UNIVERSITY OF CAMBRIDGE

TRINITY HALL CAMBRIDGE

ATLAS EXPERIMENT

HH at ATLAS

Experimental Summary

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(University of Cambridge)
on behalf of the ATLAS Collaboration

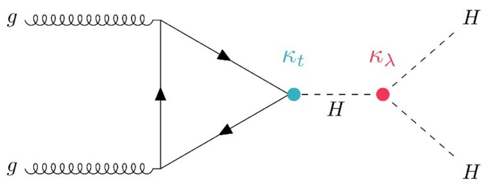
28 November 2022

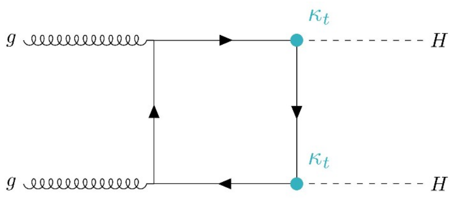
HH Production Channels

ATLAS studies HH in 3 general production topologies

Gluon-gluon fusion

σ_{SM} = 31 fb

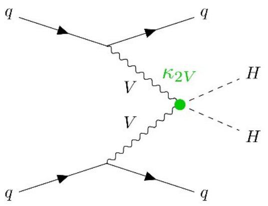


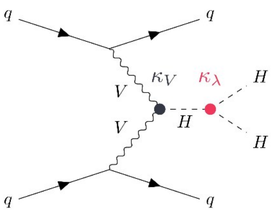


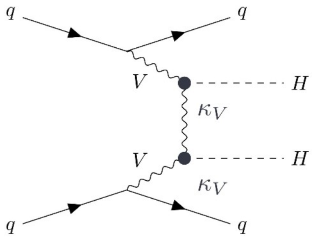
(Resonant scenarios not shown here)

Vector boson fusion

σ_{SM} = 1.7 fb

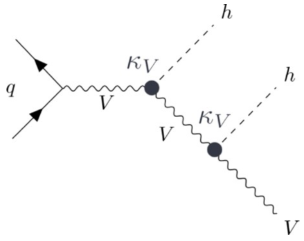


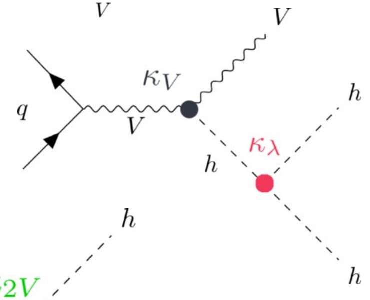


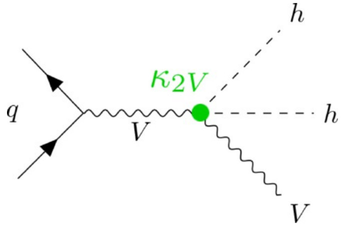


VHH: new from ATLAS!

σ_{SM} = 0.50 (0.36) fb for WHH (ZHH)







HH Decay Modes

Many options for decay modes.

- High BR final states good to mitigate small cross sections. But, they have big backgrounds.
- Complicated trade-off between signal rates, detector resolution for objects, backgrounds, ease of triggering...

	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%

Summary of ATLAS results

Decay channel	Target production mode	Reference	Release date
bbγγ	Non-resonant (ggF*) & resonant	Phys. Rev. D 106 052001	22 Dec 2021
bbττ	Non-resonant (ggF*) & resonant	arXiv:2209.10910	22 Sep 2022
	Resonant (merged H→ττ & H→bb)	JHEP 11 (2020) 163	29 July 2020
bbbb	Resonant	Phys. Rev. D 105 092002	15 Feb 2022
	Non-resonant (ggF & VBF)	ATLAS-CONF-2022-035	30 May 2022
	VHH (leptonic V, res. & non-res.)	arXiv:2210.05415	11 Oct 2022
bblνlν	Non-resonant (ggF)	Phys. Lett. B 801 135145	19 Aug 2019
Combination	Non-resonant & resonant (ggF*)	ATLAS-CONF-2021-052	16 Oct 2021
	Non-resonant + single Higgs	arXiv:2211.01216	3 Nov 2022

These are our full Run 2 results. For older ones, see our public results page

*** VBF accounted for, but not specifically targeted**

Summary of ATLAS results

No longer preliminary

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*** VBF accounted for, but not specifically targeted**

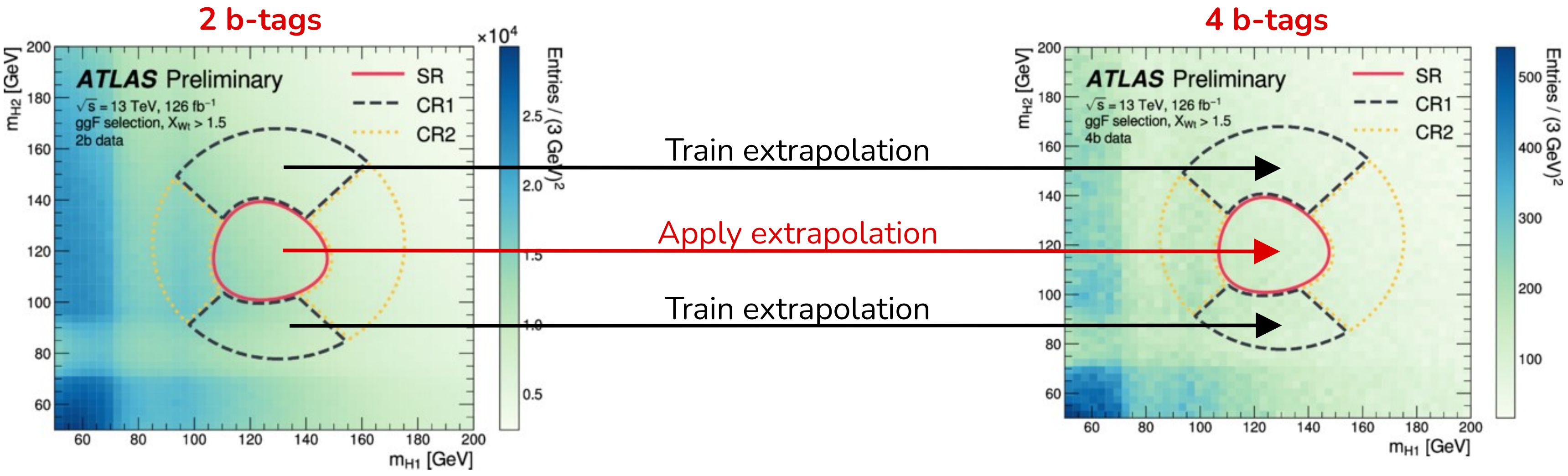
HH→bbbb (non-resonant)

bbbb channel has highest BR, but challenging background (~90% multijet, ~10% top pairs)

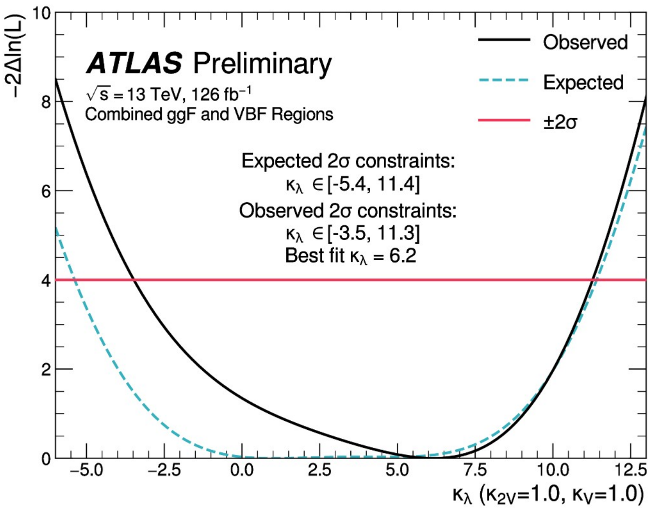
- Train neural network using CRs to extrapolate background from 2 b-tag to 4 b-tag data

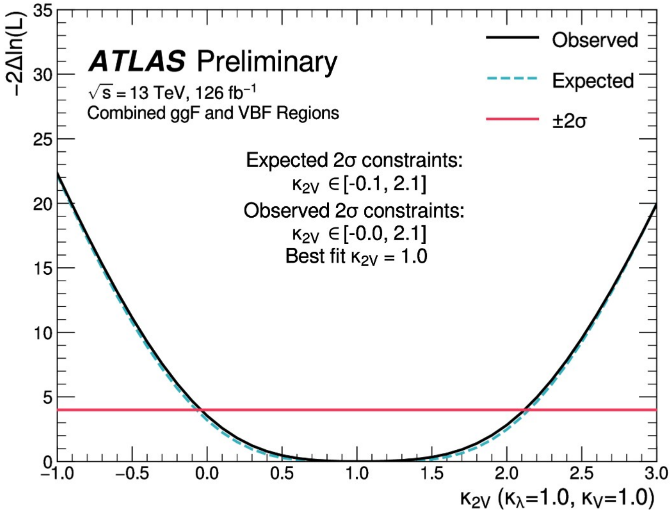
Dedicated ggF and VBF selections treated individually

- Fit m_{HH} distribution to constrain possible signals



HH→bbbb (non-resonant)





Set limits on HHH and VVHH couplings in κ framework

	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
$\sigma_{\text{ggF}}/\sigma_{\text{ggF}}^{\text{SM}}$	5.5	4.4	5.9	8.2	12.4	19.6
$\sigma_{\text{VBF}}/\sigma_{\text{VBF}}^{\text{SM}}$	130.5	71.6	96.1	133.4	192.9	279.3
$\sigma_{\text{ggF+VBF}}/\sigma_{\text{ggF+VBF}}^{\text{SM}}$	5.4	4.3	5.8	8.1	12.2	19.1

Also set limits on signal strength for SM-like production

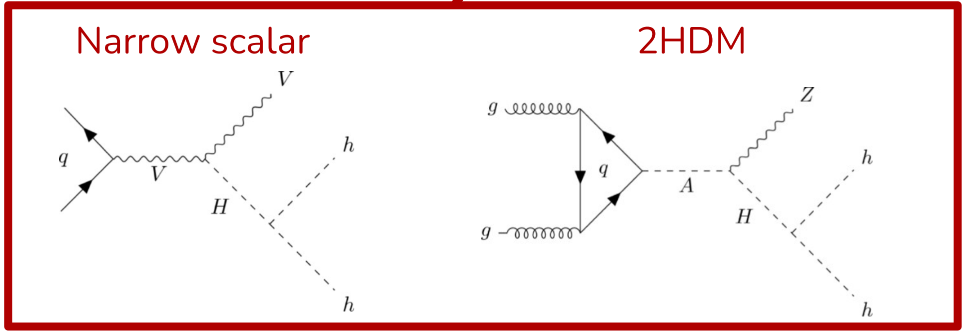
- **2.5x** improvement from previous ggF result
- **4.1x** improvement from previous VBF result

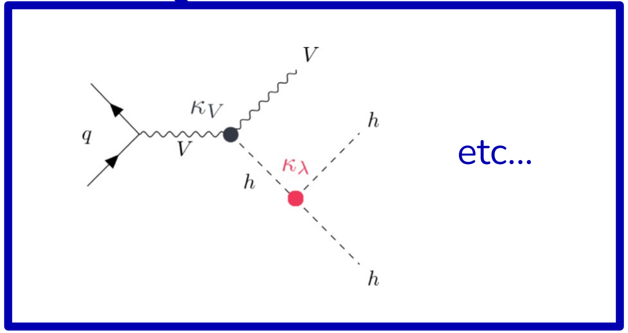
Vhh (hh→bbbb)

N.B. For this analysis:
h = 125 GeV Higgs boson
H = Heavier neutral scalar

First experimental search for Vhh production!

- 0, 1, and 2 lepton selections for Z→νν, W→lν, and Z→ll associated production (MET in 0L)
- Consider two benchmark resonant models as well as SM-like/κ-framework interpretations





Method: Apply loose pre-selection, then use BDT to construct a discriminant, which we then fit

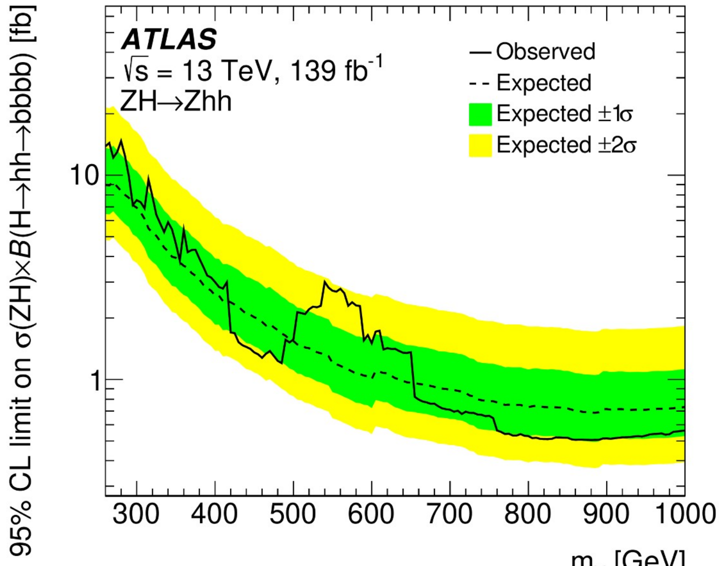
- Different BDT for each lepton category and signal model
- Main backgrounds from top and V+jets processes. Use MC, constrain with control regions.

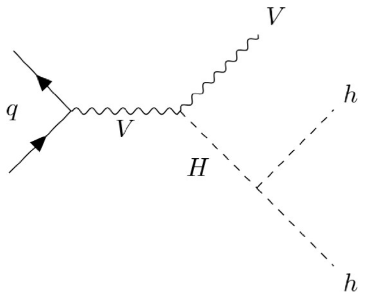
Vhh ($hh \to bbbb$)

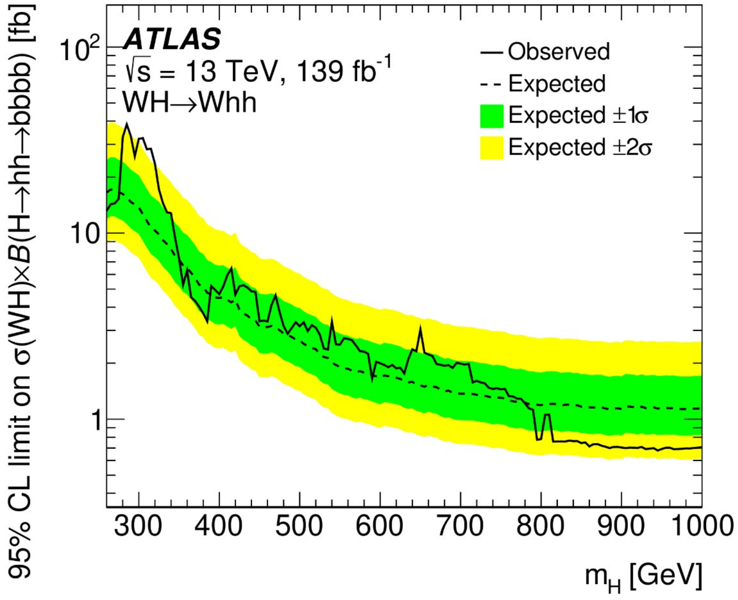
Signal strength limits on SM-like production set at 183 (87 expected) times σ_{SM} at 95% CL

- Also do κ interpretation: **$-34.4 < \kappa_\lambda < 33.3$**, **$-8.6 < \kappa_{2V} < 10.0$** at 95% CL
- Can separate W and Z couplings: **$-12.3 < \kappa_{2W} < 13.5$**, **$-9.9 < \kappa_{2Z} < 11.3$** at 95% CL

Cross section limits set on narrow scalar benchmark model:





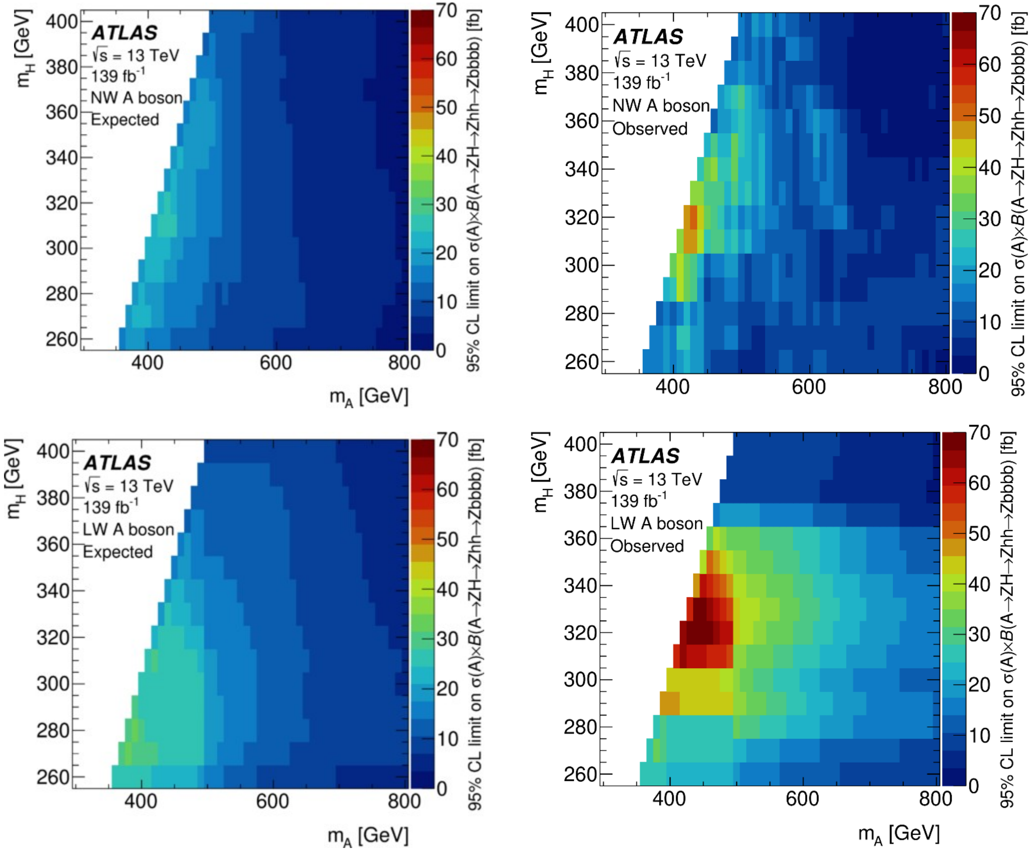


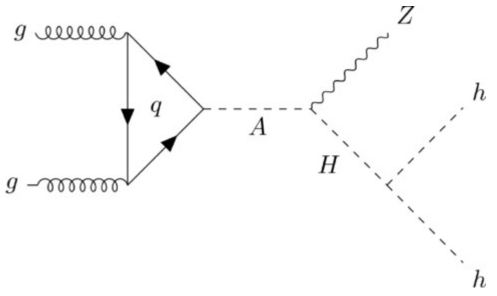
Vhh (hh→bbbb)

Expected | **Observed**

Narrow A

Wide A ($\Gamma = 0.2m$)



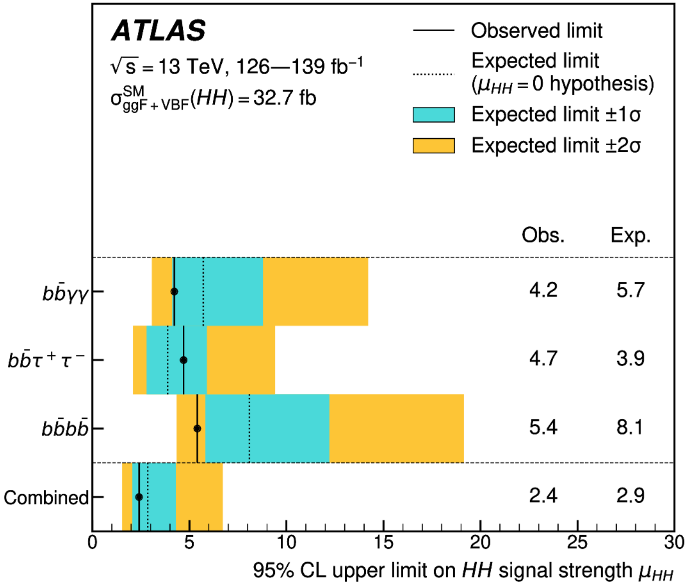


Also set limits on A→Z(H→hh)

- Narrow & large (20%) widths considered
- Largest excess is in large-width scenario at (m_A, m_H) = (420, 320) GeV
  - Significance: **2.8σ** (global),

H+HH Combination

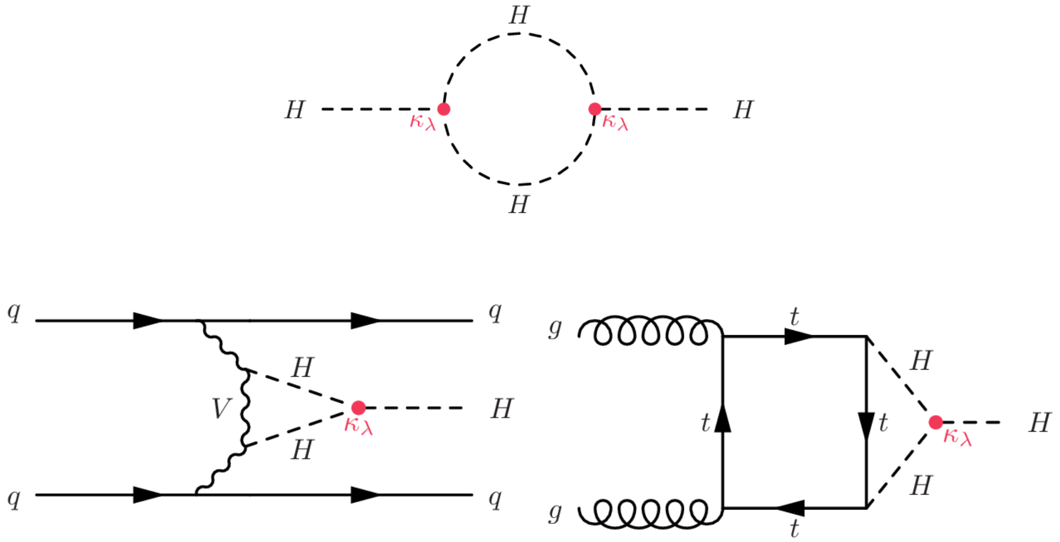
Combine 3 most sensitive HH channels for SM-like production



Closing in on SM cross section!

- Time to move from "upper limit" to "observation significance" interpretation soon?

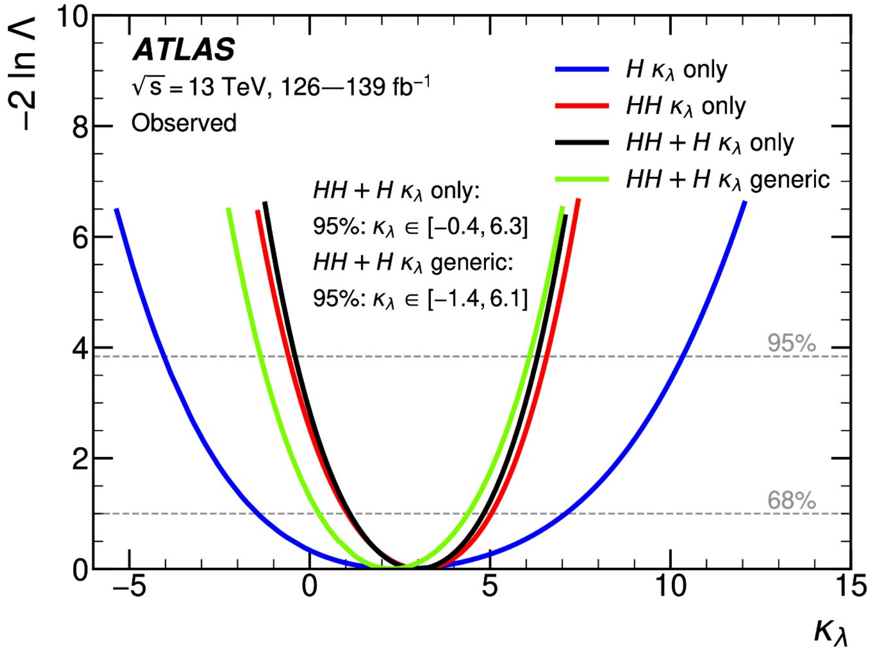
Add in single Higgs channels for their loop-level sensitivity to self-coupling

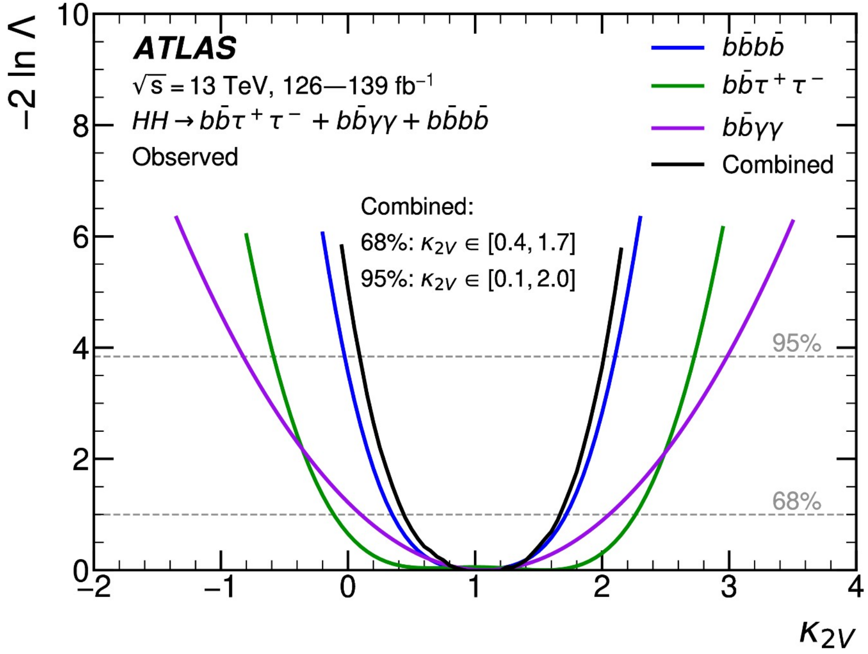


H+HH Combination

Combination provides our strongest constraints to date on κ_λ and κ_{2V}

- Limits on κ_λ alone dominated by HH channels
- Limits on κ_{2V} driven by HH →bbbb (which has dedicated VBF selection)





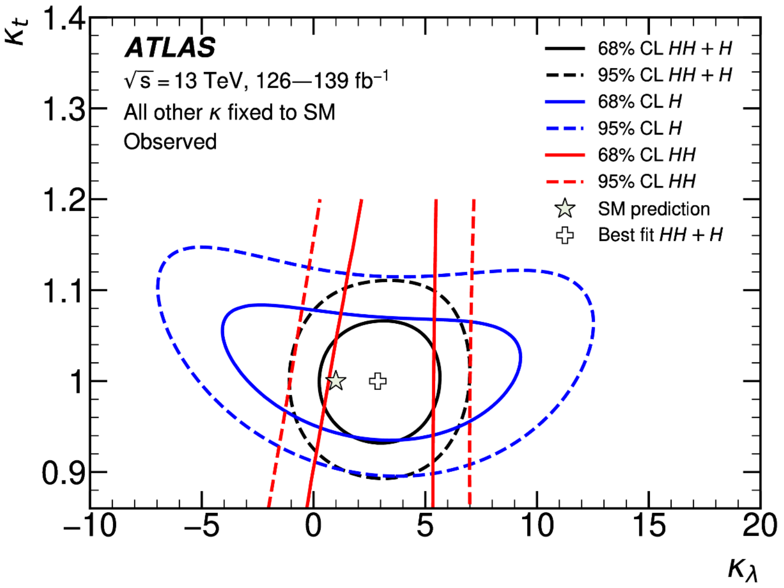
H+HH Combination

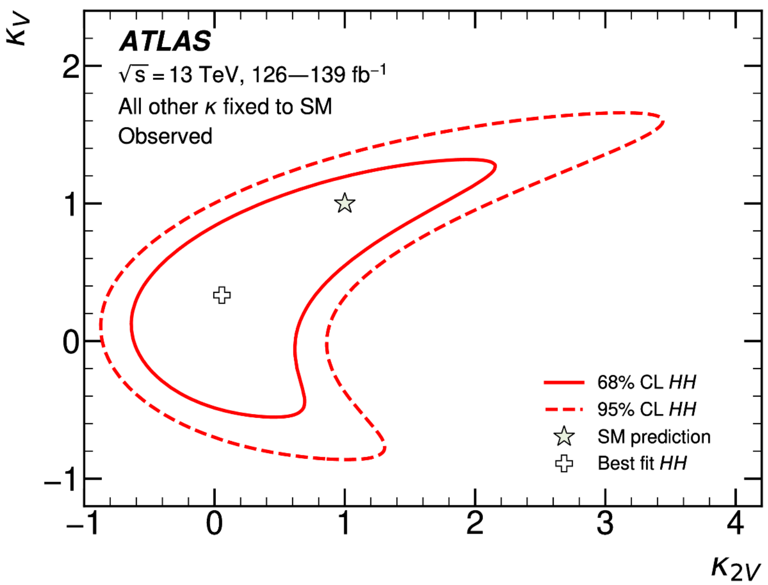
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
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	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

2-dimensional constraints now also included.

- Single Higgs channels add sensitivity to κ_t

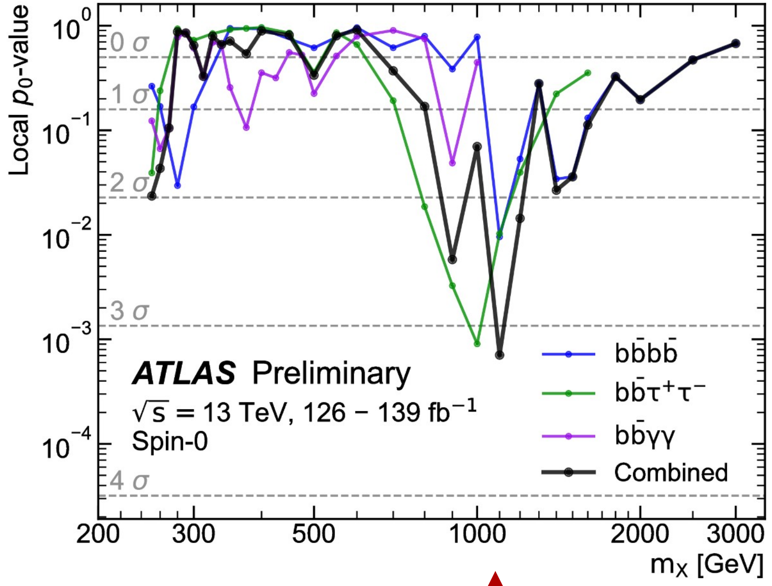
Single H also allows covering greater breadth of model assumptions



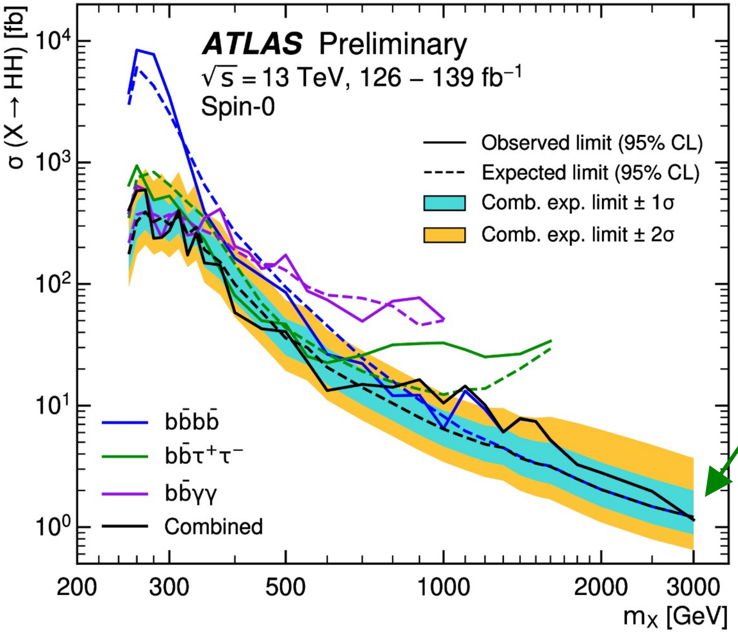


Resonant status

No major changes to the resonance search landscape in recent months



Global significance of largest excess is **2.1σ**



Latest HH→bbbb resonant paper extends this to 5 TeV

Each of the 3 decay channels is the most sensitive in a different mass range: **good complementarity**

Summary

ATLAS has been hard at work pushing the frontiers of HH searches with Run 2 data!

Highlights from the last few months include:

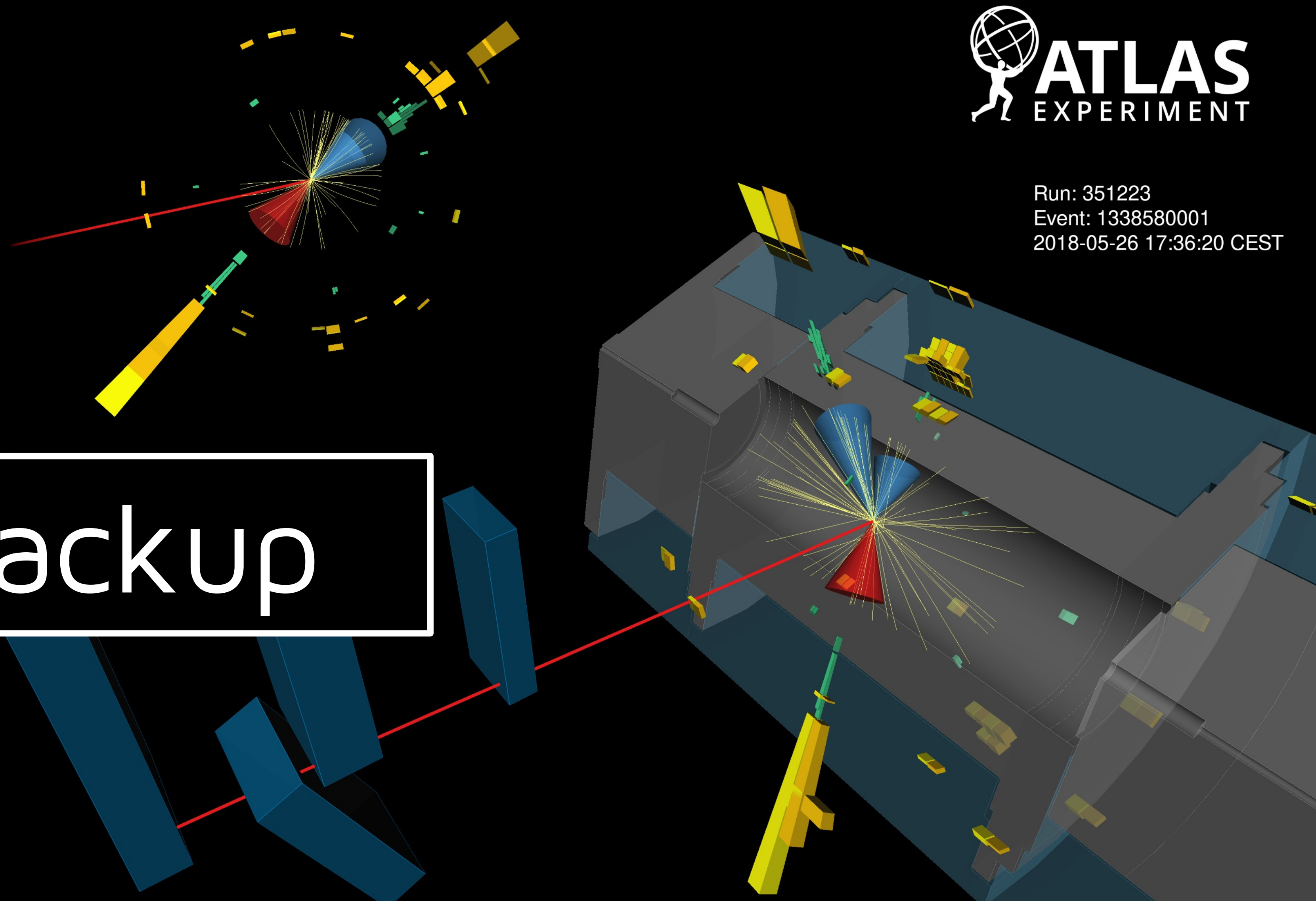
- Non-resonant results from the HH→bbbb channel
- First ever search for VHH production
- Latest & greatest combination of HH with single Higgs to constrain couplings

We're not too far from the regime where these "searches" become "measurements"

- Our combined limits on the Higgs self-coupling now stand at roughly **$-0.4 < \kappa_\lambda < 6.3$** (with slight variation depending on choice of assumptions)

See also our new HL-LHC HH projections (ATL-PHYS-PUB-2022-053) for a longer-term view of what's to come.

Backup


ATLAS EXPERIMENT
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Event: 1338580001
2018-05-26 17:36:20 CEST

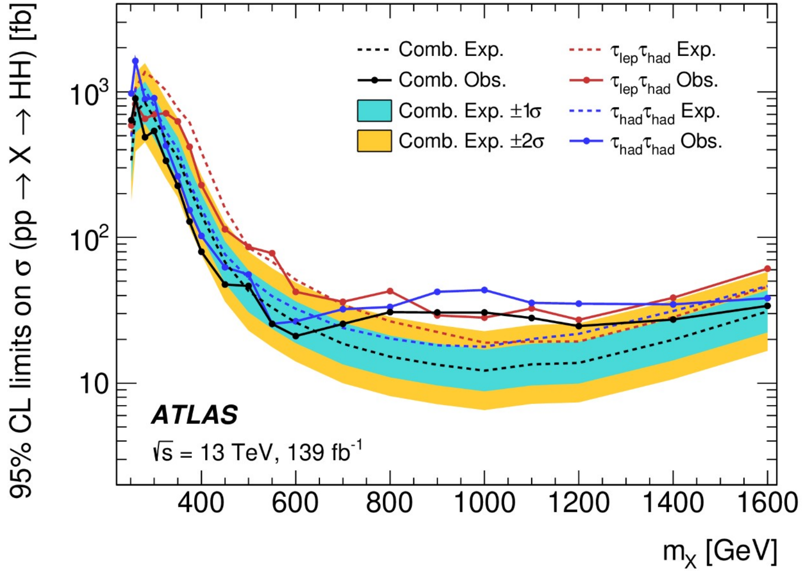
HH→bbττ

One of the most sensitive channels for SM-like HH and intermediate-mass resonance searches

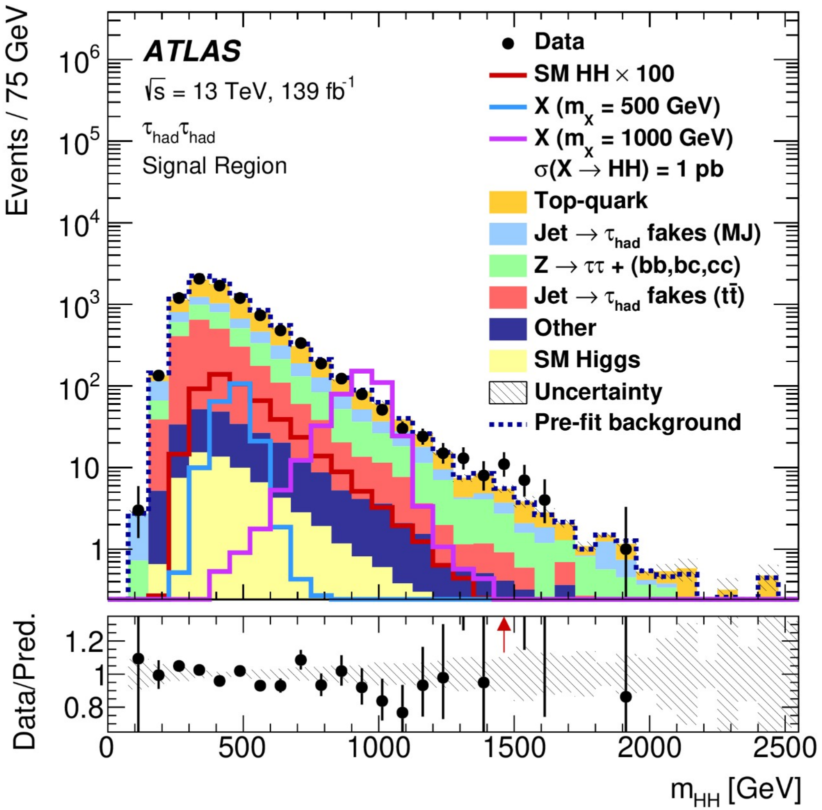
- Consider the semi-leptonic ($\tau_{lep}\tau_{had}$) and fully-hadronic ($\tau_{had}\tau_{had}$) cases
- **Method:** Select signal-like events using object-based cuts, then use BDT/NN to construct a discriminant, which we then fit

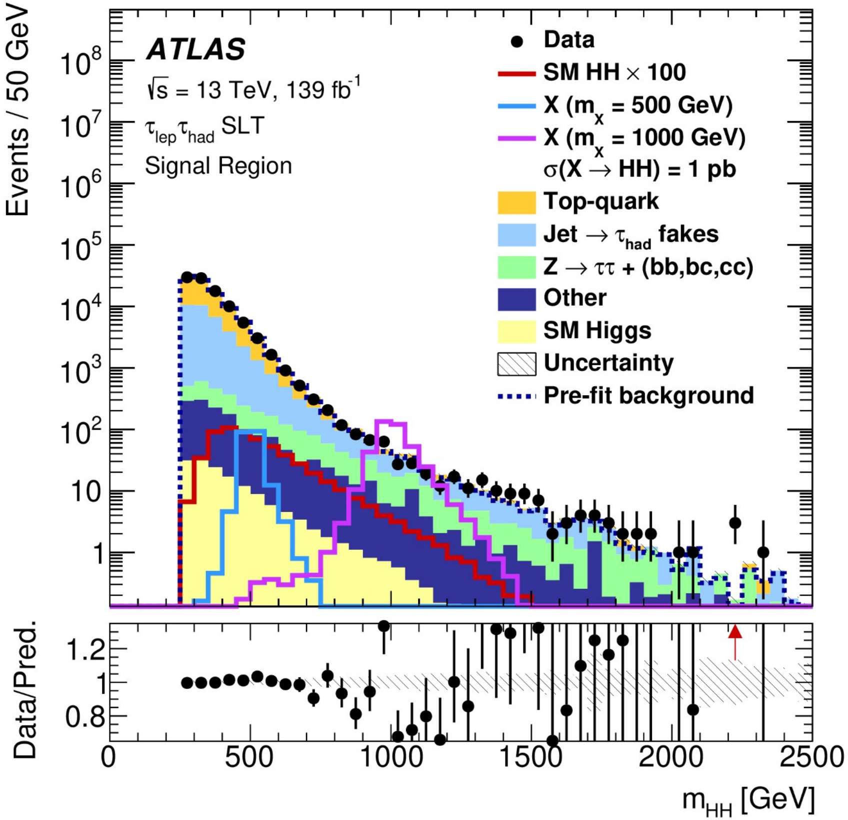
Results very similar to preliminary version

- A few minor improvements to calibrations, etc.
- HH signal strength limit set at **μ < 4.7** (3.9 expected) times the SM, at 95% CL
- Resonant cross section limits also set. Excess at 1 TeV has significance of **2.0σ** (global)



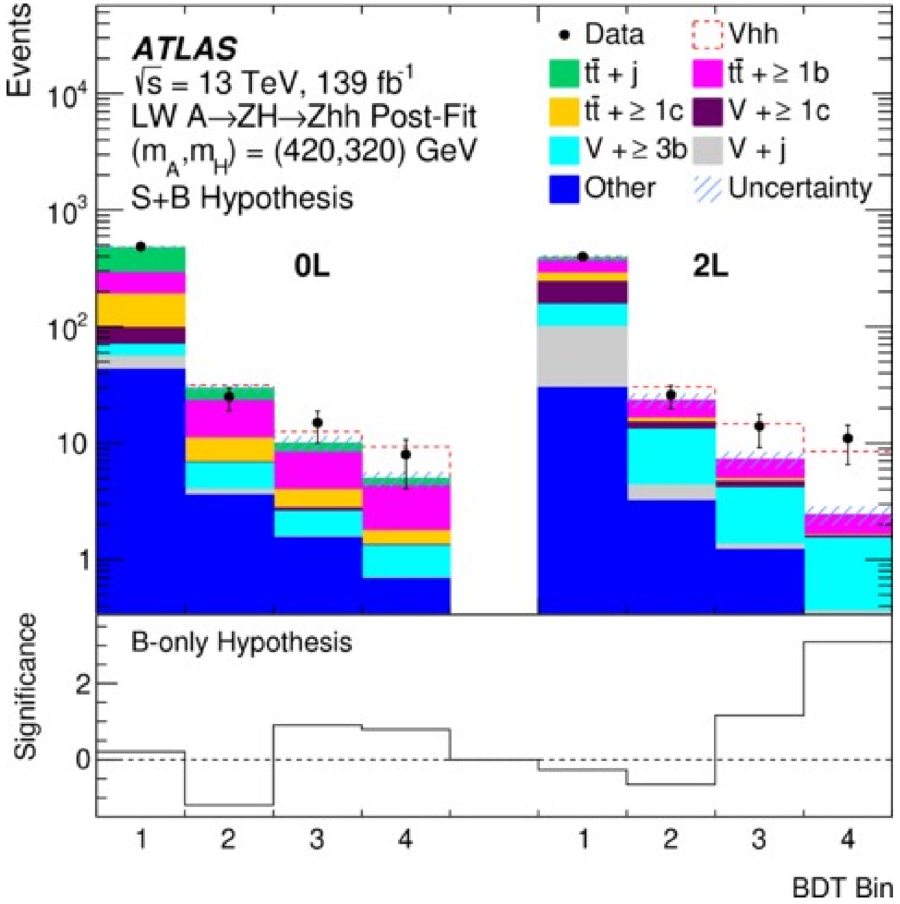
HH→bbττ: Resonance mass resolution



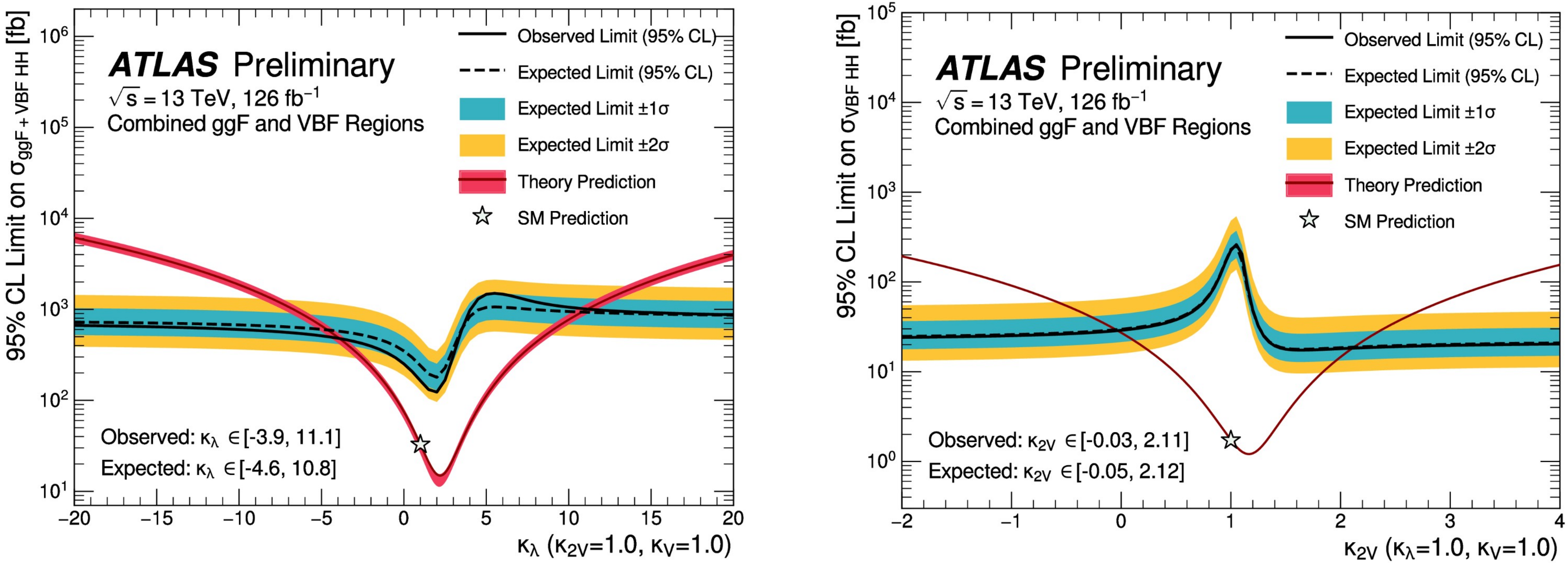


N.B. These signals are overlaid on the non-resonant background model

Vhh (hh→bbbb): Excess details

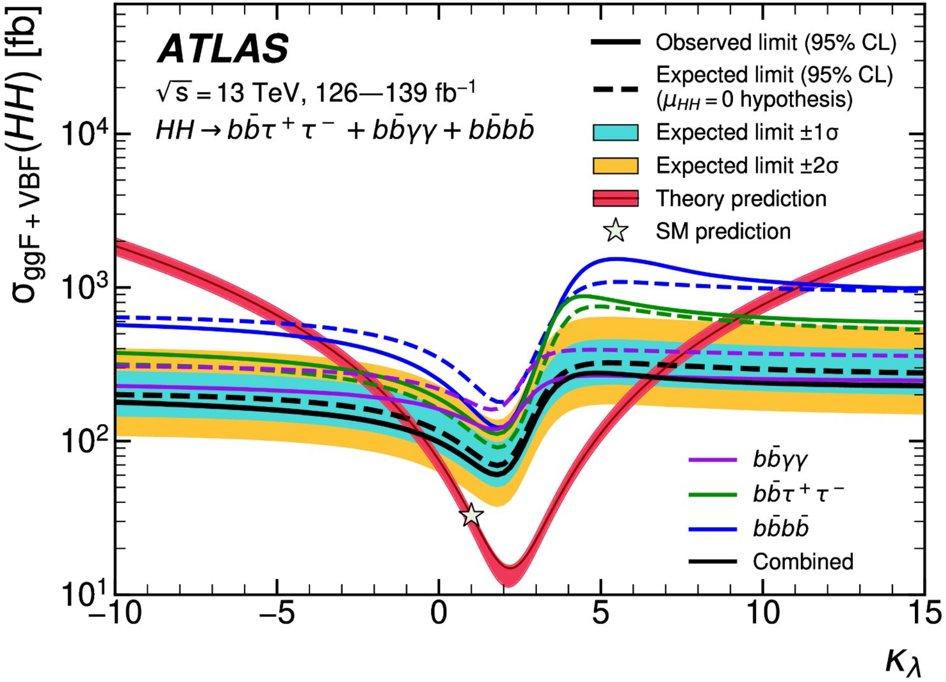


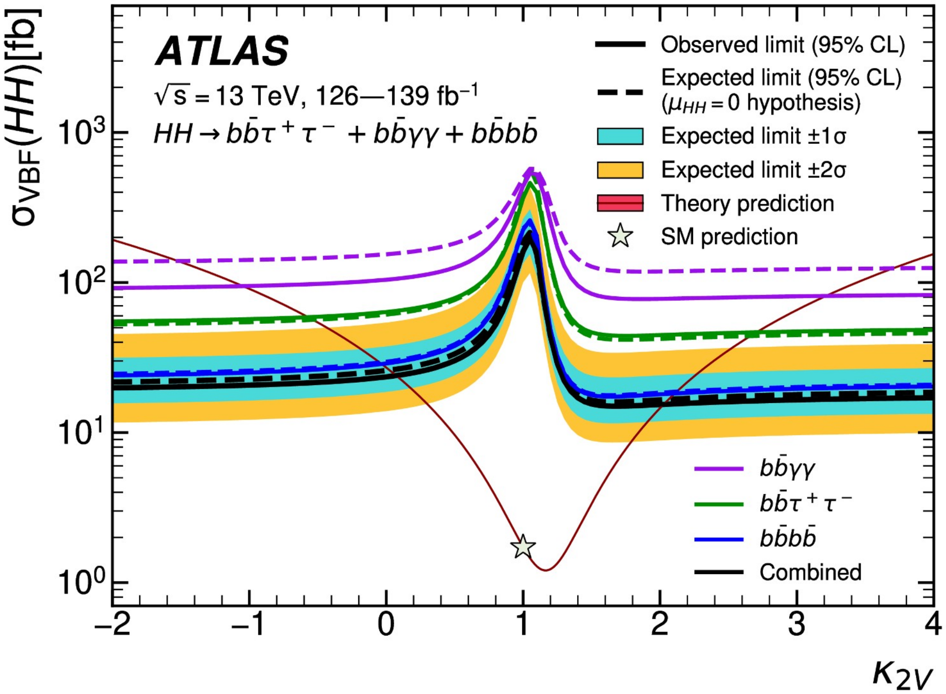
HH→bbbb: CL_s-based κ limits



"Expected" = assuming no HH production at all (not even SM)

Combination: CL_s-based κ limits





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HL-LHC projections

Baseline ATLAS HL-LHC projection expects evidence for SM HH production at 3.4σ

- Roughly **5σ** in the limit of small systematic uncertainties
- This assumes current analysis methodology: good chance we'll exceed this!