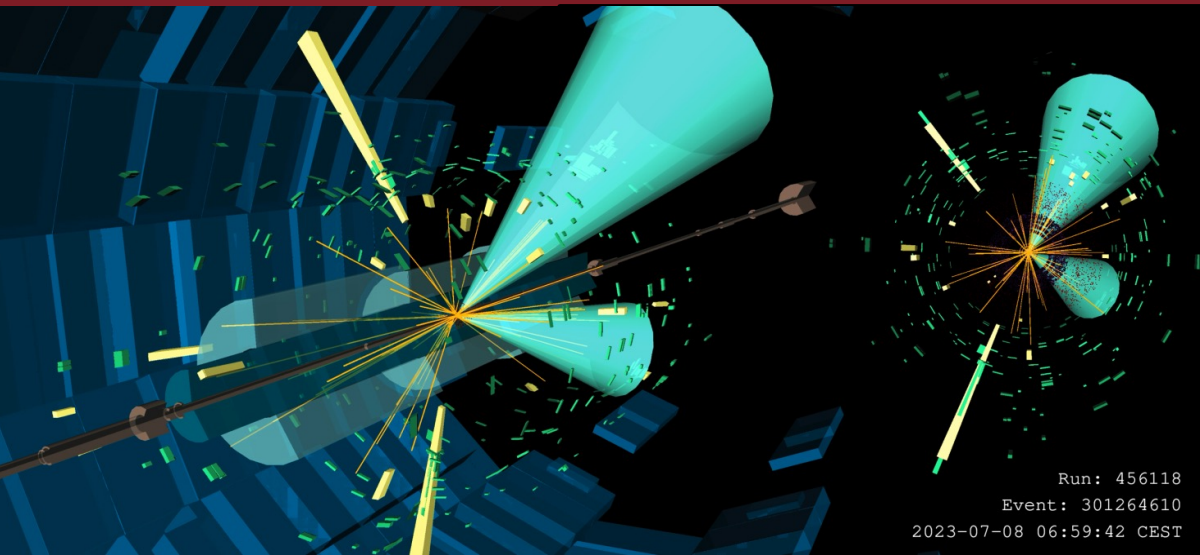


HH, HHH searches: Higgs potential at the LHC

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on behalf of the ATLAS Collaboration

September 29th 2026



QCD @LHC: University of Oxford
September 28th-October 2nd 2026

Outline

- Higgs Physics
- Run2 Results:
 - Run2 ATLAS+CMS HH Combination
 - Run2 ATLAS H+HH Combination
- What are we doing with Run3 data (so far)?
 - HH(bb $\gamma\gamma$)
 - HH(bb $\tau\tau$)
 - ttHH
- Is HHH accessible? HHH(6b)
- HL-LHC Projections: HH and HHH
- Summary

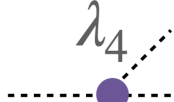
Why Search for HH (and HHH)?

- Since discovery in 2012, measurements of the Higgs properties (mass, quantum numbers and couplings) at the LHC have shown a scalar sector consistent with the SM.
- What remains unknown is the shape of the Higgs potential.
 - Higgs self-interactions provide a direct test of electroweak symmetry breaking and connect to broader questions such as the electroweak phase transition in the early Universe.

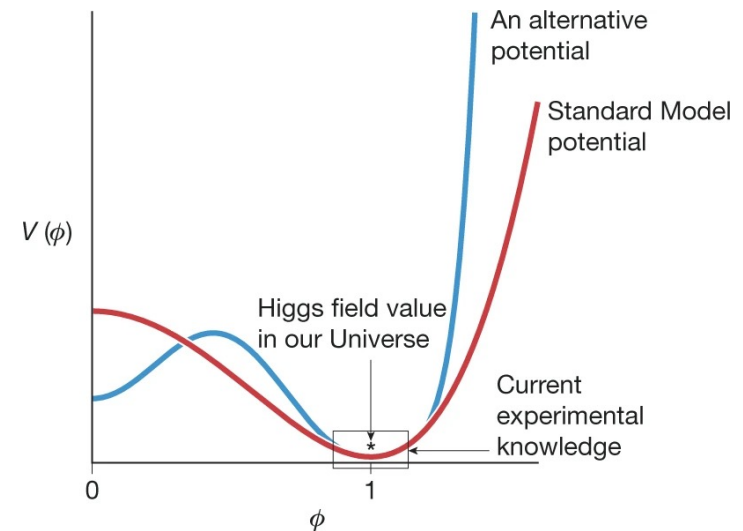
$$V(H) = \underbrace{\frac{1}{2}m_H^2 H^2}_{\text{Mass term}} + \underbrace{\lambda_3 H^3}_{\text{Trilinear Coupling}} + \underbrace{\frac{1}{4}\lambda_4 H^4}_{\text{Quartic Coupling}}$$

λ_3

 HH Production

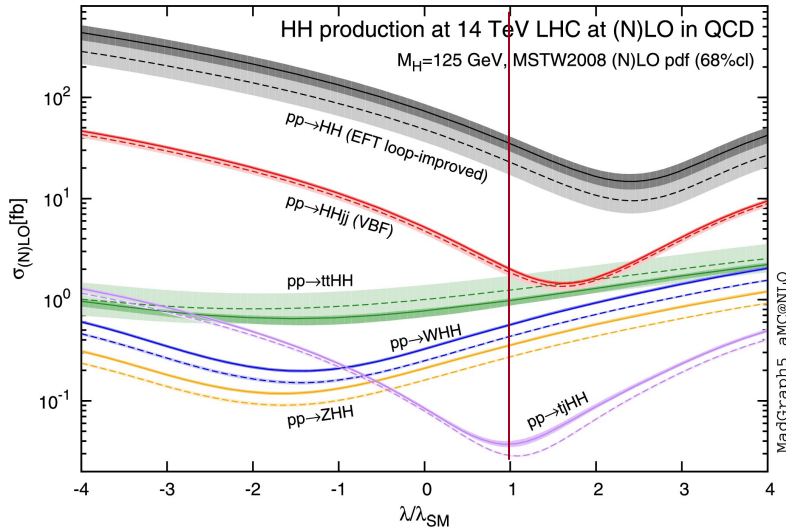
λ_4

 HHH Production

- Deviations parametrized as $\kappa_i = \lambda_i / \lambda_i^{\text{SM}}$.
- HH production gives direct access to $\kappa_\lambda(\kappa_3)$, while HHH production gives direct access to κ_4 .



Is SM $V(H)$ compatible with our universe?

HH Production @LHC

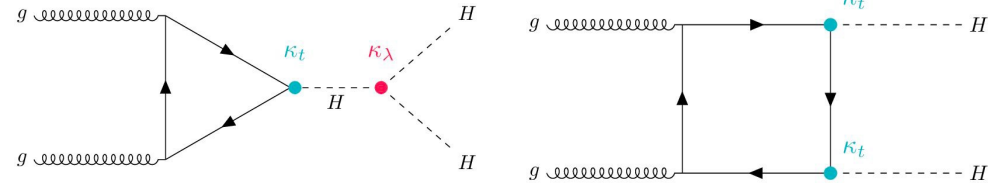
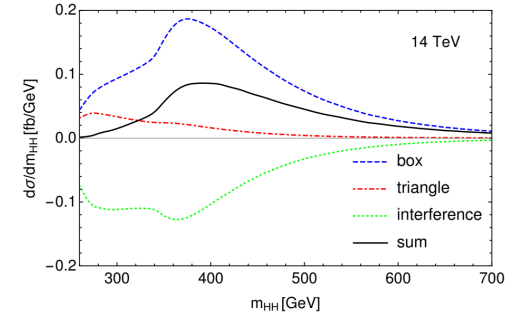


HH cross-section $\sim 1000\times$ smaller than H

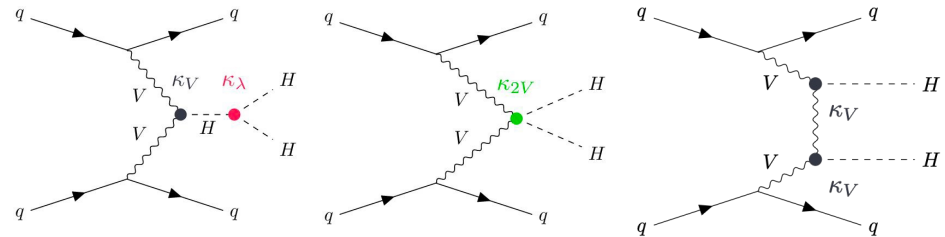
Cross-section σ		
Process	13 TeV	13.6 TeV
ggF HH	30.8 fb	34.1 fb
VBF HH	1.69 fb	1.87 fb
ttHH	0.67 fb	0.8 fb
HHH	0.079 fb	0.09 fb

Gluon-gluon fusion is the dominant production mode and gives direct sensitivity to κ_λ through box-triangle interference.

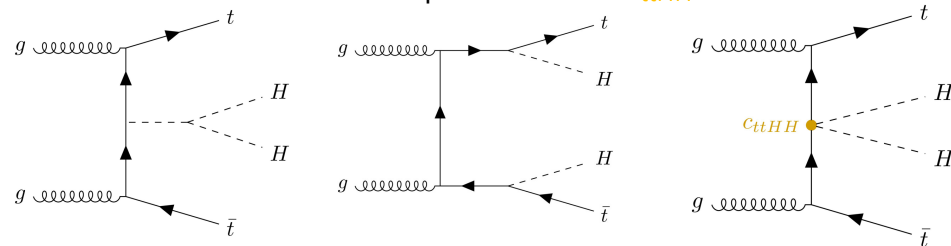
Most sensitive to κ_λ at low/intermediate m_{HH} .



Vector Boson Fusion has a smaller rate but directly probes the quartic gauge-Higgs coupling κ_{2V} .



ttHH is much rarer but can probe BSM c_{ttHH} .



Where does HH sensitivity come from?

ATLAS probes HH through many final states. Sensitivity depends on more than branching fraction: **objects, acceptance, mass resolution and background control** matter.

- Decay channels provide different experimental handles; production categories map them onto complementary constraints on μ_{HH} , κ_λ and κ_{2V} .

bbbb (34%)

- Largest branching fraction.
- QCD multijet background.

bb $\tau\tau$ (7.3%)

- Good balance of branching fraction and purity.
- τ /MET handles.

bb $\gamma\gamma$ (0.26%)

- Tiny rate, high purity.
- Excellent $m_{\gamma\gamma}$ resolution.

bb $l\bar{l}$ + MET (~2.9%)

- Leptons + MET give triggers and QCD rejection.

Multilepton / multiphoton final states (~6.5%)

- Clean low-QCD signatures; small yields.

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

Where does HH sensitivity come from?

ATLAS probes HH through many final states. Sensitivity depends on more than branching fraction: **objects**, **acceptance**, **mass resolution** and **background control** matter.

- Decay channels provide different experimental handles; production categories map them onto complementary constraints on μ_{HH} , κ_λ and κ_{2V} .

ATLAS+CMS HH Full Run2 Combination

bbbb (34%)

- Largest branching fraction.
- QCD multijet background.

bb $\tau\tau$ (7.3%)

- Good balance of branching fraction and purity.
- τ /MET handles.

bb $\gamma\gamma$ (0.26%)

- Tiny rate, high purity.
- Excellent $m_{\gamma\gamma}$ resolution.

	Channel	Details	Expected			Observed		
			μ_{HH}	κ_λ	κ_{2V}	μ_{HH}	κ_λ	κ_{2V}
ATLAS	bbbb		< 8.1	[-5.3, 12]	[0.38, 1.7]	< 5.4	[-3.4, 11]	[0.55, 1.5]
	bb $\tau\tau$		< 3.3	[-2.6, 9.2]	[-0.24, 2.4]	< 5.8	[-3.3, 9.1]	[-0.51, 2.7]
	bb $\gamma\gamma$		< 5.2	[-3.0, 7.9]	[-1.1, 3.3]	< 4.1	[-1.6, 7.0]	[-0.48, 2.7]
	bb $\ell\ell + E_T^{\text{miss}}$		< 14	[-11, 17]	[-0.50, 2.7]	< 9.6	[-6.5, 13]	[-0.19, 2.4]
	Multilepton		< 11	[-4.5, 9.6]	[-1.9, 4.1]	< 17	[-6.4, 12]	[-2.5, 4.7]
	Combined		< 2.4	[-1.7, 7.2]	[0.41, 1.7]	< 2.9	[-1.3, 7.2]	[0.57, 1.5]
CMS	bbbb		< 4.3	[-4.6, 12]	[0.63, 1.4]	< 7.0	[-5.0, 12]	[0.66, 1.4]
	bb $\tau\tau$		< 5.4	[-4.2, 11]	[-0.64, 2.8]	< 3.5	[-1.9, 8.9]	[-0.32, 2.5]
	bb $\gamma\gamma$		< 5.7	[-3.5, 8.8]	[-0.94, 3.1]	< 8.7	[-3.5, 8.0]	[-1.4, 3.6]
	bbWW		< 19	[-9.4, 16]	[-1.4, 3.5]	< 15	[-6.1, 13]	[-1.0, 3.1]
	Multilepton		< 20	[-8.0, 12]	[-2.5, 4.6]	< 22	[-5.8, 10]	[-3.4, 5.6]
	Combined		< 2.6	[-2.2, 8.0]	[0.63, 1.4]	< 3.5	[-1.4, 6.6]	[0.66, 1.4]
ATLAS + CMS combined			< 1.7	[-1.3, 6.7]	[0.66, 1.4]	< 2.5	[-0.71, 6.1]	[0.73, 1.3]

μ_{HH} : Driven by the full combination, strong constraint from **bb $\tau\tau$** balancing yield and purity.

κ_λ : ggF rate + m_{HH} shape; **bb $\gamma\gamma$** gives clean mass resolution, **bb $\tau\tau$** adds larger yield with manageable backgrounds.

κ_{2V} : Boosted/VBF categories in **bbbb** target high- m_{HH} topologies, κ_{2V} deviations are enhanced.

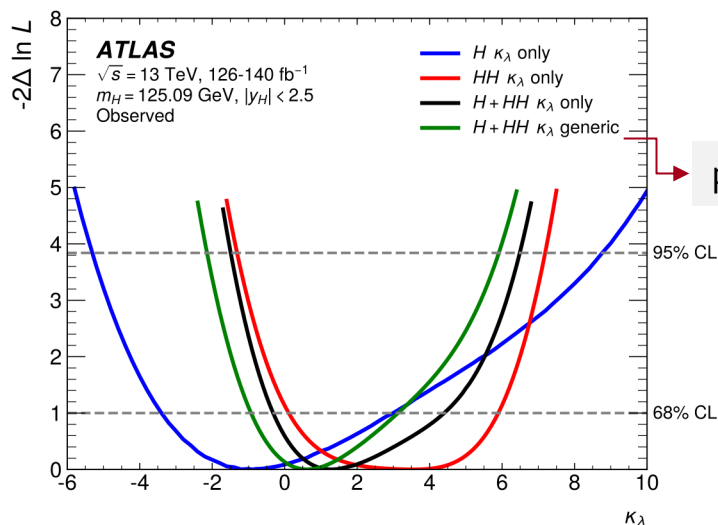
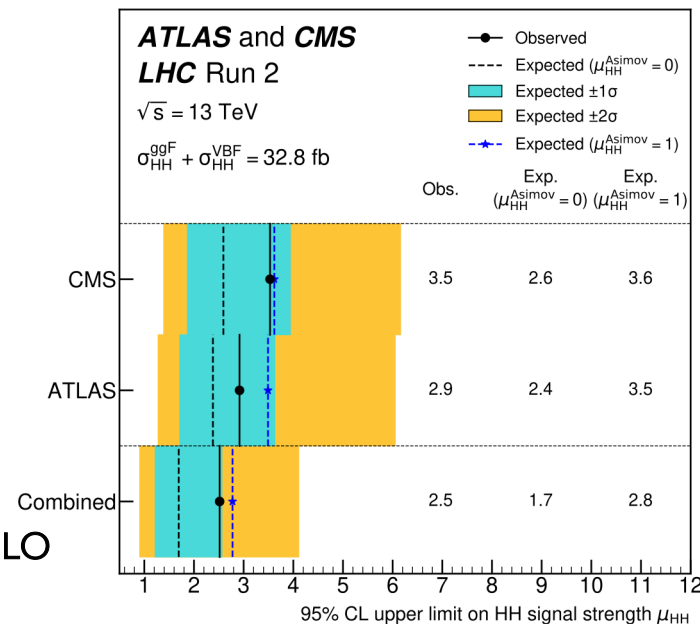
Run 2 HH Combination ATLAS+CMS

ATLAS+CMS HH Full Run2 Combination:

- Best-fit signal strength:
 - $\mu_{HH} = 0.8^{+0.9}_{-0.7} = 0.8^{+0.7}_{-0.6}(\text{stat})^{+0.4}_{-0.2}(\text{theory}) \pm 0.3(\text{exp.})$
- 1.1(1.3) σ observed(expected) HH signal significance
- $\mu_{HH} < 2.5(1.7)$ observed(expected)
- $\kappa_\lambda \in [-0.71, 6.1]$, $\kappa_{2V} \in [0.73, 1.3]$ at 95% CL

ATLAS Run 2 H+HH Combination:

- Single-Higgs processes also depend on κ_λ indirectly through NLO EW corrections to production rates and branching ratios.



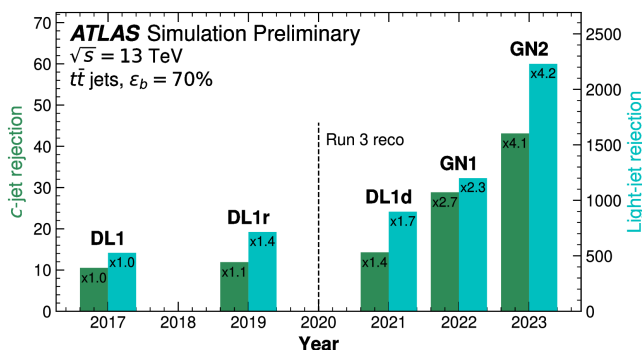
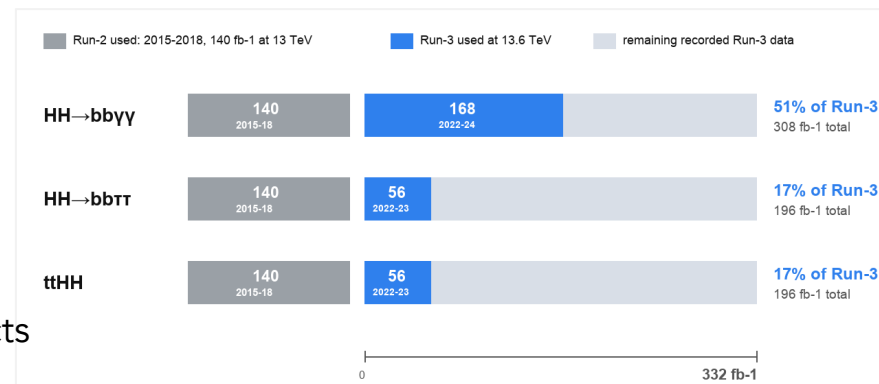
profile $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$

More details on
"Higgs Combinations
& EFT interpretations"
from Matthew
Maroun!

What are we doing with 13.6 TeV Run3 data (so far)?

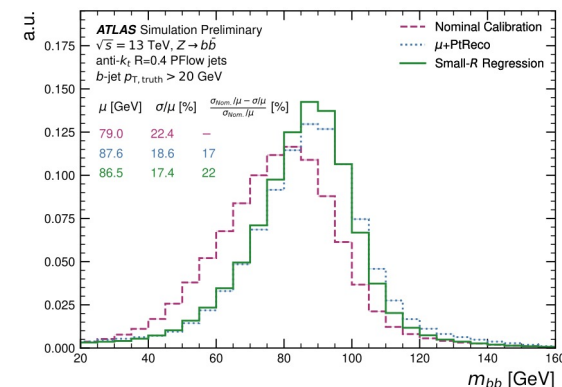
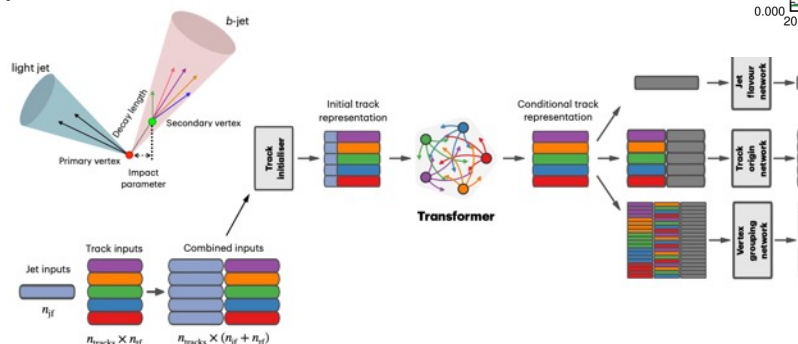
Recent ATLAS HH Run2 + partial Run3 Searches:

- HH(bb $\gamma\gamma$) 308 fb $^{-1}$: [Phys. Lett. B 876 \(2026\) 140280](#)
- HH(bb $\tau\tau$) 196 fb $^{-1}$: [arXiv:2607.26879](#)
- ttHH 196 fb $^{-1}$: [arXiv:2603.13113](#)
- Recent Run2 + partial Run3 HH results go **beyond luminosity scaling**: gains come from improved objects reconstruction and targeted event categorisation.



Topology-aware event classifiers:
transformers exploiting full event
structure

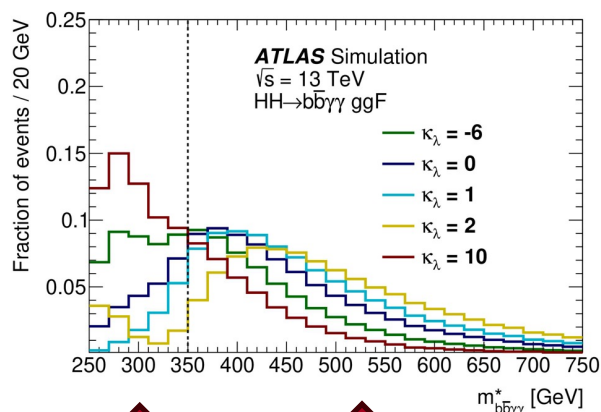
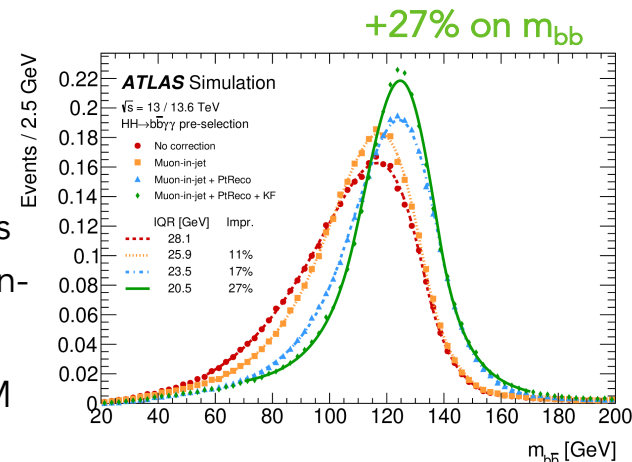
Object-level ML developments:
GN2 flavour tagging transformer



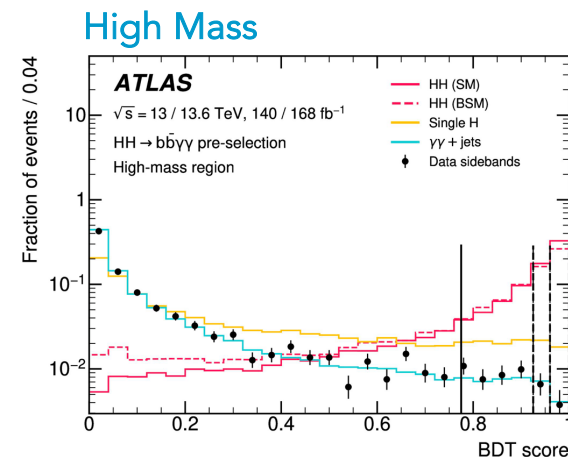
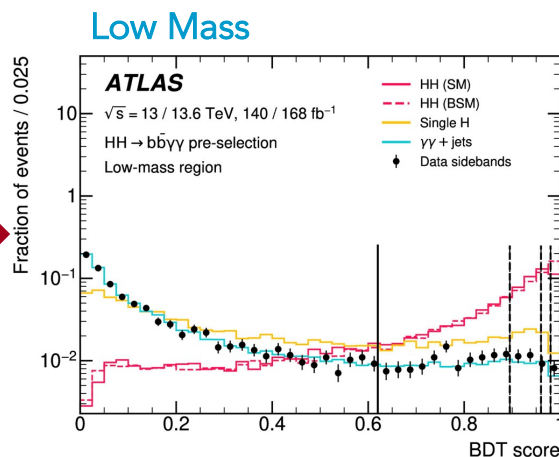
b-jet regression for better
H $\rightarrow$ bb reconstruction*

HH in Run 3: HH(bb $\gamma\gamma$)

- Uses 140 fb $^{-1}$ Run-2 + 168 fb $^{-1}$ Run-3 data, for 308 fb $^{-1}$ total.
- Diphoton trigger; 2 photons + at least two b-jets
- **ttH suppression** with lepton veto and central-jet requirements.
- Kinematic fit leverages the excellent $m_{\gamma\gamma}$ resolution and Higgs-mass constraints to improve the m_{bb} and m_{HH} resolutions, on top of muon-in-jet and PtReco corrections. **+27% on m_{bb} , +46% on m_{HH}**
- Uses high and low mass BDT categories in Run2/Run3 targeting SM and BSM-like HH.



BSM κ_λ κ_{2V}



HH in Run 3: HH(bb $\gamma\gamma$) Results

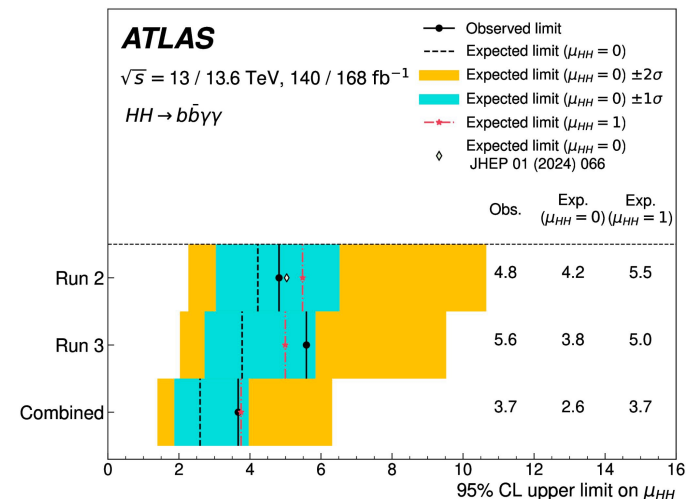
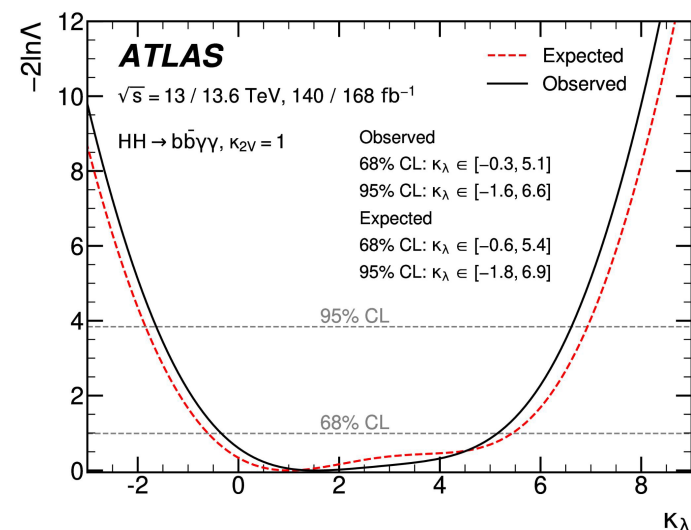
The $m_{\gamma\gamma}$ fit is performed simultaneously across all Run-2 and Run-3 BDT categories.

- Observed (expected) Significance: 0.78(1.1) σ
- $\mu_{HH} = 0.9^{+1.4}_{-1.1} = 0.9^{+1.3}_{-1.0}(\text{stat}) \pm 0.5(\text{syst.})$
- Coupling constraints:
 - $k_\lambda \in [-1.6, 6.6]$ at 95% CL
 - $k_{2\gamma} \in [-0.5, 2.6]$ at 95% CL

Statistically limited analysis, with the largest systematic impacts from photon energy scale/resolution, HH signal modelling and single-H + heavy-flavour production.

Improvements:

- ~50% more data
- ~20% b-tagging
- ~10% BDT categorization
- ~5% Kinematic Fit



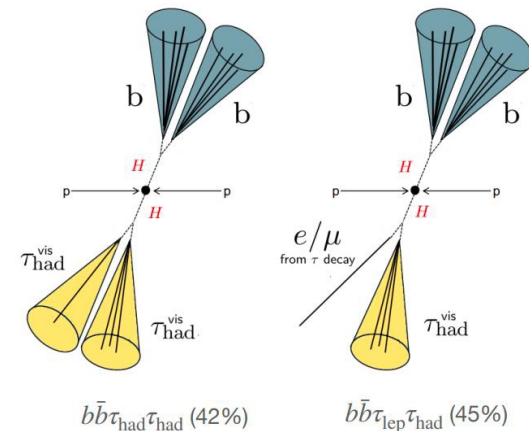
$\mu_{HH} < 3.7(2.6)$ observed(expected)

This single channel now reaches sensitivity comparable to the full Run-2 HH combination!

HH in Run 3: HH(bb $\tau\tau$)

Uses 140 fb⁻¹ Run-2 + 56 fb⁻¹ Run-3 data, for 196 fb⁻¹ total.

- Target final states: $\mathbf{T}_{\text{had}}\mathbf{T}_{\text{had}}$ and $\mathbf{T}_{\text{lep}}\mathbf{T}_{\text{had}}$
- Control regions:** dedicated regions constrain Z+HF, $t\bar{t}$, tW and fake- $\mathbf{T}_{\text{had}}$ backgrounds.
- Final discriminants use a **multiclass transformer architecture** combining **event- and object-level info**.
 - Regions enhanced in **ggF**, **BSM HH** and **VBF**, designed to target different m_{HH} and coupling-sensitive topologies.

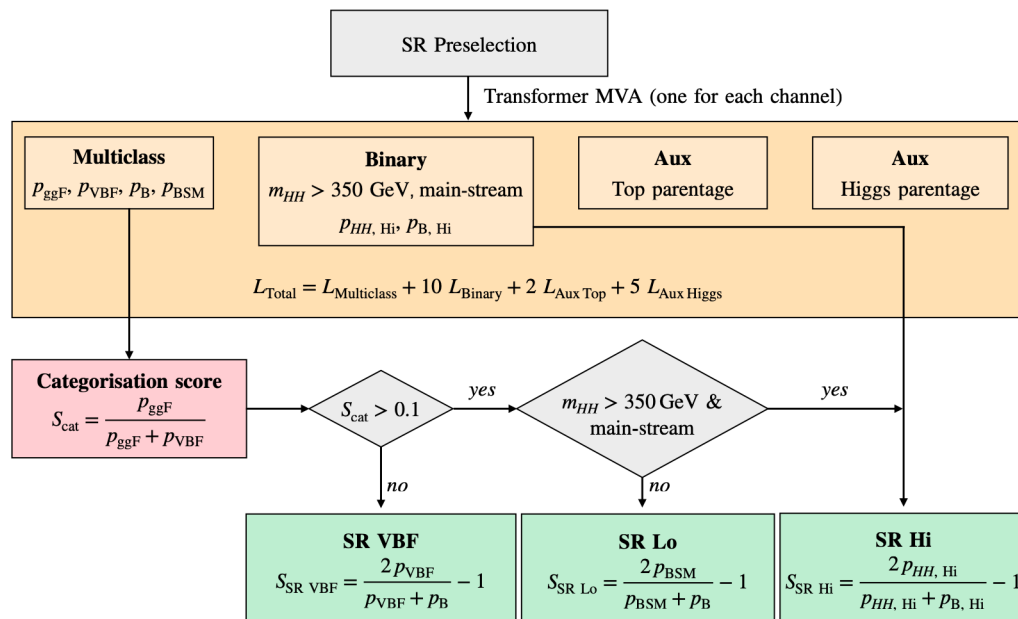


$\mathbf{T}_{\text{had}}\mathbf{T}_{\text{had}}$:

- Two 1- or 3-prong $\mathbf{T}_{\text{had}}$ candidates.
- Single- τ , di- τ and di- b -jet triggers.
- Fake- τ / multijet background.

$\mathbf{T}_{\text{lep}}\mathbf{T}_{\text{had}}$:

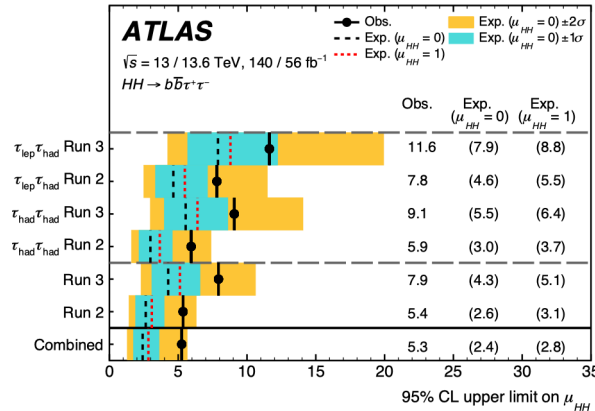
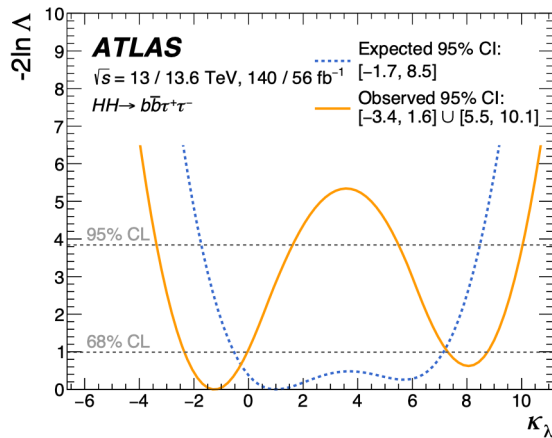
- e/μ from τ decay + one $\mathbf{T}_{\text{had}}$.
- Single-lepton trigger.
- Top-background dominated.



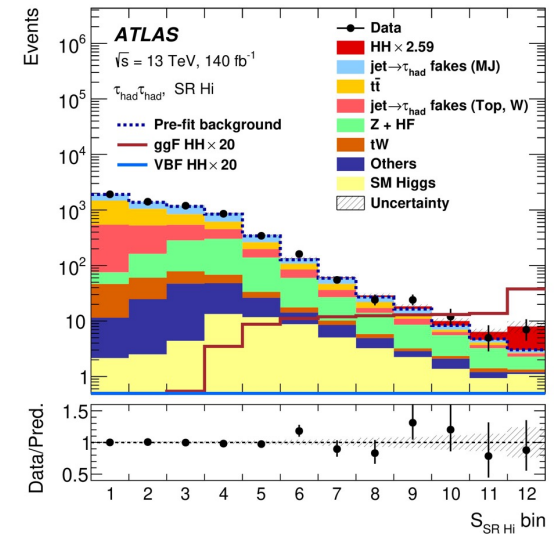
Binned profile-likelihood fit: 12 signal regions + 4 control regions.

HH in Run 3: HH(bb $\tau\tau$) Results

- Observed (expected) Significance: 2.6 (1.2) σ
- $\mu_{HH} = 2.6^{+1.4}_{-1.0} = 2.6^{+1.0}_{-0.9}$ (stat.) $^{+1.0}_{-0.5}$ (syst.)
 - Upward fluctuation in data observed. Compatible across channels.
- Coupling constraints: $k_\lambda \in [-3.4, 1.6] \cup [5.5, 10.1]$, $\kappa_{2V} \in [0.2, 2.4]$.



$\mu_{HH} < 5.3(2.4)$ observed(expected)



- The same analysis chain is validated with ZH/ZZ $\rightarrow$ bb $\tau\tau$, giving first evidence for ZH $\rightarrow$ bb $\tau\tau$ with 3.5 σ observed significance.
- 65% improvement on expected significance: ~20% MVA, ~15% additional data, ~10% GN2 b-tagging, ~5% removing eVeto in hadhad, ~20% new triggers in VBF region

Provides the strongest sensitivity for an individual channel in ATLAS and CMS, with expected sensitivity comparable to the Run-2 combination!

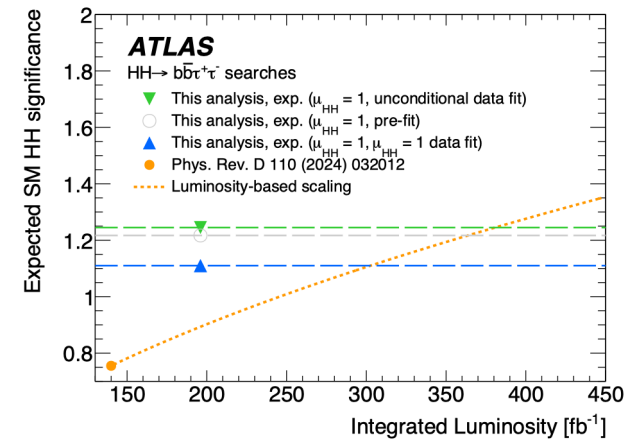
Run 3 HH Outlook:

Recent single-channel results already approach the **ATLAS Run-2 combination sensitivity**.

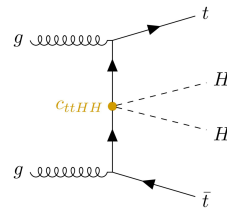
Analysis	Dataset	μ_{HH} 95% CL obs.(exp.)	κ_λ 95% CL	κ_{2V} 95% CL
ATLAS+CMS Run-2	140 fb ⁻¹	< 2.5 (1.7)	[−0.71, 6.1]	[0.73, 1.3]
ATLAS Run-2	140 fb ⁻¹	< 2.9 (2.4)	[−1.3, 7.2]	[0.57, 1.5]
ATLAS Run-2+3 bb $\gamma\gamma$	308 fb ⁻¹	< 3.7 (2.6)	[−1.6, 6.6]	[−0.5, 2.6]
ATLAS Run-2+3 bb $\tau\tau$	196 fb ⁻¹	< 5.3 (2.4)	[−3.4, 1.6] $\cup$ [5.5, 10.1]	[0.2, 2.4]

The next major step is a full Run-3 HH program and Run-2+Run-3 combination.

- Naïve full Run-3 scaling gives expected SM HH sensitivities of about **1.4 σ** in **bb $\gamma\gamma$** and **1.8 σ** in **bb $\tau\tau$** , before a combined fit or further analysis improvements.
- A full combination should gain further from additional channels, improved reconstruction, flavour tagging and categorisation.



HH in Run 3: ttHH



First ATLAS search for non-resonant ttHH production, using 196 fb^{-1} of Run2+partial Run3 data.

- Probes a **top-associated HH topology**, complementary to inclusive ggF/VBF HH searches and sensitive to possible **ttHH contact interactions**.

Three targeted final states:

1L:

- 1 lepton + ≥ 5 b-jets
- largest expected yield
- Fit **transformer** output

bbγγ :

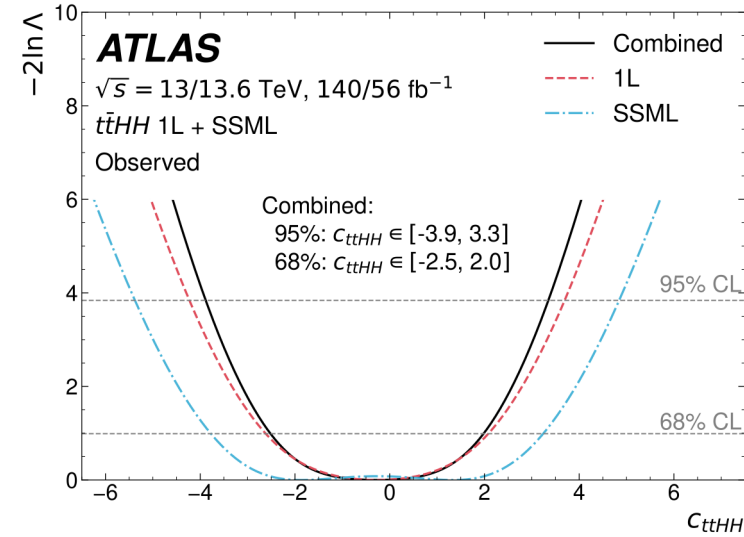
- 2 photons + ≥ 2 b-jets
- clean $H \rightarrow \gamma\gamma$ peak
- BDT categories + $m_{\gamma\gamma}$ fit

SSML:

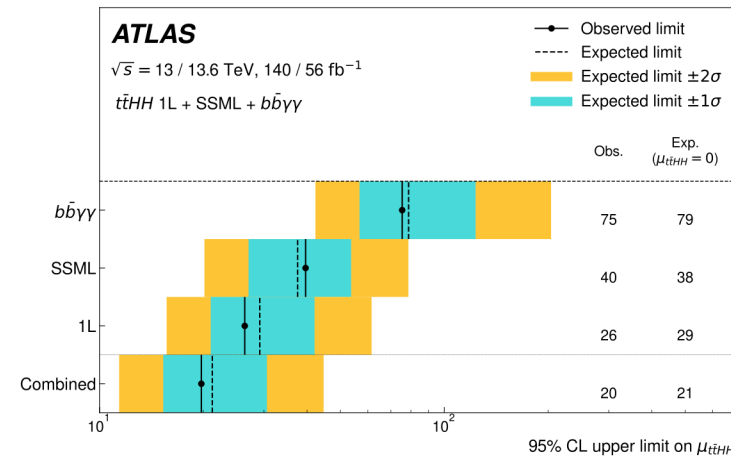
- 2 same-sign leptons or ≥ 3 leptons + ≥ 2 b-jets
- cleaner topology
- Fit **transformer** output

Results: Largest sensitivity in 1L channel

- Observed(expected) upper limit: $\mu_{ttHH} < 20(21)$ at 95% CL.
- $c_{ttHH} \in [-3.9, 3.3]$.



ATLAS ggFHH Run2: $c_{ttHH} \in [-0.19, 0.7]$.



Can we access HHH? Run 2 HHH(6b)

HHH production gives us direct access to the quartic Higgs self-coupling k_4

HHH $\rightarrow$ 6b uses the largest branching-fraction final state

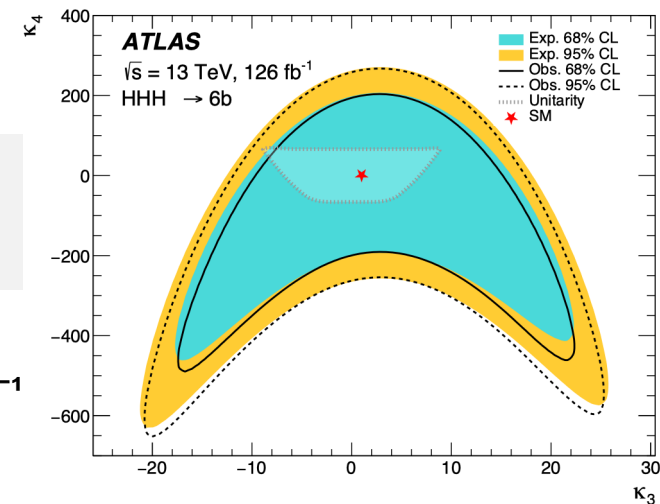
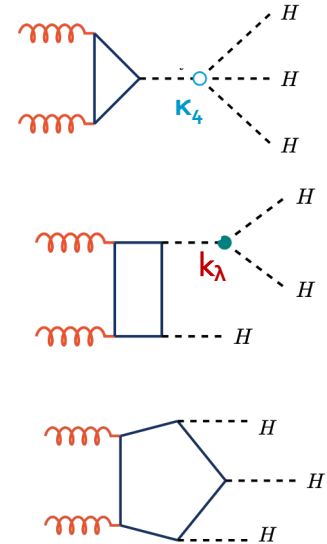
- In Run2 dataset (126 fb $^{-1}$), **expect only 1.94 HHH events** before selections.
- Enormous **QCD multijet + heavy-flavour background**, with large combinatorics from assigning six b-jets to three Higgs candidates.

Analysis strategy

- **4b, 5b and 6b regions** define background and signal-enriched regions.
- Multijet background estimated from data by extrapolating from the 4b/5b CR into the 6b SR. Background modelling is largest uncertainty.
- A **DNN classifier** is used to distinguish HHH-like six-b-jet topology from multijet background. Final fit to DNN score.

Results:

- Upper limit: observed $\sigma_{\text{HHH}} < 59 \text{ fb}$, corresponding to $\mu_{\text{HHH}} < 760$.
- First ATLAS constraints in the k_λ - k_4 plane.
- Recent CMS HHH $\rightarrow$ 6b result: observed $\sigma_{\text{HHH}} < 44 \text{ fb}$ with 138 fb^{-1}



High-Luminosity LHC Projections

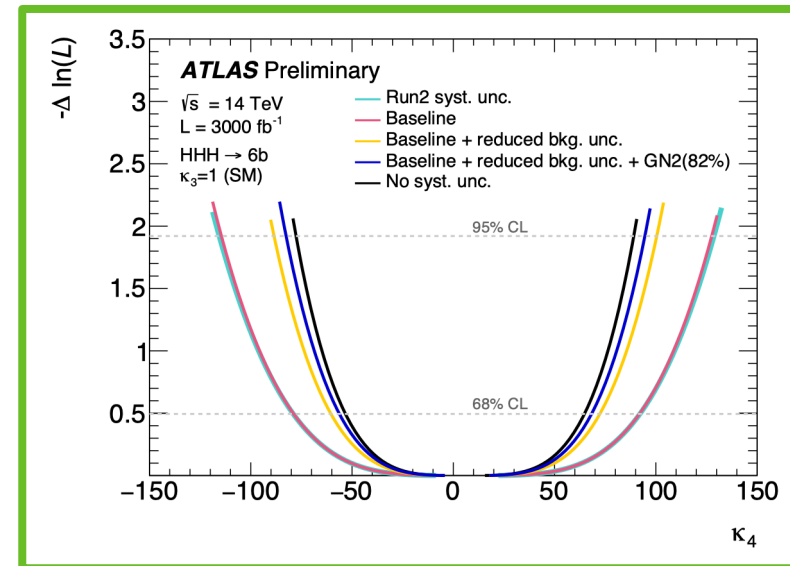
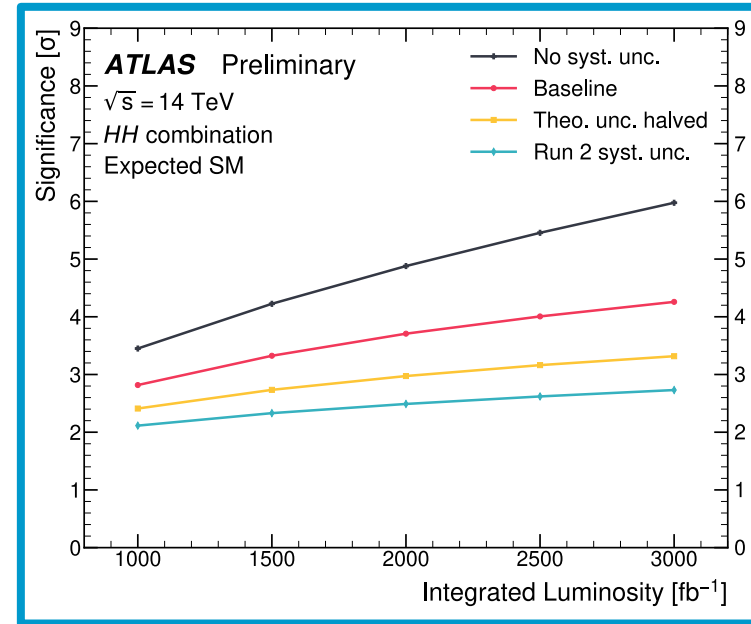
Prospects for di-Higgs with ATLAS at HL-LHC:

- Extrapolations from 6 Run2 ATLAS Analyses to 3000 fb⁻¹ @ $\sqrt{s} = 14$ TeV
- O(10⁵) SM HH events produced.
- Expected discovery significance: 4.26 σ
- Expected k_λ measured as $1.0^{+0.48}_{-0.42}$
 - Driven by bb $\tau\tau$ and bbyy
- Expected k_{2V} measured as $1.0^{+0.18}_{-0.15}$
 - Driven by boosted VBF HH(bbbb)
- Does not fully capture possible gains from future analysis optimization.

HHH(6b) HL-LHC Projections:

O(60) HHH $\rightarrow$ 6b events produced.

- κ_4 95% CL: [-84, 96] with syst.
- κ_4 95% CL: [-79, 90] without syst.



Summary

- **HH production directly probes the Higgs potential**, with complementary final states mapping different regions of m_{HH} , object topology, and coupling sensitivity.
- With **Run2 HH searches largely complete**, the ATLAS+CMS combination provides a strong constraint on HH production and Higgs self-interaction
 - **1.1σ observed** significance for SM HH production.
- New **Run2 + partial Run3 ATLAS** results already reach **Run2 combination-level sensitivity** in key final states, helped by improved reconstruction, flavour tagging and categorisation.
- **HHH searches** begin the experimental path toward **κ_4** but remain limited by tiny rates.

Many more Run3 results on the way!

Working toward **HH discovery at the HL-LHC**, where HH is expected to become an evidence-level measurement program with meaningful constraints on the Higgs potential.