Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

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On behalf of the ATLAS Collaboration

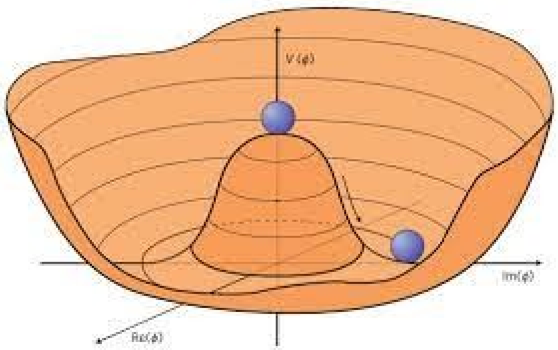
DIS 2023
March 27th-31th 2023

Higgs self coupling

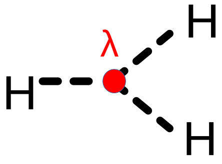
Higgs potential:

$$V(\Phi)=\mu_2\Phi*\Phi+\lambda|\Phi*\Phi|$$

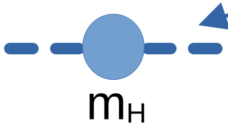
The λ can be measured directly in double Higgs boson production processes.



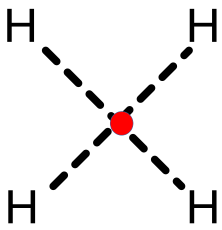
expanding around minimum:



$$V(h)\simeq\frac{1}{2}m_H^2h^2+\lambda\upsilon h^3+\frac{1}{4}\lambda h^4+\dots$$



Probably beyond LHC - not enough data from LHC will be collected



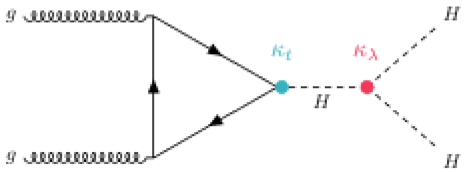
$K_\lambda=\lambda/\lambda_{SM}$, if $K_\lambda > 1$ could indicate processes beyond SM.

The measuring of λ is not the only way to probe the electroweak symmetry-breaking mechanism. Exist many scenarios with the extended Higgs sector - see Anna's talk

Double Higgs production

ggF: σ_{SM} ~ 31.5 fb

Coupling modifier $K_\lambda = \lambda/\lambda_{SM}$



involves Higgs bosons self - coupling

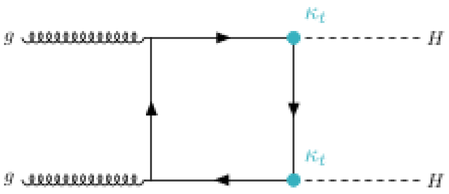
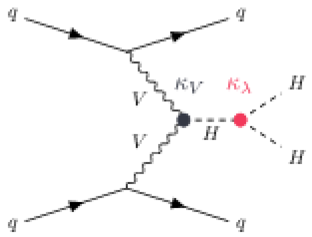
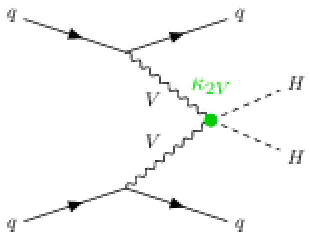


diagram interferes destructively

VBF: σ_{SM} ~ 1.72 fb



Sensitive for K_λ



Access to HHVV coupling via K_{2V} coupling modifier

Two extra forward jets, unique signature

HH decay mode	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%

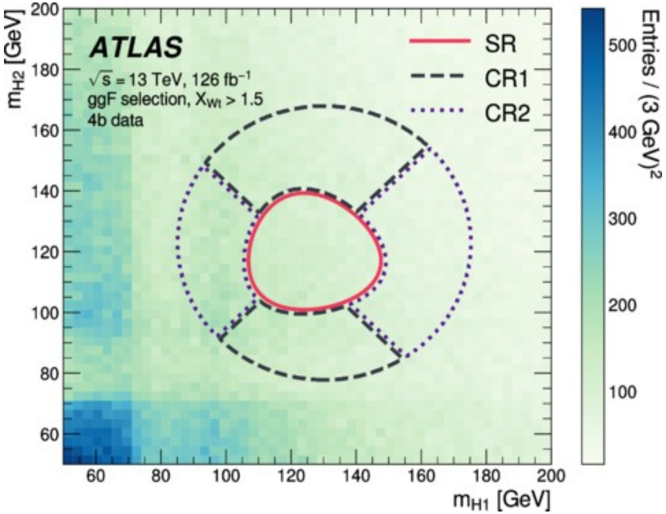
Multiple diHiggs production channels:
- 4b – largest BR, huge background
- bbττ – small BR with relatively low background
- bbγγ – very small BR, but clean channel with low background,
- the channels listed over will be discussed in this talk
- combination of the sensitive channels provide more precise results

HH → 4b

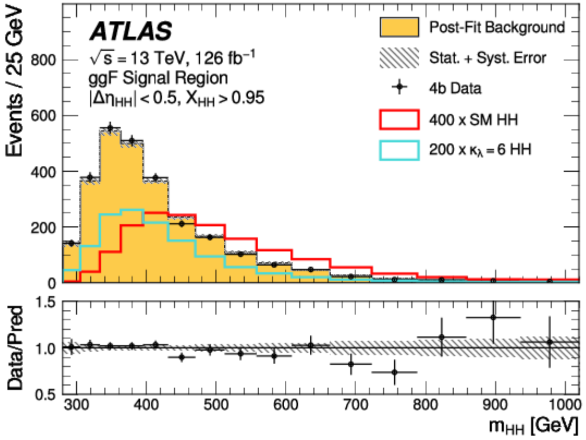
Event selection:
- 4 b-tagged jets
- Forward jets used to separate ggF and VBF regions
- Cut on HH and ttbar sensitive variables X_{HH} and X_{Wt}
- $|\Delta\eta_{HH}|$ and X_{HH} categories to improve κ_λ and κ_{2V} sensitivity

Analysis strategy:
- Jets paired to minimize ΔR for p_T leading dijet system
- Data from 2b region reweighed to 4b SR (data-driven bkg estimates)
- m_{HH} distribution used to final results

HDBS-2019-24



HDBS-2019-24

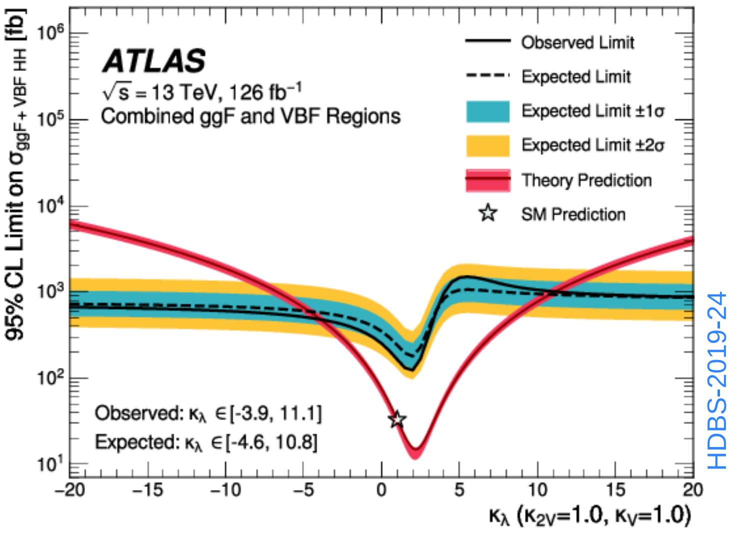


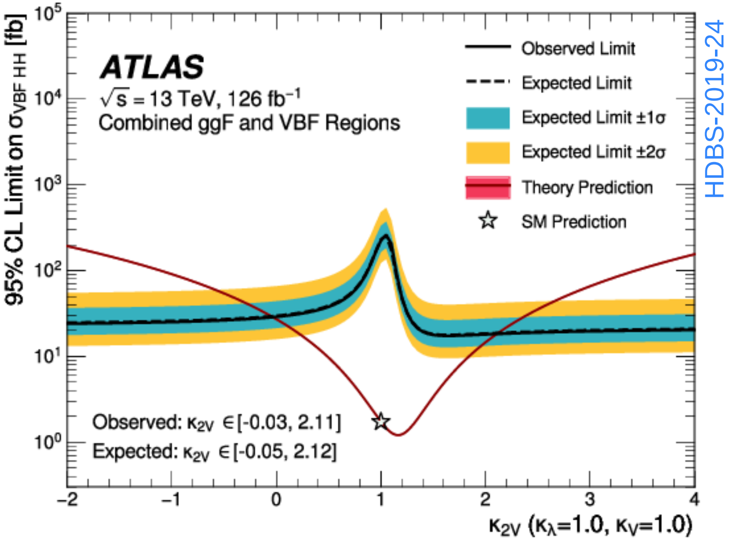
arXiv:2301.03212

Non-resonant production

HH → 4b results

σ_{HH} (Kλ=1,KV=1) < 5.4 σ_{SM} observed
8.1 σ_{SM} expected





Observed: -3.9< K_λ < 11.1
Expected: -4.6< K_λ < 10.8

Observed: -0.03< K_{2V} < 2.11
Expected: -0.05< K_{2V} < 2.12

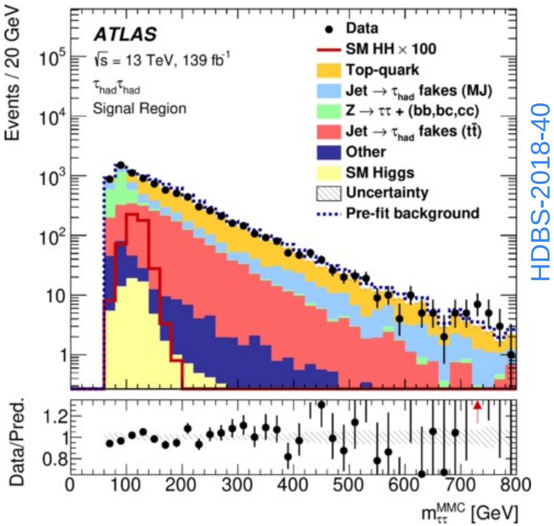
arXiv:2301.03212

HH->bbττ

Event selection:

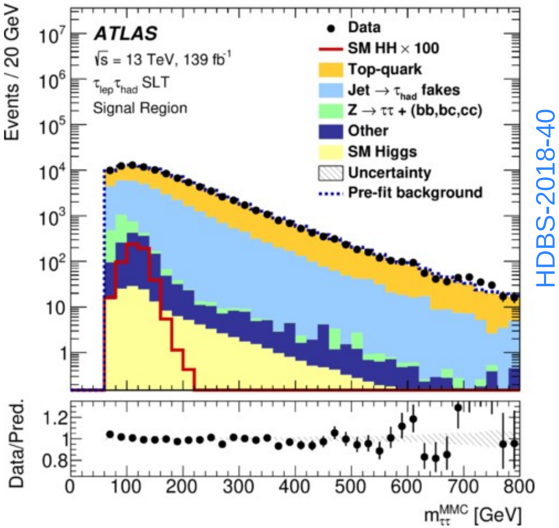
- ♦ Exactly 2 b-tagged jets
- ♦ 1 hadronic τ and 1 e/μ or 2 hadronic τ
- ♦ $\tau_{had}\tau_{had}$ – pass single-$\tau_{had\text{-}vis}$ triggers STTs ,p_T > 100-180 GeV or Di-$\tau_{had\text{-}vis}$ triggers (DTTs) p_T > 40 (30)GeV
- ♦ $\tau_{lep}\tau_{had}$ - pass Single lepton triggres SLT or Lepton-plus-$\tau_{had\text{-}vis}$ (LTTs) p_T > 30 GeV
- ♦ $m_{\tau\tau}$ > 60 GeV using Missing Mass Calculator (arXiv:1802.08168v2)

$\tau_{had}\tau_{had}$



HDBS-2018-40

$\tau_{lep}\tau_{had}$



HDBS-2018-40

Multiple techniques for background estimation:

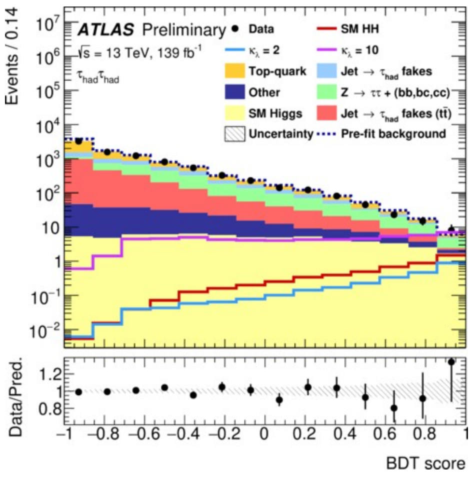
- MC shape and normalization from fit:
  - # Top-quark processes
- MC shape and normalization from Z→μμ/ee+HF CR
  - # Z→ττ + heavy flavor
- Data-driven method
  - # Fake τ background
- Estimate from MC
  - # Single Higgs and others

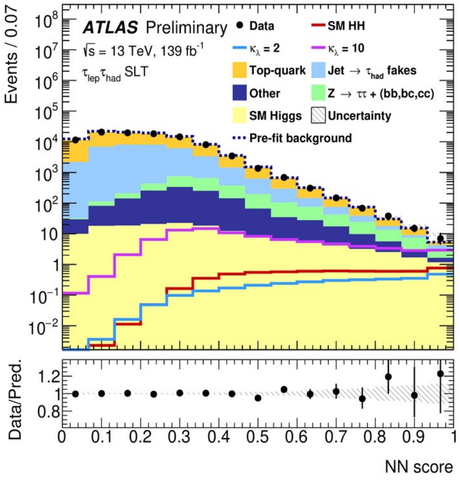
arXiv:2209.10910

HH->bbττ

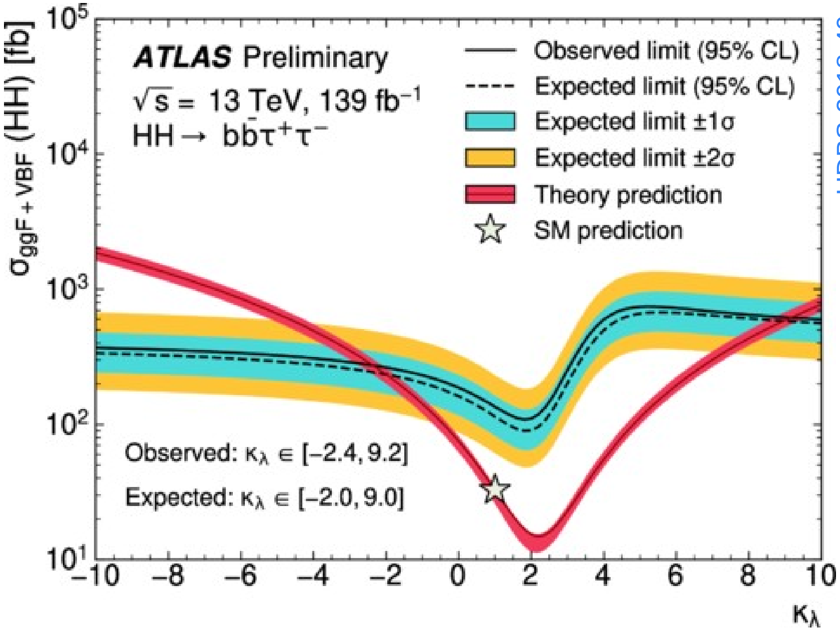
Results

Multivariate techniques (BDTs, NNs) were used to distinguish signal from background and used as the final signal/background discriminant.





HDBS-2018-40



HDBS-2018-40

ATLAS-CONF-2021-052

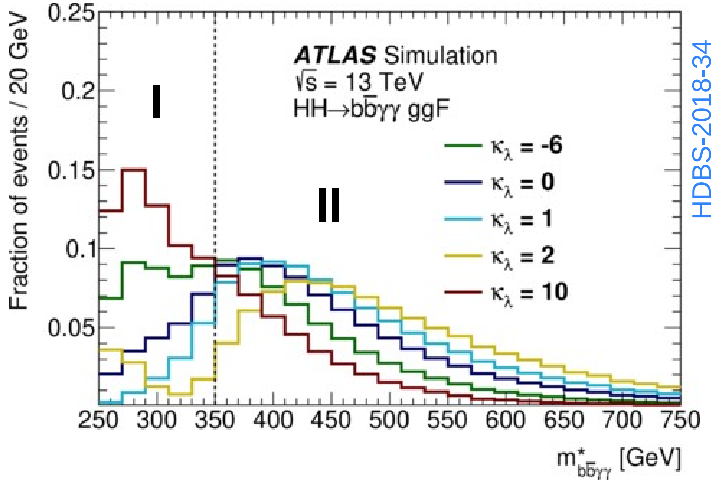
$\sigma_{HH} < 4.7\ \sigma_{SM}$ observed
($3.9\ \sigma_{SM}$ expected)

Observed: $-2.4 < \kappa_\lambda < 9.1$
Expected: $-2.0 < \kappa_\lambda < 9.0$

HH->bbγγ

Event selection:

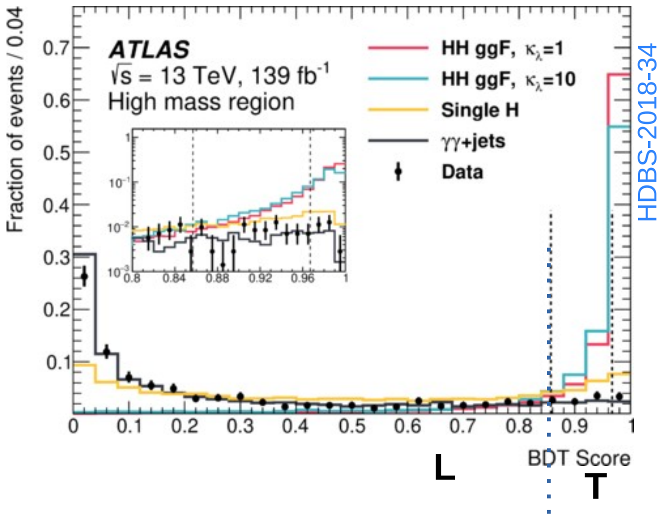
- ➔ 2 photons with 120 GeV ≤ $m_{\gamma\gamma}$ ≤ 130 GeV
- ➔ The leading (subleading) photon p_T is larger than 35% (25%) of the mass of the diphoton system.
- ➔ Exactly 2 b-tagged jets
- ➔ No e/μ in event



2 regions for increase sensitivity to:

- **I** – large kλ, BSM, (low masses)
- **II** – small kλ, SM, (high masses)

Combination of 2 BDT trainings for separate signal from single Higgs and continuum background

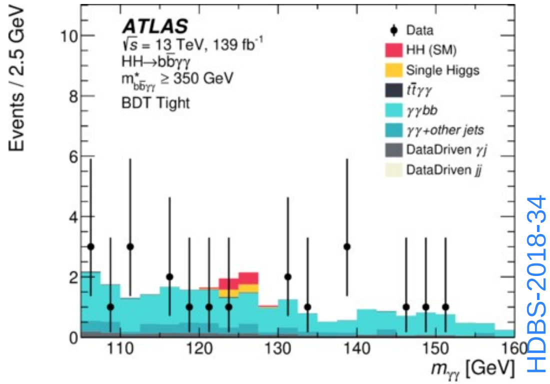


Phys. Rev. D 106 (2022) 052001

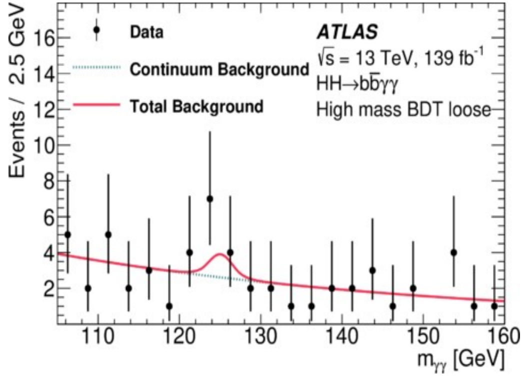
Two new categories, loose (**L**) and tight BDT (**T**).

HH->bbγγ

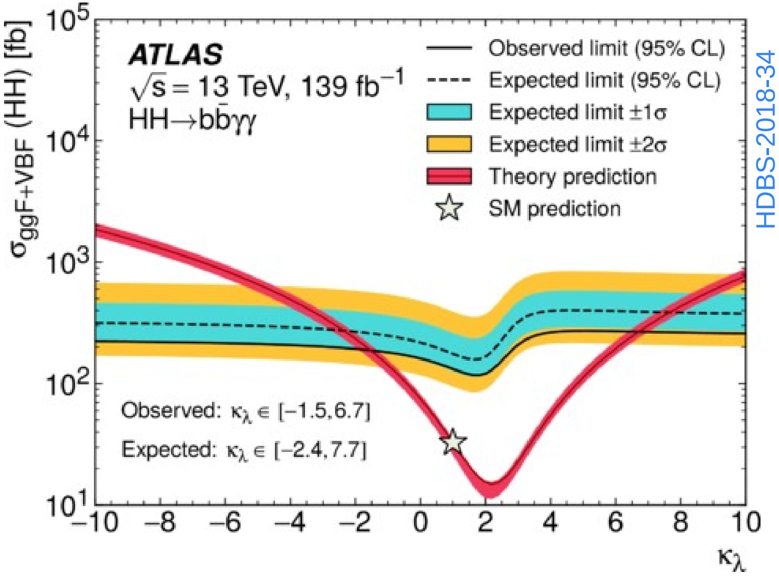
Signal extraction by fitting $m_{\gamma\gamma}$ distribution in each category and signal strength allowed to float



HDBS-2018-34



Results



HDBS-2018-34

Phys. Rev. D 106 (2022) 052001

$\sigma_{HH} < 4.2\ \sigma_{SM}$ observed

($5.7\ \sigma_{SM}$ expected)

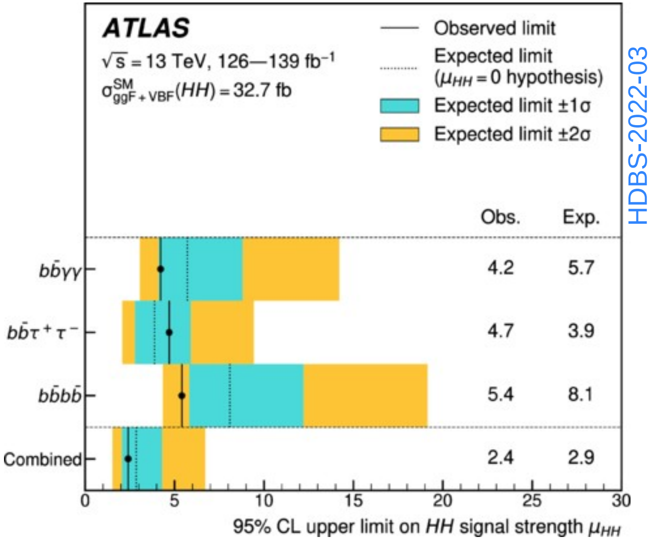
Observed: $-1.5 < \kappa_\lambda < 6.7$

Expected: $-2.4 < \kappa_\lambda < 7.7$

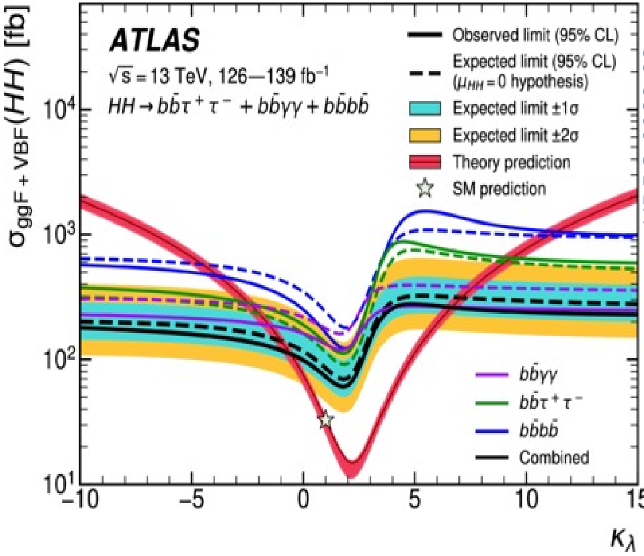
Phys. Rev. D 106 (2022) 052001

HH Combination

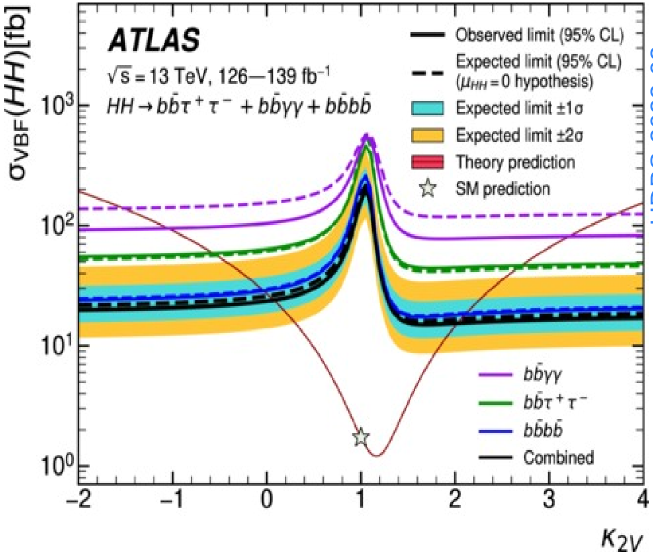
Three most sensitive HH channels have been combined.
Increased sensitivity by a statistical combination of HH channels



HDBS-2022-03



HDBS-2022-03



HDBS-2022-03

arXiv:2211.01216v1

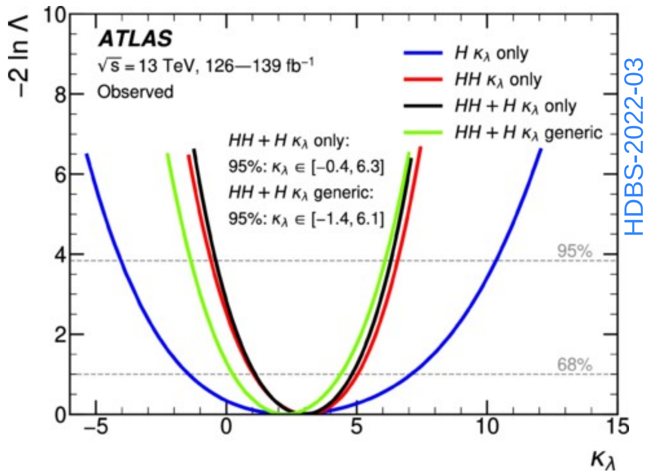
σ_{HH} < 2.4 σ_{SM} observed
(2.9 σ_{SM} expected)

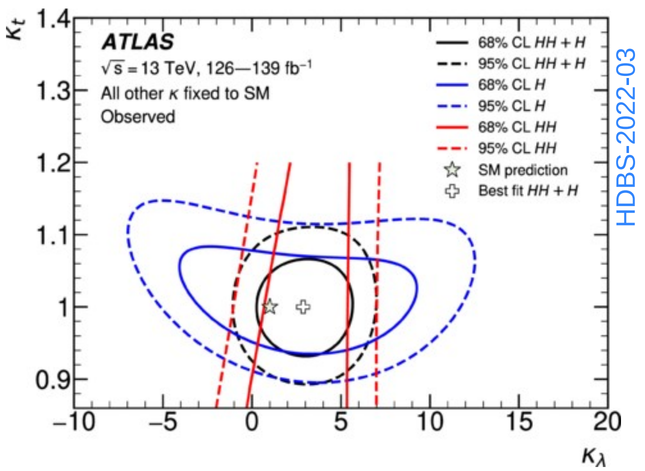
Observed: -0.6< κ_λ < 6.6
Expected: -2.1< κ_λ < 7.8

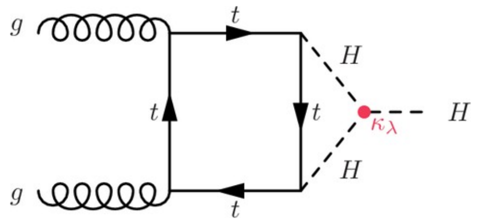
Observed: 0.1< κ_{2V} < 2.0
Expected: 0.0< κ_{2V} < 2.1

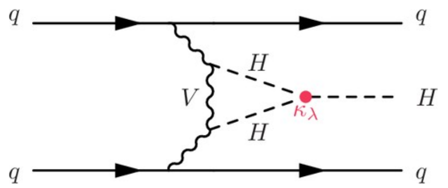
HH+H Combination

The K_λ can be measured through loop correction in single Higgs boson production.
By combining HH and H searches additional constraints can by achieved.
Offers most stringent constraint on K_λ to date.









Single H processes:
$H \to \gamma\gamma$, $H \to \tau\tau$, $H \to bb$(VH),
$H \to bb$(VBF), $H \to bb$(ttH),
H->ZZ->4l

arXiv:2211.01216v1

Observed: $-0.4 < K_\lambda < 6.3$
Expected: $-1.9 < K_\lambda < 7.6$

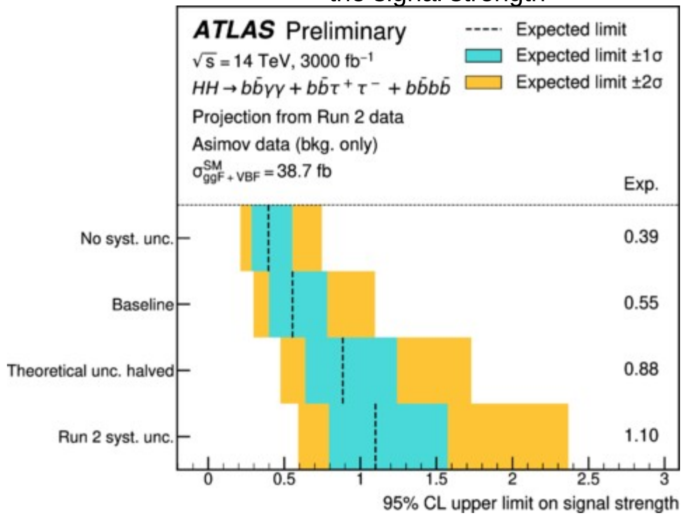
K_{2V} =1 for single Higgs, no complete parametrization NLO EW corrections

HL-LHC prospects

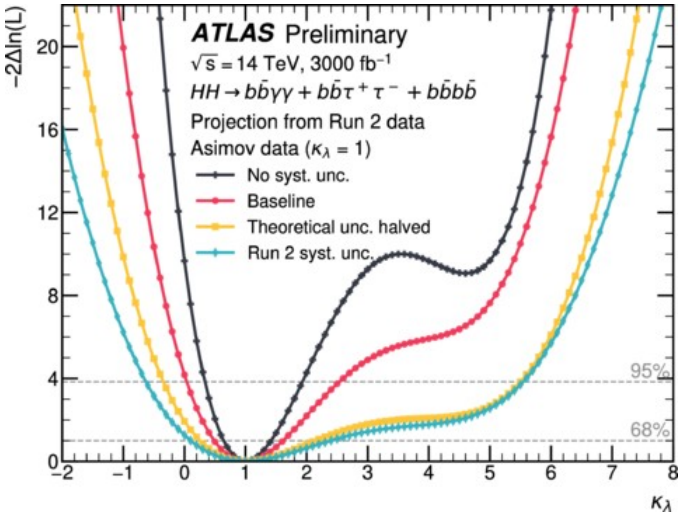
HL-LHC energy $\sqrt{s}$ =14 TeV
HH σ^{SM}_{ggF} = $36.7^{+6\%}_{-23\%}$
HH σ^{SM}_{VBF} = $2.1^{+0.03\%}_{-0.04\%}$
Expected integrated luminosity 3000 fb^{-1}

Run 2 distribution scaled by factor 1.18 and 1.19 for ggF and VBF HH signals respectively

the signal strength



ATL-PHYS-PUB-2022-053



ATL-PHYS-PUB-2022-053

Expected significance (σ) for baseline scenario is 3.4 and observation is expected while 0 > K_λ or K_λ > 5.8

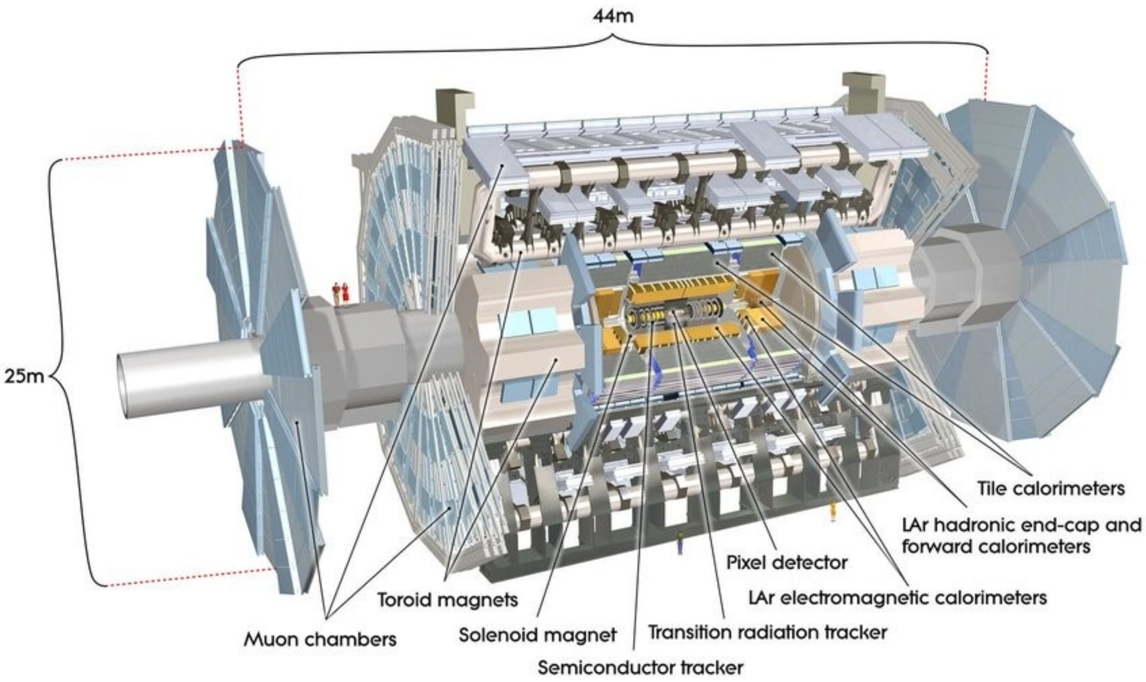
ATL-PHYS-PUB-2022-053

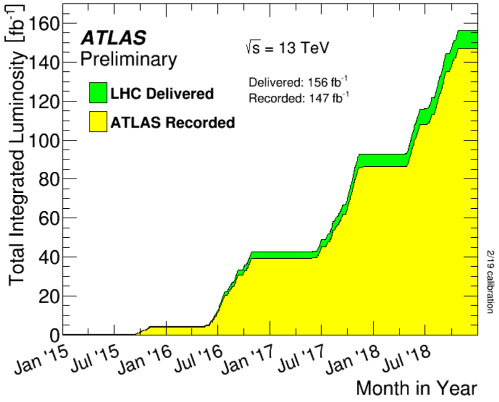
Conclusions

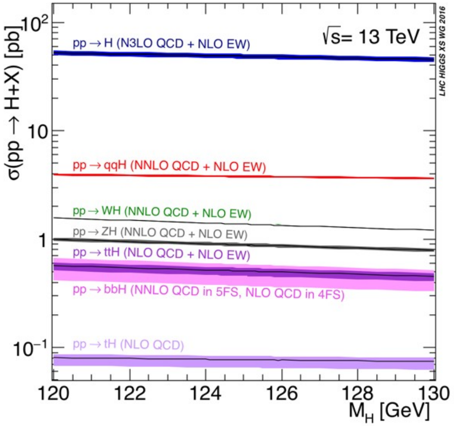
- ♦ HH searches are one of the most attractive in particle physics
- ♦ Not offering the unique channel – a combination of searches are necessary
- ♦ HH production provides insight into the Higgs mechanism
- ♦ Good probe for searching processes BSM:
  - Heavy resonance searches - see Jem's talk
  - DiHiggs production enhancement
- ♦ Interesting HL-LHC prospects
- ♦ New interesting results covering not mentioned channels in the near future...

Backup

The ATLAS detector







Combination

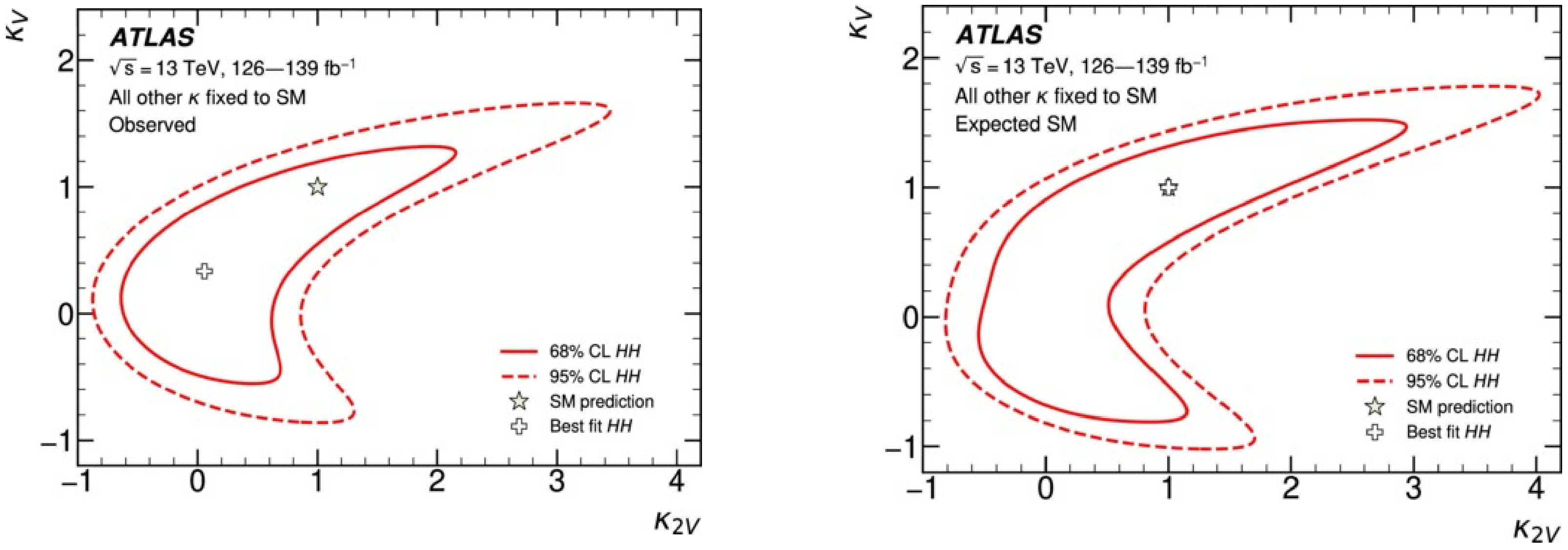
Final state	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
$HH \to b\bar{b}\gamma\gamma$	$-1.4 < \kappa_\lambda < 6.5$	$-3.2 < \kappa_\lambda < 8.1$	$\kappa_\lambda = 2.8^{+2.0}_{-2.2}$
$HH \to b\bar{b}\tau^+\tau^-$	$-2.7 < \kappa_\lambda < 9.5$	$-3.1 < \kappa_\lambda < 10.2$	$\kappa_\lambda = 1.5^{+5.9}_{-2.5}$
$HH \to b\bar{b}b\bar{b}$	$-3.3 < \kappa_\lambda < 11.4$	$-5.2 < \kappa_\lambda < 11.6$	$\kappa_\lambda = 6.2^{+3.0}_{-5.2}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$

Summary of κλ observed and expected constraints and corresponding observed best fit values with their uncertainties for the HH→ bb̄γγ, HH→ bb̄τ+τ-, HH→ bb̄bb̄ analyses and for the double-Higgs combination. Limits are obtained using the test statistic (-2 lnΛ) in the asymptotic approximation. The expected constraints are derived under the SM assumption. The κλ parameterisation of NLO EW corrections on the Higgs boson self-energy and decay have been included in the measurements. All other coupling modifiers are fixed to the SM value.

Final state	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
$HH \to b\bar{b}\gamma\gamma$	$-0.8 < \kappa_{2V} < 3.0$	$-1.6 < \kappa_{2V} < 3.7$	$\kappa_{2V} = 1.1^{+1.0}_{-1.0}$
$HH \to b\bar{b}\tau^+\tau^-$	$-0.6 < \kappa_{2V} < 2.7$	$-0.5 < \kappa_{2V} < 2.7$	$\kappa_{2V} = 1.5^{+0.7}_{-1.7}$
$HH \to b\bar{b}b\bar{b}$	$0.0 < \kappa_{2V} < 2.1$	$0.0 < \kappa_{2V} < 2.1$	$\kappa_{2V} = 1.0^{+0.7}_{-0.6}$
HH combination	$0.1 < \kappa_{2V} < 2.0$	$0.0 < \kappa_{2V} < 2.1$	$\kappa_{2V} = 1.1^{+0.6}_{-0.6}$

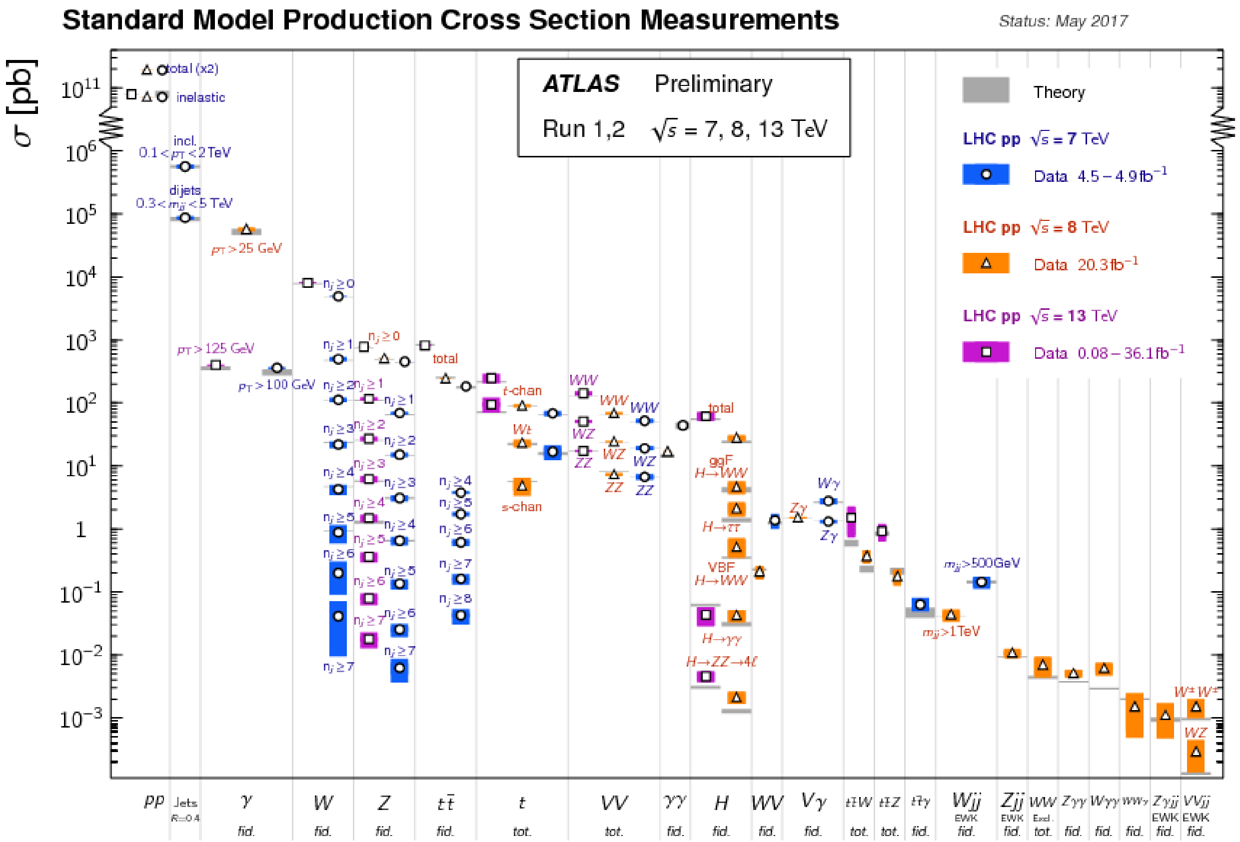
Summary of κ2V observed and expected constraints and corresponding observed best fit values with their uncertainties for the HH→ bb̄γγ, HH→ bb̄τ+τ-, HH→ bb̄bb̄ analyses and for the double-Higgs combination. Limits are obtained using the test statistic (-2 lnΛ) in the asymptotic approximation. The expected constraints are derived under the SM assumption. All other coupling modifiers are fixed to the SM value.

Combination



Observed (a) and expected (b) constraints in the κ2V–κV plane from double-Higgs combination. The solid (dashed) lines show the 68% (95%) CL contours.

cross-sections

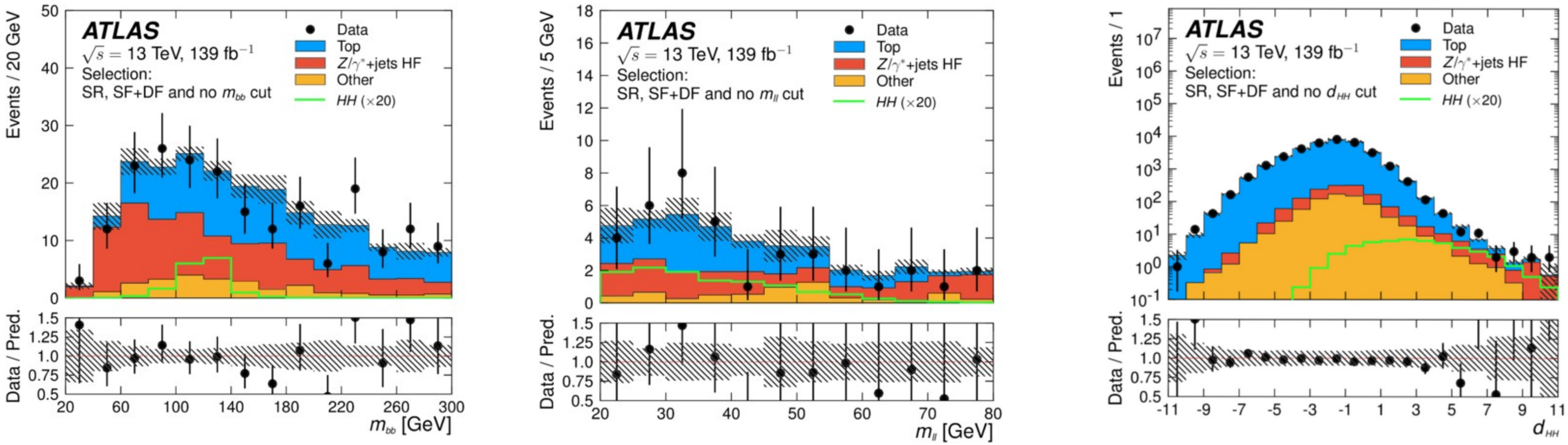


HH->bbll

Phys. Lett. B 801 (2020) 135145

Event selection:
- two light leptons (e,μ) with opposite charge
- two b-tagged jets with p_T> 20 GeV and |η| <2.5
- $m_{ll} \in$ (20, 60) GeV
- $m_{bb} \in$ (110, 140) GeV
- d_{HH} > 5.45 SF and d_{HH} > 5.55 DF

$$d_{HH} = \ln\left[\frac{p_{HH}}{p_{top} + p_{Zll} + p_{Z-\tau\tau}}\right]$$

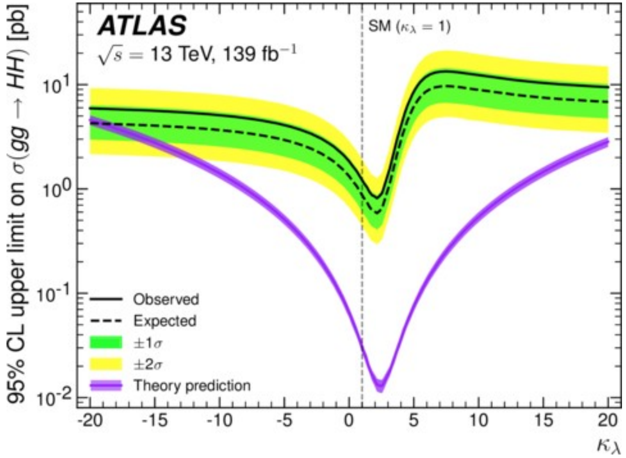


HH->bbll

Phys. Lett. B 801 (2020) 135145

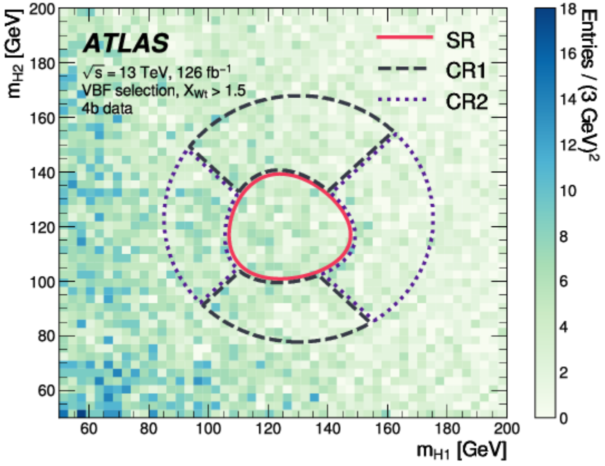
Results

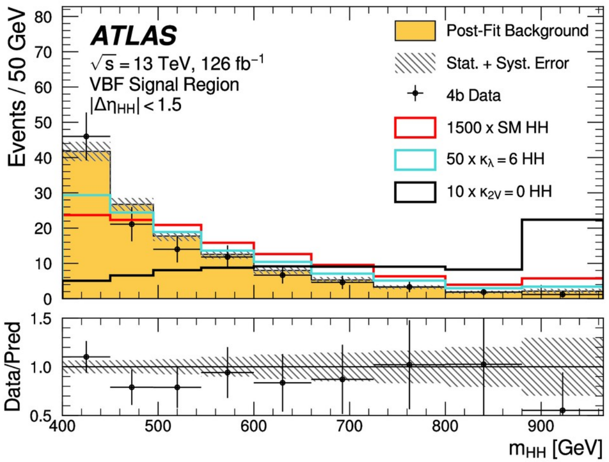
	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$	Observed
$\sigma(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \to HH)/\sigma^{SM}(gg \to HH)$	14	20	29	43	62	40



HH->4b

arXiv:2301.03212





Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\Box}$	−9.3	13.9	−8.9	14.5
c_{tH}	−10.0	6.4	−10.7	6.2
c_{tG}	−0.97	0.94	−1.12	1.15

The extracted upper and lower limits on the SMEFT parameters to which the analysis is sensitive. For each parameter, the constraints are provided assuming the other parameters are fixed to 0. The VBF HH process is ignored for this result.

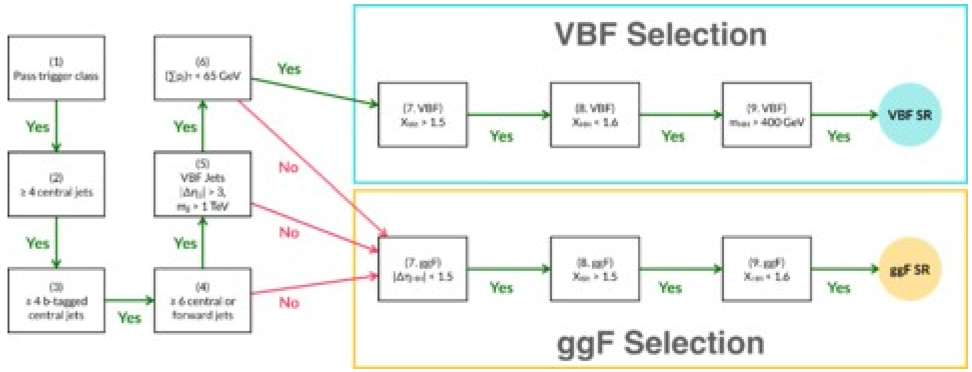
Source of Uncertainty	$\Delta\mu/\mu$
Theory uncertainties	
Theory uncertainty in signal cross-section	−9.0%
All other theory uncertainties	−1.4%
Background modeling uncertainties	
Bootstrap uncertainty	−7.1%
CR to SR extrapolation uncertainty	−7.5%
3b1f nonclosure uncertainty	−2.0%

HH->4b

arXiv:2301.03212

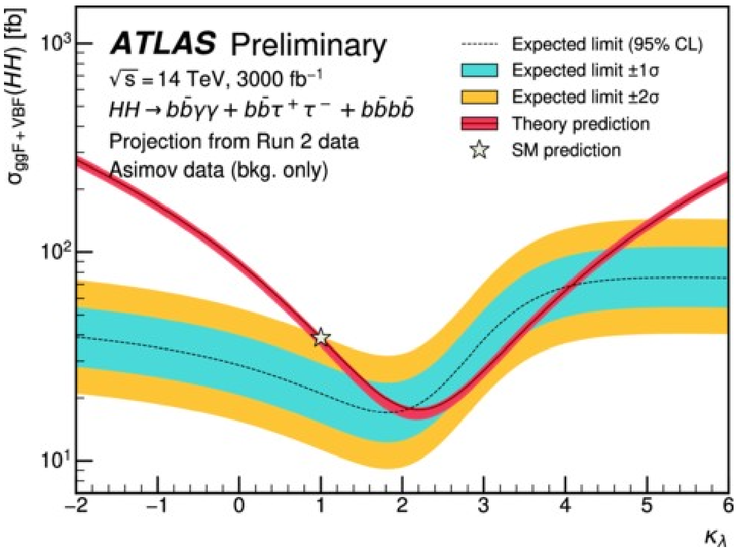
	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
μ_{ggF}	5.5	4.4	5.9	8.2	12.4	19.6
μ_{VBF}	130	70	100	130	190	280
$\mu_{\text{ggF+VBF}}$	5.4	4.3	5.8	8.1	12.2	19.1

The observed and expected upper limits on the SM ggF HH production cross-section σggF, SM VBF HH production cross-section σVBF, and combined SM ggF and VBF HH production cross-section σggF+VBF at the 95% CL, expressed as multiples of the corresponding SM cross-sections. The expected values are shown with corresponding one- and two-standard-deviation error bounds, and they are obtained using a background-only fit to the data. When extracting the limits on σggF+VBF, the relative contributions of ggF and VBF production to the total cross-section are fixed to the SM prediction.

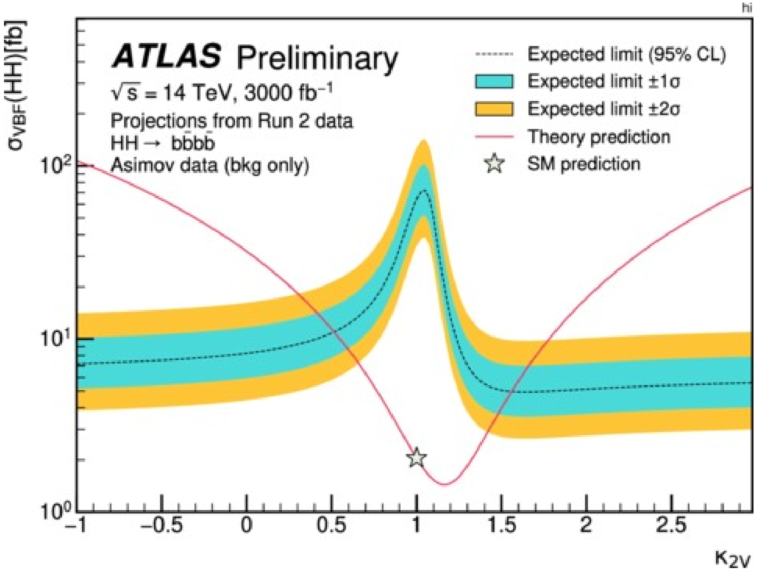


A flowchart summarizing the nine selection criteria used for the VBF and ggF analysis selections. Events must satisfy selection criteria 1-3 in order to be considered for either analysis signal region. Events failing to satisfy any of the selection criteria 4-6 are considered for inclusion in the ggF signal region, while those satisfying selection criteria 4-6 are considered for the VBF signal region.

HL-LHC prospects

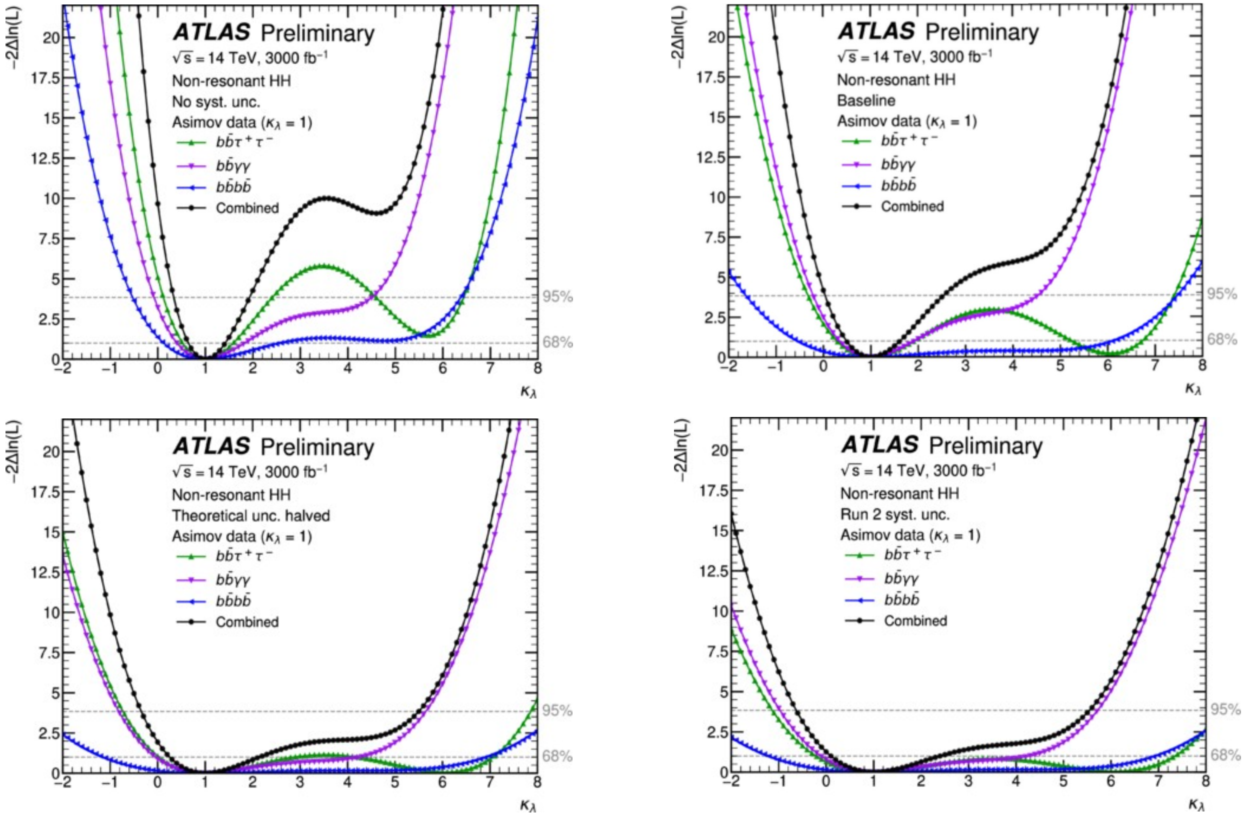


Expected 95% CL limits on the HH cross-section for different κλ hypotheses at √s = 14 TeV, 3000 fb-1 at the HL-LHC with the baseline uncertainty scenario for combination with bb̄γγ and bb̄τ+τ- channels. The expected cross-section limits assume a complete absence of HH production. The theory prediction curve represents the situation where all parameters and couplings are set to their SM values except for κλ. The SM hypothesis corresponds to κλ=1.



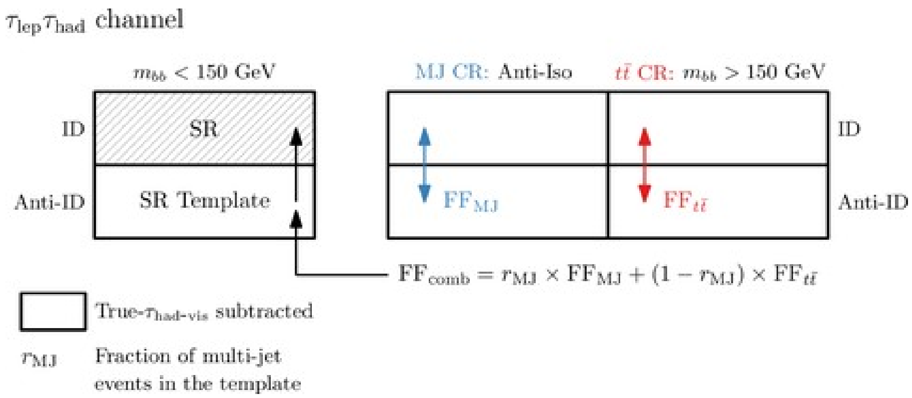
Expected 95% CL limits on the HH cross-section for different κ2V hypotheses at √s = 14 TeV, 3000 fb-1 at the HL-LHC with the baseline uncertainty scenario. The expected cross-section limits assume a complete absence of HH production. The theory prediction curve represents the situation where all parameters and couplings are set to their SM values except for κ2V. The SM hypothesis corresponds to κ2V=1.

HL-LHC prospects

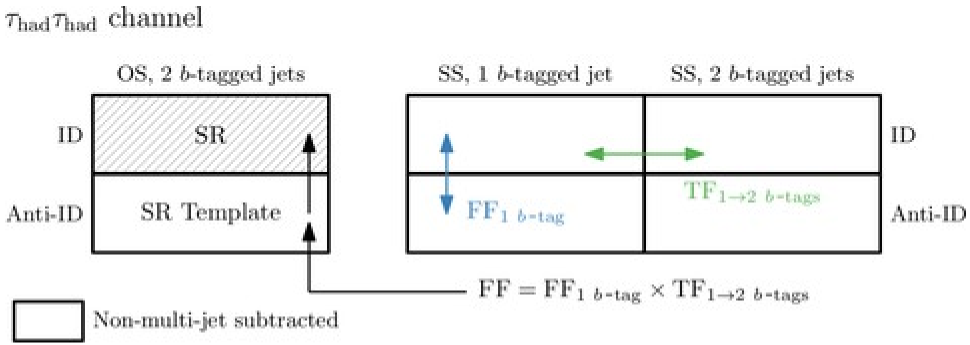


Negative log-profile-likelihood as a function of κλ evaluated on an Asimov dataset constructed under the SM hypothesis of κλ=1, for bb̄γγ, bb̄τ+τ- and bb̄bb̄ projections, and their combination assuming the four different uncertainty scenarios described in the text. The intersections of the dashed horizontal lines with the profile likelihood curve define the 68% and 95% confidence intervals, respectively.

HH->bbττ



Schematic depiction of the combined fake-factor method used to estimate multi-jet and tt̄ backgrounds with fake-τhad-vis in the τlepτhad channel. Backgrounds which are not from events with fake-τhad-vis originating from jets are estimated from simulation and are subtracted from data in all control regions. Events in which an electron or a muon is misidentified as a τhad-vis are also subtracted, but their contribution is very small. Both sources are indicated by `True-τhad-vis subtracted' in the legend.



Schematic depiction of the fake-factor method to estimate the multi-jet background with fake-τhad-vis in the τhadτhad channel. Backgrounds that are not from multi-jet events are simulated and subtracted from data in all the control regions. This is indicated by `Non-multi-jet subtracted' in the legend.

τhadτhad		τlepτhad	
STTs	DTTs	SLTs	FTTs
No e/μ Two loose τhad-vis		p_T^e> 25,27GeV p_T^μ> 21,27GeV	18GeV< p_T^e < SLTs 15GeV < p_T^μ < SLTs
p_T > 100,140, 180 (25) GeV	p_T >40 (30)GeV	one loose τhad-vis P_T > 30 GeV	