Self-coupling from single Higgs measurements: towards a common κ_λ parametrisation

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on behalf of the ATLAS and CMS collaborations

The 18th Workshop of the LHC Higgs Working Group

Introduction

- Given the Higgs scalar potential:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)$$

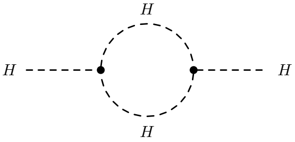
- within the SM the potential depends only on two parameters ν and m_H, fixing m_H and ν we have:

$$\lambda_3 = \lambda_4 = \lambda^{SM} = \frac{m_H^2}{2v^2} \qquad \text{and} \qquad \lambda_i = 0, \quad \text{for } i \geq 5$$

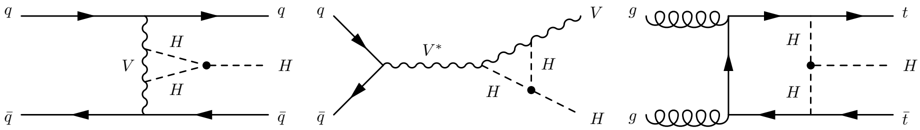
- new physics could modify the Higgs potential altering the λ_3 without affecting m_H or v: e.g. by extending the scalar sector or due to the exchange of new virtual states.
- λ_3 and its variation from SM $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$ can be directly probed by Higgs boson pair production

→ There are also processes that are indirectly sensitive to λ_3: single-Higgs production mode
  - several contributions on the topic: 1312.3322, 1607.03773, 1607.04251, 1610.05771, 1704.01953, 1709.08649

- Single Higgs processes do not depend on trilinear-coupling λ_3 at LO
- Two types of NLO EW corrections that depend on λ_3
  - one universal $O(\lambda_3^2)$ due to Higgs loops



  - one linear $O(\lambda_3)$ that is both process and kinematics dependent



- Considering a variation of the trilinear self-coupling $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$

$$\Sigma_{NLO}^{\rm BSM} = Z_H^{\rm BSM} \left[\Sigma_{LO} \left(1 + \kappa_\lambda C_1 + \delta Z_H + \delta_{EW}|_{\lambda_3=0}\right)\right] ,$$

where $Z_H^{\rm BSM}$ is:

$$Z_H^{\rm BSM}(\kappa_\lambda) = \frac{1}{1-(\kappa_\lambda^2-1)\delta Z_H} \quad \text{with} \quad \delta Z_H = -1.536 \times 10^{-3} ,$$

- $Z_H^{\rm BSM}$ arises from universal correction - wave function renormalization

→ C_1 arises from the interference between LO amplitude and the virtual NLO EW λ_3 corrections
  - it is process and kinematic dependent
  - evaluated by reweigthing LO events with momentum-dependent weight (see MG5 HiggSelfCoupling page)

$$C_1(p_i) \equiv w_i = \frac{2\Re(\mathcal{M}^{0*}\mathcal{M}^{1}_{\lambda_3^{\rm SM}})}{|\mathcal{M}^0|^2} .$$

- Production modes cross-section and decay branching ratios vary as a function of κ_λ:

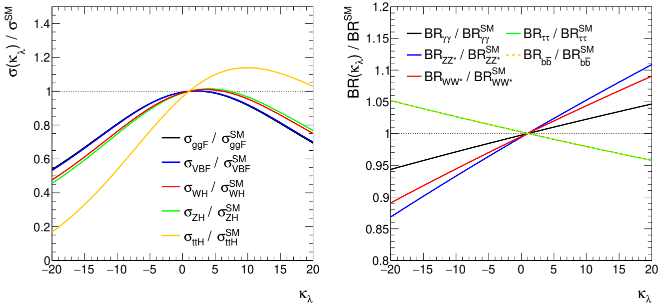
$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\rm BSM}}{\sigma^{\rm SM}} = Z_H^{\rm BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\rm EW}^i}\right],$$

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{{\rm BR}_f^{\rm BSM}}{{\rm BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j {\rm BR}_j^{\rm SM}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

where κ_i and κ_f are additional coupling modifiers such as $\kappa_{\rm F}$ or $\kappa_{\rm V}$

- Considering inclusive C_1

production mode	ggF	VBF	ZH	WH	$t\bar{t}H$
$C_1^i \times 100$	0.66	0.63	1.19	1.03	3.52



- Not only global normalization but also differential distribution are modified, since λ_3 corrections have not trivial dependency on the kinematic of each process
- *VH* and $t\bar{t}H$ production modes are the most affected ones
- No differential effects are expected from BR correction

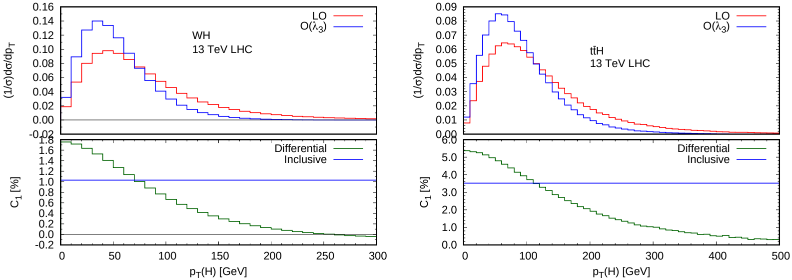


Figure: for λ_3 at the SM value

- Differential C_1 not available for *ggF* channel. Very challenging calculations.
  - Calculation of relevant two-loop $gg \to H + j$ amplitude available in heavy top quark limit see arxiv:1902.05480
  - kinematic dependence is expected to be small

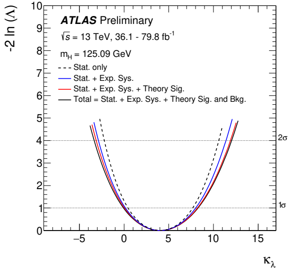
- Interpretation of single Higgs boson analyses using signal strength depending on κ_λ:

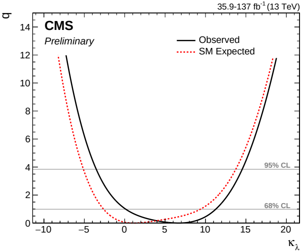
$$\mu_i^f(\kappa_\lambda) \equiv \mu_i(\kappa_\lambda) \times \mu^f(\kappa_\lambda)$$

- CMS considered inclusive
  - production cross-section: $\mu_{\text{ggF}}(\kappa_\lambda), \mu_{\text{VBF}}(\kappa_\lambda), \mu_{WH}(\kappa_\lambda), \mu_{ZH}(\kappa_\lambda), \mu_{t\bar{t}H}(\kappa_\lambda)$
  - decay rates: $\mu^{\gamma\gamma}(\kappa_\lambda), \mu^{ZZ}(\kappa_\lambda), \mu^{WW}(\kappa_\lambda), \mu^{f\bar{f}}(\kappa_\lambda)$
- ATLAS in addition used full STXS fiducial cross-sections for *VH* and *VBF* production modes in order to include differential information
- Input analyses:

Analysis	L [fb^{-1}] ATLAS	L [fb^{-1}] CMS
$H \to \gamma\gamma$	79.8	77.4
$t\bar{t}H \to \gamma\gamma$		77.4
$H \to ZZ^* \to 4\ell$	79.8	137
$H \to WW^* \to e\nu\mu\nu$	36.1	35.9
$H \to \tau\tau$	36.1	77.4
VH, $H \to \tau\tau$	–	35.9
VH, $H \to b\bar{b}$	79.8	77.4
$t\bar{t}H$, $H \to b\bar{b}$	36.1	77.4
ggF, $H \to b\bar{b}$ (boosted)	–	35.9
$t\bar{t}H$ multilepton	36.1	77.4
$H \to \mu\mu$	–	35.9

- Results obtained fitting κ_λ-only, all other couplings are set to their SM values.
- Strong assumption: BSM only affects κ_λ



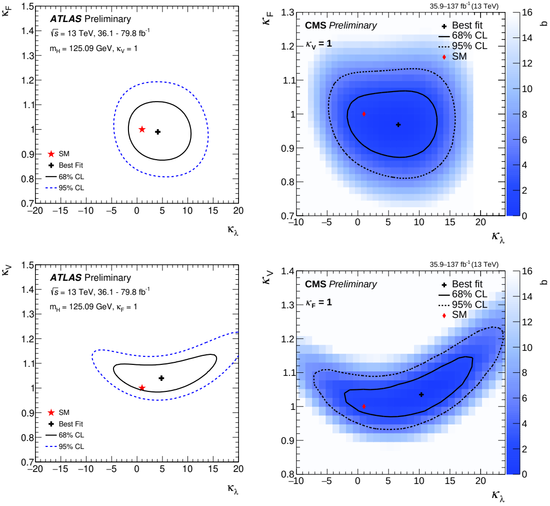


		$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
ATLAS	Observed	$4.0^{+4.3}_{-4.1}$	$[-3.2, 11.9]$
	Expected	$1.0^{+8.8}_{-4.4}$	$[-6.2, 14.4]$
CMS	Observed	$6.7^{+4.6}_{-6.6}$	$[-3.5, 14.5]$
	Expected	$1.0^{+8.3}_{-3.8}$	$[-5.1, 13.7]$

- Current stringent limit from Di-Higgs searches based on full Run 2 139 fb^{-1} :
  - ATLAS $bb\gamma\gamma$+$bb\tau\tau$: $-1.0 < \kappa_\lambda < 6.6$ ($-1.2 < \kappa_\lambda < 7.2$) [ATLAS-CONF-2021-052]

Experimental Results: $\kappa_\lambda - \kappa_F$, $\kappa_\lambda - \kappa_V$

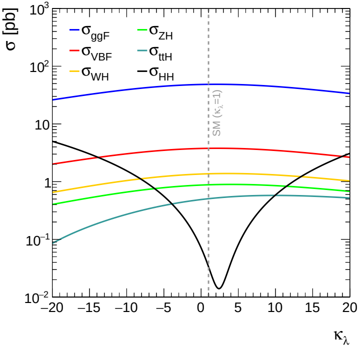
CMS-PAS-HIG-19-005
ATL-PHYS-PUB-2019-009



- the sensitivity to κ_λ is not much degraded when determining κ_F
- the sensitivity to κ_λ is degraded by 50% when determining κ_V
- Fitting κ_λ-κ_V-κ_F or fitting κ_λ-$\kappa_H = \kappa_V = \kappa_F$ results in nearly no sensitivity to κ_λ

- ATLAS has constrained κ_λ combining the information coming from the single Higgs measurements and the double Higgs analyses

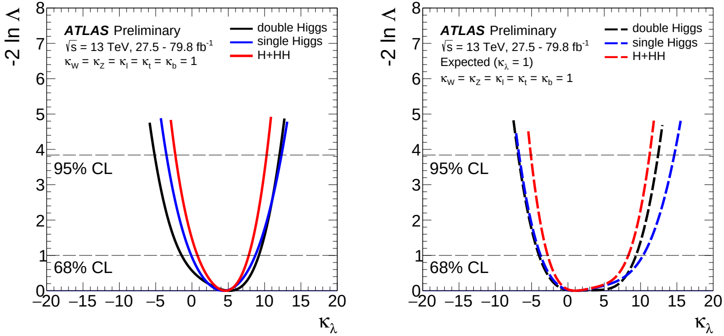
Analysis	L [fb^{-1}]
$H \to \gamma\gamma$	79.8
$H \to ZZ^* \to 4\ell$	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
$VH,\ H \to b\bar{b}$	79.8
$t\bar{t}H,\ H \to b\bar{b}$	36.1
$t\bar{t}H$ multilepton	36.1
$HH \to bbbb$	36.1
$HH \to bb\gamma\gamma$	36.1
$HH \to bb\tau\tau$	36.1



- Single-Higgs contributions in di-Higgs analysis parameterised as a function of κ_λ.
- $t\bar{t}H \to \gamma\gamma$ contribution excluded because of a large overlap with $HH \to bb\gamma\gamma$ analysis (up to 50% of the events)
- The remaining categories have a maximum overlap of less than 2%

Experimental Results: $H + HH$ Results

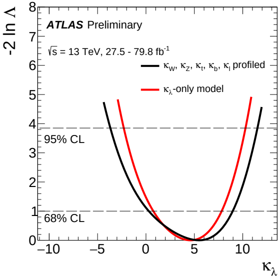
- Results obtained fitting κ_λ-only, all other couplings are set to their SM values.

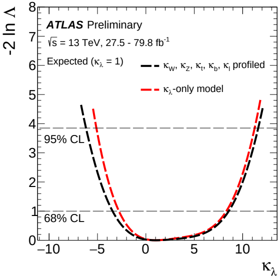


$$\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.6^{+2.9}_{-3.5}\,(\text{stat.})\,^{+1.2}_{-1.2}\,(\text{exp.})\,^{+0.7}_{-0.5}\,(\text{sig. th.})\,^{+0.6}_{-1.0}\,(\text{bkg. th.})$$

- 95% C.L. : $-2.3 < \kappa_\lambda < 10.3$ (observed), $-5.1 < \kappa_\lambda < 11.2$ (expected)
- The combination significantly improves the constraining power on κ_λ.

- Fit simultaneously several coupling modifiers: κ_λ, κ_W, κ_Z, κ_ℓ, κ_b, κ_t
- Test of BSM models that can modify at the same time κ_λ and other H couplings.





$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_{lep}{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
1	1	1	1	1	$4.6^{+3.2}_{-3.8}$ $1.0^{+7.3}_{-3.8}$	$[-2.3, 10.3]$ $[-5.1, 11.2]$
$1.03^{+0.08}_{-0.08}$ $1.00^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$ $1.00^{+0.08}_{-0.08}$	$1.00^{+0.12}_{-0.11}$ $1.00^{+0.12}_{-0.12}$	$1.03^{+0.20}_{-0.18}$ $1.00^{+0.21}_{-0.19}$	$1.06^{+0.16}_{-0.16}$ $1.00^{+0.16}_{-0.15}$	$5.5^{+3.5}_{-5.2}$ $1.0^{+7.6}_{-4.5}$	$[-3.7, 11.5]$ $[-6.2, 11.6]$

- Substantial constraints on κ_λ even in this more generic model.
- On H+HH combination see Jorge de Blas's presentation on Friday

Toward a common κ_λ parametrisation

ATLAS and CMS effort

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\rm BSM}}{\sigma^{\rm SM}} = Z_H^{\rm BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\rm EW}^i}\right],$$

- κ_λ parametrisation depends on Higgs production process and event kinematic
  → STXS bins can be a good proxy to implement a more accurate parametrization
- Common effort of ATLAS and CMS collaborations to define a shared set of C_1 parameters
  - facilitate comparison of the results and a possible future combination
- On 23/09/2021 topical meeting at LHCHXSWG2 on the κ_λ model
  - Additional clarification from theorists about the procedure to be followed
- We have developed a standalone package to easily evaluate C_1 for each STXS bin

  https://gitlab.cern.ch/LHCHIGGSXS/LHCHXSWG2/STXS/self-coupling-c1

- Almost complete, under final validation (numbers that I will show are not yet final!)

→ Very effective way to address a shared problem between the two collaborations
  - Common goal, clear project, sharing codes and developments....

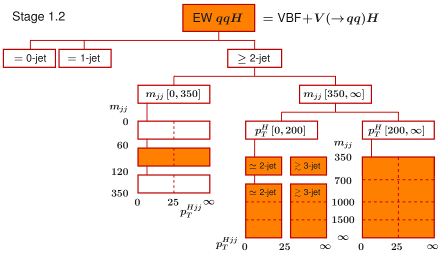
- Standalone package, not using any internal infrastructure/framework
- The package is composed by three main steps (which run with just two commands):
- Generation of the events:
  - Generation of the LO events
    - using dynamical scale
    - scale variation automatically included
    - PDF internal variations and alternative PDF sets included as additional options
  - Reweight the LO events to the virtual NLO-EW κ_λ only corrections
    - the reweighting tool produces an additional .lhe file $\rightarrow$ merging the NLO information inside the LO .lhe as additional weight(s)
  - Shower using MG5-Pythia8 interface
    - output a single .hepmc file with two sets of weights for LO and NLO corrections
    - baseline with default Pythia8 setup, it is possible to consider alternative tuning
- Processing STXS Rivet routine: showered events are run through the STXS Classification routine
- Evaluate the C_1 from the .yoda Rivet output files
- The framework includes also scale and pdf variations which account for the uncertainty on the underlying simulation of the investigated process (binned evaluation of the C_1)

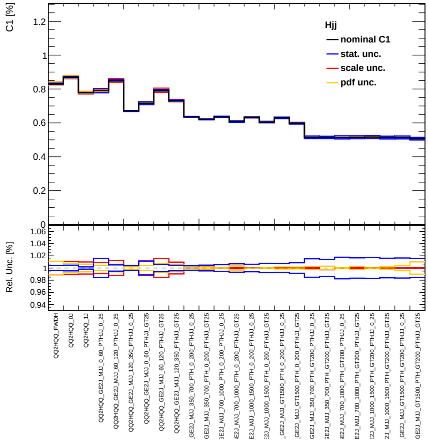
Generation setup

- Some details about the current generation setup:
- 5M events for each process
- dynamical scale plus variation: 1.0, 2.0, 0.5. Standard MG5 dynamical scale definition: $muR = H_T/2 := \sum_i mT(i)/2$, i=final state
- nominal pdf PDF4LHC15_nlo_mc plus internal variations
- alternative pdf: CT14nlo and MMHT2014nlo68clas118
- Almost no significant effects from scale, different PDF or Parton Showering tune setup

C_1 for *Hjj*

- Considering simultaneously contribution from *VBF* and $V(\to jj)H$ processes
  - generating $pp \to Hjj$ events (with complex mass scheme)

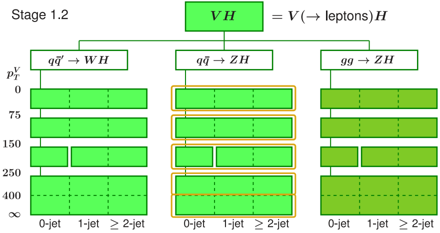


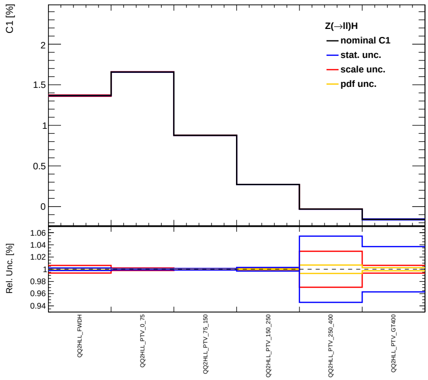


- Expected a small differential dependency for *VBF* process (see arXiv:1610.05771)
- $V(\to jj)H$ contributes mainly to 0J, 1J and QQ2HQQ_GE2J_MJJ_60_120_PTHJJ_* bins

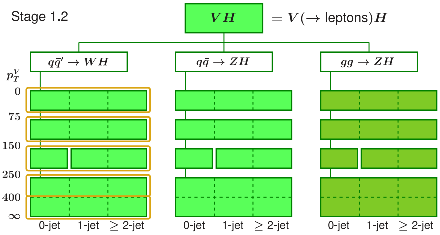
  → highest C_1 (p_T^{Hjj} not optimal variable to enhance *VH* differential dependency)

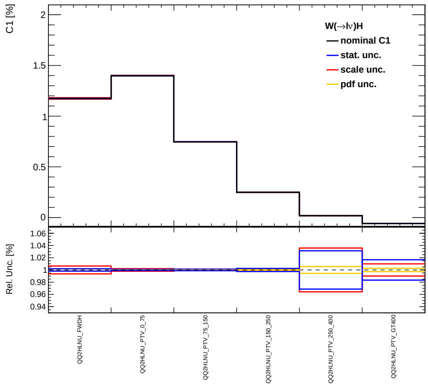
C_1 for $Z(\to \ell\ell)H$





- Significant variation of C_1 over the $p_T(Z)$ spectrum
- Evaluating C_1 merging the bins for different jet number, since κ_λ-corrections are evaluated at LO matrix element $pp \to ZH$
- larger uncertainty in the last two bins due to the central value approximate ~ 0

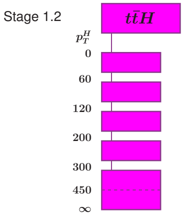


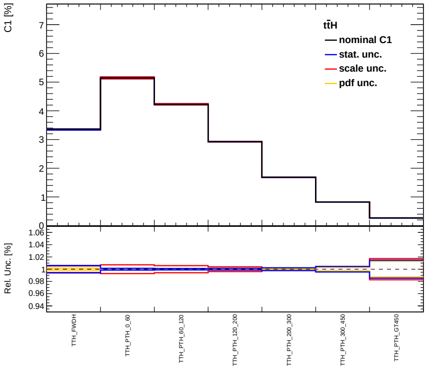


- As for ZH, significant variation of C_1 over the $p_T(W)$ spectrum
- Evaluating C_1 merging the bins for different jet number, since κ_λ-corrections are evaluated at LO matrix element $pp \to WH$
- larger uncertainty in the last two bins due to the central value approximate ~ 0

C_1 for $t\bar{t}H$

- New in STXS stage 1.2: $t\bar{t}H$ region divided in six $p_T(H)$ bins





- $t\bar{t}H$ mode has the largest sensitivity to κ_λ variations

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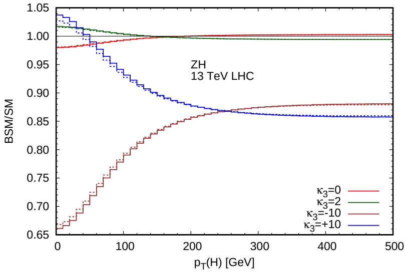
- λ_3 corrections do not fully factorise with the NLO EW contributions:

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\rm BSM}}{\sigma^{\rm SM}} = Z_H^{\rm BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\rm EW}^i}\right] \qquad K_{\rm EW}^i = \frac{\Sigma_{NLO}^{\rm SM}}{\Sigma_{LO}^{\rm SM}},$$



- At the SM EW corrections are large in the boosted regime
- Expected very small effect on the global fit by the inclusion of NLO EW correction
- Yet to be provided for each STXS bins → can be evaluated using MadGraph5_aMCNLO (see arXiv:1804.10017)

Conclusions

- Single-Higgs measurements can be used to constraint κ_λ
- First constraint on κ_λ from indirect measurement has been provided by the ATLAS and CMS
  - 95% C.L.: $-3.2 < \kappa_\lambda < 11.9$ (ATLAS) and $-3.5 < \kappa_\lambda < 14.5$ (CMS)
  - best-fit: $\kappa_\lambda = 4.0^{+4.3}_{-4.1}$ (ATLAS) and $\kappa_\lambda = 6.7^{+4.6}_{-6.6}$ (CMS)
- Results expected to improve including full Run 2 statistic for all the input analyses already considered and including additional analyses.

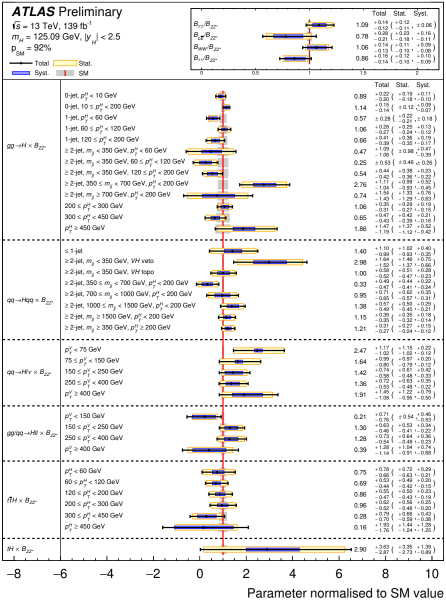
→ to be compared with *HH* full Run 2 limit:

  - ATLAS $bb\gamma\gamma$+$bb\tau\tau$: $-1.0 < \kappa_\lambda < 6.6$ ($-1.2 < \kappa_\lambda < 7.2$) [ATLAS-CONF-2021-052]

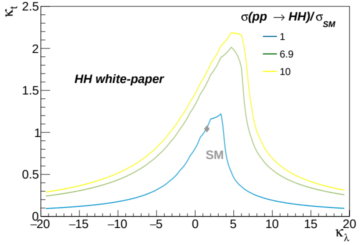
- Within LHCXSWG2 ATLAS and CMS are working to provide a common κ_λ parametrization based on STXS stage 1.2
  - Developed a common package: https://gitlab.cern.ch/LHCHIGGSXS/LHCHXSWG2/STXS/self-coupling-c1
  - Evaluated C_1 in each STXS stage 1.2 bin for *Hjj*, *WH*, *ZH*, $t\bar{t}H$
  - Preparing a documentation to share the C_1 (in a twiki or a note)

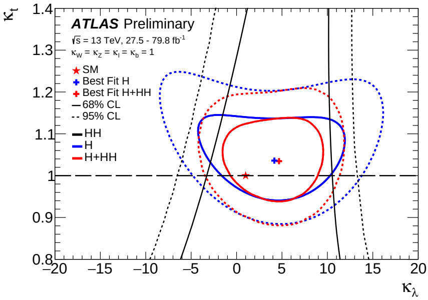
Thank you for your attention!

Bonus and back-up slides

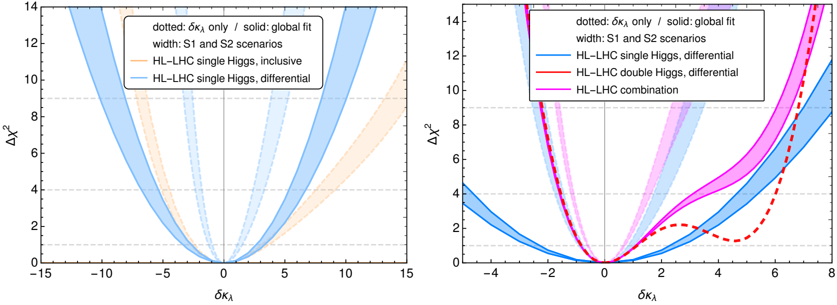

ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
p_SM = 92%
Total
Stat.
Syst.
SM
Total Stat. Syst.
B_γγ/B_ZZ* 1.09
B_bb/B_ZZ* 0.78
B_WW/B_ZZ* 1.06
B_ττ/B_ZZ* 0.86
gg→H × B_ZZ*
0-jet, p_T^H < 10 GeV 0.89
0-jet, 10 ≤ p_T^H < 200 GeV 1.14
1-jet, p_T^H < 60 GeV 0.57
1-jet, 60 ≤ p_T^H < 120 GeV 1.06
1-jet, 120 ≤ p_T^H < 200 GeV 0.66
≥ 2-jet, m_jj < 350 GeV, p_T^H < 60 GeV 0.47
≥ 2-jet, m_jj < 350 GeV, 60 ≤ p_T^H < 120 GeV 0.25
≥ 2-jet, m_jj < 350 GeV, 120 ≤ p_T^H < 200 GeV 0.54
≥ 2-jet, 350 ≤ m_jj < 700 GeV, p_T^H < 200 GeV 2.76
≥ 2-jet, m_jj ≥ 700 GeV, p_T^H < 200 GeV 0.74
200 ≤ p_T^H < 300 GeV 1.06
300 ≤ p_T^H < 450 GeV 0.65
p_T^H ≥ 450 GeV 1.86
qq→Hqq × B_ZZ*
≤ 1-jet 1.40
≥ 2-jet, m_jj < 350 GeV, VH veto 2.98
≥ 2-jet, m_jj < 350 GeV, VH topo 1.00
≥ 2-jet, 350 ≤ m_jj < 700 GeV, p_T^H < 200 GeV 0.33
≥ 2-jet, 700 ≤ m_jj < 1000 GeV, p_T^H < 200 GeV 0.95
≥ 2-jet, 1000 ≤ m_jj < 1500 GeV, p_T^H < 200 GeV 1.38
≥ 2-jet, m_jj ≥ 1500 GeV, p_T^H < 200 GeV 1.15
≥ 2-jet, m_jj ≥ 350 GeV, p_T^H ≥ 200 GeV 1.21
qq→Hlν × B_ZZ*
p_T^V < 75 GeV 2.47
75 ≤ p_T^V < 150 GeV 1.64
150 ≤ p_T^V < 250 GeV 1.42
250 ≤ p_T^V < 400 GeV 1.36
p_T^V ≥ 400 GeV 1.91
gg/qq→Hll × B_ZZ*
p_T^V < 150 GeV 0.21
150 ≤ p_T^V < 250 GeV 1.30
250 ≤ p_T^V < 400 GeV 1.28
p_T^V ≥ 400 GeV 0.39
tt̄H × B_ZZ*
p_T^H < 60 GeV 0.75
60 ≤ p_T^H < 120 GeV 0.69
120 ≤ p_T^H < 200 GeV 0.86
200 ≤ p_T^H < 300 GeV 0.96
300 ≤ p_T^H < 450 GeV 0.28
p_T^H ≥ 450 GeV 0.16
tH × B_ZZ* 2.90
−8 −6 −4 −2 0 2 4 6 8 10
Parameter normalised to SM value

- The *HH* cross section depends both on κ_t and $\kappa_\lambda \rightarrow$ cannot constrain both parameters simultaneously





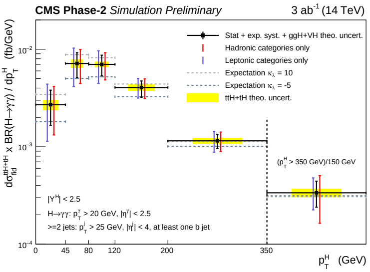
- the combination with the single–Higgs measurements allows, even for κ_λ values deviating from the SM prediction, the determination of κ_t to a sufficient precision, restoring the *HH* sensitivity to κ_λ
- the constraining power on κ_λ of the combined single and double-Higgs analyses is only slightly worse than in the κ_λ-only model

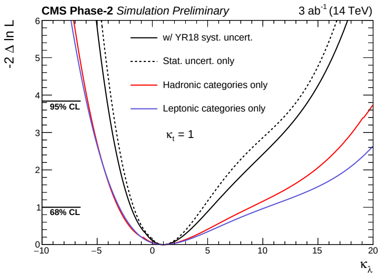


- The improvement of the indirect κ_λ constraint at HL-LH is limited by systematic uncertainties
- Larger gain in sensitivity for *HH* analyses that are currently limited by statistic uncertainties
- κ_λ measurement from single-Higgs is still very important to resolve the second minimum in *HH* likelihood shape

$t\bar{t}H + tH$, $H \to \gamma\gamma$ differential cross-section

- Constraint on κ_λ from $t\bar{t}H + tH$, $H \to \gamma\gamma$ differential cross section measurements at the HL-LHC with the CMS Phase-2 detector
- 95% C.L.: $-4.1 < \kappa_\lambda < 14.1$





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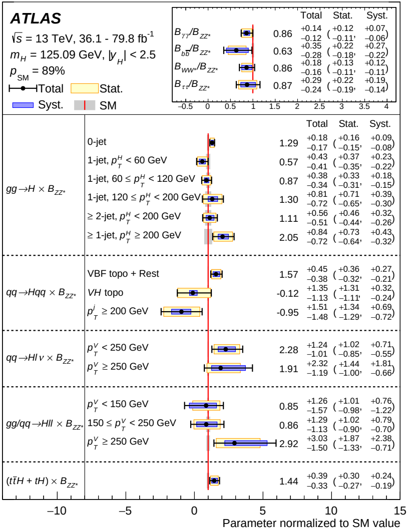
STXS region		VBF	WH	ZH
		$C_1^i \times 100$		
$VBF + V(\text{had})H$	$VBF\text{-cuts} + p_T^{j1} < 200$ GeV, $\leq 2j$	0.63	0.91	1.07
	$VBF\text{-cuts} + p_T^{j1} < 200$ GeV, $\geq 3j$	0.61	0.85	1.04
	$VH\text{-cuts} + p_T^{j1} < 200$ GeV	0.64	0.89	1.10
	no VBF/VH-cuts, $p_T^{j1} < 200$ GeV	0.65	1.13	1.28
	$p_T^{j1} > 200$ GeV	0.39	0.23	0.28
$qq \to H\ell\nu$	$p_T^V < 150$ GeV		1.15	
	$150 < p_T^V < 250$ GeV, $0j$		0.18	
	$150 < p_T^V < 250$ GeV, $\geq 1j$		0.33	
	$p_T^V > 250$ GeV		0	
$qq \to H\ell\ell$	$p_T^V < 150$ GeV			1.33
	$150 < p_T^V < 250$ GeV, $0j$			0.20
$qq \to H\nu\nu$	$150 < p_T^V < 250$ GeV, $\geq 1j$			0.39
	$p_T^V > 250$ GeV			0

Granularity	$\kappa_\lambda {}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
STXS	$4.0^{+4.3}_{-4.1}$	$[-3.2, 11.9]$
	$1.0^{+8.8}_{-4.4}$	$[-6.2, 14.4]$
inclusive	$4.6^{+4.3}_{-4.2}$	$[-2.9, 12.5]$
	$1.0^{+9.5}_{-4.3}$	$[-6.1, 15.0]$



- It is possible to use normalization modifiers

$$\mu_i^f(\kappa_\lambda) \equiv \mu_i(\kappa_\lambda) \times \mu^f(\kappa_\lambda)$$

- $\mu_i(\kappa_\lambda)$:

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}} = Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\mathrm{EW}}^i}\right],$$

where $\kappa_i = \kappa_{\mathrm{F}}, \kappa_{\mathrm{V}}$ and $Z_H^{\mathrm{BSM}}(\kappa_\lambda)$ is defined as:

$$Z_H^{\mathrm{BSM}}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H} \quad \text{with} \quad \delta Z_H = -1.536 \times 10^{-3},$$

- where term of the type $k_i^2 \kappa_\lambda$ are neglected and terms like $k_i^2 \kappa_\lambda^2$ are accounted by the $Z_H^{\mathrm{BSM}} k_i^2$ term.
- $\mu_f(\kappa_\lambda)$:

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\mathrm{BSM}}}{\mathrm{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\mathrm{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

Constraining κ_λ through a global fit (2)

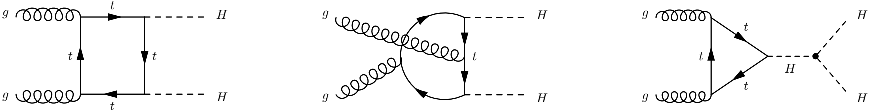
- Considering inclusively the Higgs boson production modes and decay channels:

production mode	ggF	VBF	ZH	WH	$t\bar{t}H$
$C_1^i \times 100$	0.66	0.63	1.19	1.03	3.52
K_{EW}^i	1.049	0.932	0.947	0.93	1.014
κ_i^2	κ_F^2	κ_V^2	κ_V^2	κ_V^2	κ_F^2

decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2

Double Higgs cross-section

- The SM $\sigma_{\rm ggF}(pp \to HH)$ accounts for more than 90% of the Higgs boson pair production cross-section
- It proceeds via two amplitudes: the first ($\mathcal{A}_1$) represented by the top-box diagrams and the second ($\mathcal{A}_2$) represented by the top-triangle diagram.



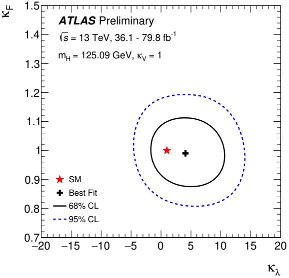
- $\mathcal{A}_1$ proportional to y_t^2 and $\mathcal{A}_2$ to the product of y_t and λ_3. The BSM HH amplitude can then be written as:

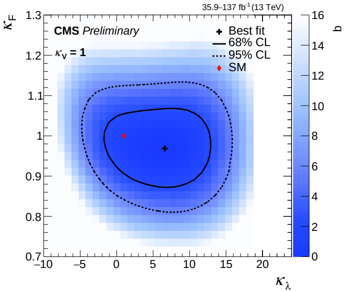
$$\mathcal{A}(\kappa_t, \kappa_\lambda) = \kappa_t^2 \mathcal{A}_1 + \kappa_t \kappa_\lambda \mathcal{A}_2 \,.$$

- omitting the integral on the final phase space and on the PDFs for simplicity, the ggF double-Higgs cross section $\sigma_{\rm ggF}(pp \to HH)$ can be expressed as:

$$\sigma_{\rm ggF}(pp \to HH) \sim \kappa_t^4 \left[|\mathcal{A}_1|^2 + 2\frac{\kappa_\lambda}{\kappa_t} \Re \mathcal{A}_1^* \mathcal{A}_2 + \left(\frac{\kappa_\lambda}{\kappa_t}\right)^2 |\mathcal{A}_2|^2 \right] \,.$$

- Fit using κ_λ and κ_{F} parameter and setting $\kappa_{\mathrm{V}} = 1$

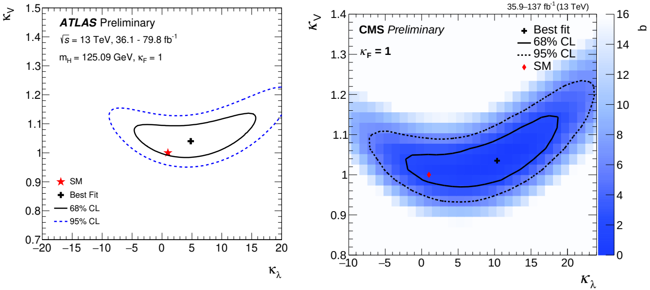




		$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
ATLAS	Obs.	$4.1^{+4.3}_{-4.1}$	$[-3.2, 11.9]$
	Exp.	$1.0^{+8.8}_{-4.4}$	$[-6.3, 14.4]$
CMS	Obs.	$6.6^{+4.5}_{-6.1}$	$[-3.3, 14.4]$
	Exp.	$1.0^{+8.2}_{-4.0}$	$[-5.5, 13.8]$

- the sensitivity to κ_λ is not much degraded when determining κ_F

- Fit using κ_λ and κ_V parameter and setting $\kappa_F = 1$

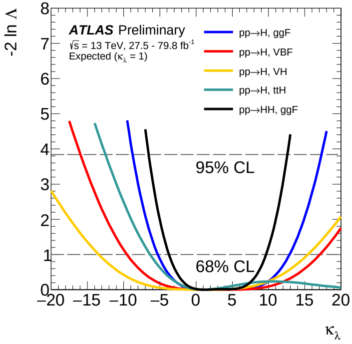


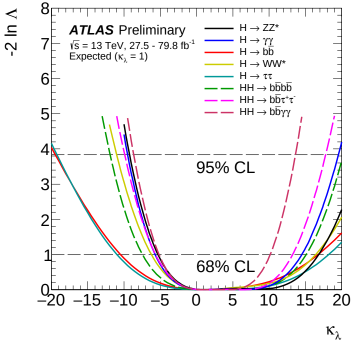
		$\kappa_{\lambda}{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
ATLAS	Obs.	$4.8^{+7.4}_{-6.7}$	$[-6.7, 18.4]$
	Exp.	$1.0^{+9.9}_{-6.1}$	$[-9.4, 18.9]$
CMS	Obs.	$10.3^{+6.1}_{-10.0}$	$[-5.5, 21.7]$
	Exp.	$1.0^{+8.8}_{-5.0}$	$[-7.4, 17.2]$

- the sensitivity to κ_λ is degraded by 50% when determining κ_V
- Fitting κ_λ-κ_V-κ_F or fitting κ_λ-$\kappa_H = \kappa_V = \kappa_F$ results in nearly no sensitivity to κ_λ

Contribution to the combination

- The global likelihood shape depends on combining the contributions from the different production and decay modes





- The expected (on Asimov) dominant contributions to the combination arises from the combined *HH* channels, from ggF single Higgs production mode, and $t\bar{t}H$ for the negative values of κ_λ .
- The double Higgs analyses set the strongest constraint on κ_λ.
- $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ are almost comparable with di-higgs analyses (also because of larger integrated luminosity)