Constraining the Higgs boson self-coupling in a combined measurement of single- and double-Higgs boson channels at the ATLAS experiment

Valerio D’Amico

Ludwig-Maximilians-Universität München

On behalf of the *ATLAS* Collaboration

7 July 2022

ICHEP 2022, Bologna (Italy)

The Higgs boson self-coupling

Within the SM, the Higgs potential is: $\boldsymbol{V(\Phi) = \mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2}$ with $\boldsymbol{\mu^2 < 0}$ and $\boldsymbol{\lambda > 0}$

Expanding Φ at low energies around the minimum v, it becomes: $\boldsymbol{V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)}$

where the Higgs self-coupling λ_3 depends only on m_H and v: $\boldsymbol{\lambda_3 = \lambda_{HHH} = \frac{m_H^2}{2v^2}}$

- New physics could modify the Higgs potential altering λ_3 without affecting m_H or v: e.g. by extending the scalar sector or due to the exchange of new virtual states

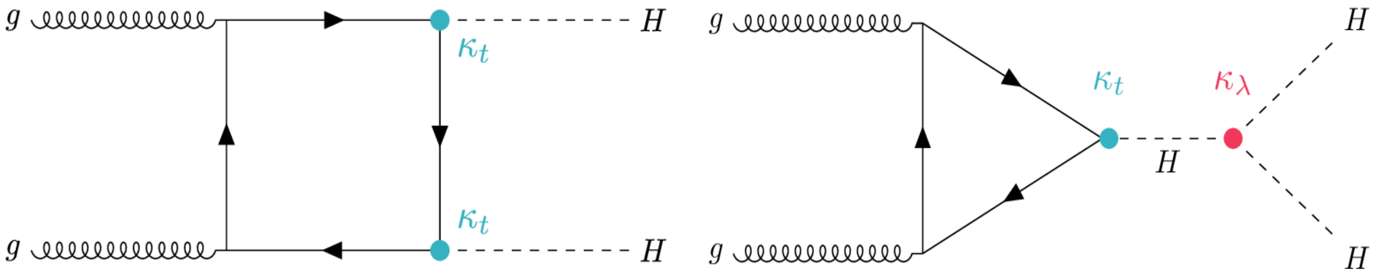
The Higgs boson self-coupling

Within the SM, the Higgs potential is: $V(\Phi) = \mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$ with $\mu^2 < 0$ and $\lambda > 0$

Expanding Φ at low energies around the minimum v, it becomes: $V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)$

where the Higgs self-coupling λ_3 depends only on m_H and v: $\lambda_3 = \lambda_{HHH} = \frac{m_H^2}{2v^2}$

- New physics could modify the Higgs potential altering λ_3 without affecting m_H or v: e.g. by extending the scalar sector or due to the exchange of new virtual states

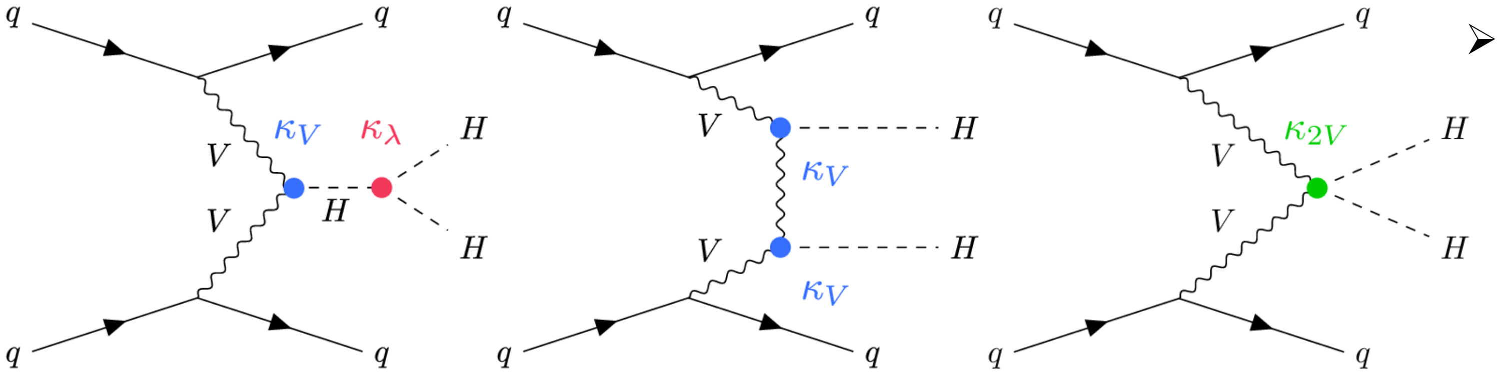


- Experimental results are expressed in terms of the coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$
- Gluon-gluon Fusion (ggF): leading production mode

  $\sigma_{ggF}^{SM}(pp \to HH) = 31.05^{+1.9}_{-7.1}$ fb at $\sqrt{s} = 13\ TeV$

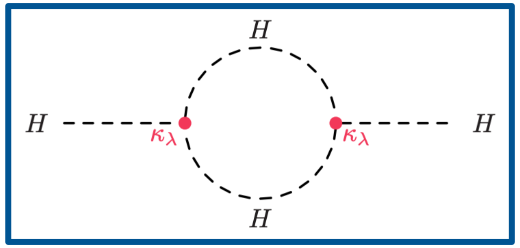
- Vector Boson Fusion (VBF) production mode gives also access to κ_{2V} coupling

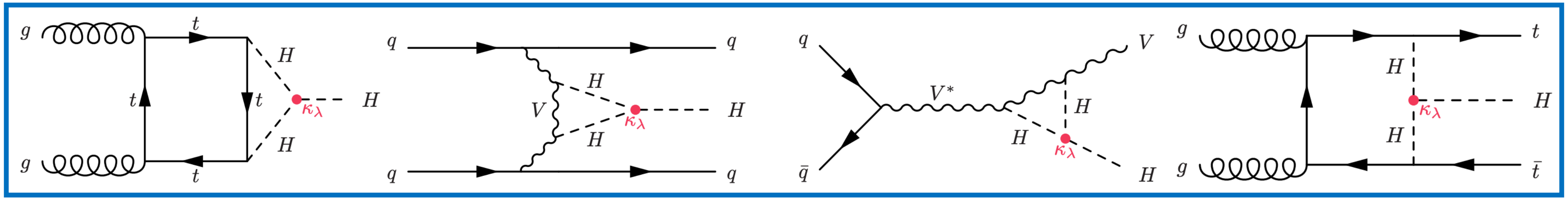
  $\sigma_{VBF}^{SM}(pp \to HH) = 1.72 \pm 0.04$ fb at $\sqrt{s} = 13\ TeV$



Self-coupling in single-Higgs process

- Single-Higgs processes are **indirectly** sensitive to κ_λ via NLO EW corrections:





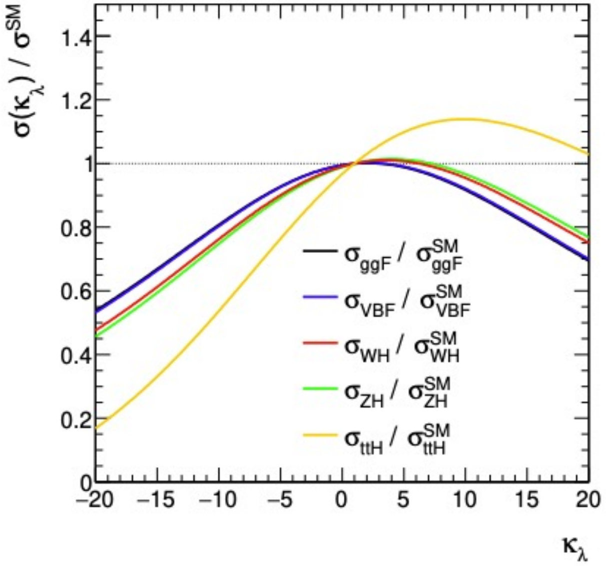
Universal correction $\boldsymbol{O(\kappa_\lambda^2)}$: Higgs loops

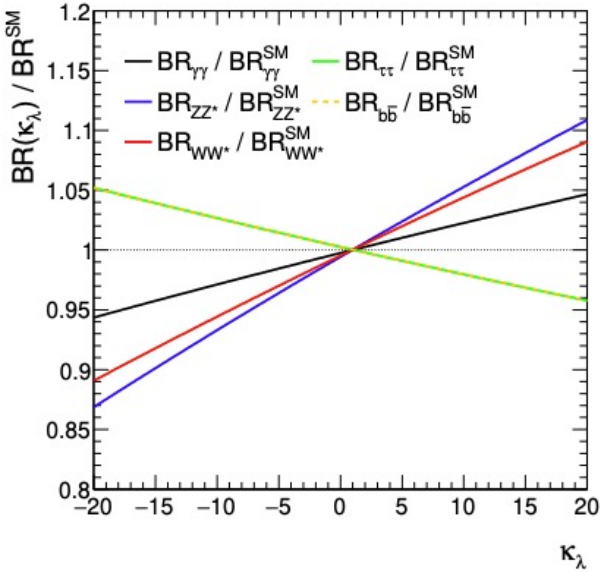
Linear correction $\boldsymbol{O(\kappa_\lambda)}$: both process and kinematics dependent

JHEP 2016, 80 (2016) - Eur. Phys. J. C77 (2017) 887

- Production modes cross section (i) and decay branching ratios (f) vary as a function of κ_λ
- Global normalization and differential distribution are modified
- Interpretation of single-Higgs-boson analyses using signal strength depending on κ_λ:

$$\boldsymbol{\mu_i^f(\kappa_\lambda) \equiv \mu_i(\kappa_\lambda) \times \mu^f(\kappa_\lambda) = \frac{\sigma_i(\kappa_\lambda)}{\sigma_{SM,i}} \times \frac{BR_f(\kappa_\lambda)}{BR_{SM,f}}}$$



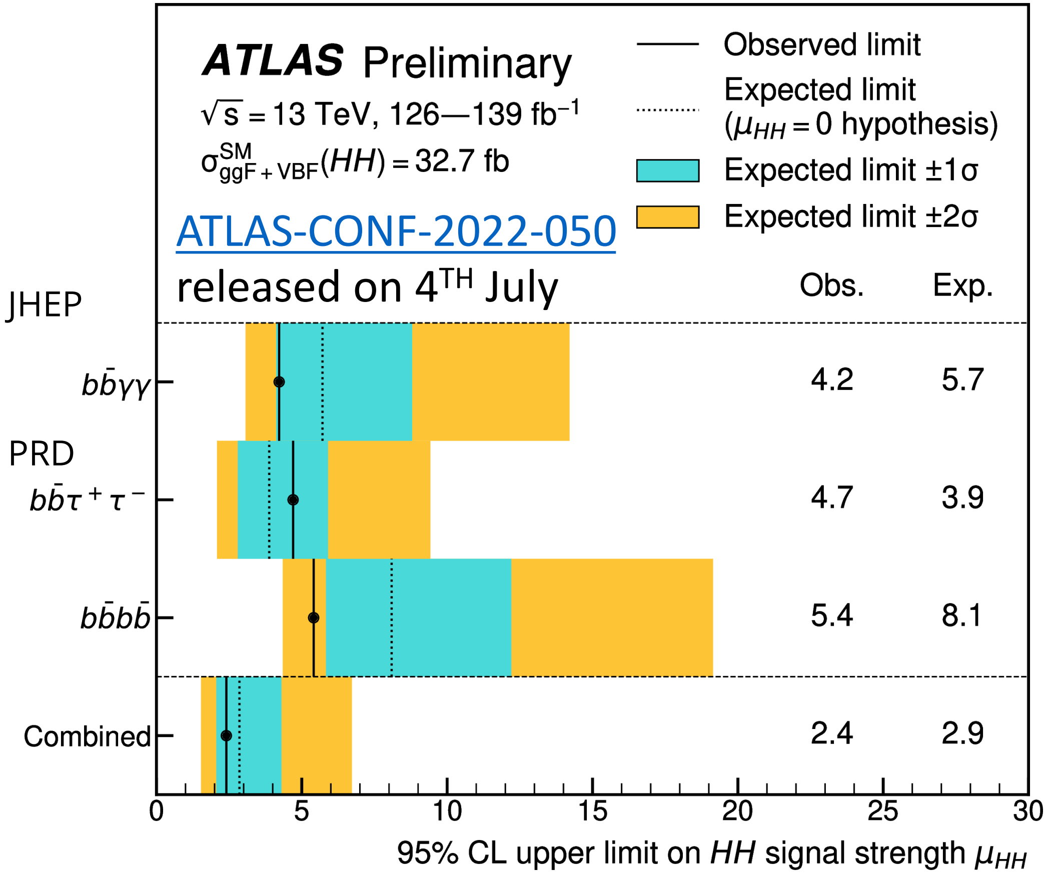


- Therefore precise measurements of inclusive and differential production cross sections and decays provide indirect constraints on κ_λ

New ATLAS combination: full Run 2 input analyses

- Take advantage of full Run 2 statistics using STXS differential information for single-Higgs channels (no STXS for ggF)

Channel	Integrated luminosity (fb^{-1})	Ref.
$HH \to b\bar{b}\gamma\gamma$	139	arXiv: 2112.11876
$HH \to b\bar{b}\tau\bar{\tau}$	139	ATLAS-CONF-2021-030
$HH \to b\bar{b}b\bar{b}$	126	ATLAS-CONF-2022-035
$H \to \gamma\gamma$	139	CERN-EP-2022-094 to appear on JHEP
$H \to ZZ^* \to 4\ell$	139	Eur. Phys. J. C 80 (2020) 957
$H \to \tau^+\tau^-$	139	arXiv:2201.08269
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139	CERN-EP-2022-078 to appear on PRD
$H \to b\bar{b}$ (VH)	139	Eur. Phys. J. C 81 (2021) 178
$H \to b\bar{b}$ (VBF)	126	Eur. Phys. J. C 81 (2021) 537
$H \to b\bar{b}$ ($t\bar{t}H$)	139	arXiv:2111.06712



- Using new single-Higgs results just released!
- Most sensitive HH analyses used: $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$

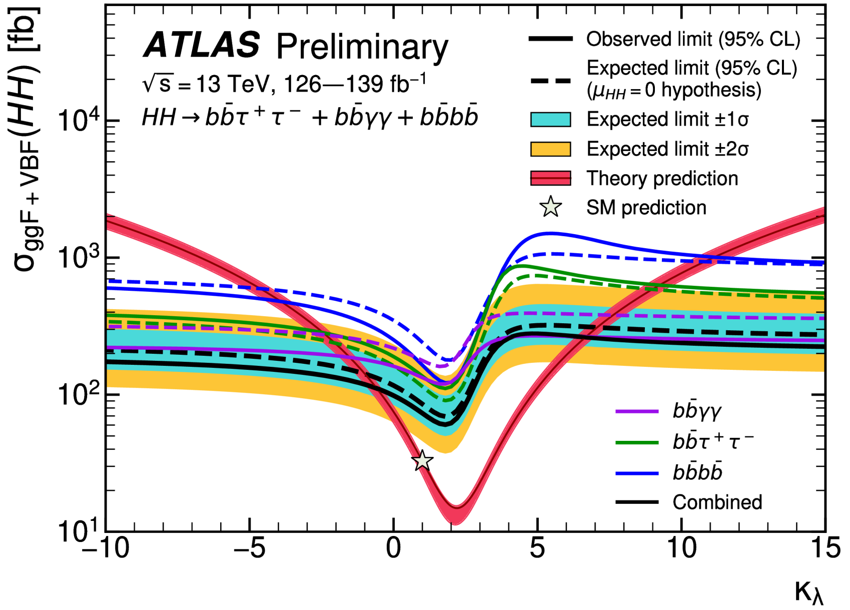
→ **NEW!!** Obs. (exp.) 95% CL combined limit on HH signal strength, assuming no HH production:

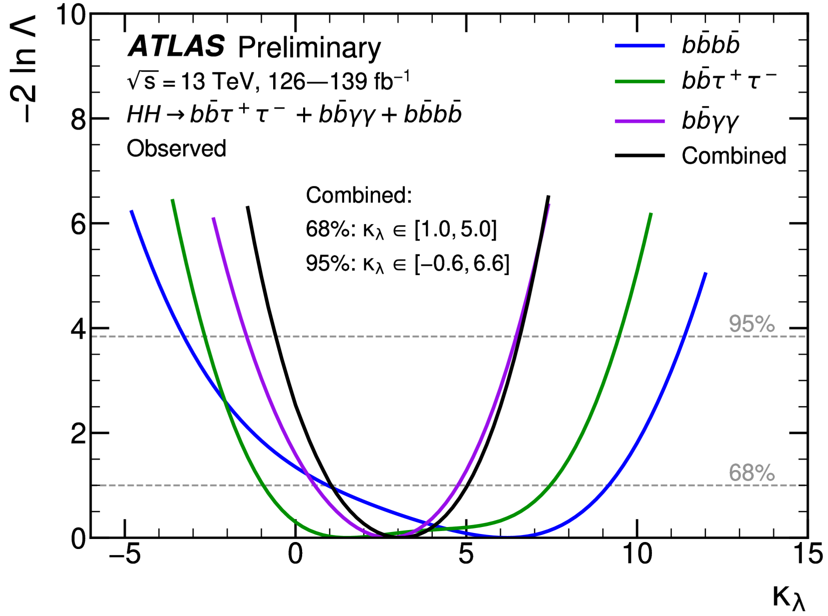
$$\mu_{HH} = \sigma^{HH}_{ggF+VBF} / \sigma^{HH,SM}_{ggF+VBF} = 2.4\ (2.9) \times SM$$

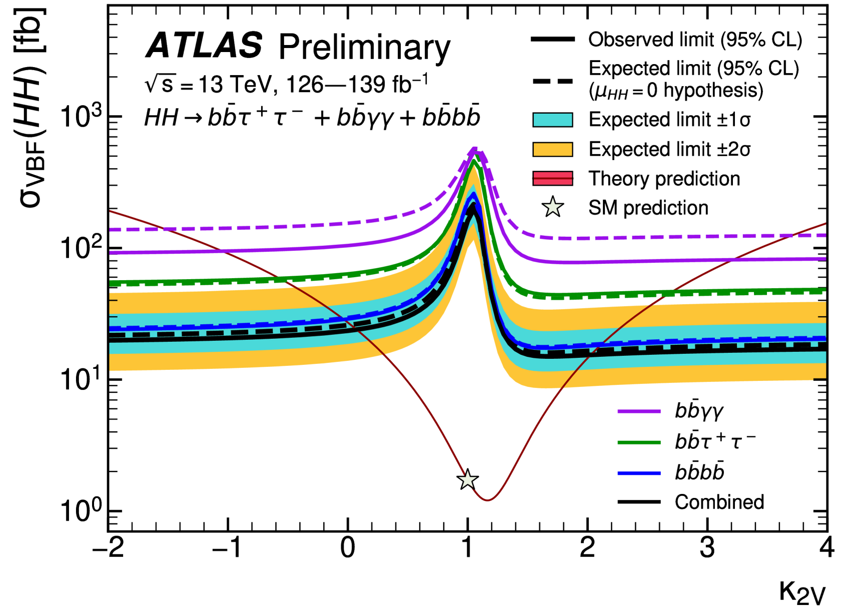
New HH results

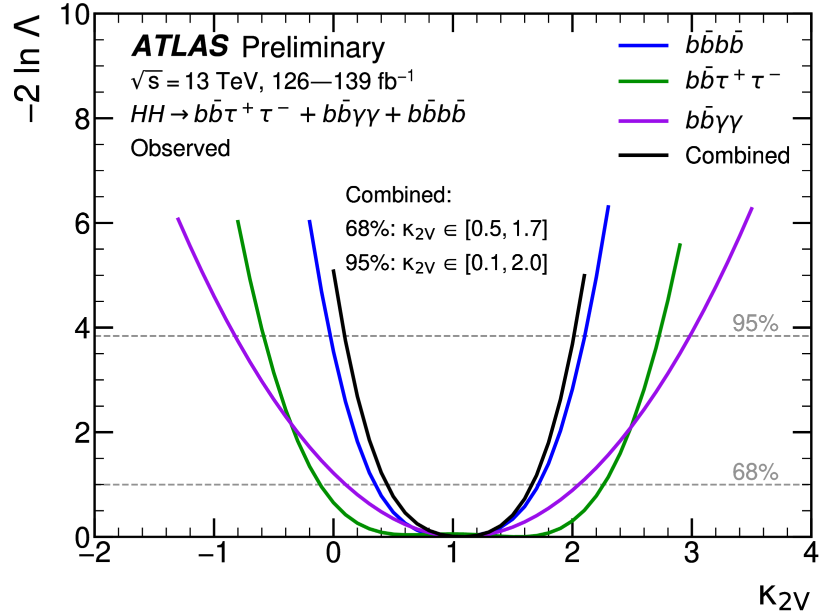
ATLAS-CONF-2022-050
released on 4TH July

Double-Higgs combination results









- 95% CL limits on HH cross section as a function of κ_λ (top left) and κ_{2V} (bottom left) have been derived, setting all the other couplings to their SM values
- Constraints on κ_λ and κ_{2V} from test statistics ($-2\ln\Lambda$) scans:

New HH results

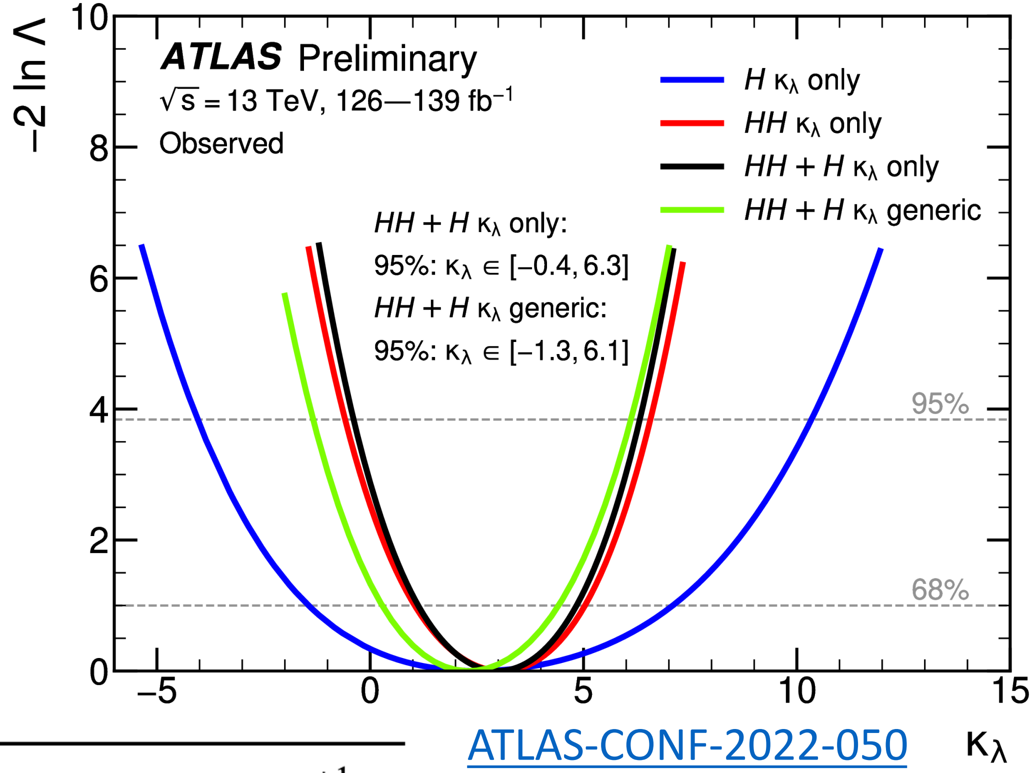
Observed (expected) 95% CL constraint on κ_λ of $\mathbf{-0.6 < \kappa_\lambda < 6.6}$ ($-2.1 < \kappa_\lambda < 7.8$)
→ Best result from $\boldsymbol{HH}$ to date!

Observed (expected) 95% CL constraint on κ_{2V} of $\mathbf{0.1 < \kappa_{2V} < 2.0}$ ($0.0 < \kappa_{2V} < 2.1$)

Single + Double-Higgs combination results

New $H + HH$ results

- Main advantage of the combination is the possibility to relax the assumptions on the coupling modifiers to other SM particles
- A global Likelihood function $L(\vec{\alpha}, \vec{\theta})$ is obtained as the product of the likelihoods of each input analyses
- Correlations between single-H and HH systematic uncertainties are taken into account
- Experimental constraints obtained on κ_λ via a scan of the negative-logarithm of the profile likelihood, for various fit configurations with different assumptions on coupling modifiers:



ATLAS-CONF-2022-050 released on 4TH July

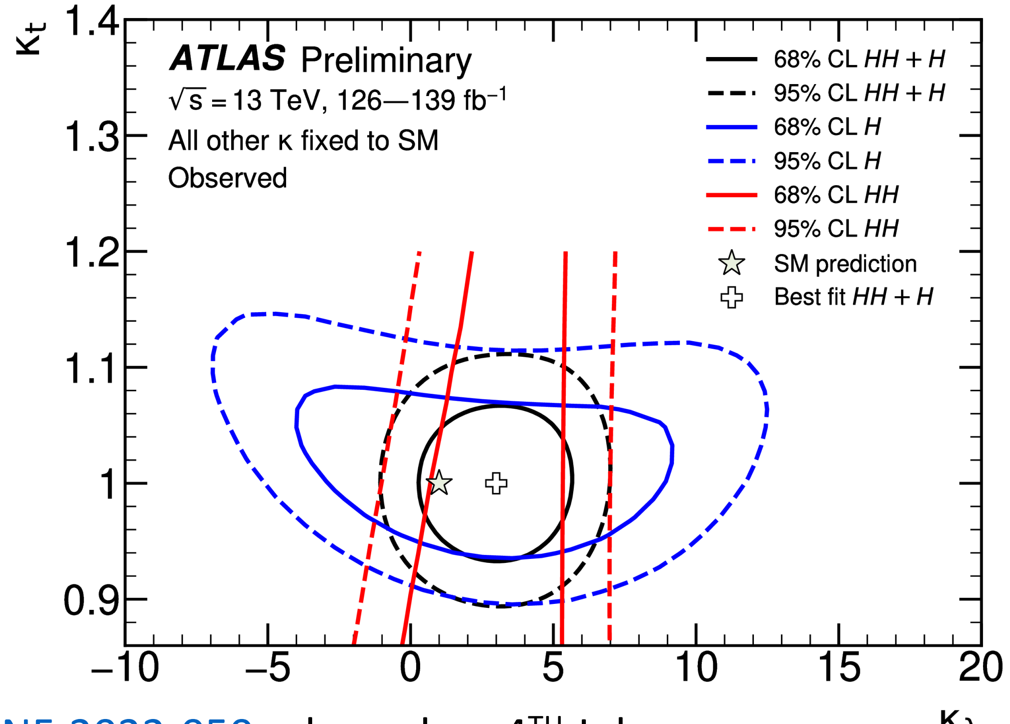
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

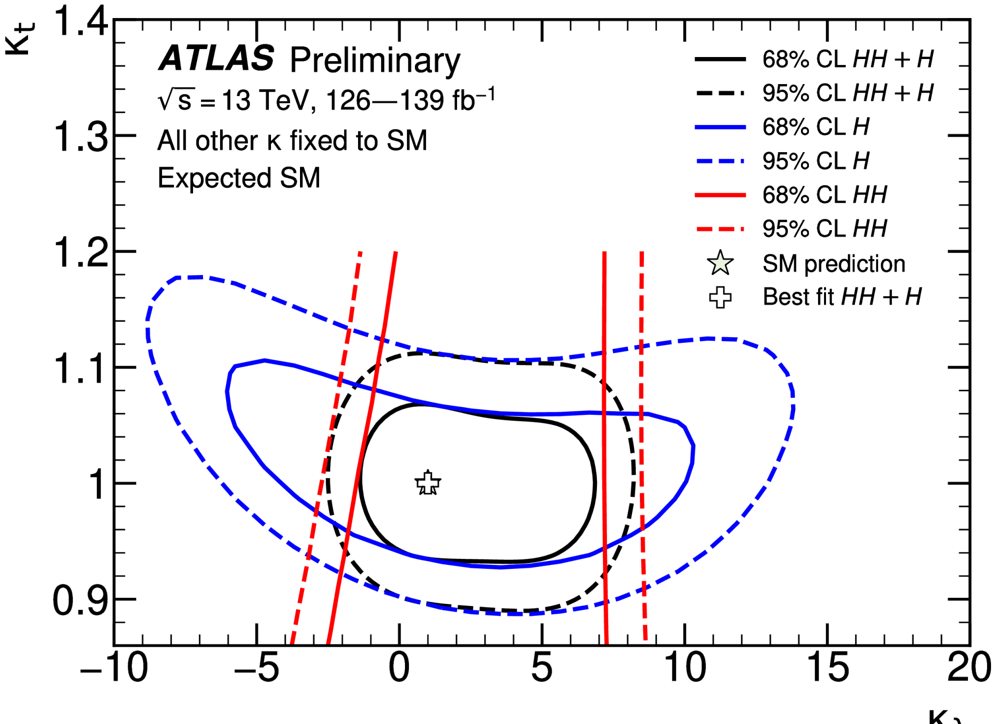
Most generic fit configuration → less model dependent results!

Single + Double-Higgs combination results

New $H + HH$ results

- Log-Likelihood contour plots are derived in the $\kappa_\lambda - \kappa_t$ plane from the fit with the only these two parameters floating
- Strong constraints on κ_t coming from single-Higgs measurements
- Big improvement obtained with respect to the previous combination result $(27.5 - 79.8\ fb^{-1})$
- Stronger constraints both from single-Higgs and from double-Higgs updated measurements





ATLAS-CONF-2022-050 released on 4TH July

Conclusions

- The most up-to-date single- and double-Higgs boson analyses, which are based on the complete Run 2 LHC dataset collected by the ATLAS detector, have been recently combined to investigate the Higgs boson self-interaction
- New combination of $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ double-Higgs analyses:
  - Observed (expected) **upper limit of $\mathbf{2.4}$ ($\mathbf{2.9}$) at $\mathbf{95\%}$ $\boldsymbol{CL}$ on $\boldsymbol{\mu_{HH}}$**
  - Observed constraint of $\mathbf{-0.6} < \boldsymbol{\kappa_\lambda} < \mathbf{6.6}$ at 95% CL with κ_λ-only fit, best limit to date from HH analyses!
  - Observed constraint of $\mathbf{0.1} < \boldsymbol{\kappa_{2V}} < \mathbf{2.0}$ at 95% CL, exploiting VBF HH production mode sensitivity
- More stringent and less model dependent constraints on κ_λ obtained from $H + HH$ analyses combination:
  - Observed constraint of $\mathbf{-0.4} < \boldsymbol{\kappa_\lambda} < \mathbf{6.3}$ (exp. $-1.9 < \kappa_\lambda < 7.5$) at 95% CL with κ_λ-only fit
  - Observed constraint of $\mathbf{-1.3} < \boldsymbol{\kappa_\lambda} < \mathbf{6.1}$ (exp. $-2.1 < \kappa_\lambda < 7.6$) at 95% CL with generic fit (κ_λ, κ_t, κ_b, κ_τ, κ_V floating)
  - **Less model dependent** but still strong **constraint on Higgs boson self-coupling** obtained from generic fit
- To date, this study provides the most stringent constraints on the Higgs boson self-coupling!

Thanks for the attention!

Backup

$\boldsymbol{HH}$ decay modes

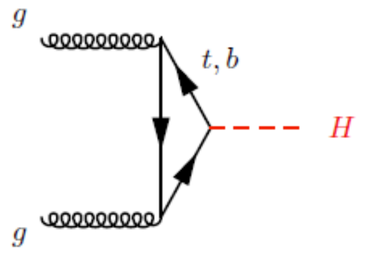
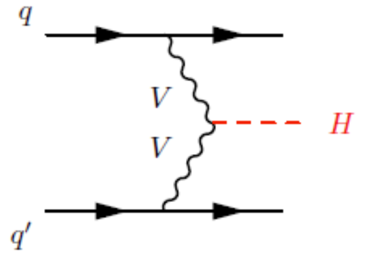
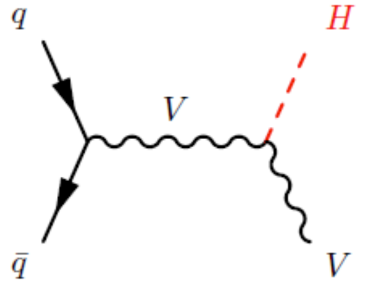
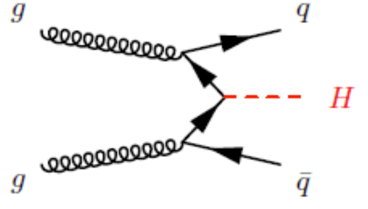
Larger BR from $H \to bb$ decay, required by the majority of analyses for one of the two H decays.

For the second Higgs, analyses focus on different decay modes, in particular the most used are:

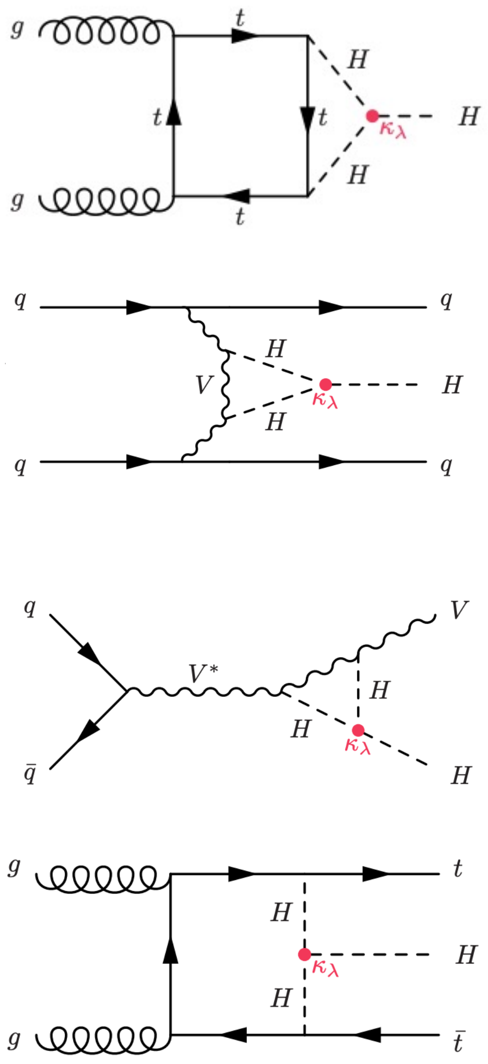
- $\boldsymbol{b\bar{b}b\bar{b}}$: larger BR, but challenging backgrounds from multijet production
- $\boldsymbol{b\bar{b}WW}$: second leading BR, large $t\bar{t}$ background, searches in both semi-leptonic and di-leptonic final states
- $\boldsymbol{b\bar{b}\tau\tau}$ and $\boldsymbol{b\bar{b}ZZ}$: smaller BRs, leptons (e/μ) or hadronic-τ used for triggering depending on the final state
- $\boldsymbol{b\bar{b}\gamma\gamma}$: smallest BR but very sensitive analysis thanks to the excellent acceptance ($\gamma\gamma$ trigger) and reconstruction resolution

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

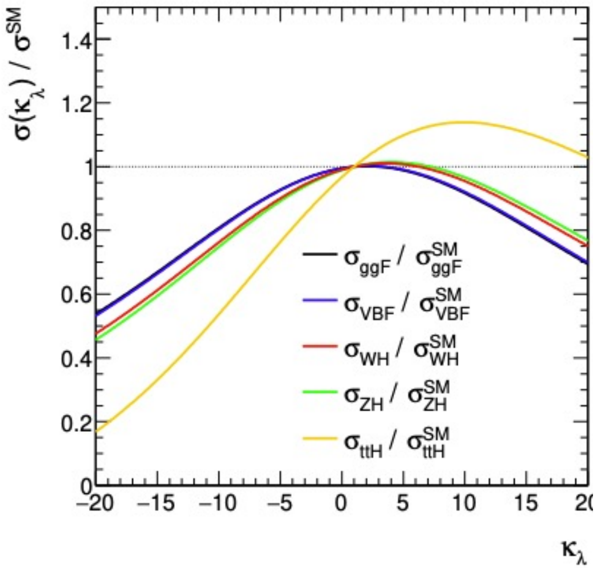
Self-coupling in Single-Higgs processes

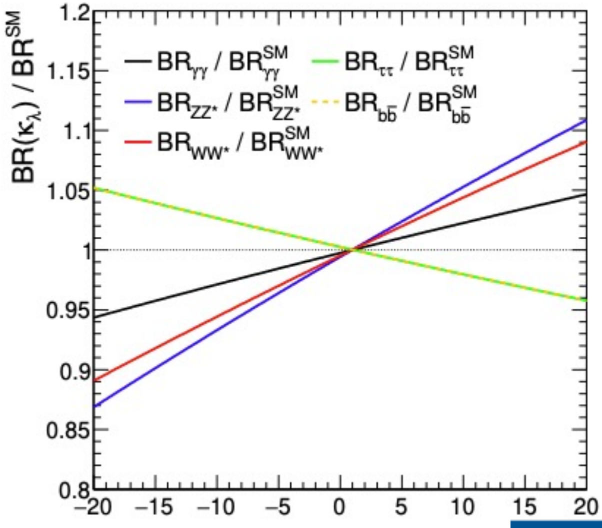
Production mode	LO diagram
ggF production	
VBF production	
VH production	
$q\bar{q}H$ production	

NLO diagrams



- Single-Higgs processes are indirectly sensitive to κ_λ via NLO EW corrections
- Production modes cross section (i) and decay branching ratios (f) vary as a function of κ_λ
- Global normalization and differential distribution are modified
- Interpretation of single-Higgs-boson analyses using signal strength depending on κ_λ: $\mu_i^f(\kappa_\lambda) \equiv \mu_i(\kappa_\lambda)\times\mu^f(\kappa_\lambda)$





Self-coupling impact on Single-Higgs

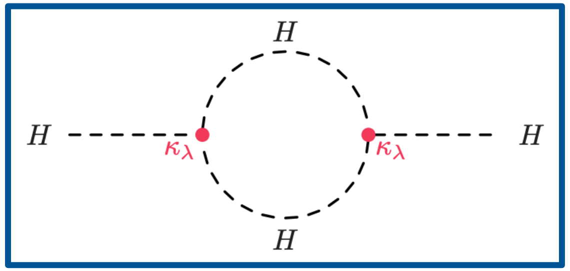
$$\boldsymbol{\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda)}$$

Impacts on the production modes (i) and the decay channels (f) expressed as:

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

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

Z_H^{BSM}: wave function renormalization, accounts for the universal correction



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

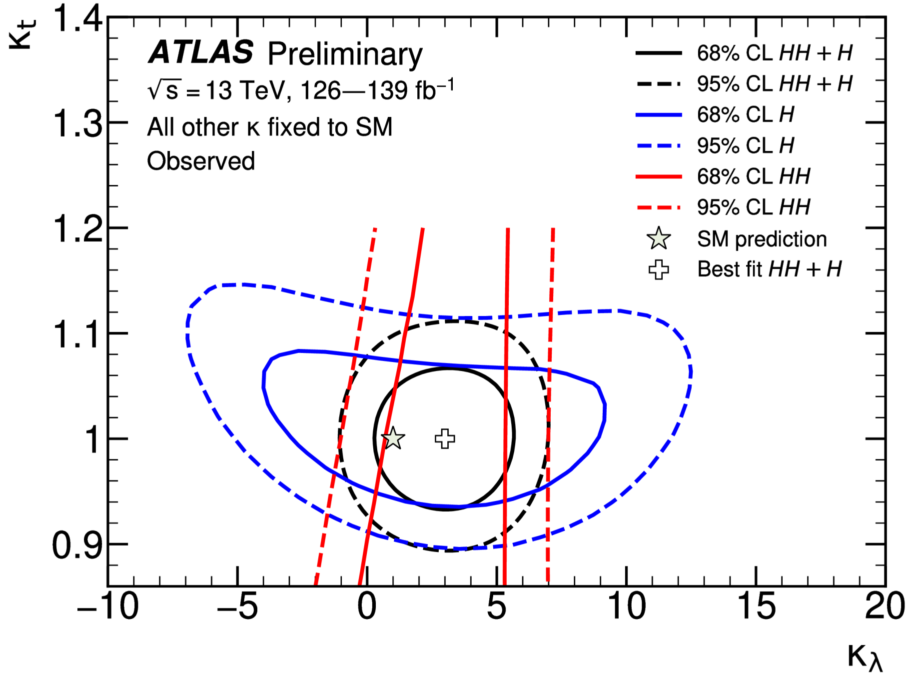
C_1: process and kinematic-dependent coefficients, it encodes the magnitude of the kl-dependent linear correction

K_{EW}: represents the full set of NLO EW corrections

κ_f and κ_i consist of: κ_λ, $\kappa_V (= \kappa_W = \kappa_Z)$, κ_t, κ_b, κ_τ, $\kappa_c (= \kappa_t)$, $\kappa_s (= k_b)$, $\kappa_\mu (= \kappa_\tau)$

ATLAS-CONF-2022-050
released on 4TH July

Single + Double-Higgs combination results



Best fit values for κ_λ and κ_t for the different fits with both coupling modifiers floating and the others set to 1:

Data	κλ	κt
H	2.5	1.0
HH	1.2	**0.1**
HH+H	3.0	1.0

From HH to HH+H: κ_t shift from 0.1 to 1
→ Therefore the constraining power on κ_λ change as well

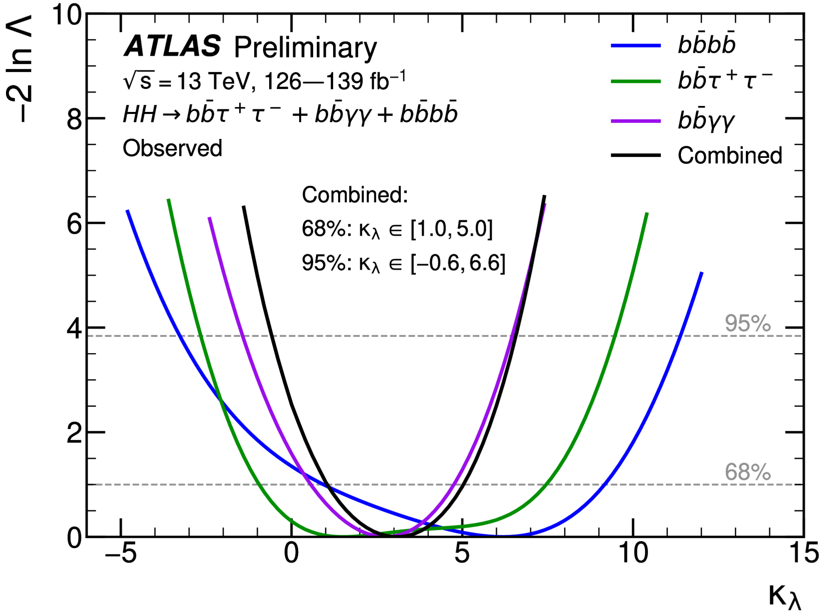
Comparison with most generic fit:

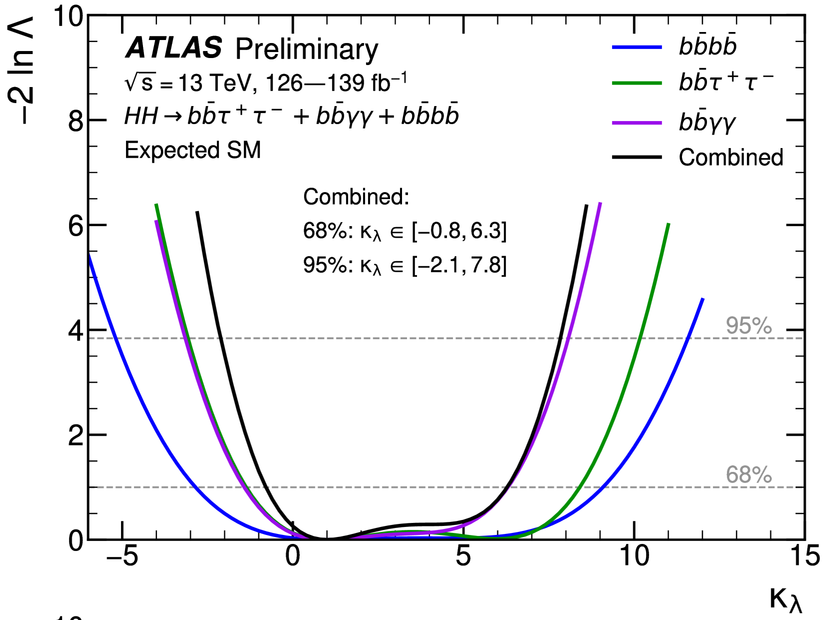
- Post-fit values of coupling modifiers for κ_λ-only and generic fit configurations
- Other couplings κ_t, κ_b, κ_τ goes below 1 causing κ_λ best fit value to go from 3.0 to 2.3

POIs	$\kappa_V{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\tau{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ	1	1	1	1	$3.0^{+1.8}_{-1.9}$	$[-0.4, 6.3]$	Obs.
					$1.0^{+4.8}_{-1.7}$	$[-1.9, 7.5]$	Exp.
κ_λ-κ_t fit	1	$1.00^{+0.05}_{-0.04}$	1	1	$3.0^{+1.8}_{-1.9}$	$[-0.4, 6.3]$	Obs.
		$1.00^{+0.05}_{-0.04}$			$1.0^{+4.8}_{-1.7}$	$[-1.9, 7.6]$	Exp.
Generic fit	$1.00^{+0.05}_{-0.05}$	$0.93^{+0.07}_{-0.06}$	$0.90^{+0.12}_{-0.11}$	$0.93^{+0.08}_{-0.07}$	$2.3^{+2.1}_{-2.0}$	$[-1.3, 6.1]$	Obs.
	$1.00^{+0.05}_{-0.05}$	$1.00^{+0.07}_{-0.07}$	$1.00^{+0.12}_{-0.12}$	$1.00^{+0.08}_{-0.08}$	$1.0^{+5.0}_{-1.8}$	$[-2.1, 7.6]$	Exp.

ATLAS-CONF-2022-050
released on 4TH July

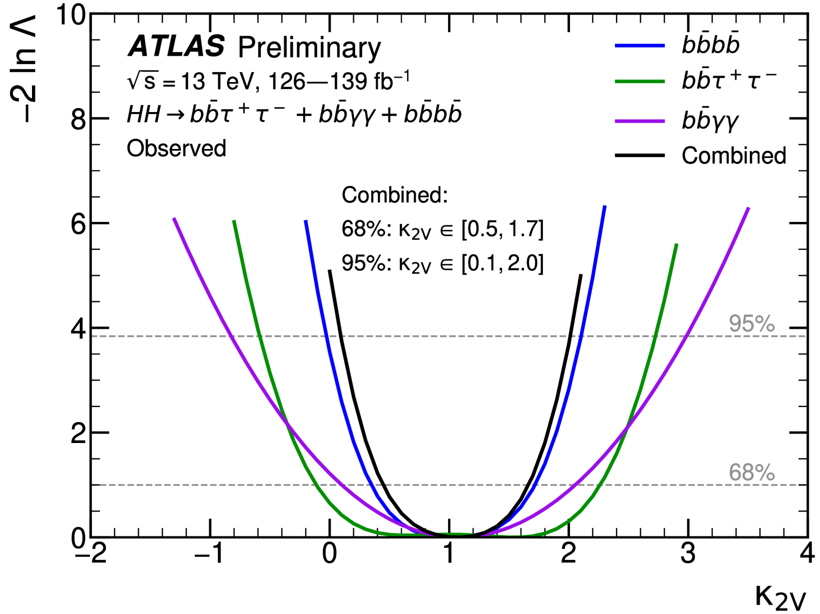
Double-Higgs combination results

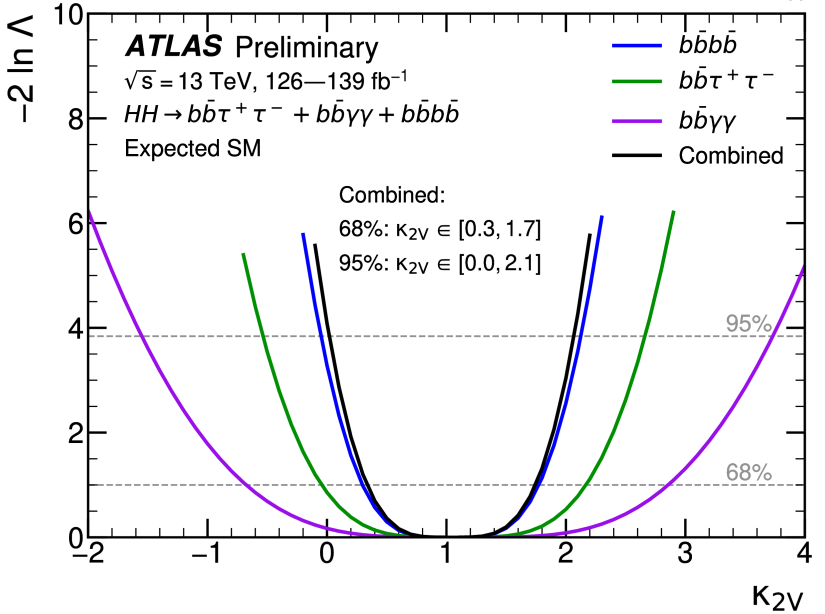




Observed (left) and expected (right) value of the test statistics ($-2\ \ln\Lambda$), as a function of the κ_λ (top) and κ_{2V} (bottom) parameter for the three leading HH analyses and their combination.

All other coupling modifiers are fixed to their SM value.



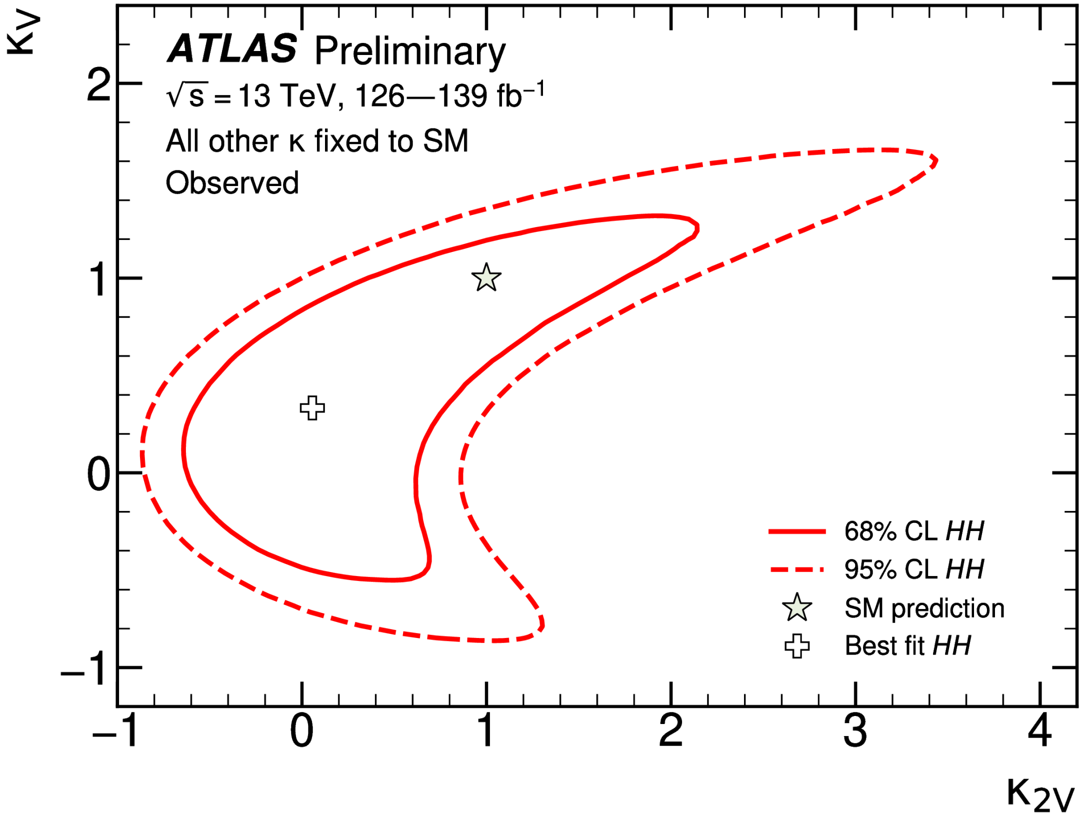


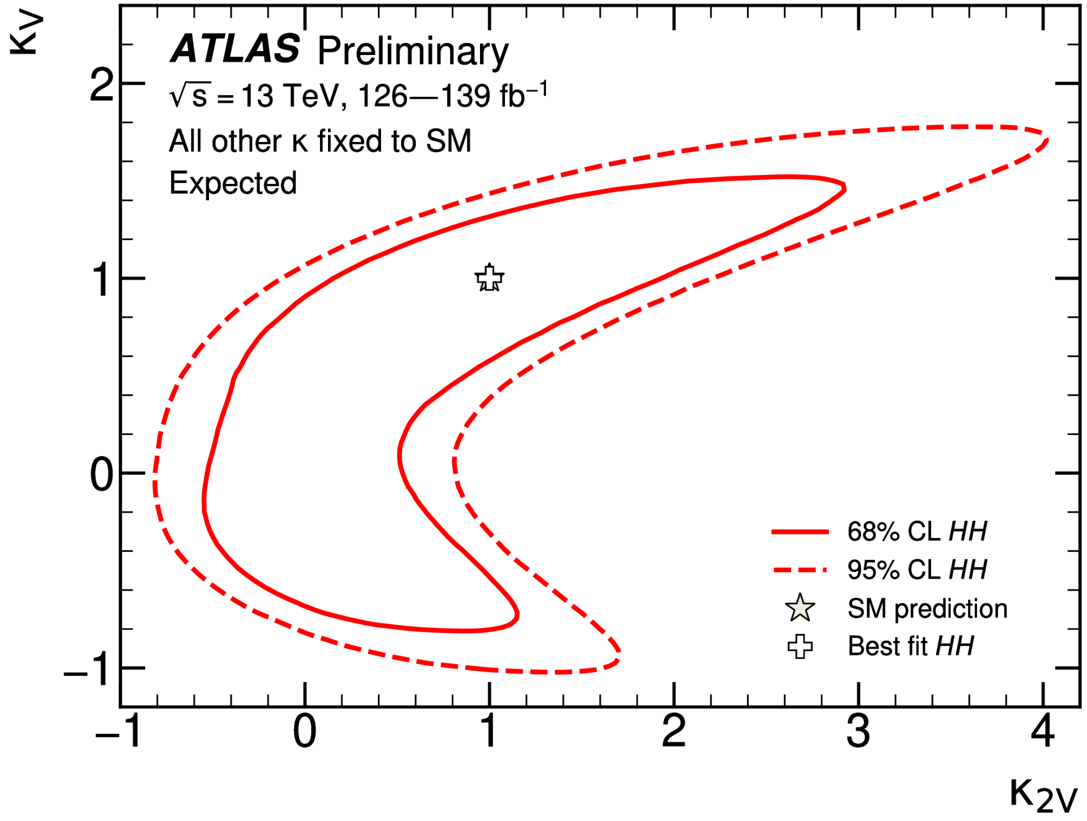
Observed (expected) 95% CL constraint on κ_λ of $\mathbf{-0.6 < \kappa_\lambda < 6.6}$ $(-2.1 < \kappa_\lambda < 7.8)$
→ Best result from $\boldsymbol{HH}$ to date!

Observed (expected) 95% CL constraint on κ_{2V} of $\mathbf{0.1 < \kappa_{2V} < 2.0}$ $(0.0 < \kappa_{2V} < 2.1)$

ATLAS-CONF-2022-050
released on 4TH July

Double-Higgs combination results

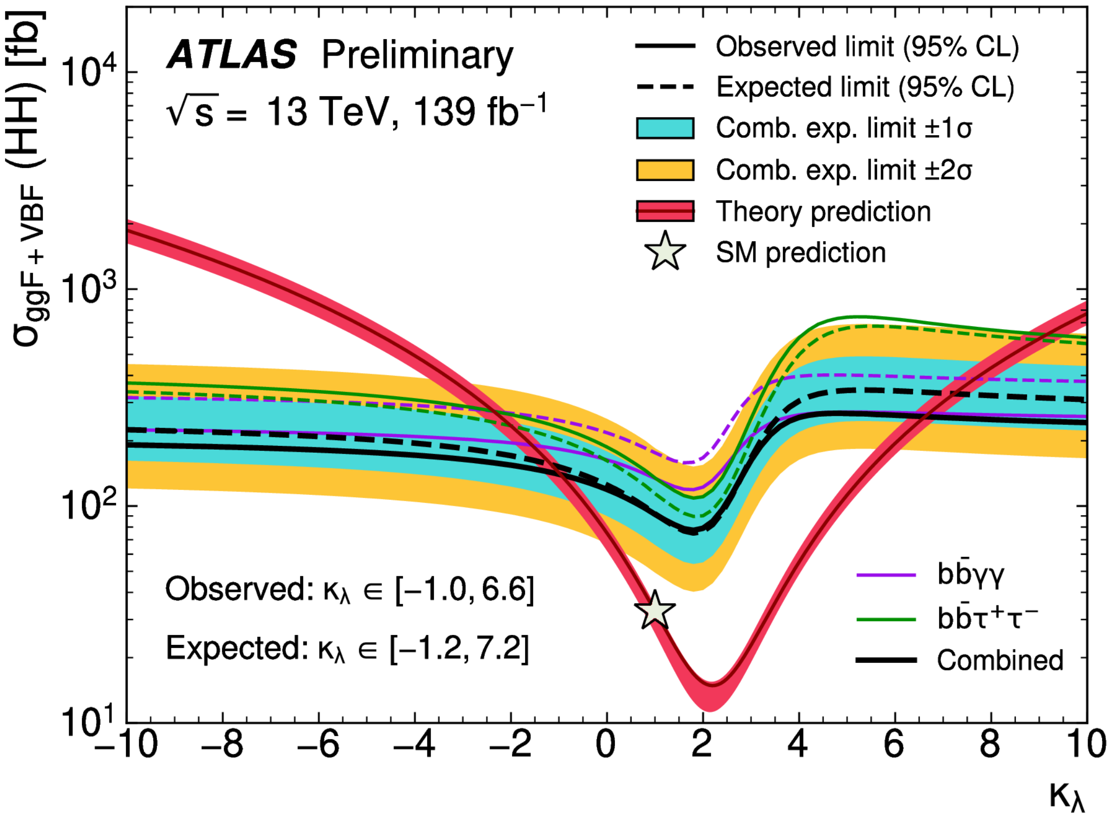


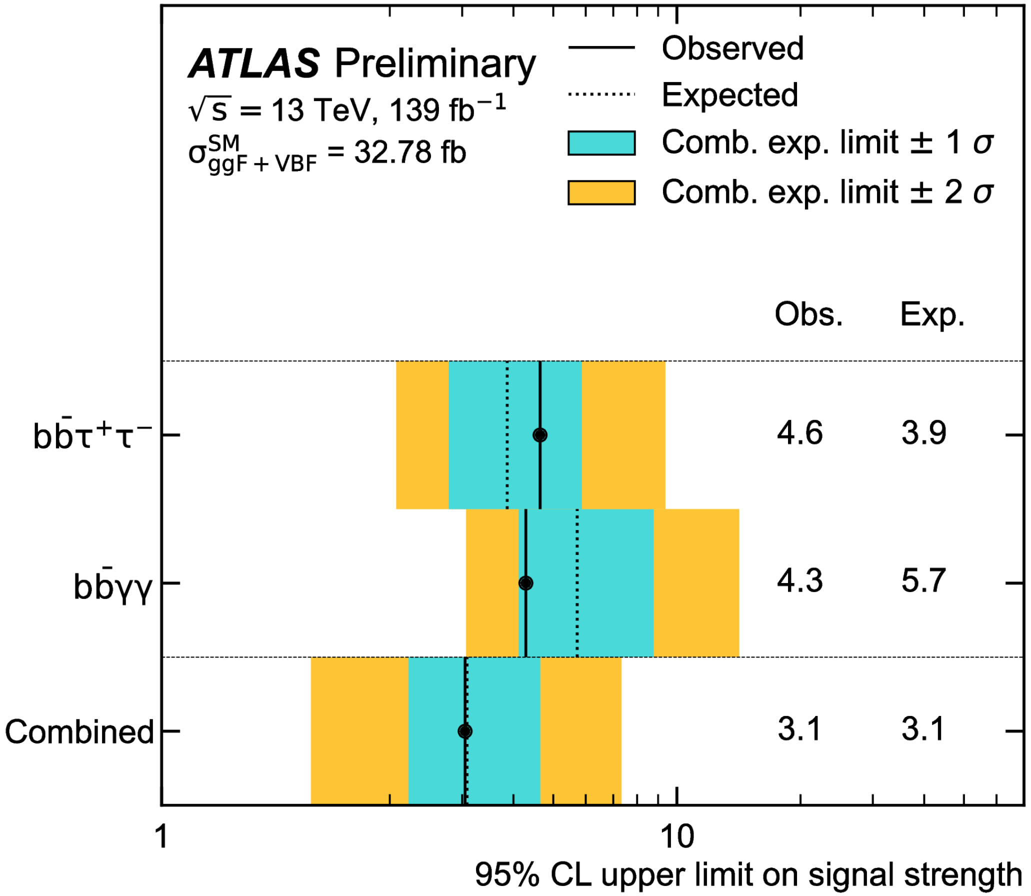


Observed (left) and expected (right) constraints in the κ_{2V}–κ_V plane from double-Higgs combination
The solid (dashed) lines show the 68% (95%) CL contours.

ATLAS HH combination (before including $HH \to b\bar{b}b\bar{b}$)

- Preliminary combination of the non-resonant HH searches
- Combination of $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ full Run2 non-resonant analyses leads to improved observed (expected) limits at 95%CL:
  - $\sigma^{HH}_{ggF+VBF} < 3.1\ (3.1) \times \sigma^{HH\,SM}_{ggF+VBF}$
  - $-1.0\ (-1.2) < \kappa_\lambda < 6.6\ (7.2)$





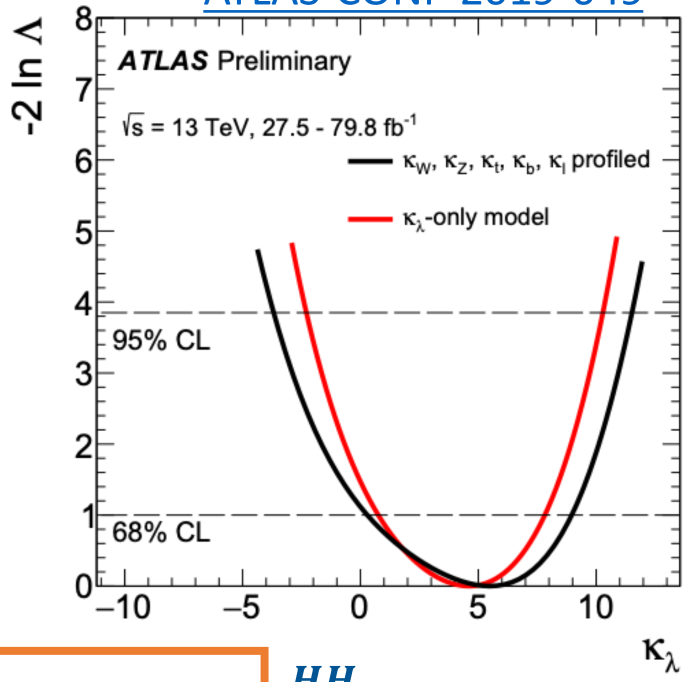
ATLAS-CONF-2021-052

Previous ATLAS $H + HH$ combination

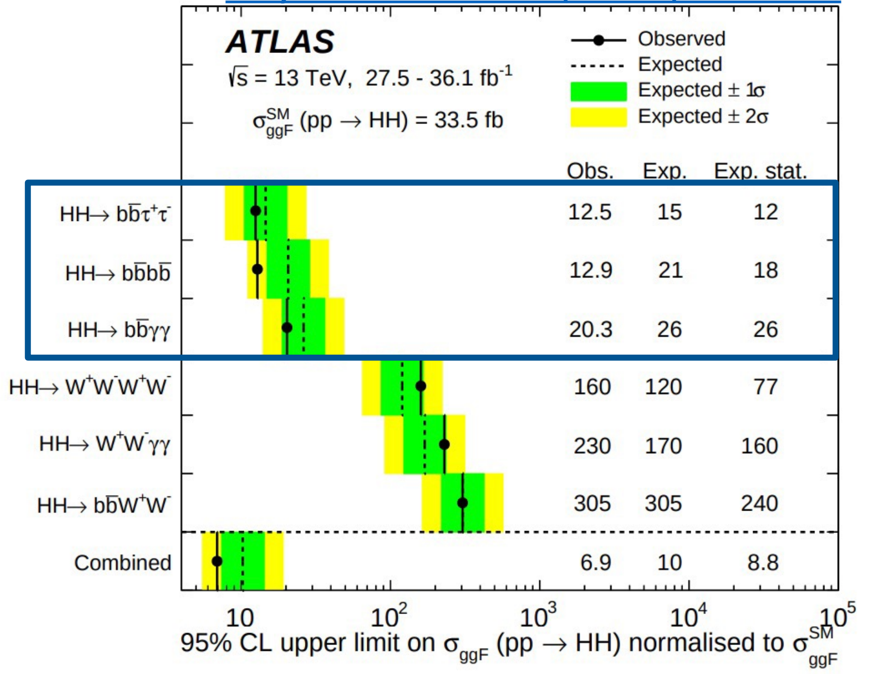
- Combination of partial Run 2 most sensitive HH analyses and single-Higgs analyses
- Simplified Template Cross Section (STXS) for VH and VBF production modes used to include differential information
- Results obtained fitting κ_λ-only (all other couplings set to 1), and with a generic model fitting all $\kappa_\lambda, \kappa_t, \kappa_b, \kappa_l, \kappa_V$ couplings

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

ATLAS-CONF-2019-049



Phys. Lett. B 800 (2020) 135103



$H + HH$

$\kappa_\lambda = 4.6^{+3.2}_{-3.8}$ best fit value κ_λ-only
$\kappa_\lambda = 5.5^{+3.5}_{-5.2}$ best fit value generic model
κ_λ-only constraint at 95% $C.L.: -2.3 < \kappa_\lambda < 10.3$
Generic model constraint at 95% $C.L.: -3.7 < \kappa_\lambda < 11.5$

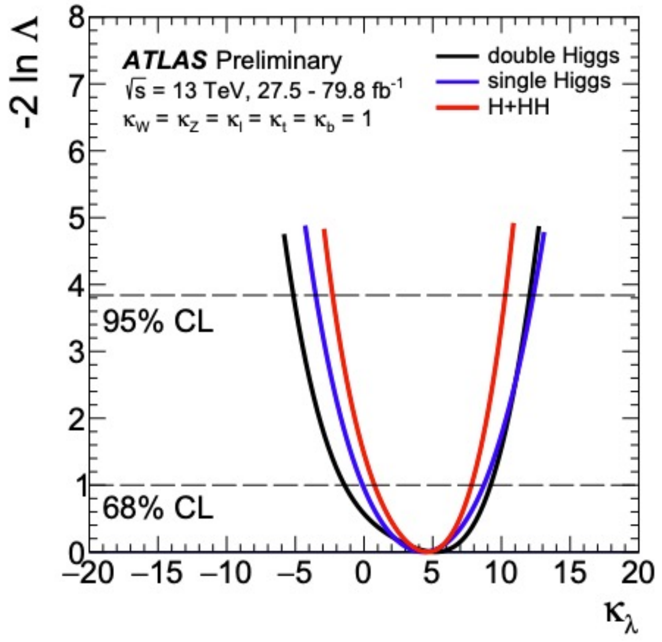
HH

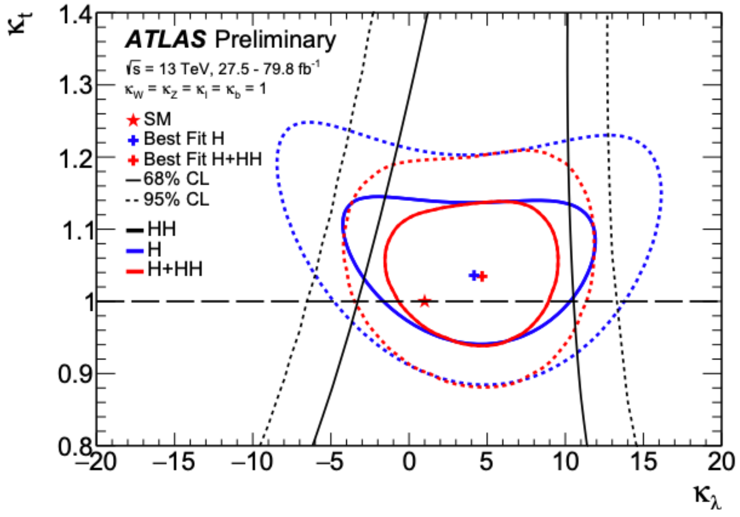
HH production signal strength result from HH analyses

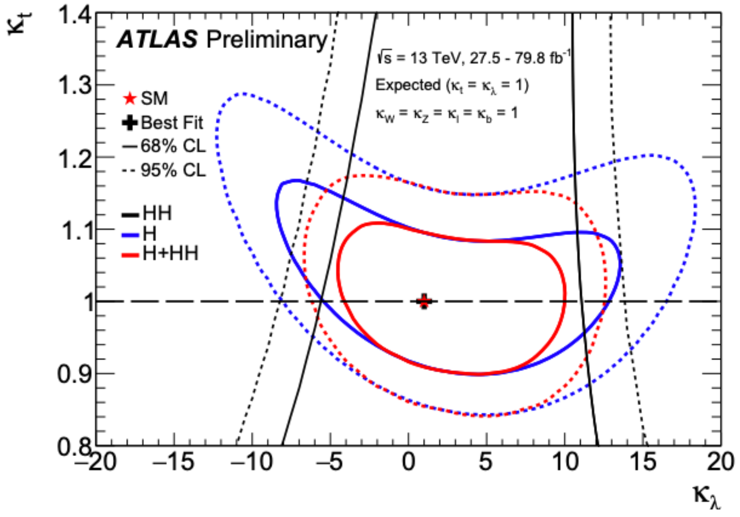
Excluding at 95% $C.L.: \sigma_{ggF}(pp \to HH) > 6.9 \times SM$

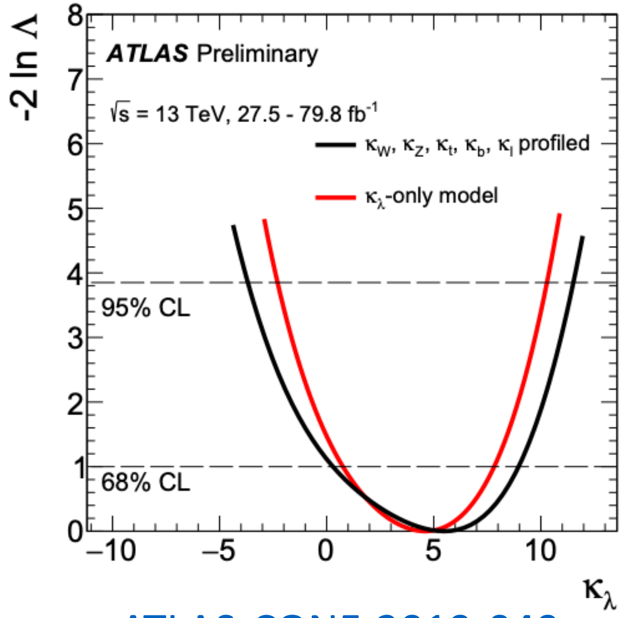
Previous ATLAS $H + HH$ combination

- Partial Run2 combination of single-Higgs and double-Higgs analyses
- Performed fit with only κ_λ floating and a generic fit with all coupling modifiers floating obtaining observed (expected) constraints on κ_λ at $95\%\ CL$:
  - κ_λ-only fit: $-2.3\ (-5.1) < \kappa_\lambda < 10.3\ (11.2)$
  - Generic fit: $-3.7\ (-6.2) < \kappa_\lambda < 11.5\ (11.6)$







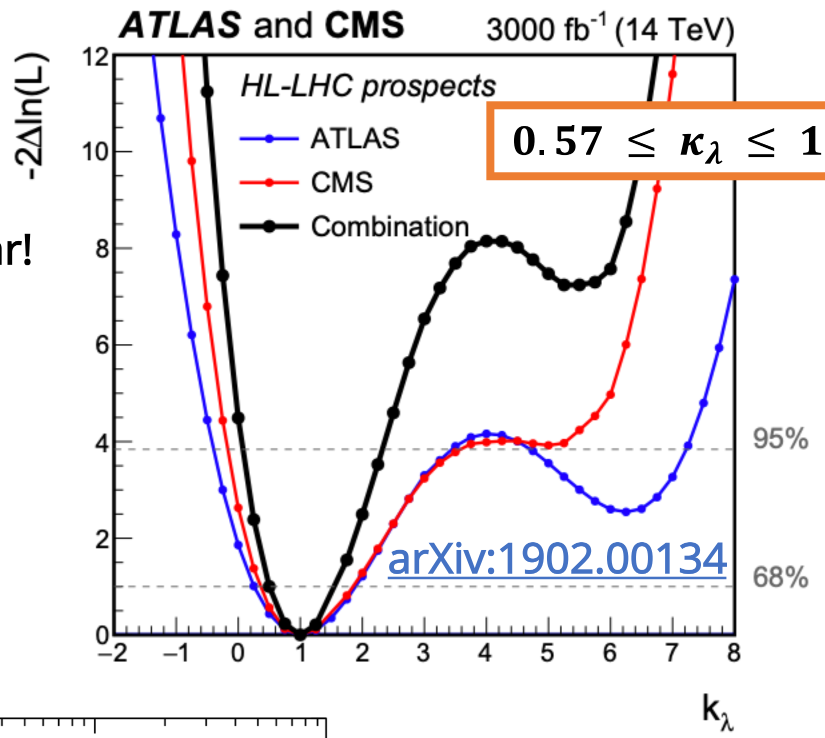


$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_{lep}{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]	
1	1	1	1	1	$4.6^{+3.2}_{-3.8}$	$[-2.3, 10.3]$	Obs.
					$1.0^{+7.3}_{-3.8}$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

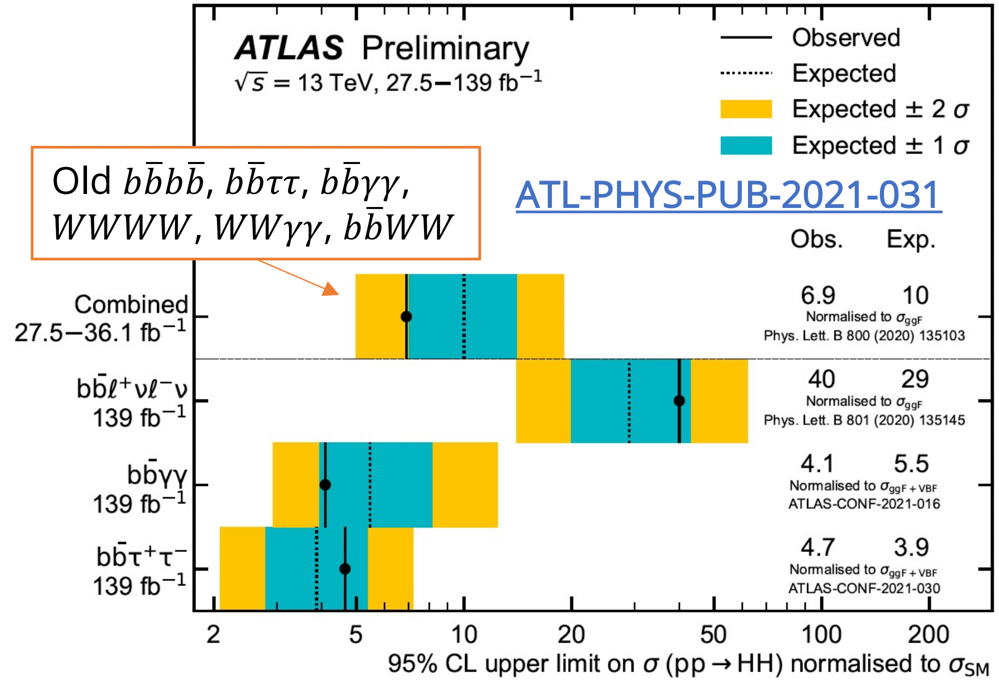
ATLAS-CONF-2019-049

Other results and prospects

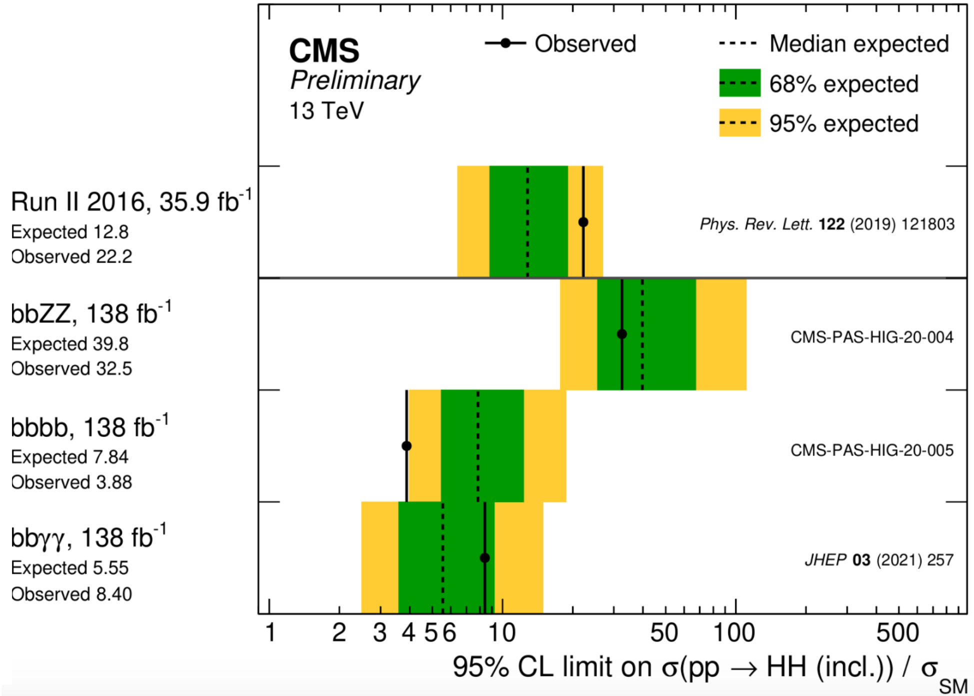
- Many new results in different HH decay channels released in the last year! And more channels coming soon!!!
- Improved limits with larger statistics and new MVA analysis techniques
- VBF production mode now accessible and results on κ_{2V} released
- Resonant HH limits improved with MVA boosted topology reconstruction
- Prospects done scaling partial-Run2 results to High-Lumi statistics



$0.57 \le \kappa_\lambda \le 1.5$



Old $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $WWWW$, $WW\gamma\gamma$, $b\bar{b}WW$



Now finishing the last analyses and combinations

Then looking forward to Run3 and High-Lumi!!