Constraining the Higgs boson self-coupling from single-Higgs and the combination of single-Higgs and double-Higgs

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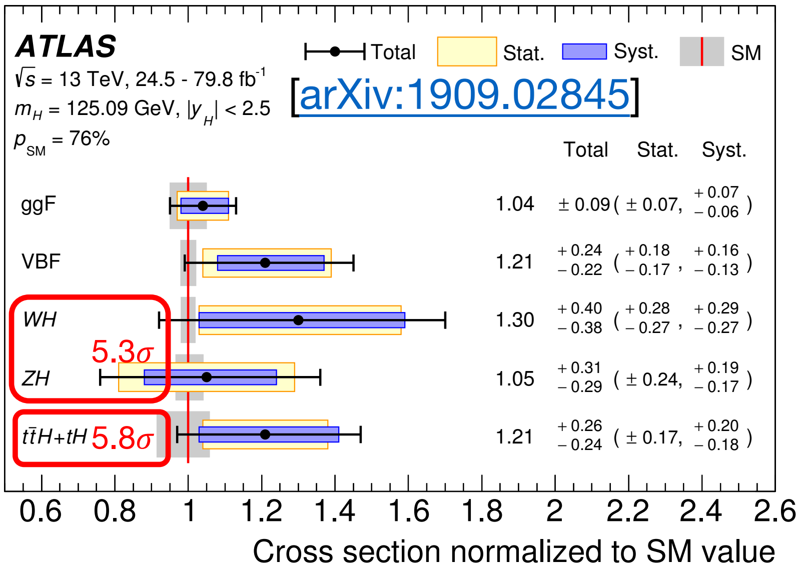
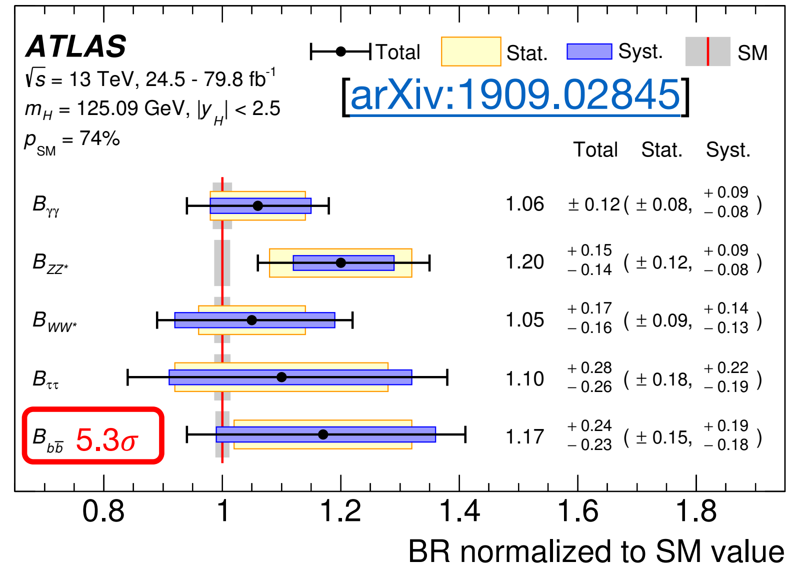
Outline

- Constraints on the Higgs self-coupling from the single-Higgs analyses
- Constraints on the Higgs self-coupling from the combination of the single-Higgs and double-Higgs analyses

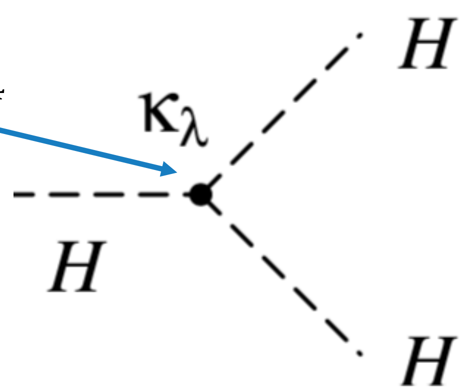
Introduction

- During Run2 data taking, the Higgs production processes and decays have been measured with an increasing precision
  - VH, ttH; $H \rightarrow bb$ were discovered during Run2





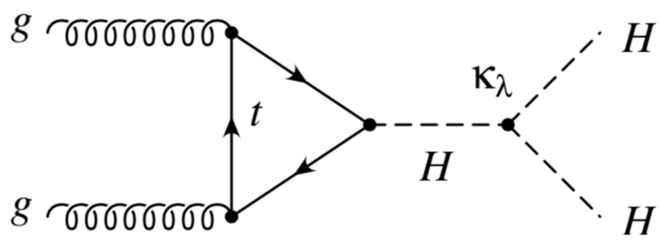
$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$



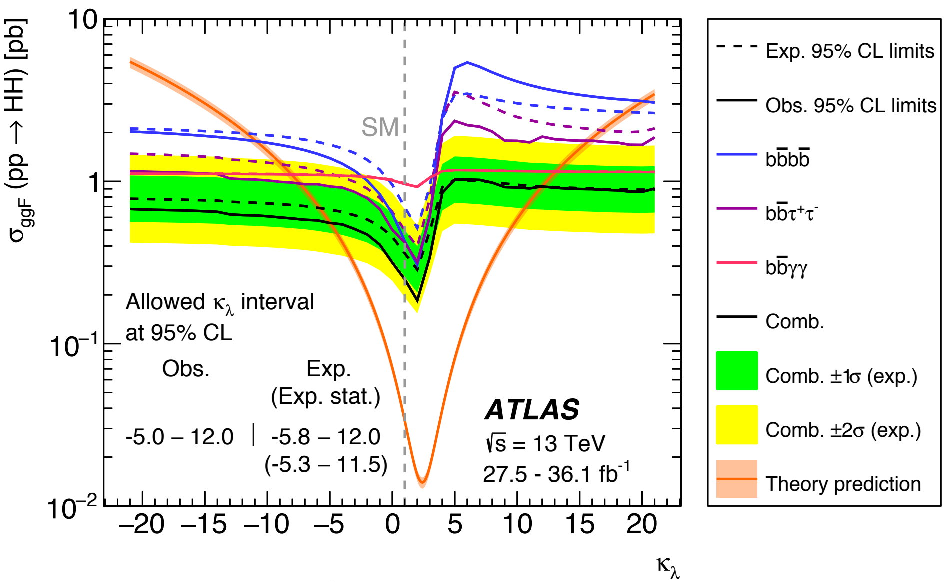
- The properties of the Higgs scalar potential, in particular the Higgs boson self-coupling, are still largely unconstrained

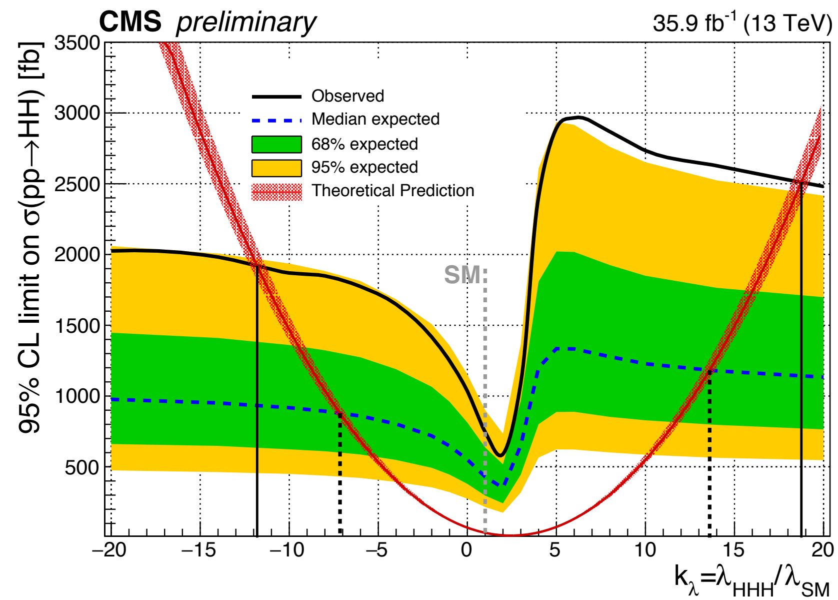
Latest results in the HH measurement

- The non-resonant HH production processes (ggF) provide a unique chance to probe $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ with direct measurements



- Constrain the κ_λ by estimating the upper limits of the HH production (assuming SM H decay) with CLs approach



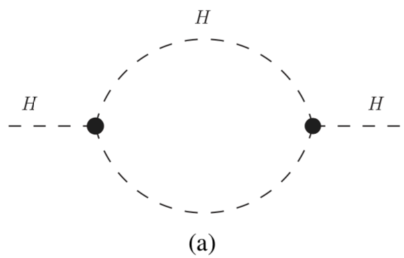


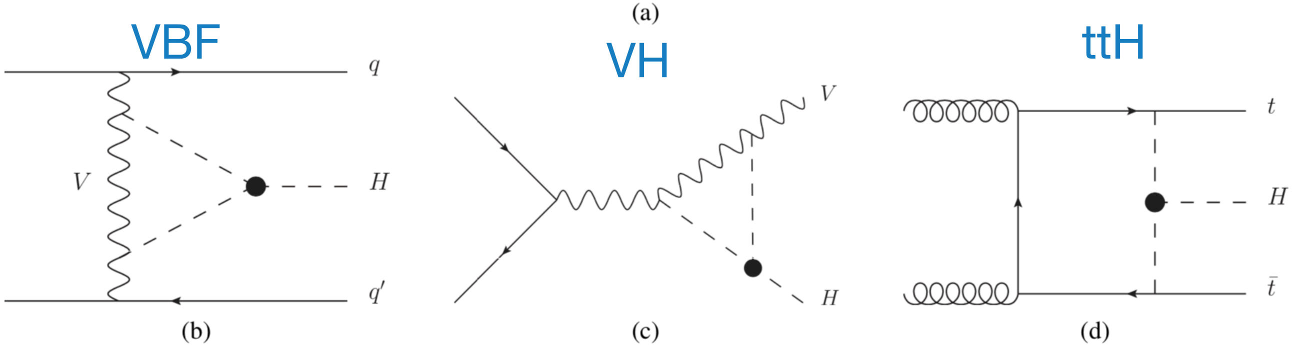
95% CL	Obs.	Exp.
ATLAS [arXiv:1906.02025]	[-5.0, 12.0]	[-5.8, 12.0]
CMS [CMS-PAS-HIG-17-030]	[-11.8, 18.8]	[-7.1, 13.6]

Indirect measurement in the single-H

- Single Higgs processes do not depend on λ_{HHH} at LO, while its contributions need to be taken into account for the complete NLO EWK corrections
- λ_{HHH} contributes via Higgs self energy loop corrections and additional diagrams

[arXiv: 1607.04251]
[arXiv: 1709.08649]

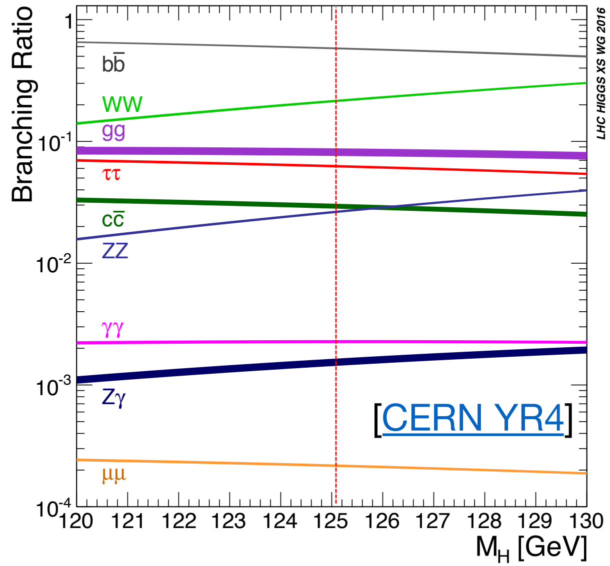




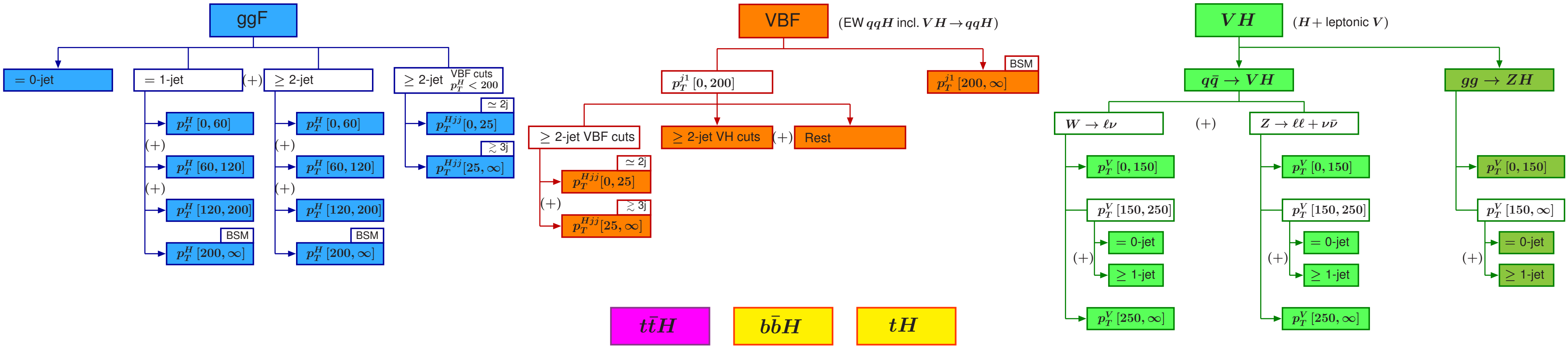
- An indirect constraint on λ_{HHH} can be extracted by comparing the single-Higgs measured results and the SM predictions corrected for the λ_{HHH} -dependent NLO EW effects
  - Signal strength: $\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda) \equiv \frac{\sigma_i(\kappa_\lambda)}{\sigma_{SM,i}} \times \frac{BR_f(\kappa_\lambda)}{BR_{SM,f}}$

Data and input measurement

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	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
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1



- Higgs couplings measurements separate production processes and kinematic regions using the simplified template cross section (STXS) framework, YR4
- The analysis categories are designed to maximize the sensitivity to each truth-level region defined within the framework



Theoretical model: production mode

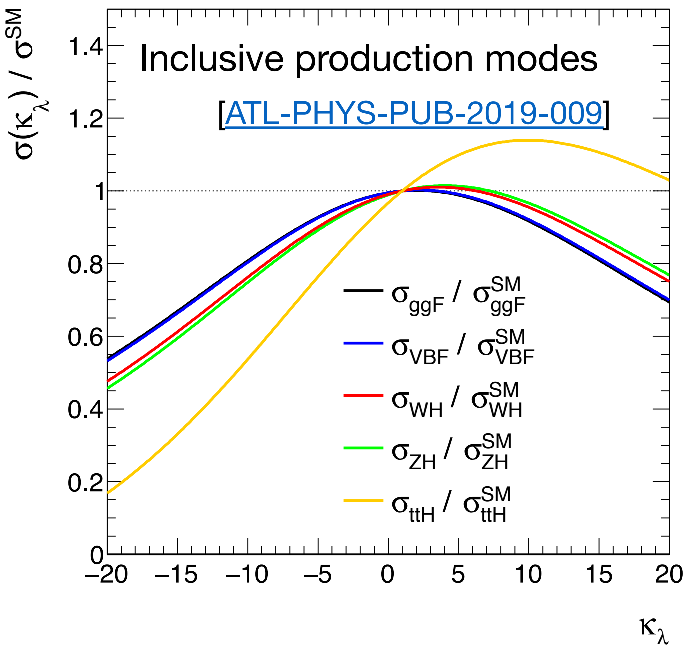
$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{BSM}}{\sigma^{SM}} = Z_H^{BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{EW}^i}\right]$$

$$Z_H^{BSM}(\kappa_\lambda) = \frac{1}{1-(\kappa_\lambda^2-1)\delta Z_H}, \; \delta Z_H = -1.536\times10^{-3}$$

- $K_{EW}^i = \frac{\sigma_{NLO}^{SM,i}}{\sigma_{LO}^{SM,i}}$: Complete NLO EW correction for the production
- C_1^i: process and kinematics-dependent linear coefficient that provides the sensitivity of the measurement to κ_λ
- $\kappa_i^2 = \frac{\sigma_{LO,i}^{BSM}}{\sigma_{LO,i}^{SM}}$: Modifiers to other Higgs boson couplings in the κ-framework
    - Only κ_F (all fermions) and κ_V (all weak vector bosons) are considered

[arXiv: 1607.04251]
[arXiv: 1709.08649]

production mode	ggF	VBF	ZH	WH	$t\bar{t}H$
inclusive $C_1^i \times 100$	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



Theoretical model: decay rate

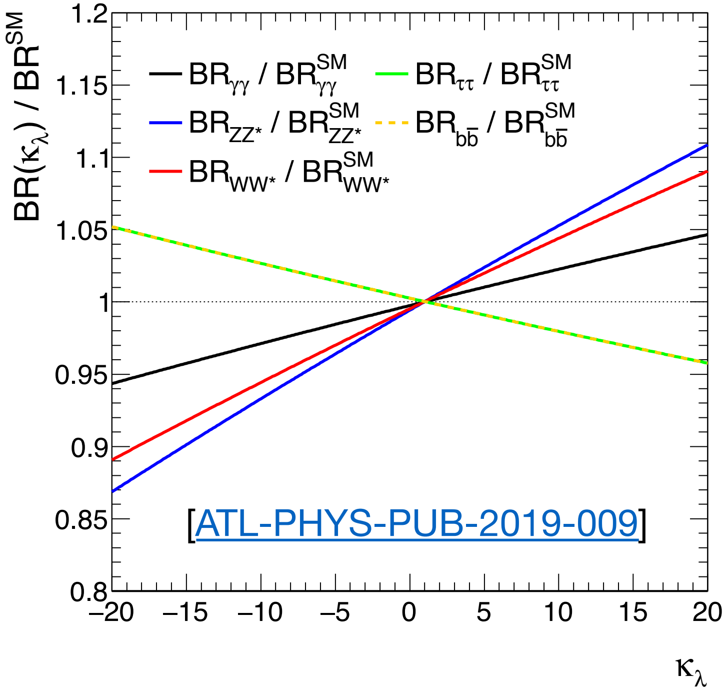
- Higgs boson decay rates

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

- C_1^f: linear coefficient provides the sensitivity to κ_λ

[arXiv: 1607.04251]
[arXiv: 1709.08649]

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



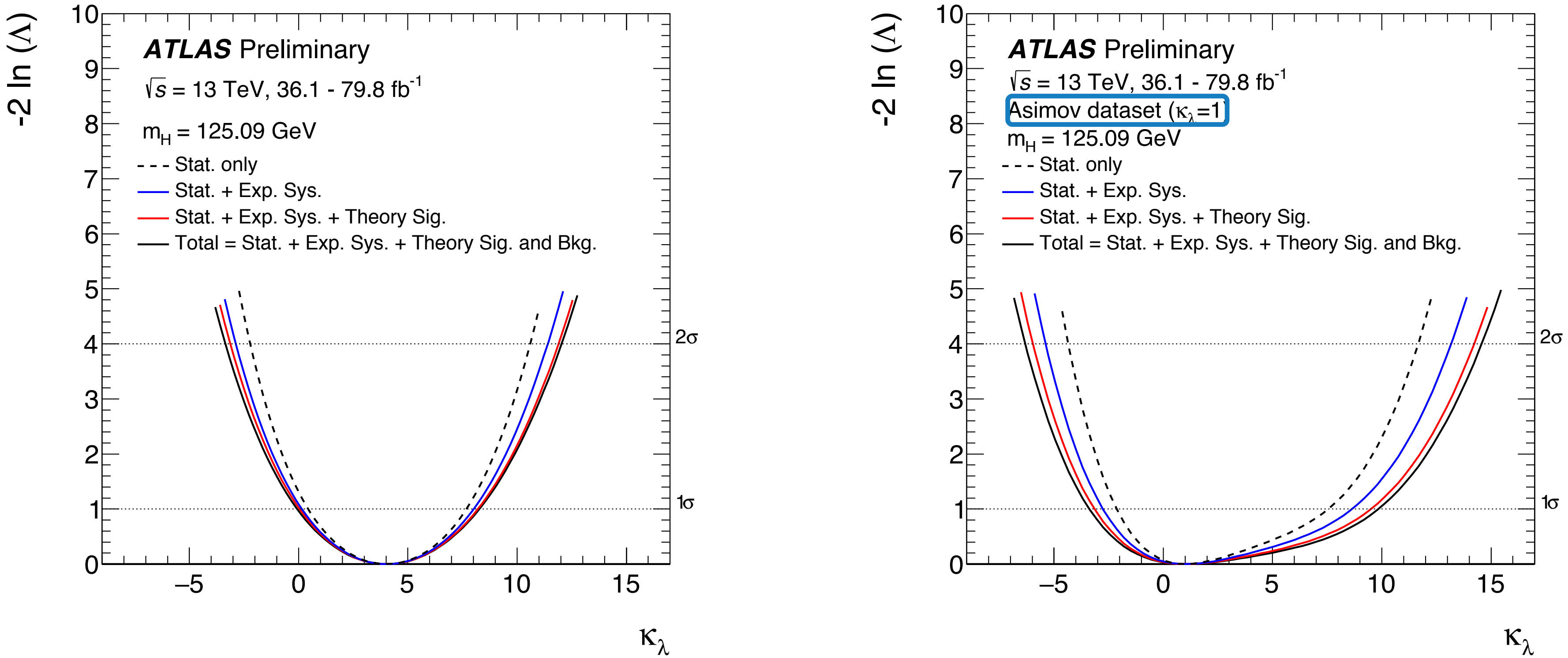
Kinematic dependence of κ_λ

- A more differential description (i.e STXS w.r.t the inclusive production processes) of the dependence on κ_λ can help
  - To reduce the potential bias on the determination of κ_λ
  - To further increase the sensitivity to κ_λ

- The dependence is considered by exploiting cross-sections in the STXS stage-1 framework
- The analysis estimated dependence in the VBF, ZH and WH
  - Re-deriving the kinematic dependent coefficients C_1^i in stage 1 truth bins
- Differential κ_λ corrections are not yet available for ggF, because these involve higher order calculations including two loop corrections
- The measurement for the ttH are inclusive so far

κ_λ-only results

- A likelihood fit is performed to constrain the Higgs boson self-coupling κ_λ in the single-Higgs measurement
  - Theory validity range [arXiv: 1607.04251]: $-20 < \kappa_\lambda < 20$



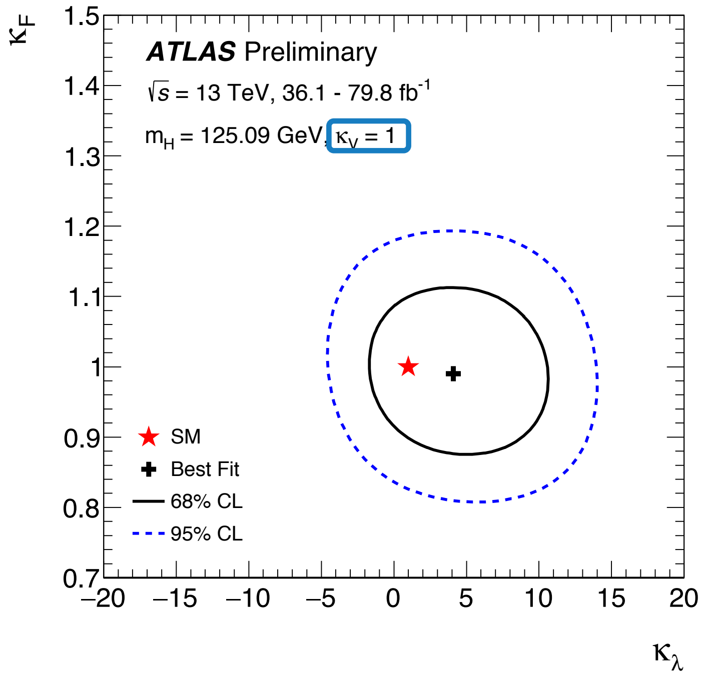
- Best fit: $\kappa_\lambda = 4.0^{+4.3}_{-4.1} = 4.0^{+3.7}_{-3.6}(stat.)^{+1.6}_{-1.5}(exp.)^{+1.3}_{-0.9}(sig.th.)^{+0.8}_{-0.9}(bkg.th.)$

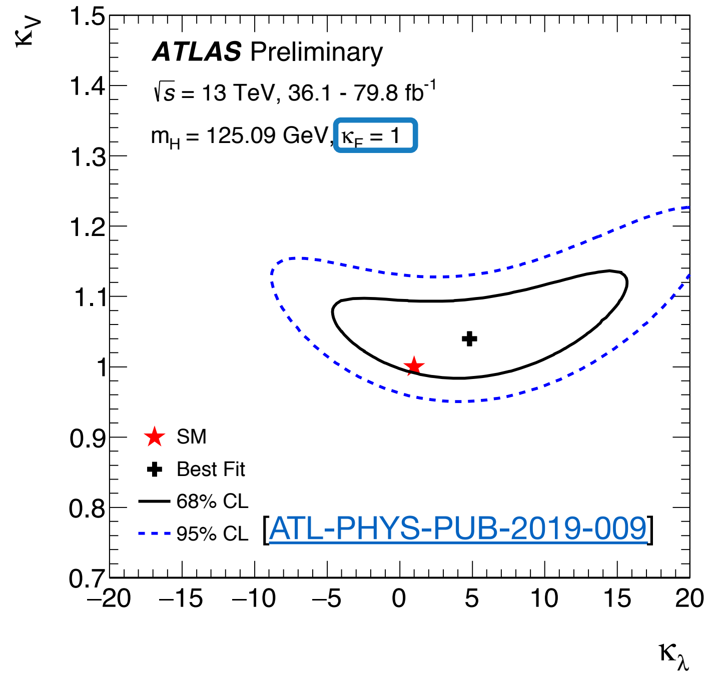
95% CL	Obs.	Exp.
H [ATL-PHYS-PUB-2019-009], up to 80 /fb	[-3.2, 11.9]	[-6.2, 14.4]
HH [arXiv:1906.02025], up to 36 /fb	[-5.0, 12.0]	[-5.8, 12.0]

- The sensitivity from single-Higgs and double-Higgs is similar

κ_λ and κ_F, κ_λ and κ_V fits

- A simultaneous fit is performed to κ_λ and κ_F ($\kappa_V = 1$), κ_λ and κ_V ($\kappa_F = 1$)
- These fits target scenarios where new physics could affect only the Yukawa type terms ($\kappa_V = 1$) or only the couplings to vector bosons ($\kappa_F = 1$), in addition to the Higgs boson self-coupling (κ_λ)





[ATL-PHYS-PUB-2019-009]

- The sensitivity to κ_λ is not much degraded when determining κ_F at the same time
- While it's degraded by 50% when determining κ_V simultaneously

POIs	Granularity	$\kappa_F{}^{+1\sigma}_{-1\sigma}$	$\kappa_V{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]	
κ_λ	STXS	1	1	$4.0^{+4.3}_{-4.1}$	[−3.2, 11.9]	Obs
				$1.0^{+8.8}_{-4.4}$	[−6.2, 14.4]	Exp
κ_λ, κ_V	STXS	1	$1.04^{+0.05}_{-0.04}$	$4.8^{+7.4}_{-6.7}$	[−6.7, 18.4]	
			$1.00^{+0.05}_{-0.04}$	$1.0^{+9.9}_{-6.1}$	[−9.4, 18.9]	
κ_λ, κ_F	STXS	$0.99^{+0.08}_{-0.08}$	1	$4.1^{+4.3}_{-4.1}$	[−3.2, 11.9]	
		$1.00^{+0.08}_{-0.08}$		$1.0^{+8.8}_{-4.4}$	[−6.3, 14.4]	

- Combine single-Higgs and double-Higgs together to maximize the sensitivity to constrain κ_λ

Data and input measurement

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
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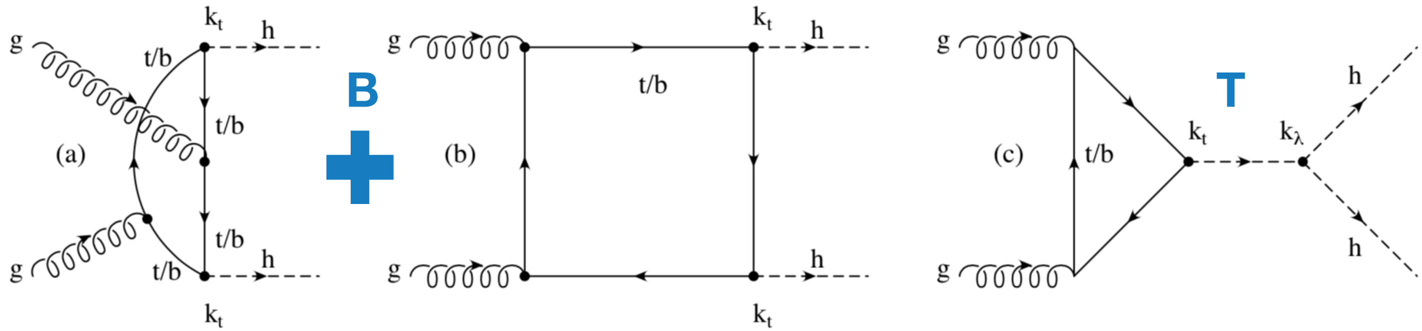
VH, $H \to b\bar{b}$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$HH \to b\bar{b}b\bar{b}$	27.5
$HH \to b\bar{b}\tau^+\tau^-$	36.1
$HH \to b\bar{b}\gamma\gamma$	36.1

- Within each of the single-Higgs and the double-Higgs analyses all the categories are orthogonal by definition
- The single-Higgs and double-Higgs categories are not all orthogonal
  - The overlap has been studied, the $ttH(\gamma\gamma)$ categories have been removed as they show large overlap with the $HH \to bb\gamma\gamma$ categories
  - Also the impact on the combined limits of removing $ttH(\gamma\gamma)$ categories is smaller w.r.t removing $HH \to bb\gamma\gamma$ categories

Theory model and interpretation in the double-Higgs

- The double-Higgs production



- The amplitude of the HH production can be parameterized as a function of ttH coupling $\kappa_t = g_{ttH}/g_{ttH}^{SM}$ and HHH coupling $\kappa_\lambda = g_{HHH}/g_{HHH}^{SM}$

$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$$

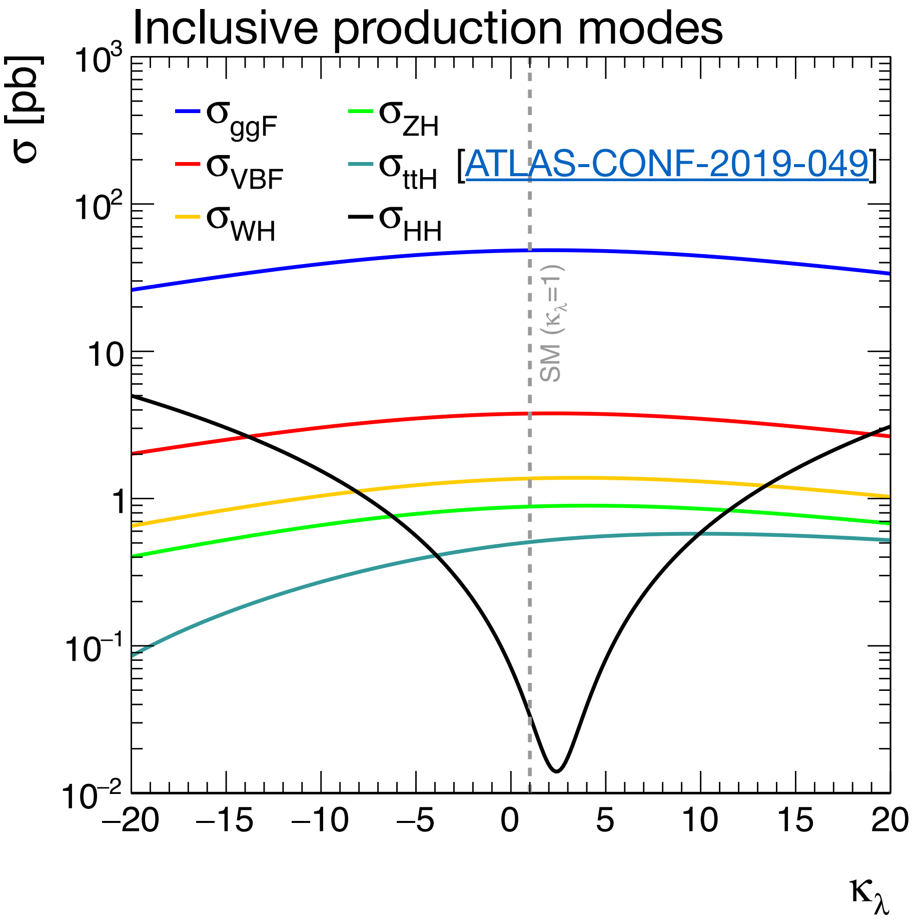
- Omitting the integral on the final phase space and on the PDFs for simplicity
- $\sigma(pp \to HH) \sim \kappa_t^4 \left[|B|^2 + \frac{\kappa_\lambda}{\kappa_t}(B^* T + T B^*) + \left(\frac{\kappa_\lambda}{\kappa_t}\right)^2 |T|^2 \right]$

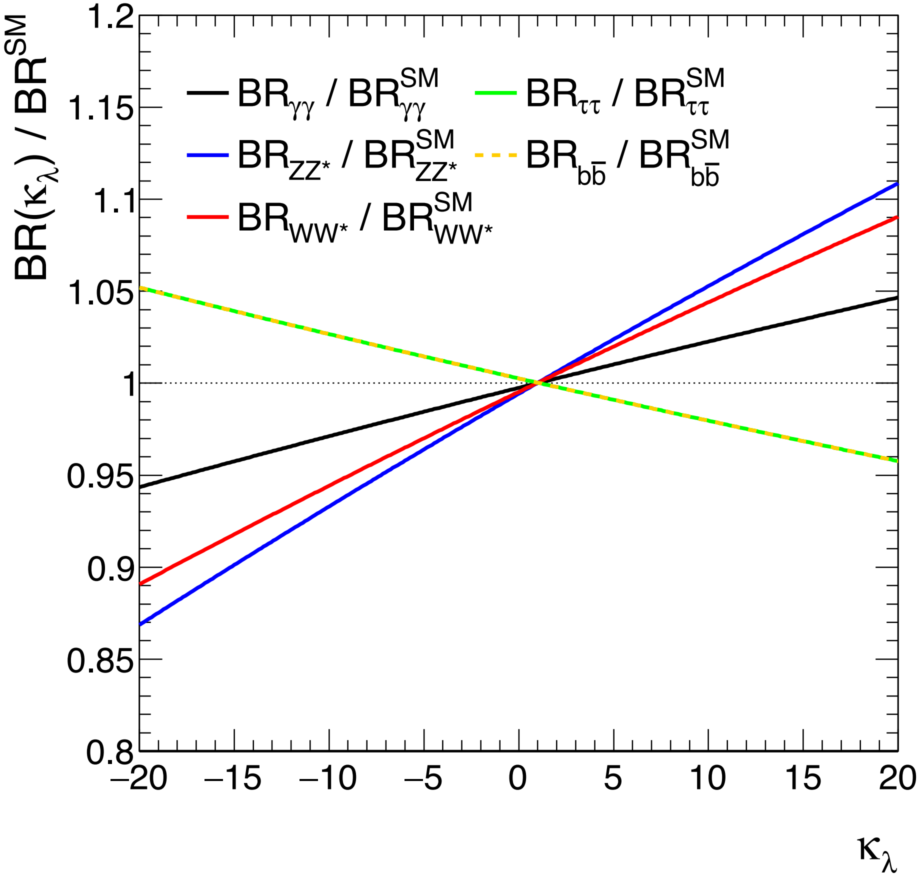
- κ_t^4 appears in the normalization, the signal acceptance depends only from κ_λ/κ_t

- When estimating $\sigma(pp \to HH)$, global normalization factors (κ_t^4) don't play a role
  - ⇒ HH-only measurement can't measure κ_λ and κ_t at the same time, κ_t is fixed to the SM in HH analysis alone

Theoretical model and parameterization

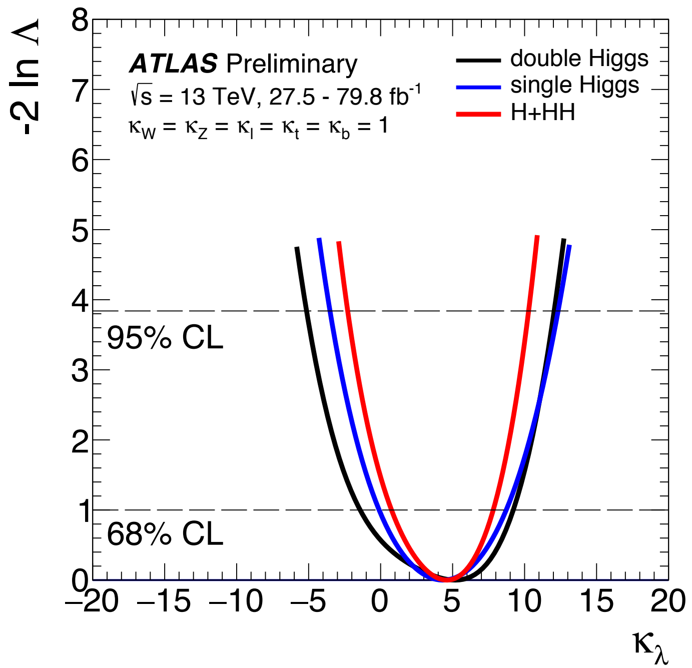
- Parametrization of single Higgs is as before, and is used consistently in double-Higgs analyses for single-Higgs backgrounds and Higgs decay branching ratios

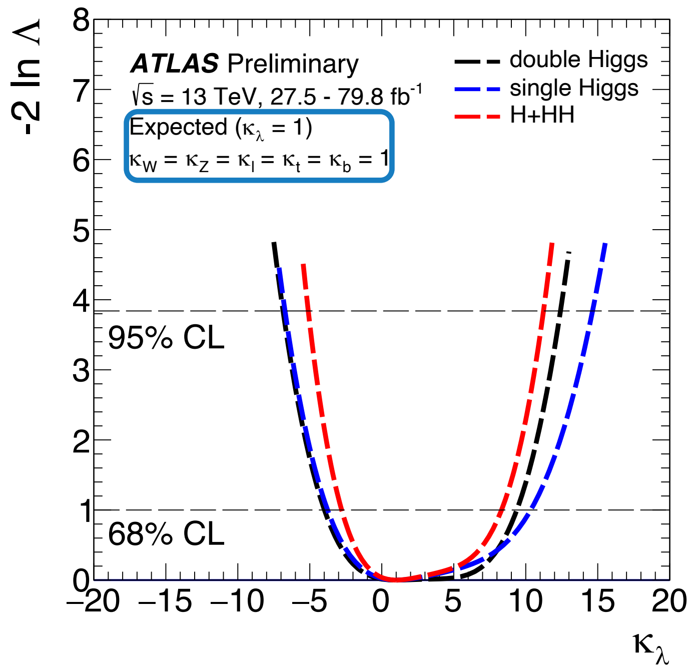




κ_λ-only results

- A likelihood fit is performed to constrain κ_λ in the combination of single-Higgs and double-Higgs
- All other Higgs boson couplings are fixed to the SM ($\kappa_t = \kappa_b = \kappa_l = \kappa_W = \kappa_Z = 1$)





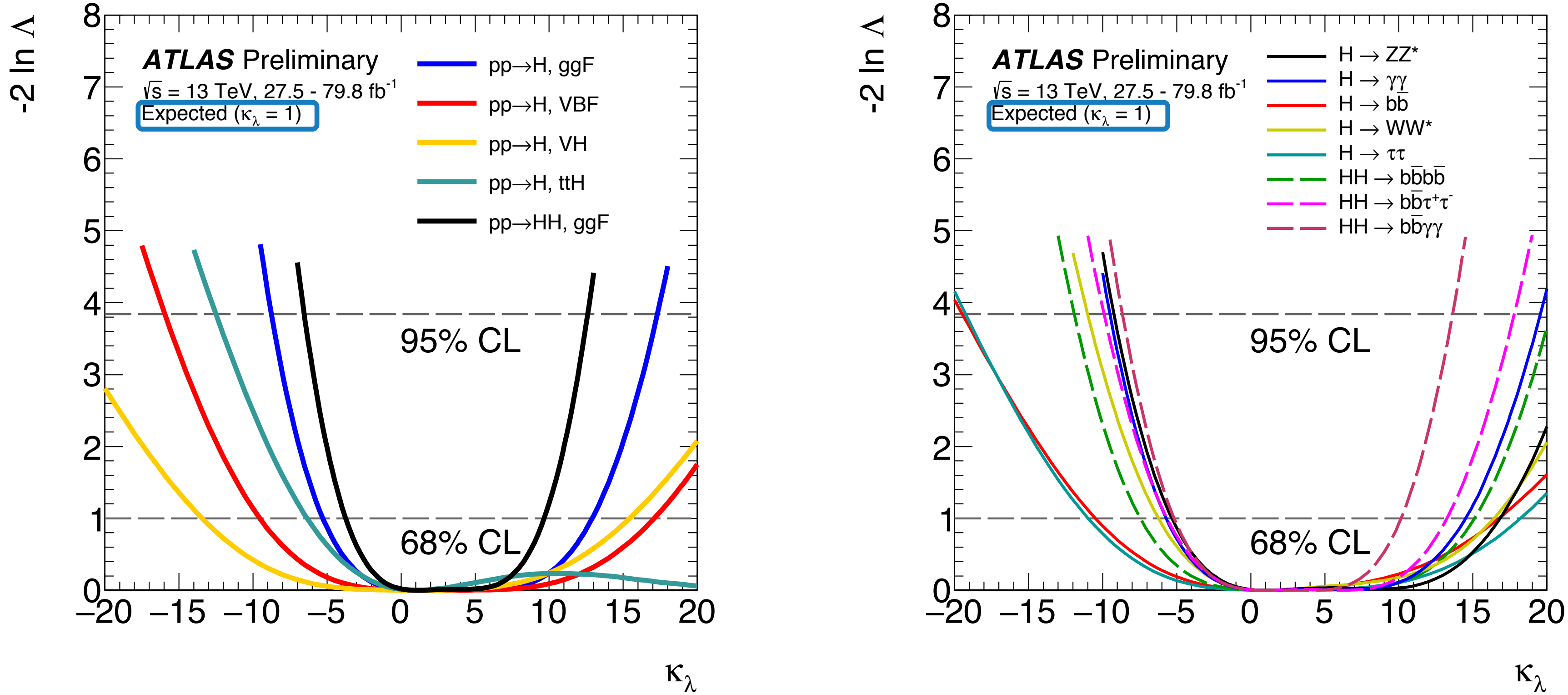
- $\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.6^{+2.9}_{-3.5}(stat.)^{+1.2}_{-1.2}(exp.)^{+0.7}_{-0.5}(sig.th.)^{+0.6}_{-1.0}(bkg.th.)$ (obs.)
- $\kappa_\lambda = 1.0^{+7.3}_{-3.8} = 1.0^{+6.2}_{-3.0}(stat.)^{+3.0}_{-1.7}(exp.)^{+1.8}_{-1.2}(sig.th.)^{+1.7}_{-1.1}(bkg.th.)$ (exp.)

95% CL	Obs.	Exp.
H [ATL-PHYS-PUB-2019-009]	[-3.2, 11.9]	[-6.2, 14.4]
HH [arXiv:1906.02025]	[-5.0, 12.0]	[-5.8, 12.0]
H+HH [ATLAS-CONF-2019-049]	[-2.3, 10.3]	[-5.1, 11.2]

- The combination can better constrain κ_λ

Higgs production/decay contributions

- Contributions from the different production and decay modes

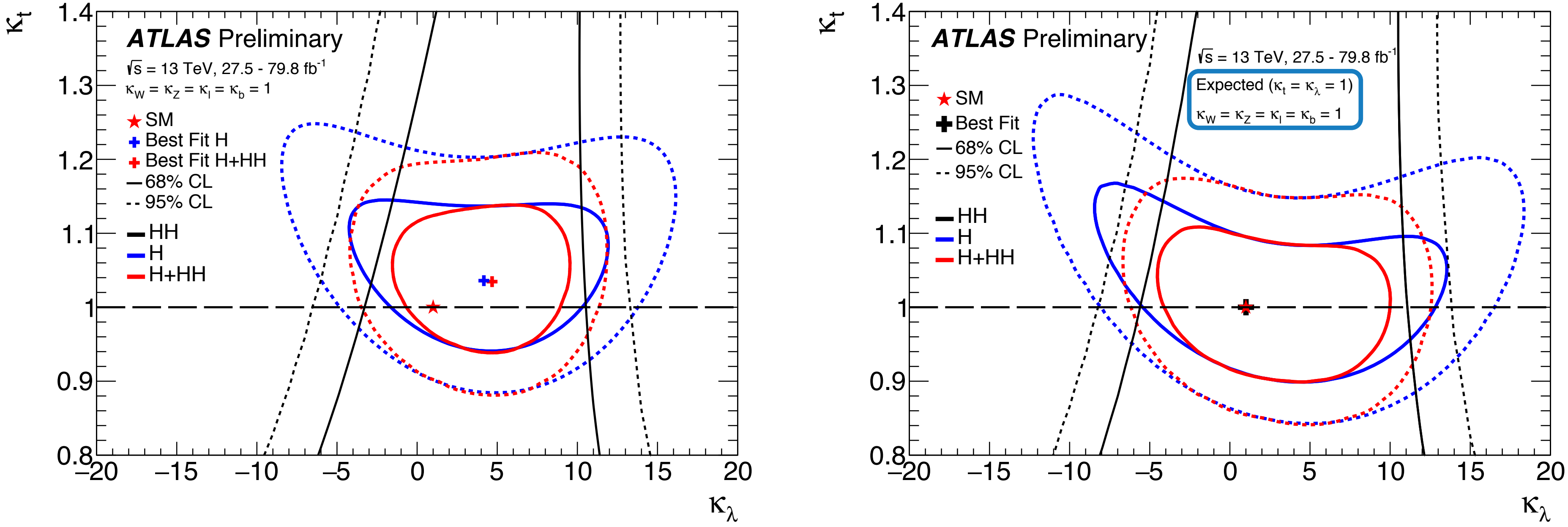


[ATLAS-CONF-2019-049]

- HH production is the most sensitive channel among all Higgs production processes, followed by ggF
- $HH \to bb\gamma\gamma$, $HH \to bb\tau\tau$ give dominant contributions in constraining κ_λ, followed by $H \to \gamma\gamma$

$\kappa_\lambda - \kappa_t$ measurement

- By fitting together double-Higgs and single-Higgs, κ_λ and κ_t can be constrained at the same time

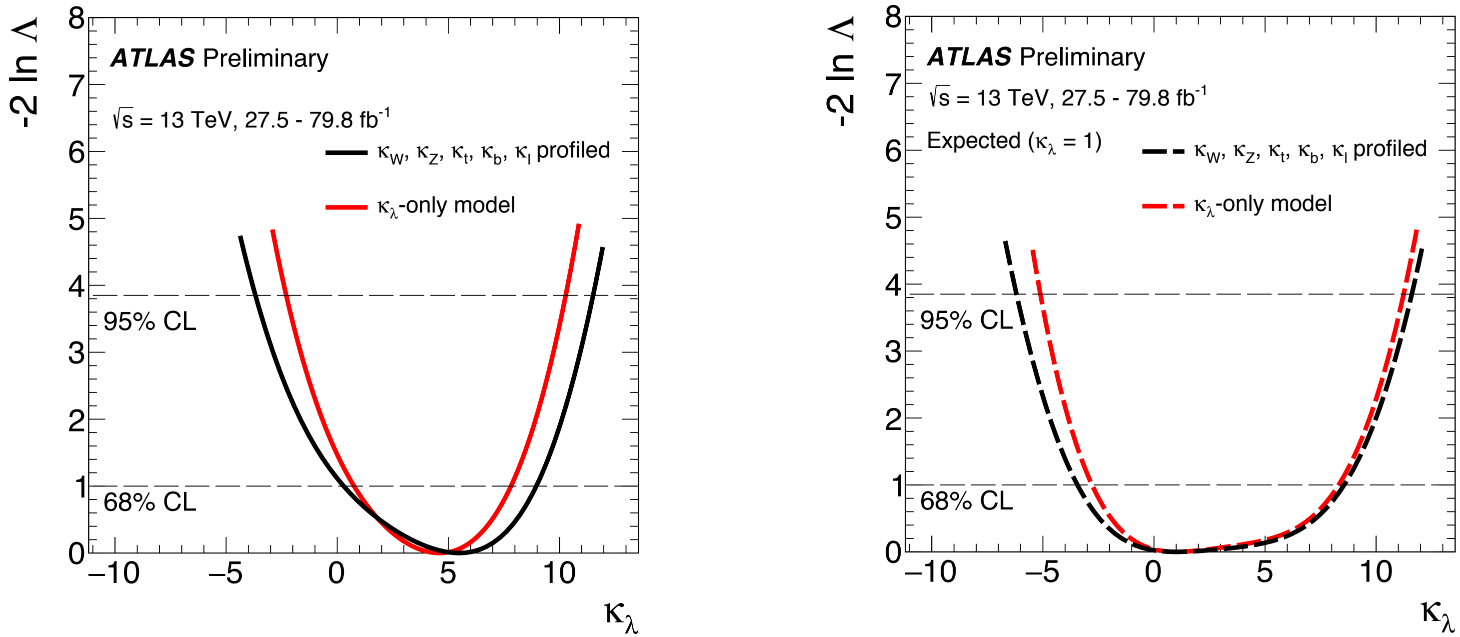


[ATLAS-CONF-2019-049]

- The double-Higgs analysis alone doesn't have sensitivity to constrain κ_λ and κ_t simultaneously

Generic model

- To give the most generic measurement, a likelihood fit is performed to constrain simultaneously κ_λ, κ_W, κ_Z, κ_t, κ_b and κ_l



[ATLAS-CONF-2019-049]

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

- Only the single-Higgs and double-Higgs combination could give enough sensitivity to exploit the generic model

Summary

- The HH searches (up to 36.1 fb^{-1}) provide a unique chance to probe the Higgs self-coupling $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$ with direct measurements, the observed 95% CL is [-5.0, 12.0]

- The single-Higgs analysis (up to 80 fb^{-1}) shows that an alternative and complementary approach to constrain the Higgs self-coupling is feasible
- This approach can provide similar sensitivity w.r.t the double Higgs production, 95% CL: [-3.2, 11.9], with other κ parameters fixed to the SM

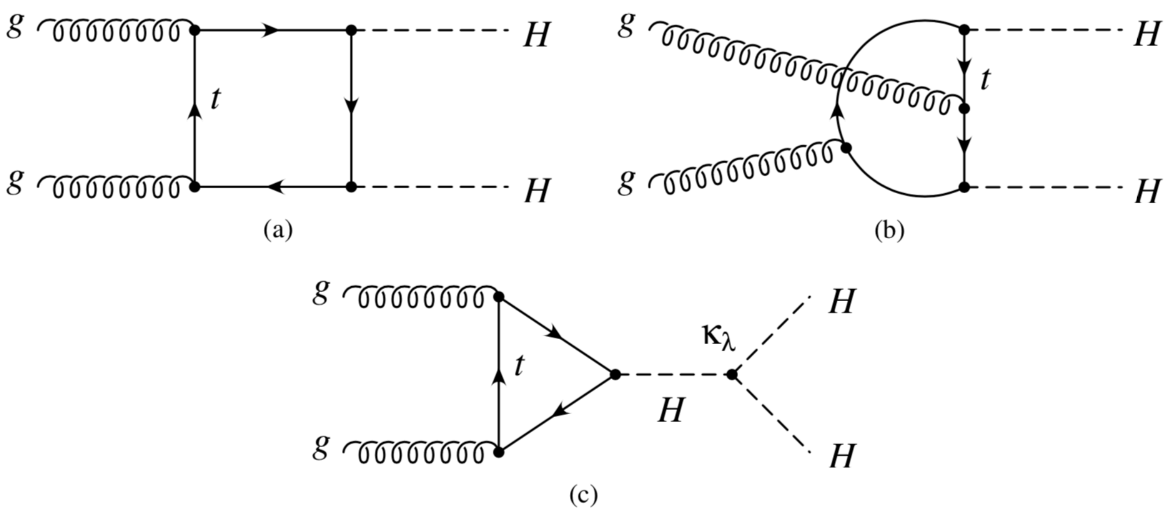
- Furthermore, κ_λ has been constrained exploiting the combination of single-Higgs analyses and double-Higgs analyses
- The combination improves the constraining power on κ_λ, 95% CL: [-2.3, 10.3], with other κ parameters fixed to the SM
- The combination can also investigate other models to which there is little sensitivity using just single-Higgs or double-Higgs measurements

Backup

Introduction about HH measurement

- During Run2 data taking, the Higgs production cross-sections and decays have been measured with an increasing precision
- The properties of the Higgs scalar potential, in particular the Higgs boson self-coupling, are still largely unconstrained

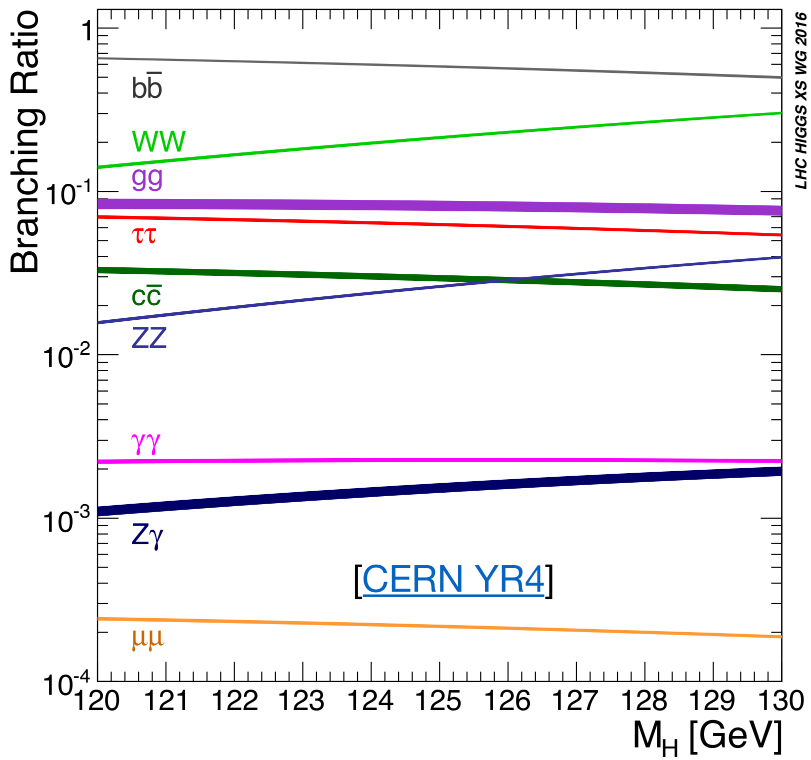
- The non-resonant HH production processes (ggF)
  - $\sigma^{SM}(pp \rightarrow HH, ggF)$: 33.41 fb at NLO QCD correction with the full top-quark mass dependence



- The tree-level diagram is sensitive to the Higgs boson trilinear self-coupling constant λ_{HHH}
- The HH searches provide a unique chance to probe it with direct measurements

Input channels up to 36.1 fb^{-1}

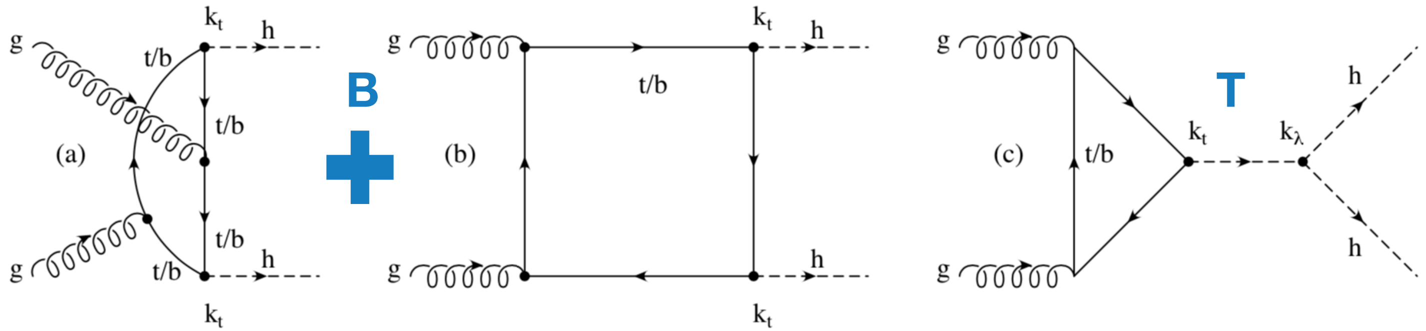
- ***bbbb***: benefitting from the largest BR of $H \to bb$
- ***bbττ***: being large decay (BR ~7.5%) and with excellent background rejection from τ performance
- ***bbγγ***: the best H resolution by $H \to \gamma\gamma$



- Channels are either kept statistically orthogonal by event selection or have negligible overlap
- The rest HH channels have negligible contributions

Theory model and interpretation

- The di-Higgs production



- The amplitude of the HH production can be parameterized as a function of ttH coupling $k_t = g_{ttH}/g_{ttH}^{SM}$ and HHH coupling $k_\lambda = g_{HHH}/g_{HHH}^{SM}$

$$A(k_t, k_\lambda) = k_t^2 B + k_t k_\lambda T$$

- Omitting the integral on the final phase space and on the PDFs for simplicity

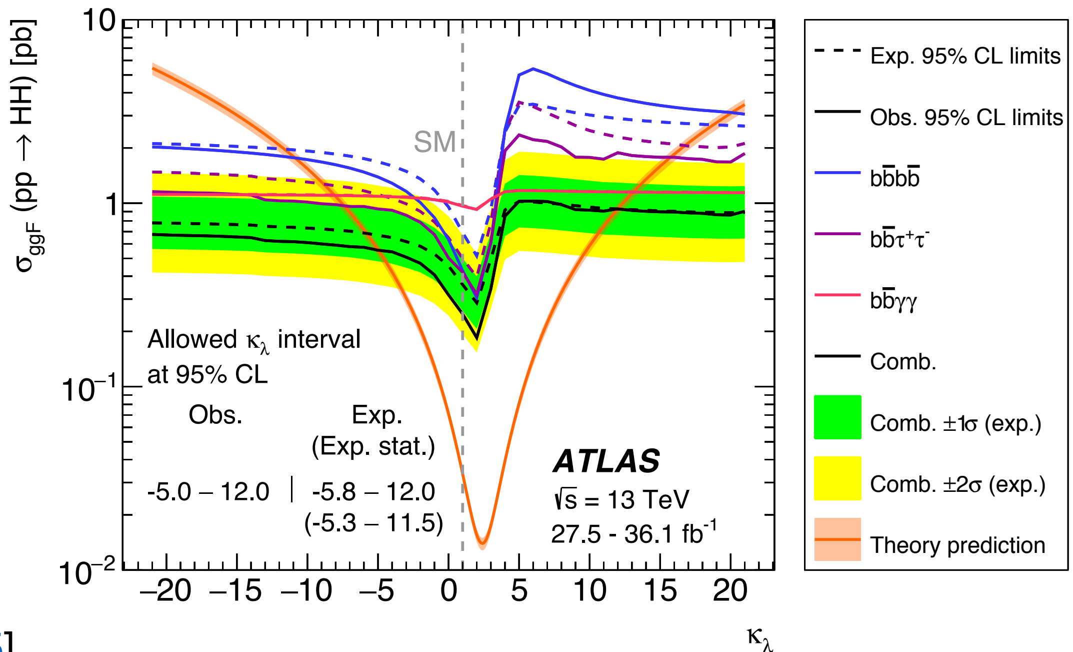
$$\sigma(pp \to HH) \sim k_t^4 \left[|B|^2 + \frac{k_\lambda}{k_t}(B^* T + T B^*) + \left(\frac{k_\lambda}{k_t}\right)^2 |T|^2 \right]$$

- The signal acceptance depends only from k_λ/k_t

- When estimating upper limits on $\sigma(pp \to HH)$ (POI), all global normalization factors (k_t^4) don't play a role, the limit can be expressed as a function of k_λ/k_t
  - ⇒ HH-only measurement can't measure k_λ and k_t at the same time

Limits on the trilinear Higgs self-coupling

- With each k_λ assumption, estimate the upper limits of the HH production (assuming SM H decay) with CLs approach
- The limit curve is compared to the predicted cross section, from which the constraint on k_λ can be determined



[arXiv:1906.02025]

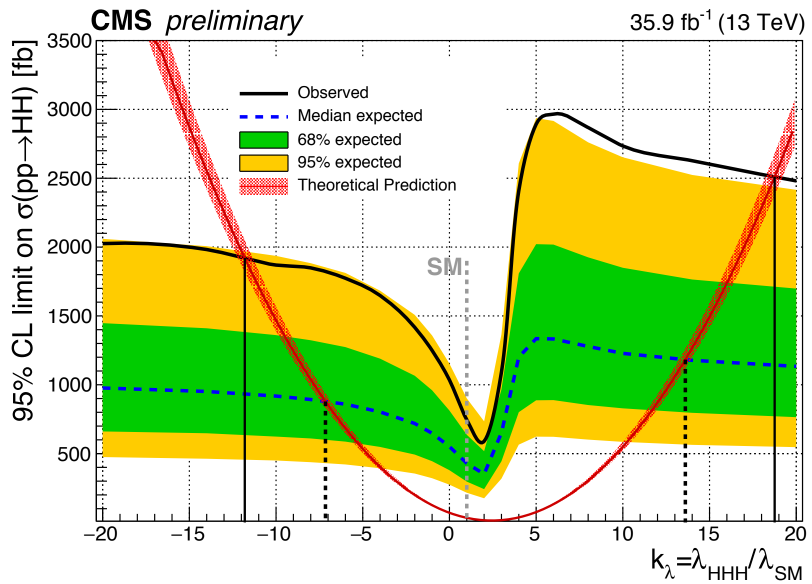
	Allowed κ_λ interval at 95% CL		
Final state	Obs.	Exp.	Exp. stat.
$b\bar{b}b\bar{b}$	−10.9 — 20.1	−11.6 — 18.8	−9.8 — 16.3
$b\bar{b}\tau^+\tau^-$	−7.4 — 15.7	−8.9 — 16.8	−7.8 — 15.5
$b\bar{b}\gamma\gamma$	−8.1 — 13.1	−8.1 — 13.1	−7.9 — 12.9
Combination	−5.0 — 12.0	−5.8 — 12.0	−5.3 — 11.5

Combination of HH channels in CMS

- CMS combines Higgs boson pair productions with 35.9 fb^{-1} data collected in 2016
- Channel
  - $bb\gamma\gamma$, $bb\tau\tau$, $bbbb$, $bbVV$ (additional channel w.r.t to the ATLAS measurement)

- A HH production scan is performed for different values of the k_λ

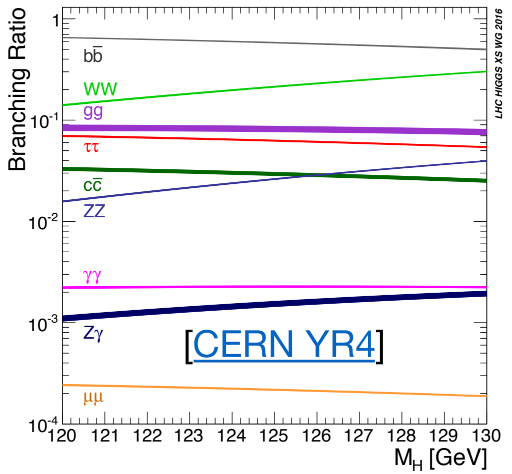
[CMS-PAS-HIG-17-030]



95% CL	Obs.	Exp.
ATLAS [arXiv:1906.02025]	[-5.0, 12.0]	[-5.8, 12.0]
CMS [CMS-PAS-HIG-17-030]	[-11.8, 18.8]	[-7.1, 13.6]

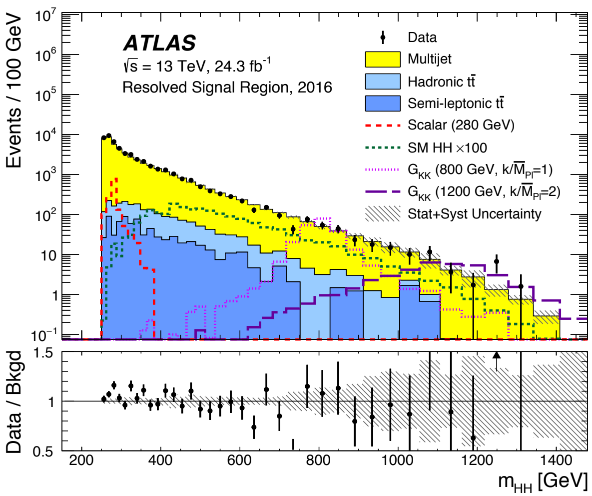
Input channels up to 36.1 fb^{-1}

- $bbbb$: benefitting from the largest BR of $H \to bb$
- $bb\tau\tau$: being large decay (BR ~7.5%) and with excellent background rejection from τ performance
- $bb\gamma\gamma$: the best H resolution by $H \to \gamma\gamma$

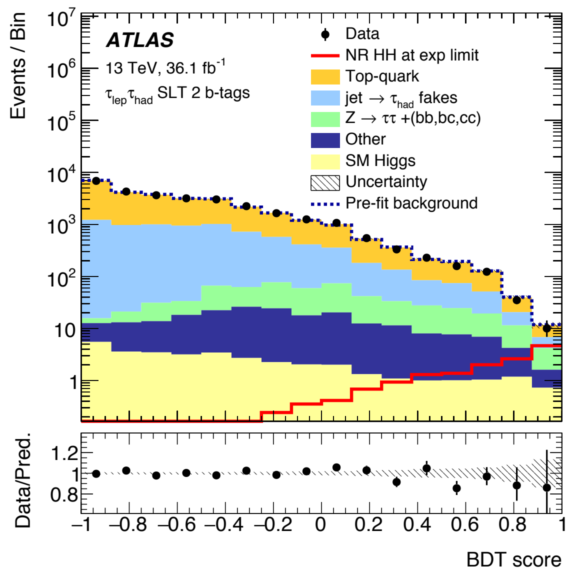


- The rest HH channels have negligible contributions

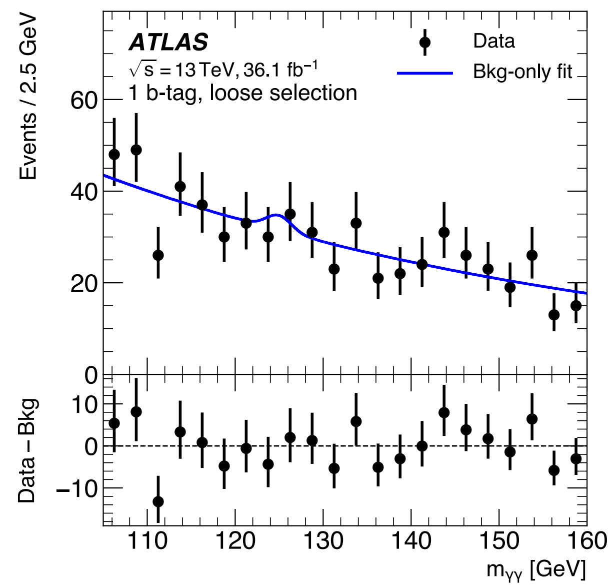
bbbb
[arXiv:1804.06174]



$bb\tau\tau$
[arXiv:1808.00336]



$bb\gamma\gamma$
[arXiv:1807.04873]



- Channels are either kept statistically orthogonal by event selection or are checked to have negligible overlap

Kinematical parameterization

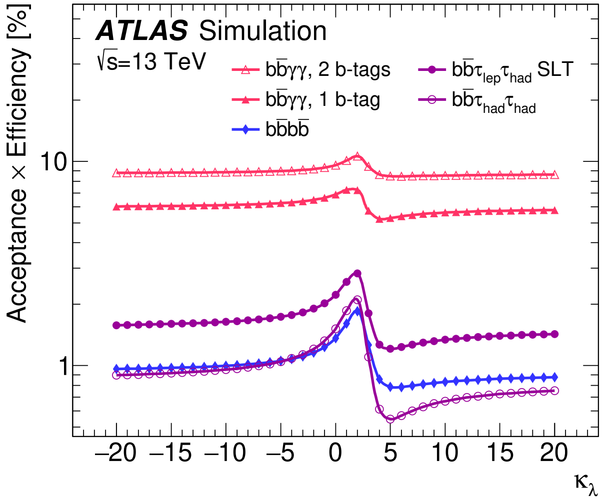
- The linear combination method
  - To avoid simulating a huge amount of events per k_λ
  - 3 basis amplitudes with certain k_λ LO samples can be linearly combined into an amplitude with any k_λ value

$$|A(k_t,k_\lambda)|^2 = k_t^2\left[\left(k_t^2+\frac{k_\lambda^2}{20}-\frac{399}{380}k_tk_\lambda\right)|A(1,0)|^2+\left(\frac{40}{38}k_tk_\lambda-\frac{2}{38}k_\lambda^2\right)|A(1,1)|^2+\frac{k_\lambda^2-k_tk_\lambda}{380}|A(1,20)|^2\right]$$

  - (k_t, k_λ) = {(1,0), (1,1), (1,20)} basis is less prone to statistical fluctuations for almost all k_λ points, due to higher number of events at low m_{HH}, coming from a softer $m_{HH}^{k_\lambda=20}$ spectrum

- The k_λ-reweighting method (LO → NLO)
  - Ratios of the m_{HH} distributions for all k_λ values to the SM distribution are computed and then used to reweight the events of NLO SM HH signal samples
  - The reweighted NLO signal sample is used to compute the signal acceptance and the kinematic distributions for different values of k_λ

[arXiv:1906.02025]

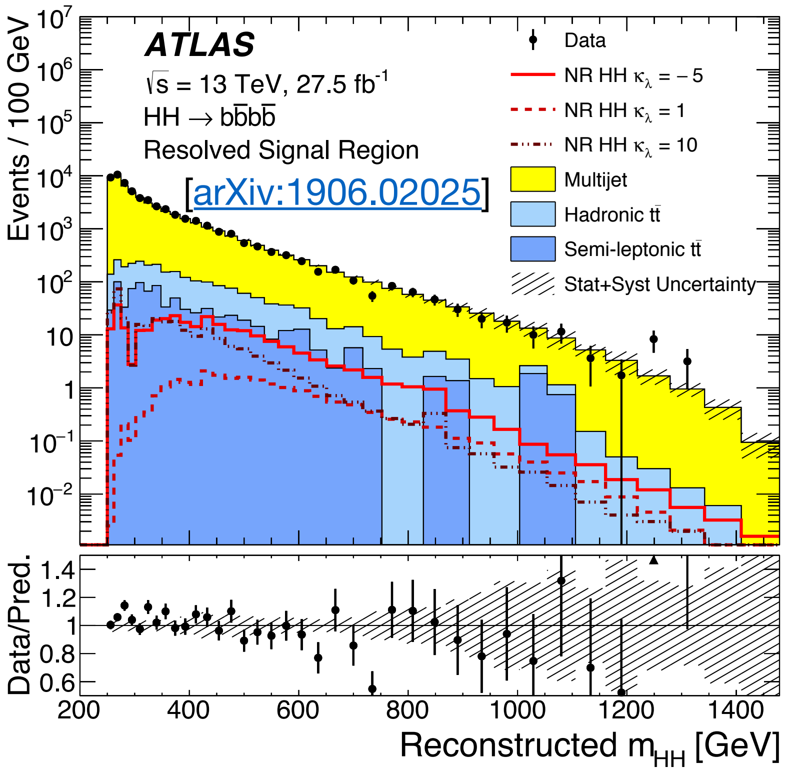


BDT training strategies

- $k_\lambda = 20$ BDT performs better than the BDT when k_λ deviates from the SM expectation, as it is more sensitive to events in softer m_{HH} spectrum, while the loss in sensitivity around $k_\lambda = 1$ is very small
- Thus the $k_\lambda = 20$ BDT is used for all varied k_λ signals

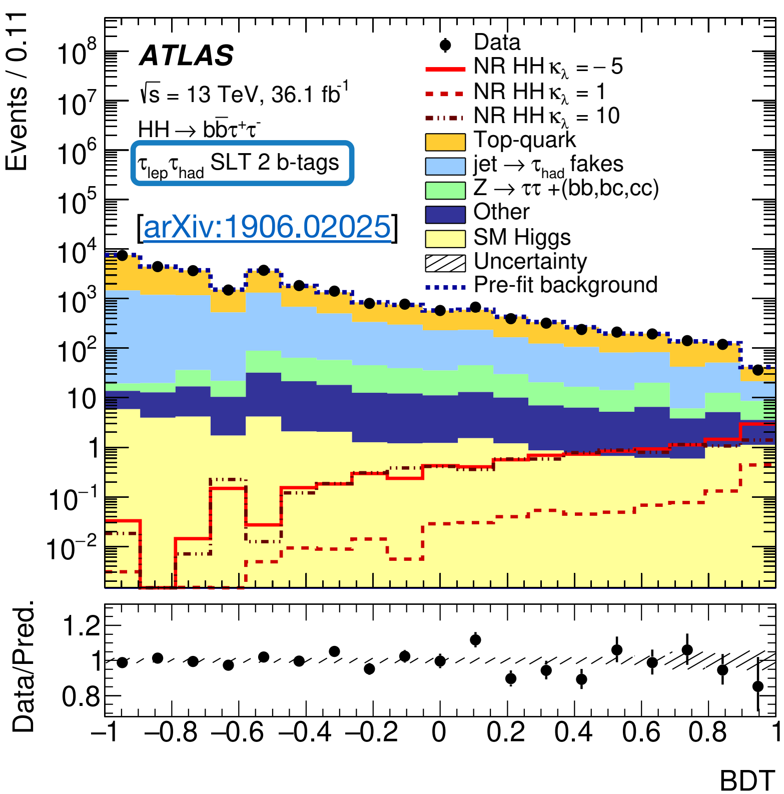
Interpretation in the bbbb channel

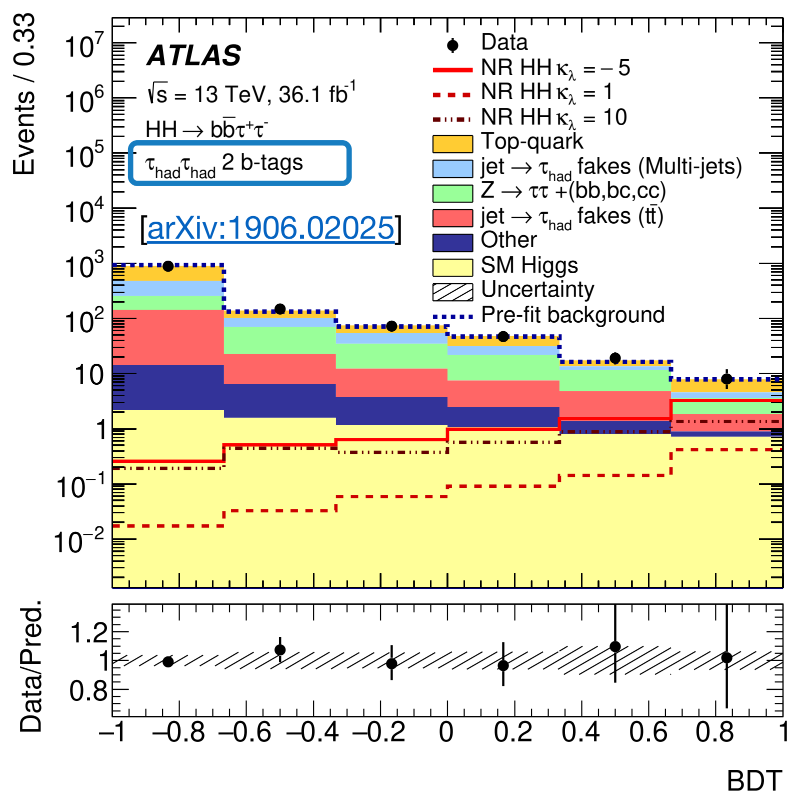
- The analysis selection is the same of the non-resonant SM search and the same final discriminant, the reconstructed m_{HH} distribution, is used as a fit template [arXiv:1804.06174]
- The signal model is modified to take into account its dependence from k_λ
- The signal acceptance varies by a factor 2.5 over the probed range of k_λ : [-20, 20]
- Both effects together determine how the exclusion limits on the HH production cross-section vary as a function of k_λ



Interpretation in the $bb\tau\tau$ channel

- Final states with two hadronic tau decays and with one leptonic and one hadronic tau decays are used
- The analysis uses a BDT discriminant trained using the re-weighted NLO signal sample corresponding to $k_\lambda = 20$, which shows good sensitivity over the whole range of probed k_λ-values: [-20, 20]
- The sensitivity is also affected by the variation of the signal acceptance of a factor 3 over the probed range of k_λ-values



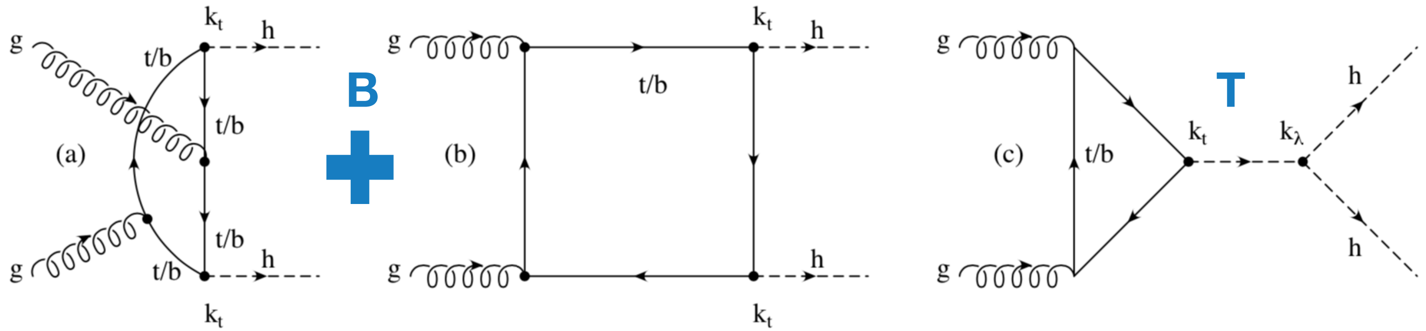


Interpretation in the $bb\gamma\gamma$ channel

- The kinematic selection used for the k_λ-scan uses looser cuts on the b–jets pT than the selection used to look for the SM HH process [arXiv:1807.04873], because the average p_T^H is lower at large values of k_λ
- The statistical analysis is performed using the $m_{\gamma\gamma}$ distribution as the fit template
- The signal acceptance varies by about 30% over the probed range of k_λ-values: [-20, 20]
- The shape of the $m_{\gamma\gamma}$ remains independent of k_λ
  - The $m_{\gamma\gamma}$ dependence is examined by comparing the generated spectrum in simulation using different k_λ values
  - They agree well within statistical uncertainties
  - Furthermore, as the $m_{\gamma\gamma}$ is modeled with DSCB, μ_{CB} and σ_{CB} are extracted as a function of k_λ
  - Both parameters are flat against k_λ variations in general

Theory model and interpretation in the double-Higgs

- The di-Higgs production



- The amplitude of the HH production can be parameterized as a function of ttH coupling $k_t = g_{ttH}/g_{ttH}^{SM}$ and HHH coupling $k_\lambda = g_{HHH}/g_{HHH}^{SM}$

$$A(k_t, k_\lambda) = k_t^2 B + k_t k_\lambda T$$

- Omitting the integral on the final phase space and on the PDFs for simplicity
- $\sigma(pp \to HH) \sim k_t^4 \left[|B|^2 + \frac{k_\lambda}{k_t}(B^* T + T B^*) + \left(\frac{k_\lambda}{k_t}\right)^2 |T|^2 \right] (bb\gamma\gamma)$

- 3 basis amplitudes with certain k_λ samples (k_t, k_λ) = {(1,0), (1,1), (1,20)} can be linearly combined into an amplitude with any k_λ value
- $|A(k_t,k_\lambda)|^2 = k_t^2 \left[\left(k_t^2 + \frac{k_\lambda^2}{20} - \frac{399}{380} k_t k_\lambda\right) |A(1,0)|^2 + \left(\frac{40}{38} k_t k_\lambda - \frac{2}{38} k_\lambda^2\right) |A(1,1)|^2 + \frac{k_\lambda^2 - k_t k_\lambda}{380} |A(1,20)|^2 \right] (bbbb,\ bb\tau\tau)$

Systematic uncertainties

- Experimental systematic uncertainty
  - With the recommendation of CP groups, the uncertainty sources are correlated by sharing the same NP across the channels
- Background uncertainty
  - The uncertainties (modeling and rates) are not correlated given different phase space and evaluation methods
- Theoretical uncertainty
  - The uncertainties on signal acceptances are correlated
  - They are from renormalization and factorization scales, PS as well as PDF sets

POI and uncertainties

- POI: $\sigma(pp \rightarrow HH)$, assuming SM branching fractions
- Detector systematic uncertainties
  - Jet reconstruction, b-jet tagging, electron, muon and photon reconstruction and identification, as well as the uncertainty of the integrated luminosity are correlated
- Theory uncertainties in the signal acceptance
  - QCD scales, PDFs and PS are correlated
- Theoretical and modelling systematic uncertainties of the backgrounds are not correlated
  - There is a negligible overlap among these background contributions to the different analyses

- The predicted HH cross section is scaled by a factor as a function of k_λ
  - The factor is calculated by non-SM-lambda xs over SM-lambda xs ($k_\lambda = 1$) at NNLO+NNLL from YR4

Event kinematic information

- Re-deriving the kinematic dependent coefficients C_1^i

STXS region		VBF	WH	ZH
		$C_1^i \times 100$		
VBF + V(had)H	VBF-cuts + $p_T^{j1} < 200$ GeV, $\leq 2j$	0.63	0.91	1.07
	VBF-cuts + $p_T^{j1} < 200$ GeV, $\geq 3j$	0.61	0.85	1.04
	VH-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	
$qq \to H\ell\ell$ / $qq \to H\nu\nu$	$p_T^V < 150$ GeV			1.33
	$150 < p_T^V < 250$ GeV, $0j$			0.20
	$150 < p_T^V < 250$ GeV, $\geq 1j$			0.39
	$p_T^V > 250$ GeV			0

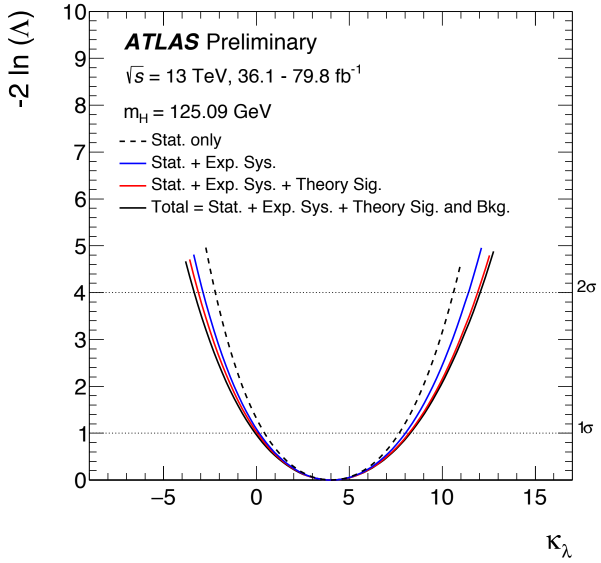
[ATL-PHYS-PUB-2019-009]

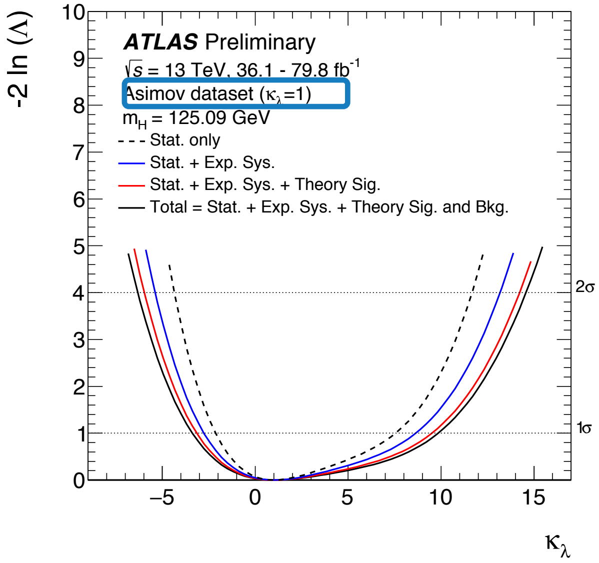
- In the phase space where K_{EW}^i corrections are most significant (~15% variations for high p_T^H), the sensitivity to the Higgs boson trilinear coupling is minimal
  - It's assumed to be constant to the inclusive values
  - A test has been performed using different K_{EW} for each STXS bin
  - The fit results with the new K_{EW} configuration differ by less than percent level w.r.t the nominal results

- The selection efficiency can also depend on k_λ, the effect has been tested using MC samples
  - In general, a negligible dependence is found

k_λ-only results

- A likelihood fit is performed to constrain the Higgs boson self-coupling k_λ
  - Theory validity range [arXiv: 1607.04251]: $-20 < k_\lambda < 20$





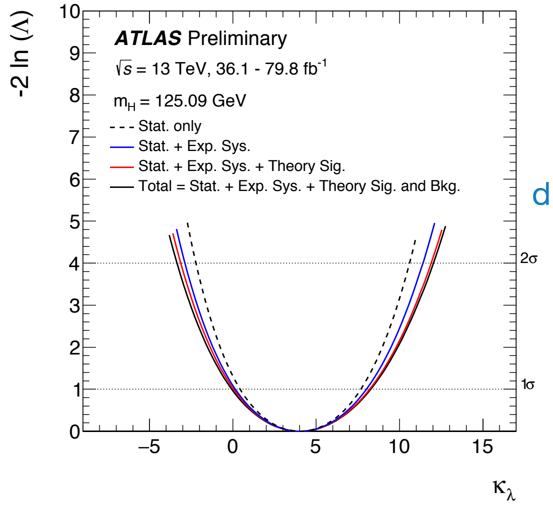
- $k_\lambda = 4.0^{+4.3}_{-4.1} = 4.0^{+3.7}_{-3.6}(stat.)^{+1.6}_{-1.5}(exp.)^{+1.3}_{-0.9}(sig.th.)^{+0.8}_{-0.9}(bkg.th.)$

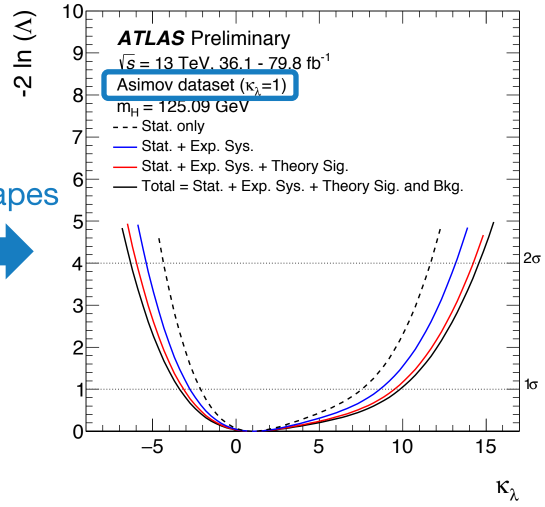
95% CL	Obs.	Exp.
H [ATL-PHYS-PUB-2019-009]	[-3.2, 11.9]	[-6.2, 14.4]
HH [arXiv:1906.02025]	[-5.0, 12.0]	[-5.8, 12.0]

- The impact on the k_λ by using an inclusive cross-section measurement has been studied, where the VBF, WH and ZH are considered as single inclusive bins
- The inclusive fit does not lead to a significant loss in sensitivity to k_λ

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

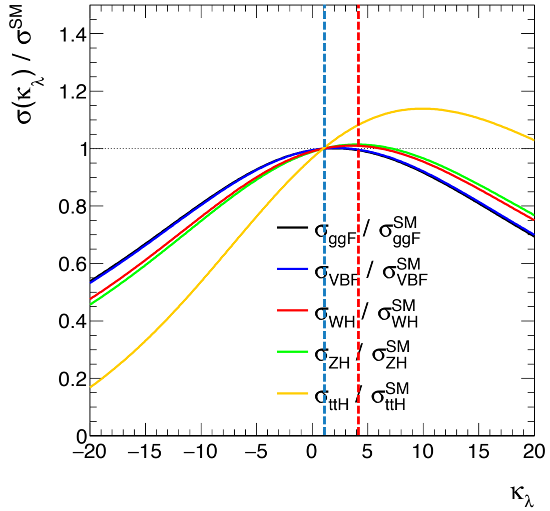
Likelihood comparison





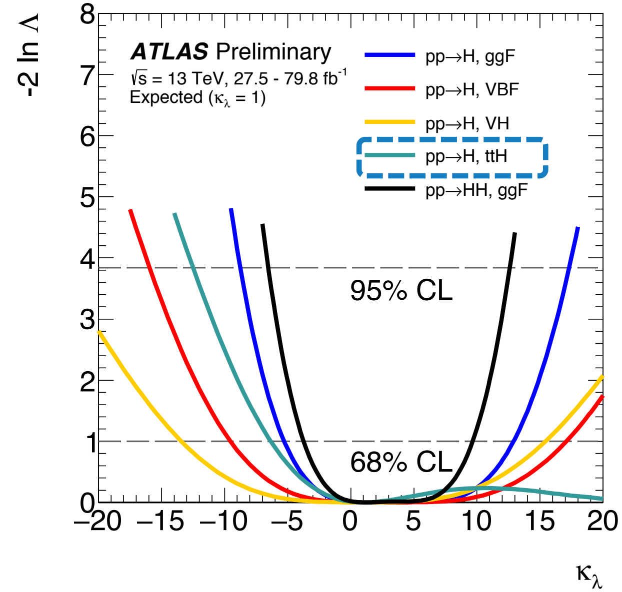
- Explanation
  1. The non-linearity of the cross-section dependence from k_λ
  2. The difference of the best-fit values of k_λ

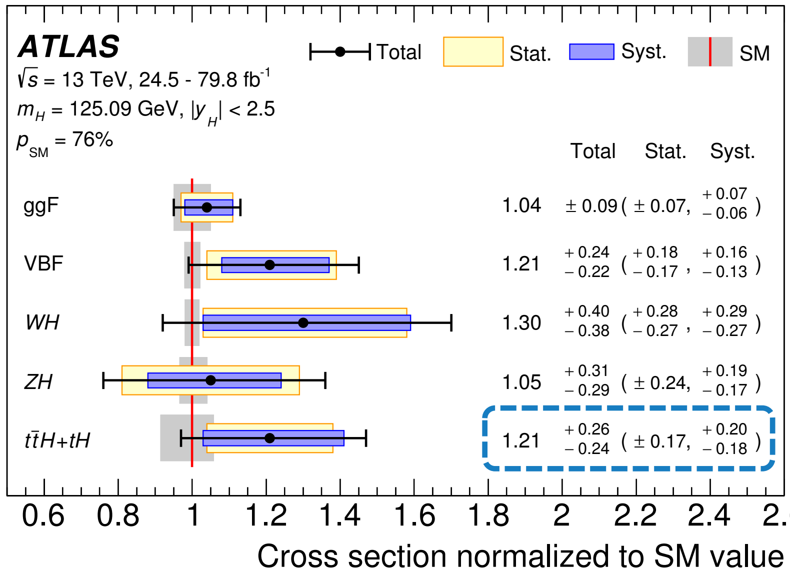
$$\mu_i(k_\lambda, k_i) = \frac{1}{1-\left(k_\lambda^2-1\right)\delta Z_H}\left[k_i^2 + \frac{(k_\lambda - 1)C_1^i}{K_{EW}^i}\right]$$

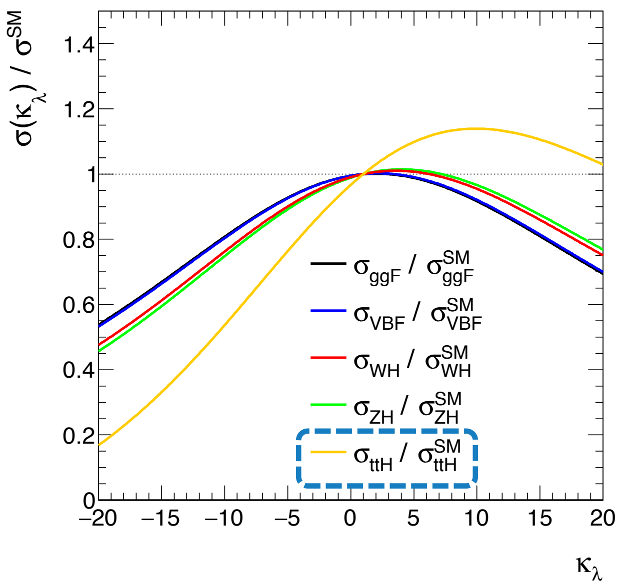


- The shape is affected by the different behavior of the quadratic and linear k_λ dependent terms
  - If $k_\lambda < 1$ both terms induce a reduction of the Higgs boson production cross-sections
  - While for $k_\lambda > 1$ there are larger cancellations that weaken the cross-section dependence

The observed $\sigma_{ggF}, \sigma_{ttH}$





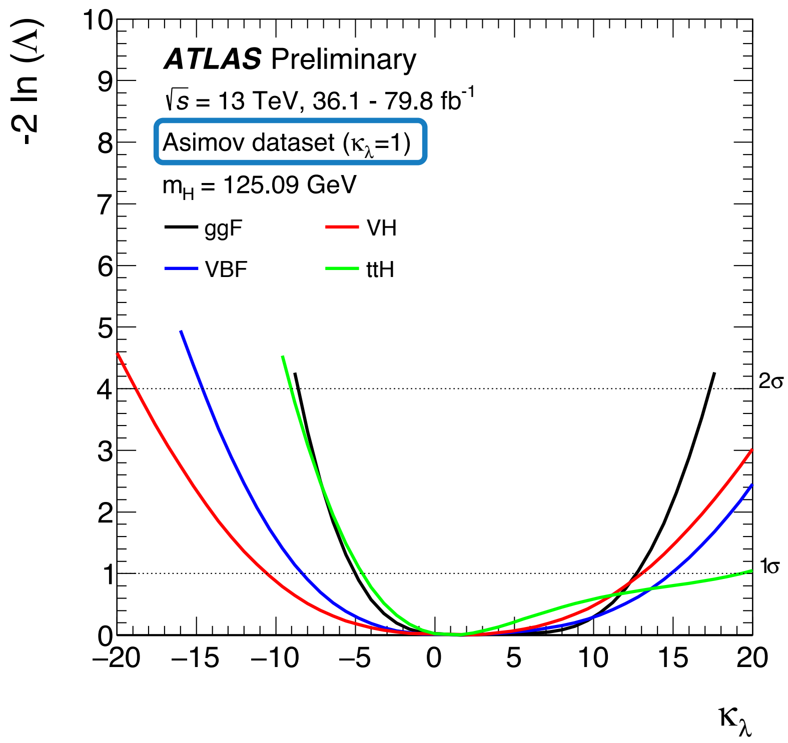


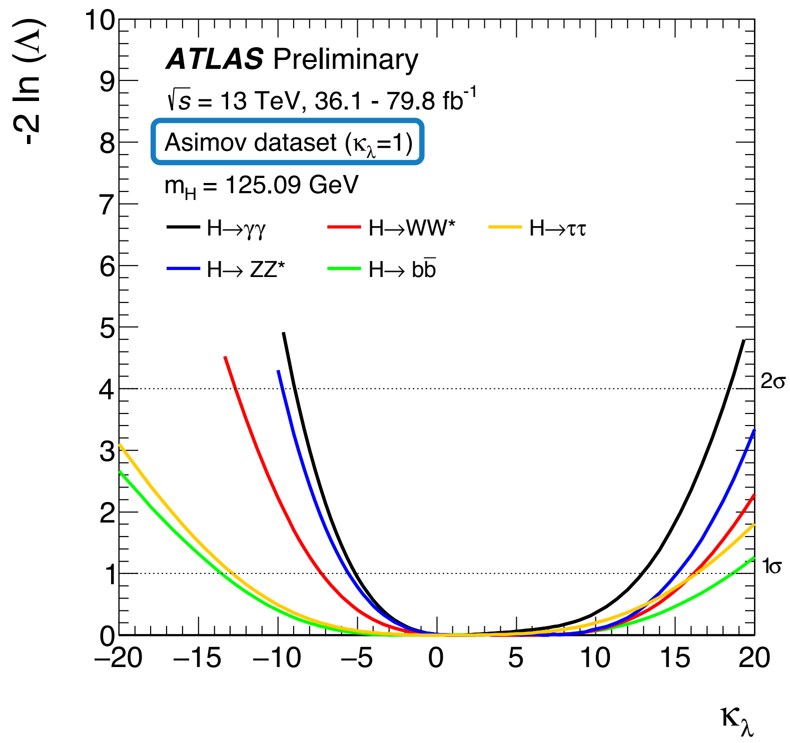
- ggF, ttH are sensitive for measuring k_λ
- The measured $\sigma_{ggF}, \sigma_{ttH+tH}$ is greater SM
- To get higher $\sigma_{ggF}, \sigma_{ttH}$, k_λ has to be greater than the SM

The sensitivity of different productions and decays

- Moreover, the global likelihood shape depends on combining the different production and decays, which have different sensitivities and significantly different likelihood shapes

[ATL-PHYS-PUB-2019-009]

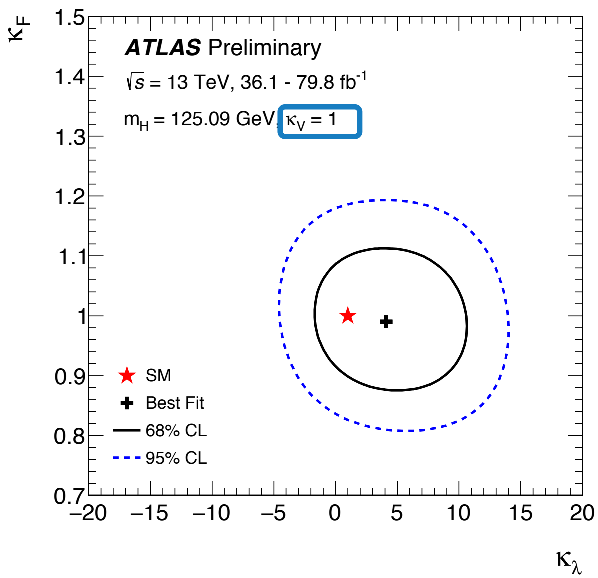


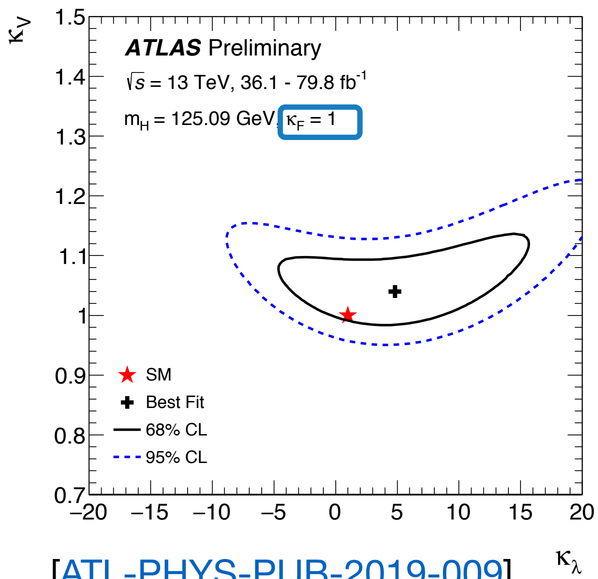


- The dominant contributions derive from the di-boson decays $\gamma\gamma$, ZZ^*, WW^* and from the ggF and ttH productions

k_λ and k_F, k_λ and k_V fits

- A simultaneous fit is performed to k_λ and k_F $(k_V = 1)$, k_λ and k_V $(k_F = 1)$
- These fits target BSM scenarios where new physics could affect only the Yukawa type terms $(k_V = 1)$ or only the couplings to vector bosons $(k_F = 1)$, in addition to the Higgs boson self-coupling (k_λ)





[ATL-PHYS-PUB-2019-009]

- The sensitivity to k_λ is not much degraded when determining k_F at the same time
- While it's degraded by 50% when determining k_V simultaneously

- An even less constrained fit, by either fitting simultaneously k_λ, k_V and k_F, or fitting simultaneously k_λ and a common coupling modifier $(k = k_V = k_F)$, results in nearly no sensitivity to k_λ

POIs	Granularity	$\kappa_F{}^{+1\sigma}_{-1\sigma}$	$\kappa_V{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
κ_λ	STXS	1	1	$4.0^{+4.3}_{-4.1}$	[−3.2, 11.9]
				$1.0^{+8.8}_{-4.4}$	[−6.2, 14.4]
κ_λ	inclusive	1	1	$4.6^{+4.3}_{-4.2}$	[−2.9, 12.5]
				$1.0^{+9.5}_{-4.3}$	[−6.1, 15.0]
κ_λ, κ_V	STXS	1	$1.04^{+0.05}_{-0.04}$	$4.8^{+7.4}_{-6.7}$	[−6.7, 18.4]
			$1.00^{+0.05}_{-0.04}$	$1.0^{+9.9}_{-6.1}$	[−9.4, 18.9]
κ_λ, κ_F	STXS	$0.99^{+0.08}_{-0.08}$	1	$4.1^{+4.3}_{-4.1}$	[−3.2, 11.9]
		$1.00^{+0.08}_{-0.08}$		$1.0^{+8.8}_{-4.4}$	[−6.3, 14.4]

Multiplicative approach in the Higgs production parameterization

- Additional cross-check about k_λ interpretation in the Higgs productions

$$\mu_i(k_\lambda, k_i) = Z_H^{BSM}(k_\lambda)\left[k_i^2 + \frac{(k_\lambda - 1)C_1^i}{K_{EW}^i}\right]$$

- Multiplicative approach: k_i can also modifies the loops together with k_λ to verify the robustness of the nominal approach against higher-order terms

$$\mu_i(k_\lambda, k_i) = Z_H^{BSM}(k_\lambda)\left[k_i^2 + \frac{\left(k_\lambda k_i^3 - 1\right)C_1^i}{K_{EW}^i}\right]$$

- k_λ measurements have been performed comparing the nominal results and the ones using this additional configuration
- Negligible discrepancies w.r.t the uncertainty of the nominal measurement have been found

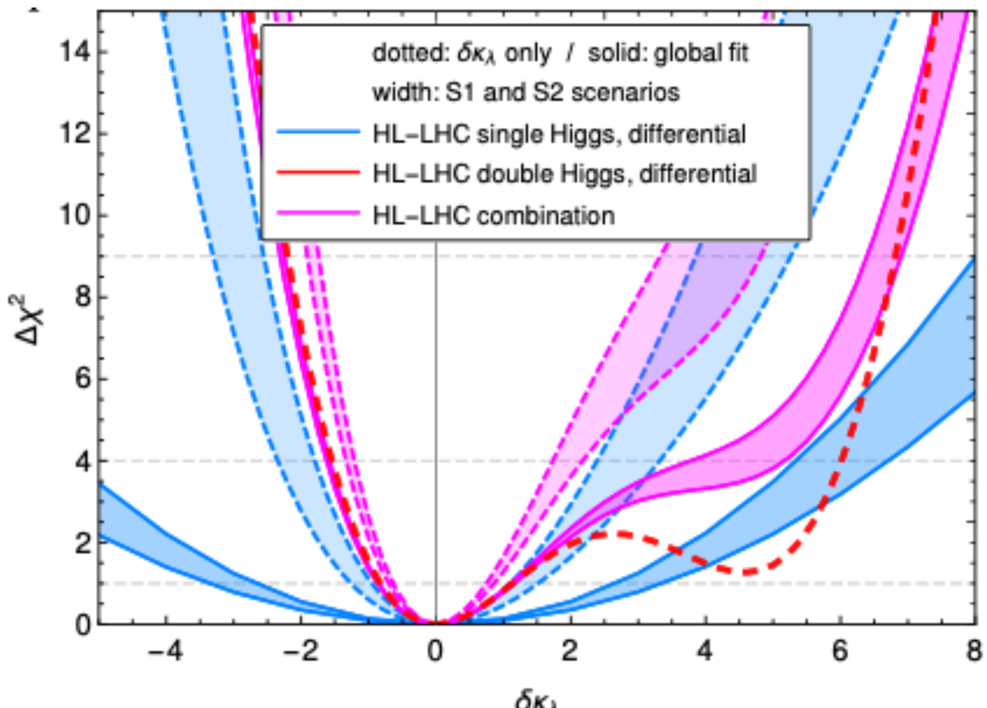
- $bb\gamma\gamma$: no signal sample is used
- The analysis acceptance depends on k_λ/k_t and has been implemented

Systematic correlations

- The principles for making systematic uncertainties correlations
  - Correlate CP uncertainties where possible
  - Correlate theory signal uncertainties where possible
  - Uncorrelate uncertainties in different releases
  - Uncorrelate background uncertainties due to different phase spaces in different analyses
- Only ~50 NPs need to be studied and correlated

- HH currently are very limited by statistics also in its systematic uncertainties (eg. bkg systematics), therefore at HL they can gain a lot in sensitivity
- The gain for SH is not so enhanced by the increasing of luminosity since at a certain point it becomes limited by systematic uncertainties, that in the HL projection are not so much reduced

- The HL-LHC report that the combination of HH with H brings little additional constraint on the HH constraints alone seems to be a little excessive (especially considering the 2 sigma line)



Higgs Physics at the HL-LHC and HE-LHC: arXiv:1902.00134

- Htautau
- https://gitlab.cern.ch/atlas_higgs_combination/projects/HiggsCouplingProspectCombSummer2018/blob/master/WS_300/Reduced/Htautau/HLLHCred300mu_125.root

```
RooProduct::WH125_Htt_yearAll_chanhh_catboostloose_regsig_selCBA_overallNorm_x_sigma_epsilon[ SigXsecOverSM * Mu_VBF_tautau * Mu_VH_tautau *
XS13_WH_tautau * oneover_XS13_WH * oneover_BR_tautau * lumi_1516 * oneover_lumi_1516 *
WH125_Htt_yearAll_chanhh_catboostloose_regsig_selCBA_epsilon ] = 1.00001
```

- All WH, ZH categories have "Mu_VBF_tautau * Mu_VH_tautau" handlers
- And there is no WH, ZH POIs (i.e Mu_WH_tautau, Mu_ZH_tautau)

- Would it possible to remove Mu_VBF_tautau and add WH, ZH POIs in it?

```
RooProduct::ttH125_Htt_yearAll_chanhh_catboostloose_regsig_selCBA_overallNorm_x_sigma_epsilon[ SigXsecOverSM * Mu_gg2H_tautau *
Mu_ttH_tautau * XS13_ttH * oneover_XS13_ttH * lumi_1516 * oneover_lumi_1516 * ttH125_Htt_yearAll_chanhh_catboostloose_regsig_selCBA_epsilon
] = 1
```

- All ttH categories have "Mu_gg2H_tautau * Mu_ttH_tautau" handlers

- Would it possible take Mu_gg2H_tautau out?

- Currently we can only use Mu_gg2H_tautau and Mu_VBF_tautau in the Htautau workspace