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Twice the Higgs, twice the fun!

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

Arnaud Ferrari (Uppsala University, Sweden)

UCLouvain, 16/09/2025

- Introduction
- Higgs boson pairs: production and decay modes
- ATLAS results: individual Run 2 HH searches
- Combined Run 2 HH search results in ATLAS
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Once upon a time in the Universe...

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*.

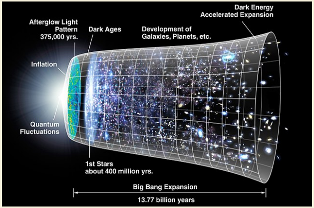

Image: NASA/WMAP Science Team

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About 13.8 billion years later...

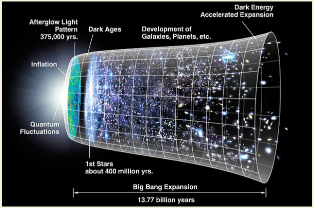
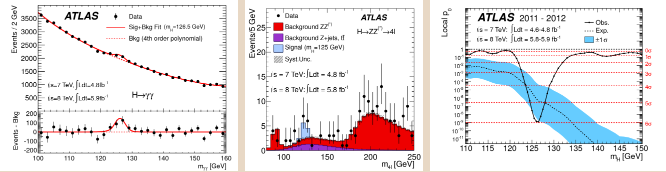


Image: NASA/WMAP Science Team

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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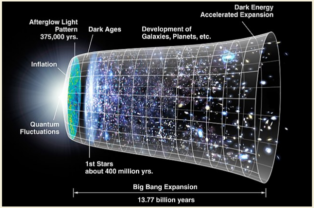

Image: NASA/WMAP Science Team

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.

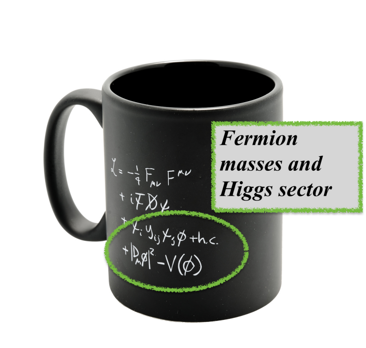

Image: https://visit.cern/shop

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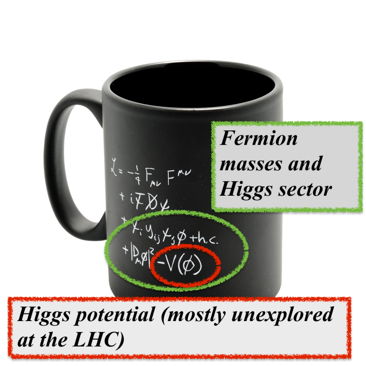
Since the Higgs boson discovery in 2012, the scalar sector has been greatly studied by ATLAS and CMS. All of it? No, the indomitable Higgs potential has not yet been conquered by the LHC physicists.



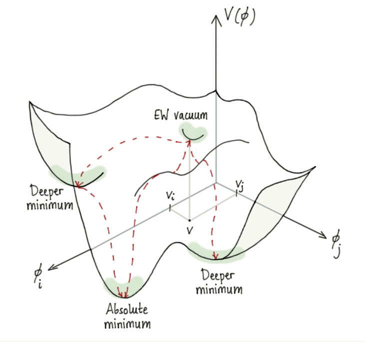


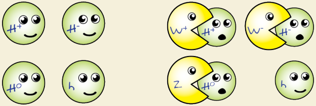
Image by Kateryna Radchenko Serdula

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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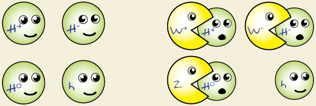
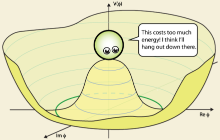


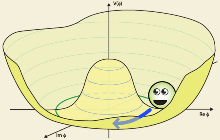
The second term, $V(\phi)$, is the Higgs potential. In its *minimal* form, it is:

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

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

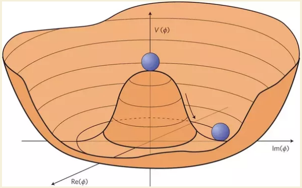


Universe = a cool place to live in

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.

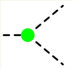


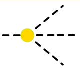
$$< \phi_0 > = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = \sqrt{\mu^2/\lambda}.$$

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

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

self-interaction terms (never observed)

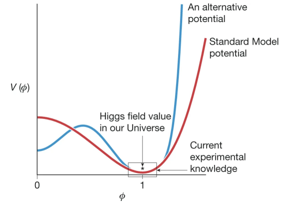




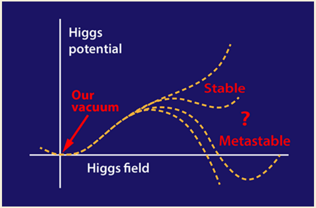
$\Longrightarrow$ To fully test the Higgs sector, one must observe the self-interaction term(s) and measure the Higgs boson self-coupling λ via Higgs boson pair production.

Why does it matter?

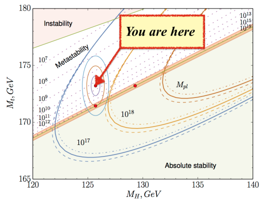
- Experimental data only provides information on the position of the minimum of the Higgs potential, in which our Universe lives.
- The (unconstrained) shape of the Higgs potential has implications beyond the mass-generation mechanism, in particular on the vacuum state of the Universe.
- In the absence 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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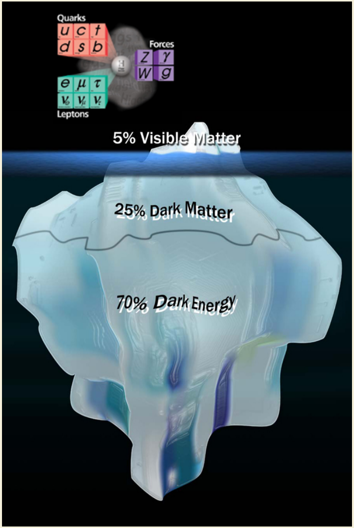
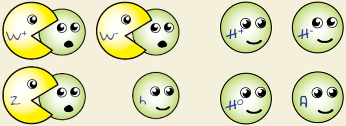


Sketches adapted from www.quantumdiaries.com

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?



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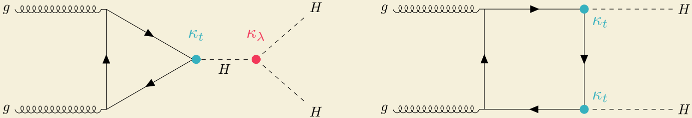
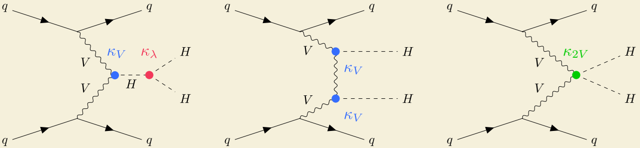
Higgs boson pair production at the LHC

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

Gluon-gluon fusion: $\sigma_{\text{ggF}}^{\text{SM}} \simeq 31$ fb $\pm\, 3\%(\text{PDF} + \alpha_s)\,^{+6\%}_{-23\%}(\text{scale} + m_t)$ [13 TeV].



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



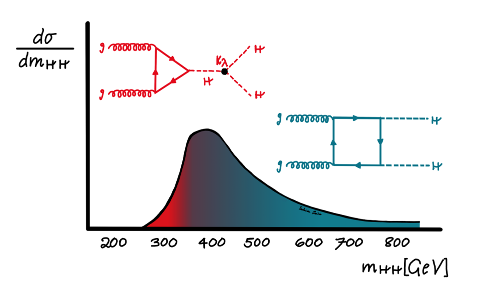
Other production modes (e.g. VHH, ttHH) have even smaller cross-sections.

Non-resonant HH mass distribution(s)

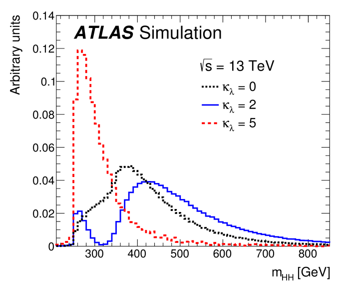
- HH events from the self-interaction diagrams are soft.

  $\Rightarrow$ 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

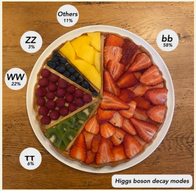


Image: @PhysicsCakes (Twitter)

Multitude of Higgs boson decays $\Rightarrow \mathcal{O}(\text{multitude}^2)$ 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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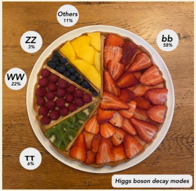

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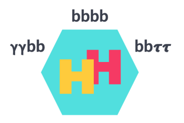
- Not a single "golden" channel;
- Three silver bullets!



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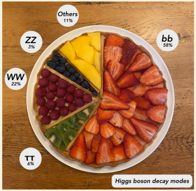

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Multitude of Higgs boson decays $\Rightarrow \mathcal{O}(\text{multitude}^2)$ of HH search channels, each with specific experimental challenges and sensitivity reach.

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

	bb	WW	ττ	ZZ	γγ
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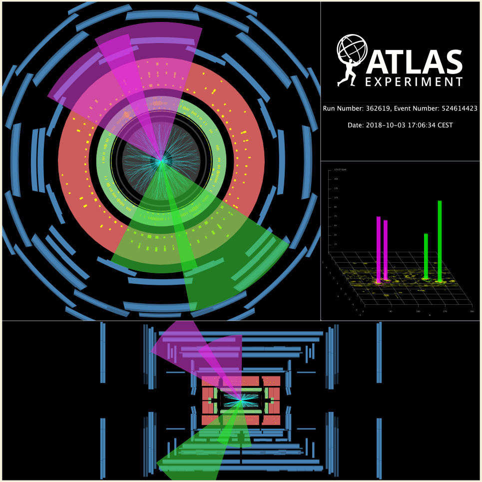
HH → bbbb

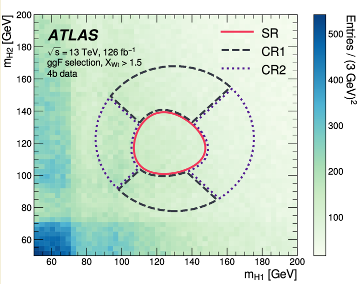


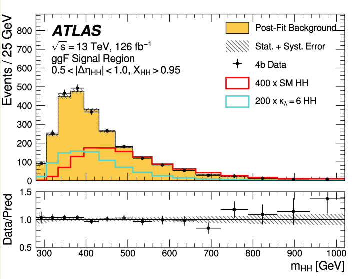
- Highest branching ratio... but large multi-jet background!
- Mostly probes large m_{HH} ⇒ sensitivity to HH events with large p_T^H.

- 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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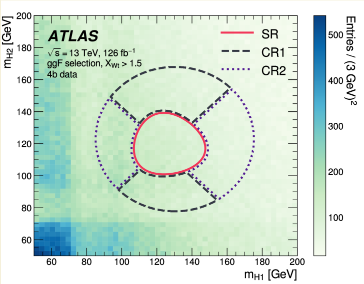
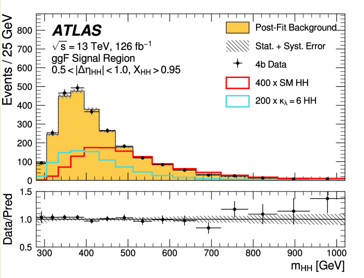
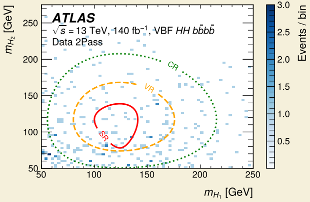


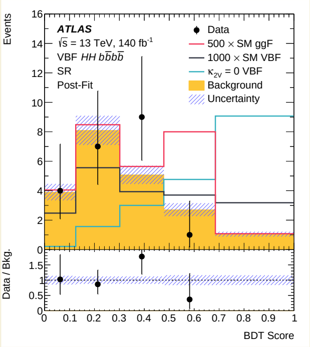


Obs. (exp.) 95% CL upper limit on $\sigma_{\mathrm{HH}}^{\mathrm{ggF+VBF}} = 5.4\ (8.1) \times$ SM prediction.

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:
  - $1J_{Hbb} \to 2J_{Hbb}$ 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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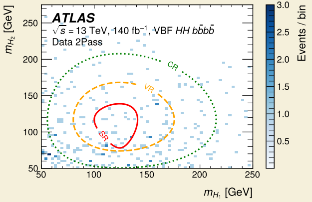
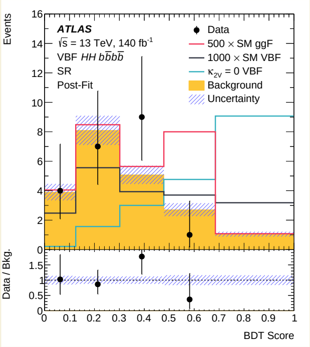
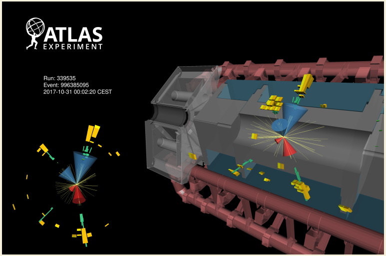
Obs. (exp.) exclusion of $\kappa_{2V} = 0$ with 3.4σ (2.9σ).





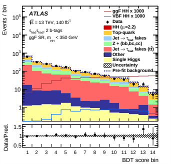
HH → bb$\tau\tau$

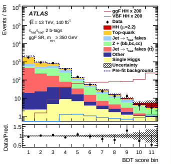


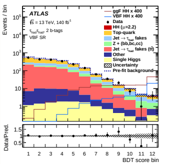
- Intermediate branching ratio but clean final state with moderate backgrounds!
- Sensitive to a broad range of κ_λ values.
- Phys. Rev. D 110 (2024) 032012

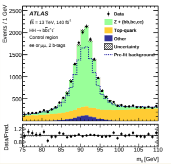
- bb$\tau_h\tau_\ell$ and bb$\tau_h\tau_h$ final states + further event categories:
  - 3 regions based on the trigger strategy (1 $\tau_h\tau_h$ & 2 $\tau_h\tau_\ell$);
  - 1 VBF-like & 2 ggF-like (low/high-m_{HH}) sub-categories per region;
  - 1 CR to constrain the Z+bb/cc background.
- Background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

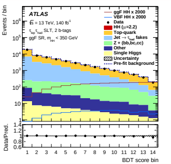
HH $\rightarrow$ bb$\tau\tau$

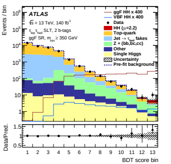


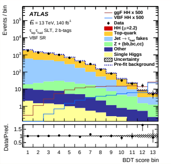


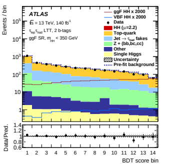


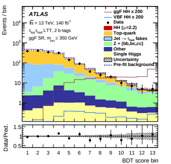


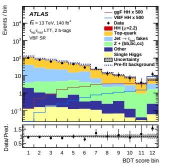




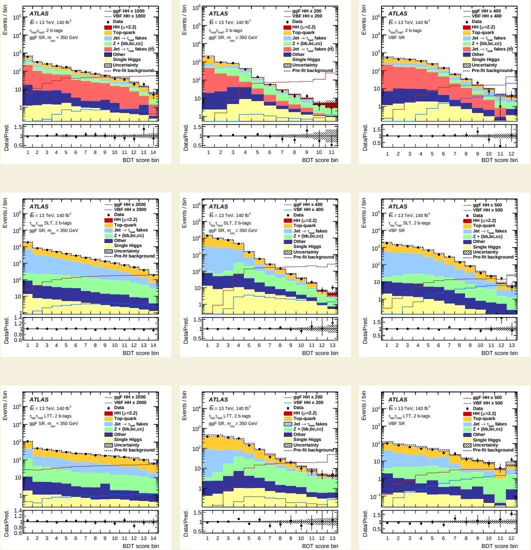


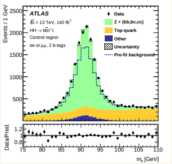




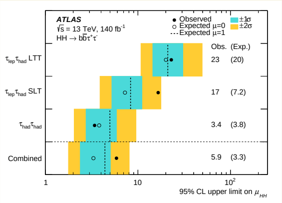


HH → bb$\tau\tau$

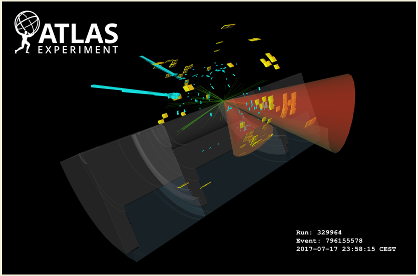




Obs. (exp.) 95% CL upper limit on $\sigma_{\mathrm{HH}}^{\mathrm{ggF+VBF}} = 5.9\ (3.3) \times$ SM prediction.

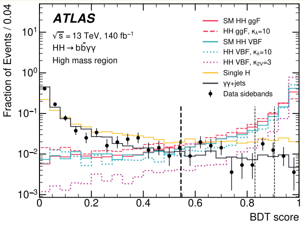


HH → $bb\gamma\gamma$



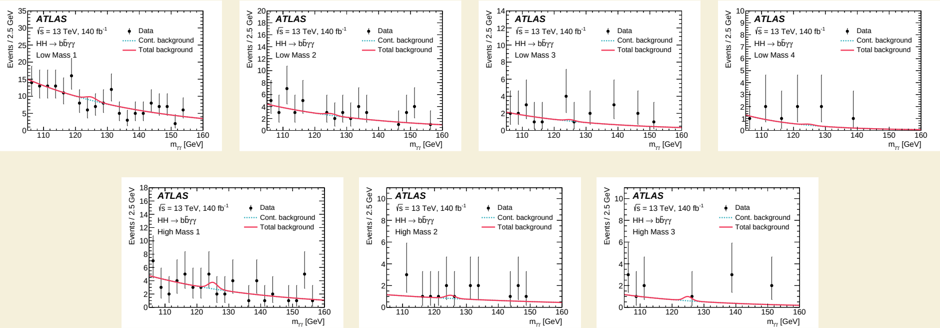
- Tiny branching ratio but very clean signature: excellent $m_{\gamma\gamma}$ resolution and small backgrounds!
- Enhanced sensitivity at low m_{HH}, hence to the Higgs self-interaction.
- JHEP 01 (2024) 066

- 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.



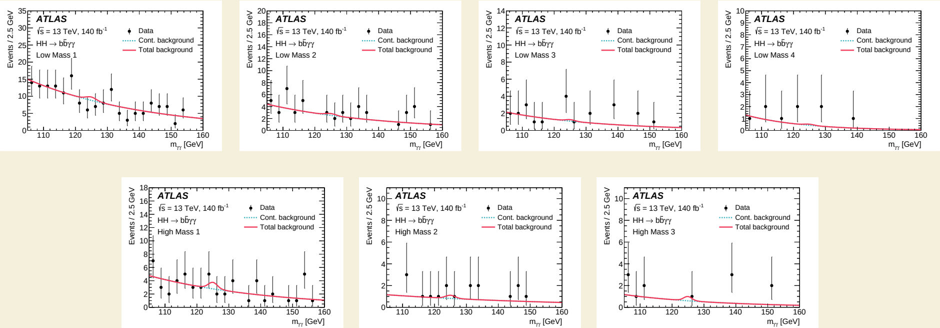
HH → bbγγ

- 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 → bbγγ

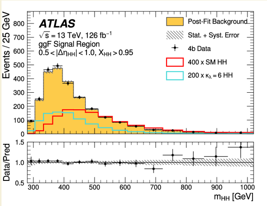
- Signal and backgrounds:
  - HH and single-H shapes from simulation;
  - continuum background shape from data.
- Signal extraction through parametric fits of $m_{\gamma\gamma}$.

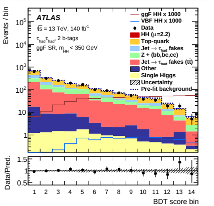


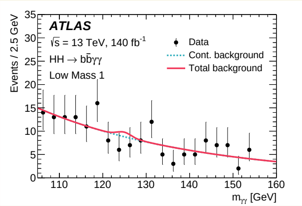
Obs. (exp.) 95% CL upper limit on $\sigma_{HH}^{ggF+VBF} = 4.0\ (5.0) \times$ SM prediction.

- Introduction
- Higgs boson pairs: production and decay modes
- ATLAS results: individual Run 2 HH searches
- Combined Run 2 HH search results in ATLAS
- Beyond the LHC Run 2

Putting it all together...

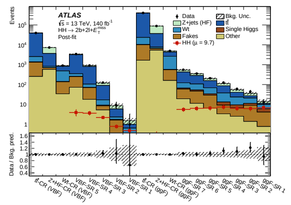


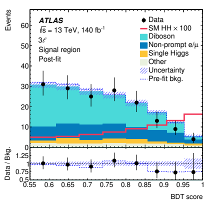


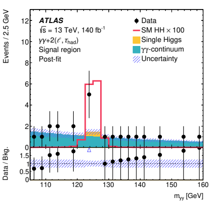


No golden HH search channel: combinations are key.

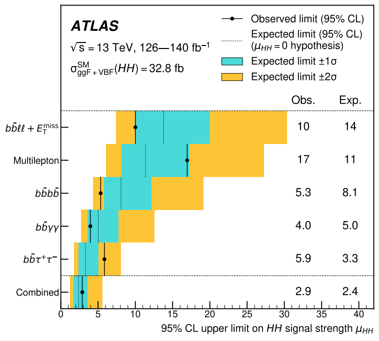
- Phys. Rev. Lett. 133 (2024) 101801





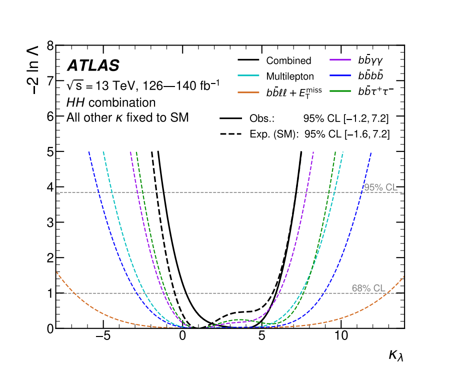


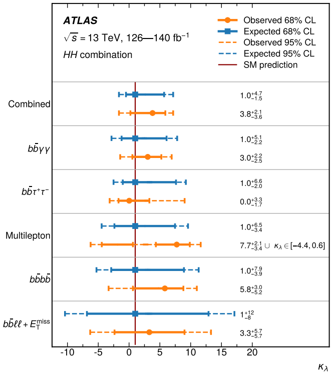
HH combination: limits on $\sigma^{\mathrm{HH}}_{\mathrm{ggF+VBF}}$



- **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).

HH combination: constraints on κ_λ

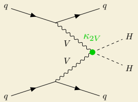


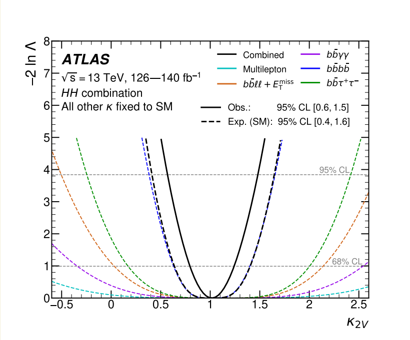


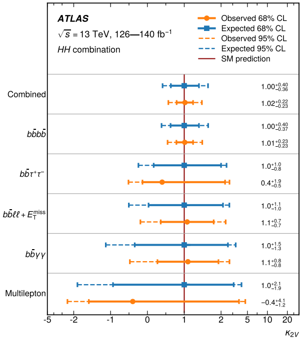
- **Obs. (exp.) 95% CI for κ_λ = [-1.2; 7.2] ([-1.6; 7.2]).**
- When profiling κ_λ, other Higgs boson couplings are set to their SM values.

HH combination: VVHH quartic coupling

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

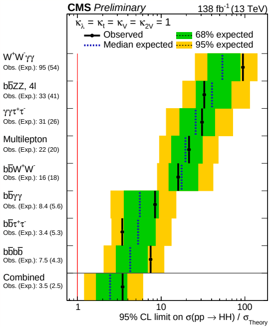


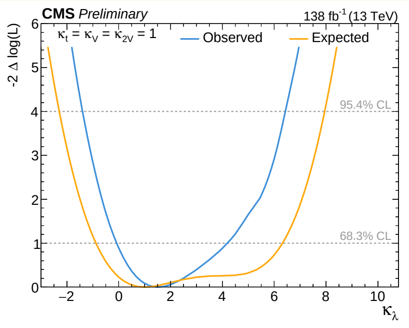




- **Obs. (exp.) 95% CI for $\kappa_{2V} = [0.6; 1.5]$ ([0.4; 1.6]), dominated by the VBF HH → bbbb search in boosted topologies.**

HH combination – comparison with CMS





- Results from CMS-PAS-HIG-20-011.
- Similar sensitivity to the HH signal strength (exp. 2.5, obs. 3.5) but the leading channel is HH → bbbb, in which CMS has a search for ggF boosted topologies.
- Obs. (exp.) 95.4% CI for κ_λ = [-1.40; 6.43] ([-2.29; 7.95]).

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.

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

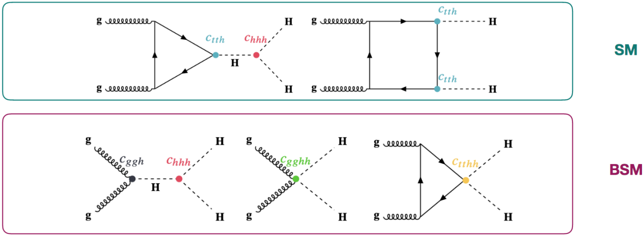


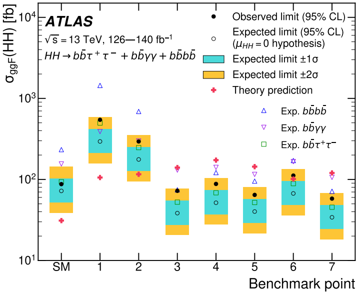
Image by Christina Dimitriadi

HH in Effective Field Theories

ATLAS has performed HEFT re-interpretations of Run 2 HH legacy 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).

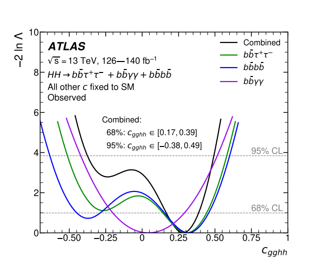
benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6	−0.68	0.90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

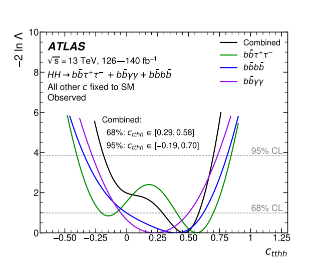


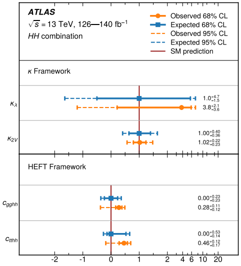
HH in Effective Field Theories

ATLAS has performed HEFT re-interpretations of Run 2 HH legacy 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):



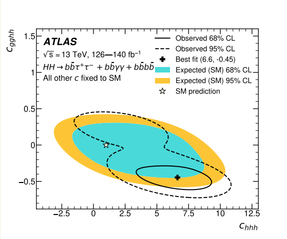


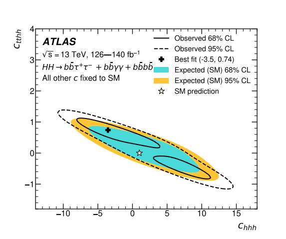


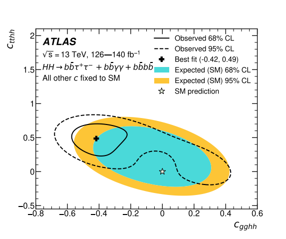
HH in Effective Field Theories

ATLAS has performed HEFT re-interpretations of Run 2 HH legacy 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.

- Introduction
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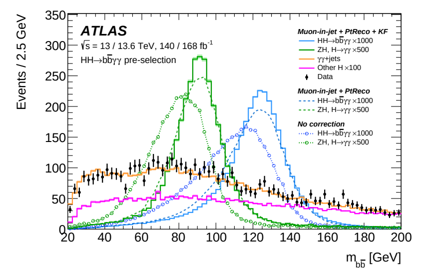
- Combined Run 2 HH search results in ATLAS
- Beyond the LHC Run 2

New search for HH $\rightarrow$ bb$\gamma\gamma$ (1)

ATLAS published a new search for HH $\rightarrow$ bb$\gamma\gamma$ [arxiv:2507.03495] with some improvements with respect to the Run 2 result:

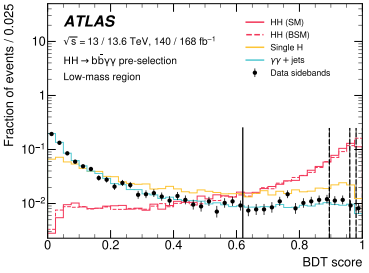
- Addition of a partial Run 3 dataset (2022–2024, i.e. 168 fb^{-1});
- New samples of simulated events, updated HH cross-sections;
- New GN2 algorithm at 85% working point (instead of 77%) for b-tagging, and relaxed requirement of $N_b \geq 2$;
- Kinematic fit relying on the p_x/p_y balance against photons to improve the mass resolutions of the H $\rightarrow$ bb candidate and bb$\gamma\gamma$ system.

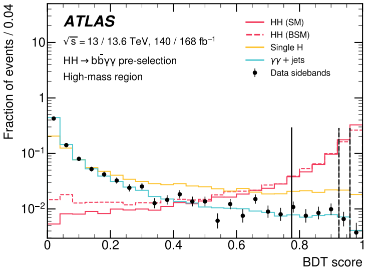


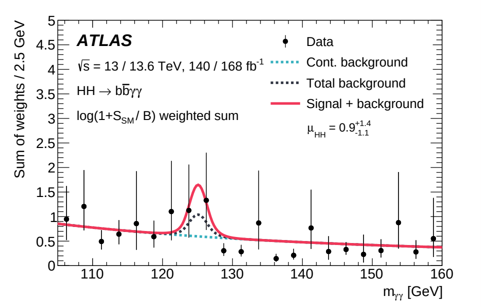
New search for HH $\to$ bb$\gamma\gamma$ (2)

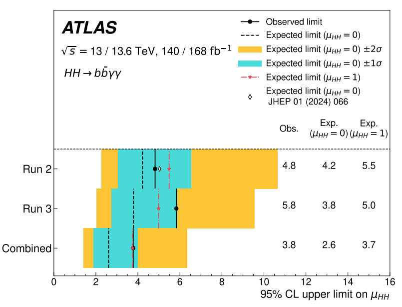
Event categories similar to the Run 2 legacy search:

- Low- and high-mass regions with a threshold at $m^{\star}_{bb\gamma\gamma} = 350\,\mathrm{GeV}$;
- $2\times(4+3)=14$ categories based on resp. low- and high-mass BDT scores and Run 2/3 datasets;
- Same BDT score thresholds and di-photon continuum background shapes for the corresponding Run 2 and Run 3 categories.



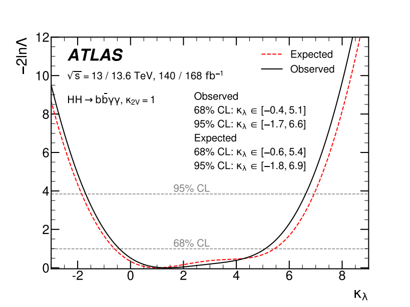


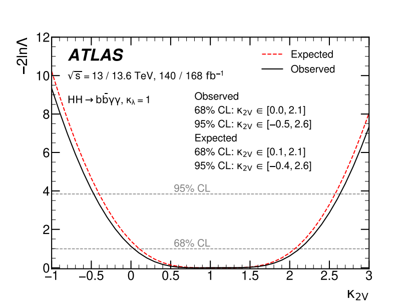


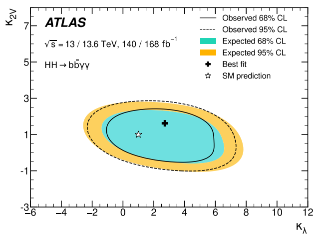


- Best-fit HH signal strength of $0.9^{+1.4}_{-1.1}$ (exp. $1^{+1.3}_{-1.0}$ in the SM);
- Signal significance of 0.84σ (exp. 1.0σ in the SM);
- Obs. (exp.) 95% CL upper limit on $\mu_{\mathrm{HH}} = 3.8\ (2.6) \times$ SM prediction
  $\Rightarrow$ sensitivity close to the *combined* ATLAS Run 2 legacy result!

New search for HH → $bb\gamma\gamma$ (4)



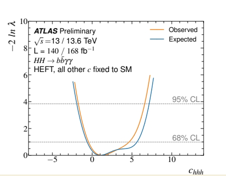


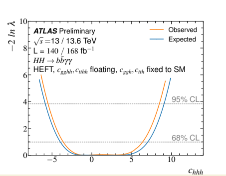


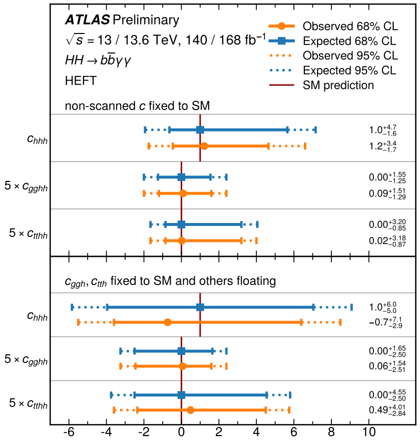
- Expected width of the κ_λ and κ_{2V} 95% CI improved by resp. 20% and 30% with respect to the Run 2 legacy result.
- 2D scan → $(\kappa_\lambda; \kappa_{2V}) = (2.7^{+2.3}_{-3.0}; 1.6^{+0.6}_{-1.9})$ (exp. $(1^{+4.7}_{-1.7}; 1^{+1.1}_{-1.3})$).

HEFT interpretations:

- Extend the analysis to include EFT effects on VBF HH;
- Perform likelihood scans while profiling other HEFT anomalous couplings → better represents sensitivity when other (correlated) HEFT operators also affect HH production.



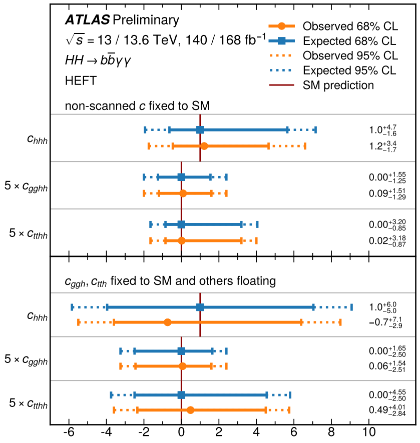




New HH → $bb\gamma\gamma$ EFT results (1)

HEFT interpretations:

- Extend the analysis to include EFT effects on VBF HH;
- Perform likelihood scans while profiling other HEFT anomalous couplings → better represents sensitivity when other (correlated) HEFT operators also affect HH production.
- 1D constraints are comparable to those obtained in the Run 2 HH combination!
- Large differences between 1D and 3D constraints show important correlations of the three HEFT operators on the HH signal yield, most significantly between c_{hhh} and c_{tthh}.



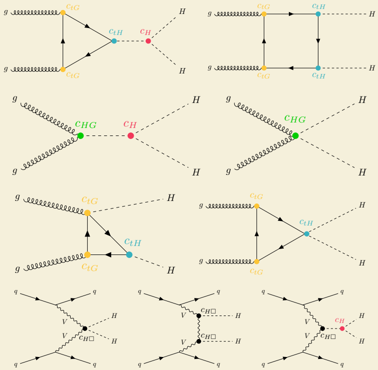
New HH $\rightarrow$ bb$\gamma\gamma$ EFT results (2)

SMEFT interpretations:

- Same pattern of electroweak symmetry breaking as in the SM $\Rightarrow$ this enforces correlations among the new interactions involving the Higgs boson.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4}\sum_j c_j^{(8)}\mathcal{O}_j^{(8)} \dots$$

- Five operators and Wilson coefficients of interest in HH production, where $c_H\mathcal{O}_H$ uniquely modifies the Higgs self-coupling and is of primary interest in the SMEFT analysis.



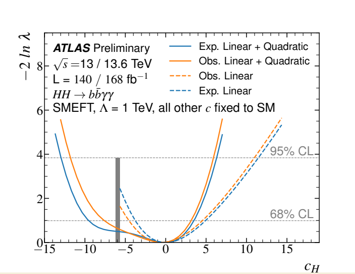
SMEFT interpretations:

- For each Wilson coefficient, linear-only and linear-quadratic truncation schemes are probed ⇒ indicates the validity of the SMEFT truncation and the potential size of dimension-8 contributions.

$$\frac{\sigma_{HH}^{SMEFT}}{\sigma_{HH}^{SM}} \approx 1 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \underbrace{\frac{2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_{SM}^*\right)}{|\mathcal{M}_{SM}|^2}}_{A_i} + \sum_{i,j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} \underbrace{\frac{\mathcal{M}_i^{(6)} \mathcal{M}_j^{(6)*}}{|\mathcal{M}_{SM}|^2}}_{B_{ij}}$$

No Dim-8

$$+ \sum_i \frac{c_i^{(8)}}{\Lambda^4} \cancel{\frac{2\mathrm{Re}\left(\mathcal{M}_i^{(8)} \mathcal{M}_{SM}^*\right)}{|\mathcal{M}_{SM}|^2}}$$



$\Lambda = 1$ TeV and a gray bar indicates where one of the ggF HH category yields becomes negative.

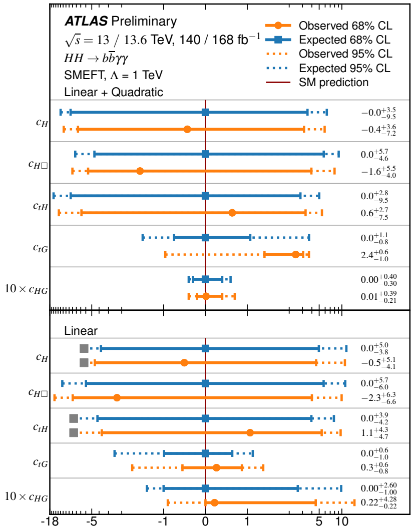
SMEFT interpretations:

- For each Wilson coefficient, linear-only and linear-quadratic truncation schemes are probed ⇒ indicates the validity of the SMEFT truncation and the potential size of dimension-8 contributions.

$$\frac{\sigma_{HH}^{SMEFT}}{\sigma_{HH}^{SM}} \approx 1 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \underbrace{\frac{2\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_{SM}^*\right)}{|\mathcal{M}_{SM}|^2}}_{A_i} + \sum_{i,j} \frac{c_i^{(6)}c_j^{(6)}}{\Lambda^4} \underbrace{\frac{\mathcal{M}_i^{(6)}\mathcal{M}_j^{(6)*}}{|\mathcal{M}_{SM}|^2}}_{B_{ij}}$$

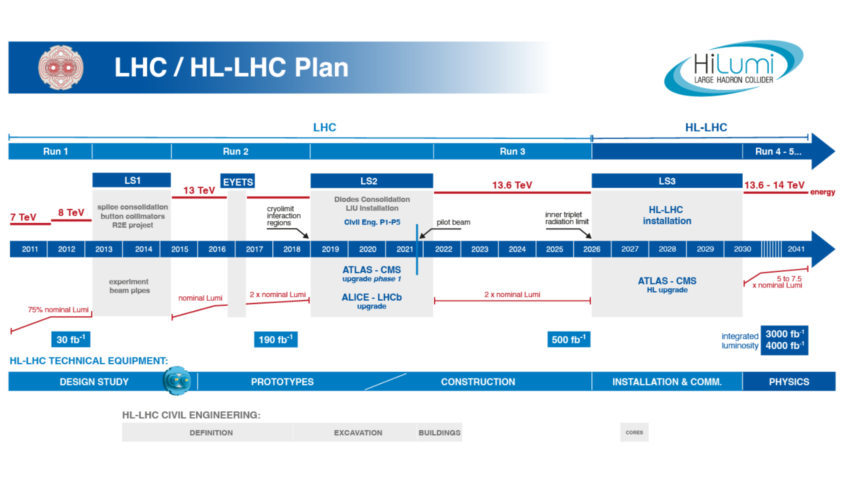
No Dim-8

$$+ \cancel{\sum_i \frac{c_i^{(8)}}{\Lambda^4} \frac{2\mathrm{Re}\left(\mathcal{M}_i^{(8)}\mathcal{M}_{SM}^*\right)}{|\mathcal{M}_{SM}|^2}}$$



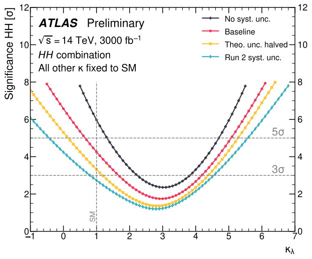
HL-LHC timeline

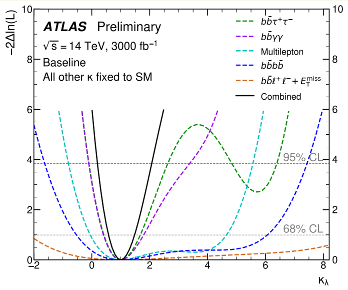
A major task of the HL-LHC is to further explore the Higgs sector, in particular establish and measure the Higgs self-interaction.

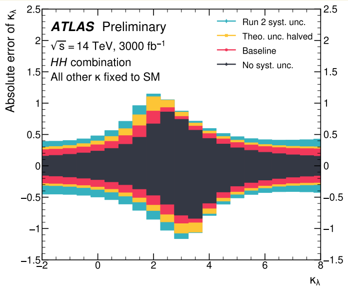


New ATLAS HH prospects at HL-LHC

- Latest projections based on the Run 2 legacy publications, see ATL-PHYS-PUB-2025-006.
  - Combined significance at 4.3;
  - The 68% confidence interval for κ_λ is $1.0^{+0.48}_{-0.42}$, improved w.r.t 2020 ATLAS+CMS projections.







Combined HH prospects at HL-LHC

ATL-PHYS-PUB-2025-018
CMS-HIG-25-002

31st March 2025

ATL-PHYS-PUB-2025-018

Highlights of the HL-LHC physics projections by ATLAS and CMS

The ATLAS[1] and CMS[2] Collaborations

In the following:

- S2 $\simeq$ ATLAS and CMS baseline scenario for systematic uncertainties;
- S3 = S2 + 5% improvements in b-tagging and τ-identification efficiencies.

Combined HH prospects at HL-LHC

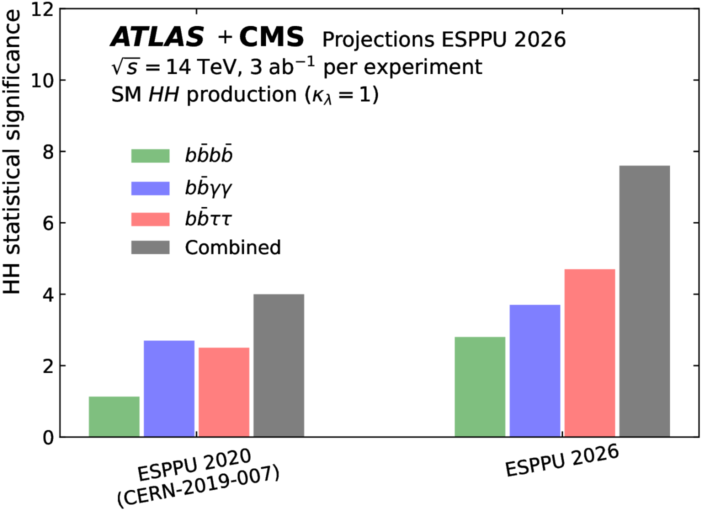
Projected ATLAS+CMS results on the HH signal significance:

	3 ab^{-1} (*S2*)		3 ab^{-1} (*S3*)	
	ATLAS	CMS	ATLAS	CMS
$b\bar{b}\tau^+\tau^-$	$3.5^\dagger$	2.4	$\mathbf{3.8}^\dagger$	**2.7**
$b\bar{b}\gamma\gamma$	$2.4^\dagger$	$2.4^\dagger$	$\mathbf{2.6}^\dagger$	$\mathbf{2.6}^\dagger$
$b\bar{b}b\bar{b}$ resolved	1.0	$1.2^\dagger$	**1.0**	$\mathbf{1.3}^\dagger$
$b\bar{b}b\bar{b}$ boosted	–	$2.2^\dagger$	–	$\mathbf{2.2}^\dagger$
Multilepton	$1.0^\dagger$	–	$\mathbf{1.0}^\dagger$	–
$b\bar{b}\ell^+\ell^-$	$0.5^\dagger$	–	$\mathbf{0.5}^\dagger$	–
Combination	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	7.2		**7.6**	

Only one † symbol per row ⇒ measurement extrapolated to $6\,\mathrm{ab}^{-1}$ assuming the same sensitivity for both experiments.

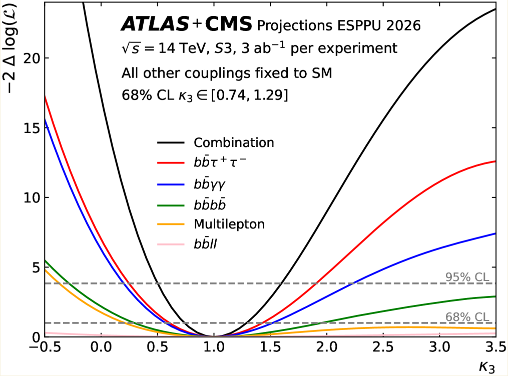
Combined HH prospects at HL-LHC

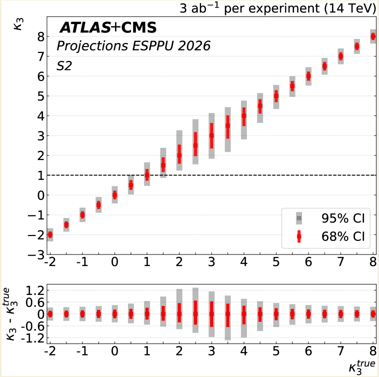
Projected ATLAS+CMS results on the HH signal significance:



Combined HH prospects at HL-LHC

Projected ATLAS+CMS results on the Higgs self-interaction:





A precision on the Higgs self-coupling modifier below 30% can be obtained in the S3 scenario with 3 ab^{-1} of data per experiment!

Summary

- Elusive non-resonant pairs of Higgs bosons are the prime experimental signature of the Higgs self-interaction.
- ATLAS published impressive results with the Run 2 data (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.
  - Novel re-interpretations of HH searches in Effective Field Theories.
- ATLAS recently published the first HH search with Run 3 data in the $\mathrm{bb}\gamma\gamma$ final state.
- The Run 2 legacy results served as the basis in recent HL-LHC prospect studies for the 2026 update of the European Strategy for Particle Physics. With 3000 fb^{-1} of data at 14 TeV per experiment:
  - HH signal significance of 4.5 per experiment, above 7 after combination.
  - Precise measurement of the Higgs self-interaction, with an uncertainty better than 50% per experiment, and close to 30% after combination.
- Significant improvements with respect to the 2020 update of the ESPP.

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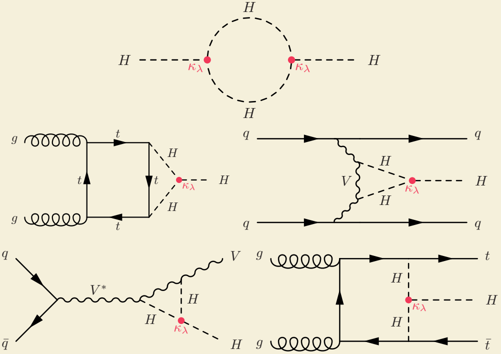
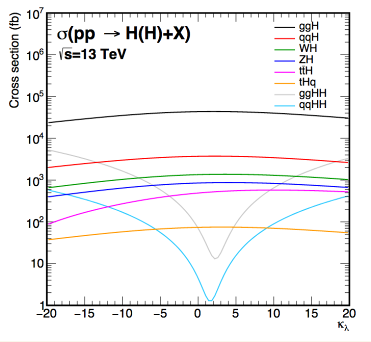
So imagine what we can do in the next 20 years!

Back-up slides

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.



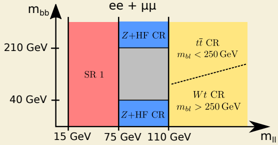


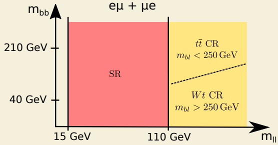
LHCHWG-2022-002

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

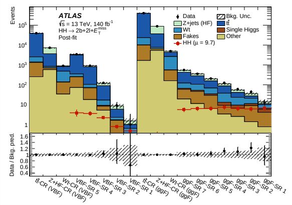
- Captures HH di-lepton decays to bbWW, bbZZ and bb$\tau_\ell \tau_\ell$.
- Large $t\bar{t}$ background for ggF HH but only small backgrounds in VBF topologies.
- JHEP 02 (2024) 037

- 2 e/μ and 2 b-jets, no requirement on $E_{\mathrm{T}}^{\mathrm{miss}}$;
- 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.



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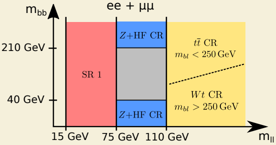

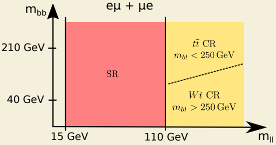

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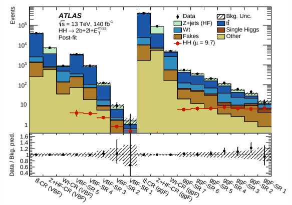


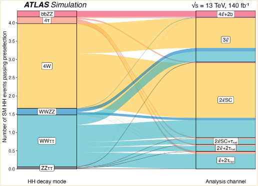
Obs. (exp.) 95% CL upper limit on $\sigma_{\mathrm{HH}}^{\mathrm{ggF+VBF}} = 9.7\ (16.2) \times$ SM prediction.

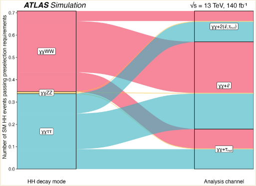
Multi-lepton HH decays

- 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).





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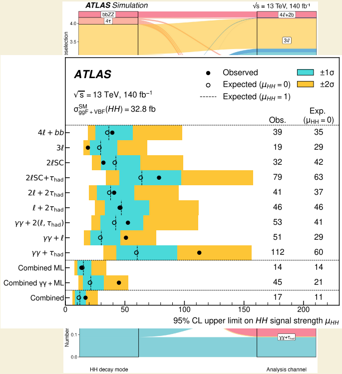
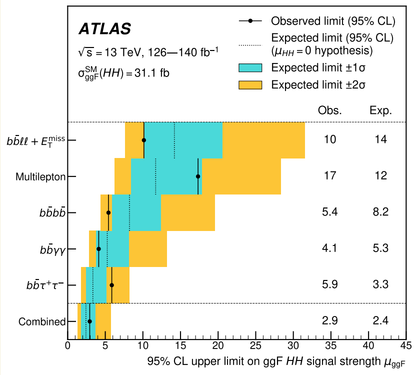
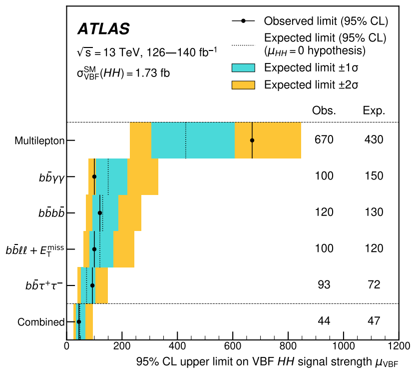
Obs. (exp.) 95% CL upper limit on $\sigma_{\mathrm{HH}}^{\mathrm{ggF+VBF}} = 17\ (11) \times$ SM prediction.



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

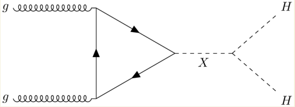
When deriving the limits on ggF (VBF) HH, the VBF (ggF) HH production cross-section is fixed to the SM predicted value.



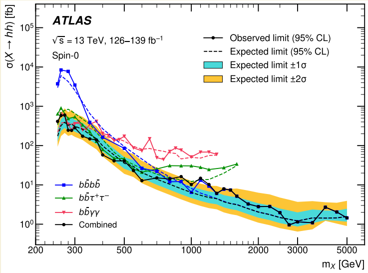


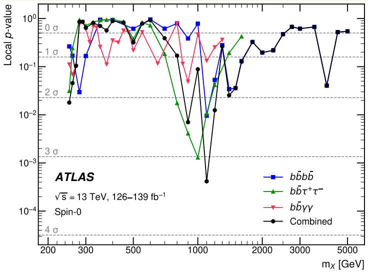
Resonant HH searches

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).





Phys. Rev. Lett. 132 (2024) 231801

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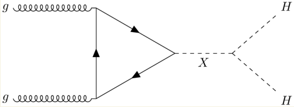
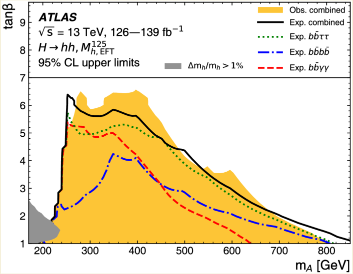
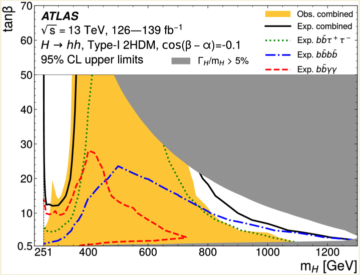


Searches for resonant HH production can then be interpreted in various BSM scenarios with an extended Higgs sector, e.g. in the MSSM (left) and in the type-I 2HDM for $\cos(\beta - \alpha) = -0.1$ (right).





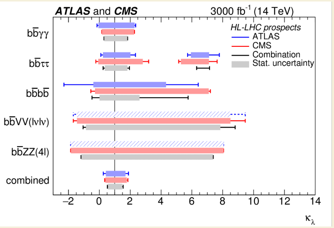
Phys. Rev. Lett. 132 (2024) 231801

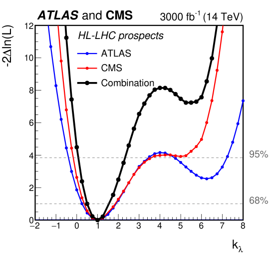
Old HH prospects at HL-LHC

HH prospect studies for the European Particle Physics Strategy Update in 2020:

- 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 $[0.52; 1.5]$.

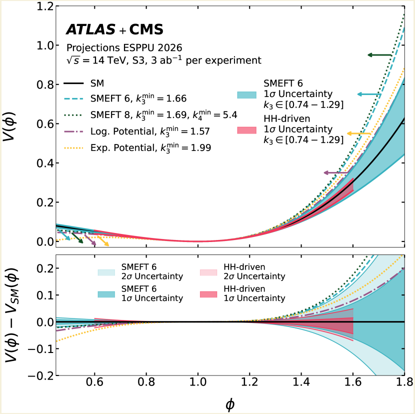
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6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





Combined HH prospects at HL-LHC

- Projected CIs for κ_λ can constrain BSM scenarios with new particles beyond the HL-LHC energy reach that deform the Higgs potential.
- Constraints from HH production probe κ_λ in a model-independent way only close to the minimum.
- The shape of the potential across a wider range of ϕ can be probed in EFTs (e.g. dim-6 SMEFT).
- Arrows indicate where four BSM scenarios predict a strong FOPT (first-order phase transition).



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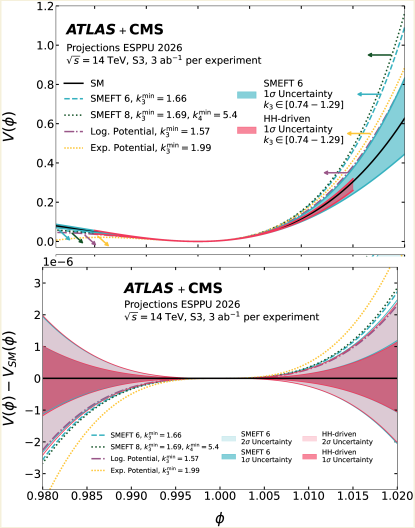
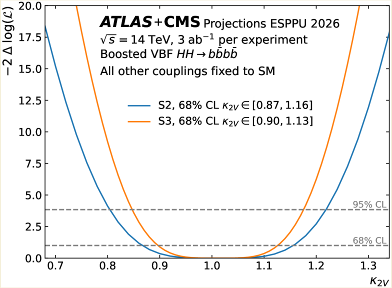


Near the minimum, the 95% CL red band excludes all strong-FOPT scenarios across the four BSM hypotheses. The HL-LHC is thus of extreme importance to understand the early universe!

Combined HH prospects at HL-LHC

Other projected ATLAS+CMS results:

Measurement of the VVHH quartic coupling with a precision better than 15%.



Improvement on the sensitivity to $S \to HH$ by roughly an order of magnitude.