Overview of *HH* searches at ATLAS

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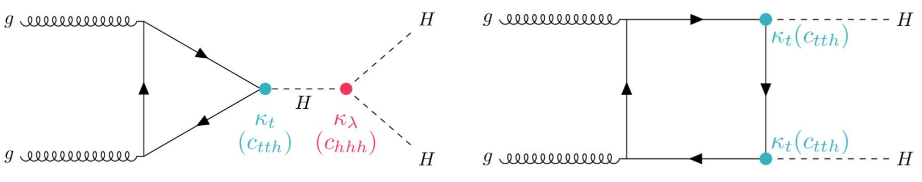
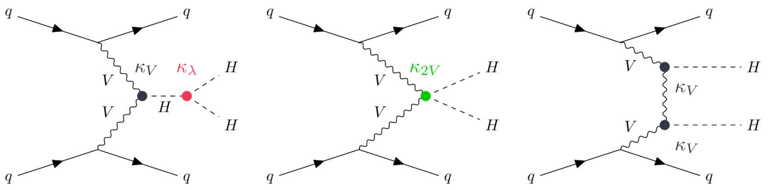
Run 2 *HH* combination

$\sigma^{\text{SM}}_{\text{ggF}}(HH) = 31.1^{+1.9}_{-7.1}\,(\text{scale} + m_{\text{top}}) \pm 0.9\,(\text{PDF} + \alpha_s)$ fb at NNLO in QCD

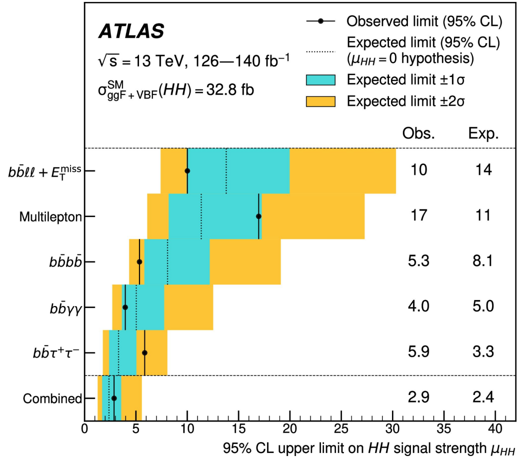


$\sigma^{\text{SM}}_{\text{VBF}}(HH) = 1.73 \pm 0.04$ fb at N^{3}LO in QCD



Expected limit improved from 2.9 to 2.4 from previous ATLAS *HH* combination [Phys. Lett. B 843 (2023) 137745]

Channel	Production mode	Lumi	Journal reference
$HH \to bb\ell\ell + E_{\text{T,miss}}$	ggF + VBF	140 fb^{-1}	JHEP 02 (2024) 037
$HH \to$ Multilepton	ggF + VBF	140 fb^{-1}	JHEP 08 (2024) 164
$HH \to bbbb$	ggF + VBF VBF	126 fb^{-1} 140 fb^{-1}	PRD 108 (2023) 052003 PLB 858 (2024) 139007
$HH \to bb\gamma\gamma$	ggF + VBF	140 fb^{-1}	JHEP 01 (2024) 066
$HH \to bb\tau\tau$	ggF + VBF	140 fb^{-1}	PRD 110 (2024) 032012
Combination	ggF + VBF	126-140 fb^{-1}	PRL 133 (2024) 101801

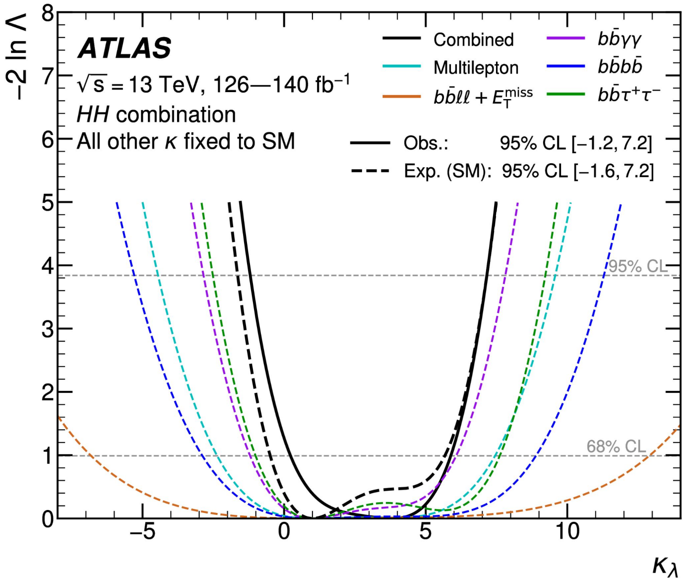


Run 2 *HH* combination

- Higgs boson self-coupling modifier κ_λ and quartic *HHVV* coupling modifier κ_{2V} 95% CL intervals constrained
- Best constraint on κ_λ provided by $HH \rightarrow bb\gamma\gamma$ and on κ_{2V} by $HH \rightarrow bbbb$

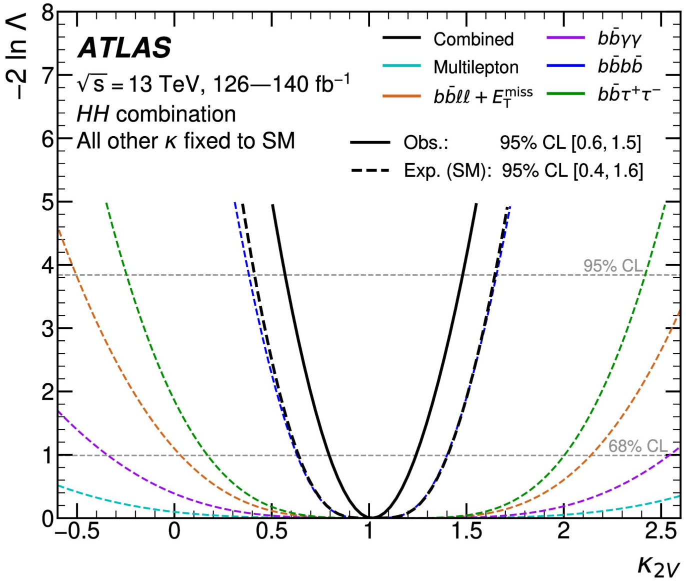
$-1.2 < \kappa_\lambda < 7.2$ (observed)

$-1.6 < \kappa_\lambda < 7.2$ (expected)



$0.6 < \kappa_{2V} < 1.5$ (observed)

$0.4 < \kappa_{2V} < 1.6$ (expected)



Run 2 *HH* combination

- Most sensitive channels updated, re-analyse Run 2 data to enhance the sensitivity:
  - $HH \rightarrow bbbb$ with BR of 34%
  - $HH \rightarrow bb\tau\tau$ with BR of 7.3%
  - $HH \rightarrow bb\gamma\gamma$ with BR of 0.26%

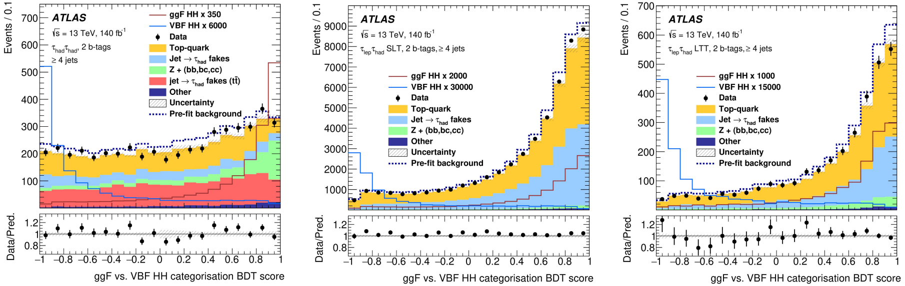
	bb	WW	ττ	ZZ	γγ
bb	34 %				
WW	25 %	4.6 %			
ττ	7.3 %	2.7 %	0.39 %		
ZZ	3.1 %	1.1 %	0.33 %	0.069 %	
γγ	0.26 %	0.10 %	0.028 %	0.012 %	0.0005 %

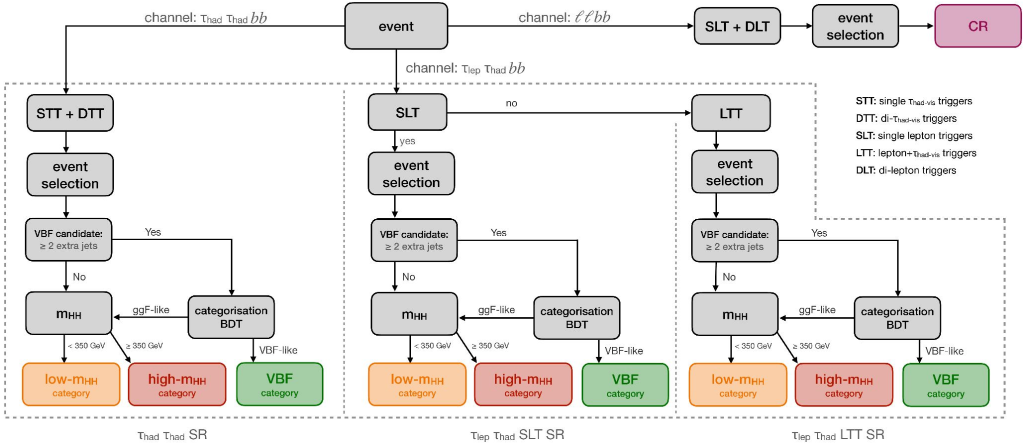
- New channels included:
  - $HH \rightarrow bbZZ^*$ / VV^*VV^* / $VV^*\tau^+\tau^-$ / $\tau^+\tau^-\tau^+\tau^-$ / $\gamma\gamma VV^*$ / $\gamma\gamma\tau^+\tau^-$ where $V = W$ or Z with BR of 6.5%
  - $HH \rightarrow bb + WW^*$ / ZZ^* / $\tau^+\tau^- \rightarrow bb + \ell^+\ell^-$ + neutrinos where $\ell = e, \mu$ with BR of 2.9%
- Final discriminating variable can be the *HH* invariant mass, the diphoton invariant mass, or the multivariate classifiers used to separate signal from background
- These results bring a 17% improvement with respect to the previous publication:
  - 13% from the improvements in the $bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$ final states
  - 4% from the inclusion of the multilepton and $bb\ell\ell + E_{T,miss}$ final states

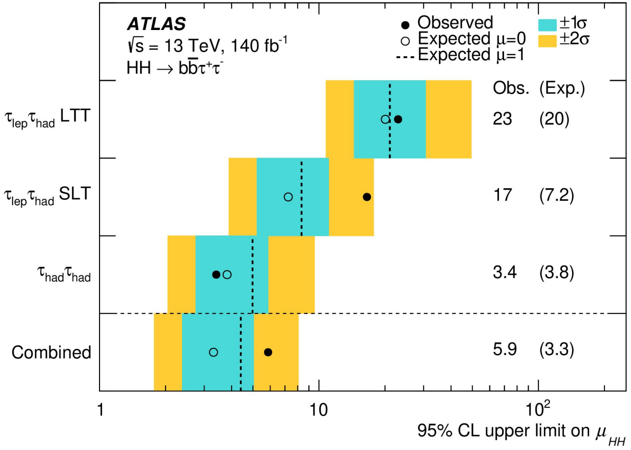
Updates in $HH \rightarrow bb\tau\tau$

Old: JHEP 07 (2023) 040	< 4.7 (obs)	< 3.9 (exp)
New: PRD 110 (2024) 032012	< 5.9 (obs)	< 3.3 (exp)

- Three SRs: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ SLT and $\tau_{lep}\tau_{had}$ LTT
- Three categories: ggF low m_{HH}, ggF high m_{HH} and VBF
  - BDTs to separate ggF from VBF production
  - m_{HH} cut in 350 GeV to increase sensitivity in κ_λ in ggF
- Main backgrounds (*tt* and *Z* + hf jets) estimated from MC
- Fake τ_{had} contribution from *tt* and multijet backgrounds extracted using data driven techniques
- **15% reduction** in signal strength μ_{HH} wrt previous results







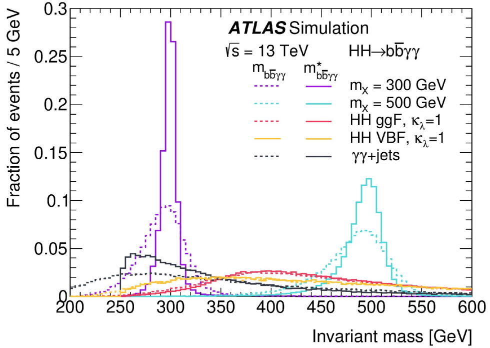
Updates in $HH \rightarrow bb\gamma\gamma$

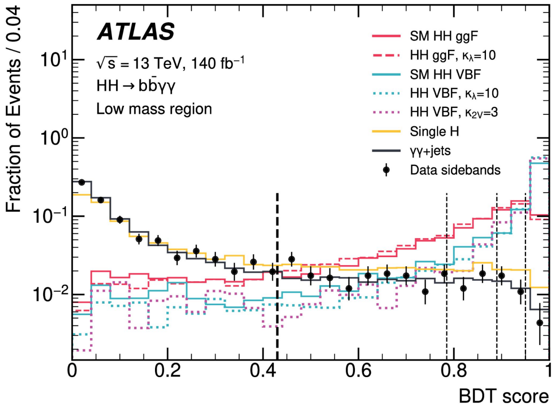
Old: PRD 106 (2022) 052001	< 4.2 (obs)	< 5.7 (exp)
New: JHEP 01 (2024) 066	< 4.0 (obs)	< 5.0 (exp)

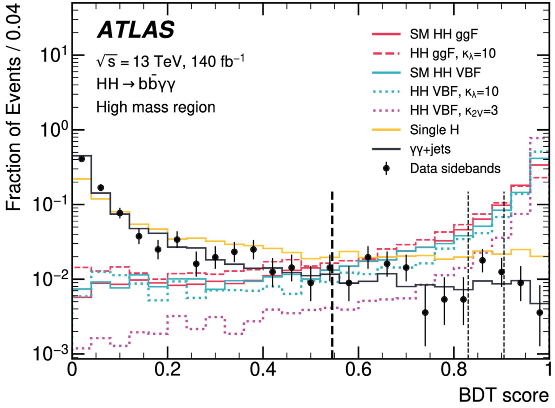
- *HH* VBF process considered for the first time in the analysis
- **Seven categories** defined based on BDT score and the four-body inv mass:

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\ \text{GeV}) - (m_{\gamma\gamma} - 125\ \text{GeV})$$

Category	Selection criteria
High Mass 1	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.545, 0.830]$
High Mass 2	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.830, 0.905]$
High Mass 3	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.905, 1.000]$
Low Mass 1	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.430, 0.785]$
Low Mass 2	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.785, 0.890]$
Low Mass 3	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.890, 0.950]$
Low Mass 4	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.950, 1.000]$





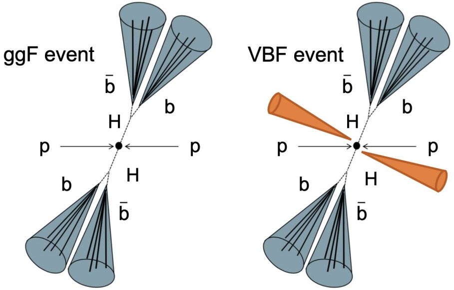


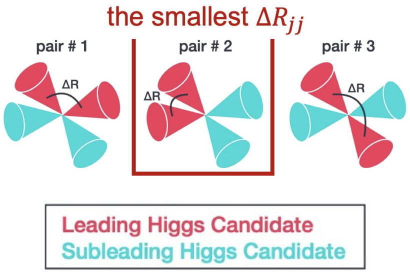
- Main backgrounds: $\gamma\gamma$ + jets and $H \rightarrow \gamma\gamma$
- SR: 120 < $m_{\gamma\gamma}$ < 130 GeV, SBs: 105 < $m_{\gamma\gamma}$ < 120 GeV, 130 < $m_{\gamma\gamma}$ < 160 GeV
- Parametrization of $m_{\gamma\gamma}$ discriminant:
  - Double-sided Crystal Ball function for *HH* signal and single *H* background
  - Exponential for background (normalized to SBs)
- **12% reduction** in signal strength μ_{HH} with respect to previous results

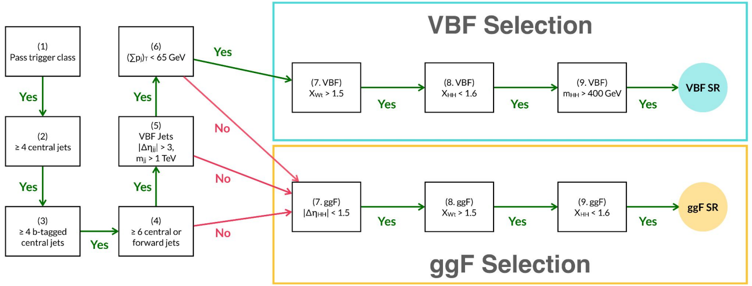
Updates in $HH \to bbbb$

ggF (36.1 fb^{-1}): JHEP 01 (2019) 030 VBF (126 fb^{-1}): JHEP 07 (2020) 108	< 12.9 (obs) < 840 (obs)	< 20.7 (exp) < 550 (exp)
New: PRD 108 (2023) 052003	< 5.4 (obs)	< 8.1 (exp)

- Two orthogonal selections targeting ggF and VBF







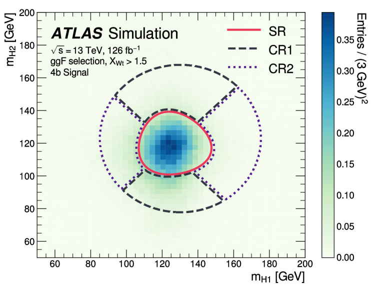
- Analysis categorizations to improve sensitivity
- Main backgrounds: multijet (~90%) and *tt* (~10%)
- Suppress multijet and tt using $|\Delta\eta_{HH}| < 1.5$ and $\chi_{Wt} > 1.5$

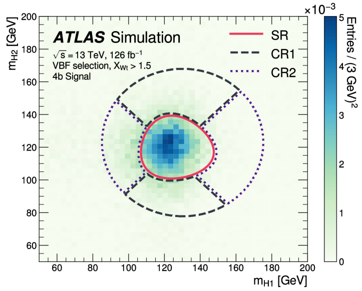
$$X_{Wt} = \min\left[\sqrt{\left(\frac{m_W - 80.4\,\text{GeV}}{0.1\,m_W}\right)^2 + \left(\frac{m_t - 172.5\,\text{GeV}}{0.1\,m_t}\right)^2}\right]$$

- Signal region $X_{HH} < 1.6$:

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

- Fully data-driven background estimation using a neural network to estimate multijet background

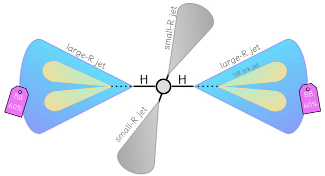




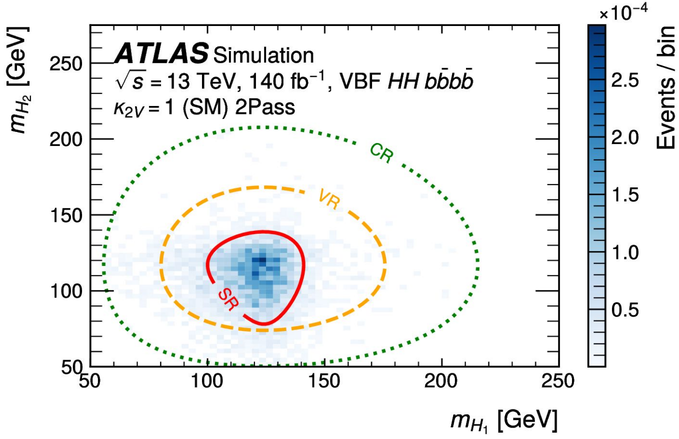
	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
μ_{ggF}	5.5	4.4	5.9	8.2	12.4	19.6
μ_{VBF}	130	70	100	130	190	280
$\mu_{\text{ggF+VBF}}$	5.4	4.3	5.8	8.1	12.2	19.1

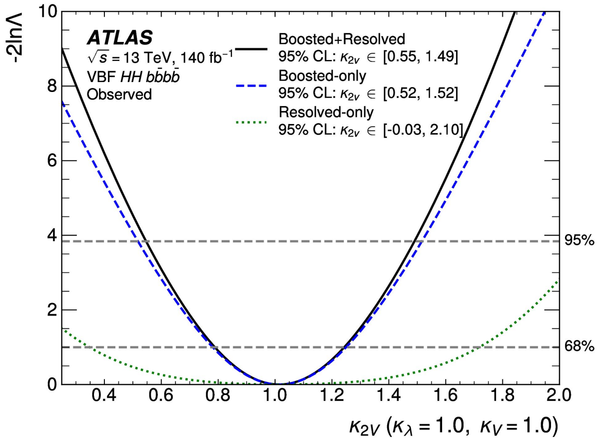
$HH \to bbbb$ VBF boosted regime

- Search for non-resonant and resonant VBF $HH \to bbbb$ production using the full Run 2 data (140 fb^{-1})
- Boosted regime reconstruction:
  - HH system reconstructed with 2 large-R (R = 1.0) jets
  - VBF signature from 2 resolved small-R (R = 0.4) jets



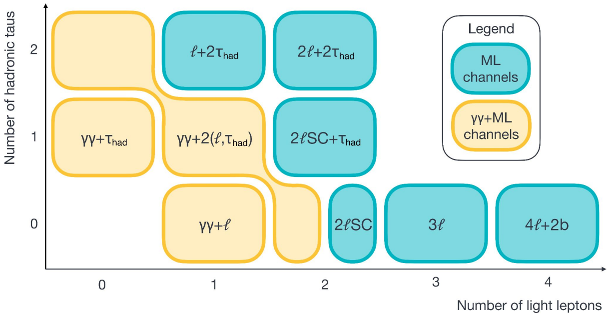
- SR/VR/CR defined using the mass-plane
- VR and CR used for the data-driven background estimation
- BDT selection for further discrimination power between signal and background in the SR
- To maximise the sensitivity to the κ_{2V} parameter, the non-resonant VBF $HH \to bbbb$ searches are combined:
  - Resolved analysis [PRD 108 (2023) 052003]
  - Boosted analysis [PLB 858 (2024) 139007]



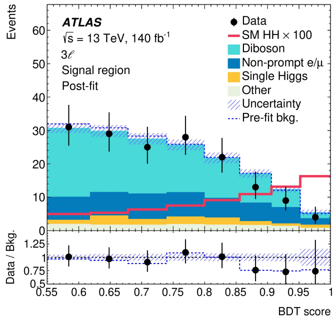


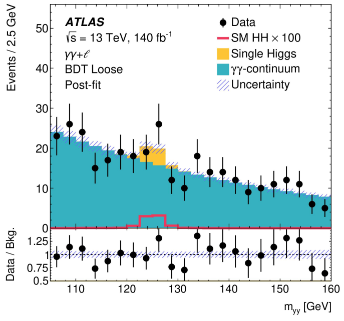
$HH \rightarrow$ Multilepton

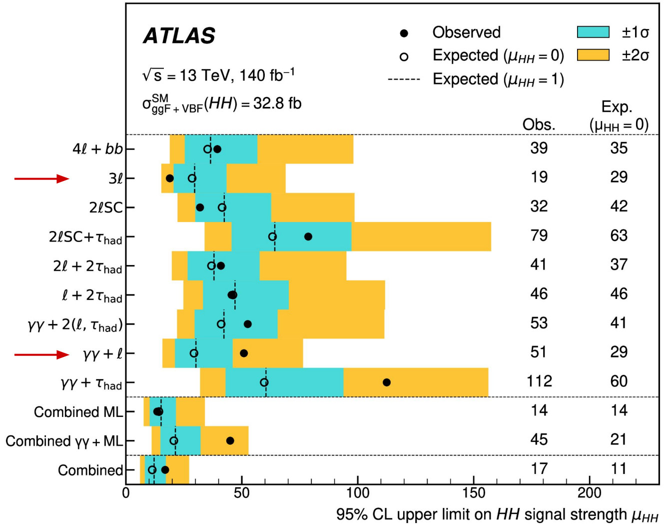
- Final states from different HH decay channels [JHEP 08 (2024) 164]: $HH \rightarrow bbZZ^*$ / VV^*VV^* / $VV^*\tau^+\tau^-$ / $\tau^+\tau^-\tau^+\tau^-$ / $\gamma\gamma VV^*$ / $\gamma\gamma\tau^+\tau^-$ (6.5% BR)
- Two main categories:
  - **$\gamma\gamma$ + ML channel** (Diphoton plus multilepton): 3 sub-channels
  - **ML channel** (light leptons and hadronic taus): 6 sub-channels



- Dominant backgrounds:
  - For the $\gamma\gamma$ + ML channel is non-resonant $\gamma\gamma$ production
  - For the ML channel is diboson production
- BDT output score distribution used as final discriminant in each ML SR
- $m_{\gamma\gamma}$ distribution used as final discriminant in each $\gamma\gamma$ + ML SR

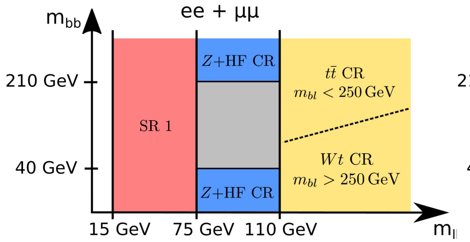


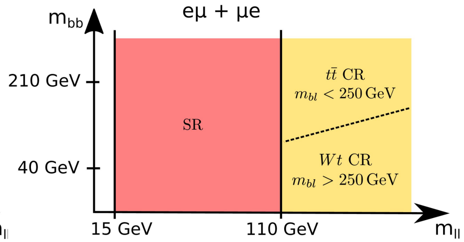


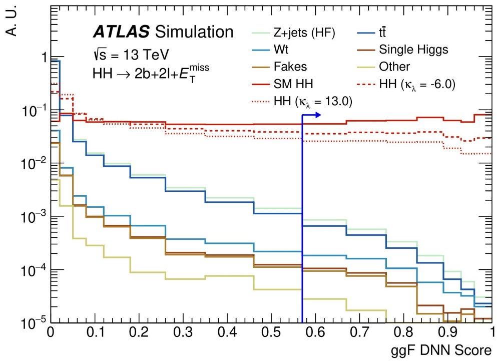


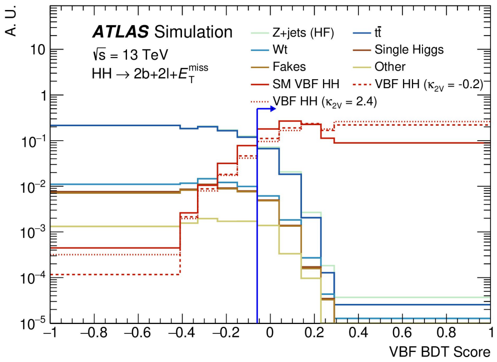
$HH \rightarrow bb\ell\ell + E_{T,miss}$

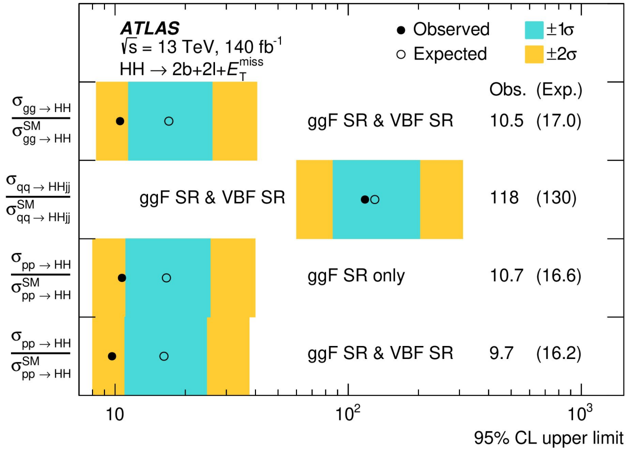
- Final states from different *HH* decay channels [JHEP 02 (2024) 037]:
  $HH \rightarrow bb + WW^* / ZZ^* / \tau^+\tau^- \rightarrow bb + \ell^+\ell^-$ + neutrinos (2.9% BR)
- Dominant background: *tt*, single top (*Wt*), Z/γ^* + hf jets
- MVA to separate signal from background:
  - DNN to classify events in ggF
  - BDT to classify events in VBF (due to low stat)











EFT interpretations: HEFT and SMEFT

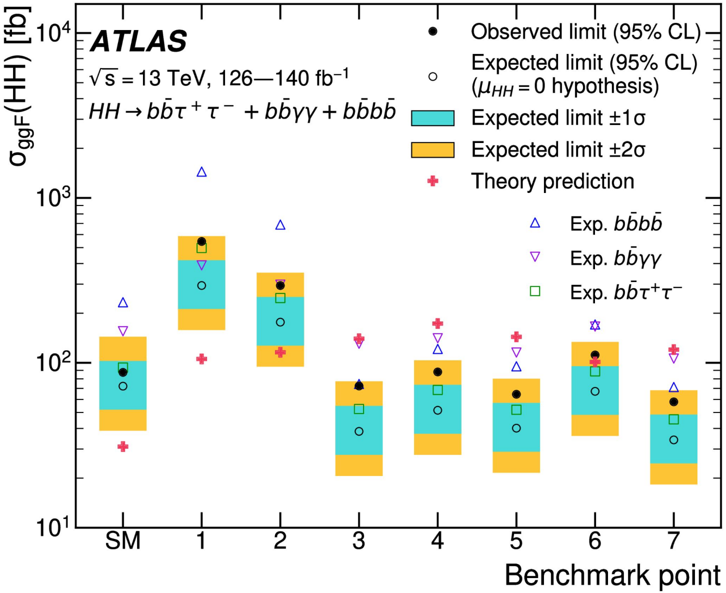
- Interpretation of the results in two effective field theory (EFT) extensions to the SM, the **Higgs effective field theory (HEFT)** and the **SM effective field theory (SMEFT)**
- Benchmark definition in the latest ATLAS *HH* combination (arXiv:2304.01968 [hep-ph])
- The VBF *HH* process is neglected for these results
- Constrain 7 m_{HH} shape benchmarks within the HEFT framework, upper limits on the $\sigma_{\text{ggF } HH}$ for 7 HEFT shape benchmarks

$HH \rightarrow bb\gamma\gamma$ [JHEP 01 (2024) 066]

$HH \rightarrow bb\tau\tau$ [PRD 110 (2024) 032012]

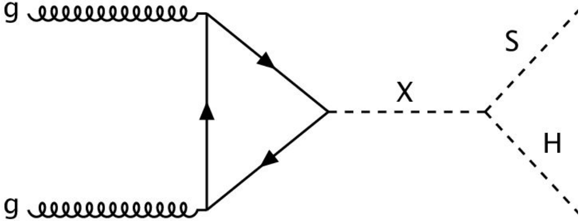
$HH \rightarrow bbbb$ [PRD 108 (2023) 052003]

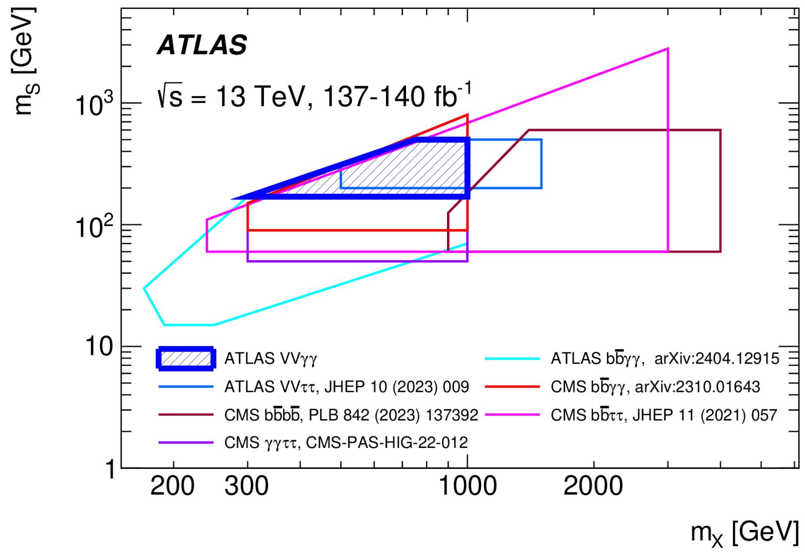
Combination [PRL 133 (2024) 101801]



Run 2 BSM *HH* searches

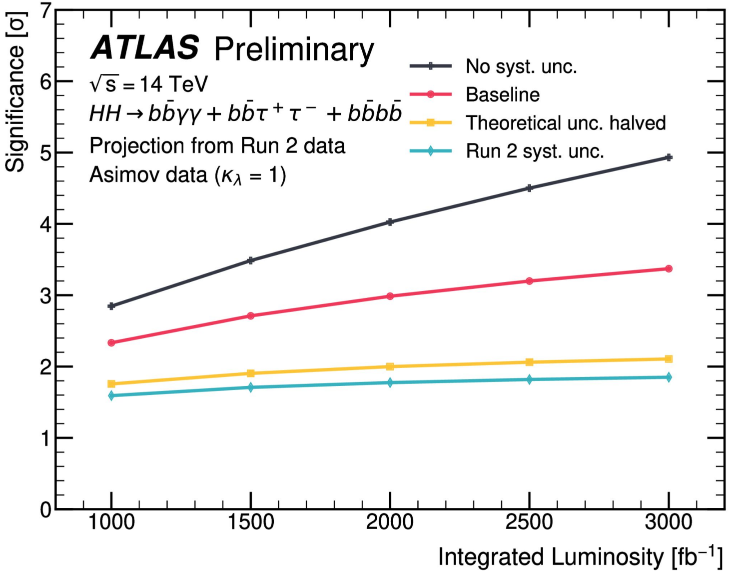
- The current experimental precision does not exclude that *H* may have a small mixing with additional scalar bosons, and may be part of an extended Higgs sector
- Many BSM theories predict such an extended Higgs sector (e.g. 2HDM)
- Search for two additional scalar bosons *X* and *S* under the condition $m_X > m_S + m_H$, the decay $X \to SH$ is kinematically allowed
- Brand new ATLAS searches using the full Run 2 data:
  - $X \to S(\to VV)\, H(\to \tau\tau)$ [JHEP 10 (2023) 009]
  - $X \to S(\to VV)\, H(\to \gamma\gamma)$ [JHEP 10 (2024) 104]
  - $X \to S(\to bb)\, H(\to \gamma\gamma)$ [JHEP 11 (2024) 047]

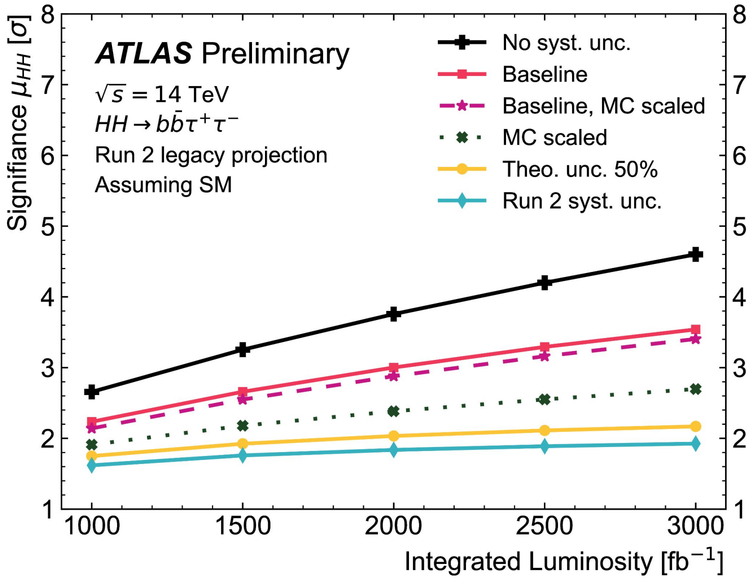




HL-LHC Prospects

- ATLAS and CMS combination in the Yellow report [CERN-2019-007] and Snowmass White paper [ATL-PHYS-PUB-2022-018]
- Latest ATLAS combination results using the three most sensitive channels $HH \rightarrow bb\gamma\gamma$, $HH \rightarrow bb\boldsymbol{\tau\tau}$ and $HH \rightarrow bbbb$ [ATL-PHYS-PUB-2022-053]
- Updated ATLAS projection of the $HH \rightarrow bb\boldsymbol{\tau\tau}$ channel [ATL-PHYS-PUB-2024-016]





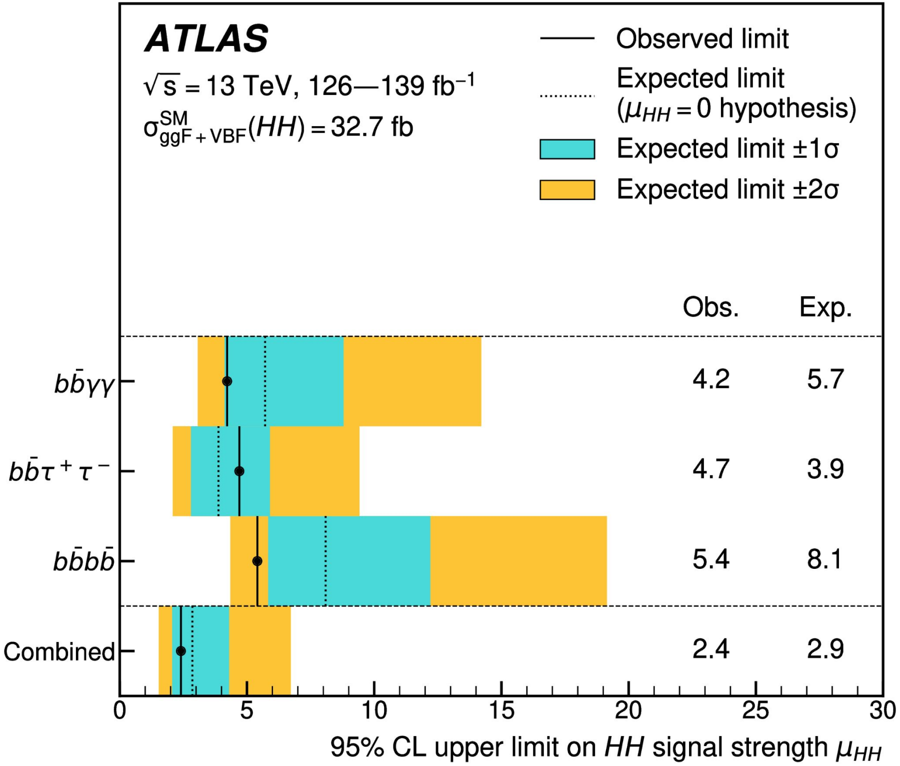
Final remarks

- Wealth of legacy Run 2 results from ATLAS
- Updated ATLAS *HH* combination with full Run 2 data published this year:
  - Double-Higgs production cross-section normalised to its SM prediction μ_{HH} constrained with observed (expected) 95% CL upper limit of $\mu_{\rm HH} < 2.9$ (2.4)
  - Higgs boson self-coupling modifier κ_λ constrained with observed (expected) 95% CL intervals of $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$)
  - Quartic *HHVV* coupling modifier κ_{2V} constrained with observed (expected) 95% CL intervals of $0.6 < \kappa_{2V} < 1.5$ ($0.4 < \kappa_{2V} < 1.6$)
- Interpretation of the results in the HEFT and the SMEFT
- Many $X \rightarrow SH$ searches performed in ATLAS with the Run 2 dataset
- New ATLAS projections for the HL-LHC at 3000 fb^{-1} obtained
- ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

BACKUP

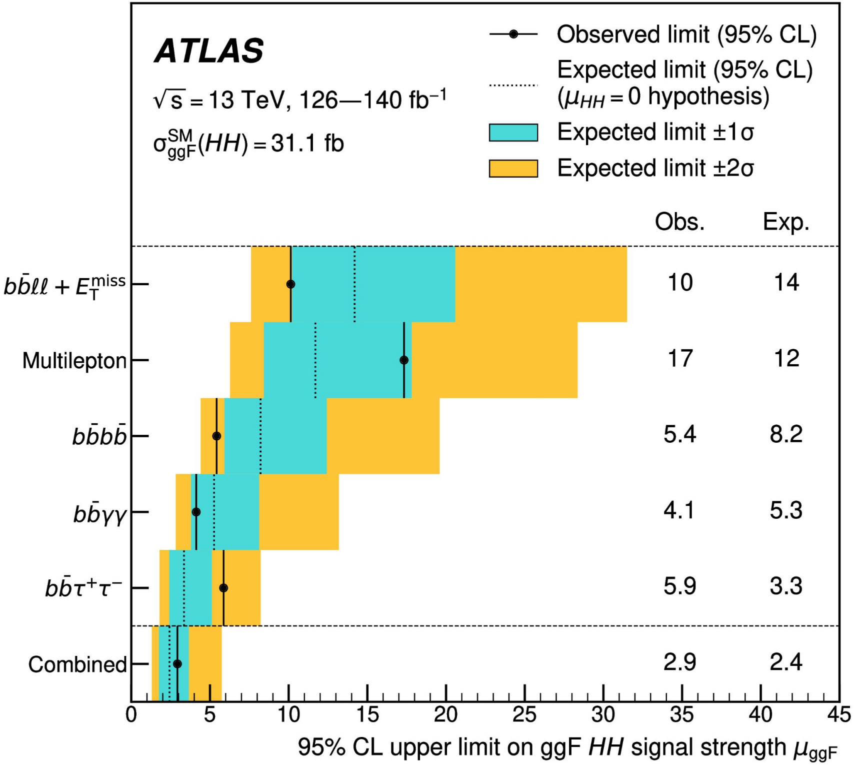
Previous Run 2 *HH* combination

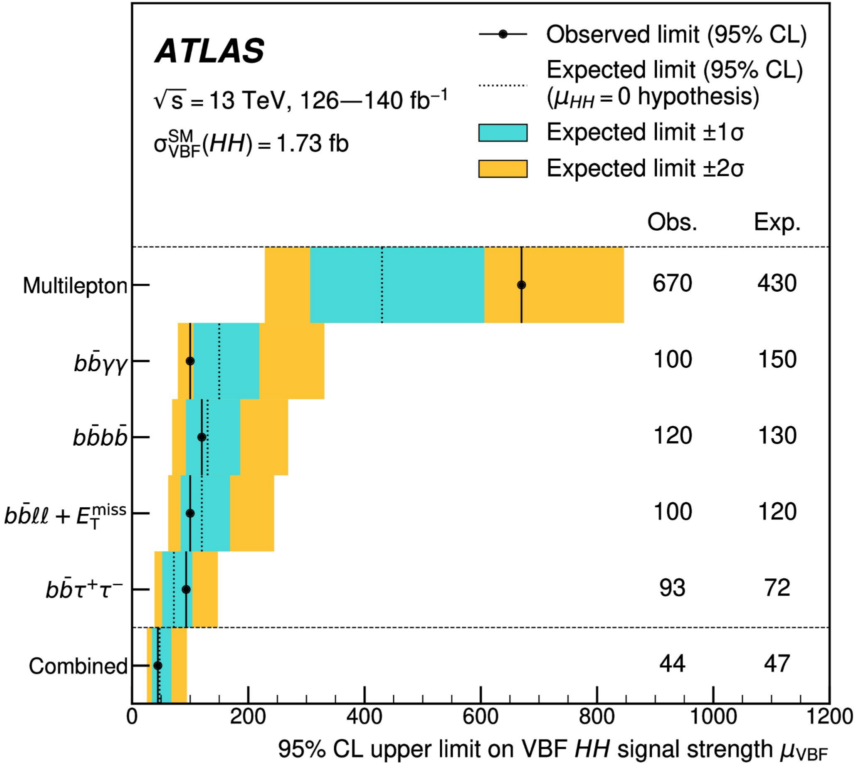
Phys. Lett. B 843 (2023) 137745



Run 2 *HH* combination

[Phys. Rev. Lett. 133 (2024) 101801](https://doi.org/10.1103/PhysRevLett.133.101801)





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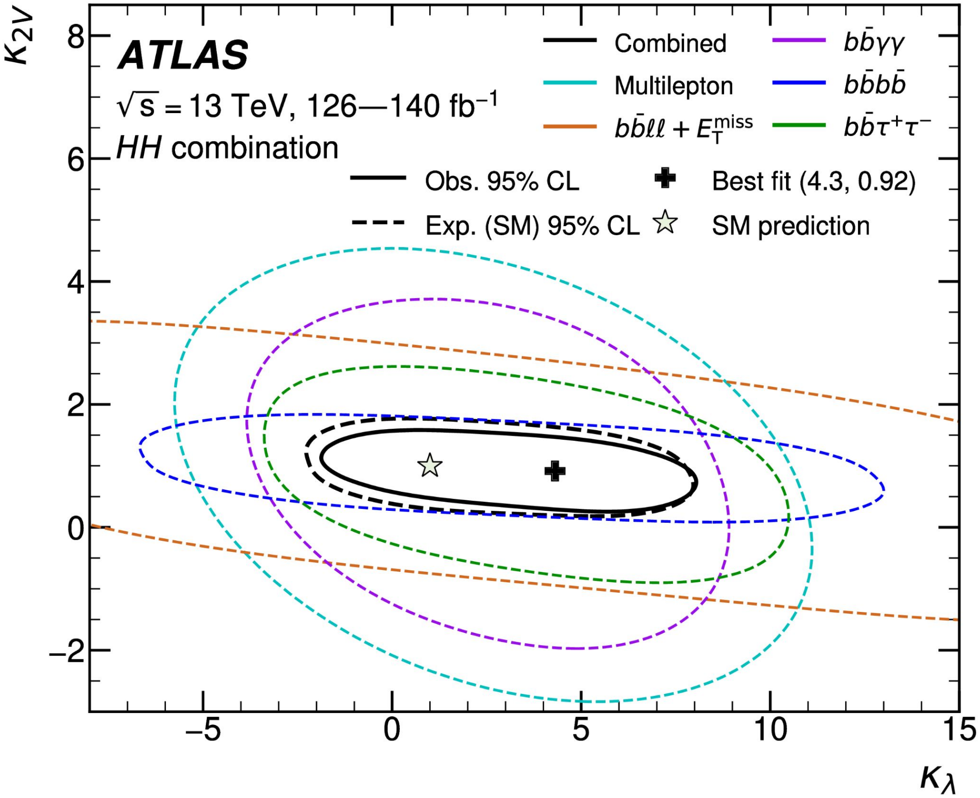
Phys. Rev. Lett. 133 (2024) 101801



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- Best constraint on κ_λ provided by $HH \rightarrow bb\gamma\gamma$ and on κ_{2V} by $HH \rightarrow bbbb$

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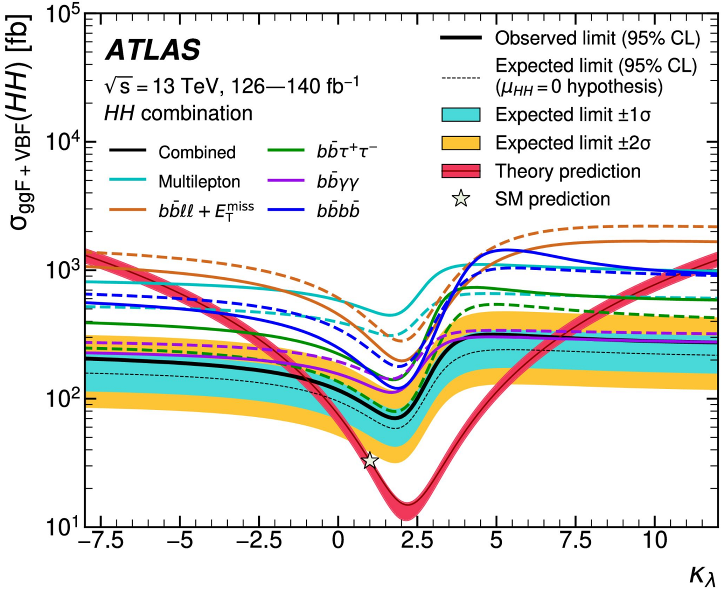
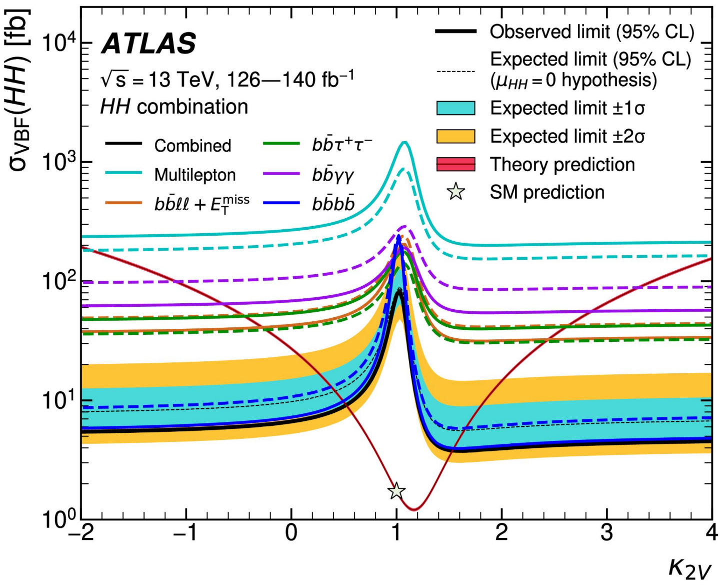


$0.6 < \kappa_{2V} < 1.5$ (observed)

$0.4 < \kappa_{2V} < 1.6$ (expected)



EFT interpretations: HEFT and SMEFT

- Interpretation of the results in two effective field theory (EFT) extensions to the SM, the **Higgs effective field theory (HEFT)** and the **SM effective field theory (SMEFT)**
- The VBF *HH* process is neglected for these results
- Constrain 7 m_{HH} shape benchmarks within the HEFT framework, upper limits on the $\sigma_{\text{ggF } HH}$ for 7 HEFT shape benchmarks

$HH \to bb\gamma\gamma$	$HH \to bb\tau\tau$	$HH \to bbbb$
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