Direct and indirect constraints on the Higgs boson self coupling

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on behalf of the ATLAS and CMS collaborations

LHCP 2020

- Given the Higgs scalar potential:

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

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

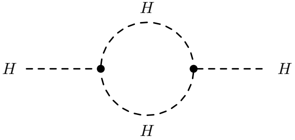
$$\lambda_3 = \lambda_4 = \lambda^{SM} = \frac{m_H^2}{2\nu^2} \qquad \text{and} \qquad \lambda_i = 0, \quad \text{for } i \geq 5$$

- new physics could modify the Higgs potential altering the λ_3 without affecting m_H or ν: 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
  - constraints from ATLAS *HH* at 36 fb^{-1}: $-5.0 < \lambda_3/\lambda_3^{SM} < 12.0$ at 95% C.L. (Exp. $-5.8 < \lambda_3/\lambda_3^{SM} < 12.0$)
  - constraints from CMS *HH* at 36 fb^{-1}: $-11.8 < \lambda_3/\lambda_3^{SM} < 18.8$ at 95% C.L. (Exp. $-7.1 < \lambda_3/\lambda_3^{SM} < 13.6$)

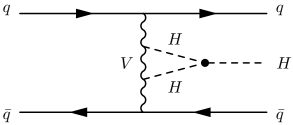
→ There are also processes that are indirectly sensitive to λ_3: single-Higgs production mode

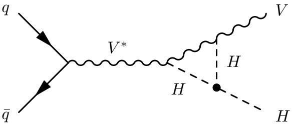
Higgs Self-Coupling constraint from single Higgs analyses

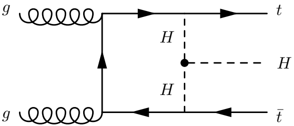
- Single Higgs processes do not depend on trilinear-coupling λ_3 at LO
- Two types of NLO EW corrections that depend on λ_3
  - one universal $O(\lambda_3^2)$ due to Higgs loops



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





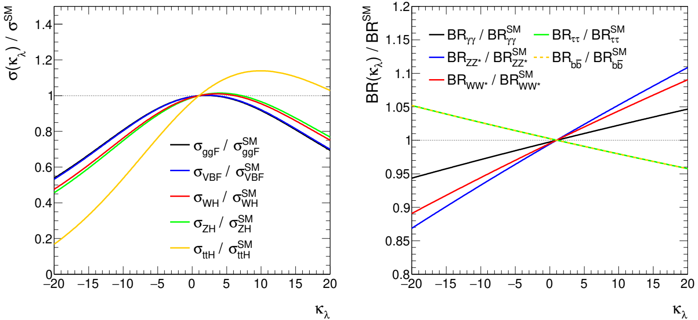


- Following λ_3 corrections each production mode cross-section and decay branching ratio varies as a function of $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$.

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

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

where κ_i and κ_f are additional coupling modifiers such as $\kappa_{\rm F}$ (Higgs to fermions coupling modifier), $\kappa_{\rm V}$ (Higgs to W/Z coupling modifier)



Differential distributions and λ_3 corrections

- 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

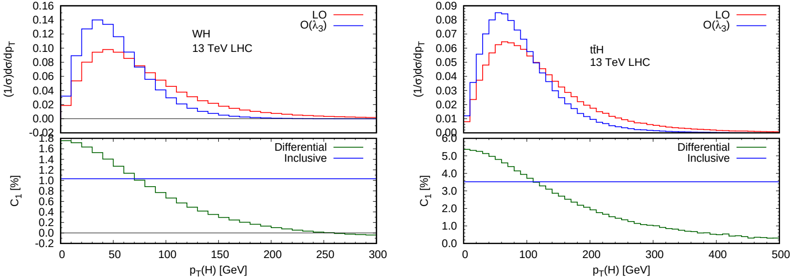


Figure: for λ_3 at the SM value

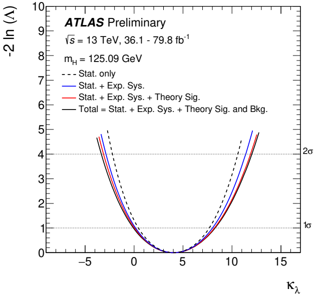
- Interpretation of single Higgs boson analyses using signal strength depending on κ_λ:

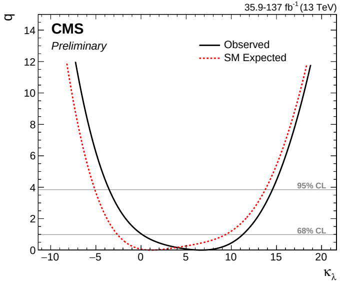
$$\mu_i^f(\kappa_\lambda) \equiv \mu_i(\kappa_\lambda) \times \mu^f(\kappa_\lambda)$$

- CMS considered inclusive
  - production cross-section: $\mu_{\mathrm{ggF}}(\kappa_\lambda), \mu_{\mathrm{VBF}}(\kappa_\lambda), \mu_{WH}(\kappa_\lambda), \mu_{ZH}(\kappa_\lambda), \mu_{t\bar{t}H}(\kappa_\lambda)$
  - 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	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

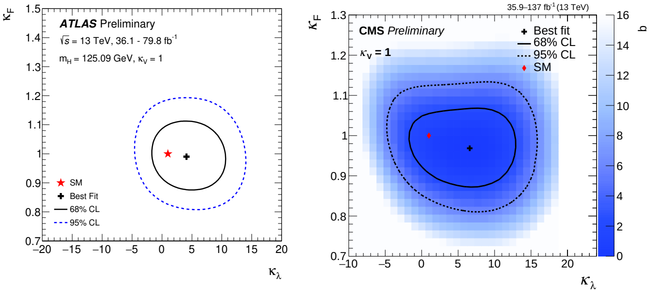




		$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
ATLAS	Observed	$4.0^{+4.3}_{-4.1}$	$[-3.2, 11.9]$
	Expected	$1.0^{+8.8}_{-4.4}$	$[-6.2, 14.4]$
CMS	Observed	$6.7^{+4.6}_{-6.6}$	$[-3.5, 14.5]$
	Expected	$1.0^{+8.3}_{-3.8}$	$[-5.1, 13.7]$

- complementary to the limit from *HH* 36.1 fb^{-1} combination:
  - ATLAS: $-5.0 < \kappa_\lambda < 12.1$ CMS: $-11.8 < \kappa_\lambda < 18.8$

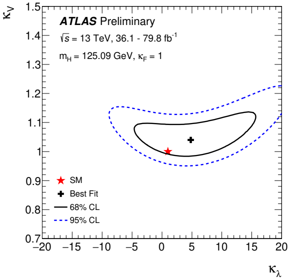
- Fit using κ_λ and κ_F parameter and setting $\kappa_V = 1$

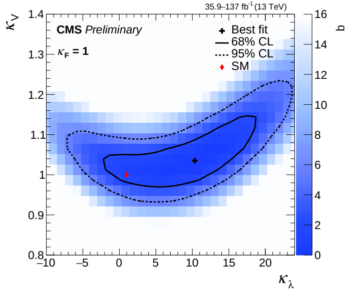


		$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
ATLAS	Obs.	$4.1^{+4.3}_{-4.1}$	$[-3.2, 11.9]$
	Exp.	$1.0^{+8.8}_{-4.4}$	$[-6.3, 14.4]$
CMS	Obs.	$6.6^{+4.5}_{-6.1}$	$[-3.3, 14.4]$
	Exp.	$1.0^{+8.2}_{-4.0}$	$[-5.5, 13.8]$

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

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





		$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	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.	$1.0^{+8.8}_{-5.0}$	$[-7.4, 17.2]$

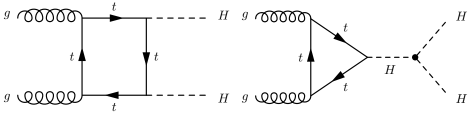
- the sensitivity to κ_λ is degraded by 50% when determining κ_V
- Fitting κ_λ-κ_V-κ_F or fitting κ_λ-$\kappa_H = \kappa_V = \kappa_F$ results in nearly no sensitivity to κ_λ

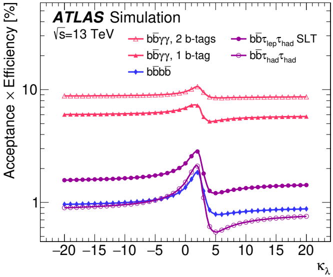
Higgs Self-Coupling constraint
from the combination of single and double Higgs analyses

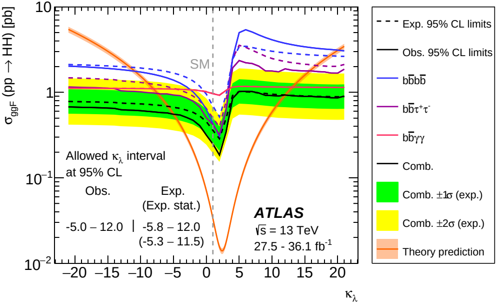
DiHiggs constraint on κ_λ

Phys. Lett. B 800 (2020) 135103

- Double Higgs production directly sensitive to Higgs boson self-coupling



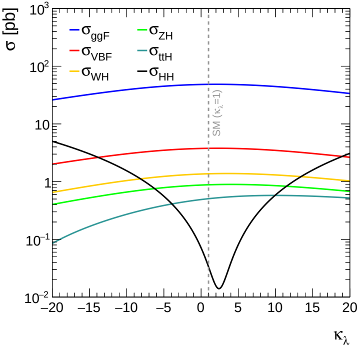




- Observed 95% C.L.: $-5.0 < \kappa_\lambda < 12.0$
- Expected 95% C.L.: $-5.8 < \kappa_\lambda < 12.0$

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

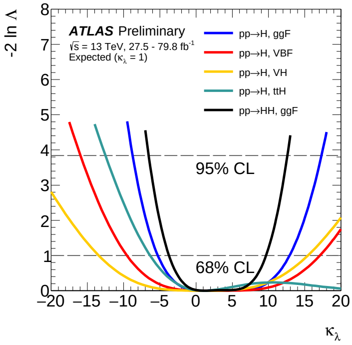
Analysis	L [fb^{-1}]
$H \to \gamma\gamma$	79.8
$H \to ZZ^* \to 4\ell$	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
$VH,\ H \to b\bar{b}$	79.8
$t\bar{t}H,\ H \to b\bar{b}$	36.1
$t\bar{t}H$ multilepton	36.1
$HH \to bbbb$	36.1
$HH \to bb\gamma\gamma$	36.1
$HH \to bb\tau\tau$	36.1

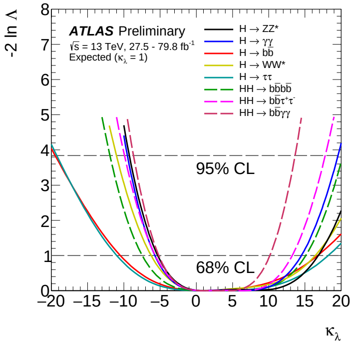


- Single-Higgs contributions in di-Higgs analysis parameterised as a function of κ_λ.
- $t\bar{t}H \to \gamma\gamma$ contribution excluded because of a large overlap with $HH \to bb\gamma\gamma$ analysis (up to 50% of the events)
- The remaining categories have a maximum overlap of less than 2%

Contribution to the combination

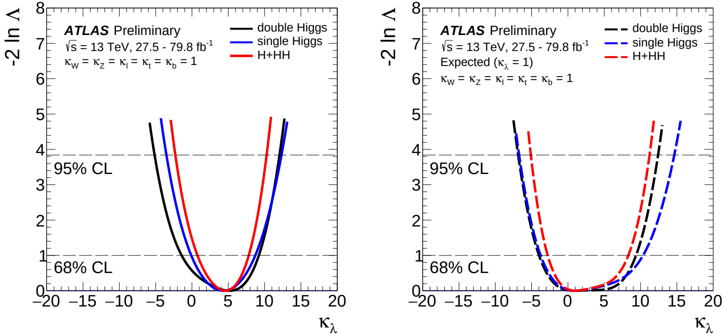
- The global likelihood shape depends on combining the contributions from the different production and decay modes





- 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.
- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ are almost comparable with di-higgs analyses (also because of larger integrated luminosity)

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



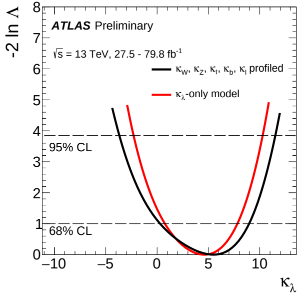
$$\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.6^{+2.9}_{-3.5}\,(\text{stat.})\,^{+1.2}_{-1.2}\,(\text{exp.})\,^{+0.7}_{-0.5}\,(\text{sig. th.})\,^{+0.6}_{-1.0}\,(\text{bkg. th.})$$

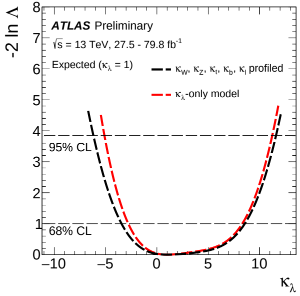
- 95% C.L. : $-2.3 < \kappa_\lambda < 10.3$ (observed), $-5.1 < \kappa_\lambda < 11.2$ (expected)
- The combination significantly improves the constraining power on κ_λ.

Results Generic model

ATLAS-CONF-2019-049

- 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 Higgs boson 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.

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)

→ comparable with HH results at $L = 36\ \text{fb}^{-1}$: $-5.0 < \kappa_\lambda < 12.0$ (ATLAS) and $-11.8 < \kappa_\lambda < 18.8$ (CMS)

- ATLAS collaboration has provided a more stringent constraint combining single and double-higgs measurements:
  - 95% C.L.: $-2.3 < \kappa_\lambda < 10.3$
  - best-fit: $\kappa_\lambda = 4.6^{+3.2}_{-3.8}$
- Combining the direct and indirect measurement allows to test generic model where several parameters are floated together with κ_λ
  - fitting κ_λ, κ_W, κ_Z, κ_ℓ, κ_b, κ_t 95% C.L.: $-3.7 < \kappa_\lambda < 11.5$
  - substantial constraints on κ_λ even in this more generic model.

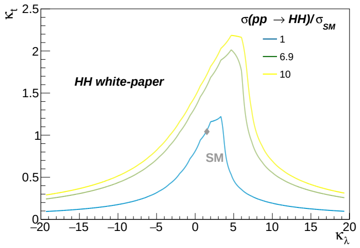
Thank you for your attention!

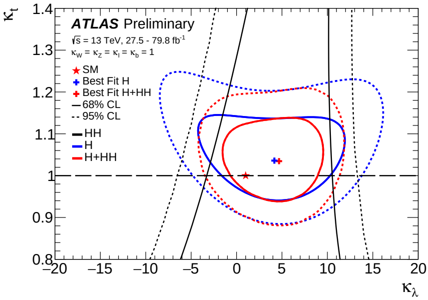
I am available for additional discussion, Zoom meeting following this session:

- ID: 923 4908 0316 https://cern.zoom.us/j/92349080316
- Password: same as for this session

Bonus and back-up slides

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

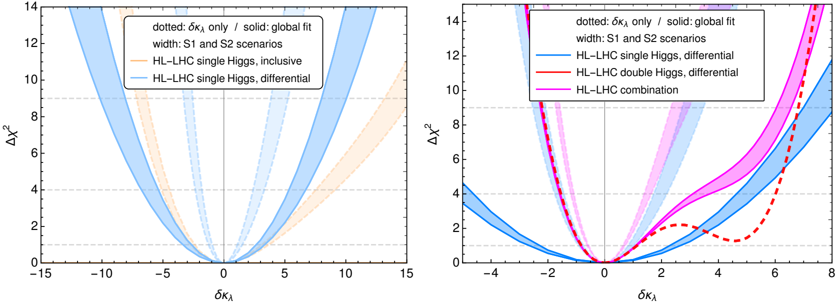




- the combination with the single–Higgs measurements allows, even for κ_λ values deviating from the SM prediction, the determination of κ_t to a sufficient precision, restoring the *HH* sensitivity to κ_λ
- the constraining power on κ_λ of the combined single and double-Higgs analyses is only slightly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

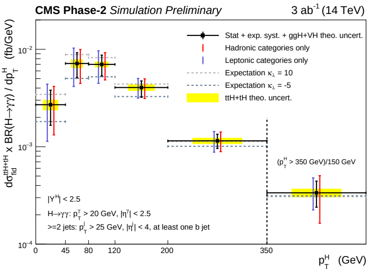
Higgs boson self-coupling at HL-LHC

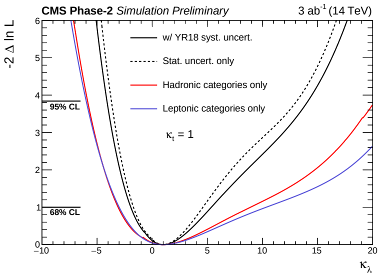
CERN-LPCC-2018-04



- 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

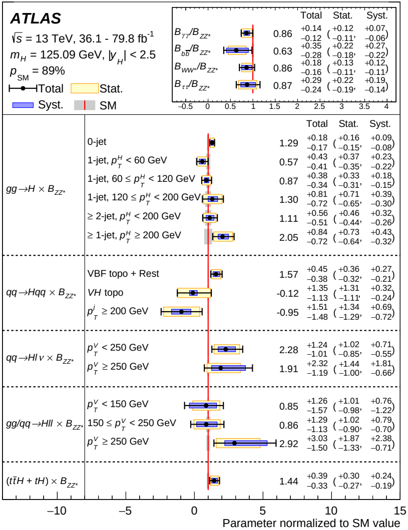
- Constraint on κ_λ from $t\bar{t}H + tH$, $H \to \gamma\gamma$ differential cross section measurements at the HL-LHC with the CMS Phase-2 detector
- 95% C.L.: $-4.1 < \kappa_\lambda < 14.1$





	STXS region	VBF	WH	ZH
		$C_1^i \times 100$		
$VBF+V(\text{had})H$	$V\text{BF-cuts} + p_T^{j1} < 200$ GeV, $\leq 2j$	0.63	0.91	1.07
	$V\text{BF-cuts} + p_T^{j1} < 200$ 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	$4.6^{+4.3}_{-4.2}$	$[-2.9, 12.5]$
	$1.0^{+9.5}_{-4.3}$	$[-6.1, 15.0]$



Constraining κ_λ through a global fit (1)

- It is possible to use normalization modifiers

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

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

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

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

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

- 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 $Z_H^{\rm BSM}k_i^2$ term.
- $\mu_f(\kappa_\lambda)$:

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

Constraining κ_λ through a global fit (2)

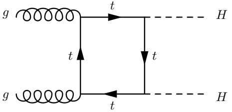
- Considering inclusively the Higgs boson production modes and decay channels:

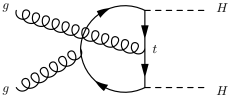
production mode	ggF	VBF	ZH	WH	$t\bar{t}H$
$C_1^i \times 100$	0.66	0.63	1.19	1.03	3.52
K_{EW}^i	1.049	0.932	0.947	0.93	1.014
κ_i^2	κ_F^2	κ_V^2	κ_V^2	κ_V^2	κ_F^2

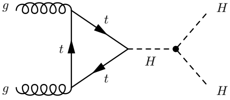
decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2

Double Higgs cross-section

- The SM $\sigma_{\mathrm{ggF}}(pp \to HH)$ 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 $\sigma_{\mathrm{ggF}}(pp \to HH)$ can be expressed as:

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