Di-Higgs searches by ATLAS and CMS

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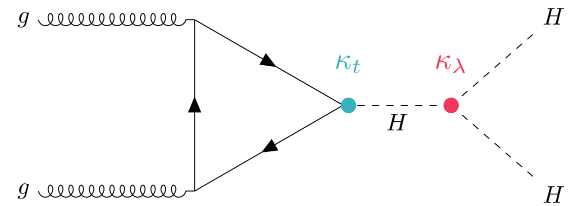
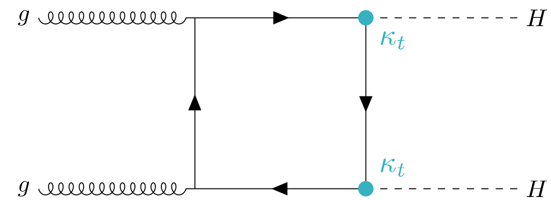
on behalf of the ATLAS and CMS collaborations

24.03.2023

Graphs from arXiv:2211.01216
and ATL-PHYS-PUB-2021-031

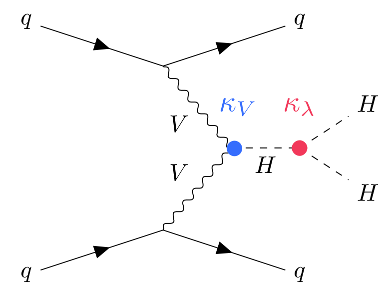
Motivation



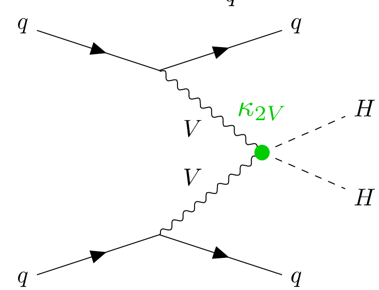


- Many of the Higgs boson's couplings experimentally validated since it's discovery, but not yet the self-coupling parameter λ

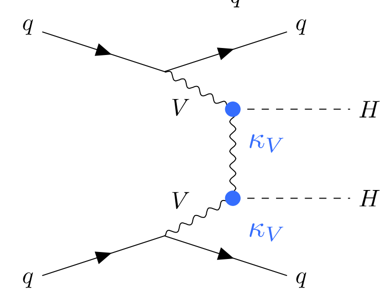
$$V(\phi) \supseteq \frac{1}{2} m_H^2 \phi^2 + \lambda v \phi^3 + \frac{1}{4} \lambda \phi^4$$

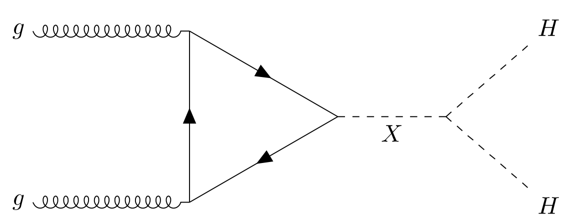


- Direct measurement of trilinear coupling λ by analysis of events with two Higgs boson
  - Coupling modifiers κ defined as coupling strength w.r.t. SM predictions: $\kappa_\lambda = \lambda / \lambda_{SM}$

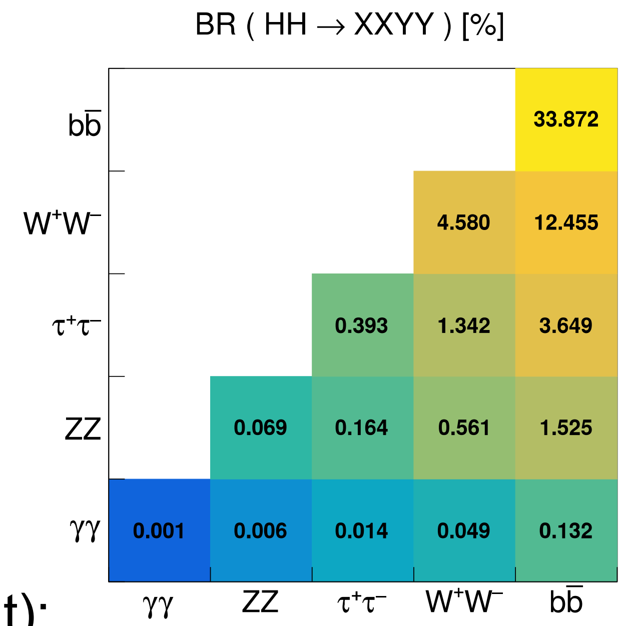


- Resonant X → HH searches and SMEFT / HEFT interpretations also of interest for BSM physics





Branching fractions



- Which final state(s) should be studied?
  - Final states with high branching fractions have larger backgrounds

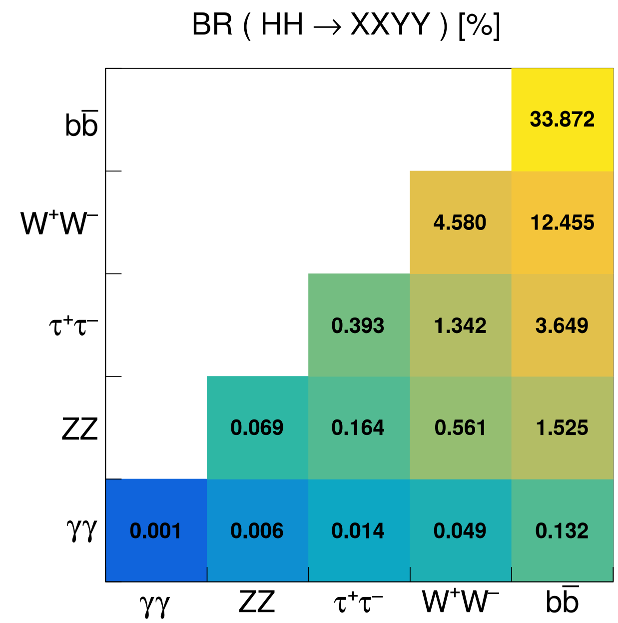
  → Make combinations of multiple channels!

- Many channels already covered (non-resonant):

	ATLAS	CMS
bb bb	arXiv:2301.03212	Phys. Rev. Lett. 129 (2022) 081802 & boosted: arXiv:2205.06667
bb ττ	arXiv:2209.10910	arXiv:2206.09401
bb γγ	Phys. Rev. D 106 (2022) 052001	JHEP 03 (2021) 257
bb WW	Phys. Lett. B 801 (2020) 135145	
bb ZZ		arXiv:2206.10657
Multilepton (W/τ)		arXiv:2206.10268

All analyses using Full Run2 data

Branching fractions



- Which final state(s) should be studied?
  - Final states with high branching fractions have larger backgrounds

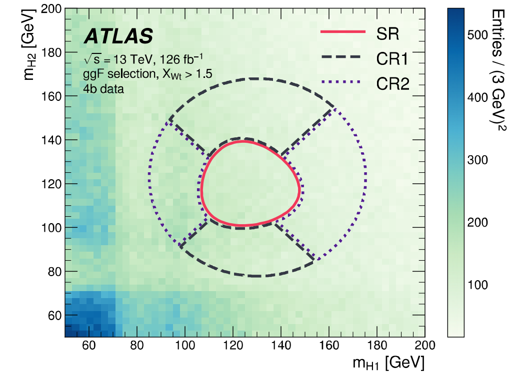
  → Make combinations of multiple channels!

- The following analyses are presented:
  - ATLAS HH → bbbb: arXiv:2301.03212
  - CMS HH → WWγγ: CMS-HIG-21-014
  - CMS VHH (HH → bbbb): CMS-HIG-22-006
  - ATLAS VHH (HH → bbbb): arXiv:2210.05415
  - CMS combination: Nature 607 (2022) 60-68
  - ATLAS combination: arXiv:2211.01216
  - Summary of resonant searches

All analyses using Full Run2 data

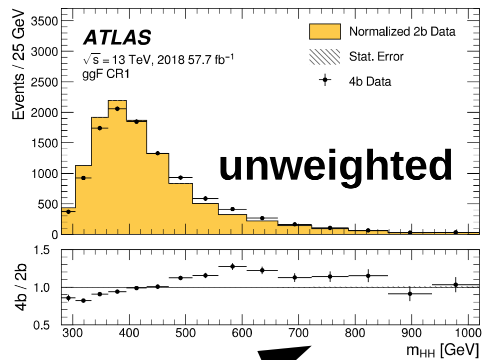
ATLAS: HH → bbbb

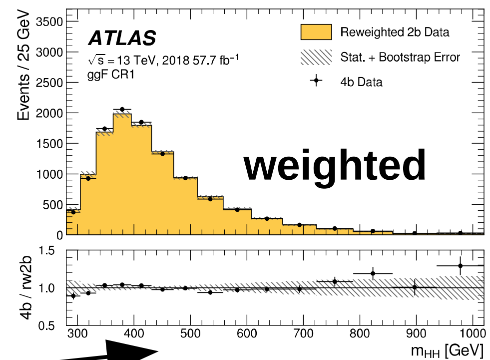
arXiv:2301.03212



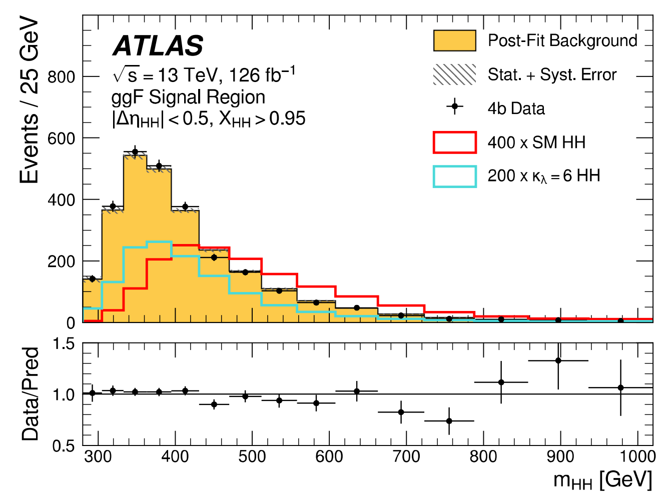
- Select events with 4 b-tagged jets
- Pair jets together, such that highest-p_T pair has smallest separation ΔR

  → 90% correct pairing efficiency for SM signal



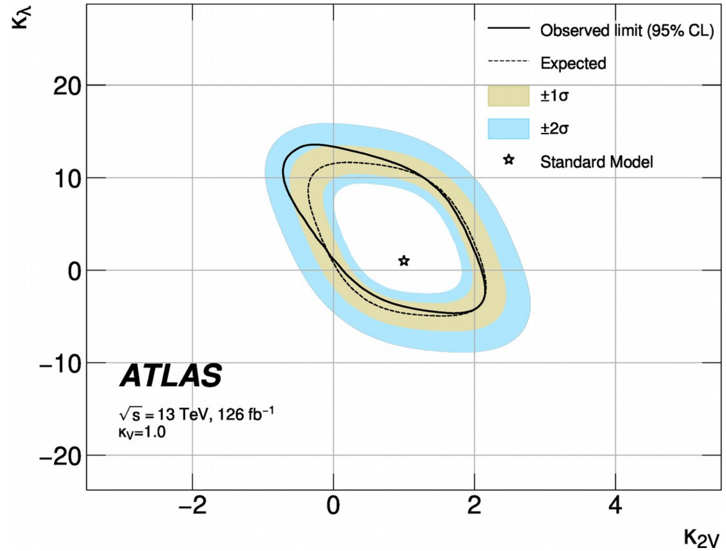


- Backgrounds are 90% Multijet, 10% Top quarks
- Background fully estimated from data
  - Get data from signal region, but where only 2 b-tagged jets are selected
  - Reweight using data from control region
  - Neural network used to obtain weight as function of kinematic variables



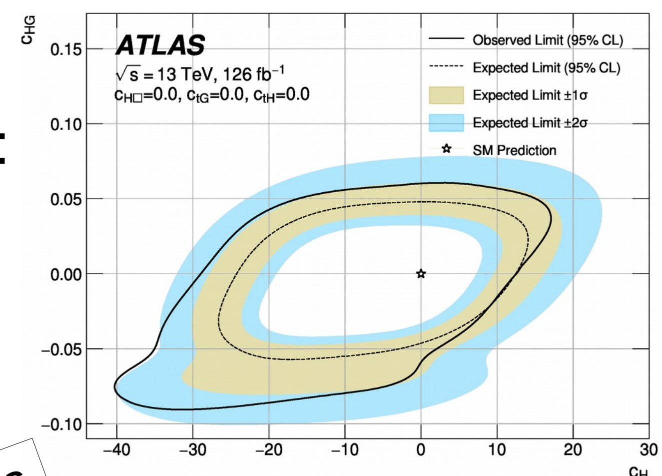
ATLAS: HH → bbbb

- 95% CL Observed (expected) results:
  - Limit on σ / σ_{SM}: 5.4 (8.1)
  - Constraints:
    $-3.9 < \kappa_\lambda < 11.1$ ($-4.6 < \kappa_\lambda < 10.8$)
    $-0.03 < \kappa_{2V} < 2.11$ ($-0.05 < \kappa_{2V} < 2.12$)



- More interpretations in SM EFT and H EFT models
  - Limits on SM EFT Wilson coefficients:

Parameter	Expected Constraint Lower	Expected Constraint Upper	Observed Constraint Lower	Observed Constraint Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\square}$	−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



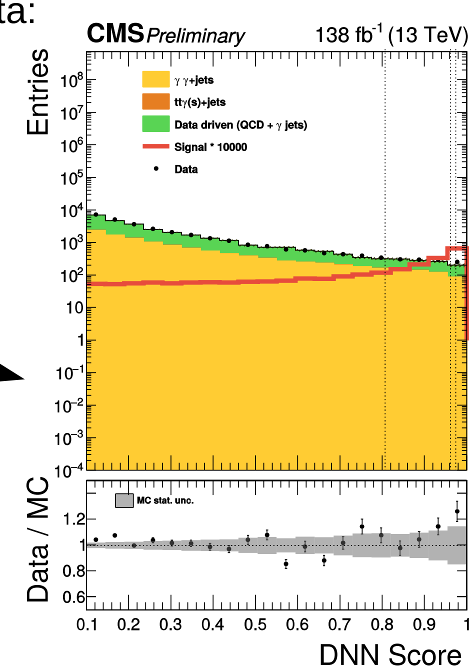
More results in backup!

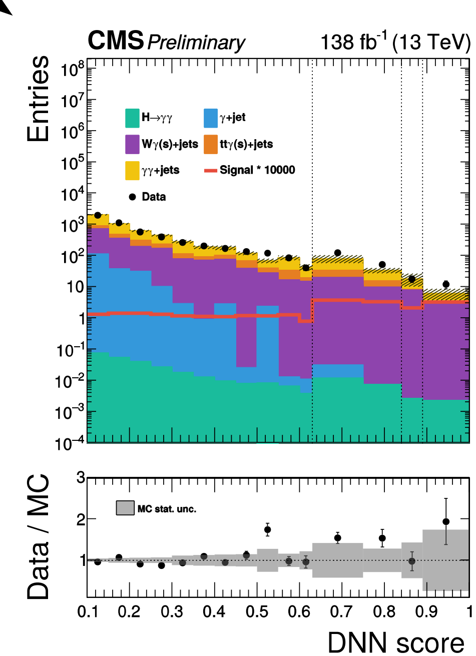
CMS: HH → WWγγ

CMS-only analysis
ATLAS analysis for 2015-16 data:
Eur. Phys. J. C 78 (2018) 1007

CMS-HIG-21-014

- ggF only, three categories based on WW decay (**F**ully **L**eptonic, **S**emi **L**eptonic, **F**ully **H**adronic)
- Selection requirement includes $m_{\gamma\gamma}$ between 100 and 180 GeV
- Backgrounds:
  - (tt/W)+γ(s)+jets
  - Single H→γγ
  - **FL**: DY Z→ℓℓ
- Using DNNs in **FH** and **SL** to discriminate the signal from backgrounds and sort events into 4 categories based on signal score





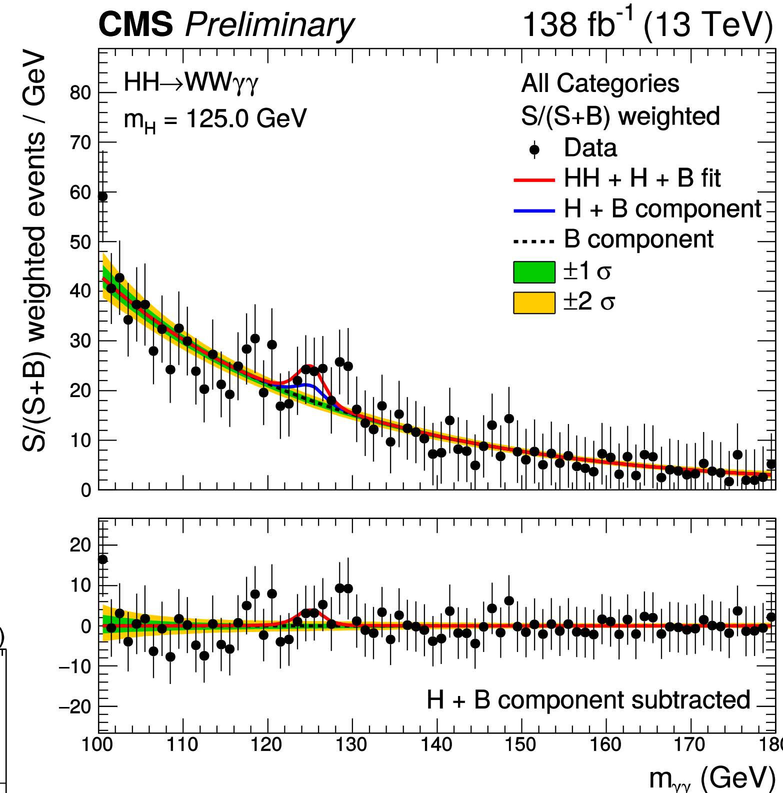
[CMS-HIG-21-014](CMS-HIG-21-014)

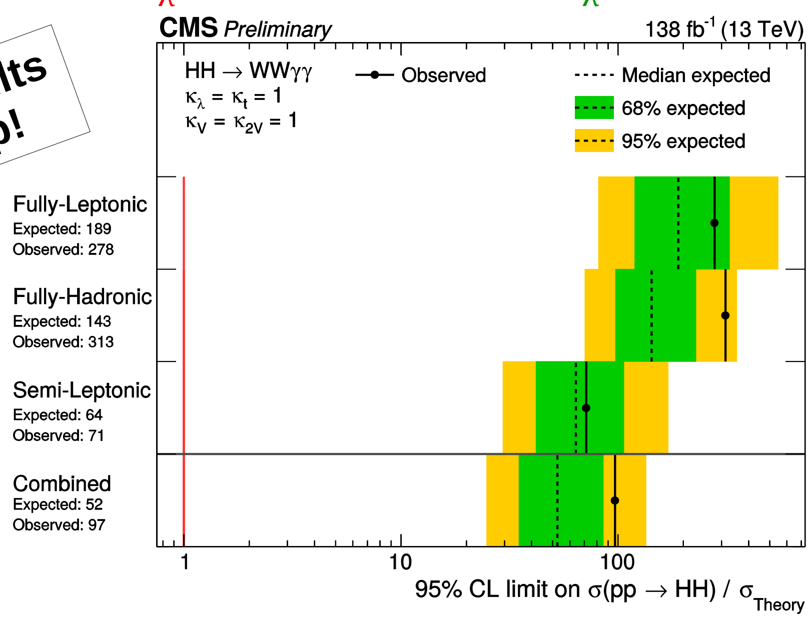
CMS: HH → WWγγ

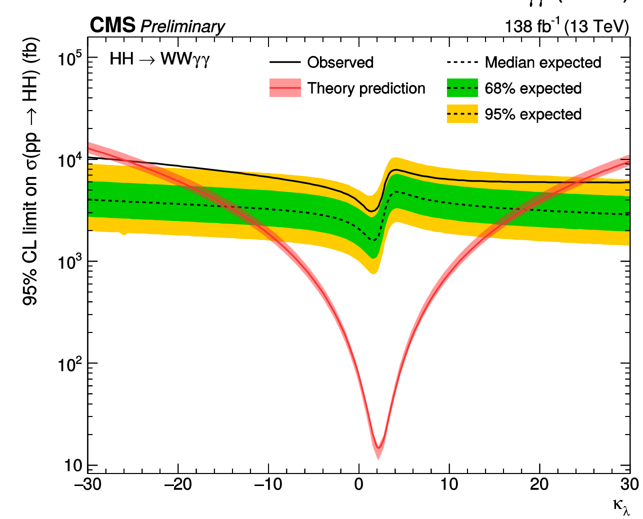
- No significant excesses observed
- 95% CL Observed (exp.) results:
  - Limit on σ / σ_{SM}: 96.8 (52.5)
  - Constraint on κ_λ:

    $-25.8 < \kappa_\lambda < 24.1$ ($-14.4 < \kappa_\lambda < 18.3$)

More results in backup!





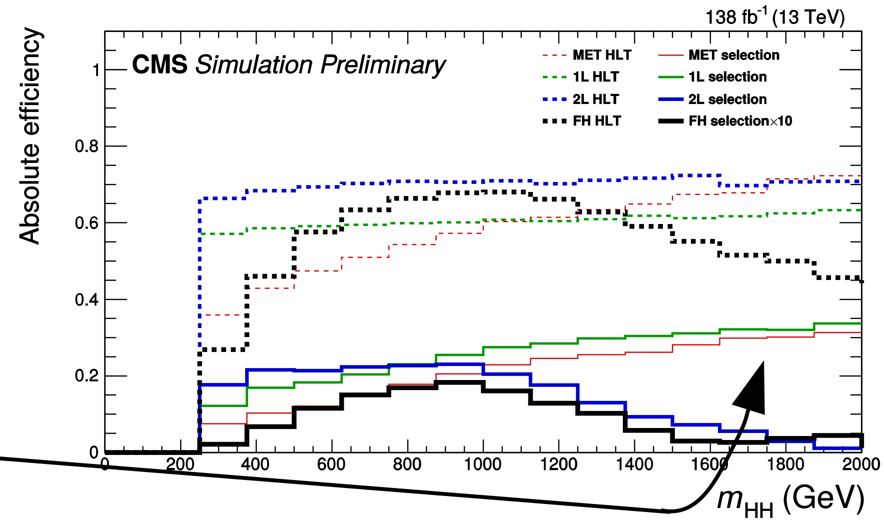


CMS: VHH (HH → 4b)

NEW!

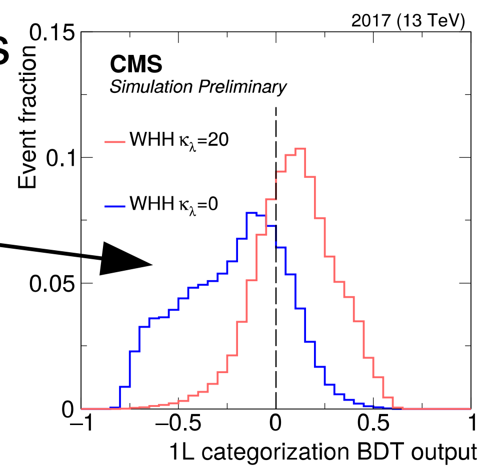
[CMS-HIG-22-006]

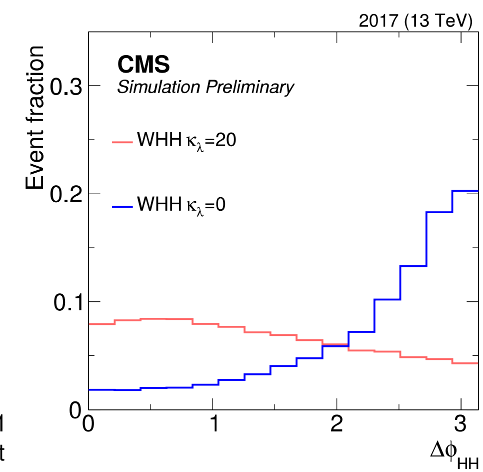
- Construct HH from 4 jets with highest b-tag scores
- All W/Z decays considered:
  - **1L**: $W \to \ell\nu$, **2L**: $Z \to \ell\ell$
  - **MET**: $Z \to \nu\nu$, **FH**: $W/Z \to qq$



- All channels: Resolved (4 AK4 jets), **1L** and **MET**: Boosted (2 AK8 jets)
- Resolved categories: Split events into κ_λ and κ_{2V} enriched regions

→ Done using BDT



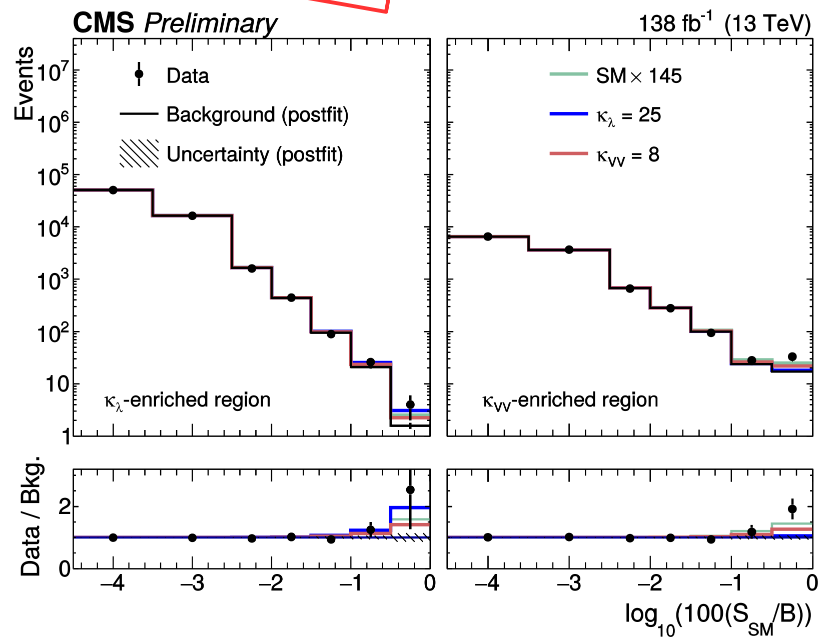


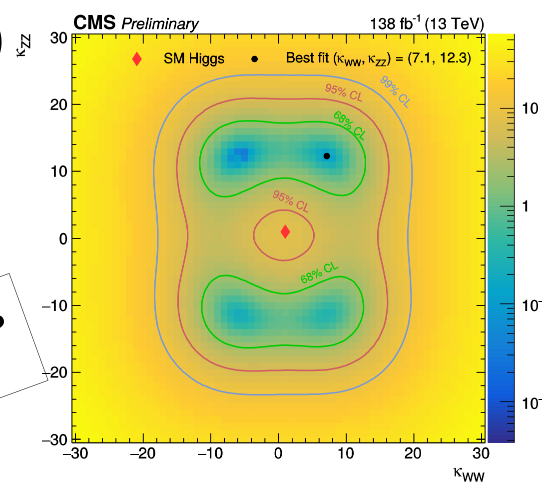
CMS: VHH (HH → 4b)

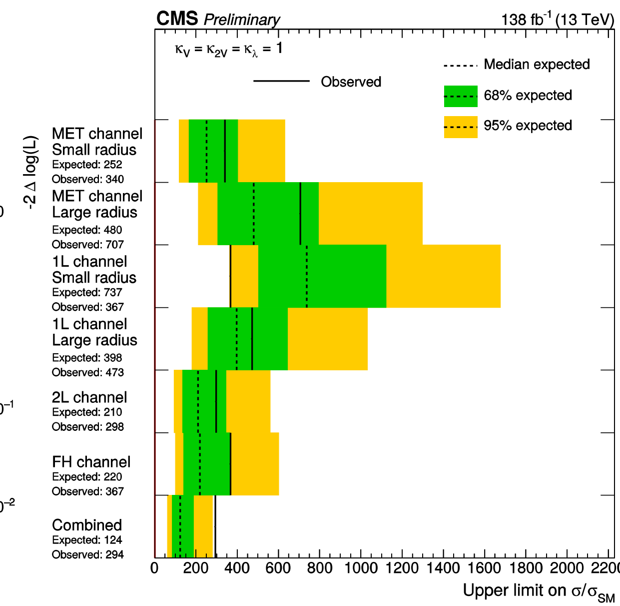
NEW!

CMS-HIG-22-006

- Observed signal strength is 145 (+81 / -63) over SM pred.
- 95% CL Observed (exp.) upper limit on σ / σ_{SM} is 288 (122)
- Able to separate κ_{2V} into κ_{2W} and κ_{2Z} components:
  - $-14.0 < \kappa_{2W} < 15.4$ $(-10.2 < \kappa_{2W} < 11.6)$
  - $-17.4 < \kappa_{2Z} < 18.5$ $(-10.5 < \kappa_{2Z} < 11.6)$



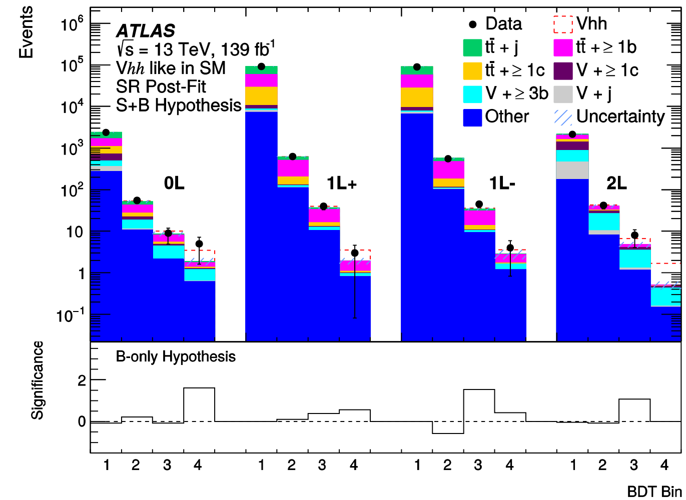




More results in backup!

arXiv:2210.05415

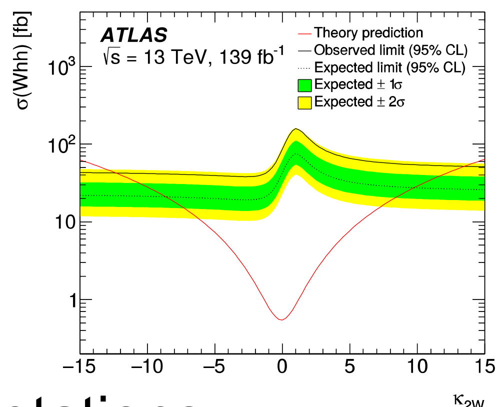
ATLAS: VHH (HH → 4b)

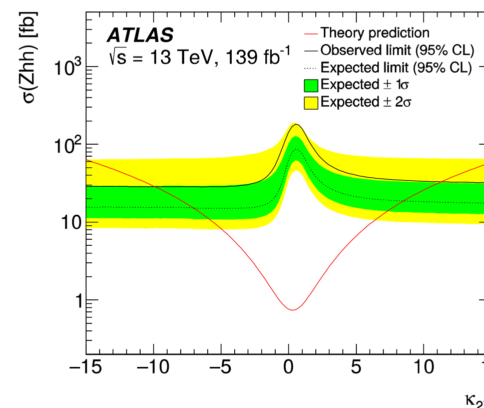


- 95% CL Observed (exp.) upper limit on σ / σ_{SM} is 184 (87)

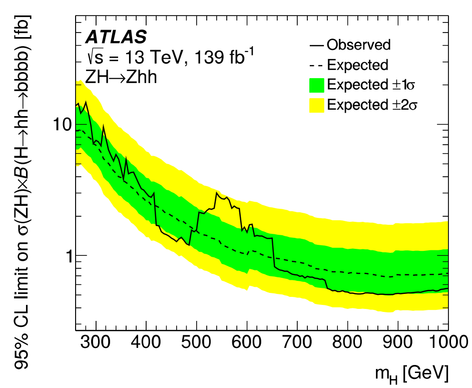
More results in backup!

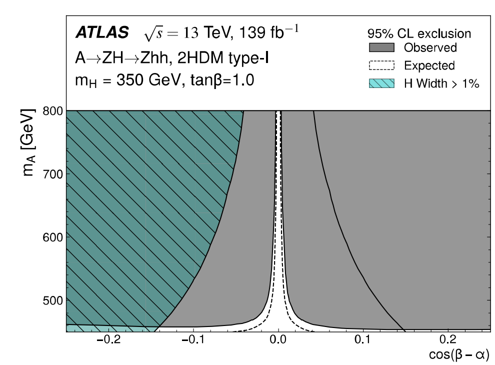
- Constraints:
  - $-12.3 < \kappa_{2W} < 13.5$ ($-8.6 < \kappa_{2W} < 9.8$)
  - $-9.9 < \kappa_{2Z} < 11.3$ ($-7.1 < \kappa_{2Z} < 8.5$)





- Also provides 2HDM interpretations:
  - V → VH → Vhh → V+4b
  - A → ZH → Zhh → Z+4b





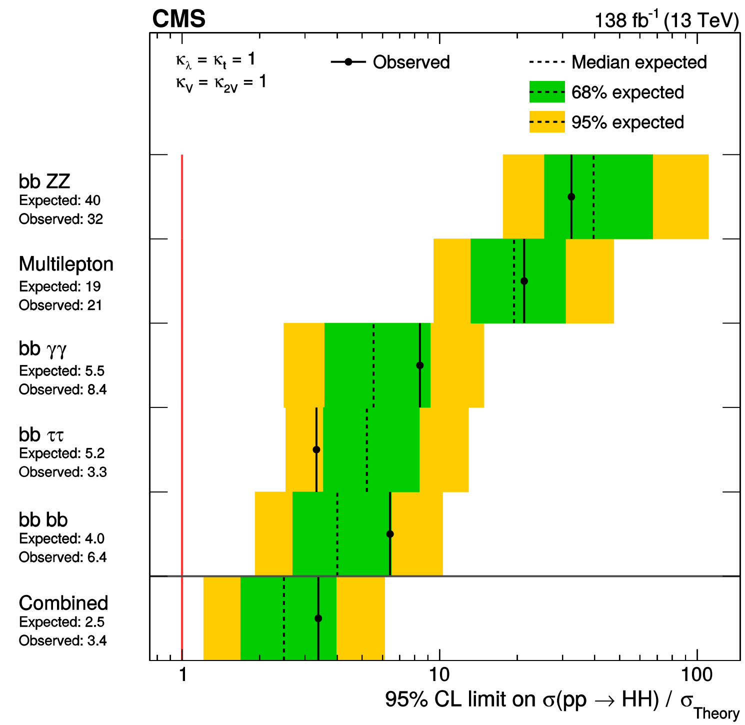
CMS combination

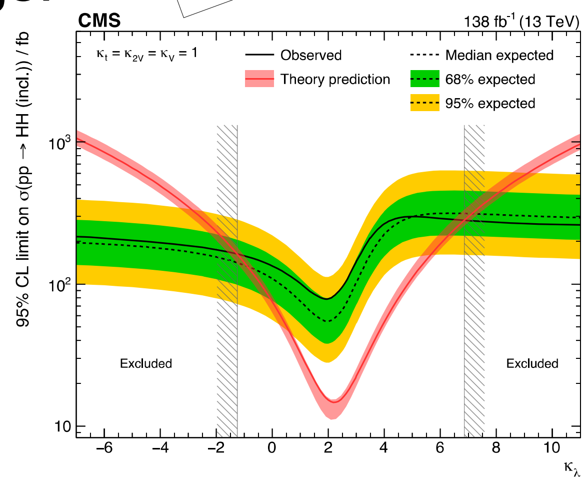
[Nature 607 (2022) 60-68]

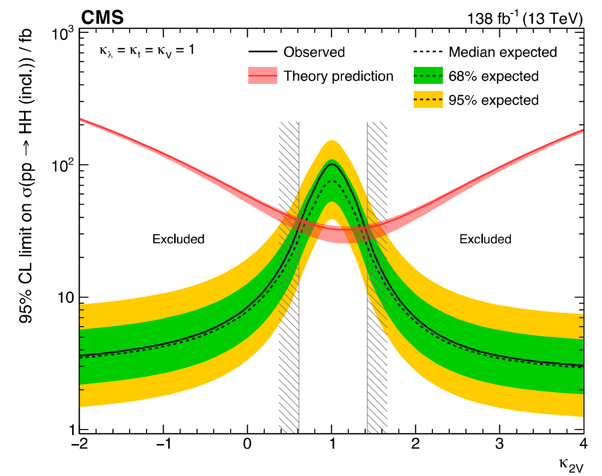
> *"The whole is greater than the sum of its parts"* - Aristotle

- Combining five CMS analyses:
  - bbbb, bbττ, bbγγ, bbZZ and Multilepton (4W / 2W2τ / 4τ)
- 95% CL Observed (exp.) limit on σ / σ_{SM} is 3.4 (2.5)
- Constrained couplings:
  - $-1.25 < \kappa_\lambda < 6.85$ $(-0.89 < \kappa_\lambda < 7.12)$
  - $0.61 < \kappa_{2V} < 1.42$ $(0.68 < \kappa_{2V} < 1.37)$

More results in backup!







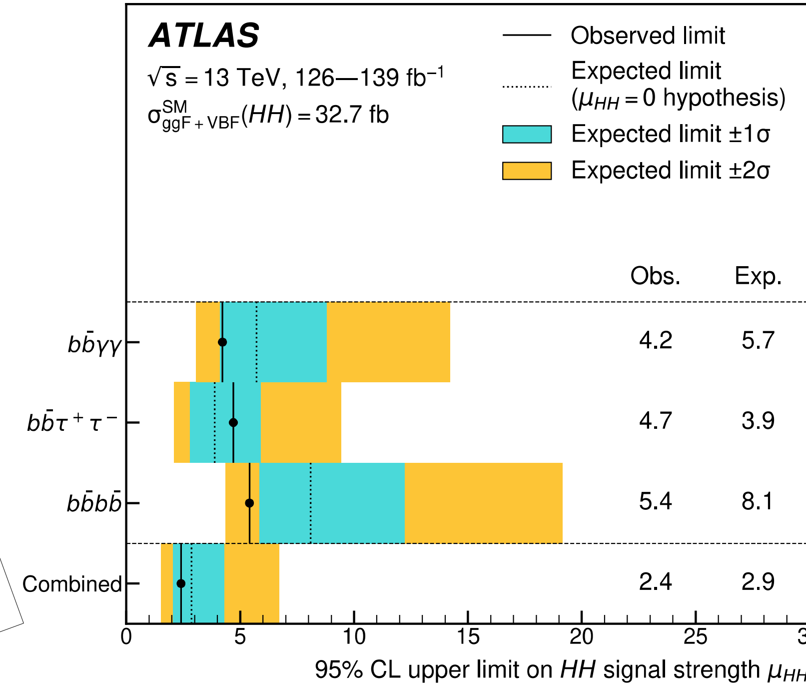
arXiv:2211.01216

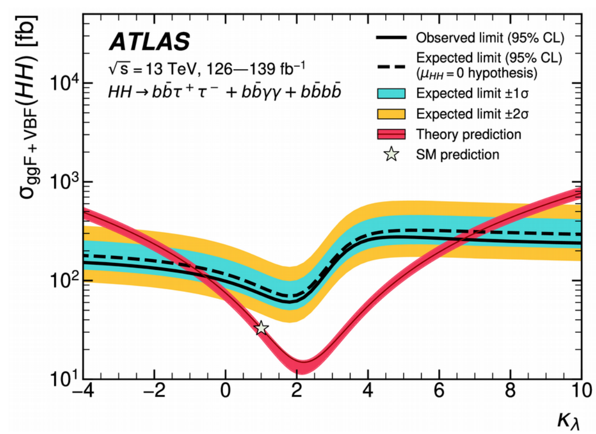
ATLAS combination

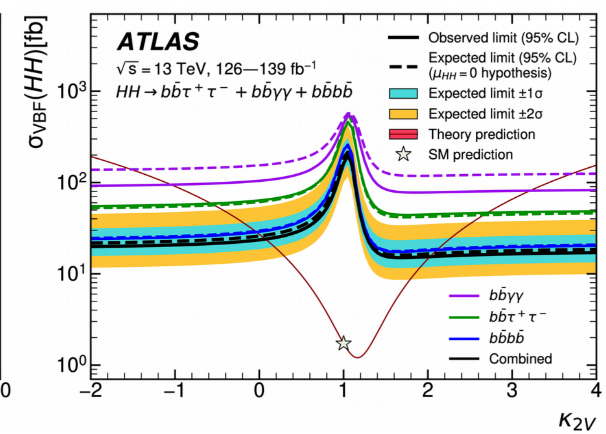
> *"The whole is greater than the sum of its parts"* - Aristotle

- Combining three ATLAS analyses:
  - bbbb, bbττ, bbγγ
- 95% CL Observed (exp.) limit on σ / σ_{SM} is 2.4 (2.9)
- Constrained couplings:
  - $-0.6 < \kappa_\lambda < 6.6$ $(-2.1 < \kappa_\lambda < 7.8)$
  - $0.1 < \kappa_{2V} < 2.0$ $(0.0 < \kappa_{2V} < 2.1)$

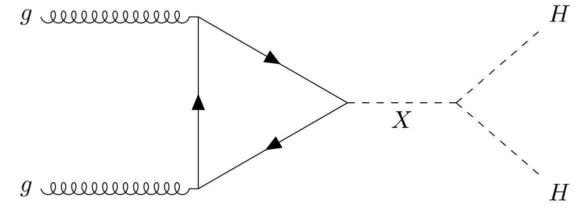
More results in backup!





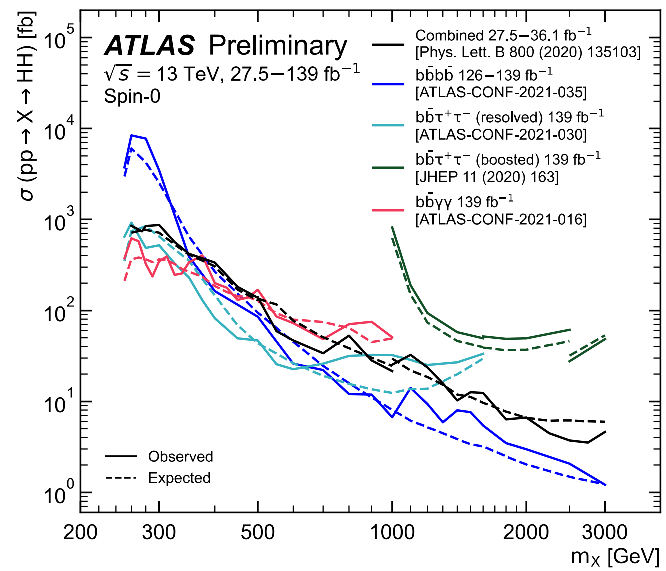


Resonant Di-Higgs searches



- Also many resonant searches
  - bbbb
  - bbττ
  - bbγγ
  - bbWW
  - Multilepton

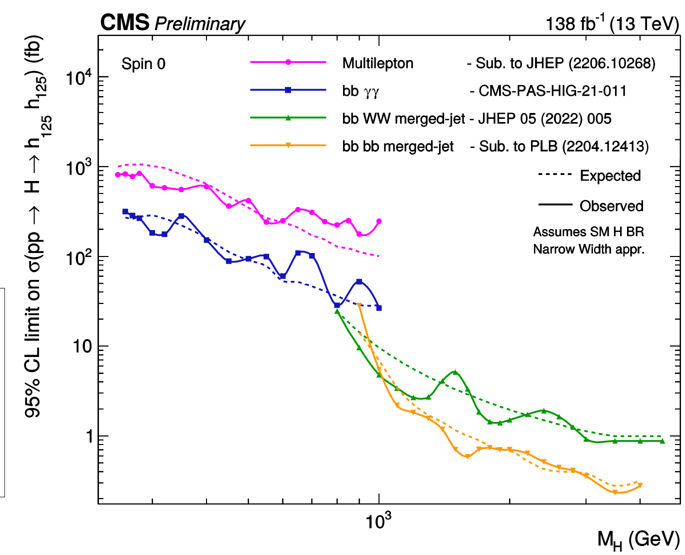
[Phys. Lett. B 800 (2020) 135103](#)
[Phys. Rev. D 105 (2022) 092002](#)
[arXiv:2209.10910](#)
[JHEP 11 (2020) 163](#)
[Phys. Rev. D 106 (2022) 052001](#)



- Different interpretations
  - 0 or 2 spin resonance
  - RS bulk graviton

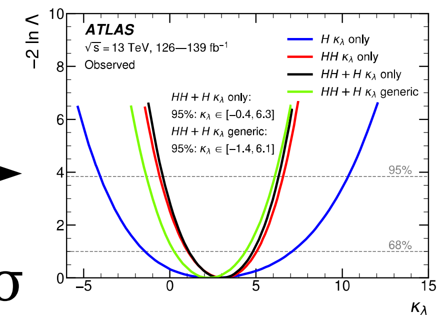
- No observed excess

[arXiv:2206.10268](#)
[CMS-PAS-HIG-21-011](#)
[JHEP 05 (2022) 005](#)
[arXiv:2204.12413](#)

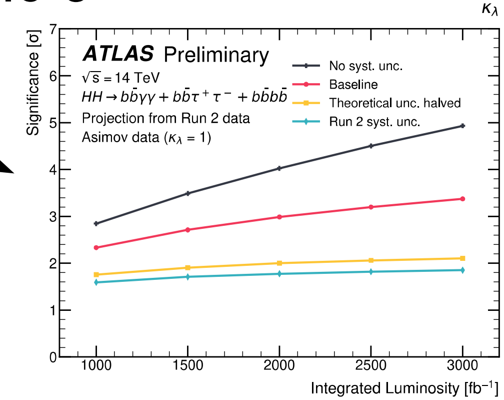


Conclusion

- A summary of the most recent Di-Higgs analyses and combinations has been presented
- Limits are being improved every year
  - Combined Run 2 results still not final
- Best 95% CL observed limits by either ATLAS or CMS:
  - $\sigma_{HH} / \sigma_{HH,SM} < 2.4$
  - $-0.4 < \kappa_\lambda < 6.3$ → HH + H result
  - $0.67 < \kappa_{2V} < 1.38$ → $\kappa_{2V} = 0.0$ excluded with 6.6 σ



- Will find first direct evidence of Di-Higgs production by both ATLAS and CMS during HL-LHC operations, with less than 3000 fb^{-1}

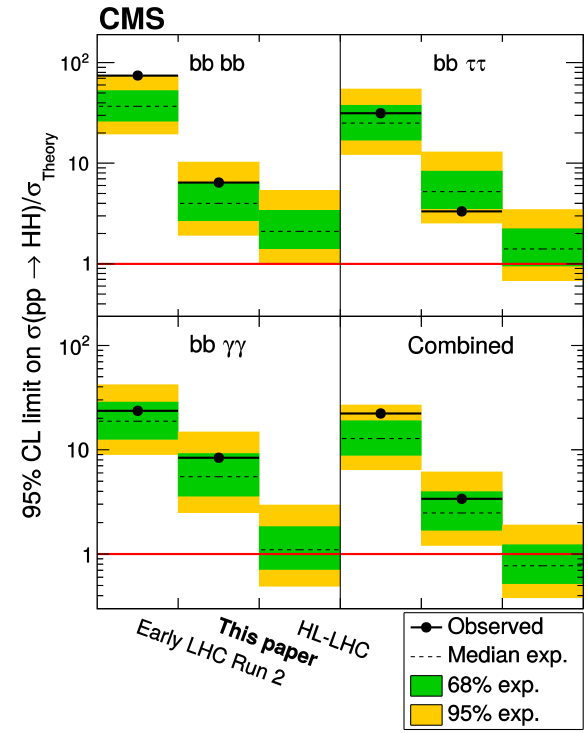


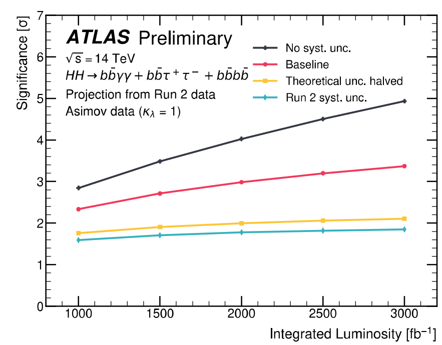
Backup

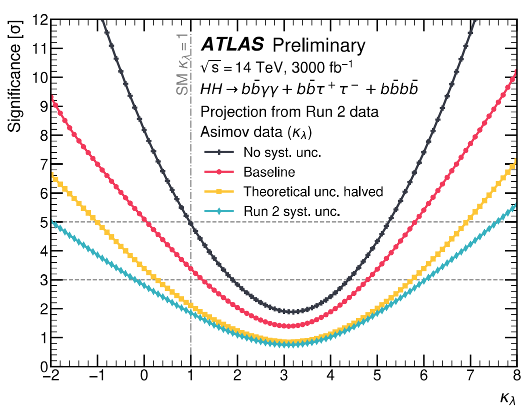
HL-LHC Prospects

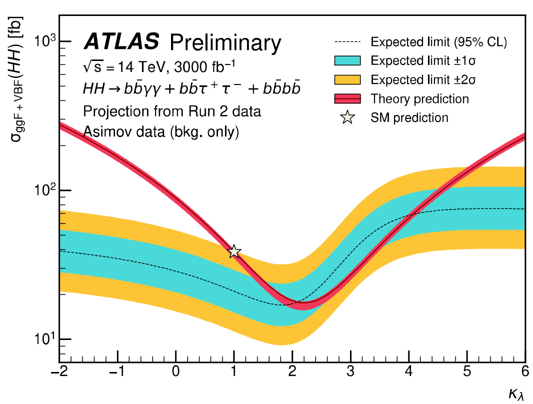
ATL-PHYS-PUB-2022-053
Nature 607 (2022) 60-68

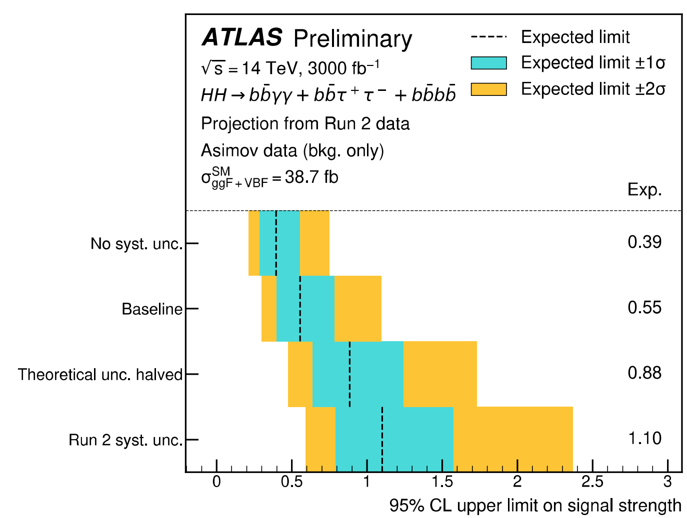
- Both ATLAS and CMS expect a σ/σ_{SM}<1.0 limit after combining different channels
- ATLAS prediction: 3.4 σ significance if κ_λ=1 with expected HL-LHC uncertainties
  - 4.9 σ with no syst. unc.











arXiv:2301.03212

ATLAS: HH → bbbb

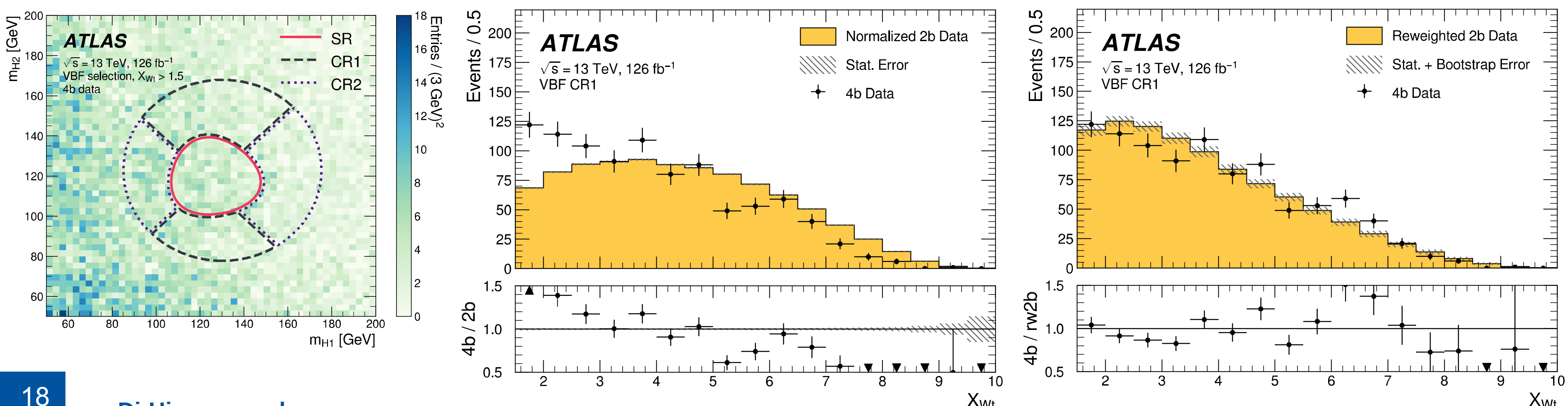
- Some details about background estimation:
  - SR defined by $X_{HH} < 1.6$

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

  - CR defined by circle R_{CR}

$$R_{\text{CR}} = \sqrt{\left(m_{H1} - 1.05 \cdot 124\ \text{GeV}\right)^2 + \left(m_{H2} - 1.05 \cdot 117\ \text{GeV}\right)^2} = 45\ \text{GeV}$$

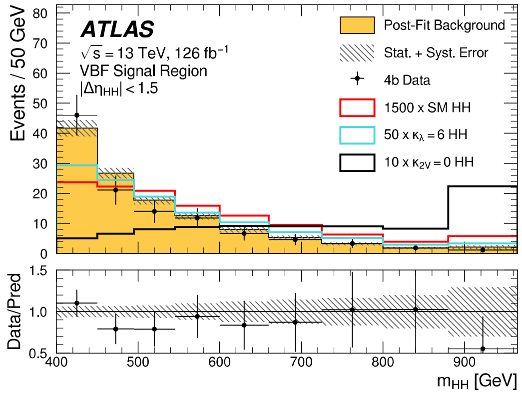
  - CR1 used for background estimation, CR2 used to obtain uncertainties
- Plots for weight derivation in VBF region:

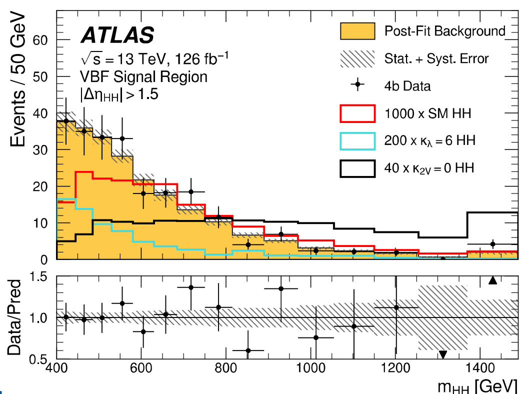


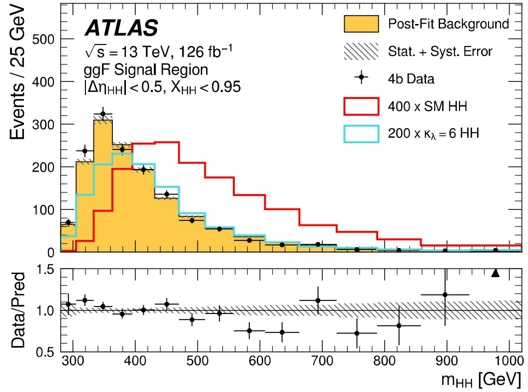
ATLAS: HH → bbbb

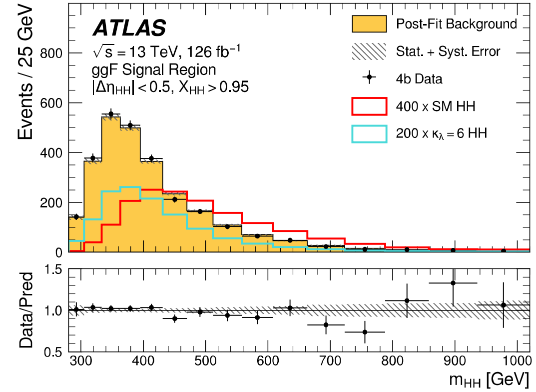
- All 8 signal regions

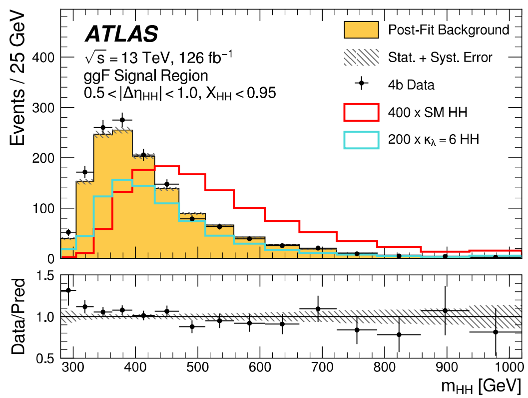
VBF ↘ ggF →

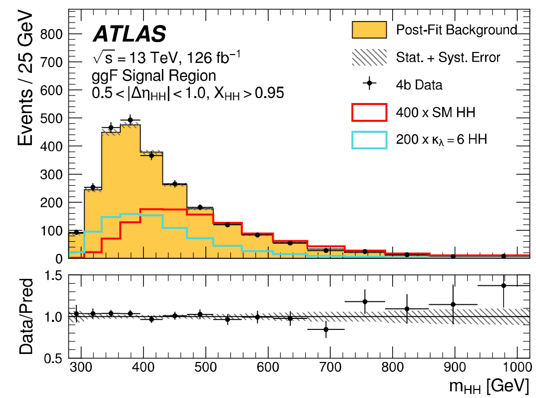


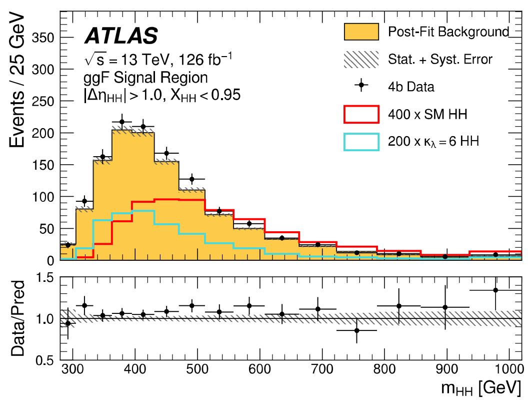


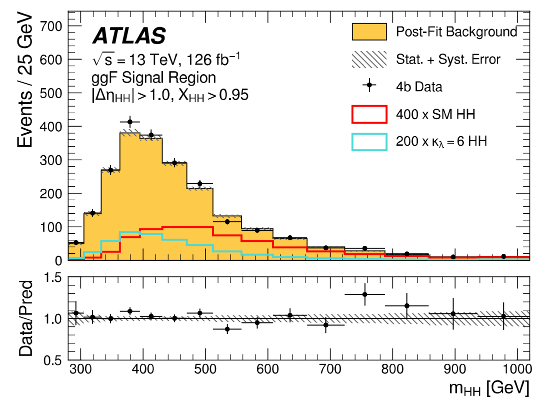








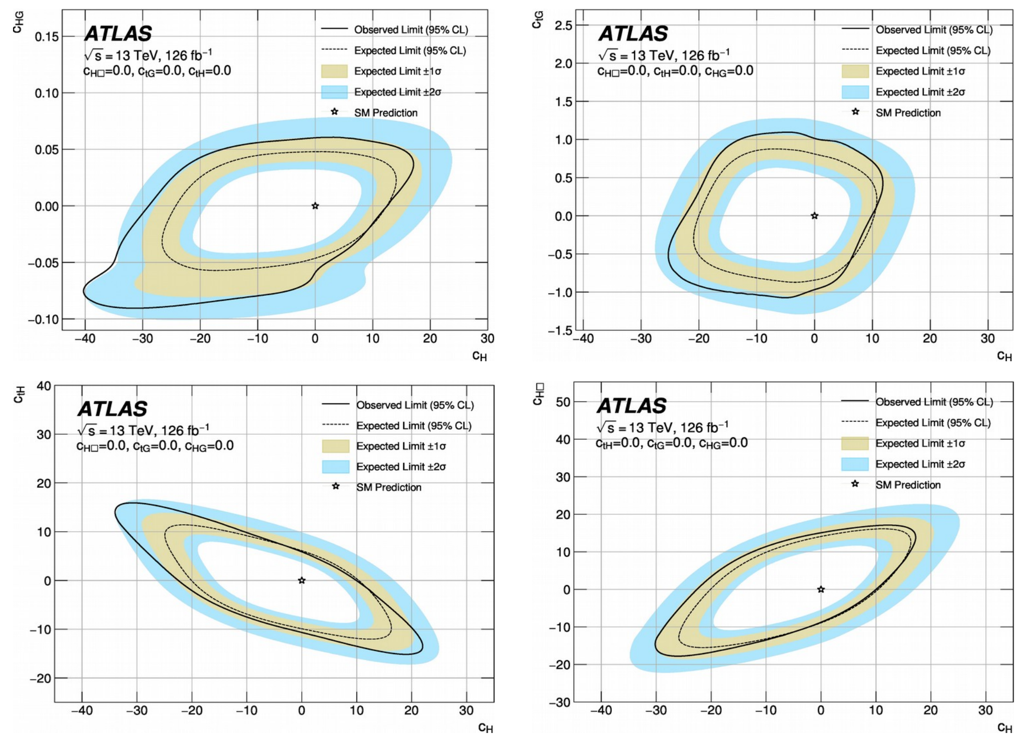




arXiv:2301.03212

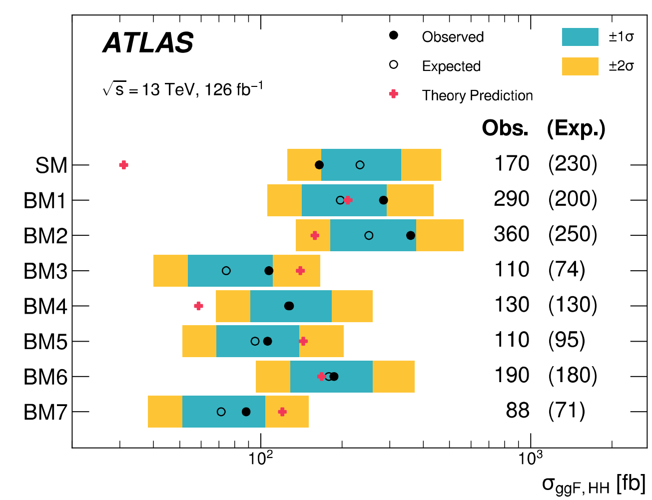
ATLAS: HH → bbbb

- Various limits on sets of one of the SM EFT coefficients c_{HG}, c_{tG}, c_{tH},$c_{H\Box}$ over c_H:



- Limits on H EFT benchmark scenarios:

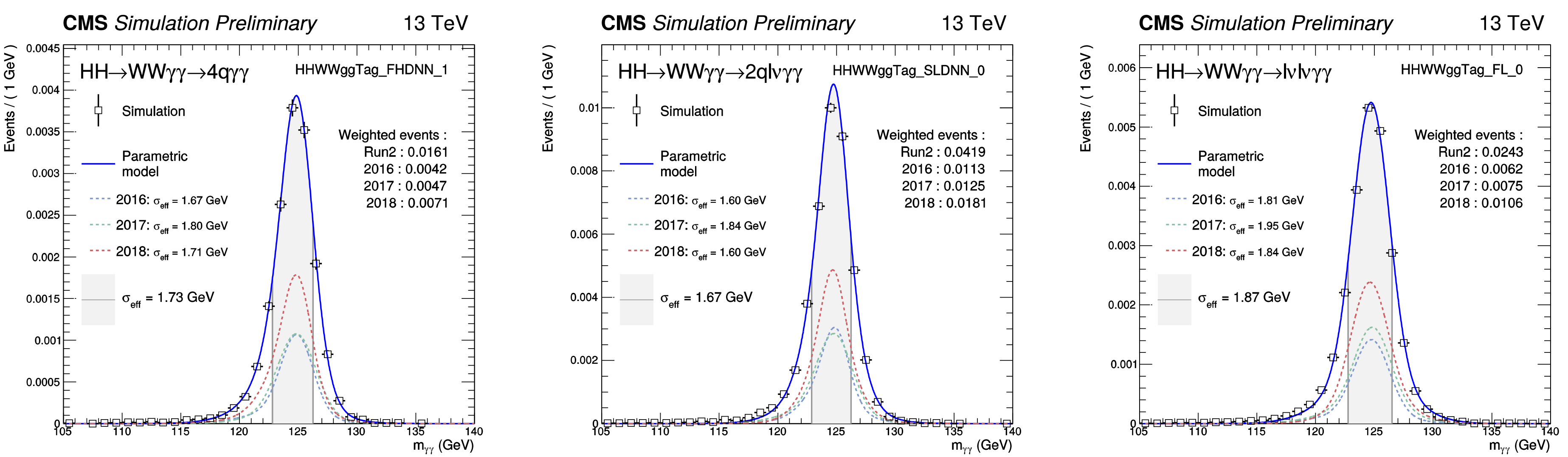
Benchmark Model	c_{HHH}	c_{ttH}	c_{ggH}	c_{ggHH}	c_{ttHH}
SM	1	1	0	0	0
BM1	3.94	0.94	1/2	1/3	−1/3
BM2	6.84	0.61	0.0	−1/3	1/3
BM3	2.21	1.05	1/2	1/2	−1/3
BM4	2.79	0.61	−1/2	1/6	1/3
BM5	3.95	1.17	1/6	−1/2	−1/3
BM6	5.68	0.83	−1/2	1/3	1/3
BM7	−0.10	0.94	1/6	−1/6	1



CMS: HH → WWγγ

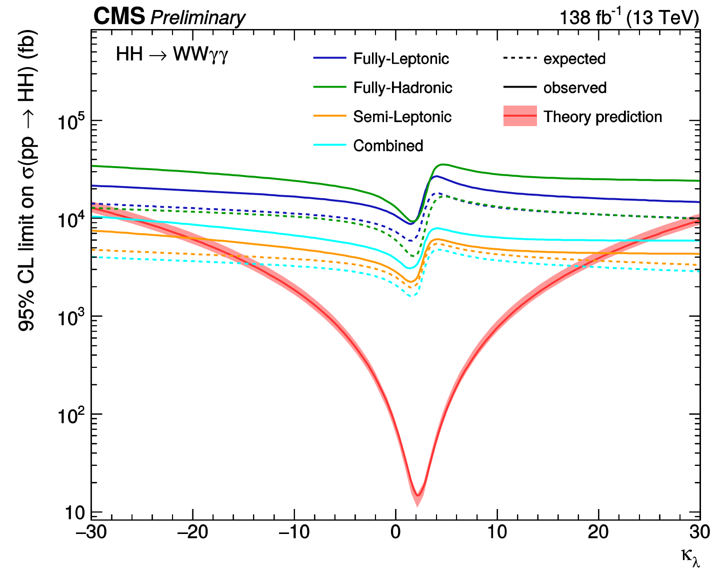
[CMS-HIG-21-014]

- Signal shapes obtained per final state, category and year
  - Left, Fully Hadronic: second highest DNN bin
  - Middle, Semi Leptonic: Highest DNN bin
  - Right, Full Leptonic (single category)

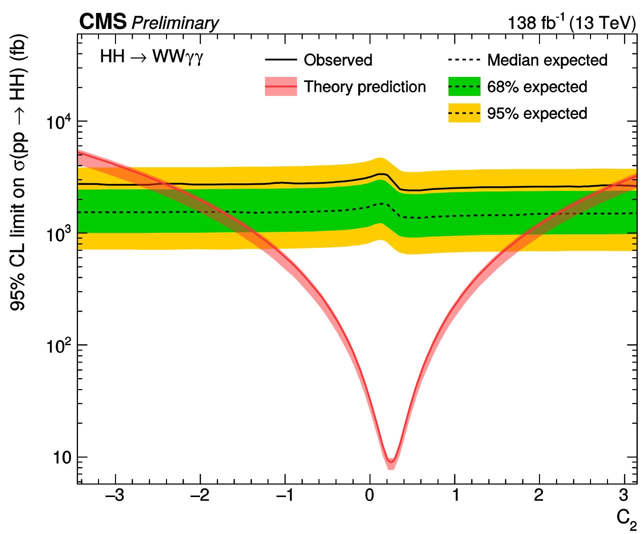


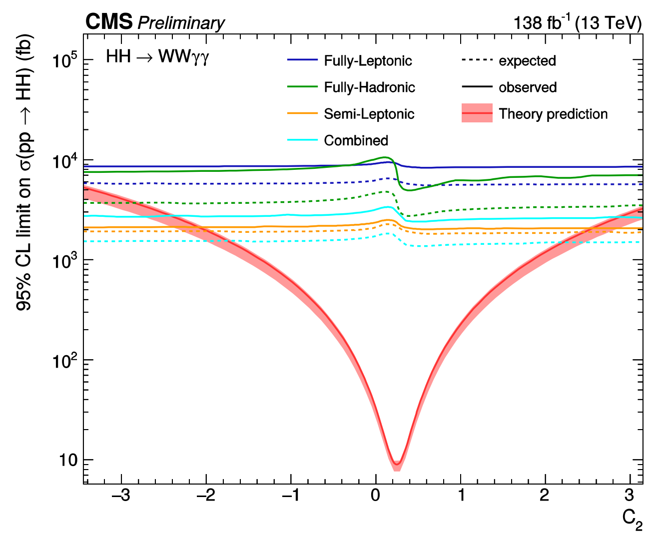
CMS: HH → WWγγ

- Limits on κ_λ per channel →



- Limits on parameter c_2 (ttHH coupling) of Higgs-EFT
  - Obs. (exp.) constraints are $-2.4 < c_2 < 2.9$ ($-1.7 < c_2 < 2.2$)

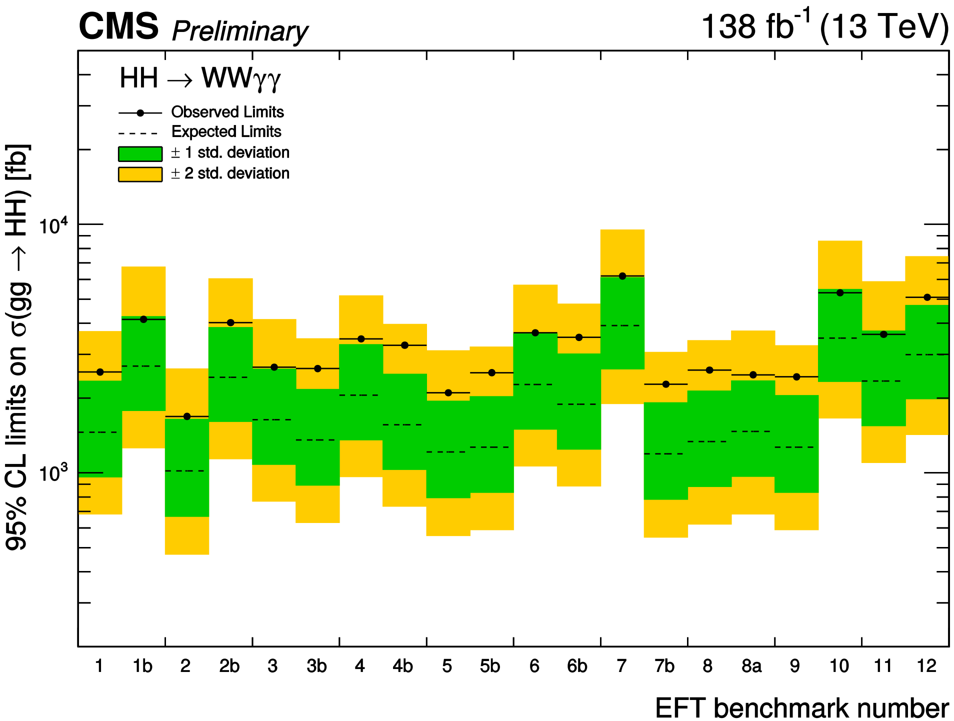




CMS: HH → WWγγ

CMS-HIG-21-014

- Results for various Higgs-EFT benchmark scenarios

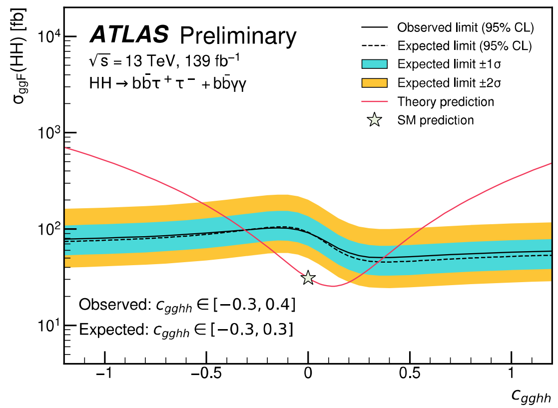


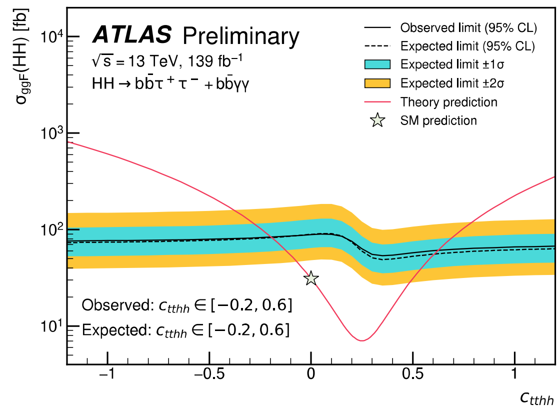
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
1b	3.94	0.94	$\frac{-1}{3}$	0.75	-1
2b	6.84	0.61	$\frac{1}{3}$	0.0	1.0
3b	2.21	1.05	$\frac{-1}{3}$	0.75	-1.5
4b	2.79	0.61	$\frac{1}{3}$	-0.75	-0.5
5b	3.95	1.17	$\frac{-1}{3}$	0.25	1.5
6b	5.68	0.83	$\frac{1}{3}$	-0.75	-1.0
7b	-0.10	0.94	1.0	0.25	0.5

ATL-PHYS-PUB-2022-019

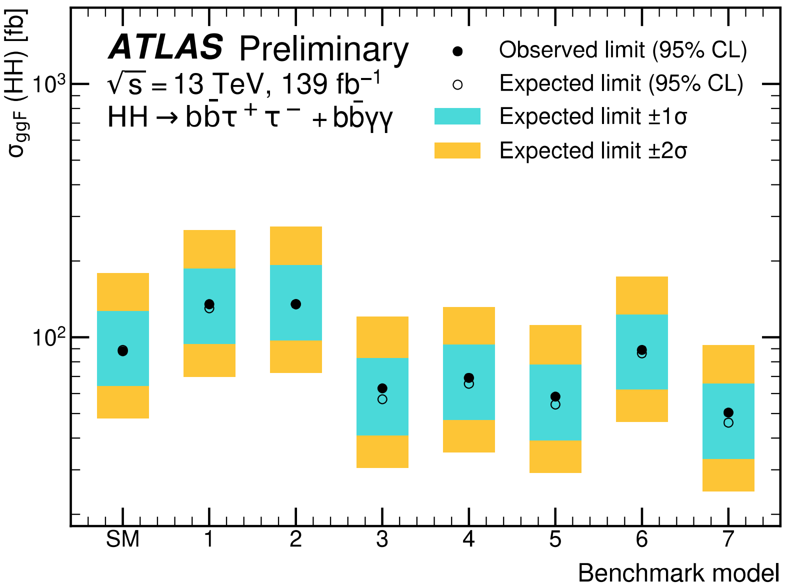
ATLAS: HEFT combination

- HEFT interpretations from combined bbττ and bbγγ analyses
  - Obs. (exp.) constraints are $-0.3 < c_{gghh} < 0.4$ ($-0.3 < c_{gghh} < 0.3$), $-0.2 < c_{tthh} < 0.6$ ($-0.2 < c_{tthh} < 0.6$)





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



CMS: VHH (HH $\rightarrow$ 4b)

CMS-HIG-22-006

- Choosing combination of b-tagged jets
  - **2L / 1L / MET**:
    Pair jets together based on their resulting invariant mass

$$D_{HH} = \frac{|m_{H1} - 1.05 \times m_{H2}|}{\sqrt{1 + 1.05^2}}$$

  - **FH**:
    Pair jets together based on their ΔR w.r.t. full invariant mass

$$\frac{360\,\mathrm{GeV}}{m_{4j}} - 0.5 < \quad \text{Leading } S_T \text{ dijet } \Delta R(j,j) < \max\left(1.5, \frac{650\,\mathrm{GeV}}{m_{4j}} + 0.5\right)$$

$$\frac{235\,\mathrm{GeV}}{m_{4j}} \quad < \text{Sub-leading } S_T \text{ dijet } \Delta R(j,j) < \max\left(1.5, \frac{650\,\mathrm{GeV}}{m_{4j}} + 0.7\right)$$

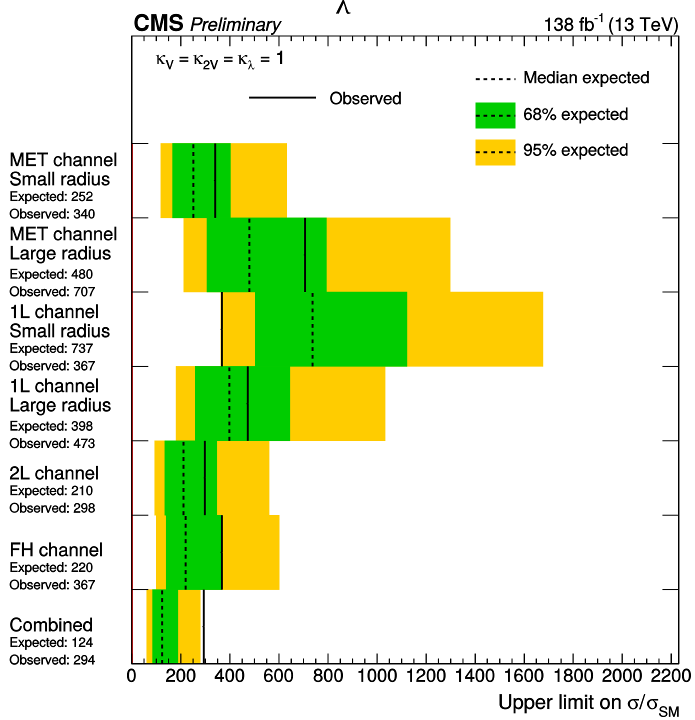
CMS: VHH (HH → 4b)

[CMS-HIG-22-006]

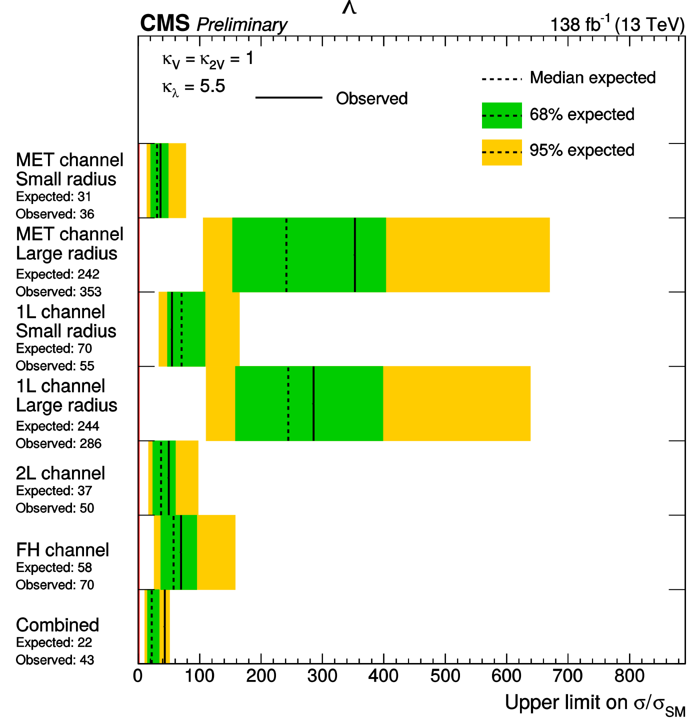
- Separate σ / σ_{SM} upper limits for κ_λ=5.5

  → Higher sensitivity in κ_λ-enriched regions in resolved categories
  (Boosted categories are κ_{2V}-enriched by construction)

κ_λ = 1.0



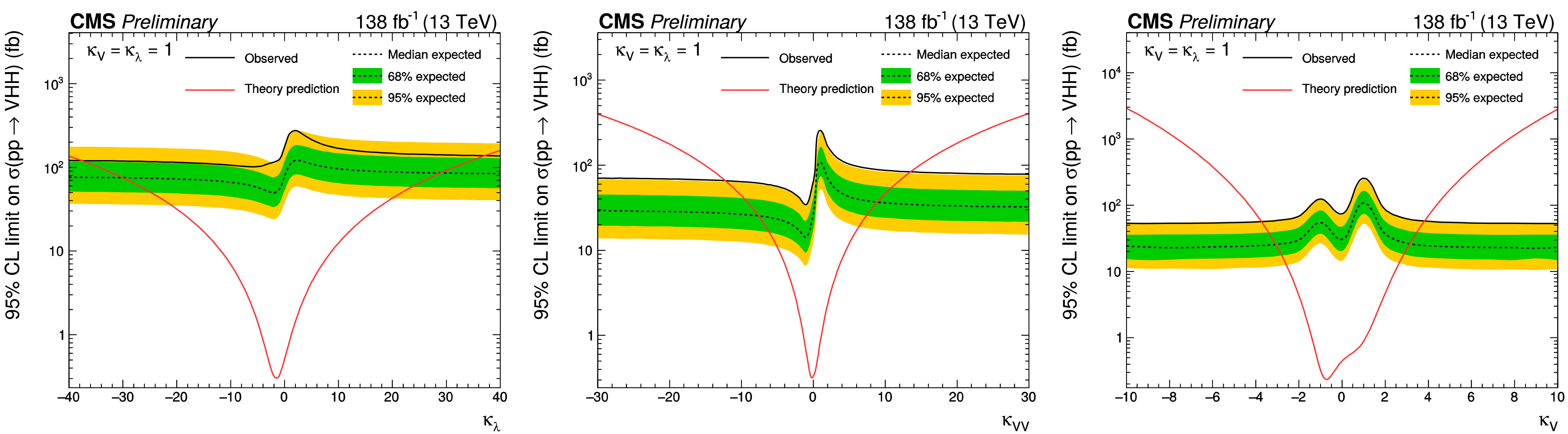
κ_λ = 5.5



CMS: VHH (HH → 4b)

CMS-HIG-22-006

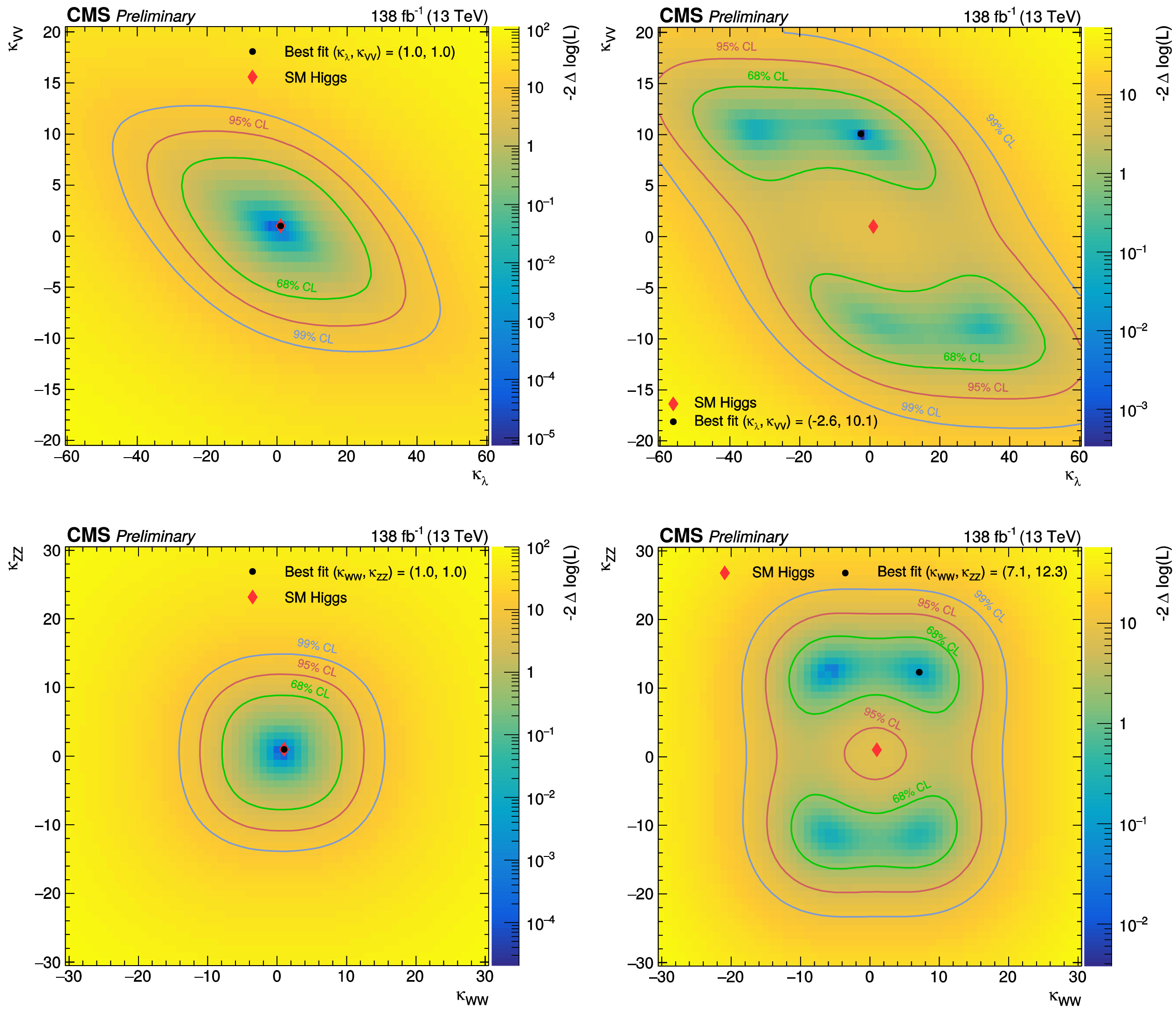
- Observed (expected) constraints on κ_λ, $\kappa_{2V,}$ κ_V:, and κ_{ZZ}, κ_{WW}
  - $-37.7 < \kappa_\lambda < 37.2$ $(-30.1 < \kappa_\lambda < 28.9)$
  - $-3.7 < \kappa_V < 3.8$ $(-3.1 < \kappa_V < 3.1)$
  - $-12.2 < \kappa_{2V} < 13.5$ $(-7.2 < \kappa_{2V} < 8.9)$



CMS: VHH (HH → 4b)

CMS-HIG-22-006

- Limit on κ_λ vs. κ_{2V} (top)
- Limit on separate κ_{2V} contributions: κ_{WW} vs. κ_{ZZ} (bottom)

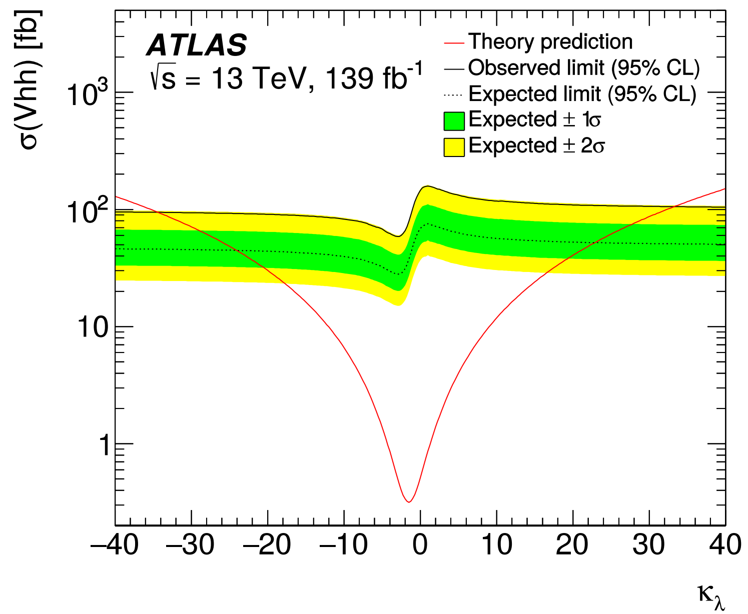


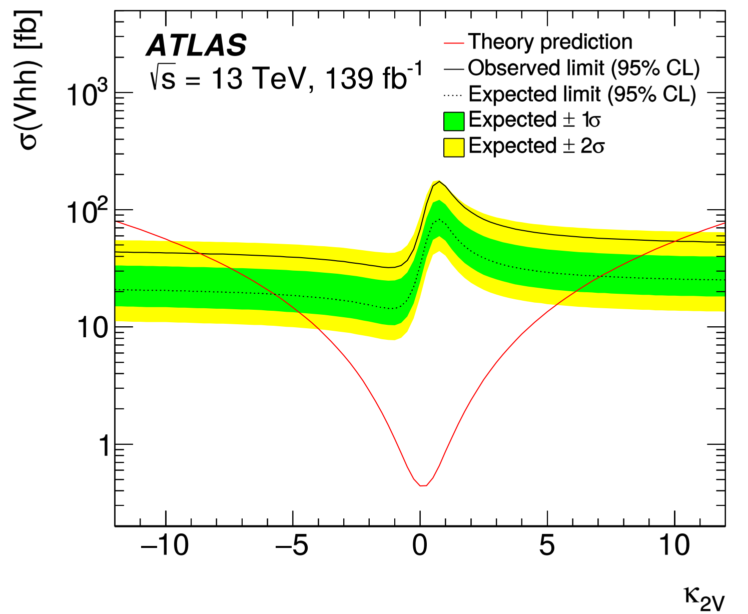
- Left: Expectation
- Right: Observation

ATLAS: VHH (HH → 4b)

arXiv:2210.05415

- Observed (expected) constraints on κ_λ and κ_{2V}:
  - $-34.4 < \kappa_\lambda < 33.3$ ($-24.1 < \kappa_\lambda < 22.9$)
  - $-8.6 < \kappa_{2V} < 10.0$ ($-5.7 < \kappa_{2V} < 7.1$)

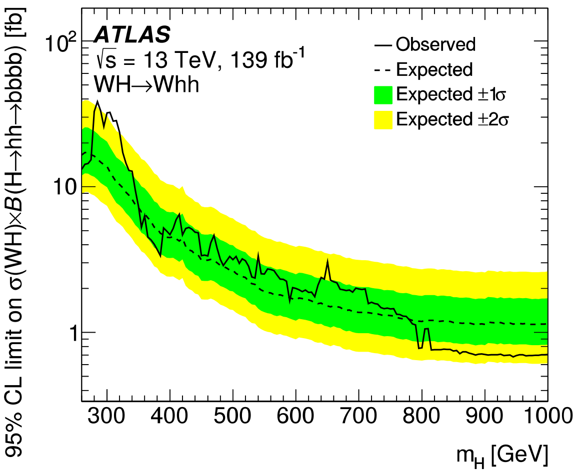


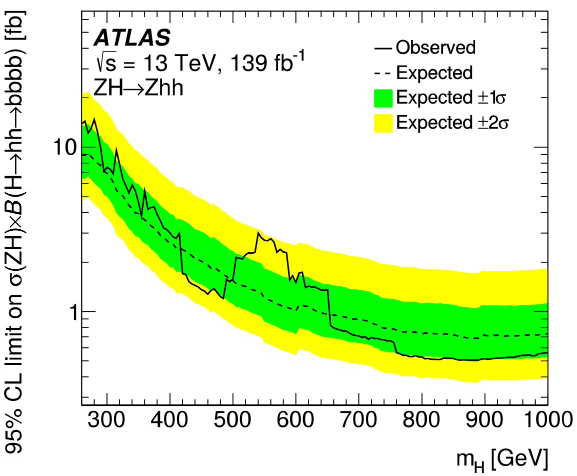


[arXiv:2210.05415](https://arxiv.org/abs/2210.05415)

ATLAS: VHH (HH → 4b)

- 2HDM interpretations: Limits on H / A:

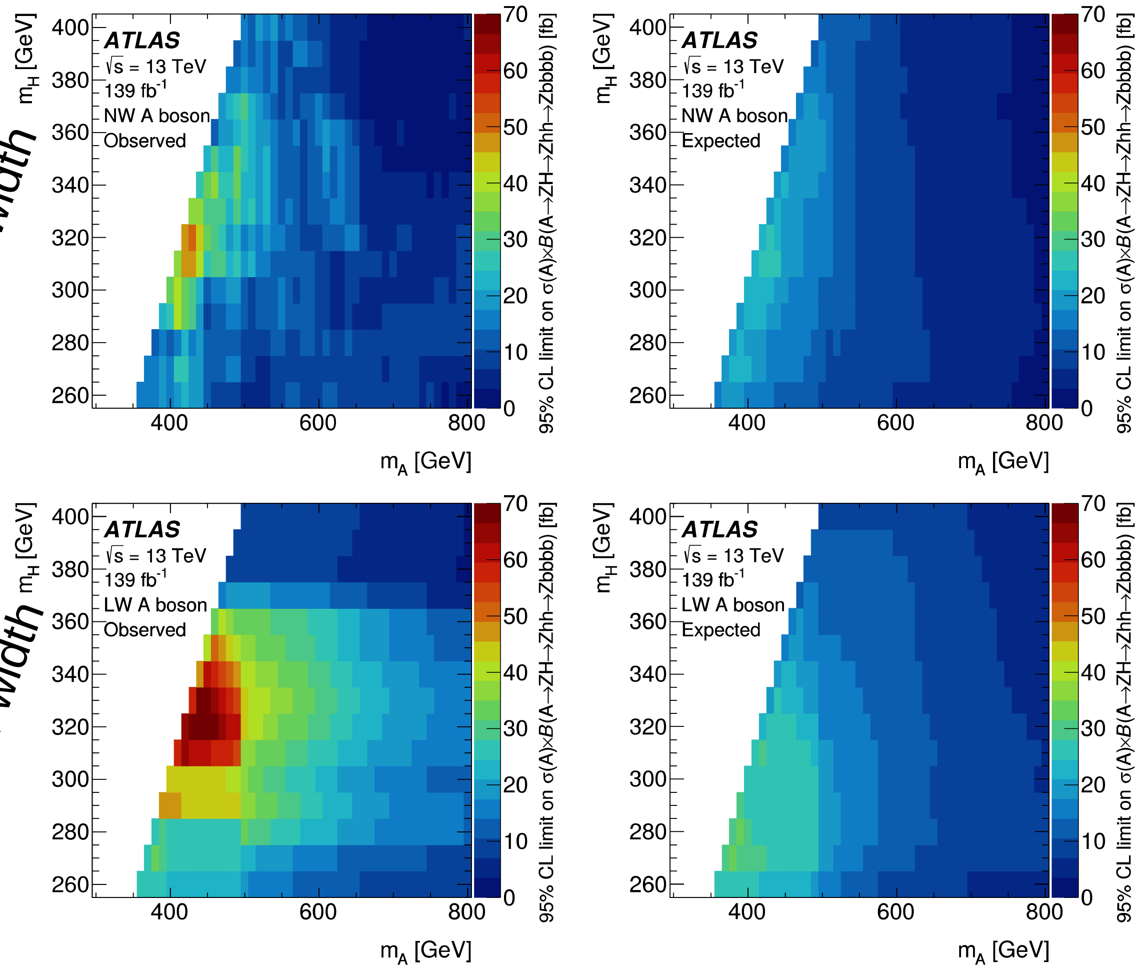




Observed | Expected

Narrow width

20% rel. width



ATLAS: VHH (HH → 4b)

arXiv:2210.05415

- 2HDM interpretations over cos(β-α) and m_A:

Type-1 2HDM

Lepton-specific 2HDM

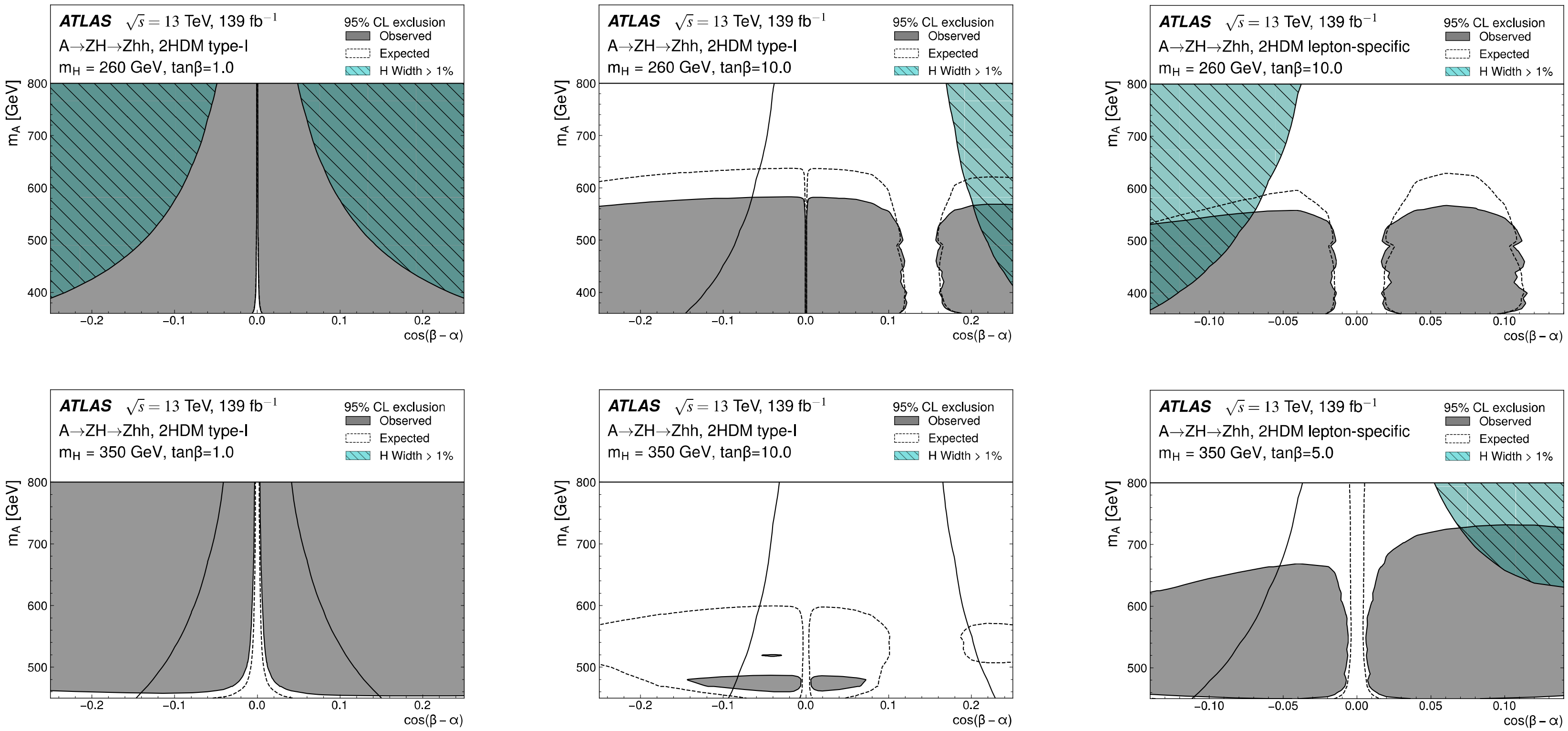
tanβ = 1

tanβ = 10

tanβ = 10

$m_H = 260$ GeV

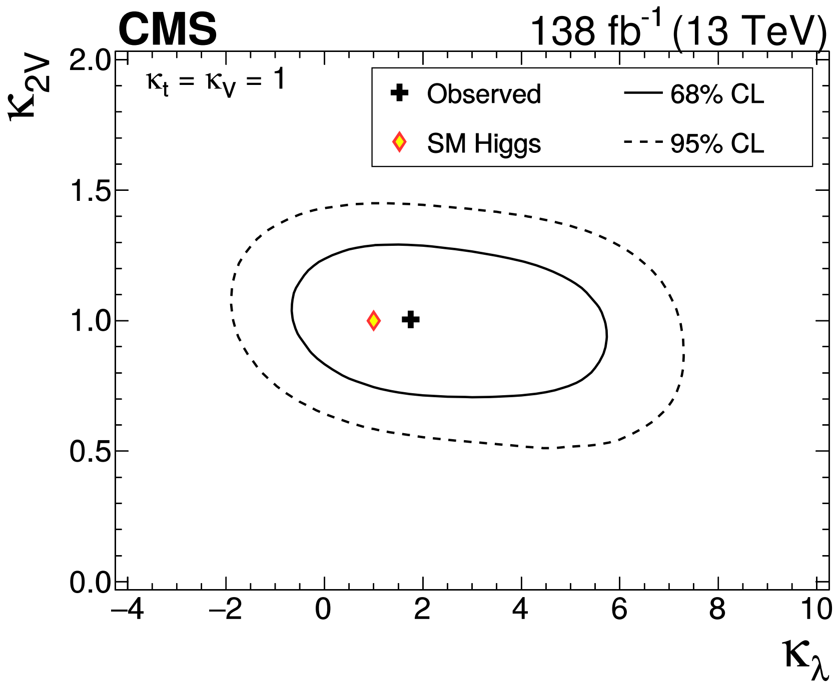
$m_H = 350$ GeV

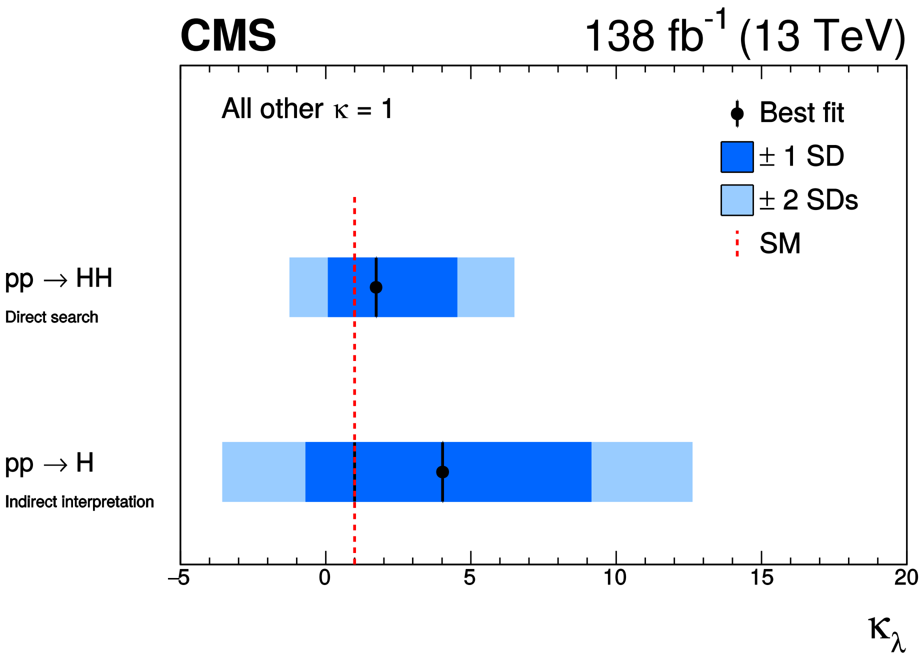


tanβ = 5

Constraints on Higgs boson self-interaction and quartic coupling

[Nature 607 (2022) 60-68]



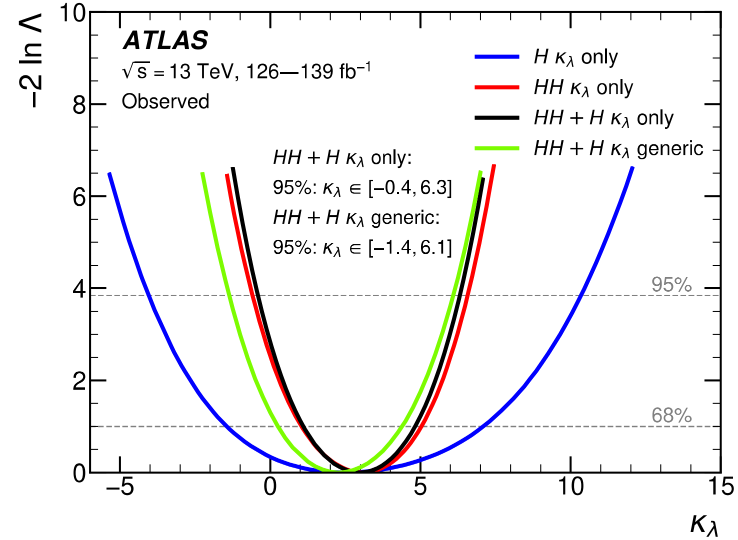


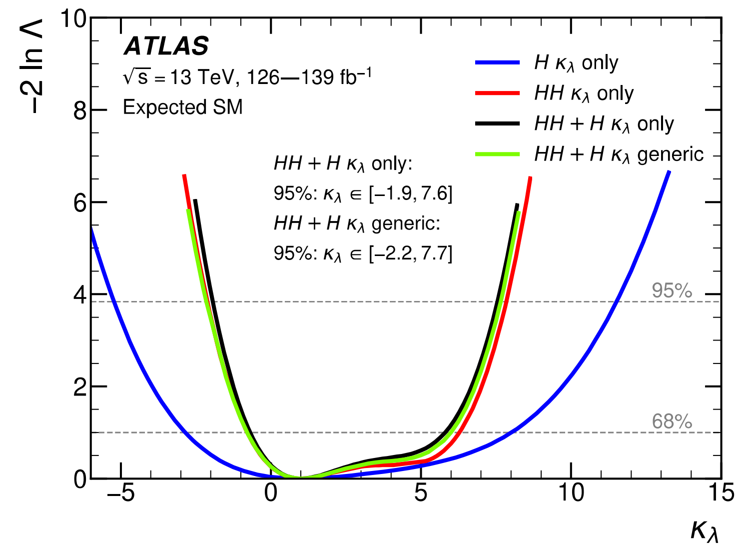
- Constraints on κ_{λ} and κ_{2V} from the production of Higgs boson pairs
- Constraint on the Higgs boson self-coupling modifier κ_{λ} from single and pair production of Higgs boson(s)

Likelihood scans from combinations

arXiv:2211.01216
Nature 607 (2022) 60-68

- CMS observed ranges:
  - $-1.24 < \kappa_\lambda < 6.49$
  - $0.67 < \kappa_{2V} < 1.38$
- ATLAS observed (exp.) ranges:
  - HH only:
    - $-0.6 < \kappa_\lambda < 6.6$ ($-2.1 < \kappa_\lambda < 7.8$)
    - $0.1 < \kappa_{2V} < 2.0$ ($0.0 < \kappa_{2V} < 2.1$)
  - H + HH:
    - $-0.4 < \kappa_\lambda < 6.3$ ($-1.9 < \kappa_\lambda < 7.6$)





κ_t-κ_λ

- Scans of κ_t over κ_λ by ATLAS
  - Blue: H
  - Red: HH
  - Black: HH + H
- Top: Observed
- Bottom: Expected