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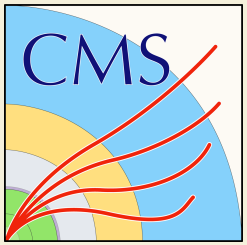


The Higgs boson self-interaction

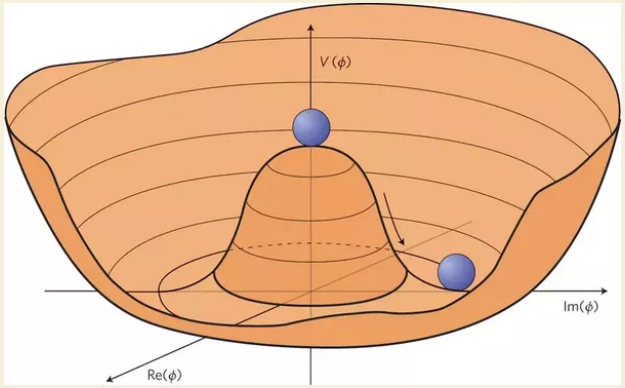
a.k.a: Twice the Higgs, twice the fun!

Arnaud Ferrari (Uppsala University, Sweden)
on behalf of the ATLAS and CMS Collaborations

Higgs10 Symposium, CERN, 04/07/2022

The ultimate probe of the scalar sector

- With the Higgs boson discovery, only a portion of the Higgs potential has been measured.
- Its shape completely determines the properties of the scalar sector.

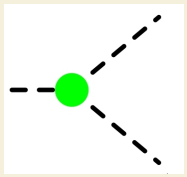


$$\langle \phi_0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \; v = \sqrt{\mu^2/\lambda}.$$

SM: $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \overset{\phi \to v+H}{\supset} \lambda v^2 H^2 + \lambda v H^3 + \ldots$

mass term $\frac{1}{2} m_H^2 H^2$

self-interaction terms (never observed)

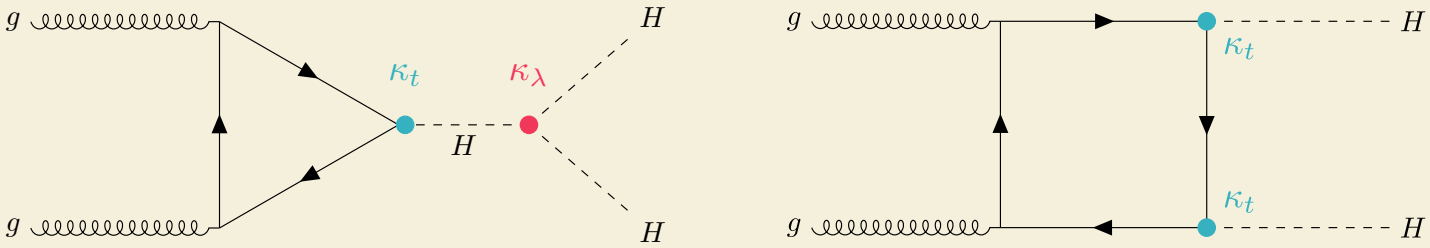


- Higgs boson pair (HH) production allows to probe *directly* the Higgs boson self-interaction and, ultimately, the shape of the Higgs potential.
- Any deviation from the self-interaction predicted by the SM would be a sign of new physics!

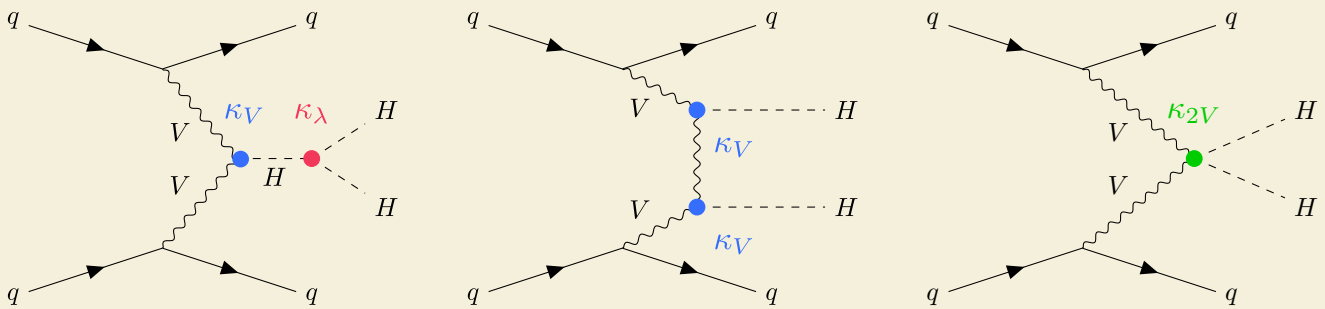
Higgs boson pair production

Non-resonant pairs of Higgs bosons (HH) arise from several diagrams, some of which interfere destructively. Very small cross-sections!

Gluon-gluon fusion: $\sigma^{\mathrm{SM}}_{\mathrm{ggF}} \simeq 31$ fb [13 TeV].



Vector-boson fusion: $\sigma^{\mathrm{SM}}_{\mathrm{VBF}} \simeq 1.7$ fb [13 TeV].

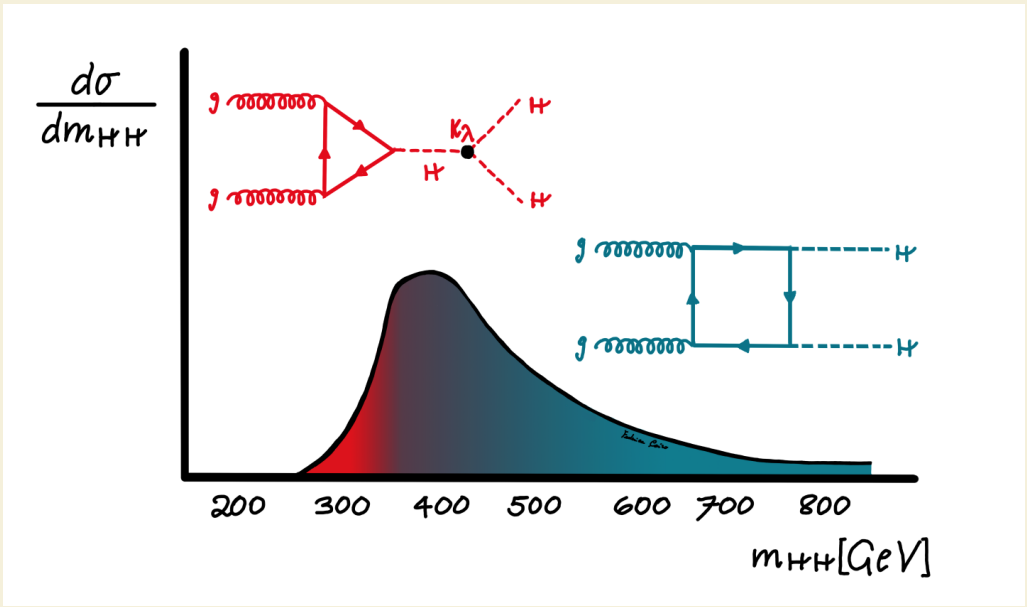


Other production modes (e.g. VHH, ttHH) have even smaller cross-sections.

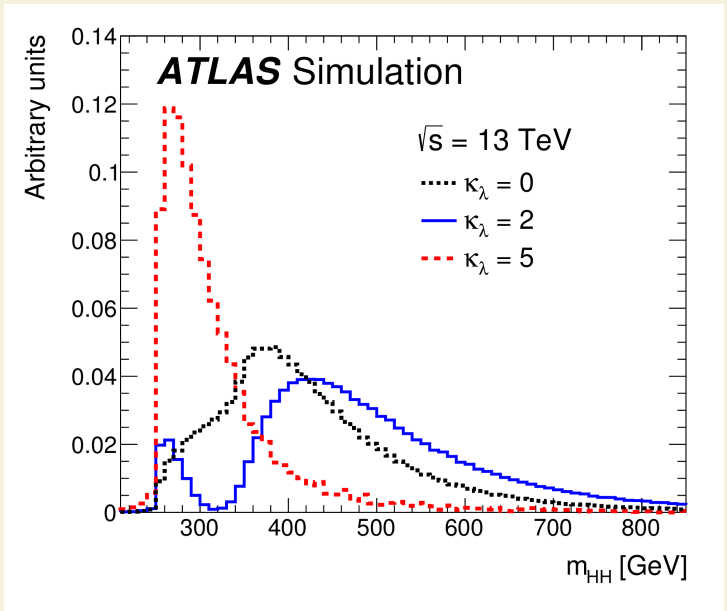
Non-resonant HH mass distribution(s)

- HH events from the self-interaction diagrams are soft.

  $\Rightarrow$ Challenging for triggers and detector object reconstruction/identification!
- $\kappa_\lambda \neq 1$ modifies the cross-section and kinematical properties of HH pairs.



ATLAS Physics Briefing: Twice the Higgs, twice the challenge

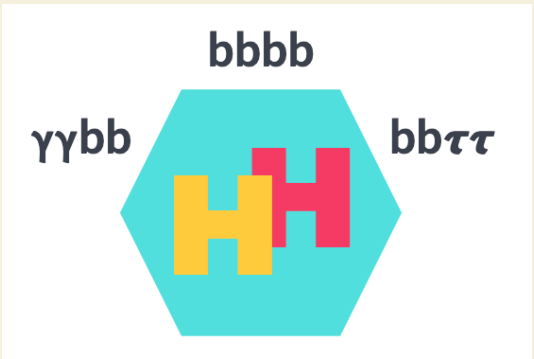


Phys. Lett. B 800 (2020) 135103

HH decays and search channels

Multitude of Higgs boson decay modes $\Rightarrow \mathcal{O}(\text{multitude}^2)$ of HH search channels, each with specific experimental challenges and sensitivity reach.

- Not a single "golden" channel.
- But (at least) three silver bullets!

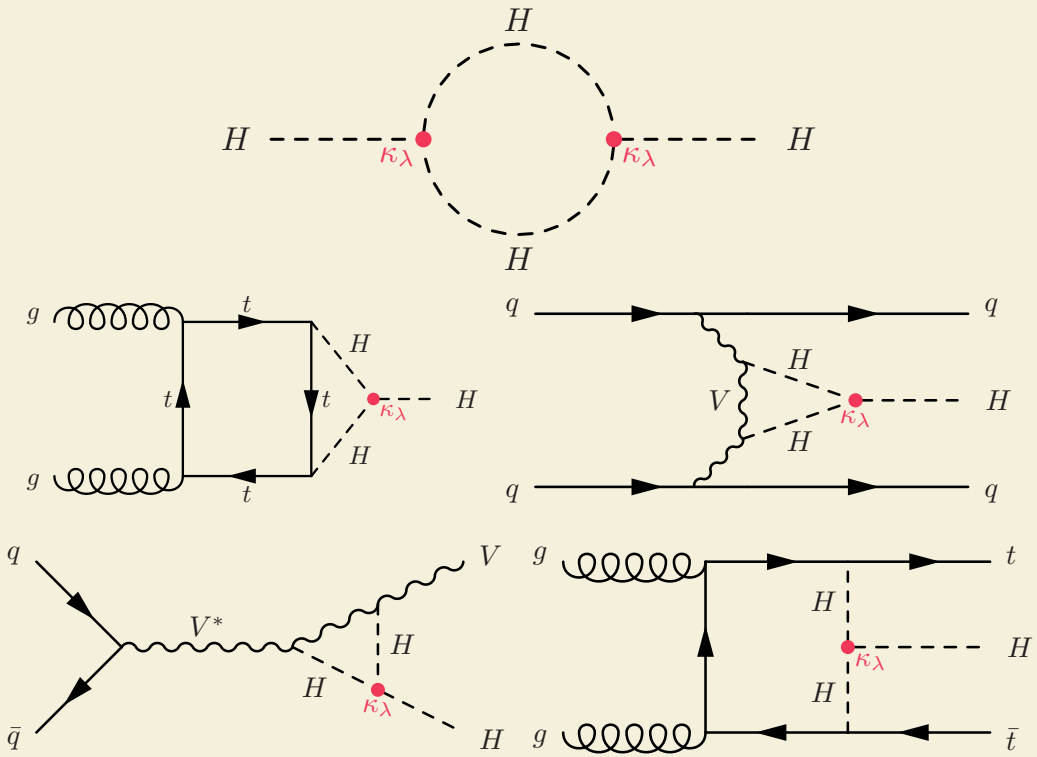


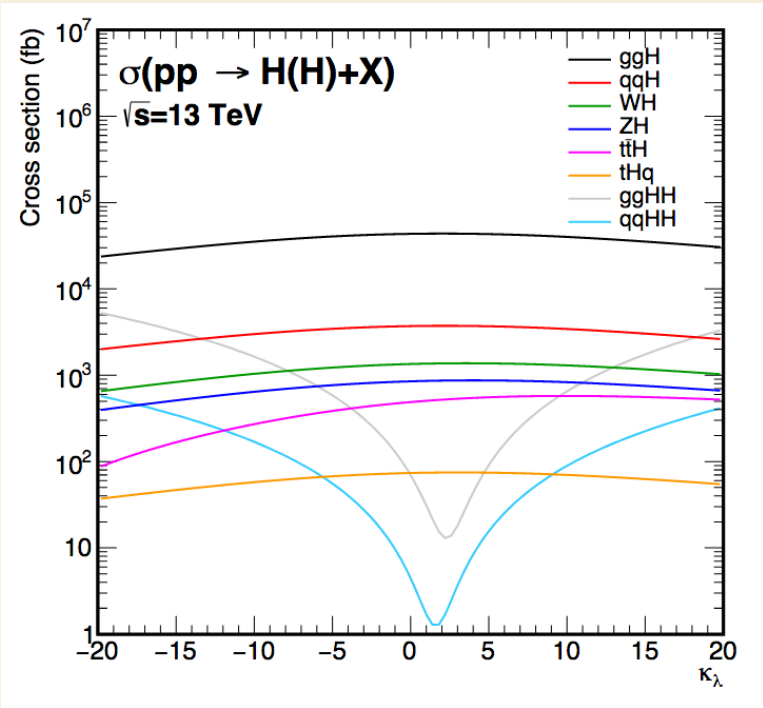
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Image by Katharine Leney

Impact of the self-interaction on single-H

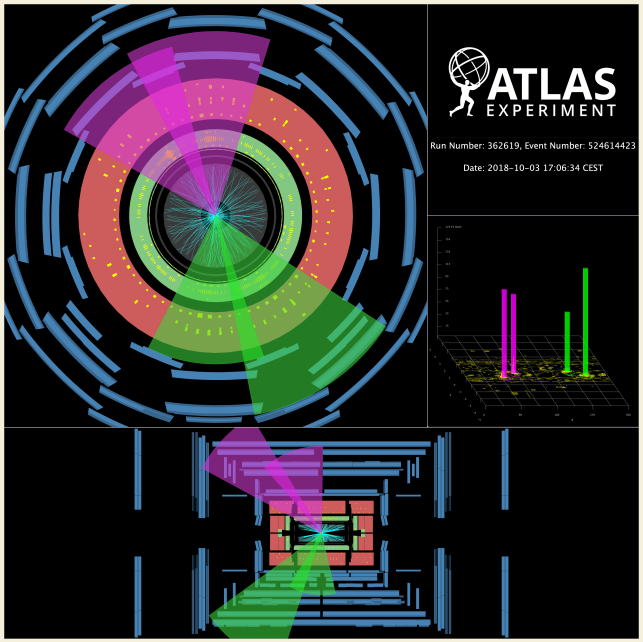
- Single Higgs boson processes do not depend on κ_λ at LO.
- However, NLO electroweak loops allow κ_λ to affect single Higgs boson production and decay modes.

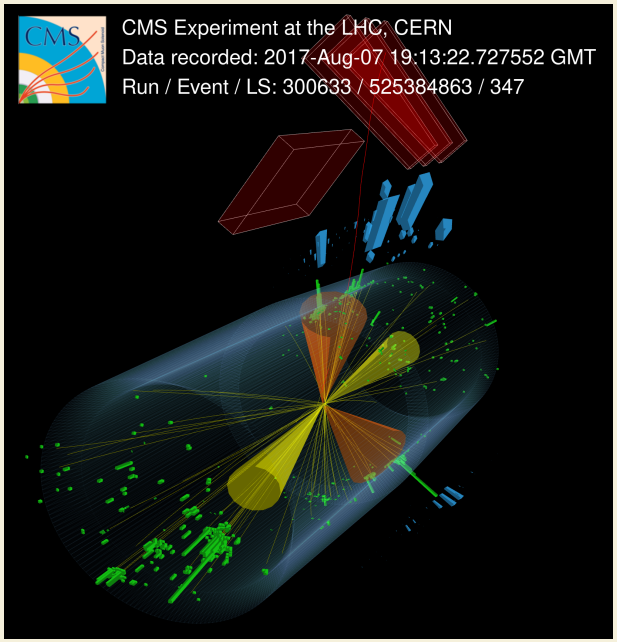




LHCHWG-2022-002

HH → bbbb



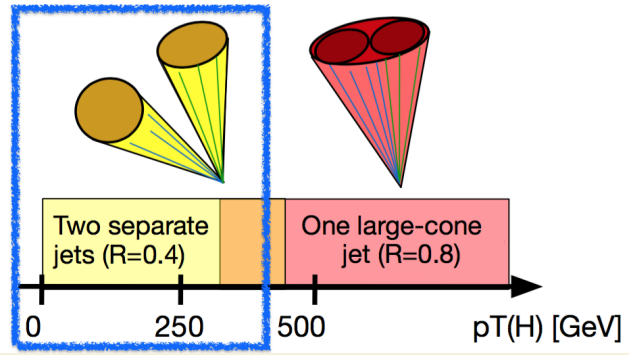


- Highest branching ratio... but large multi-jet background!
- Mostly probes large $m_{HH} \Rightarrow$ sensitivity to HH events with large $p_{\mathrm{T}}^{\mathrm{H}}$.

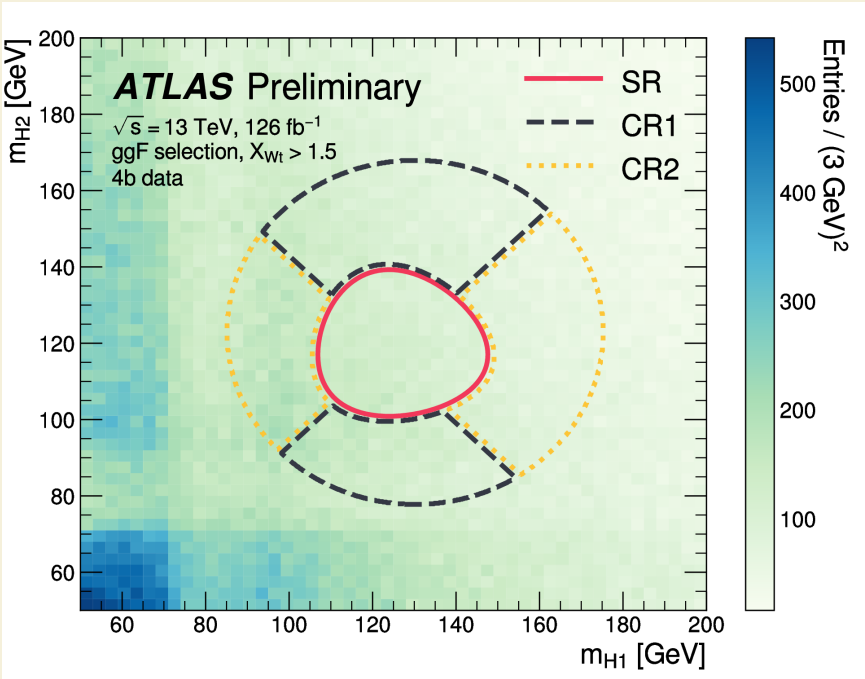
- ATLAS: ATLAS-CONF-2022-035
- CMS: arXiv:2202.09617 [hep-ex] & arXiv:2205.06667 [hep-ex]

HH → bbbb – resolved topology

- Start from triggered events with ≥2 (ATLAS) or ≥3 (CMS) b-jets.
- SR = two b-jet pairs compatible with a Higgs boson.
- Data-driven background model based on SR event re-weighting:
  - 2b → 4b (ATLAS);
  - 3b → 4b (CMS);
  - Re-weighting function derived with machine-learning techniques in CRs around the SR.

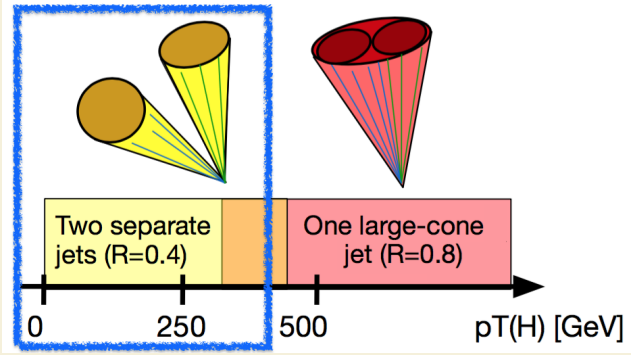


Sketch by Daniel Guerrero



HH → bbbb – resolved topology

- ggF- and VBF-like event categories based on forward jets and kinematic properties of HH.
  - ATLAS: fit m_{HH} in all categories;
  - CMS: fit an MVA classifier output or m_{HH} in different categories.



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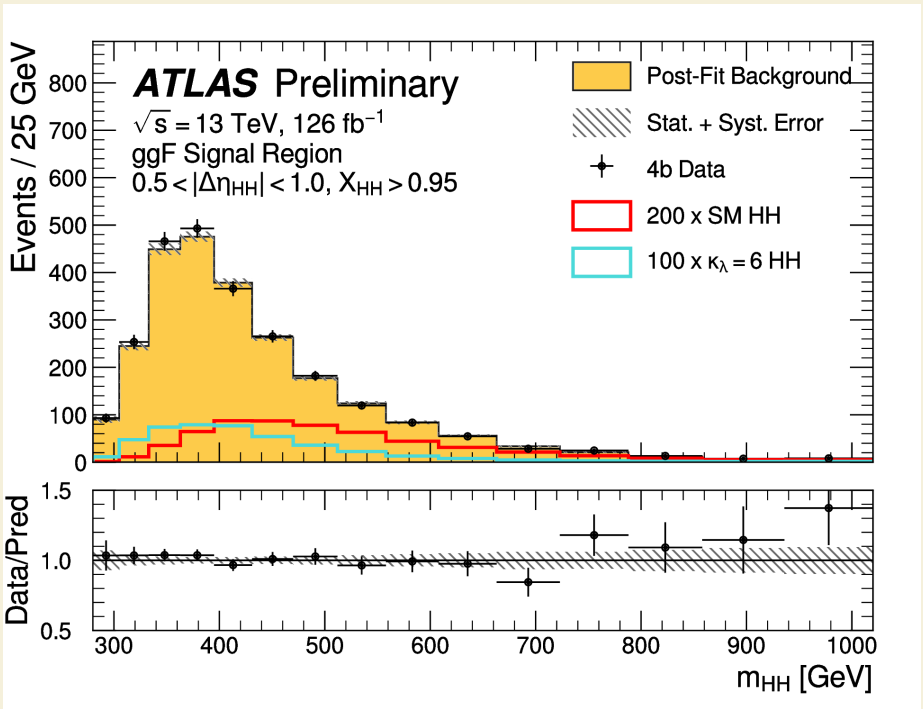
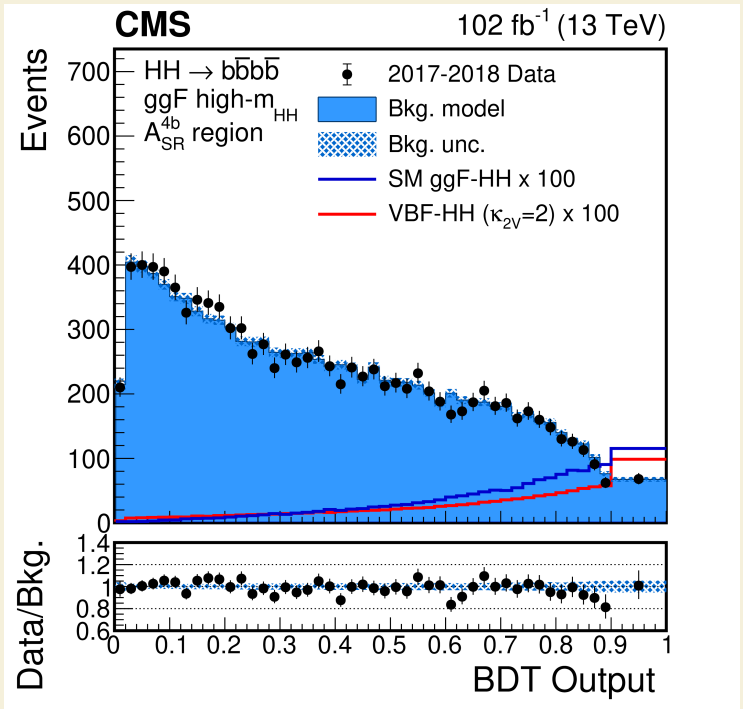
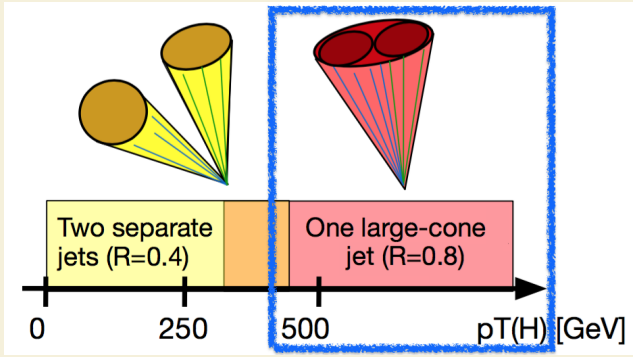




HH → bbbb – boosted topology (CMS)

- Two large-radius jets as H→bb candidates.
- Sophisticated tagger to discriminate against QCD-induced jets.
- Multi-jet background based on transfer factors from CRs with looser H→bb tagging requirements.
- ggF-like SRs: jet mass as discriminant.
- VBF-like SRs ↔ 7 bins in H→bb tagger purity and m_{HH}.



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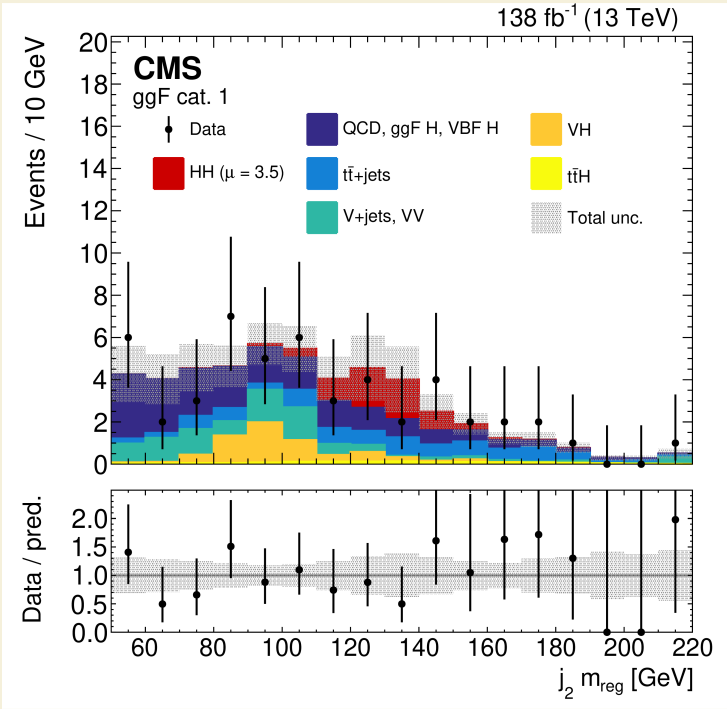

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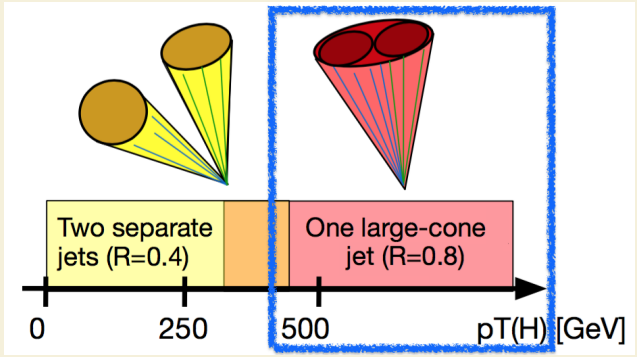
- ggF-like SRs: jet mass as discriminant.
- VBF-like SRs ↔ 7 bins in H→bb tagger purity and m_{HH}.

$\Rightarrow$ **$\kappa_{2V} = 0$ hypothesis excluded with $\gtrsim 6\sigma$ (other κ's at 1)!**



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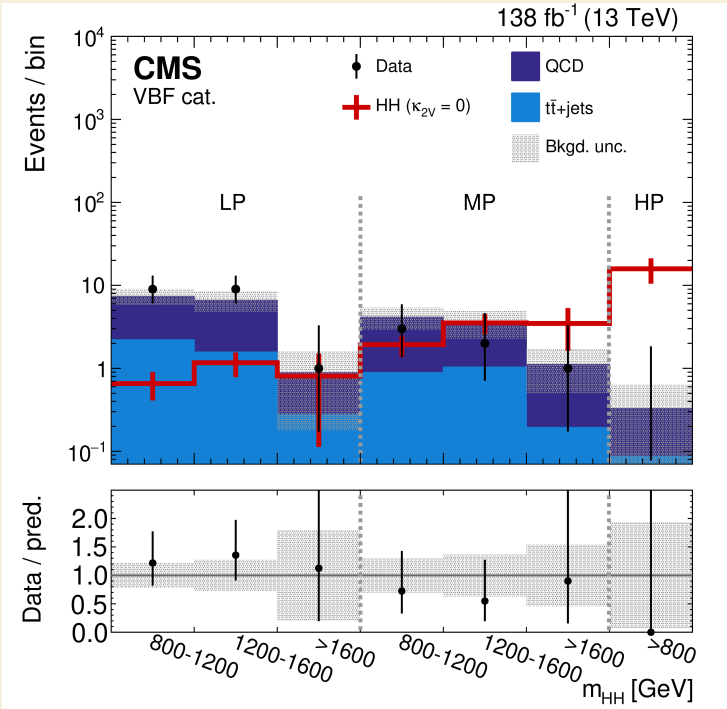
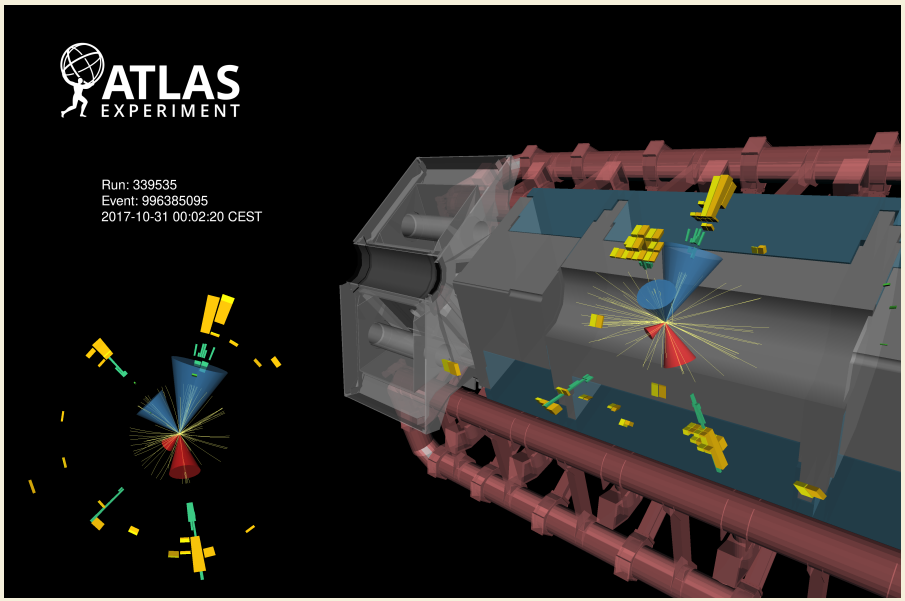
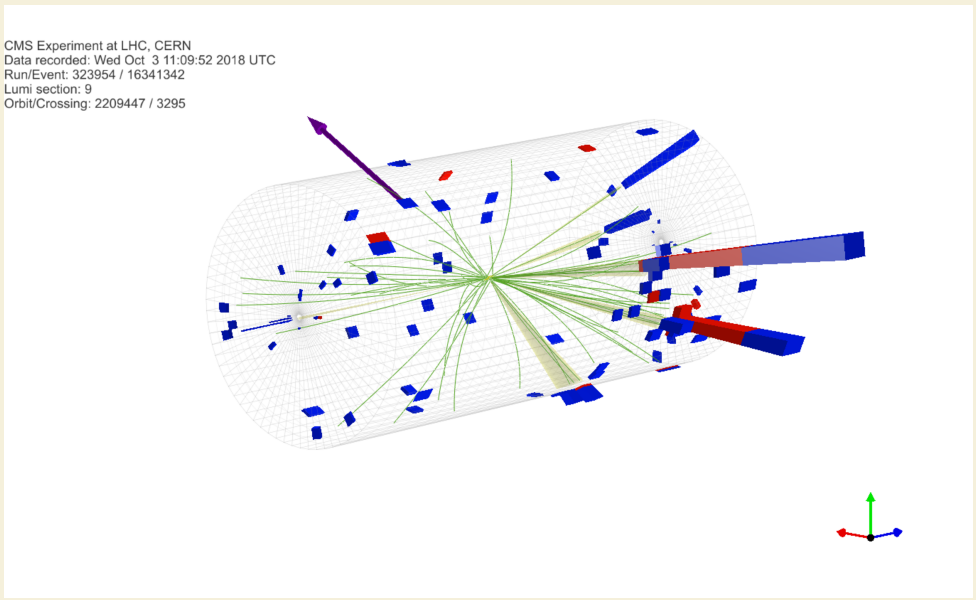


HH $\to$ bb$\tau\tau$



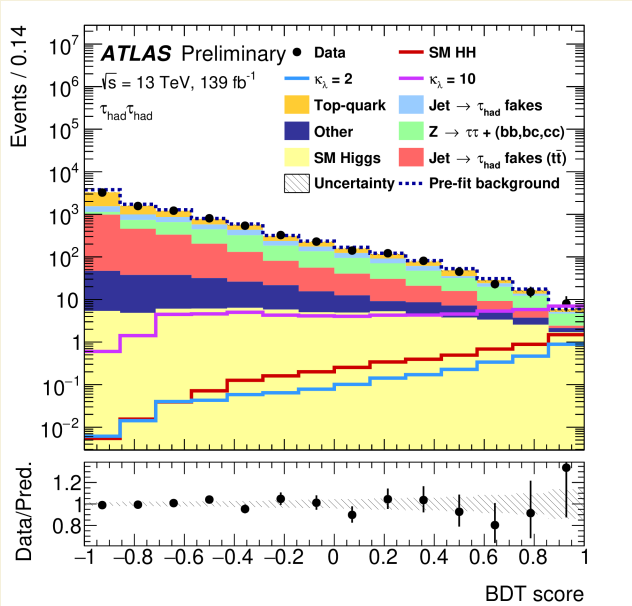


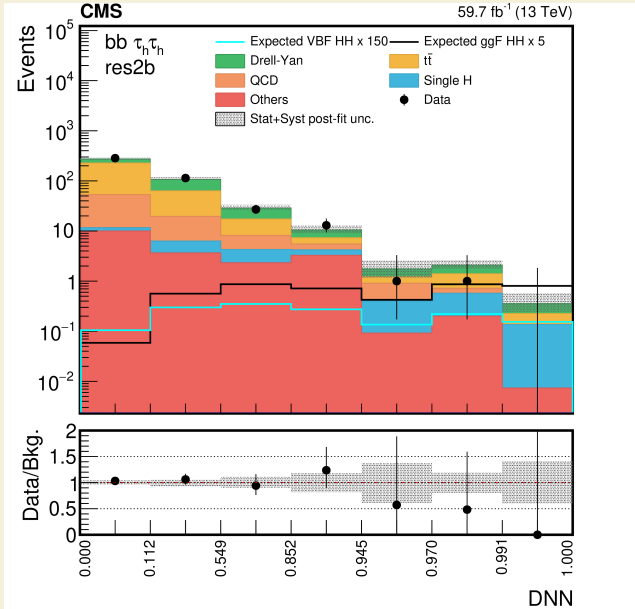
- Intermediate branching ratio... but clean final state with moderate backgrounds!

- ATLAS: ATLAS-CONF-2021-030
- CMS: arXiv:2206.09401 [hep-ex]

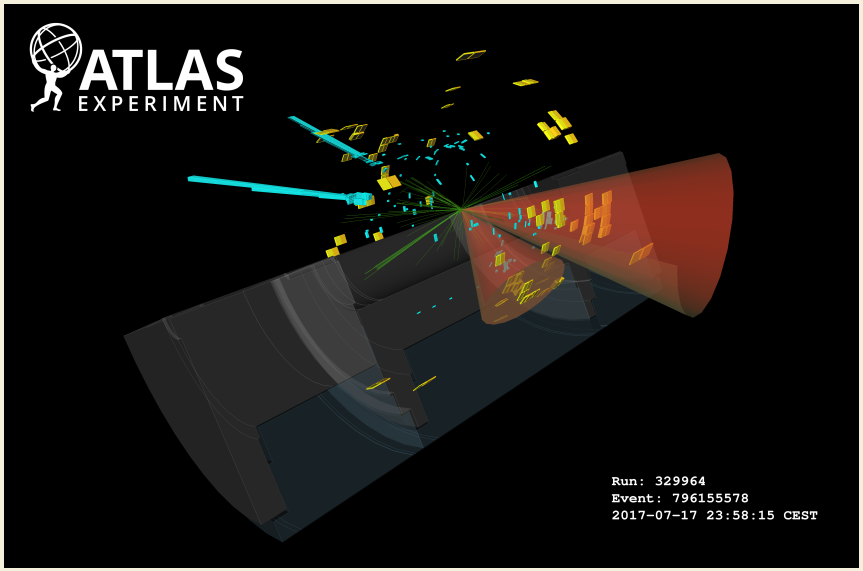
HH → bb$\tau\tau$

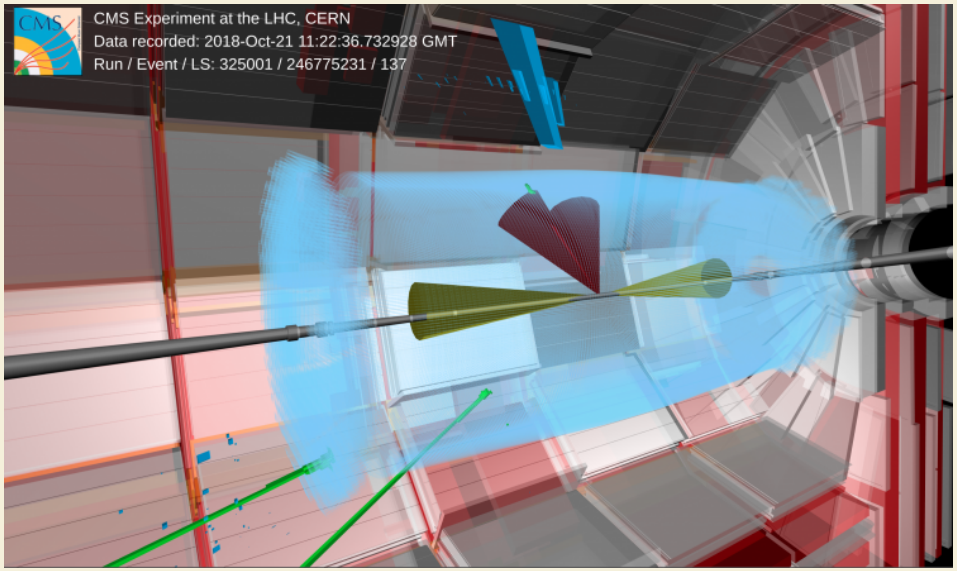
- bb$\tau_h\tau_e$, bb$\tau_h\tau_\mu$ and bb$\tau_h\tau_h$ final states + further event categories:
  - CMS: 5 VBF-like regions + 3 ggF-like regions based on the H→bb topology (resolved 2b, resolved 1b, boosted);
  - ATLAS: 3 inclusive regions based on the trigger strategy.
- Background modelling:
  - $t\bar{t}$ and Z+jets: simulation with data-driven corrections;
  - data-driven method if a gluon- or quark-initiated jet mimics τ_h.
- Signal extraction: MVA classifiers for both ATLAS and CMS.





HH → bbγγ



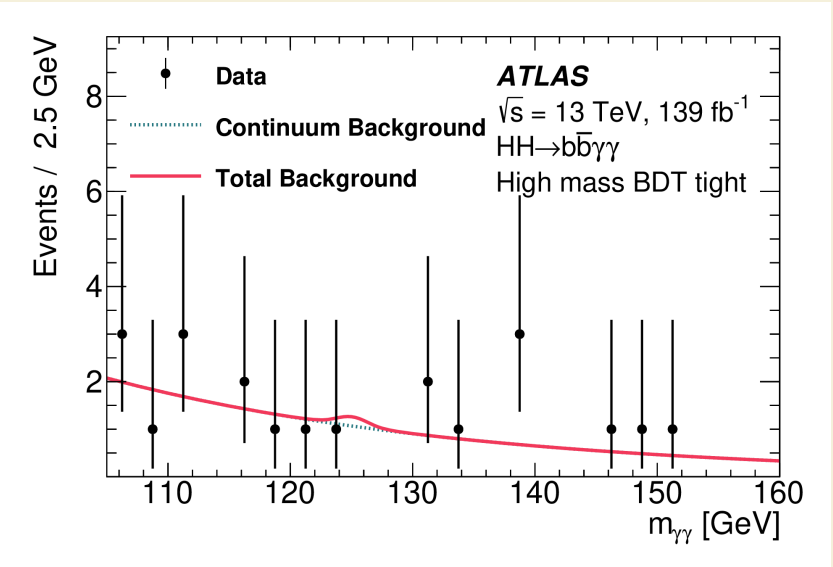


- Tiny branching ratio... but very clean signature: excellent $m_{\gamma\gamma}$ resolution and small backgrounds!
- Enhanced sensitivity at low m_{HH}, hence to the Higgs boson self-interaction.

- ATLAS: arXiv:2112.11876 [hep-ex]
- CMS: JHEP03 (2021) 257

HH → bbγγ

- Di-photon trigger and event selection + 2 b-jets.
- Event categories based on:
  - $m_{bb\gamma\gamma}$;
  - various purity regions based on MVA outputs;
  - ggF- and VBF-like topologies (in CMS).
- Signal and backgrounds:
  - HH and single-H shapes from simulation;
  - continuum background shape from data;
- ATLAS: parametric fit of $m_{\gamma\gamma}$ only.
- CMS: parametric fit in the $(m_{\gamma\gamma}; m_{bb})$ plane.



HH → bbγγ

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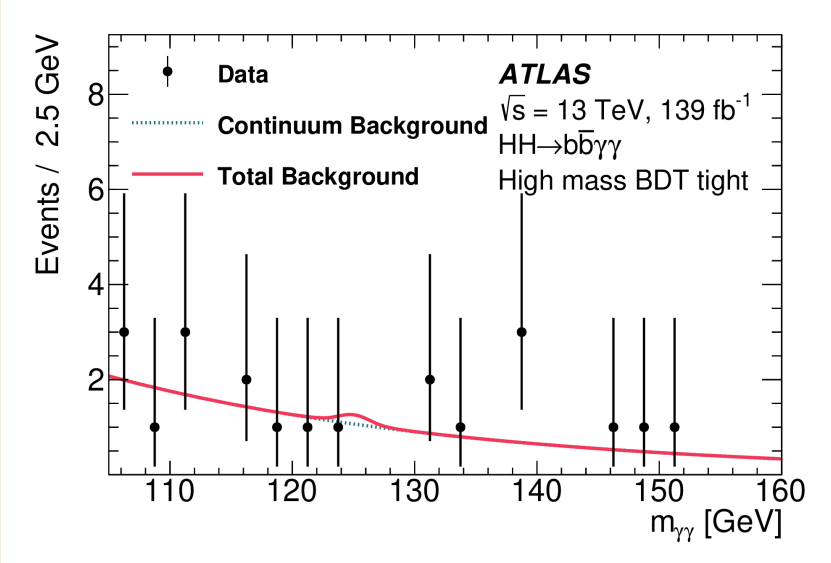
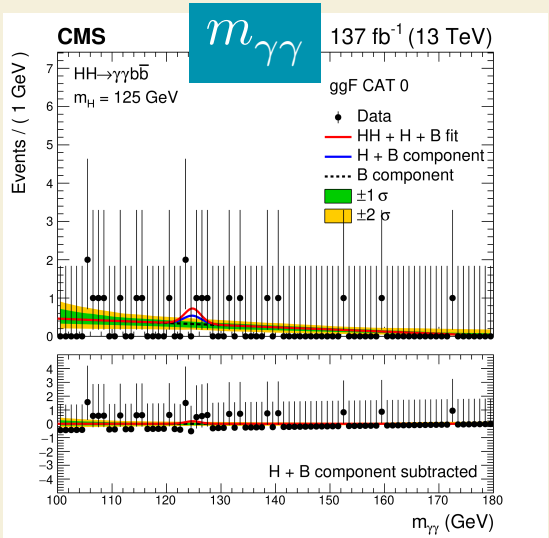
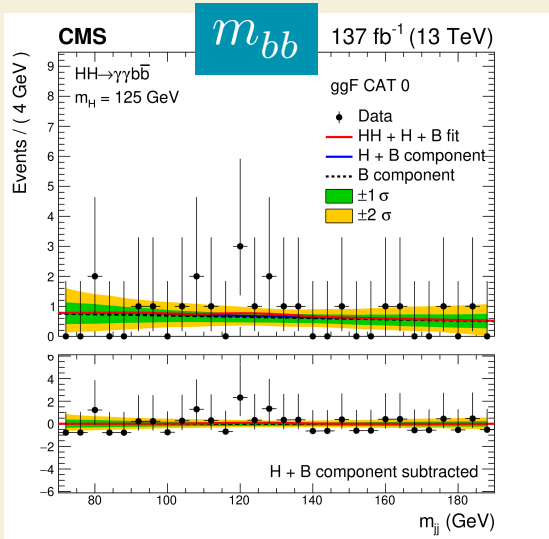
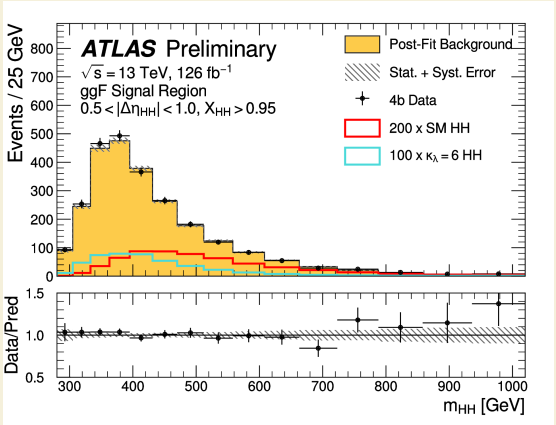
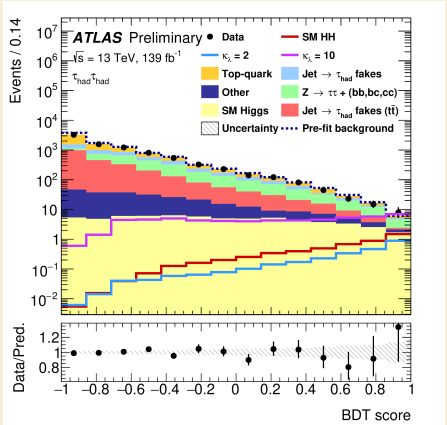


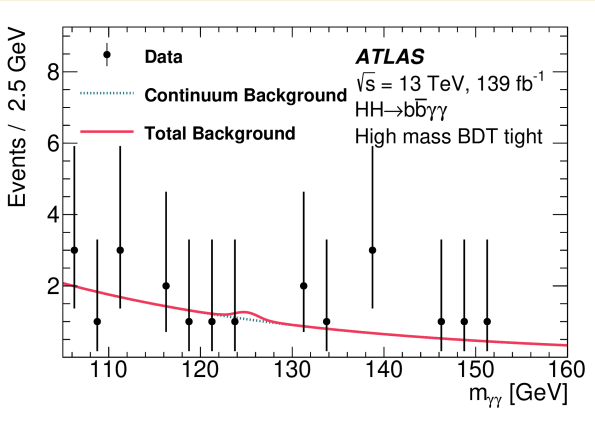




Putting it all together...

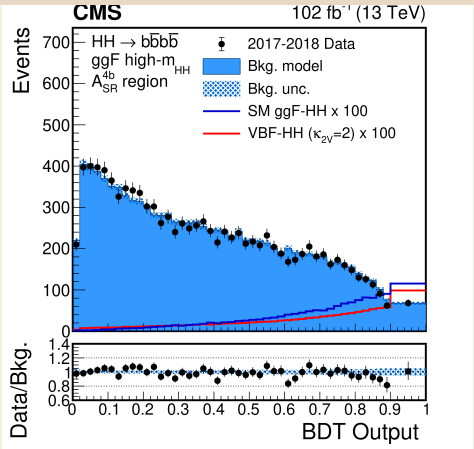


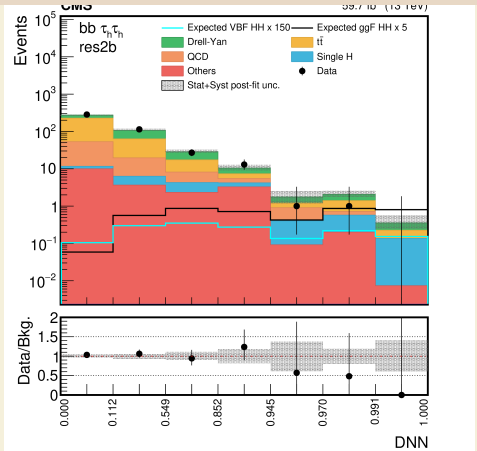


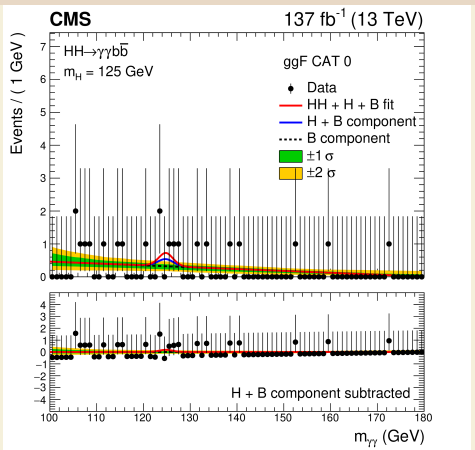


No golden HH search channel: combinations are key. [HOT OFF THE PRESS!]

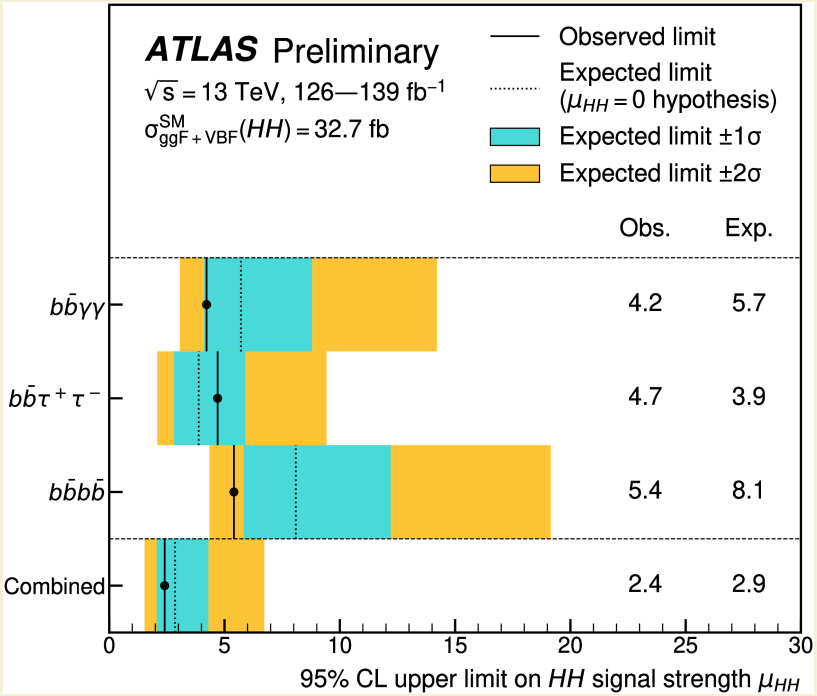
- ATLAS: ATLAS-CONF-2022-050
- CMS: Nature 607, 60-68 (2022)

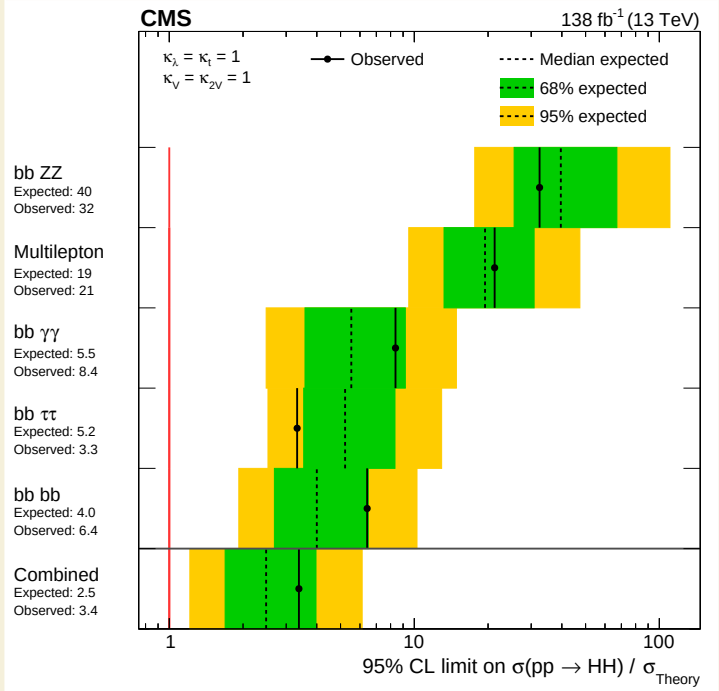






HH combined results: limits on $\sigma^{HH}_{ggF+VBF}$





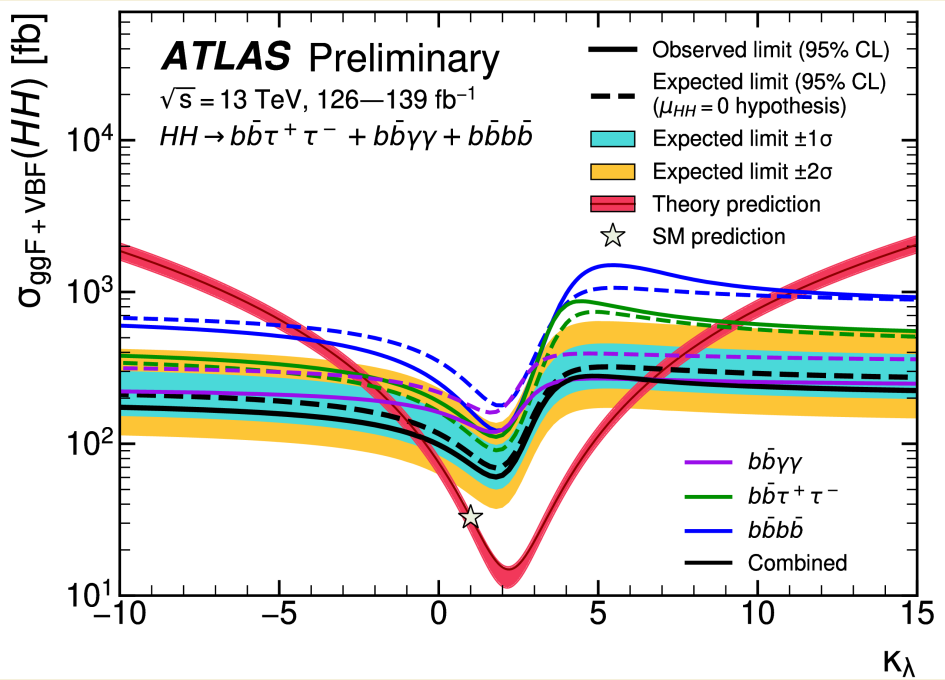
Obs. (exp.) 95% CL combined limit: 2.4 (2.9) × SM prediction.

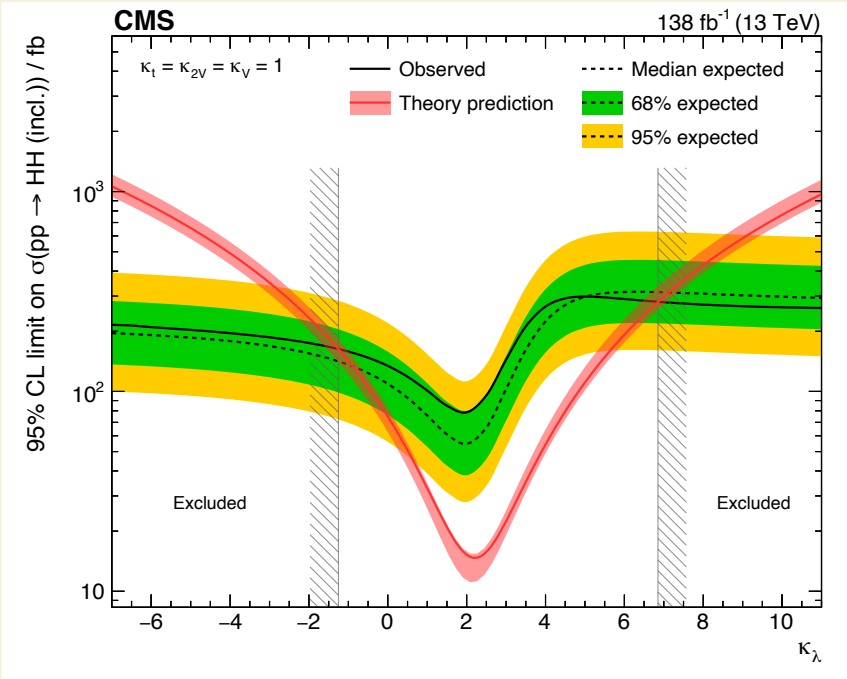
Obs. (exp.) 95% CL combined limit: 3.4 (2.5) × SM prediction.

CMS: the individual *bbbb* limit combines resolved and boosted topologies.

HH combined results: limits on κ_λ

ATLAS and CMS 95% CL limits on $\sigma^{\mathrm{HH}}_{\mathrm{ggF+VBF}}$ vs κ_λ (all other κ's at 1):

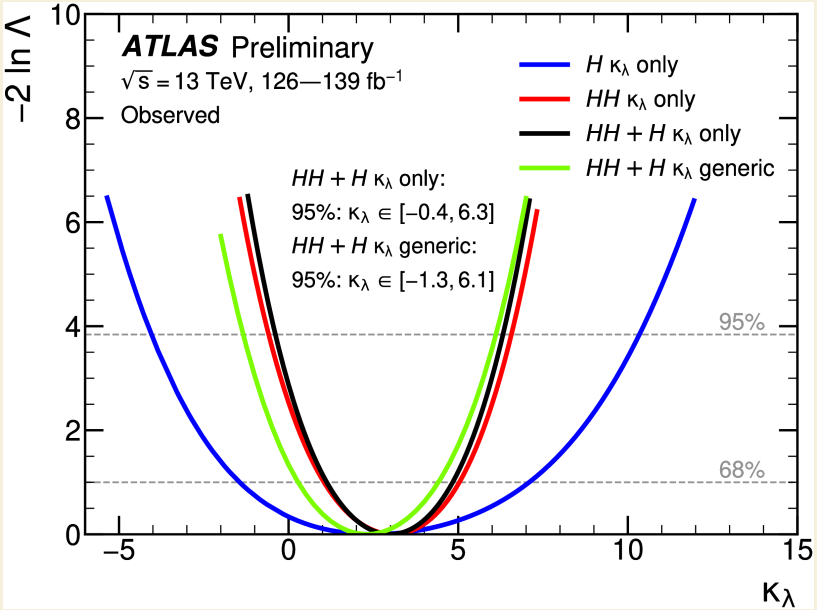


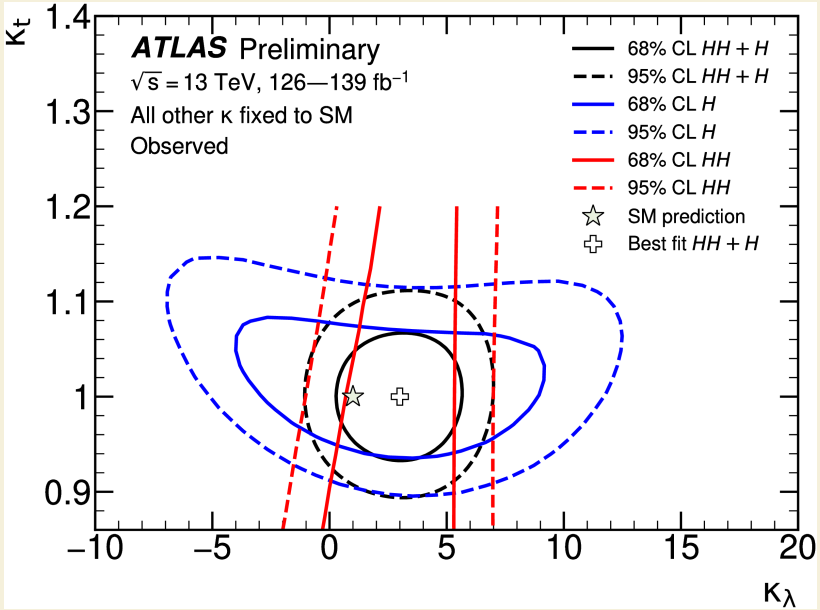


HH+H: constraints on κ_λ [ATLAS]

Constraints on κ_λ via a scan of the negative-logarithm of the profile likelihood, for various fit configurations:

- HH searches only, single-H measurements only, or their combinations.





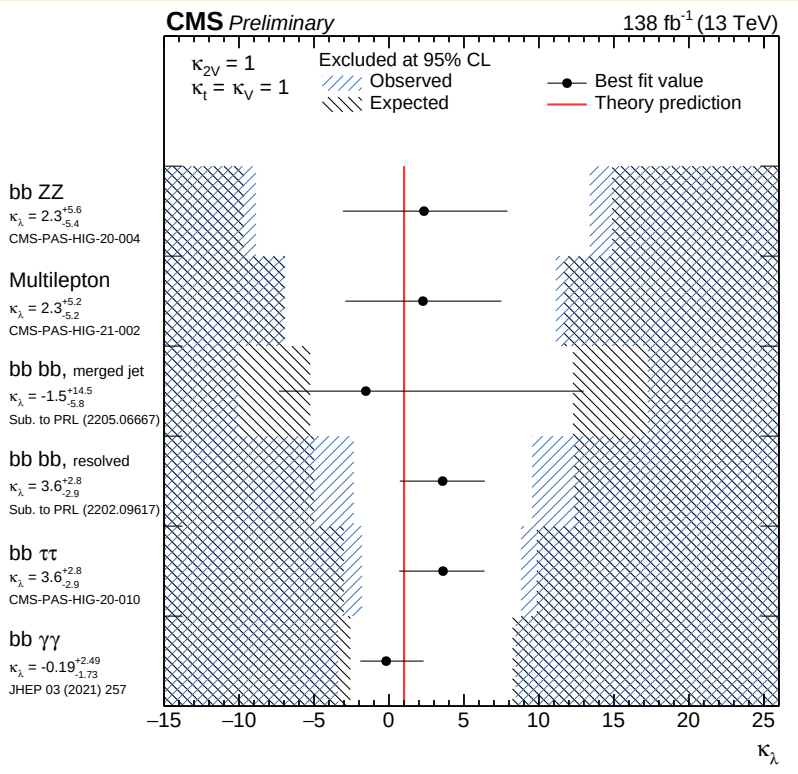
Summary of ATLAS HH+H combined results:

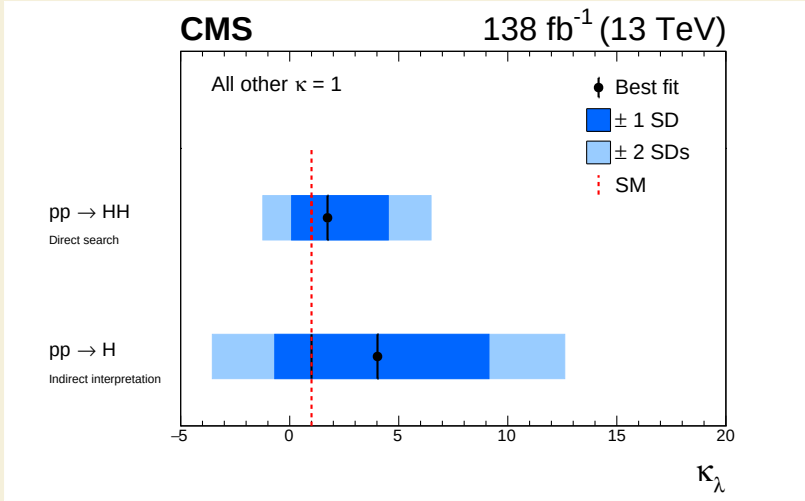
- Profile κ_λ only: $-0.4 < \kappa_\lambda < 6.3$ (95% CL).
- Profile κ_λ, κ_t, κ_V, κ_b, κ_τ: $-1.3 < \kappa_\lambda < 6.1$ (95% CL).

HH+H: constraints on κ_λ [CMS]

Constraints on κ_λ via a scan of the negative-logarithm of the profile likelihood, for various fit configurations:

- HH searches only, single-H measurements only.





Summary of CMS single-H and HH results (profile κ_λ only):

- Single-H: $-3.6 < \kappa_\lambda < 12.6$ (95% CL).
- HH: $-1.3 < \kappa_\lambda < 6.4$ (95% CL).

Summary

- Elusive non-resonant pairs of Higgs bosons are the prime experimental signature of the Higgs boson self-interaction.
- Electroweak corrections in single-H processes provide additional sensitivity to the Higgs boson self-interaction.
- ATLAS+CMS have published impressive results with LHC Run 2 data:
  - σ_{HH} above 2.4–3.4 times the SM predictions is excluded at 95% CL;
  - $\kappa_\lambda \in [-0.4; +6.3]$ at 95% CL (ATLAS).
  - $\kappa_\lambda \in [-1.3; +6.4]$ at 95% CL (CMS).
- We are all eager to analyse Run 3 data to further probe HH events.
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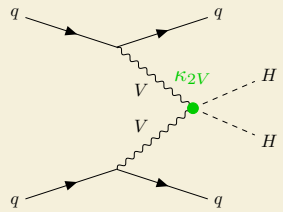
Many tHHanks for your attention!!

To my Mum, in loving memory.

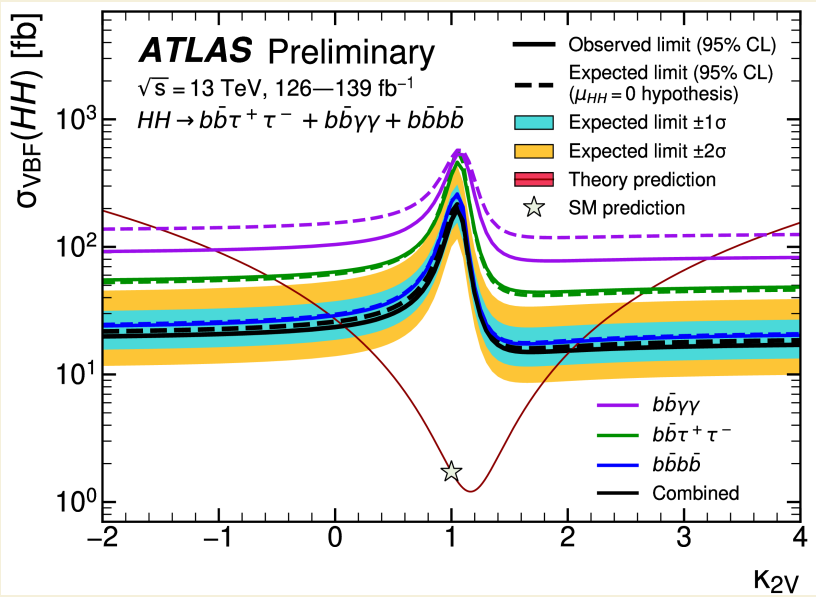
Back-up slides

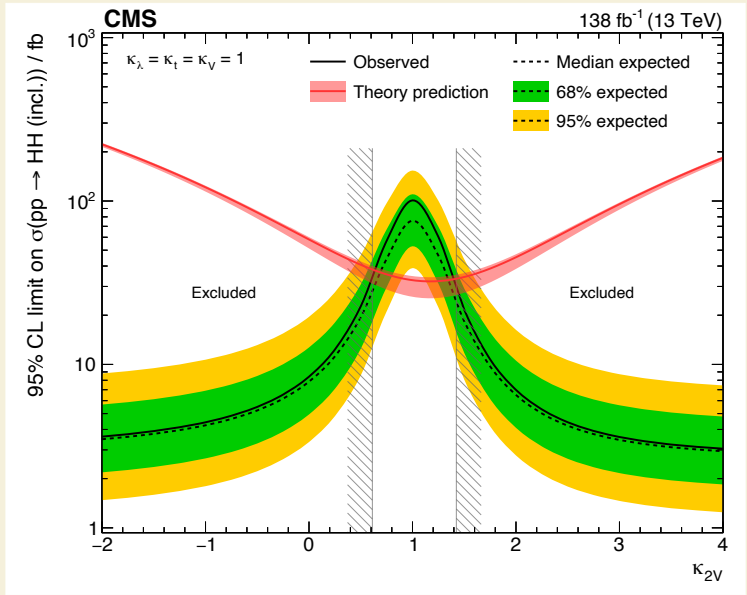
Beyond the Higgs boson self-interaction

Searches for VBF Higgs boson pair production allow to uniquely probe the VVHH quartic coupling.



ATLAS and CMS 95% CL limits on HH cross-sections as a function of κ_{2V} (all other κ's at their SM values):





κ_{2V} values outside [0.1; 2.0] are excluded at 95% CL.

κ_{2V} values outside [0.7; 1.4] are excluded at 95% CL.

Beyond the Higgs boson self-interaction

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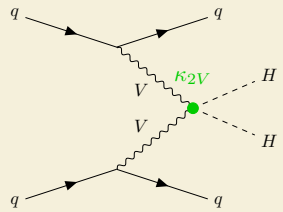

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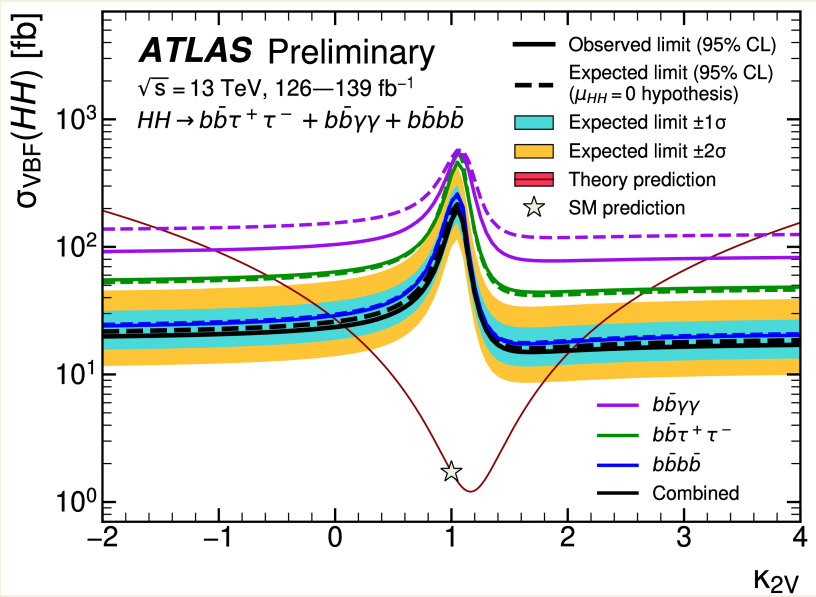
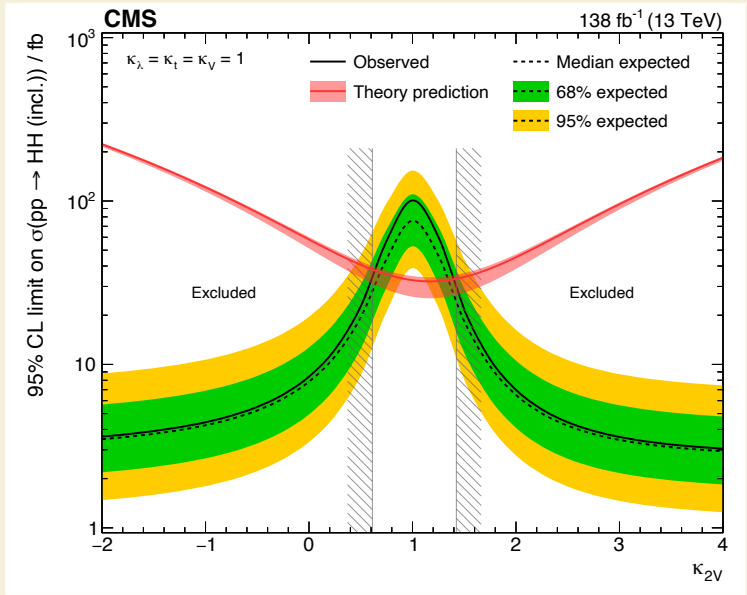
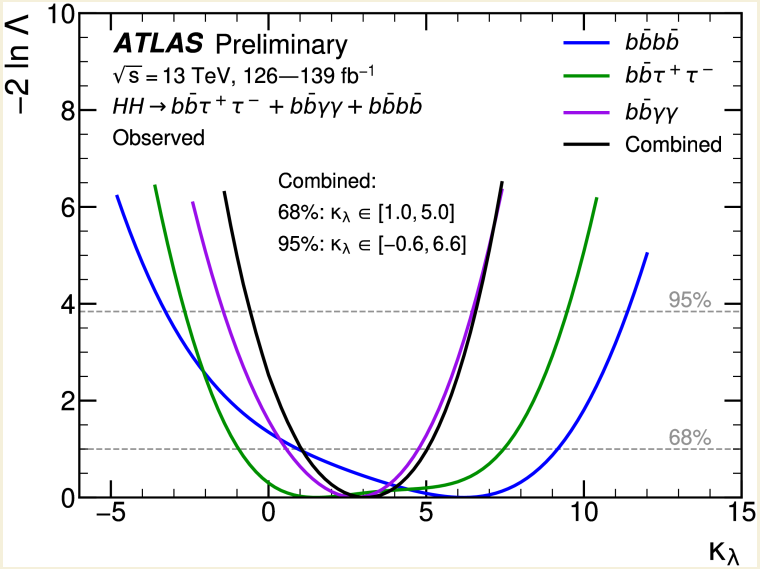
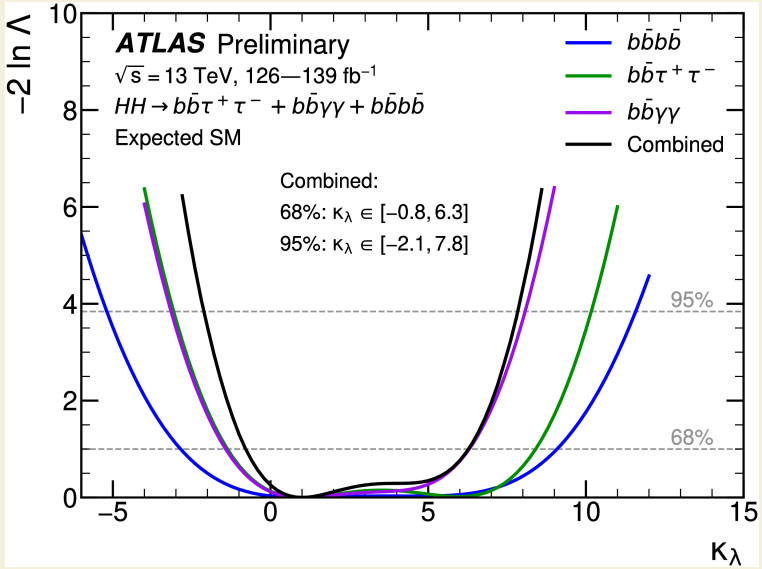




CMS excludes the $\kappa_{2V} = 0$ hypothesis with a significance of 6.6σ!

Additional plots – ATLAS





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	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
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	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Additional plot – CMS