Twice the Higgs, twice the fun!

a.k.a: The Higgs self-interaction at the LHC (and beyond)

Arnaud Ferrari (Uppsala University, Sweden)

Nikhef, Amsterdam, 25/10/2024

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- Higgs boson pairs: production and decay modes
- ATLAS results: individual HH searches
- Combined HH searches in ATLAS and comparison with CMS
- Beyond the Higgs self-interaction
- Beyond the LHC Run 2
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Only picoseconds after the Big Bang, the Universe experienced a phase transition into a state of lower energy, in which nearly all fundamental particles became massive by interacting with the *Higgs field*.

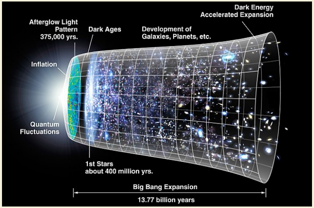

Image: NASA/WMAP Science Team

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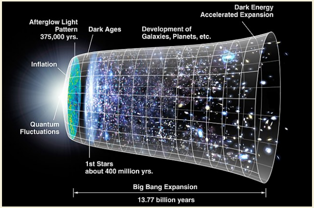
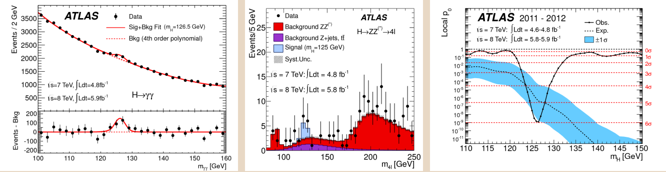


Image: NASA/WMAP Science Team

First came the Higgs-dependence Day...

4 July 2012: the ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC) announced the discovery of a spin-0 particle with a mass of about 125 GeV.



Images: ATLAS Collaboration, Phys. Lett. B 716 (2012) 1.

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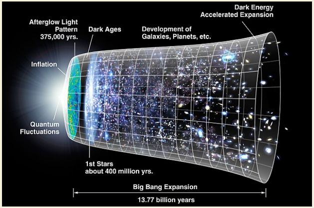


Image: NASA/WMAP Science Team

Then came the Nobel prize.

8 October 2013: the Nobel prize in physics was awarded to Englert and Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's LHC".

The Higgs sector in the Standard Model

The Standard Model (SM) has been vastly explored and confirmed by the LHC experiments. At its core lies a scalar sector, responsible for electroweak symmetry breaking and mass generation.

Since the Higgs boson discovery in 2012, the scalar sector has been greatly studied by ATLAS and CMS.

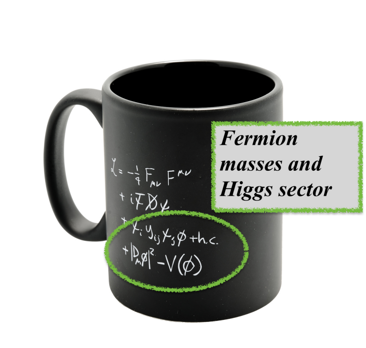
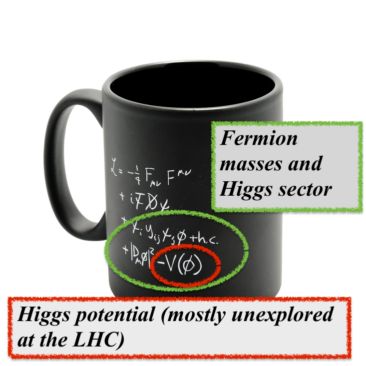


Image: https://visit.cern/shop

The Standard Model (SM) has been vastly explored and confirmed by the LHC experiments. At its core lies a scalar sector, responsible for electroweak symmetry breaking and mass generation.

Since the Higgs boson discovery in 2012, the scalar sector has been greatly studied by ATLAS and CMS. All of it? No, the indomitable Higgs potential has not yet been conquered by the LHC physicists.



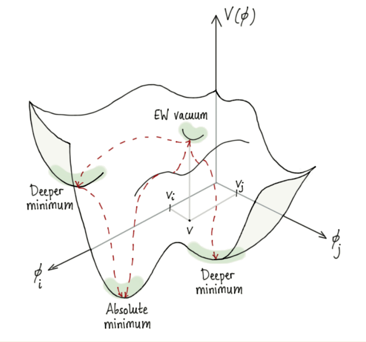


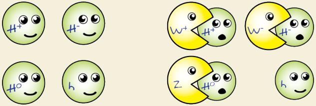
Image by Kateryna Radchenko Serdula

The Higgs sector in the Standard Model

In the mathematical framework of the SM, the Higgs field is a complex Higgs doublet ϕ and the Higgs sector is described by:

$$\mathcal{L} = |D_\mu \phi|^2 - V(\phi).$$

The first term describes the coupling of ϕ to gauge bosons:



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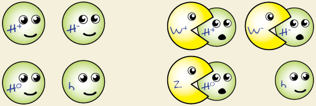
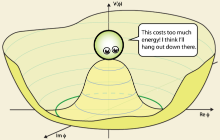


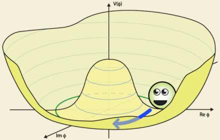
The second term, $V(\phi)$, is the Higgs potential. In its *minimal* form, it is:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4.$$

If μ^2 and λ are both positive, the minimum of the Higgs potential lies at a vacuum expectation value $v \neq 0$.



Universe = a hot soup of massless stuff

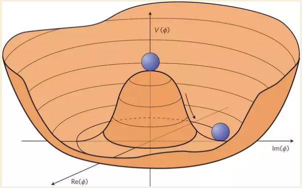


Universe = a cool place to live in

All sketches from www.quantumdiaries.org

The ultimate probe of the Higgs sector

The shape of the Higgs potential, which is controlled by the parameters μ^2 and λ, completely determines the properties of the Higgs sector.

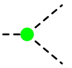


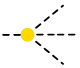
$$< \phi_0 > = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = \sqrt{\mu^2/\lambda}.$$

$$\text{SM: } V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \overset{\phi \to v+H}{\supset} \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

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

self-interaction terms (never observed)

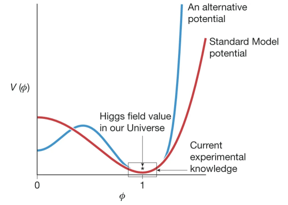




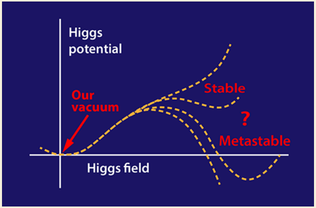
$\Longrightarrow$ To fully test the Higgs sector, one must observe the self-interaction term(s) and measure the Higgs boson self-coupling λ via Higgs boson pair production.

Why does it matter?

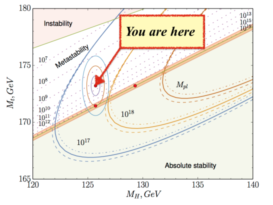
- Experimental data only provides information on the position of the minimum of the Higgs potential, in which our Universe lives.
- The (unconstrained) shape of the Higgs potential has implications beyond the mass-generation mechanism, in particular on the vacuum state of the Universe.
- In the absence of new physics that may affect the Higgs sector, there is a (borderline) possibility that our Universe is in a metastable state, i.e. a false vacuum.



Nature 607 (2022) 41



APS/Alan Stonebraker



Phys. Rev. Lett. 115 (2015) 201802

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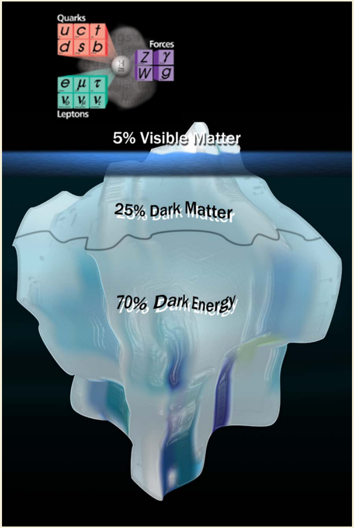
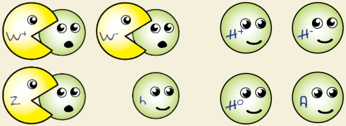


Sketches adapted from www.quantumdiaries.com

There are already many (indirect) hints of new physics beyond the SM! And its Higgs sector has serious short-comings:

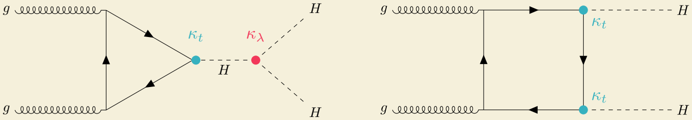
- Why so many orders of magnitude across the fermion couplings to the Higgs field?
- m_H should be driven to a very large scale by quantum loop corrections, why such a remarkably precise cancellation against the bare mass?
- Why should the Higgs potential have a minimal form, and could there be an extended Higgs sector?



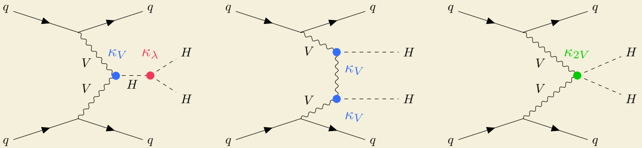
Higgs boson pair production at the LHC

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 $\pm\, 3\%(\mathrm{PDF} + \alpha_s)\,^{+6\%}_{-23\%}(\mathrm{scale} + m_t)$ [13 TeV].

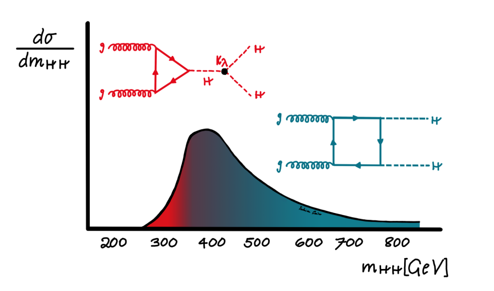


Vector-boson fusion: $\sigma^{\mathrm{SM}}_{\mathrm{VBF}} \simeq 1.7$ fb $\pm\, 2.1\%(\mathrm{PDF} + \alpha_s)\,^{+0.03\%}_{-0.04\%}(\mathrm{scale})$ [13 TeV].

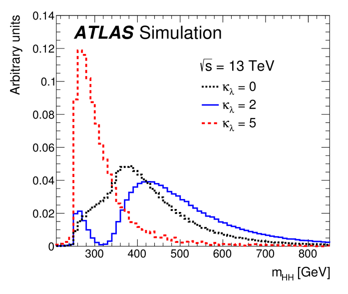


Other production modes (e.g. VHH, ttHH) have even smaller cross-sections.

- HH events from the self-interaction diagrams are soft.
  $\Rightarrow$ Challenge for triggers and detector object reconstruction/identification!
- $\kappa_\lambda \neq 1$ modifies the cross-section and kinematical properties of HH pairs.
  $\Rightarrow$ Allows to disentangle κ_λ hypotheses (it also holds for other couplings, e.g. κ_{2V} in VBF).



ATLAS Physics Briefing: Twice the Higgs, twice the challenge



Phys. Lett. B 800 (2020) 135103

HH decays and search channels

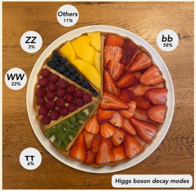


Image: @PhysicsCakes (Twitter)

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

- Not a single "golden" channel;

	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

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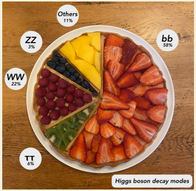

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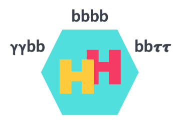
- Not a single "golden" channel;
- Three silver bullets!



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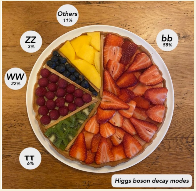

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Multitude of Higgs boson decays ⇒ $\mathcal{O}(\text{multitude}^2)$ of HH search channels, each with specific experimental challenges and sensitivity reach.

- Not a single "golden" channel;
- Three silver bullets!
- Additional channels with sizeable sensitivity:
  - $2b + 2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$,
  - multi-lepton/photon final states.

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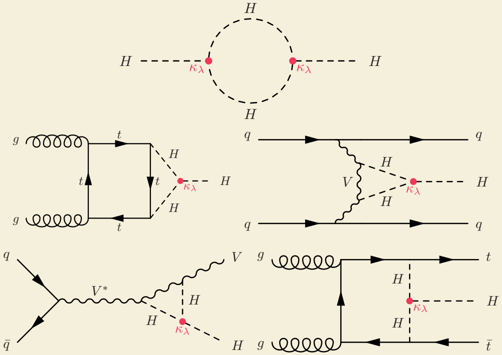
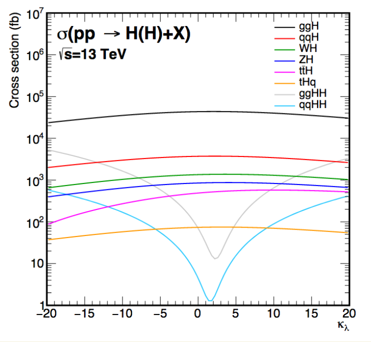
Image by Katharine Leney

Self-interaction and single Higgs bosons

- 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

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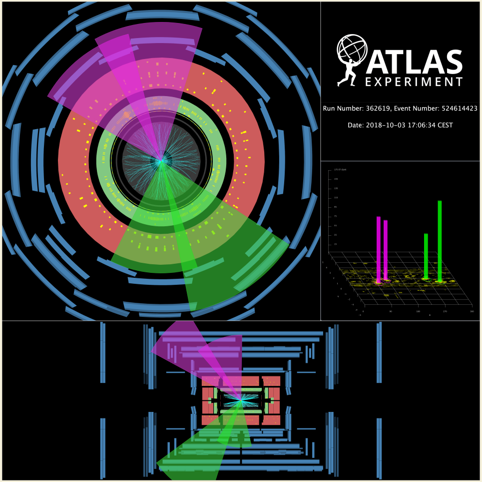
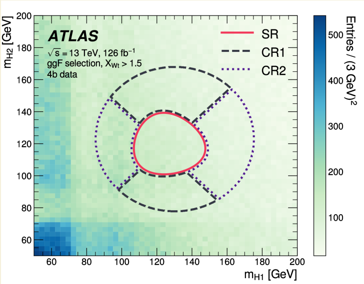
HH → bbbb

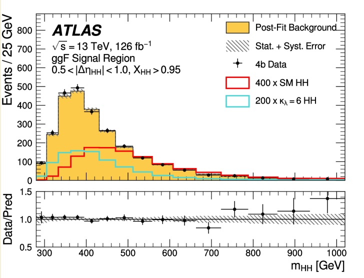


- Highest branching ratio... but large multi-jet background!
- Mostly probes large m_{HH} ⇒ sensitivity to HH events with large p_T^H.
- Phys. Rev. D 108 (2023) 052003 (ggF and VBF resolved topologies)
- Phys. Lett. B 858 (2024) 139007 (VBF boosted topologies)

HH → bbbb – resolved topologies

- Trigger events with ≥2 b-jets.
- SR = two b-jet pairs compatible with a Higgs boson (pairing based on angular distances).
- Data-driven background model based on SR event re-weighting:
  - 2b → 4b re-weighting function derived with machine-learning techniques in CRs around the SR.
- ggF- and VBF-like event categories based on forward jets and kinematic properties of HH.
- Fit m_{HH} in all categories.





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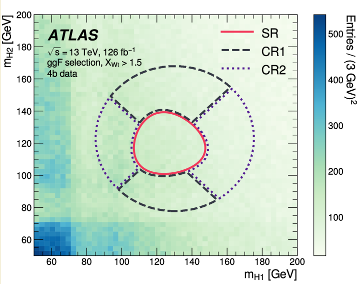
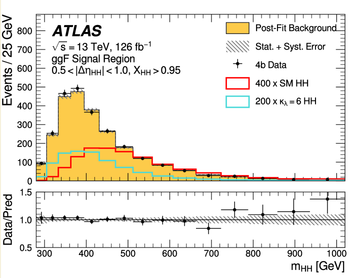
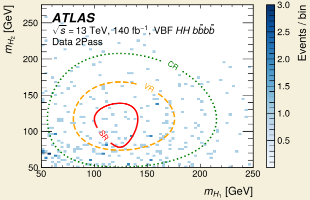
Obs. (exp.) 95% CL upper limit on $\sigma_{\mathrm{HH}}^{\mathrm{ggF+VBF}} = 5.4\ (8.1) \times$ SM prediction.

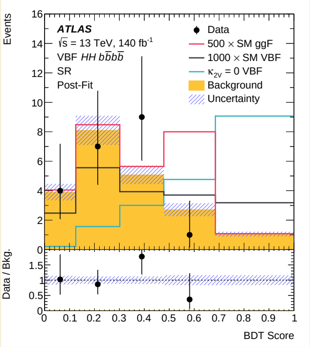




HH → bbbb – VBF boosted topologies

- Trigger events with a large-R jet.
- SR = two 2b-tagged large-R jets compatible with a Higgs boson + two VBF jets.
- Data-driven background model based on SR event re-weighting:
  - $1J_{Hbb} \rightarrow 2J_{Hbb}$ re-normalisation derived in the CR around the SR.
- Fit a BDT trained with $\kappa_{2V} = 0$ in the SR.
- Combination with ggF and VBF categories of the resolved HH → bbbb search.





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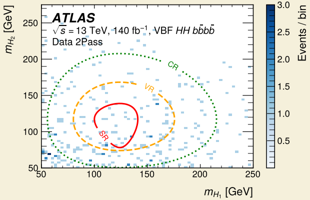
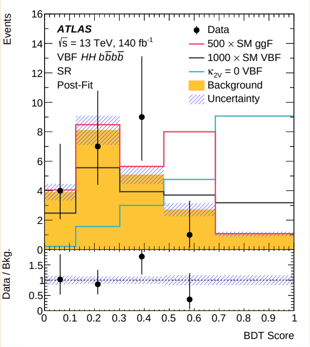
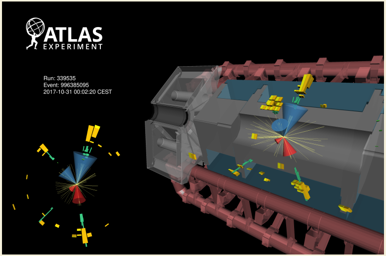
Obs. (exp.) exclusion of $\kappa_{2V} = 0$ with 3.4σ (2.9σ).





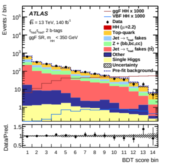
HH $\to$ bb$\tau\tau$

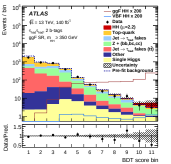


- Intermediate branching ratio but clean final state with moderate backgrounds!
- Sensitive to a broad range of κ_λ values.
- Phys. Rev. D 110 (2024) 032012

- bb$\tau_h\tau_\ell$ and bb$\tau_h\tau_h$ final states + further event categories:
  - 3 regions based on the trigger strategy (1 $\tau_h\tau_h$ & 2 $\tau_h\tau_\ell$);
  - 1 VBF-like & 2 ggF-like (low/high-m_{HH}) sub-categories per region;
  - 1 CR to constrain the Z+bb/cc background.
- 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: BDT classifiers in the 9 SRs, $m_{\ell\ell}$ in the CR.

HH → bbττ


ATLAS
√s = 13 TeV, 140 fb-1
τhadτhad, 2 b-tags
ggF SR, mHH < 350 GeV
ggF HH x 1000
VBF HH x 1000
Data
HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Jet → τhad fakes (tt̄)
Other
Single Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin


ATLAS
√s = 13 TeV, 140 fb-1
τhadτhad, 2 b-tags
ggF SR, mHH ≥ 350 GeV
ggF HH x 200
VBF HH x 200
Data
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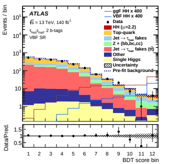
ATLAS
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ggF HH x 400
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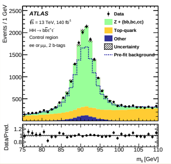
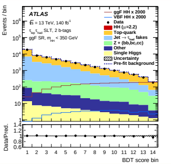
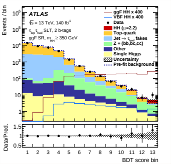
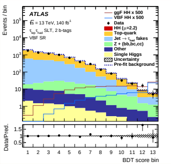
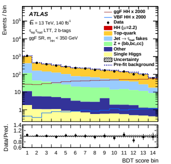
HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Jet → τhad fakes (tt̄)
Other
Single Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin

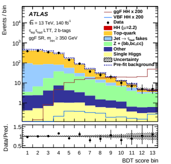

ATLAS
√s = 13 TeV, 140 fb-1
HH → bb̄τ+τ-
Control region
ee or μμ, 2 b-tags
Data
Z + (bb,bc,cc)
Top-quark
Other
Uncertainty
Pre-fit background
Events / 1 GeV
Data/Pred.
mll [GeV]

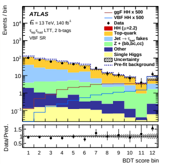

ATLAS
√s = 13 TeV, 140 fb-1
τlepτhad SLT, 2 b-tags
ggF SR, mHH < 350 GeV
ggF HH x 2000
VBF HH x 2000
Data
HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Other
Single Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin


ATLAS
√s = 13 TeV, 140 fb-1
τlepτhad SLT, 2 b-tags
ggF SR, mHH ≥ 350 GeV
ggF HH x 400
VBF HH x 400
Data
HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Other
Single Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin

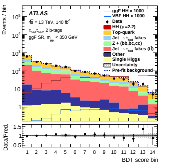

ATLAS
√s = 13 TeV, 140 fb-1
τlepτhad SLT, 2 b-tags
VBF SR
ggF HH x 500
VBF HH x 500
Data
HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Other
Single Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin

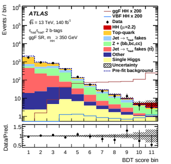

ATLAS
√s = 13 TeV, 140 fb-1
τlepτhad LTT, 2 b-tags
ggF SR, mHH < 350 GeV
ggF HH x 2000
VBF HH x 2000
Data
HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Other
Single Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin

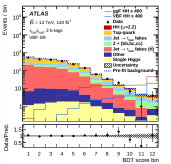

ATLAS
√s = 13 TeV, 140 fb-1
τlepτhad LTT, 2 b-tags
ggF SR, mHH ≥ 350 GeV
ggF HH x 200
VBF HH x 200
Data
HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Other
Single Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin

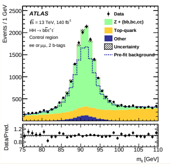

ATLAS
√s = 13 TeV, 140 fb-1
τlepτhad LTT, 2 b-tags
VBF SR
ggF HH x 500
VBF HH x 500
Data
HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Other
Single Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin

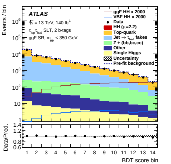
HH → bb$\tau\tau$

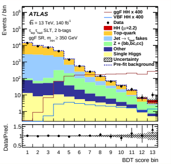


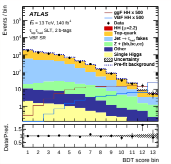




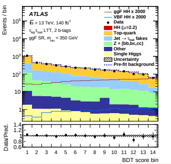


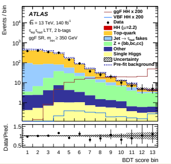


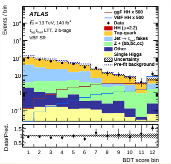


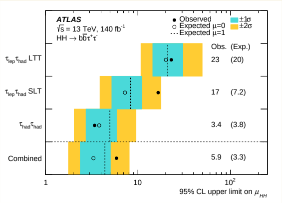


Obs. (exp.) 95% CL upper limit on $\sigma^{\mathrm{ggF+VBF}}_{\mathrm{HH}} = 5.9\ (3.3) \times$ SM prediction.

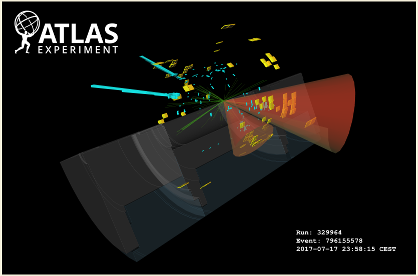






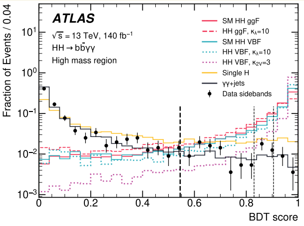


HH → $bb\gamma\gamma$



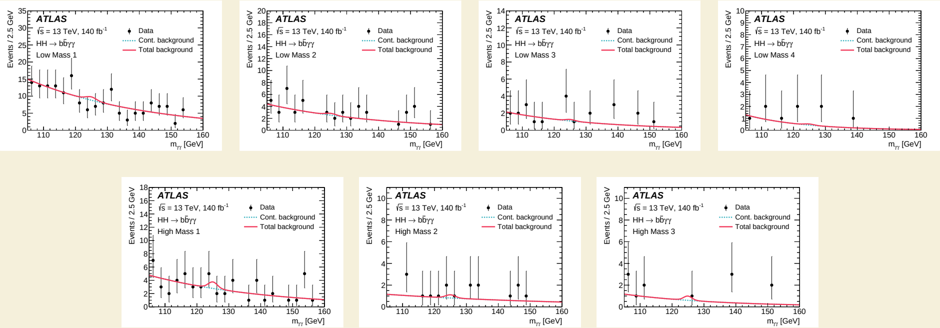
- Tiny branching ratio but very clean signature: excellent $m_{\gamma\gamma}$ resolution and small backgrounds!
- Enhanced sensitivity at low m_{HH}, hence to the Higgs self-interaction.
- JHEP 01 (2024) 066

- Di-photon trigger and event selection + 2 b-jets.
- 7 event categories based on:
  - $m^*_{bb\gamma\gamma}$ (low vs high);
  - classification BDT output ranges, trained on different signal hypotheses.
- No dedicated VBF category but the mass and $\Delta\eta$ of VBF-tagged jets are inputs to the BDTs.



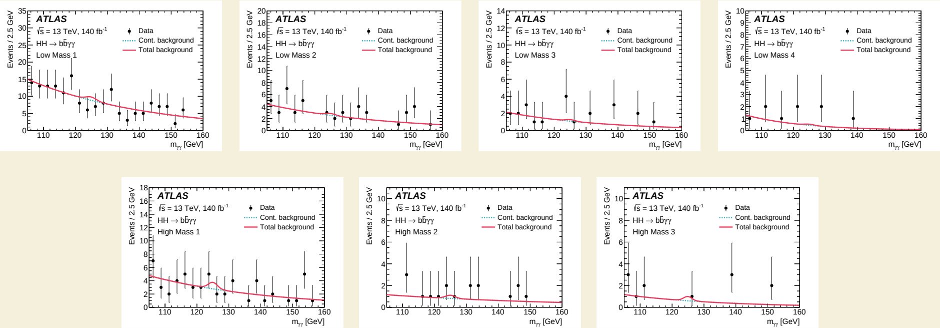
HH → bbγγ

- Signal and backgrounds:
  - HH and single-H shapes from simulation;
  - continuum background shape from data.
- Signal extraction through parametric fits of $m_{\gamma\gamma}$.



HH $\rightarrow$ bb$\gamma\gamma$

- Signal and backgrounds:
  - HH and single-H shapes from simulation;
  - continuum background shape from data.
- Signal extraction through parametric fits of $m_{\gamma\gamma}$.

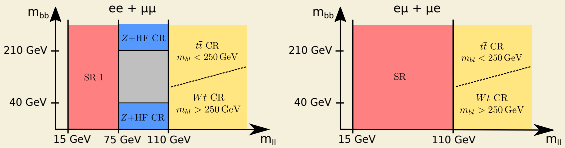


Obs. (exp.) 95% CL upper limit on $\sigma_{\mathrm{HH}}^{\mathrm{ggF+VBF}} = 4.0\ (5.0) \times$ SM prediction.

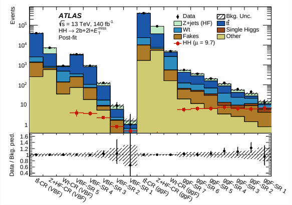
HH $\rightarrow 2b + 2\ell + E_T^{miss}$

- Captures HH di-lepton decays to bbWW, bbZZ and bb$\tau_\ell \tau_\ell$.
- Large $t\bar{t}$ background for ggF HH but only small backgrounds in VBF topologies.
- JHEP 02 (2024) 037

- 2 e/μ and 2 b-jets, no requirement on E_T^{miss};
- SRs and CRs based on $m_{\ell\ell}$ and m_{bb};
- VBF and ggF categories.



Fit of highest-score BDT (DNN) bins and CR event yields in the VBF (ggF) categories.



HH $\rightarrow 2b + 2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$

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- JHEP 02 (2024) 037

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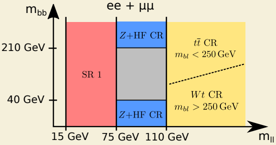
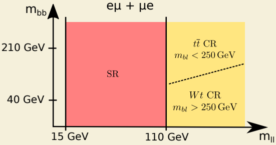
- SRs and CRs based on $m_{\ell\ell}$ and m_{bb};
- VBF and ggF categories.





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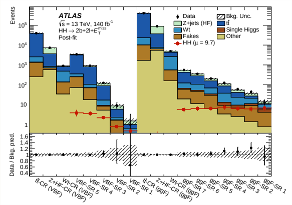
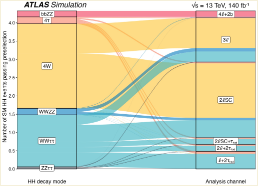


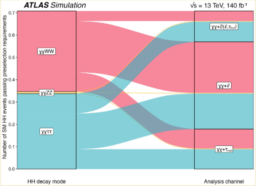
Obs. (exp.) 95% CL upper limit on $\sigma_{\mathrm{HH}}^{\mathrm{ggF+VBF}} = 9.7\ (16.2) \times$ SM prediction.

Multi-lepton HH decays

- Captures HH decays to bbZZ, 4V, VV$\tau\tau$, 4τ, VV$\gamma\gamma$ and $\gamma\gamma\tau\tau$.
- Multi-lepton final states have small associated backgrounds.
- JHEP 08 (2024) 164

- Event categories based on N_γ, N_{τ_h} and N_ℓ;
- Signal = ggF+VBF HH in all categories;
- Prompt leptons and true τ_h: simulation with normalisation factors from dedicated CRs;
- Non-prompt and wrong-charge leptons, fake τ_h and non-resonant $\gamma\gamma$ processes: data-informed corrections to simulation.
- Fit of BDT scores (ML) and $m_{\gamma\gamma}$ ($\gamma\gamma$+ML).





Multi-lepton HH decays

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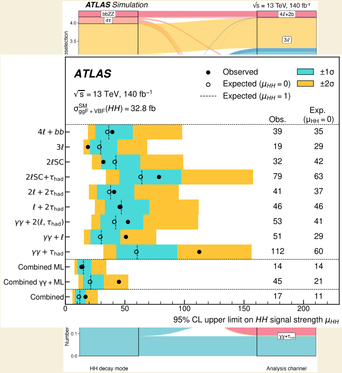
- JHEP 08 (2024) 164

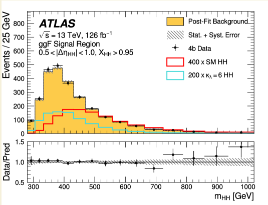
- Event categories based on N_{γ}, N_{τ_h} and N_{ℓ};
- Signal = ggF+VBF HH in all categories;
- Prompt leptons and true τ_h: simulation with normalisation factors from dedicated CRs;
- Non-prompt and wrong-charge leptons, fake τ_h and non-resonant $\gamma\gamma$ processes: data-informed corrections to simulation.
- Fit of BDT scores (ML) and $m_{\gamma\gamma}$ ($\gamma\gamma$+ML).

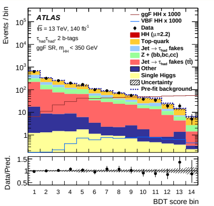
Obs. (exp.) 95% CL upper limit on $\sigma_{\mathrm{HH}}^{\mathrm{ggF+VBF}} = 17\ (11) \times$ SM prediction.

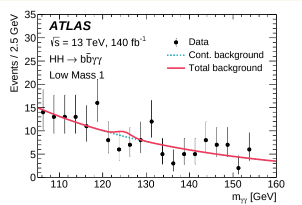


- Introduction
- Higgs boson pairs: production and decay modes
- ATLAS results: individual HH searches
- Combined HH searches in ATLAS and comparison with CMS
- Beyond the Higgs self-interaction
- Beyond the LHC Run 2
- Conclusion

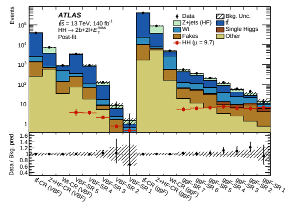
Putting it all together...

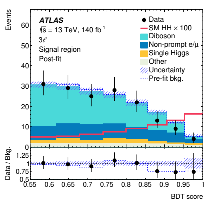


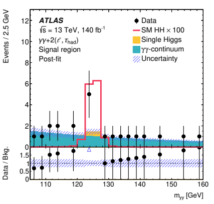




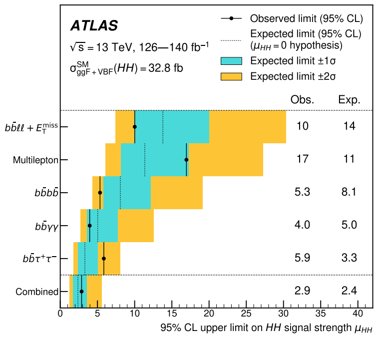
- Phys. Rev. Lett. 133 (2024) 101801





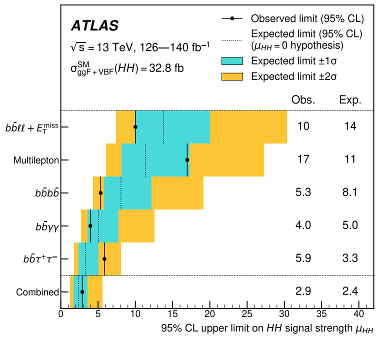


HH combination: limits on $\sigma^{HH}_{ggF+VBF}$



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

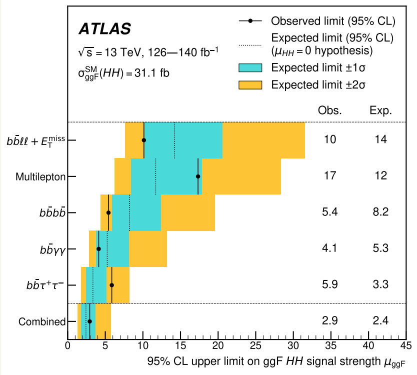
HH combination: limits on $\sigma^{HH}_{ggF+VBF}$

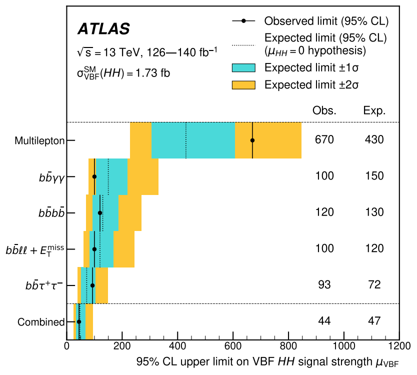


- **Obs. (exp.) 95% CL combined limit: 2.9 (2.4) × SM prediction.**
- Expected limit reduced by 17% w.r.t Phys. Lett. B 843 (2023) 137745 (13% from analysis improvements of the three silver-bullet HH searches, 4% from adding two new channels).
- Slightly different limits for HH $\rightarrow 2b + 2\ell + E_T^{miss}$ due to a different treatment of negative best-fit signal strengths and signal MC statistical uncertainties.

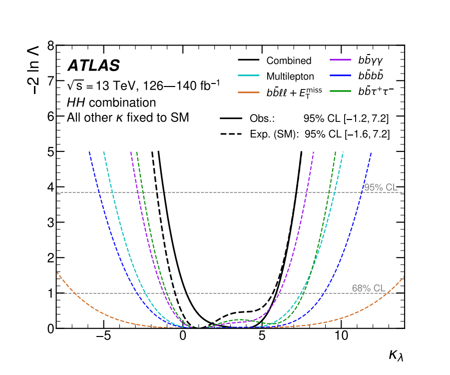
HH combination: limits on σ^{HH}_{ggF} & σ^{HH}_{VBF}

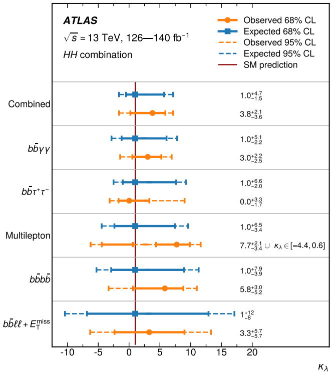
When deriving the limits on ggF (VBF) HH, the VBF (ggF) HH production cross-section is fixed to the SM predicted value.





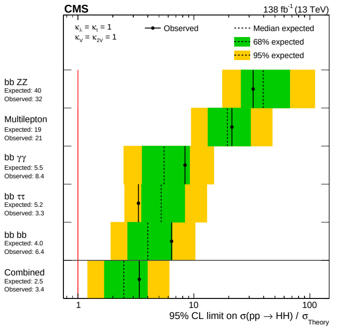
HH combination: constraints on κ_λ

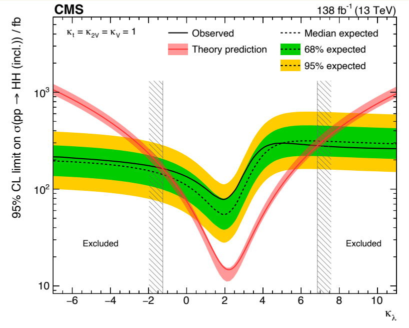




- **Obs. (exp.) 95% CI for κ_λ = [-1.2; 7.2] ([-1.6; 7.2]).**
- When profiling κ_λ, other Higgs boson couplings are set to their SM values.

Comparison with CMS

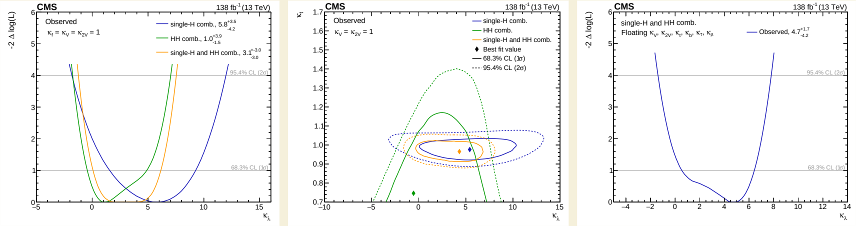




- Results from Nature 607, 60-68 (2022).
- Similar sensitivity to the HH signal strength (exp. 2.5, obs. 3.4) but the leading channel is HH → bbbb, in which CMS has a search for ggF boosted topologies.
- Obs. 95% CI for κ_λ = [-1.24; 6.49].

Comparison with CMS

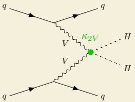
CMS also published constraints on the Higgs self-interaction by combining single- and double-Higgs-boson productions [CMS-HIG-23-006].

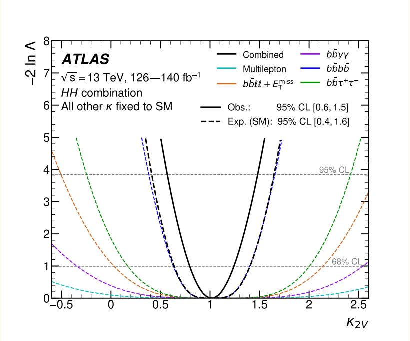


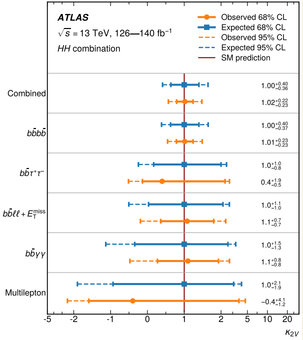
- **Obs. (exp.) 95% CI for κ_λ = [-1.4; 7.8] ([-2.3; 7.8]) when floating all coupling modifiers.**
- ATLAS performed an H+HH combination in Phys. Lett. B 843 (2023) 137745: obs. (exp.) 95% CI for κ_λ = [-1.4; 6.1] ([-2.2; 7.7]).

VVHH quartic coupling

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



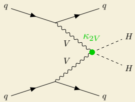


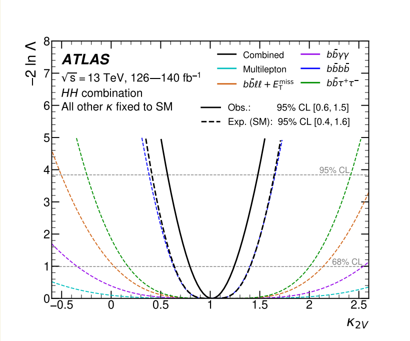


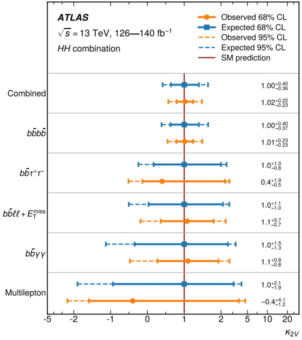
- **Obs. (exp.) 95% CI for κ_{2V} = [0.6; 1.5] ([0.4; 1.6]), dominated by the VBF HH → bbbb search in boosted topologies.**

VVHH quartic coupling

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







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

HH in Effective Field Theories

Effective Field Theories (EFTs) provide a model-independent framework to parametrise deviations from the SM, where higher-dimension operators modify the interactions of the SM particles.

In the Higgs EFT (HEFT) formalism, anomalous couplings are expected to be the dominant source of new physics. Also, the couplings to single Higgs bosons and Higgs boson pairs are separate → most suitable for HH interpretations.

$$\mathscr{L}_{\text{HEFT}} \supset -m_t \left(c_{tth}\frac{h}{v} + c_{tthh}\frac{h^2}{v^2} \right) \bar{t}t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2} \right) G^a_{\mu\nu}G^{a,\,\mu\nu}$$

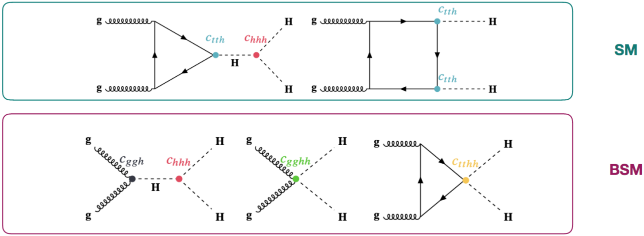


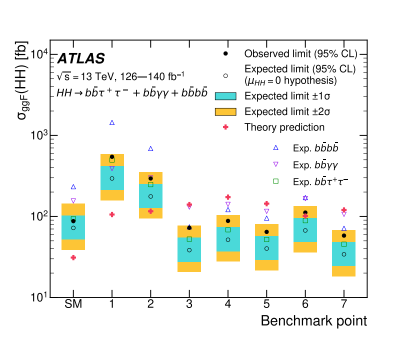
Image by Christina Dimitriadi

HH in Effective Field Theories

ATLAS has performed HEFT re-interpretations of HH searches in the bbbb, bb$\tau\tau$ and bb$\gamma\gamma$ decay channels, as well as their combination.

Seven HEFT benchmarks are used, with representative m_{HH} shape features, from SciPost Phys. Comm. Rep. 2 (2024).

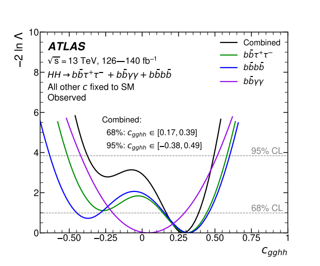
benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6	−0.68	0.90	$-\frac{1}{6}$	$\frac{1}{2}$	0.25
7	−0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$

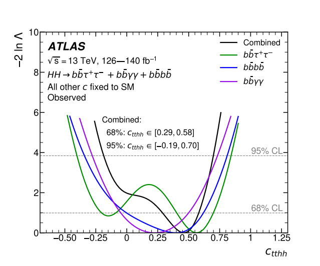


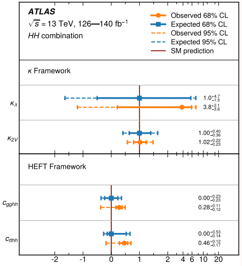
HH in Effective Field Theories

ATLAS has performed HEFT re-interpretations of HH searches in the bbbb, bb$\tau\tau$ and bb$\gamma\gamma$ decay channels, as well as their combination.

Constraints on the c_{gghh} and c_{tthh} anomalous couplings (all others are set to their SM value):



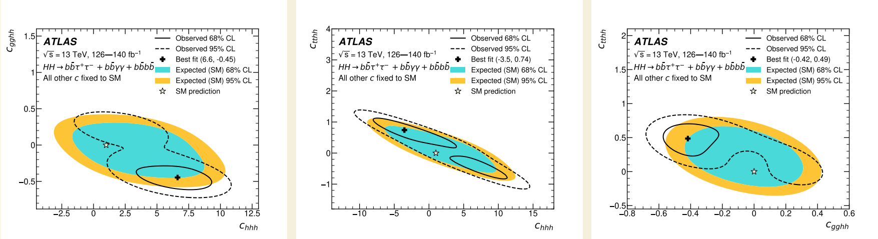




HH in Effective Field Theories

ATLAS has performed HEFT re-interpretations of HH searches in the bbbb, bb$\tau\tau$ and bb$\gamma\gamma$ decay channels, as well as their combination.

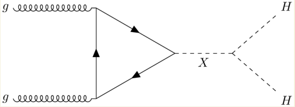
Constraints on the anomalous couplings corresponding to HHx vertices (all others are set to their SM value):



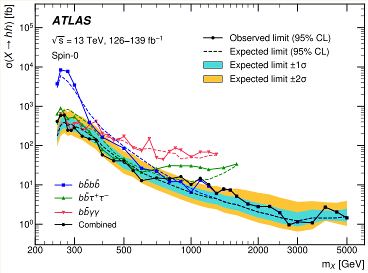
- Tension with the SM, arising mostly from a low-mass excess in the HH $\to$ bbbb search channel.

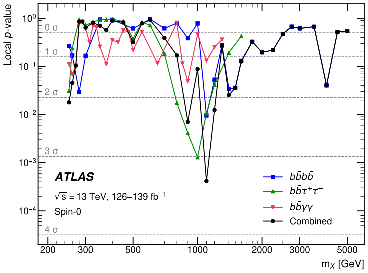
Resonant HH searches

Pairs of Higgs bosons can also be produced via the decay of a hypothetical heavy resonance, and many BSM theories predict the existence of such heavy particles.



Summary of individual and combined resonant HH limits ($bb\gamma\gamma$, $bb\tau\tau$, $bbbb$): the largest excess in the combined limit is found at 1.1 TeV and corresponds to a local (global) significance of 3.2σ (2.1σ).





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Resonant HH searches

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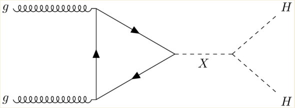
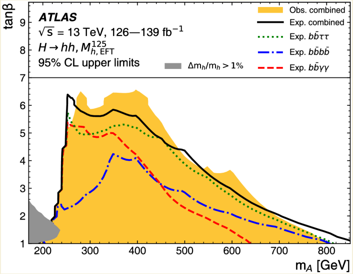
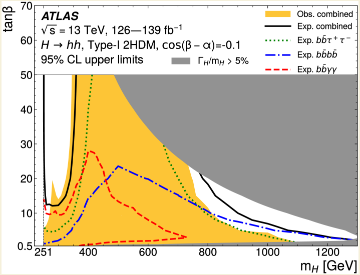


Searches for resonant HH production can then be interpreted in various BSM scenarios with an extended Higgs sector, e.g. in the MSSM (left) and in the type-I 2HDM for $\cos(\beta - \alpha) = -0.1$ (right).





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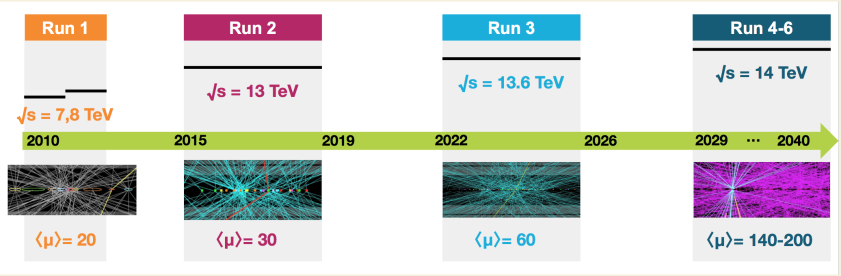
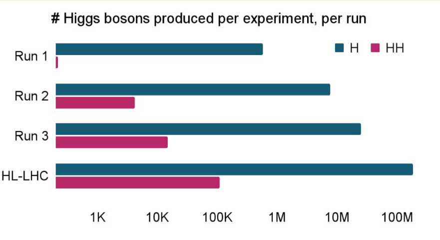
HH prospects at the HL-LHC



A major task of the HL-LHC is to further explore the Higgs sector, in particular establish and measure the Higgs self-interaction.



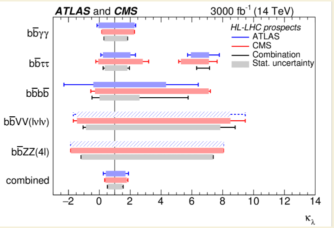
Both images by Elizabeth Brost

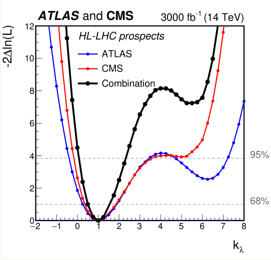
HH prospects at the HL-LHC

HH prospect studies for the European Particle Physics Strategy Update in 2018:

- Combination of five HH channels, many of which were based on the extrapolation of partial ATLAS and CMS Run 2 results.
- The combined significance was $\gtrsim 4$;
- The 68% confidence interval for κ_λ was $[0.52; 1.5]$.

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

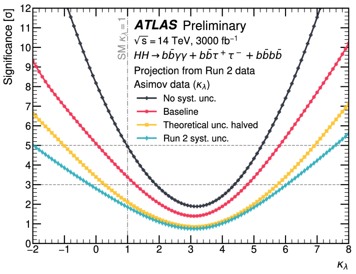


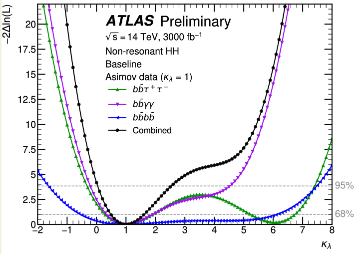


HH prospects at the HL-LHC

Updated HH prospect studies (2022):

- ATLAS updated their projections in the $bb\gamma\gamma + bb\tau\tau + bbbb$ channels, based on the extrapolations of full Run 2 HH search results:
  - 95% CL limit at 0.55 × the SM prediction;
  - Combined significance at 3.4;
  - 68% confidence interval for κ_λ at $[0.5; 1.6]$, comparable to 2018 ATLAS+CMS projections.
  - See ATL-PHYS-PUB-2022-053.
- Projections based on the HH searches performed prior to the Run-2 legacy publications.

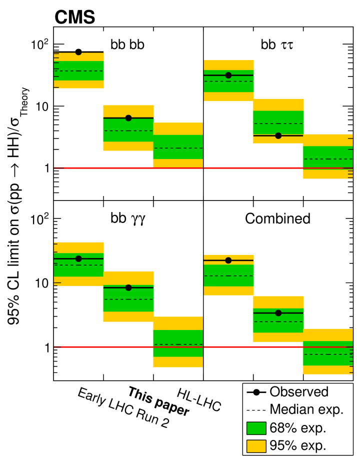




HH prospects at the HL-LHC

Updated HH prospect studies (2022):

- CMS also updated their projections based on their three main HH search channels:
  - 95% CL limit below 0.8 × the SM prediction.



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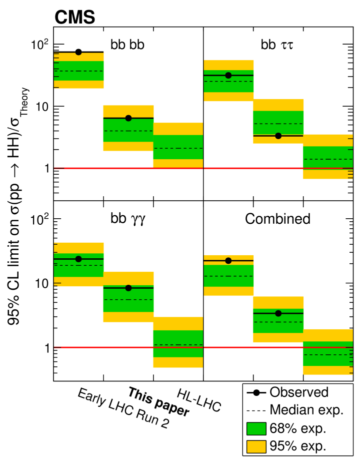
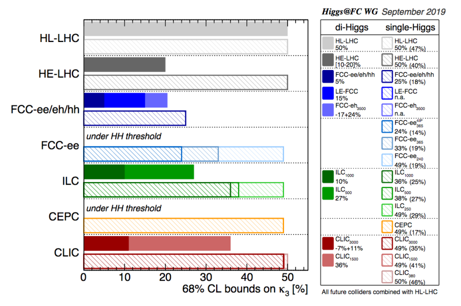


- Despite experimental challenges at the HL-LHC, hard work and creativity in both event reconstruction and analysis techniques have allowed to improve the projected sensitivities since 2018.
- **Imagine what we can do in the next 20 years!!**

HH prospects beyond the HL-LHC

- Direct HH searches:
  - lead the sensitivity to the Higgs self-interaction;
  - but require large $\sqrt{s}$ at e^+e^- colliders;
  - ZHH above $\simeq$ 500 GeV, also VBF HH$\nu_e\bar{\nu}_e$ beyond 1 TeV.
- Indirect but accurate measurement of the self-interaction via single-H production at future e^+e^- colliders once large datasets are available.



The HL-LHC results on the Higgs self-interaction will represent an important legacy for several decades.

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Summary

- Elusive non-resonant pairs of Higgs bosons are the prime experimental signature of the Higgs self-interaction.
- ATLAS has published impressive results with the LHC Run 2 dataset (and so did CMS):
  - σ_{HH} above 2.9 times the SM prediction is excluded at 95% CL;
  - $\kappa_\lambda \in [-1.2; +7.2]$ at 95% CL.
- VBF HH searches uniquely allow to probe the VVHH quartic coupling: the $\kappa_{2V} = 0$ hypothesis has been excluded with a significance above 3σ in ATLAS (and 6.6σ in CMS).
- Novel re-interpretations of HH searches in the framework of Effective Field Theories.
- Resonant production of Higgs boson pairs allows to probe several models with an extended Higgs sector.
- LHC physicists are eagerly analysing the LHC Run-3 dataset to further probe HH events.