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

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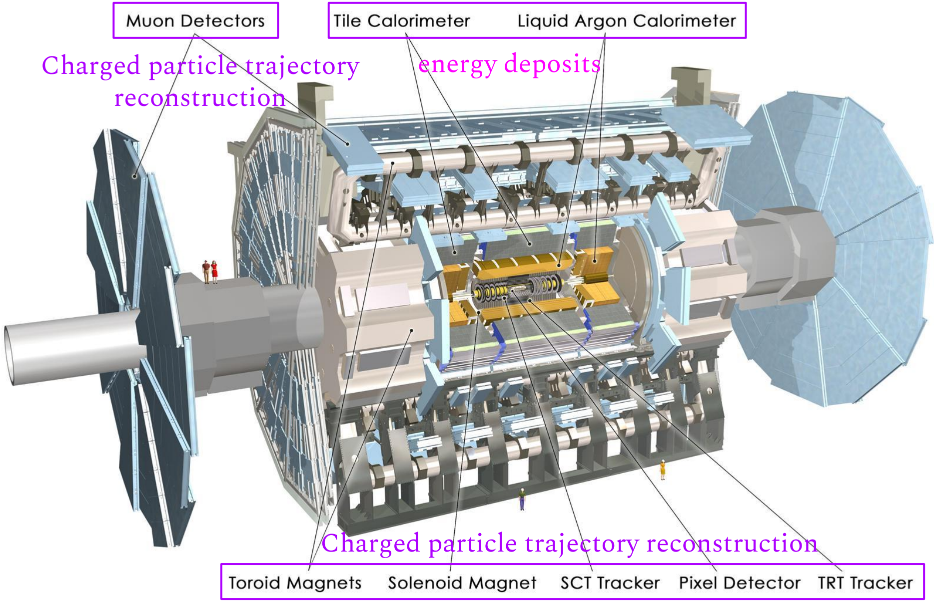
Instituto de Física Corpuscular (IFIC, CSIC-UV)

30th Anniversary of the Rencontres du Vietnam - Windows on the Universe
Vietnam, 6-12 August 2023

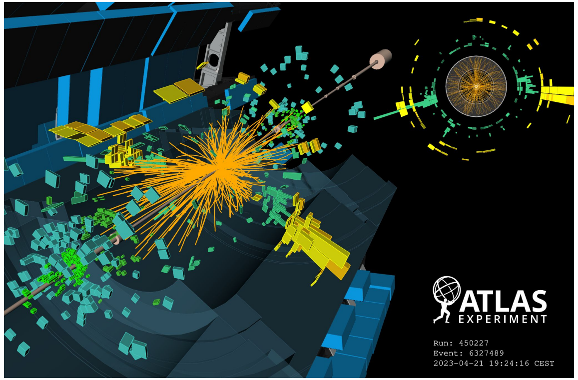
The ATLAS Experiment



Bunch crossing: 40 MHz

Detector readout (first level trigger): 100 kHz

Write to disk (second level trigger): 1 kHz



Higgs Boson Self-Coupling *(why Higgs pairs?)*

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2 \xrightarrow{\text{Expanding around minimum}} V_H = \frac{1}{2}m_H H^2 + \lambda v H^3 + \ldots$$

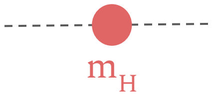
Spontaneous symmetry breaking when $v \neq 0$

when $\lambda > 0$, $\mu^2 < 0$: Minimum $(v) = \sqrt{(\mu^2/2\lambda)}$

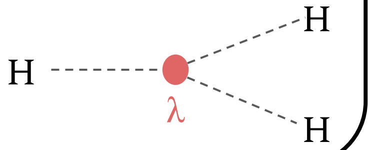
v_{SM}(computed) = $(\sqrt{2}G_F)^{-1/2}$= 246 GeV

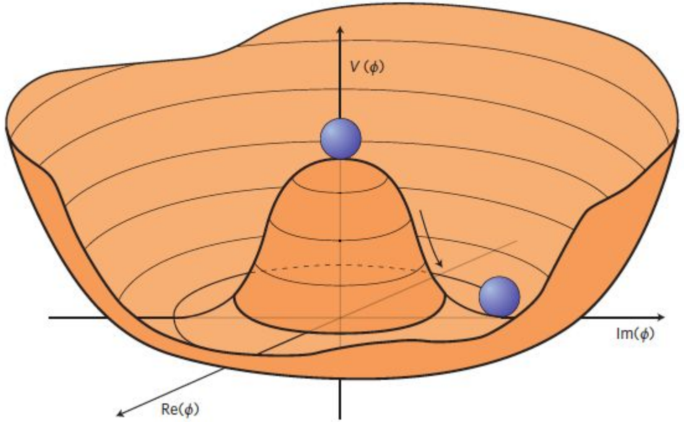
$\Rightarrow \lambda_{SM}$(computed) $\simeq$ 0.129

Higgs boson mass term



Self-interaction term





Higgs boson pair-production measurement

↓

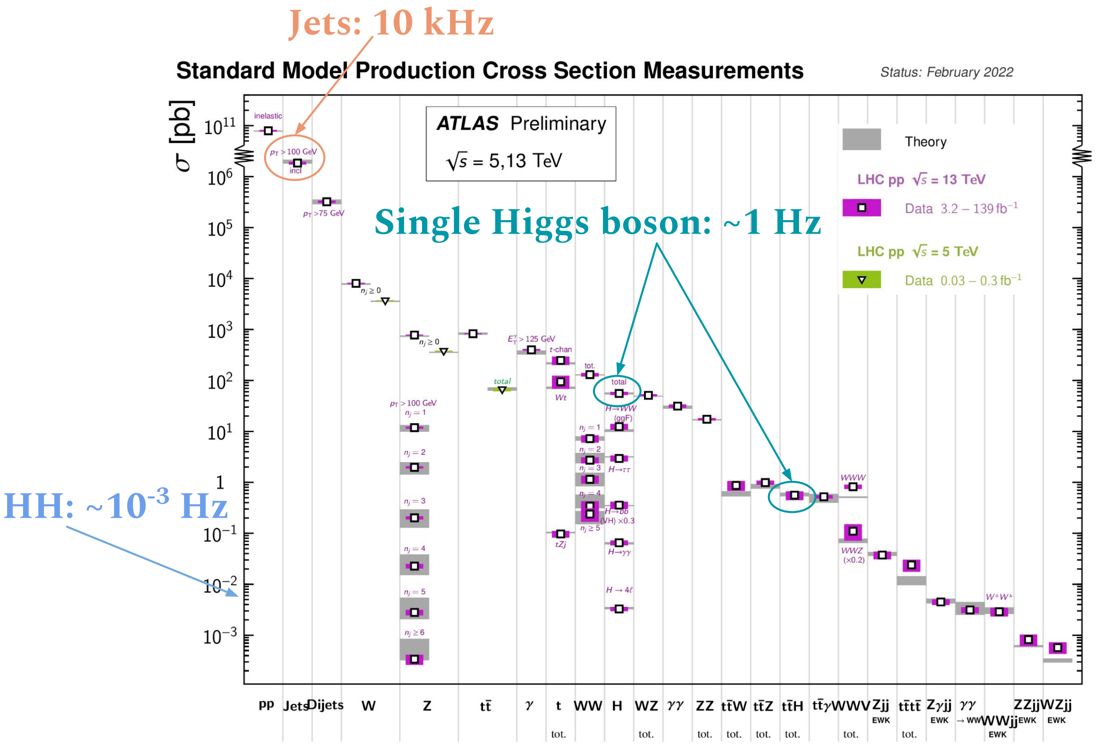
direct measurement of Higgs boson self-coupling

↓

direct probe of shape of Higgs potential

$\lambda \neq \lambda_{SM} \Rightarrow$ new physics

HH production cross sections *(needle in a haystack…)*



ATL-PHYS-PUB-2022-009

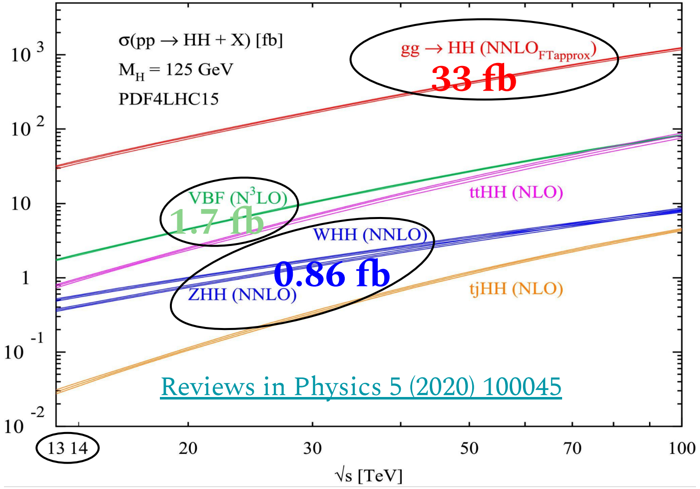
Non-resonant HH production: 1/hr

$\sigma_{HH} \rightarrow \sim 10^3$ times smaller than σ_H

$\Rightarrow$ difficult search

HH production modes

ATLAS EXPERIMENT



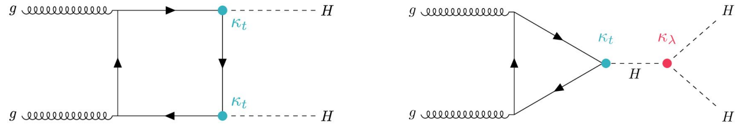
Using the κ framework to parametrize BSM physics

Assumption: New physics only modifies SM couplings, where κ is the coupling strength modifier

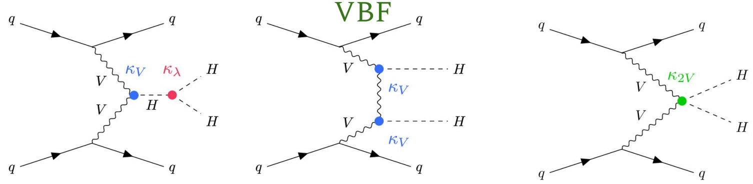
$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} \quad \therefore \quad \kappa_i \neq 1 \Rightarrow \text{new physics}$$

Non-resonant production modes probed in ATLAS

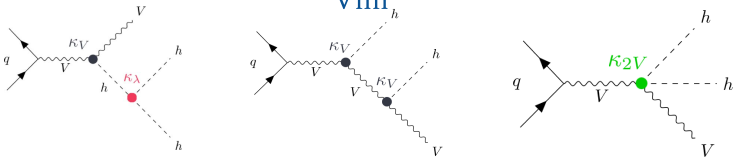
gluon- gluon fusion



VBF



Vhh



$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

- κ_λ: Higgs trilinear coupling strength modifier
- κ_t: top - Higgs coupling strength modifier
- κ_V: VVH coupling strength modifier
- κ_{2V}: VVHH coupling strength modifier

HH decay modes *(no single golden channel...)*

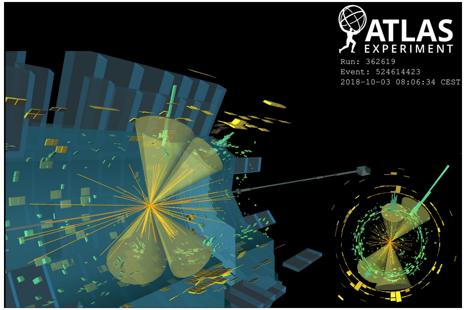
ATLAS EXPERIMENT

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Channels probed in ATLAS

- Exploit all decays channel with at least one $b\bar{b}$ pair in the final state - comparatively higher BR than without $b\bar{b}$
- Different production modes (non- resonant: ggF, VBF; resonant production) exploited
- 3 main channels & their production modes probed in ATLAS:
  - $b\bar{b}b\bar{b}$ - highest BR, large background (ggF, VBF, VHH)
  - $b\bar{b}\gamma\gamma$ - small background, low signal yields (ggF, VBF)
  - $b\bar{b}\tau\tau$ - balance of both (ggF, VBF)

HH→$b\bar{b}b\bar{b}$ *(largest signal)*

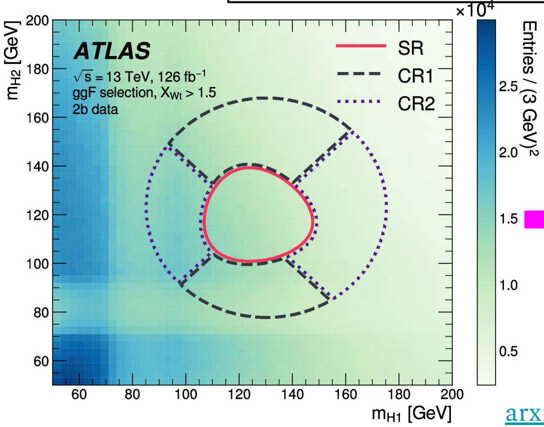


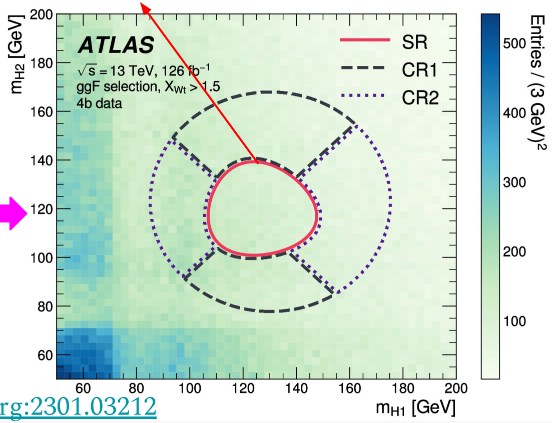
Event selection: 4 b-tagged jets

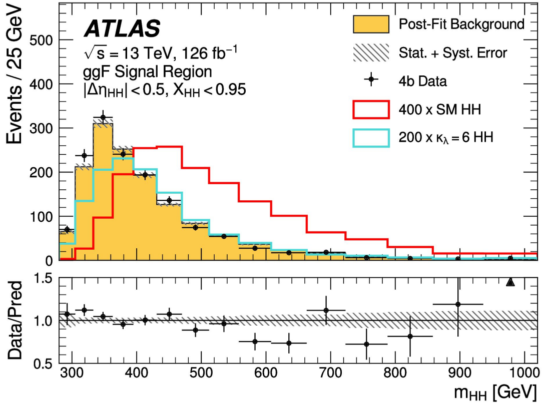
Analysis strategy:

- *Higgs reconstruction*: jets paired to minimize ΔR for p_T leading dijet system
- $|\Delta\eta_{HH}|$ and X_{HH} categories to improve κ_λ and κ_{2V} sensitivity
- *Background estimate*:
  - Data from 2b region reweighted to 4b SR (defined in m_{H1}- m_{H2} plane) using NN
- *Signal extraction:* Limit from fit to m_{HH} distribution

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\ GeV}{0.1\ m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\ GeV}{0.1\ m_{H2}}\right)^2}$$

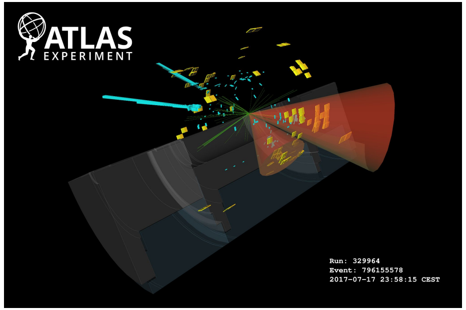


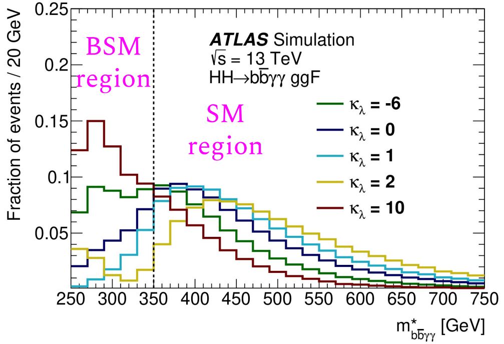




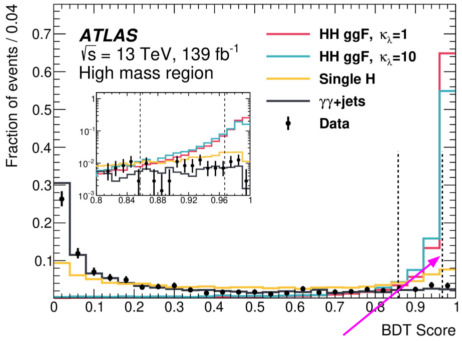
arxiv.org:2301.03212

HH→$b\bar{b}\gamma\gamma$ *(clean signature)*





$(m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\ \text{GeV})$

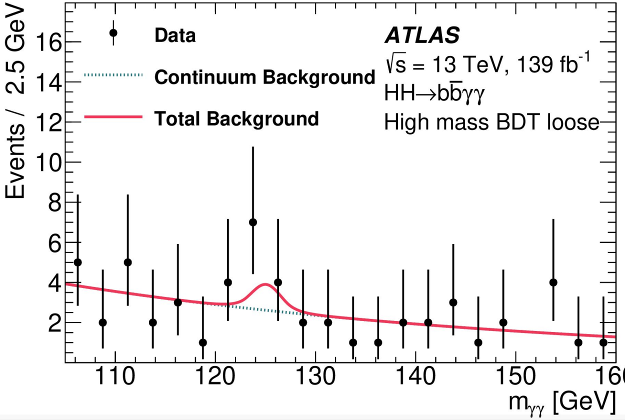


BDT loose: BDT Score ∈ [0.967,1]

Event selection: 2 photons, 2 b-tagged jets, no e/μ

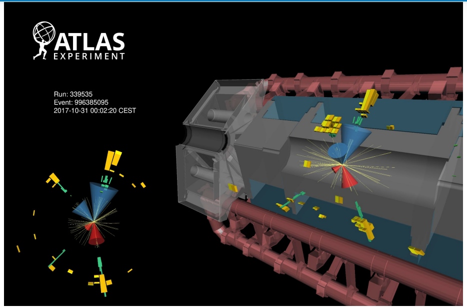
Analysis strategy:

- *Signal region definitions*: regions based on $m^*_{b\bar{b}\gamma\gamma}$ targeting SM and BSM couplings
- *Signal extraction*: 2 BDT categories: tight, loose by maximizing the combined counting significance using signal and background yields in $m_{\gamma\gamma} \in [120, 130\ \text{GeV}]$



Phys. RevD 106, 052001 (2022)

HH→$b\bar{b}\tau\tau$ *(balance of both)*



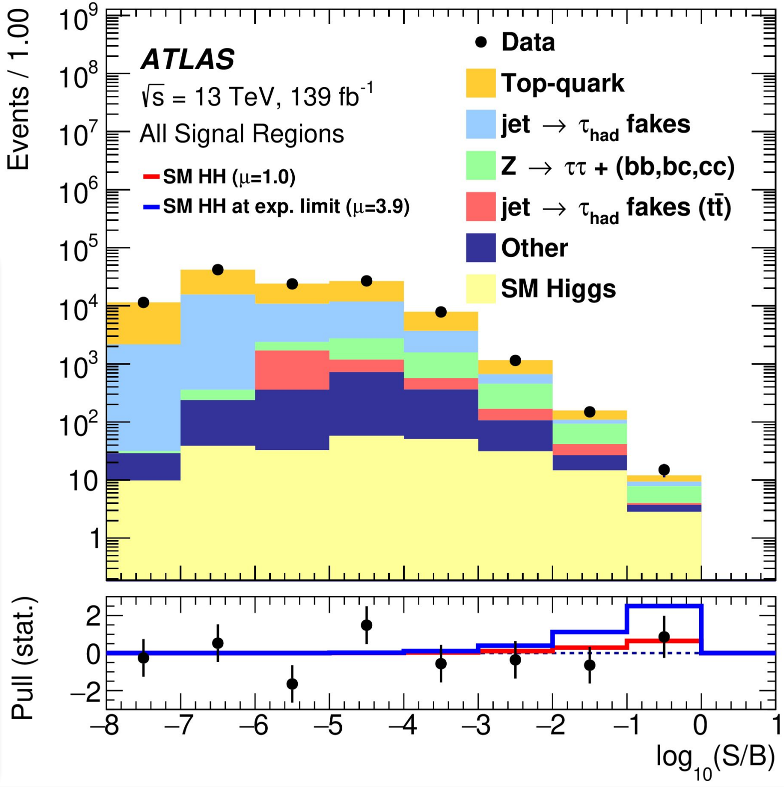
JHEP 07 (2023) 040

Event selection:

- 2 hadronic τs ($\tau_{had}\tau_{had}$) OR 1 τ + 1e/μ ($\tau_{lep}\tau_{had}$); $m_{\tau\tau}$ > 60 GeV using MMC
- 2 b-tagged jets

Analysis strategy:

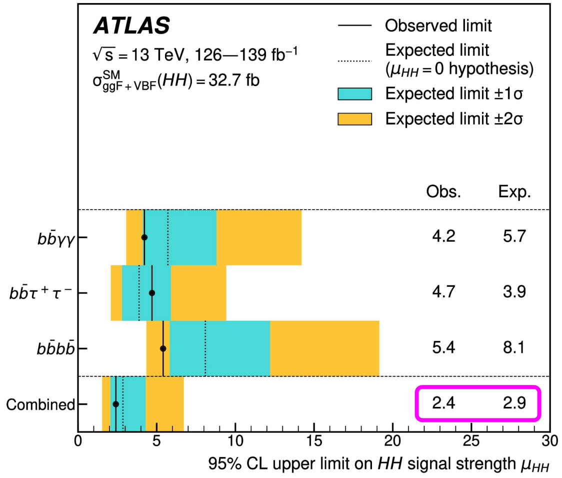
- *Signal region definitions*: 3 regions
  - $\tau_{had}\tau_{had}$
  - $\tau_{lep}\tau_{had}$ *SLT* - single lepton triggers
  - $\tau_{lep}\tau_{had}$ *LTT* - lepton - τ triggers
- *Signal extraction:*
  - $\tau_{had}\tau_{had}$ *channel*: BDT; $\tau_{lep}\tau_{had}$ *channel*: NN
  - *Final discriminant*: MVA score
  - combine 3 channels - bins of $\log_{10}$(S/B)

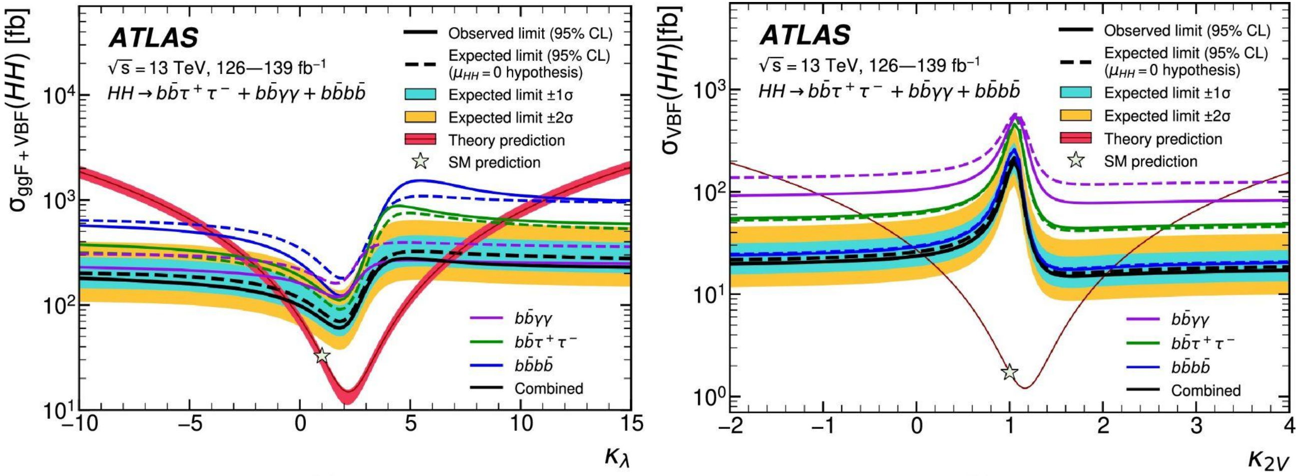


Results (combination)

Limits on μ_{HH}, κ_λ and κ_{2V} at 95% CL

μ_{HH} < 2.4 observed **κ_λ(observed) ∈ [-0.6,6.6]** **κ_{2V}(observed) ∈ [0.1,2.0]**





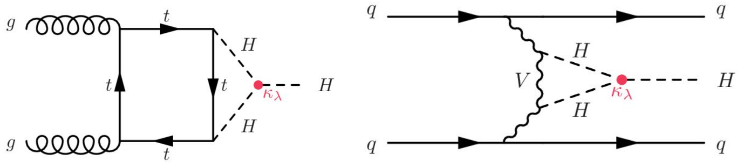
(a) (b)

Combining 3 most sensitive channels increases sensitivity

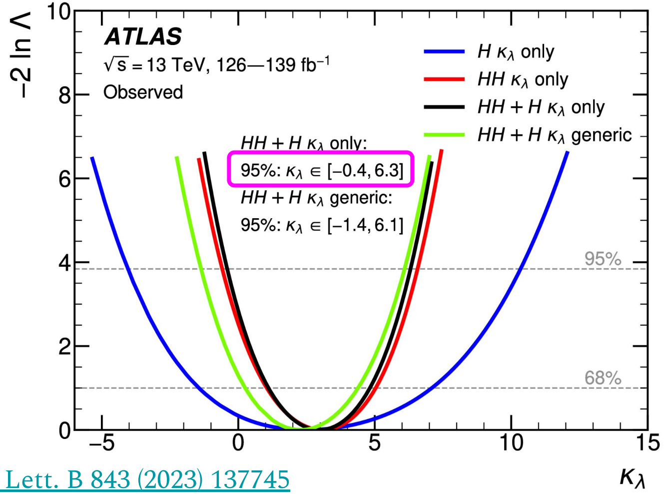
[Phys. Lett. B 843 (2023) 137745]

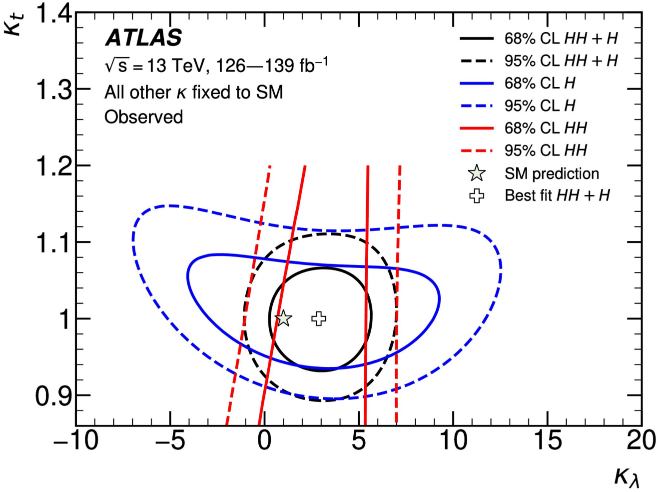
H+HH combination

Single Higgs boson production is also sensitive to λ through loop corrections. Examples (ggF and VBF):



Better sensitivity: HH combination: $\kappa_\lambda \in$ [-0.6,6.6] vs HH+H combination: $\kappa_\lambda \in$ [-0.4,6.3]





Phys. Lett. B 843 (2023) 137745

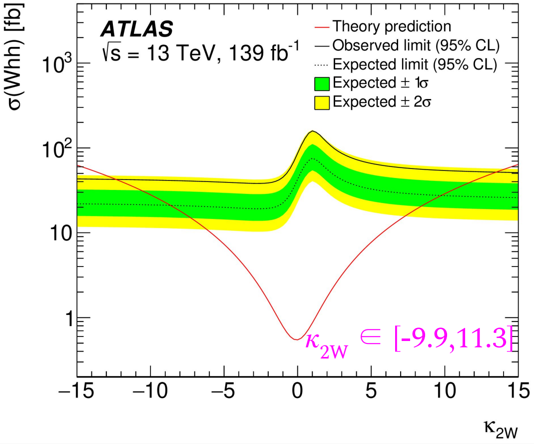
VHH production

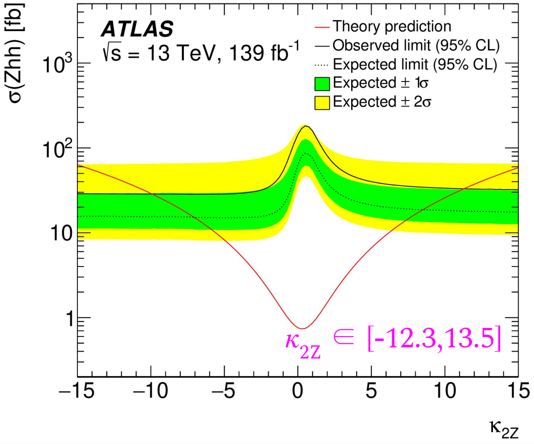
Sensitive to ZZHH and WWHH separately as opposed to VBF
Probed in the $b\bar{b}b\bar{b}$ final state

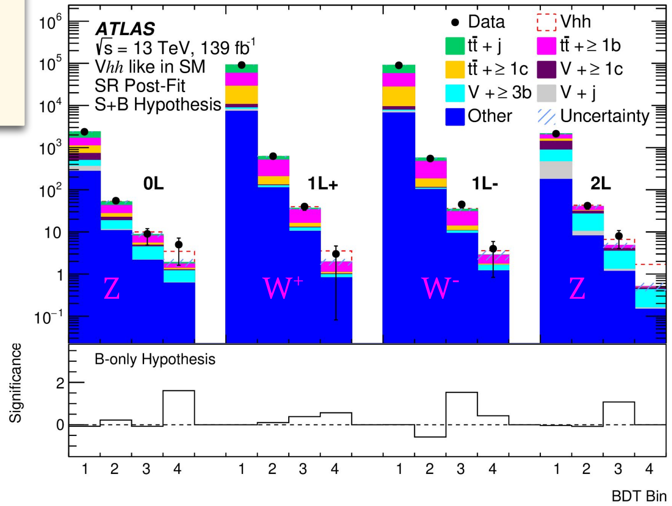
Event selection:
- 4 b-tagged jets (from HH)
- $Z\to\nu\nu$ (0L), $W\to l\nu$ (1L), $Z\to ll$ (2L)

Analysis Strategy:
- 3 signal regions (0L, 1L, 2L)
- S-B separation: simultaneous fit to BDT distributions

Observed limits at 95% CL:
- $-34.4 < \kappa_\lambda < 33.3$
- $-8.6 < \kappa_{2V} < 10.0$





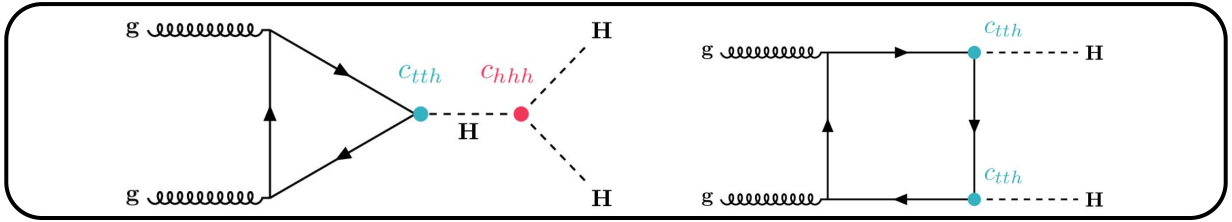


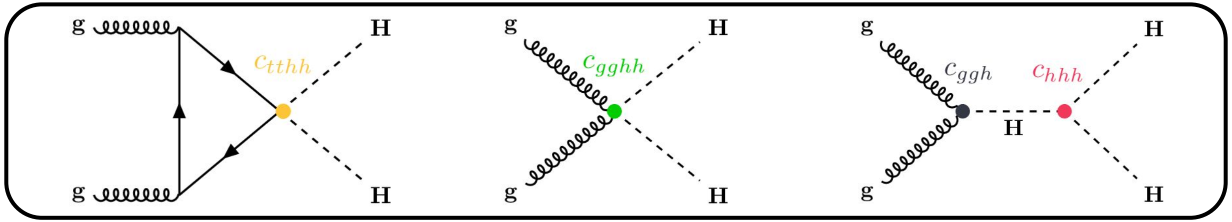
Eur. Phys. J. C 83 (2023) 519

ATLAS EXPERIMENT

Parametrise new physics without strong model dependance
Two common frameworks in HH: SMEFT and Higgs EFT (HEFT); HEFT ⊂ SMEFT
Effective operators can modify gg→HH production in various ways

HEFT coupling parameters





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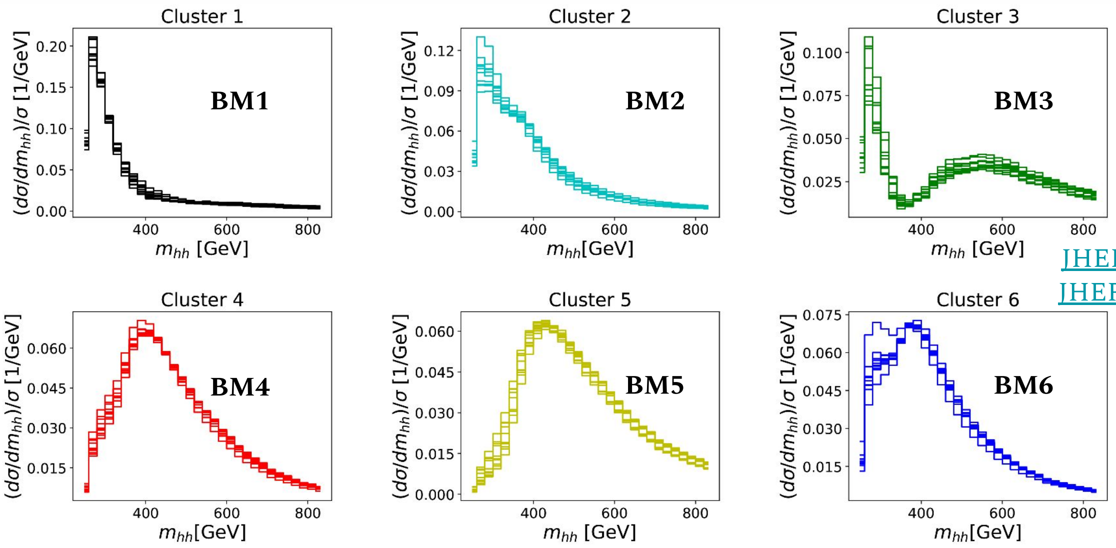
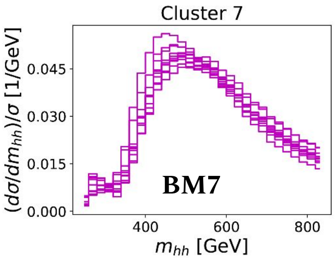
Effective Field Theory (EFT) interpretations for HH

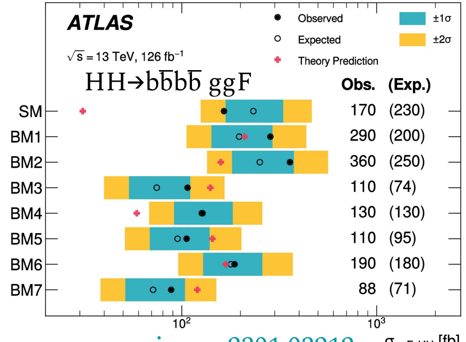


JHEP03(2020)091
JHEP04(2016)126

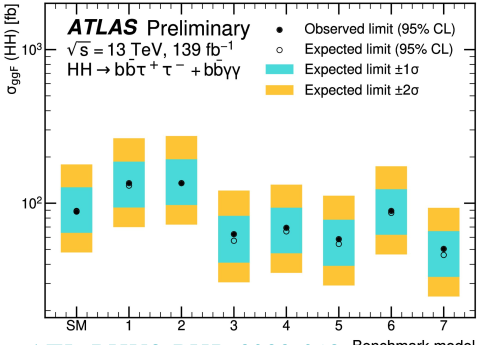


Cluster analysis: define groups of different HEFT models (with specific values for the 5 HEFT coupling parameters) according to their impact on the shape of m_{HH} distribution

Upper limits on benchmark models at 95% CL



arxiv.org:2301.03212



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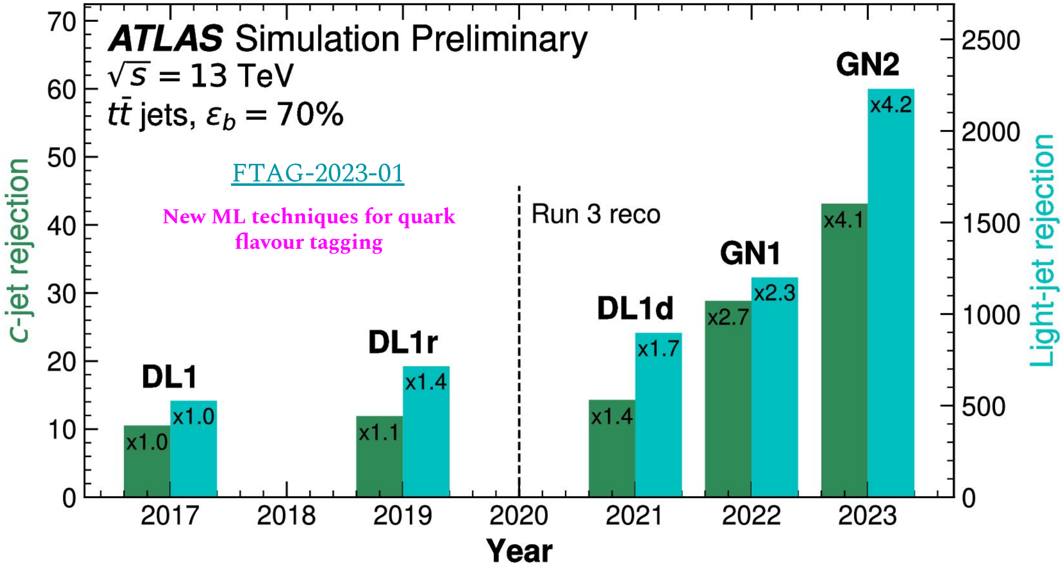
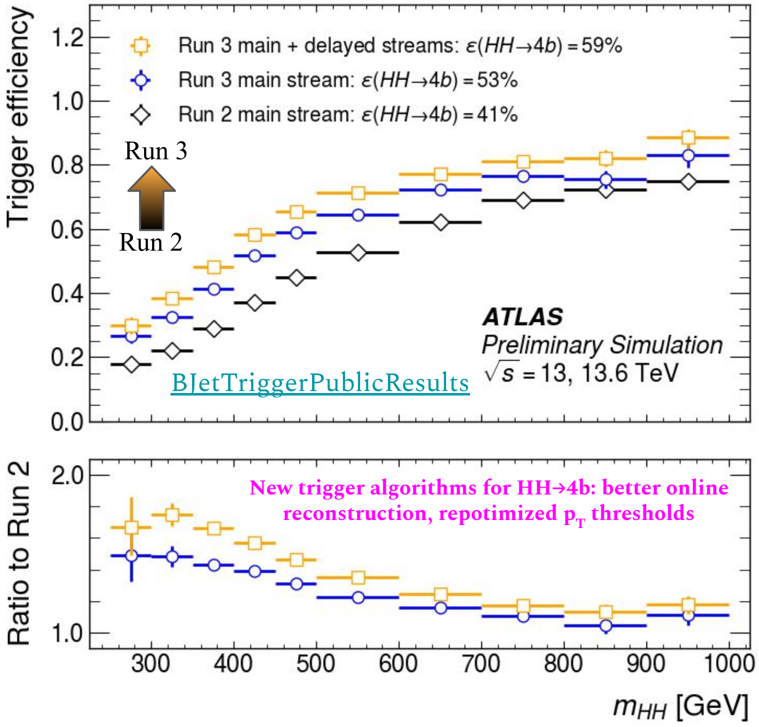
Run 3 improvements *(some examples)*

- √s = 13 TeV → 13.6 TeV
- Detector hardware upgrades
- Faster reconstruction algorithms
- Improved triggers





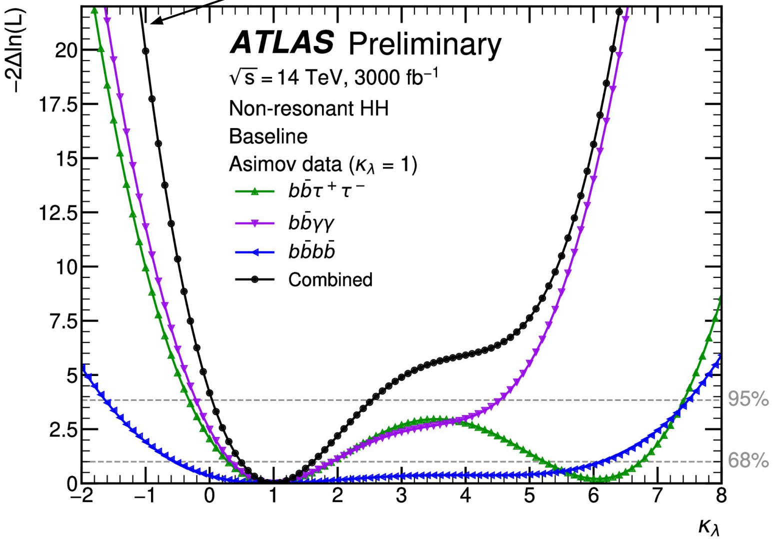
High Lumi - LHC prospects for HH *(ultimate sensitivity?)*

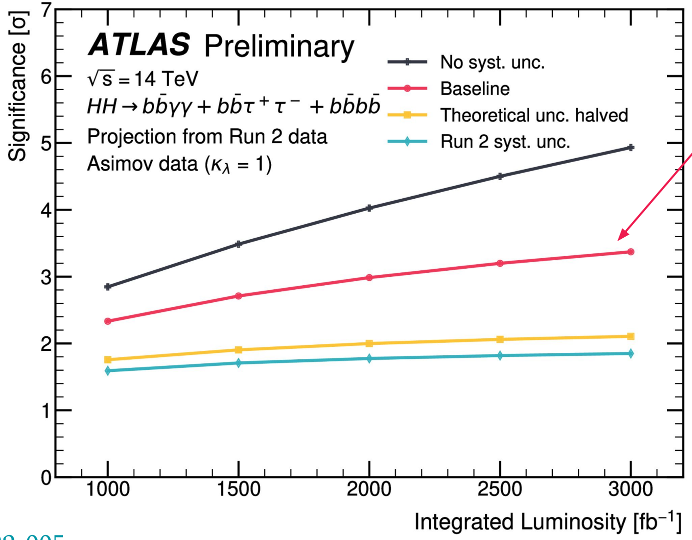
ATLAS EXPERIMENT

HL-LHC conditions:
$\sqrt{s}$ = 14 TeV; L_{int} = 3 ab^{-1}
High pile up

Prospects studied for $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ channels

- Predicted constraints for combination at 95% CL:
  - **$0.22 < \kappa_\lambda < 2.2$**
- Expected SM HH production significance combining 3 channels: **3.4σ**





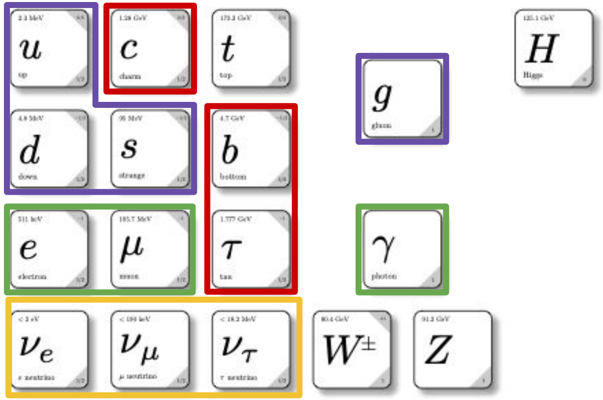
ATL-PHYS-PUB-2022-005

Conclusions

- No new physics so far, HH search - useful next step if BSM physics exists
- No single golden channel $\Rightarrow$ parallel searches and combination are necessary
- Can easily be extrapolated to BSM heavy resonance searches
- *HH in ATLAS during Run 2*: enhanced results with combining 3 most sensitive channels, adding single Higgs contributions provides additional constraints
- *Run 3*: Higher centre-of-mass energy, improved detector hardware, software (triggers, reconstruction algorithms etc.)
- *HL-LHC*: 20 $\times$ current luminosity, run 2 extrapolation very promising (**3.4σ significance expected**)

BACKUP

Particle reconstruction in ATLAS



Stable - tracks + calorimeter deposits

Jets - reconstruct cones of QCD radiation from tracks & calorimeter information

Unstable - jet reconstruction + MVAs using track information for particle ID

Invisible - missing transverse momentum calculations

HH→$b\bar{b}b\bar{b}$ 2b → 4b reweighting: NN input variables

ggF	VBF
1. $\log(p_{\mathrm{T}})$ of the 2^{nd} leading Higgs boson candidate jet 2. $\log(p_{\mathrm{T}})$ of the 4^{th} leading Higgs boson candidate jet 3. $\log(\Delta R)$ between the closest two Higgs boson candidate jets 4. $\log(\Delta R)$ between the other two Higgs boson candidate jets 5. Average absolute η value of the Higgs boson candidate jets 6. $\log(p_{\mathrm{T}})$ of the di-Higgs system 7. ΔR between the two Higgs boson candidates 8. $\Delta\phi$ between jets in the leading Higgs boson candidate 9. $\Delta\phi$ between jets in the subleading Higgs boson candidate 10. $\log(X_{Wt})$ 11. Number of jets in the event 12. Trigger class index as one-hot encoder	1. Maximum dijet mass from the possible pairings of the four Higgs boson candidate jets 2. Minimum dijet mass from the possible pairings of the four Higgs boson candidate jets 3. Energy of the leading Higgs boson candidate 4. Energy of the subleading Higgs boson candidate 5. Second-smallest ΔR between the jets in the leading Higgs boson candidate (from the three possible pairings for the leading Higgs candidate) 6. Average absolute η value of the four Higgs boson candidate jets 7. $\log(X_{Wt})$ 8. Trigger class index as one-hot encoder 9. Year index as one-hot encoder (for years inclusive training)

Phys. Rev. D 105 (2022) 092002

HH→$b\bar{b}b\bar{b}$ NN input variables for 2b → 4b reweighting

ATLAS EXPERIMENT

ggF	VBF
1. $\log(p_T)$ of the 2^{nd} leading Higgs boson candidate jet	1. Maximum dijet mass from the possible pairings of the four Higgs boson candidate jets
2. $\log(p_T)$ of the 4^{th} leading Higgs boson candidate jet	2. Minimum dijet mass from the possible pairings of the four Higgs boson candidate jets
3. $\log(\Delta R)$ between the closest two Higgs boson candidate jets	3. Energy of the leading Higgs boson candidate
4. $\log(\Delta R)$ between the other two Higgs boson candidate jets	4. Energy of the subleading Higgs boson candidate
5. Average absolute η value of the Higgs boson candidate jets	5. Second-smallest ΔR between the jets in the leading Higgs boson candidate (from the three possible pairings for the leading Higgs candidate)
6. $\log(p_T)$ of the di-Higgs system	6. Average absolute η value of the four Higgs boson candidate jets
7. ΔR between the two Higgs boson candidates	7. $\log(X_{Wt})$
8. $\Delta\phi$ between jets in the leading Higgs boson candidate	8. Trigger class index as one-hot encoder
9. $\Delta\phi$ between jets in the subleading Higgs boson candidate	9. Year index as one-hot encoder (for years inclusive training)
10. $\log(X_{Wt})$	
11. Number of jets in the event	
12. Trigger class index as one-hot encoder	

Phys. Rev. D 105 (2022) 092002

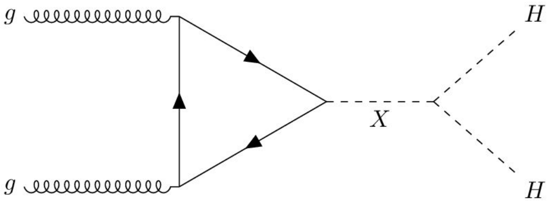
HH→$b\bar{b}b\bar{b}$: Signal Region categories

Category	Data	Expected Background	ggF Signal SM	VBF Signal SM
ggF signal region				
$\|\Delta\eta_{HH}\| < 0.5$, $X_{HH} < 0.95$	1940	1940(130)	6.99	0.038
$\|\Delta\eta_{HH}\| < 0.5$, $X_{HH} > 0.95$	3602	3620(200)	6.49	0.036
$0.5 < \|\Delta\eta_{HH}\| < 1.0$, $X_{HH} < 0.95$	1924	1870(120)	5.15	0.037
$0.5 < \|\Delta\eta_{HH}\| < 1.0$, $X_{HH} > 0.95$	3540	3490(190)	4.75	0.040
$\|\Delta\eta_{HH}\| > 1.0$, $X_{HH} < 0.95$	1880	1740(120)	2.92	0.043
$\|\Delta\eta_{HH}\| > 1.0$, $X_{HH} > 0.95$	3285	3210(200)	2.81	0.041
VBF signal region				
$\|\Delta\eta_{HH}\| < 1.5$	116	125(12)	0.37	0.090
$\|\Delta\eta_{HH}\| > 1.5$	241	231(20)	0.06	0.207

arxiv.org:2301.03212

HH→b$\bar{b}$b$\bar{b}$ (resonant production)

BSM HH production via decays of heavy resonance (X)



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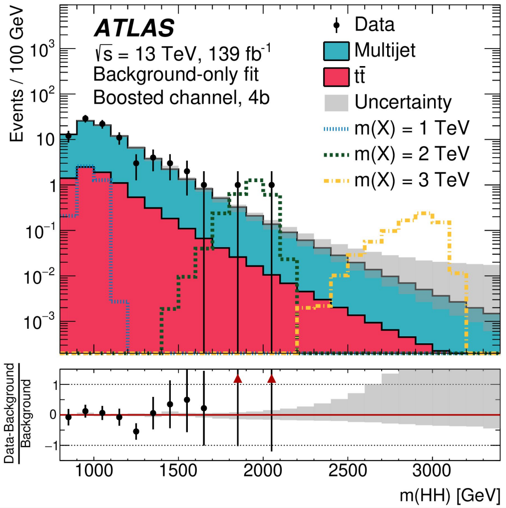
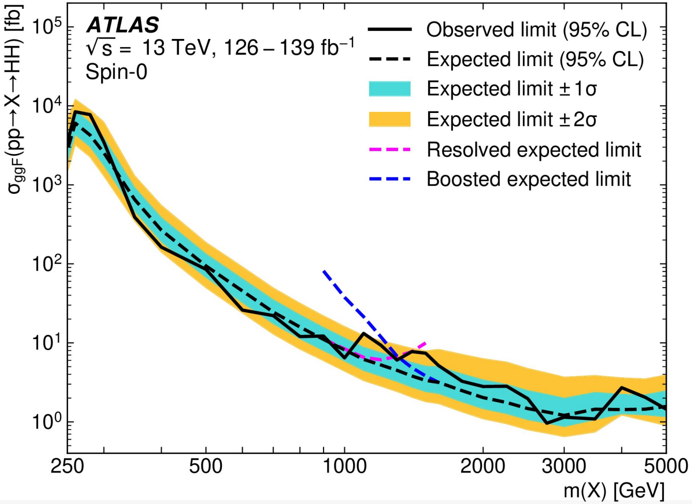
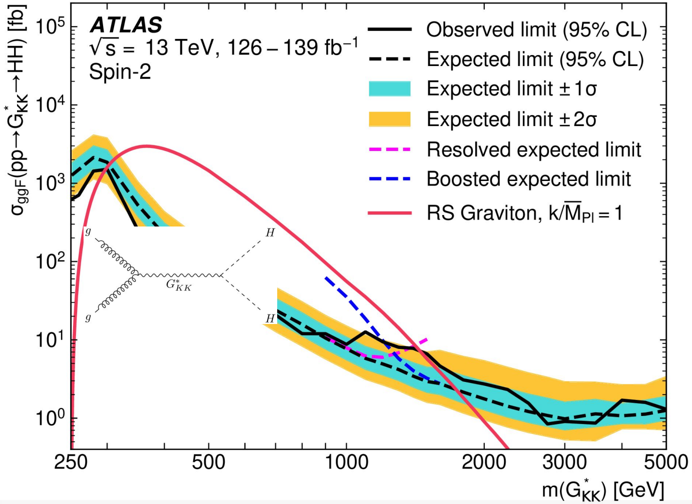
Signal vs bkg modelling for 3 resonance mass points



Limits in production cross-section for different mass values for 2 different theoretical models





HH→$b\bar{b}\gamma\gamma$ (non-resonant) MVA categories and inputs

ATLAS EXPERIMENT

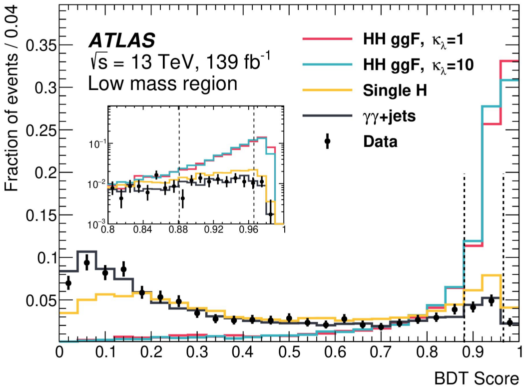
Category	Selection criteria
High mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.967, 1]$
High mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.857, 0.967]$
Low mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.966, 1]$
Low mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.881, 0.966]$

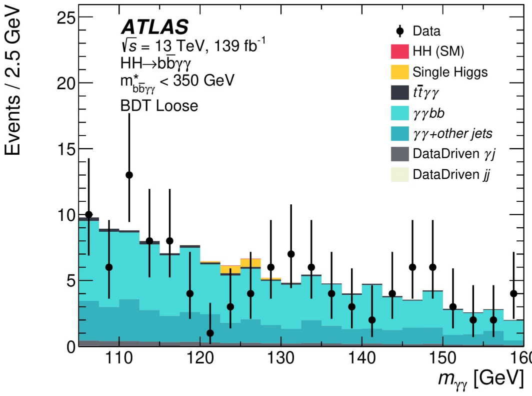
Variable	Definition
Photon-related kinematic variables	
$p_T/m_{\gamma\gamma}$	Transverse momentum of each of the two photons divided by the diphoton invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of the leading and subleading photon
Jet-related kinematic variables	
b-tag status	Tightest fixed b-tag working point (60%, 70%, or 77%) that the jet passes
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of the two jets with the highest b-tagging score
$p_T^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudorapidity and azimuthal angle of the b-tagged jets system
$m_{b\bar{b}}$	Invariant mass of the two jets with the highest b-tagging score
H_T	Scalar sum of the p_T of the jets in the event
Single topness	For the definition, see Eq. (**??**)
Missing transverse momentum variables	
E_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

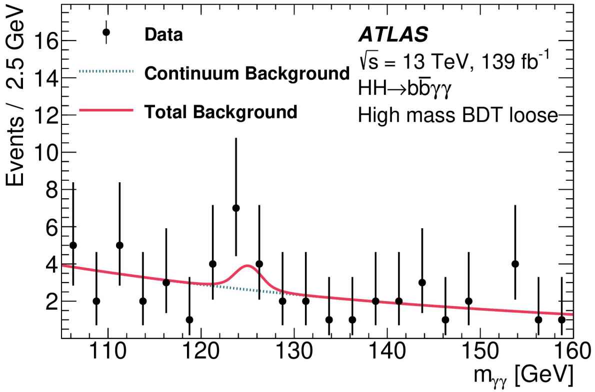
Phys. RevD 106, 052001 (2022)

HH→$b\bar{b}\gamma\gamma$ (κ_λ scan)

Region with low $m^*_{b\bar{b}\gamma\gamma}$ values - large number of events for BSM κ_λ values





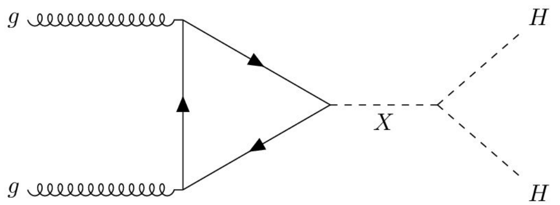


[Phys. RevD 106, 052001 (2022)]

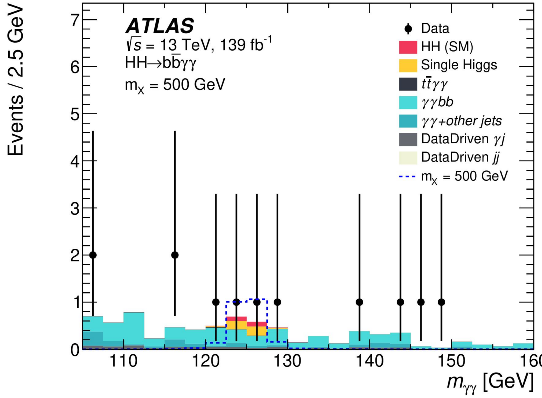
HH→bb̄γγ (resonant production)

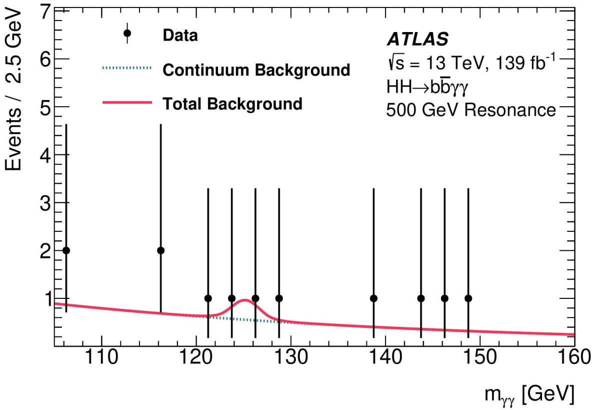
BSM HH production via decays of heavy resonance (X)

Phys. RevD 106, 052001 (2022)

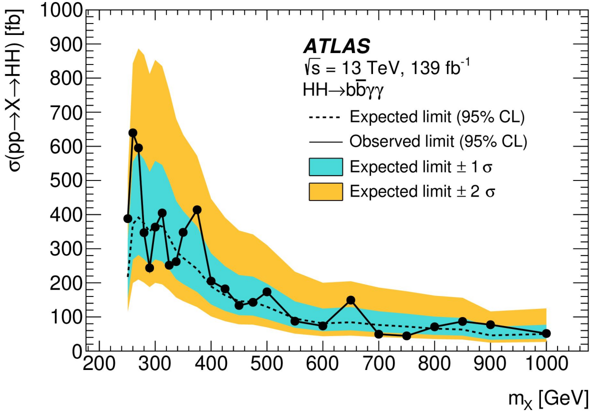


Example: m_X = 500 GeV





Limits in production cross-section for different mass values for X



HH→$b\bar{b}\tau\tau$ non-resonant production: SR categories

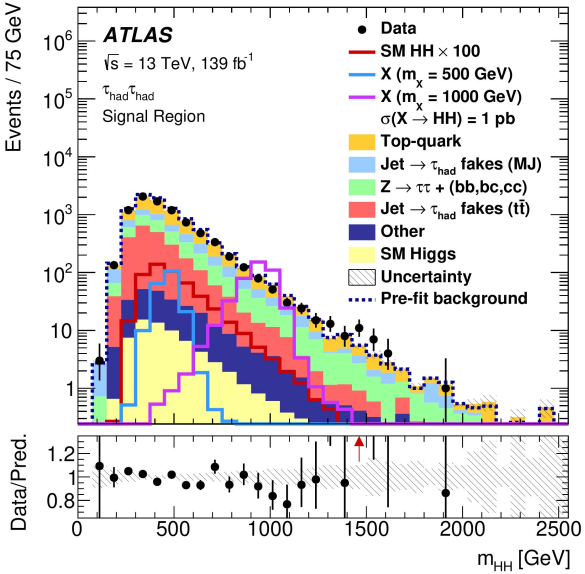
$\tau_{had}\tau_{had}$ category		$\tau_{lep}\tau_{had}$ categories	
STT	DTT	SLT	LTT
e/μ selection			
No loose e/μ with $p_T > 7$ GeV		Exactly one tight e or medium μ	
		$p_T^e > 25, 27$ GeV $p_T^\mu > 21, 27$ GeV	18 GeV $< p_T^e <$ SLT cut 15 GeV $< p_T^\mu <$ SLT cut
		$\|\eta^e\| < 2.47$, not $1.37 < \|\eta^e\| < 1.52$ $\|\eta^\mu\| < 2.7$	
$\tau_{had\text{-}vis}$ selection			
Two loose $\tau_{had\text{-}vis}$ $\|\eta\| < 2.5$		One loose $\tau_{had\text{-}vis}$ $\|\eta\| < 2.3$	
$p_T > 100, 140, 180$ (25) GeV	$p_T > 40$ (30) GeV	$p_T > 20$ GeV	$p_T > 30$ GeV
Jet selection			
≥ 2 jets with $\|\eta\| < 2.5$			
$p_T > 45$ (20) GeV	Trigger dependent	$p_T > 45$ (20) GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{MMC} > 60$ GeV			
Opposite-sign electric charges of $e/\mu/\tau_{had\text{-}vis}$ and $\tau_{had\text{-}vis}$			
Exactly two b-tagged jets			
		$m_{bb} < 150$ GeV	

JHEP 07 (2023) 040

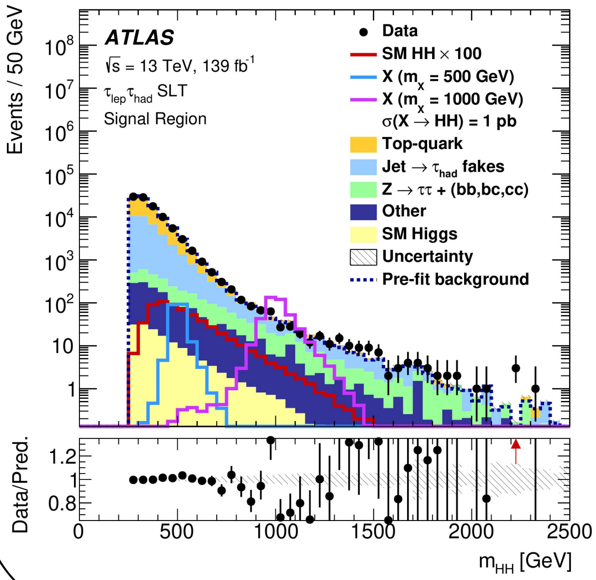
$HH\to b\bar{b}\tau\tau$ non-resonant production: backgrounds

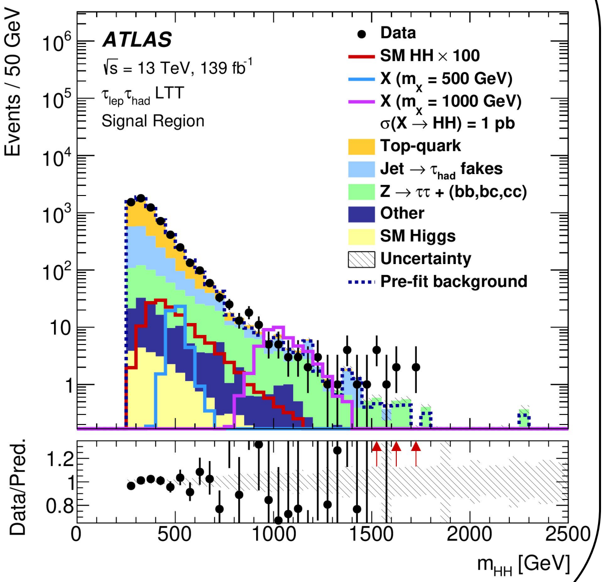
ATLAS EXPERIMENT

BDT for background estimation



NN for background estimation





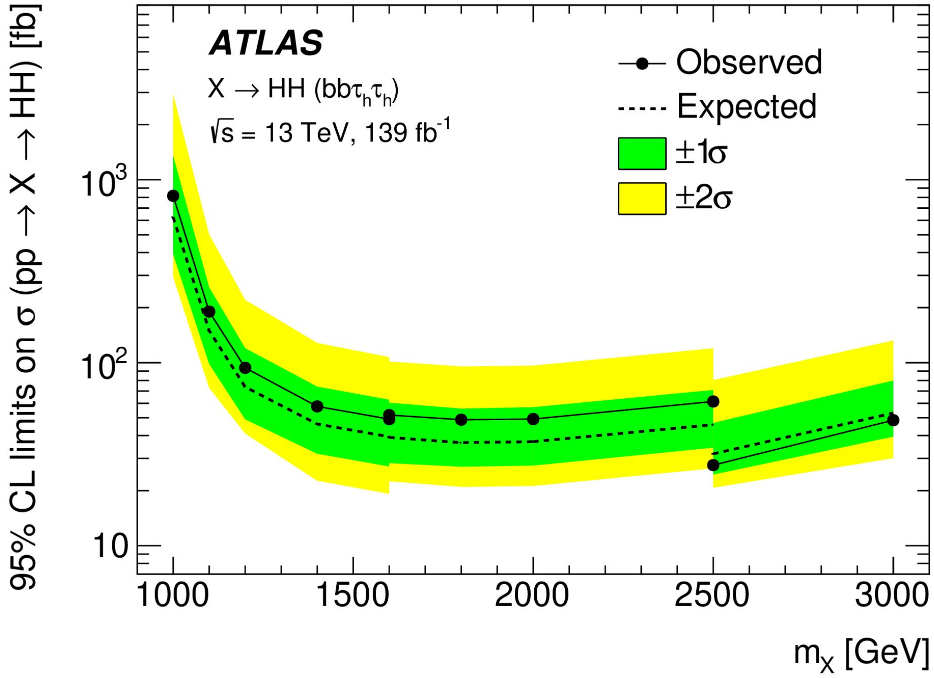
JHEP 07 (2023) 040

HH→$b\bar{b}\tau\tau$ (non-resonant production) MVA inputs

Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_{T}(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_{T}		✓	
m_{T}^{W}		✓	
E_{T}^{miss}		✓	
$\mathbf{p}_{T}^{miss}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_{T}^{miss})$			✓
$\Delta\phi(\tau\tau, \mathbf{p}_{T}^{miss})$			✓
S_{T}			✓

JHEP 07 (2023) 040

HH→b$\bar{b}$ττ (resonant production)



JHEP 07 (2023) 040

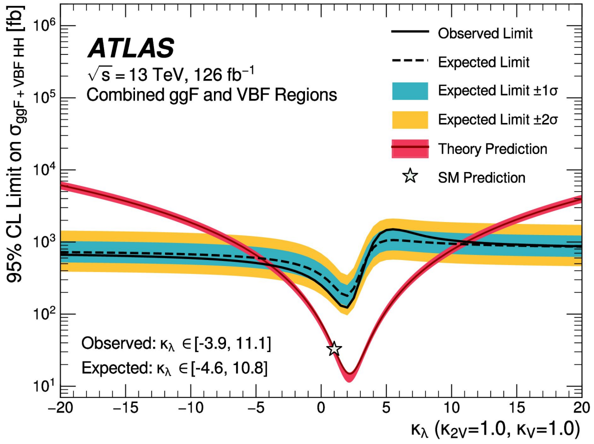
HH→$b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$ results

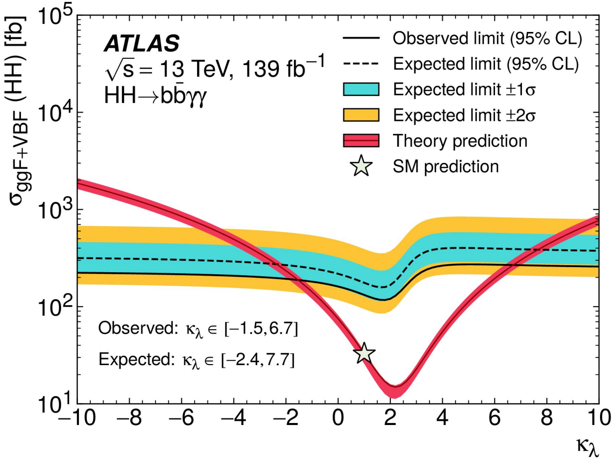
κ_λ observed limits at 95% CL

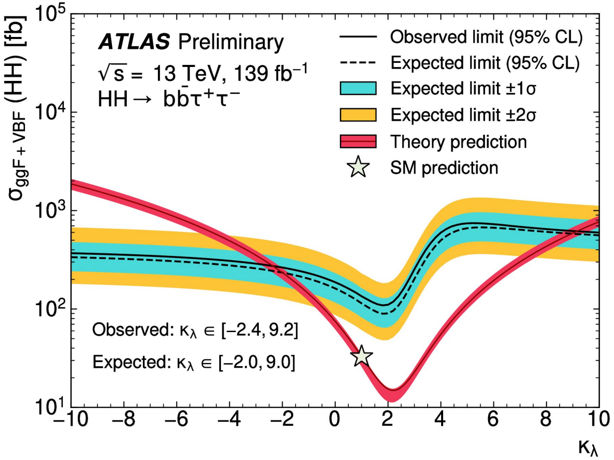
HH→$b\bar{b}b\bar{b}$: $\kappa_\lambda \in$ [-3.3,11.4]

HH→$b\bar{b}\gamma\gamma$: $\kappa_\lambda \in$ [-1.4,6.5]

HH→$b\bar{b}\tau\tau$: $\kappa_\lambda \in$ [-2.7,9.5]







κ_{2V} observed limits at 95%CL

$b\bar{b}b\bar{b}$: $\kappa 2V \in$ [-0.0,2.1]

$b\bar{b}\gamma\gamma$: $\kappa 2V \in$ [-0.8,3.0]

$b\bar{b}\tau\tau$: $\kappa 2V \in$ [-0.6,2.7]

VHH production: Signal regions

	Signal regions			Control regions	
	0L	1L (1L+/1L−)	2L	$t\bar{t}$	V + jets
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	single-lepton	single-lepton	single-lepton	single-photon
Lepton or photon	0 *loose* leptons	= 1 *tight* electron with $p_{\mathrm{T}} > 27$ GeV OR 1 *medium* muon with $p_{\mathrm{T}} > 25$ GeV, 0 additional *loose* leptons	= 2 *loose* leptons (e^+e^- or $\mu^+\mu^-$), ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV, 81 GeV $< m_{\ell\ell} <$ 101 GeV	= 2 *loose* leptons ($e^{\pm}\mu^{\mp}$), ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV	= 1 photon with $p_{\mathrm{T}} > 150$ GeV, 0 *loose* leptons
$\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}}) > 12$, $\lvert\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, h)\rvert > 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	—	—	—
Jets	≥ 4 jets with $p_{\mathrm{T}} > 20$ GeV and passing the 85% b-tagging WP				

Eur. Phys. J. C 83 (2023) 519

VHH production: BDT inputs

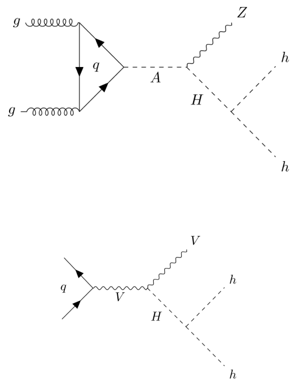
Variable	0L Vhh	0L VH	0L $A \to ZH$	1L Vhh	1L VH	2L Vhh	2L VH	2L $A \to ZH$
	Channel and signal model							
$m_{h_1} + m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1} - m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
N_{jets}	✓	✓	✓	✓	✓	✓	✓	✓
H_{T}^{ex}	✓	✓	✓	✓	✓	✓	✓	✓
$\sum s_{b\text{-tag}}^{\text{pc}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1}^{\text{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_2}^{\text{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
m_{hh}	✓			✓		✓		
p_{T}^{hh}	✓	✓		✓	✓	✓	✓	
$E_{\text{T}}^{\text{miss}}$	✓	✓		✓	✓	✓	✓	✓
p_{T}^{V}				✓	✓	✓	✓	
m_{T}^{W}				✓				
$\cosh(\Delta\eta)_1 - \cos(\Delta\phi)_1$	✓	✓		✓	✓	✓	✓	
$\cosh(\Delta\eta)_2 - \cos(\Delta\phi)_2$	✓	✓		✓	✓	✓	✓	
$\lvert y_{h_1} - y_{h_2} \rvert$	✓	✓		✓	✓	✓	✓	
$\lvert y_V - y_{hh} \rvert$						✓	✓	

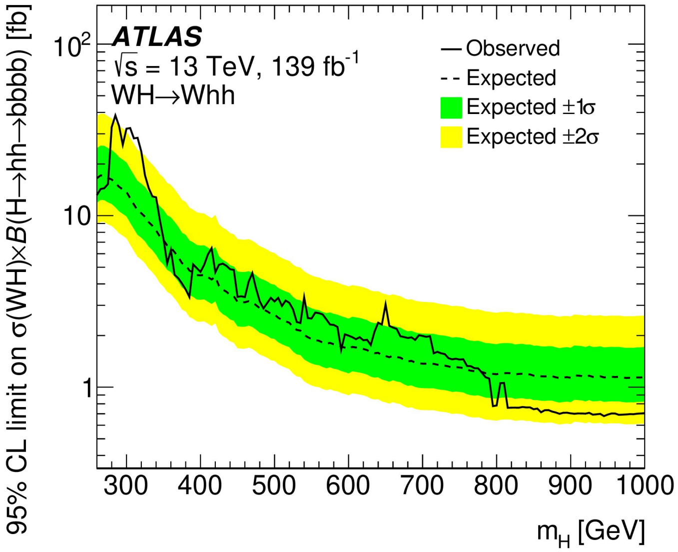
Eur. Phys. J. C 83 (2023) 519

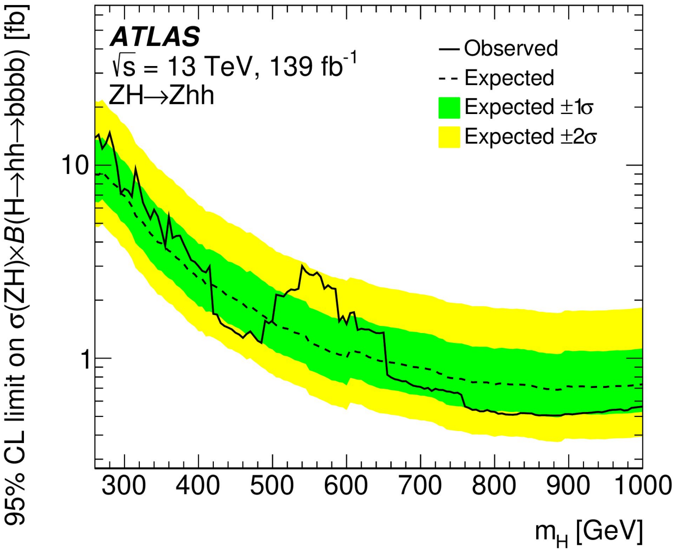
VHH (BSM scenarios)

Limits in production cross-section for different mass values for H in the H→hh BSM model in the $b\bar{b}b\bar{b}$ final state

Production modes







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Effective Field Theory (EFT) interpretations for HH

Definitions of the benchmark points for the SM, 7 EFT models using cluster analysis

Benchmark model	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	−1/3
BM 2	6.84	0.61	0.0	−1/3	1/3
BM 3	2.21	1.05	1/2	1/2	−1/3
BM 4	2.79	0.61	−1/2	1/6	1/3
BM 5	3.95	1.17	1/6	−1/2	−1/3
BM 6	5.68	0.83	−1/2	1/3	1/3
BM 7	−0.10	0.94	1/6	−1/6	1

1	enhanced low m_{hh}
2	enhanced low m_{hh}, slowly falling or shoulder
3	enhanced low m_{hh}, second local maximum above $m_{hh} \simeq 2m_t$
4	SM-like
5	SM-like with enhanced tail
6	close-by double peaks or shoulder left
7	no steep slope at low m_{hh}, enhanced tail

ATL-PHYS-PUB-2022-019

arxiv.org:2301.03212

Run 3 improvements: New triggers for HH→4b searches

Two new triggers:
1) Main stream: asymmetric 4 jet trigger (3 b-tags)
2) Delayed stream: 4 jet trigger (2 b-tags)