_d}}{\Lambda^2} y_d (H^\dagger H)(\bar q d H) + \frac{C_{y_u}}{\Lambda^2} y_u (H^\dagger H)(\bar q u \widetilde{H})$$
$$+ \frac{C_{3G}}{\Lambda^2}\frac{g_s}{3!} f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{C_H}{\Lambda^2}\frac{1}{2}\left(\partial^\mu |H|^2\right)^2 + \frac{C_{uG}}{\Lambda^2} y_u (\bar q\sigma^{\mu\nu}T^A u)\widetilde{H}\, G^A_{\mu\nu}$$
$$+ \frac{C_{WW}}{\Lambda^2} g^2 H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu} + \frac{C_{BB}}{\Lambda^2} g'^2 H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{C_{GG}}{\Lambda^2} g_s^2 H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}\,.$$

- Fit done with the SMEFT Warsaw
- 20 parameters relevant for the di-boson, electroweak precision and Higgs observables
- **LEP1** :11 Z-pole observables
- **SLC:** 1 Z-pole observable
- **Tevatron:** W mass measurement
- **LEP2:** e + e – ➝ W +W – ➝ 4f measurements
- **LHC1:** ATLAS+CMS 20 Higgs sign. strengths
  H➝μμ combination
  ATLAS h ➝ Zγ measurement
  ATLAS W mass measurement
- **LHC2:** CMS: 25 Higgs measurements
  ATLAS: 23 Higgs measurements
  ATLAS: pp➝WW➝eνμν
  (pT(l)>120 GeV)

Coefficient	Z-pole + m_W	WW at LEP2	Higgs Run1	Higgs Run2	LHC WW high-p_T
C_{yd}	×	×	10	8.1	×
C_{ye}	×	×	2.9	1.3	×
C_{3G}	×	×	0.5	9.1	×
C_{BB}	×	×	$9.9\cdot10^5$	$2.0\cdot10^6$	×
C_H	×	×	8.1	15	0.1
C_{Hd}	$7.4\cdot10^3$	×	2.0	1.5	9.8
C_{HD}	$4.3\cdot10^5$	51	4.6	4.5	$5.5\cdot10^2$
C_{He}	$6.5\cdot10^5$	14	$1.1\cdot10^{-2}$	$3.7\cdot10^{-2}$	×
C_{GG}	×	×	$9.8\cdot10^5$	$8.6\cdot10^5$	$1.5\cdot10^4$
C_{HL}	$1.1\cdot10^6$	51	$1.1\cdot10^{-2}$	$3.6\cdot10^{-2}$	$4.6\cdot10^{-3}$
$C_{HL}^{(3)}$	$1.7\cdot10^6$	$1.3\cdot10^3$	51	49	$3.5\cdot10^3$
C_{HQ}	$6.4\cdot10^4$	×	2.3	1.0	37
$C_{HQ}^{(3)}$	$4.9\cdot10^5$	$9.1\cdot10^2$	$5.9\cdot10^2$	$3.3\cdot10^2$	$5.0\cdot10^3$
C_{Hu}	$1.4\cdot10^4$	×	18	12	83
C_{WW}	×	×	$9.1\cdot10^4$	$1.8\cdot10^5$	$7.0\cdot10^{-3}$
C_{WB}	$3.3\cdot10^6$	$1.9\cdot10^2$	$3.0\cdot10^5$	$5.7\cdot10^5$	$2.2\cdot10^3$
C_{LL}	$5.5\cdot10^5$	$3.3\cdot10^2$	16	21	$6.0\cdot10^2$
C_{uG}	×	×	18	97	×
C_{yu}	×	×	0.4	1.8	×
C_{3W}	×	6.7	×	×	19

Fisher information in current measurements

Global fit: Current and future sensitivity

J. Ellis, C.W. Murphy, V. Sanz, T. You

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{C_{HL}^{(3)}}{\Lambda^2}(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar\ell \tau^I \gamma^\mu \ell) + \frac{C_{HL}}{\Lambda^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar\ell \gamma^\mu \ell) + \frac{C_{LL}}{\Lambda^2}(\bar\ell \gamma_\mu \ell)(\bar\ell \gamma^\mu \ell)$$
$$+ \frac{C_{HD}}{\Lambda^2}\left|H^\dagger D_\mu H\right|^2 + \frac{C_{WB}}{\Lambda^2} g g' H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$$
$$+ \frac{C_{He}}{\Lambda^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e \gamma^\mu e) + \frac{C_{Hu}}{\Lambda^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u \gamma^\mu u) + \frac{C_{Hd}}{\Lambda^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d \gamma^\mu d)$$
$$+ \frac{C_{HQ}^{(3)}}{\Lambda^2}(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q \tau^I \gamma^\mu q) + \frac{C_{HQ}}{\Lambda^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q \gamma^\mu q) + \frac{C_{3W}}{\Lambda^2}\frac{g}{3!}\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho ,$$

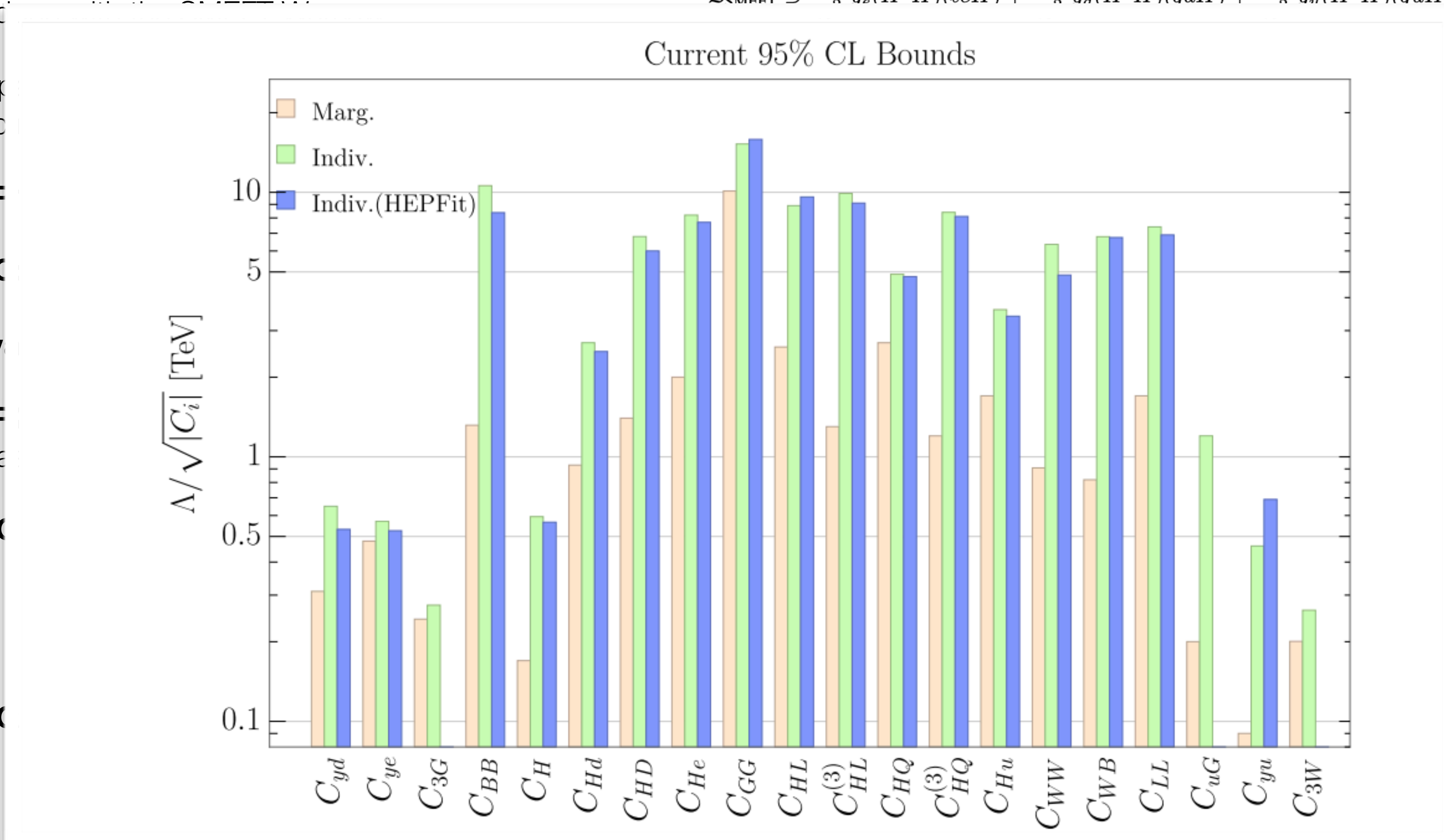
NLO

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{C_{y_e}}{\ }y_e(H^\dagger H)(\bar\ell e H) + \frac{C_{y_d}}{\ }y_d(H^\dagger H)(\bar q d H) + \frac{C_{y_u}}{\ }y_u(H^\dagger H)(\bar q u \widetilde H)$$

$u)\widetilde H G^A_{\mu\nu}$

$G^A_{\mu\nu} G^{A\mu\nu}$.

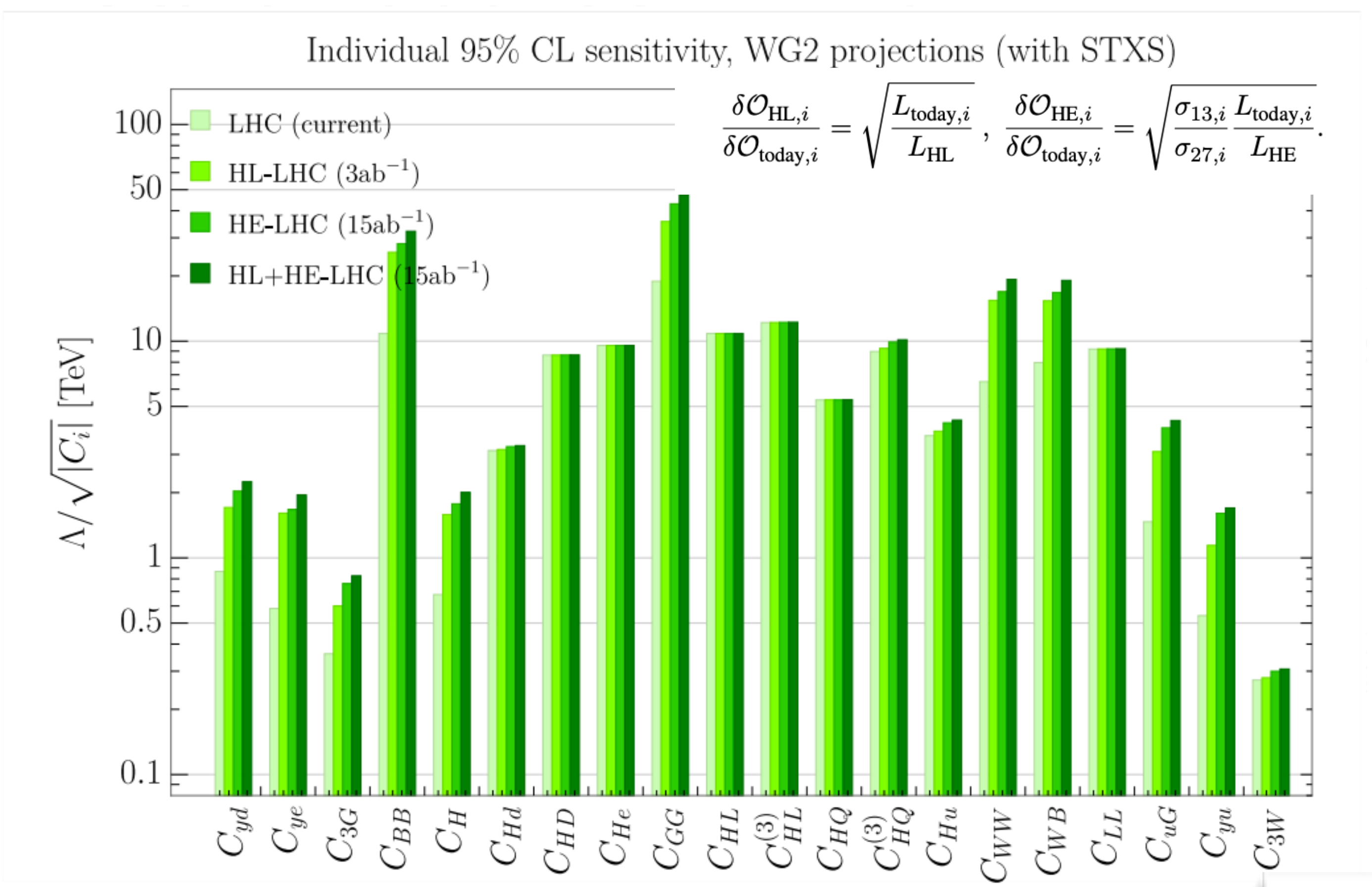
- Fit d…
- 20 p… elec…
- **LEP**
- **SLC**
- **Tev**
- **LEP** mea…
- **LHC**
- **LHC**



W high-p_T
×
×
×
×
0.1
9.8
$\cdot 10^2$
×
$\cdot 10^4$
$\cdot 10^{-3}$
$\cdot 10^3$
37
$\cdot 10^3$
83
$\cdot 10^{-3}$
$\cdot 10^3$
$\cdot 10^2$
×
×

C_{3W}	×	6.7	×	×	19

Fisher information in current measurements



$$\mathcal{L}^{\mathrm{Warsaw}}_{\mathrm{SMEFT}} \supset \frac{C^{(3)}_{HL}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar\ell\tau^I\gamma^\mu\ell) + \frac{C_{HL}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar\ell\gamma^\mu\ell) + \frac{C_{LL}}{\Lambda^2}(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)$$
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$$+ \frac{C^{(3)}_{HQ}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q\tau^I\gamma^\mu q) + \frac{C_{HQ}}{\Lambda^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q\gamma^\mu q) + \frac{C_{3W}}{\Lambda^2}\frac{g}{3!}\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho,$$

NLO

$$\supset \frac{C_{y_e}}{\Lambda^2} y_e(H^\dagger H)(\bar\ell e H) + \frac{C_{y_d}}{\Lambda^2} y_d(H^\dagger H)(\bar q d H) + \frac{C_{y_u}}{\Lambda^2} y_u(H^\dagger H)(\bar q u\widetilde H)$$
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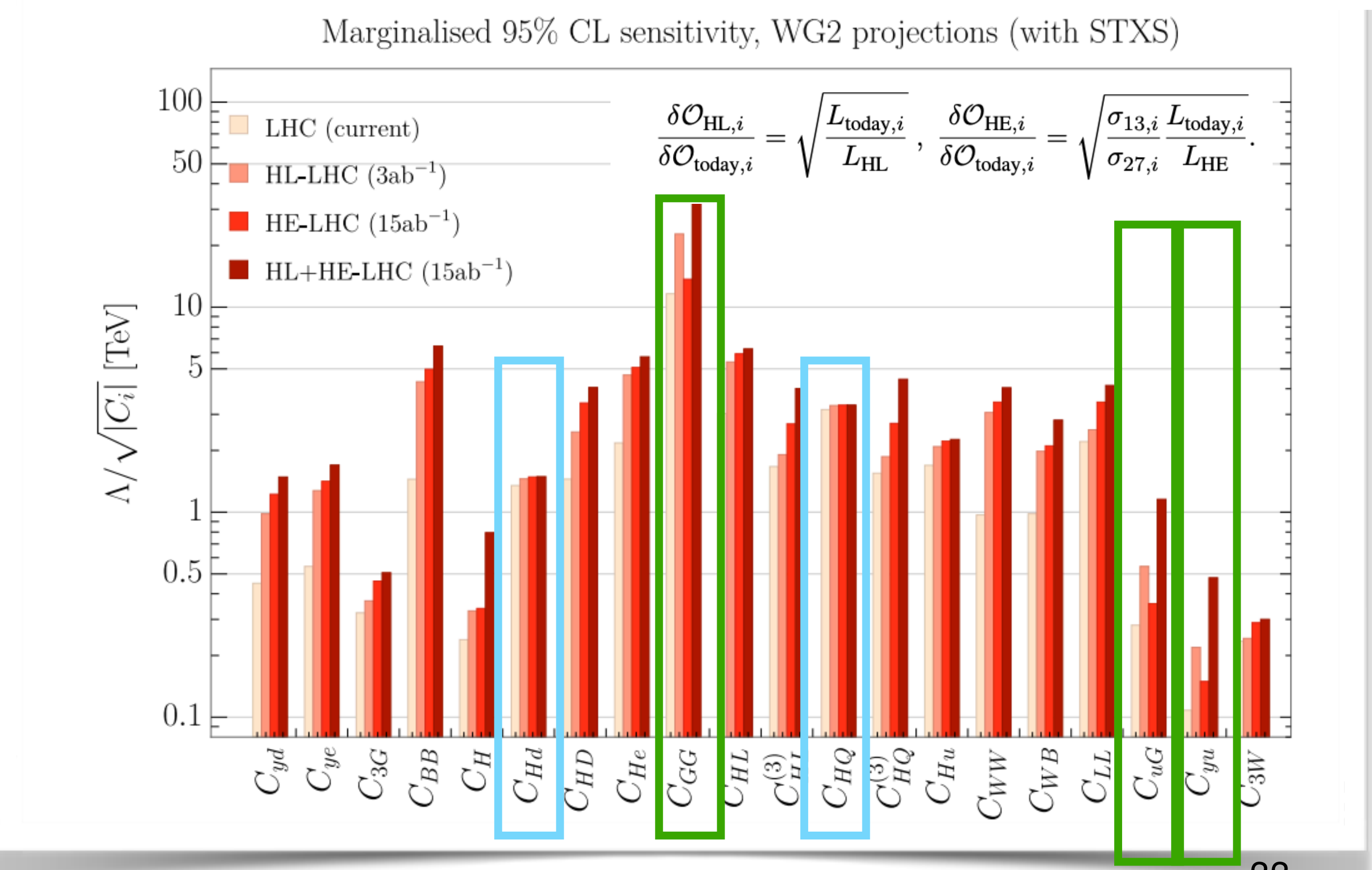
ble

×
×
×
×

Improvements using 27 TeV data:

- **ttH**
- **different energy to break degeneracy between CGG, CuG and Cyu**

No big gain since dominated by LEP data



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C_H
C_{Hd}
C_{HD}
C_{He}
C_{GG}
C_{HL}
$C^{(3)}_{HL}$
C_{HQ}
$C^{(3)}_{HQ}$
C_{Hu}
C_{WW}
C_{WB}
C_{LL}
C_{uG}
C_{yu}
C_{3W}

Fisher info

Universal new physics: Current and future sensitivity

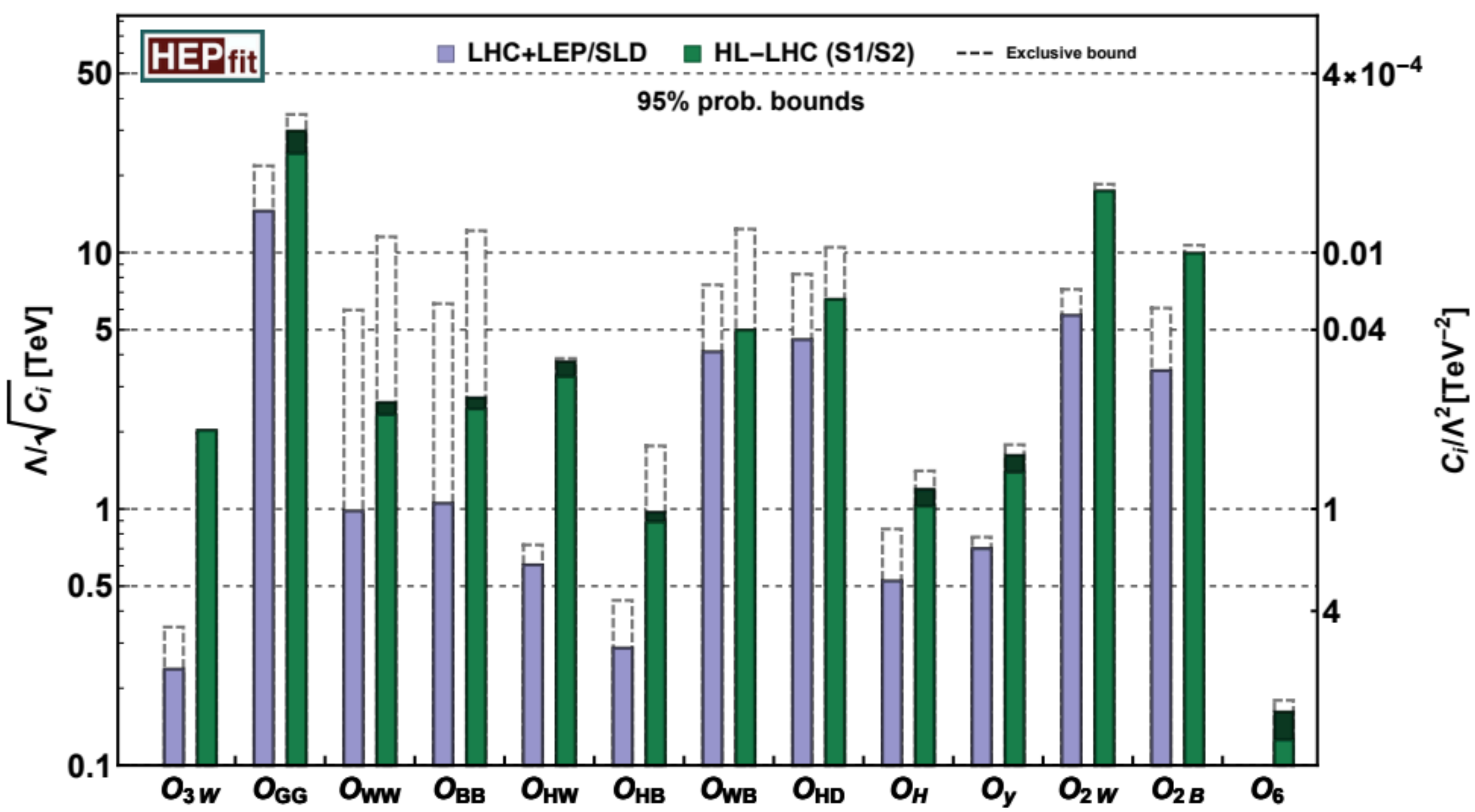
J. de Blas, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, L. Silvestrini

Higgs-Only Operators		
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \vert H\vert^2)^2$	$\mathcal{O}_6 = \lambda \vert H\vert^6$	
$\mathcal{O}_{y_u} = y_u \vert H\vert^2 \bar{Q}\widetilde{H}u$	$\mathcal{O}_{y_d} = y_d \vert H\vert^2 \bar{Q}Hd$	$\mathcal{O}_{y_e} = y_e \vert H\vert^2 \bar{L}He$
$\mathcal{O}_{BB} = g'^2 \vert H\vert^2 B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{GG} = g_s^2 \vert H\vert^2 G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{WW} = g^2 \vert H\vert^2 W^I_{\mu\nu}W^{I\mu\nu}$
Universal Operators		
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	$\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{abc} G^{a\,\nu}_\mu G^b_{\nu\rho} G^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$	$\mathcal{O}_{WB} = gg'(H^\dagger \sigma^I H) W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_{2G} = \frac{1}{2}\left(D^\nu G^a_{\mu\nu}\right)^2$	$\mathcal{O}_{2B} = \frac{1}{2}\left(\partial^\rho B_{\mu\nu}\right)^2$	$\mathcal{O}_{2W} = \frac{1}{2}\left(D^\rho W^a_{\mu\nu}\right)^2$
and $\mathcal{O}_H, \mathcal{O}_6, \mathcal{O}_{BB}, \mathcal{O}_{WW}, \mathcal{O}_{GG}, \mathcal{O}_y = \sum_\psi \mathcal{O}_{y_\psi}$		

- Fit done with the SMEFT Warsaw in HEPfit package
- Interested in new physics effects that arise in the context of the so-called **universal theories:**
  - **All new physics effects can be captured by operators involving SM bosons only (via field redefinition)**
- EWPO measurements
- LHC Higgs measurements
- Differential distribution of mHH in bbγγ final state
- Differential distribution of mZH in ZH,Hbb final state
- High-energy measurements in the di-boson channels
- Sensitivity study to the W and Y parameters in Drell Yan production

Used here

$$\{\mathcal{O}_H, \mathcal{O}_{HD}, \mathcal{O}_6, \mathcal{O}_{GG}, \mathcal{O}_{BB}, \mathcal{O}_{WW}, \mathcal{O}_{WB}, \mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{2B}, \mathcal{O}_{2W}, \mathcal{O}_{3W}, \mathcal{O}_y\}.$$



Universal new physics: Current and future sensitivity

J. de Blas, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, L. Silvestrini

Higgs-Only Operators		
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$	$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	
$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}\widetilde{H}u$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}Hd$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}He$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^I_{\mu\nu}W^{I\mu\nu}$
Universal Operators		
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	$\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{abc} G^{a\,\nu}_\mu G^b_{\nu\rho} G^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$	$\mathcal{O}_{WB} = gg'(H^\dagger \sigma^I H) W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_{2G} = \frac{1}{2}\left(D^\nu G^a_{\mu\nu}\right)^2$	$\mathcal{O}_{2B} = \frac{1}{2}\left(\partial^\rho B_{\mu\nu}\right)^2$	$\mathcal{O}_{2W} = \frac{1}{2}\left(D^\rho W^a_{\mu\nu}\right)^2$
and $\mathcal{O}_H, \mathcal{O}_6, \mathcal{O}_{BB}, \mathcal{O}_{WW}, \mathcal{O}_{GG}, \mathcal{O}_y = \sum_\psi \mathcal{O}_{y_\psi}$		

- Fit done with the SMEFT Warsaw in HEPfit package
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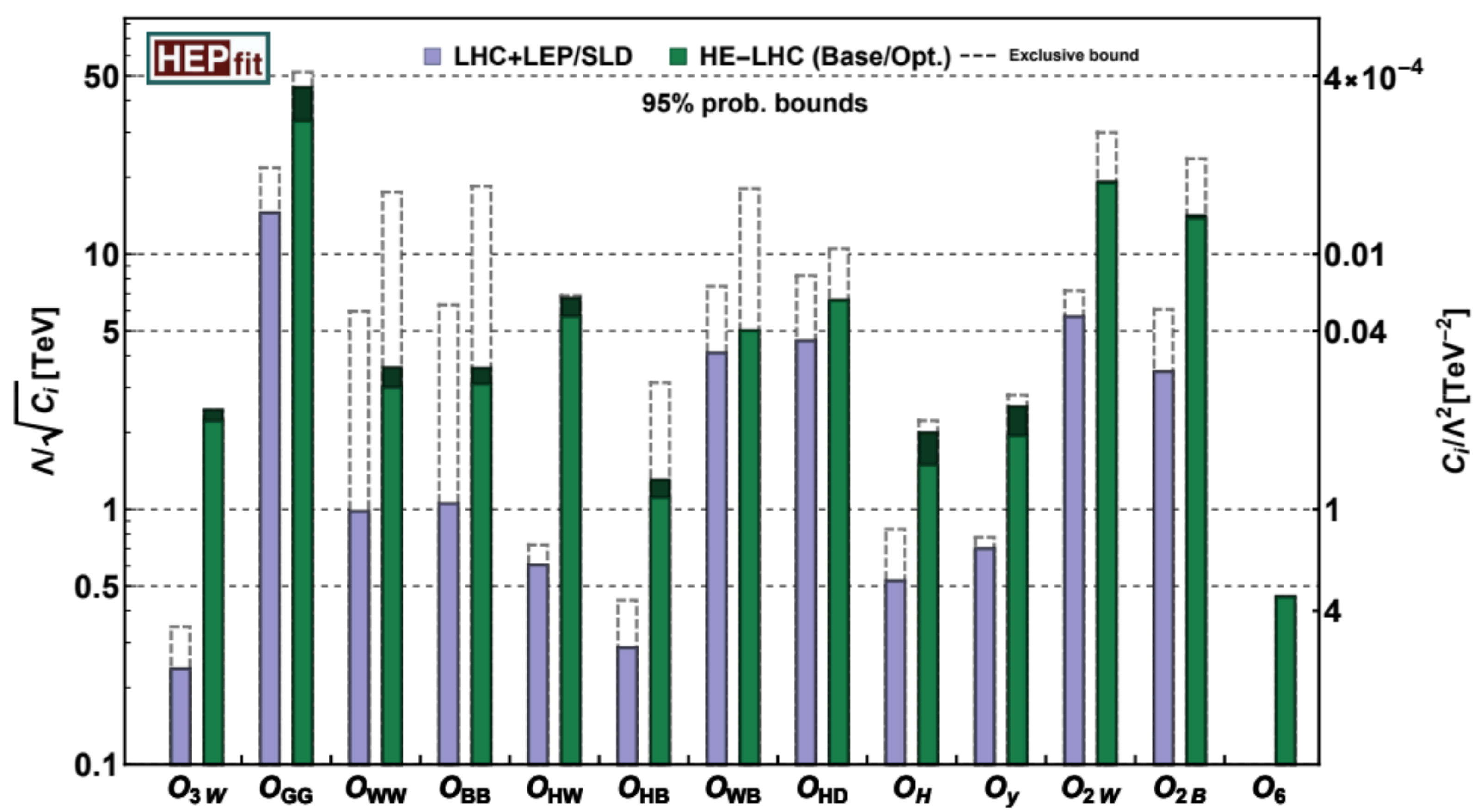
- Sensitivity study to the W and Y parameters in Drell Yan production

Used here

$$\{\mathcal{O}_H, \mathcal{O}_{HD}, \mathcal{O}_6, \mathcal{O}_{GG}, \mathcal{O}_{BB}, \mathcal{O}_{WW}, \mathcal{O}_{WB}, \mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{2B}, \mathcal{O}_{2W}, \mathcal{O}_{3W}, \mathcal{O}_y\}.$$

$$\delta_{\text{stat}}\mu_{\text{HE-LHC}} = \sqrt{\frac{\sigma^{14\text{TeV}}_{pp\to H} \times 3\,\text{ab}^{-1}}{\sigma^{27\text{TeV}}_{pp\to H} \times 15\,\text{ab}^{-1}}}\,\delta_{\text{stat}}\mu_{\text{HL-LHC}}.$$



Global fit with self coupling: Current and future sensitivity

A. Biekötter, D. Gonçalves, T. Plehn, M. Takeuchi, D. Zerwas

$$\mathcal{L}_{\rm eff} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2}\mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} + \frac{f_{\phi 2}}{\Lambda^2}\mathcal{O}_{\phi 2} + \frac{f_{\phi 3}}{\Lambda^2}\mathcal{O}_{\phi 3} + \frac{f_\tau m_\tau}{v\Lambda^2}\mathcal{O}_{e\phi,33} + \frac{f_b m_b}{v\Lambda^2}\mathcal{O}_{d\phi,33} + \frac{f_t m_t}{v\Lambda^2}\mathcal{O}_{u\phi,33} + \text{invisible decays}\,.$$

$$\mathcal{O}_{\phi 2} = \frac{1}{2}\partial^\mu(\phi^\dagger\phi)\partial_\mu(\phi^\dagger\phi) \qquad \mathcal{O}_{\phi 3} = -\frac{1}{3}(\phi^\dagger\phi)^3\,,$$

- Interested in including EFT modifications when testing the Higgs self coupling
- **Current expected bound on trilinear coupling at 27 TeV 1.5ab:**

$$\frac{\lambda_{3H}}{\lambda_{3H}^{(\rm SM)}} = \begin{cases} 1 \pm 15\% & 68\%\ \text{C.L.} \\ 1 \pm 30\% & 95\%\ \text{C.L.}\end{cases}$$

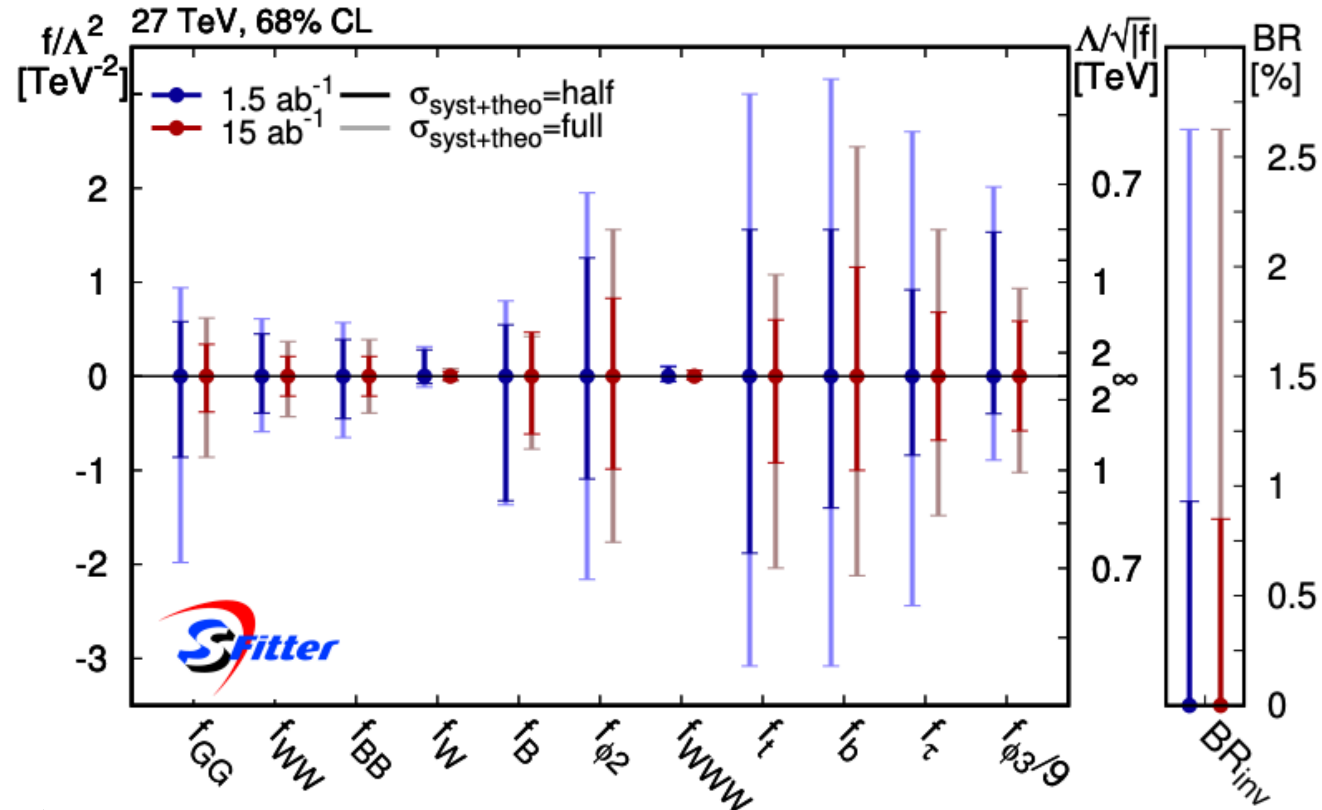
which becomes

$$\lambda_{3H} = \lambda_{3H}^{(\rm SM)}\left(1 + \frac{2v^2}{3m_H^2}\frac{f_{\phi 3}v^2}{\Lambda^2}\right) \quad \text{and} \quad \left|\frac{\Lambda}{\sqrt{f_{\phi 3}}}\right| \gtrsim \begin{cases} 1\ \text{TeV} & 68\%\ \text{C.L.} \\ 700\ \text{GeV} & 95\%\ \text{C.L.}\end{cases}$$

Using global fit to assess how these limits change.

Measurements used:

channel	observable	# bins	range [GeV]
$WW \to (\ell\nu)(\ell\nu)$	$m_{\ell\ell'}$	10	$0 - 4500$
$WW \to (\ell\nu)(\ell\nu)$	$p_T^{\ell_1}$	8	$0 - 1750$
$WZ \to (\ell\nu)(\ell\ell)$	m_T^{WZ}	11	$0 - 5000$
$WZ \to (\ell\nu)(\ell\ell)$	$p_T^{\ell\ell}\ (p_T^Z)$	9	$0 - 2400$
WBF, $H \to \gamma\gamma$	$p_T^{\ell_1}$	9	$0 - 2400$
$VH \to (0\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$VH \to (1\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$VH \to (2\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$HH \to (b\bar{b})(\gamma\gamma), 2j$	m_{HH}	9	$200 - 1000$
$HH \to (b\bar{b})(\gamma\gamma), 3j$	m_{HH}	9	$200 - 1000$



Result in the global fit

$$\frac{\Lambda}{\sqrt{|f_{\phi 3}|}} > 430\ \text{GeV} \qquad 68\%\ \text{C.L.}$$

$$\frac{\Lambda}{\sqrt{|f_{\phi 3}|}} > 245\ \text{GeV}\ \ (f_{\phi 3} > 0) \quad \text{and} \quad \frac{\Lambda}{\sqrt{|f_{\phi 3}|}} > 300\ \text{GeV}\ \ (f_{\phi 3} < 0) \qquad 95\%\ \text{C.L.}$$

Outline

- Summary of the Higgs measurements
- How to extract info on EFT
- Global fit & Extrapolation to HL-HE LHC
- **Future Colliders**

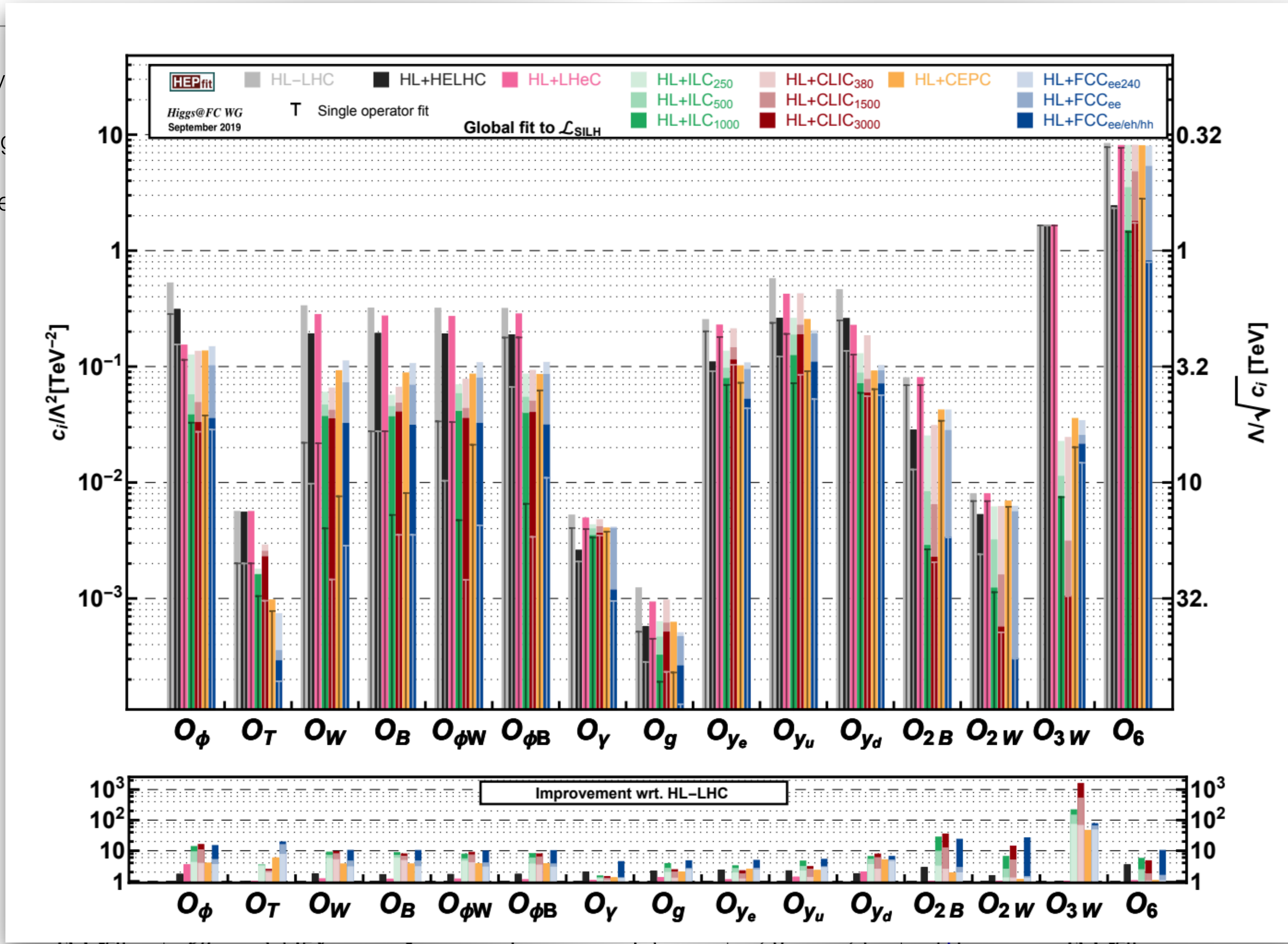
Future Colliders

- The physics of the Higgs boson is a key aspect in the discussion for future colliders.
- Coupling measurements interpreted in EFT is an important part of the ongoing discussion towards the European Strategy Update.
- Measurements used in this fit extrapolated similarly to the one commented on the Universal new physics

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[13]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[13]	HE-LHC
FCC-hh$^{(*)}$	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 14]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5	[4]	ILC$_{1000}$
							(+1-2)		(1-2y SD after 500 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[15]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[12]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Future Colliders

- The phy
- Couplin … date.
- Measure



Conclusion

- Higgs discovery 7 years ago was an important milestone in particle physics
- A lot of its nature has been tested in the past years, but a lot remains to be measured.
- We have several options to describe in the best way we can the characteristics of this new boson.
- EFT interpretations have already been used by the experiments, and we are equipping ourself with all the needed technologies to report our finding in the best way:
  - Measurement of quantities that are sensitive to EFT effects (i.e. going differential)
  - Preparing the road to combine the information from Higgs physics with all the other measurement to get a global view beyond the SM.

Backup

M. Duehrssen and N. Berger in LHC-HXSWG

Let's try a wish list

Since none of the proposals so far got wide acceptance, let's try to make a wish list and discuss it. From this it might be easier to converge.

- **The parameters should be as sensitive as possible, e.g. not average over large phase space volumes that could provide extra sensitivity**
- **The parameters should have some intuitive meaning. For example, something directly related to the partial decay width**
  - **Imagine reading and <u>understanding</u>: "We measure the CP-even part of $H \to \tau\tau$ as 230±30 keV and the CP-odd part is <50 keV @ 95% CL. The SM prediction (CP-even) is 256±5 keV"**
- **As general as needed with as few parameters as possible**
- **We know there is interference in decays. Whatever is chosen should make dealing with interference not too complicated**
- **Can be well measured together with production STXS bins**
- **More?**

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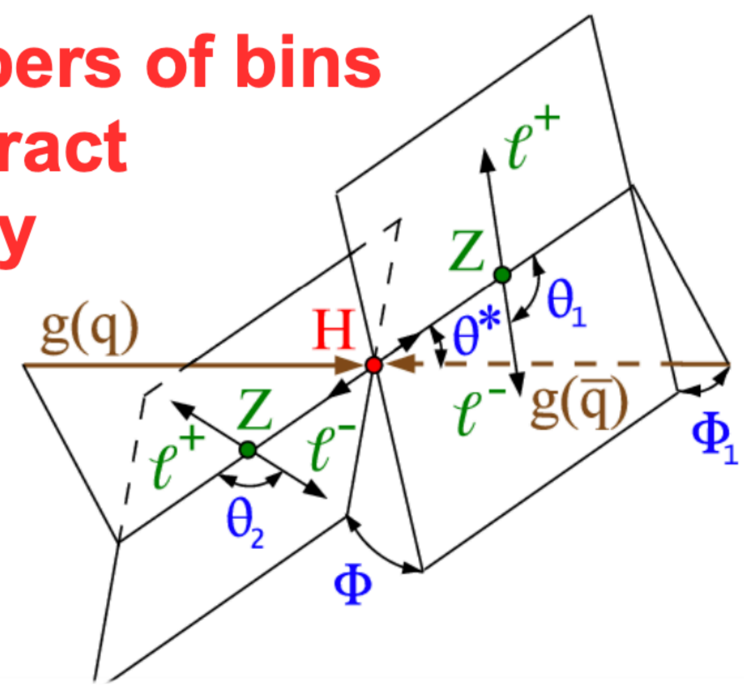
M. Duehrssen and N. Berger in LHC-HXSWG

Trivial: measure in bins (STXS)?

Linear (parameters are ~ partial width Γ_j like)

- **Bin the decay phase space into a suitable number of bins to extract all information**
- **Pro: Intuitively understandable, well defined**
- **Pro: Interference enters in the interpretation step**
- **Con: Likely need a large numbers of bins in order to simultaneously extract the information about ~5 decay observables with good sensitivity (for h→4l)**
  TO BE CHECKED
  → Les Houches project



M. Duehrssen and N. Berger in LHC-HXSWG

Continues: Linear or Quadractic?

Reminder: the observable rate for a Higgs signal is

$$\sigma_i * \Gamma_j / \Gamma_H$$

Extract decay information with continuous parameters

(a) with the decay rate depending linearly on the parameters, e.g. Γ_j(CP-odd)

(b) with the decay rate depending quadratically on the parameters, e.g. Γ_j=poly2(κ_m) as in the κ-framework

- **In both cases, interference effects between parameters need to be treated correctly**

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M. Duehrssen and N. Berger in LHC-HXSWG

Most general proposal so far: POs

(b) PO	(a) *Physical* PO	Relation to the eff. coupl.
$\kappa_f,\ \delta_f^{\rm CP}$	$\Gamma(h \to f\bar{f})$	$= \Gamma(h \to f\bar{f})^{\rm (SM)}[(\kappa_f)^2 + (\delta_f^{\rm CP})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{\rm CP}$	$\Gamma(h \to \gamma\gamma)$	$= \Gamma(h \to \gamma\gamma)^{\rm (SM)}[(\kappa_{\gamma\gamma})^2 + (\delta_{\gamma\gamma}^{\rm CP})^2]$
$\kappa_{Z\gamma},\ \delta_{Z\gamma}^{\rm CP}$	$\Gamma(h \to Z\gamma)$	$= \Gamma(h \to Z\gamma)^{\rm (SM)}[(\kappa_{Z\gamma})^2 + (\delta_{Z\gamma}^{\rm CP})^2]$
κ_{ZZ}	$\Gamma(h \to Z_L Z_L)$	$= (0.209\ \ {\rm MeV}) \times \lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h \to Z_T Z_T)$	$= (1.9 \times 10^{-2}\ \ {\rm MeV}) \times \lvert\epsilon_{ZZ}\rvert^2$
$\epsilon_{ZZ}^{\rm CP}$	$\Gamma^{\rm CPV}(h \to Z_T Z_T)$	$= (8.0 \times 10^{-3}\ \ {\rm MeV}) \times \lvert\epsilon_{ZZ}^{\rm CP}\rvert^2$
ϵ_{Zf}	$\Gamma(h \to Zf\bar{f})$	$= (3.7 \times 10^{-2}\ \ {\rm MeV}) \times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h \to W_L W_L)$	$= (0.84\ \ {\rm MeV}) \times \lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h \to W_T W_T)$	$= (0.16\ \ {\rm MeV}) \times \lvert\epsilon_{WW}\rvert^2$
$\epsilon_{WW}^{\rm CP}$	$\Gamma^{\rm CPV}(h \to W_T W_T)$	$= (6.8 \times 10^{-2}\ \ {\rm MeV}) \times \lvert\epsilon_{WW}^{\rm CP}\rvert^2$
ϵ_{Wf}	$\Gamma(h \to Wf\bar{f}')$	$= (0.14\ \ {\rm MeV}) \times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$
κ_g	$\sigma(pp \to h)_{gg-{\rm fusion}}$	$= \sigma(pp \to h)_{gg-{\rm fusion}}^{\rm SM}\kappa_g^2$
κ_t	$\sigma(pp \to t\bar{t}h)_{\rm Yukawa}$	$= \sigma(pp \to t\bar{t}h)_{\rm Yukawa}^{\rm SM}\kappa_t^2$
κ_H	$\Gamma_{\rm tot}(h)$	$= \Gamma_{\rm tot}^{\rm SM}(h)\kappa_H^2$

Table 110 in YR4:
https://arxiv.org/abs/1610.07922

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M. Duehrssen and N. Berger in LHC-HXSWG

Physical POs

Linear (parameters are ~ partial width Γ_j like)

- **Pro: continuous parameter (so only ~5 for h→4l)**
- **Pro: closely related to the σ*B==event rate**
- **Mixed: Appears to be intuitively understandable (its like a partial width), but because of interference the partial width components in the same decay mode do not sum up to the observable partial width!**
- **Con: interference terms ~ ugly/difficult**

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M. Duehrssen and N. Berger in LHC-HXSWG

POs

Quadratic (parameters are ~ kappa k_j like)

- Pro: more closely related to underlying theory
- Pro: interference terms natural and simple
- Con: value/meaning not necessarily intuitively or directly connected to observable quantities
  - Factors of 2, π, … (any constant) can be put into the definition of the parameters without changing physics
  - Option to make this more intuitive: κ_i, ε_i, c_i, ...==1 could correspond to something well defined
- Possible Con: Covariance matrix of a joined measurement with STXS bins could be insufficient (TO BE CHECKED!), if κ^2, ε^2 terms dominate

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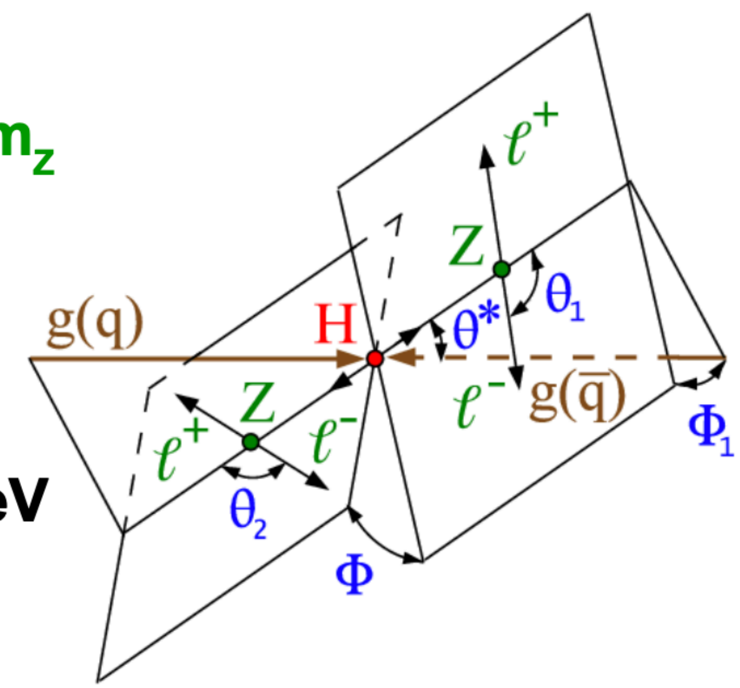
M. Duehrssen and N. Berger in LHC-HXSWG

A compromise ?

$H \to 4l$:

- **1st Z usually ~ on-shell, mass $m_{12} \sim m_Z$**
- **2nd Z off-shell, mass $q^2 = m_{34}$**
- **STXS for q^2 dependence: make bins in m_{34}. Experiments usually cut m_{34}>~10 GeV**
- **Within each bin, q^2 is ~ constant**
  - **Can chose bins or continuous parameters without worry about q^2 expansion**
  - **Continuous parameters could be stage 2**



$H \to l\nu l\nu$:

- **Want to be as independent from production bins as possible**
- **Only one Lorentz invariant observable: m_{ll} → Let's make bins**

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Even more minimal starting point

We have seen in the EFT discussions that acceptance effects in decays play a role. Treat it like $|Y_H|>2.5$ in production

- **$H \to ZZ^*$**
  - **Add 3 $H \to ZZ^*$ sub-bins**
    - **$H \to 4l$, $m_{34} < X$ (X ~ 10 GeV, not measured region)**
    - **$H \to 4l$, $X < m_{34} < 62.5$ GeV**
    - **$H \to ZZ^* \to !4l$ (populated in ttH multilepton)**
- **$H \to WW^*$**
  - **Add 4 $H \to WW^*$ sub-bins**
    - **$H \to l\nu l\nu$, $m_{ll} < X1$ (X1 ~ 10 GeV, not measured region)**
    - **$H \to l\nu l\nu$, $X1 < m_{ll} < X2$ (X2 ~ 50-60 GeV)**
    - **$H \to l\nu l\nu$, $X2 < m_{ll}$**
    - **$H \to WW^* \to !l\nu l\nu$ (populated in ttH multilepton, VHWW)**

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C. Hays in LHC-HXSWG

Acceptance corrections

SM extrapolation to total decay width biases EFT interpretation

Particularly for $H \to 4\ell$ and $H \to \ell\nu\ell\nu$ where new classes of diagrams appear at dimension-6

Ideally STXS would be split into $m_{\ell_3\ell_4}$ bins for $H \to 4\ell$ and $m_{\ell\ell}$ bins for $H \to \ell\nu\ell\nu$

For now we can estimate a correction based on published event selection in these channels
The correction for requirements on invariant masses is approximately universal for the production modes
Apply to decay ratio equations

$$y_j = \sum_i A_{ji} \cdot r_i \cdot (\sigma_i \cdot \mathrm{B}_{4\ell})_{\mathrm{SM}} \cdot r_f \cdot \left(\frac{\mathrm{B}_f}{\mathrm{B}_{4\ell}}\right)_{\mathrm{SM}} \cdot \mathcal{L}$$

$$\downarrow$$

$$\left(\frac{\mathcal{B}_S}{\mathcal{B}_{4\ell}}\right)_{SM} \left(\frac{\mathcal{A}_S}{\mathcal{A}_{4\ell}}\right)_{SM} \left[1 + \sum_\alpha \left(\frac{\delta\Gamma_S}{\Gamma_S^{SM}}\right)^\alpha \left(\frac{\mathcal{A}_S^{SMEFT}}{\mathcal{A}_S^{SM}}\right)^\alpha - \sum_\beta \left(\frac{\delta\Gamma_{4\ell}}{\Gamma_{4\ell}^{SM}}\right)^\beta \left(\frac{\mathcal{A}_{4\ell}^{SMEFT}}{\mathcal{A}_{4\ell}^{SM}}\right)_\beta (\right]$$

Can be calculated with Madgraph or analytically, e.g.

$$\left[\frac{2\delta g_{L,ei}^{W,\ell}}{\mathrm{Re}[(g_{L,ej}^{\mathcal{W},\ell})^{SM}]} + \frac{2\delta g_{L,\mu k}^{W,\ell}}{\mathrm{Re}[(g_{L,\mu l}^{\mathcal{W},\ell})^{SM}]} + 2\left[\frac{\delta M_W^2}{\hat{M}_W^2} - \frac{\delta G_F}{\sqrt{2}} + C_{H,\mathrm{kin}}\right]\right] \int dps^4 \frac{\mathcal{A}_{WW}^{N_1}}{\mathcal{A}_{WW}^{SM}} + \ldots$$

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C. Hays in LHC-HXSWG

Acceptance correction: $H \to \ell\nu\ell\nu$

Use Rivet routine from ATLAS Run 1 fiducial cross section measurement

Coefficient (=0.1)	σ_{total} [fb]	$\sigma^{\text{cuts}}_{\text{0j bin}}$ [fb]	$A_{\text{tot}} = \lvert\sigma^{\text{int}}_{\text{tot}}\rvert/\sigma^{\text{SM}}_{\text{tot}}$	$A_{\text{cuts}} = \lvert\sigma^{\text{int}}_{\text{cuts}}\rvert/\sigma^{\text{SM}}_{\text{cuts}}$	Correction ($A_{\text{cuts}}/A_{\text{tot}}$)
SM	85.2	4.60	-	-	-
cHW	-12.6	-0.83	0.148 ± 0.001	0.181 ± 0.001	1.219 ± 0.002
cHl3	-31.9	-1.65	0.374 ± 0.002	0.359 ± 0.002	0.959 ± 0.002

$$\frac{\Gamma^{SMEFT}_{H\ell\nu\ell\nu}}{\Gamma^{SM}_{H\ell\nu\ell\nu}} = 1 - 0.15\texttt{cHW} - 0.37\texttt{cHl3} \longrightarrow \left(\frac{\Gamma^{SMEFT}_{H\ell\nu\ell\nu}}{\Gamma^{SM}_{H\ell\nu\ell\nu}}\right)\left(\frac{A^{SMEFT}_{H\ell\nu\ell\nu}}{A^{SM}_{H\ell\nu\ell\nu}}\right) = 1 - 0.18\texttt{cHW} - 0.36\texttt{cHl3}$$

Approximately half the effect is from $m_{\ell\ell} < 55$ GeV

Agrees with analytical calculation

Verified with Madgraph that the correction is independent of production (checked ggF and VBF)

I Brivio, CH, H Smith, M Trott, G Zemaityte
in preparation

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C. Hays in LHC-HXSWG

Acceptance correction: $H \to 4\ell$

Use Rivet routine to implement ATLAS selection

Coefficient (=0.1)	σ_{total} [fb]	$\sigma^{\text{cuts}}_{\text{0j bin}}$ [fb]	$A_{\text{tot}} = \lvert\sigma^{\text{int}}_{\text{tot}}\rvert/\sigma^{\text{SM}}_{\text{tot}}$	$A_{\text{cuts}} = \lvert\sigma^{\text{int}}_{\text{cuts}}\rvert/\sigma^{\text{SM}}_{\text{cuts}}$	Correction ($A_{\text{cuts}}/A_{\text{tot}}$)
SM	3.08	0.658	-	-	-
cHW	-0.452	-0.029	0.147 ± 0.001	0.044 ± 0.001	0.213 ± 0.001
cHB	-0.305	-0.101	0.099 ± 0.001	0.154 ± 0.001	1.555 ± 0.001
cHWB	0.312	0.015	0.101 ± 0.001	0.023 ± 0.001	0.222 ± 0.001
cHl1	0.697	0.141	0.226 ± 0.001	0.215 ± 0.001	0.950 ± 0.002
cHl3	-1.16	-0.259	0.375 ± 0.001	0.393 ± 0.002	1.046 ± 0.002
cHe	-0.559	-0.112	0.181 ± 0.001	0.171 ± 0.001	0.942 ± 0.002
cll1	0.929	0.198	0.301 ± 0.001	0.301 ± 0.001	0.999 ± 0.002

Preliminary indications that some parameters are more significantly affected
To be checked with analytical calculation

I Brivio, CH, H Smith, M Trott, G Zemaityte
in preparation

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Operators used in
Prospective SMEFT Constraints from HL- and HE-LHC Data

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$$\bar{C}_H = \frac{v^2}{\Lambda^2} C_6 \,,\; \bar{C}^{(3)}_{H\ell} = \frac{v^2}{\Lambda^2} C^{(3)}_{HL} \,,\; \bar{C}^{(1)}_{H\ell} = \frac{v^2}{\Lambda^2} C_{HL} \,,\; \bar{C}_{\ell\ell} = \frac{v^2}{\Lambda^2} C_{LL} \,,\; \bar{C}_{HD} = \frac{v^2}{\Lambda^2} C_{HD} \,,$$

$$\bar{C}_{HWB} = \frac{v^2}{\Lambda^2} g g' C_{WB} \,,\; \bar{C}_{He,Hu,Hd} = \frac{v^2}{\Lambda^2} C_{He,Hu,Hd} \,,\; \bar{C}^{(3)}_{Hq} = \frac{v^2}{\Lambda^2} C^{(3)}_{HQ} \,,\; \bar{C}^{(1)}_{Hq} = \frac{v^2}{\Lambda^2} C_{HQ} \,,$$

$$\bar{C}_W = \frac{v^2}{\Lambda^2} \frac{g}{3!} C_{3W} \,,\; \bar{C}_{eH,dH,uH} = \frac{v^2}{\Lambda^2} C_{ye,yd,yu} \,,\; \bar{C}_{H\Box} = \frac{v^2}{\Lambda^2} \frac{1}{2} C_H \,,\; \bar{C}_{HW} = \frac{v^2}{\Lambda^2} g^2 C_{WW} \,,$$

$$\bar{C}_{HB} = \frac{v^2}{\Lambda^2} g'^2 C_{BB} \,,\; \bar{C}_{HG} = \frac{v^2}{\Lambda^2} g_s^2 C_{GG} \,,\; \bar{C}_G = \frac{v^2}{\Lambda^2} \frac{g_s}{3!} C_{3G} \,.$$

Anomalous couplings VS EFT

- **Two equivalent parameterizations: Effective Lagrangian**

ZZ

$$L(HVV) \sim a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 H Z^\mu \Box Z_\mu - \frac{\kappa_3}{2(\Lambda_Q)^2} m_Z^2 \Box H Z^\mu Z_\mu - \frac{1}{2} a_2 H Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 H Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

WW

$$+ a_1^{WW} m_W^2 H W^{+\mu} W^-_\mu - \frac{1}{(\Lambda_1^{WW})^2} m_W^2 H \left(\kappa_1^{WW} W^-_\mu \Box W^{+\mu} + \kappa_2^{WW} W^+_\mu \Box W^{-\mu}\right)$$

$$- \frac{\kappa_3^{WW}}{\left(\Lambda_Q^{WW}\right)^2} m_W^2 \Box H W^{+\mu} W^-_\mu - a_2^{WW} H W^{+\mu\nu} W^-_{\mu\nu} - a_3^{WW} H W^{+\mu\nu} \tilde{W}^-_{\mu\nu}$$

Zγ

$$+ \frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 H Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} H F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} H F^{\mu\nu} \tilde{Z}_{\mu\nu}$$

γγ

$$- \frac{1}{2} a_2^{\gamma\gamma} H F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} H F^{\mu\nu} \tilde{F}_{\mu\nu}$$

gg

$$- \frac{1}{2} a_2^{gg} H G_a^{\mu\nu} G^a_{\mu\nu} - \frac{1}{2} a_3^{gg} H G_a^{\mu\nu} \tilde{G}^a_{\mu\nu},$$

- **or Amplitude**

$$A = \frac{1}{v}\left(\left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_1+q_2)^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{q_1^2+q_2^2}{(\Lambda_1)^2}\right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}\right)$$

A. Gritsan

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{a3}^{\mathrm{ggH}} = \frac{|a_3^{\mathrm{ggH}}|^2}{|a_2^{\mathrm{ggH}}|^2 + |a_3^{\mathrm{ggH}}|^2},$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \ldots}, \qquad \phi_{\Lambda 1},$$

$$f_{\Lambda 1}^{Z\gamma} = \frac{\tilde{\sigma}_{\Lambda 1}^{Z\gamma}/\left(\Lambda_1^{Z\gamma}\right)^4}{|a_1|^2\sigma_1 + \tilde{\sigma}_{\Lambda 1}^{Z\gamma}/\left(\Lambda_1^{Z\gamma}\right)^4 + \ldots}, \qquad \phi_{ai}^{Z\gamma},$$

Coupling measurement in ATLAS H→ZZ

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$$\begin{aligned}\mathcal{L}_0^V = \Big\{ & \kappa_{\rm SM}\left[\frac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] \\ & - \frac{1}{4}\left[\kappa_{Hgg}g_{Hgg}G^a_{\mu\nu}G^{a,\mu\nu} + \tan\alpha\,\kappa_{Agg}g_{Agg}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right] \\ & - \frac{1}{4}\frac{1}{\Lambda}\left[\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \tan\alpha\,\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & - \frac{1}{2}\frac{1}{\Lambda}\left[\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \tan\alpha\,\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0.\end{aligned}$$

Table 10: Expected and observed confidence intervals at 95% CL on the κ_{Agg}, κ_{HVV} and κ_{AVV} coupling parameters, their best-fit values and corresponding compatibility with the SM expectation, as obtained from the negative log-likelihood scans performed with 36.1 fb^{-1} of data at $\sqrt{s}$ = 13 TeV. The coupling κ_{Hgg} is fixed to the SM value of one in the fit, while the coupling $\kappa_{\rm SM}$ is either fixed to the SM value of one or left as a free parameter of the fit.

BSM coupling $\kappa_{\rm BSM}$	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{\rm BSM}$	Best-fit $\hat{\kappa}_{\rm SM}$	Deviation from SM
κ_{Agg}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ = 1)	[−0.47, 0.47]	[−0.68, 0.68]	±0.43	-	1.8σ
κ_{HVV}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ = 1)	[−2.9, 3.2]	[0.8, 4.5]	2.9	-	2.3σ
κ_{HVV}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ free)	[−3.1, 4.0]	[−0.6, 4.2]	2.2	1.2	1.7σ
κ_{AVV}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ = 1)	[−3.5, 3.5]	[−5.2, 5.2]	±2.9	-	1.4σ
κ_{AVV}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ free)	[−4.0, 4.0]	[−4.4, 4.4]	±1.5	1.2	0.5σ

Table 11: The best-fit coupling values and corresponding deviation from the SM expectation, as obtained from the two-dimensional $\kappa_{HVV} - \kappa_{AVV}$ negative log-likelihood scans performed with 36.1 fb^{-1} of data at $\sqrt{s}$ = 13 TeV.

Fit configuration	Best-fit $\hat{\kappa}_{HVV}$	Best-fit $\hat{\kappa}_{AVV}$	Best-fit $\hat{\kappa}_{\rm SM}$	Deviation from SM
κ_{Hgg} = 1, $\kappa_{\rm SM}$ = 1	2.9	±0.5	-	1.9σ
κ_{Hgg} = 1, $\kappa_{\rm SM}$ free	2.1	±0.3	1.7	1.2σ

K-measurement in ATLAS