

Probing the Higgs Potential at Colliders

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**YETI 2026: Precision x Collider
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Standard Model of Particle Physics

Theory proposed in the decade of 1970

Describes the elementary particles and their interactions

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	≈4.8 MeV/c ²	≈95 MeV/c ²	≈4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	0	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	±1	
	0	0	0	1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
				GAUGE BOSONS	

Matter: particles spin 1/2 (fermions)

- Three generations of **quarks** and **leptons** (same quantum numbers, only differ in mass)

Carriers: particles spin 1 (vector bosons)

- Strong (QCD)** interaction
group of gauge symmetry **SU(3)_c**
- Electroweak (EW)** interaction
group of gauge symmetry **SU(2)_L × U(1)_Y**
- 12 gauge fields: 8 gluons, W[±], Z, γ
- 3 gauge couplings: g₁, g₂, g₃

Scalar sector: **Higgs boson** spin 0

- Electroweak symmetry breaking (EWSB)**
Brout-Englert-Higgs mechanism confers mass to the W and Z bosons: **SU(2)_L × U(1)_Y → U(1)_{em}**
- Yukawa coupling** between Higgs and fermions, unique interaction which distinguishes between the three generations of fermions

Standard Model of Particle Physics

ATL-PHYS-PUB-2024-011

Status: June 2024

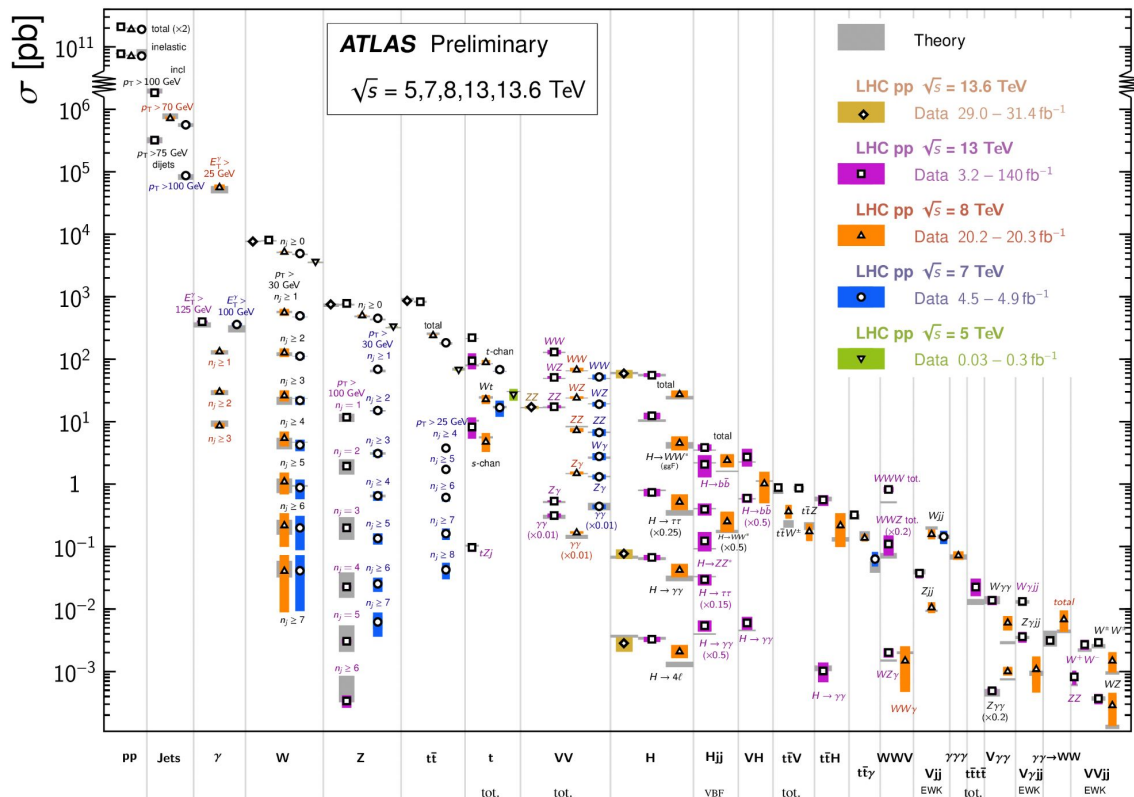
Large Hadron Collider (LHC)

“The Energy Frontier”

- Large variety of measurements at energies of 5, 7, 8, 13, 13.6 TeV
- 10 orders of magnitude in cross section measured
- Precision $\gtrsim 5\%$
- Effective theory at “low energies” (EW scale $\sim M_Z$)
- Assuming to be valid at high energies

Future Colliders will be able to reach up to 100 TeV

Standard Model Production Cross Section Measurements



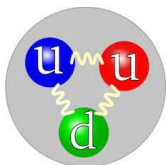
Unresolved questions

➤ Origin of dark matter and dark energy

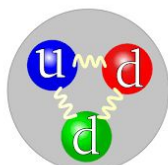
Standard Model matter in the universe $< 5\%$

➤ Matter-antimatter asymmetry

Preponderance of matter in the universe



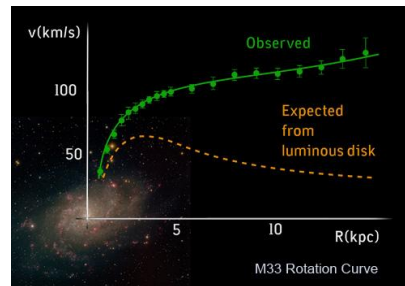
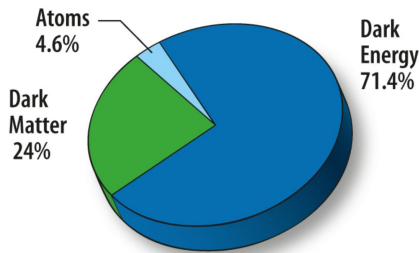
Proton



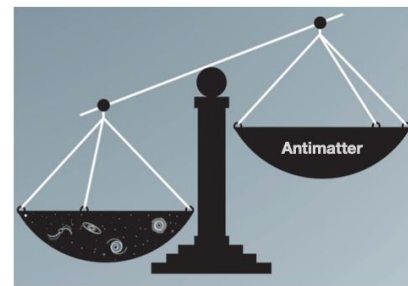
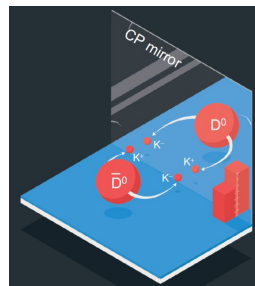
Neutron

➤ Unification of forces (Grand Unified Theory)

gravity not described in quantum field theory (only QCD and EW)



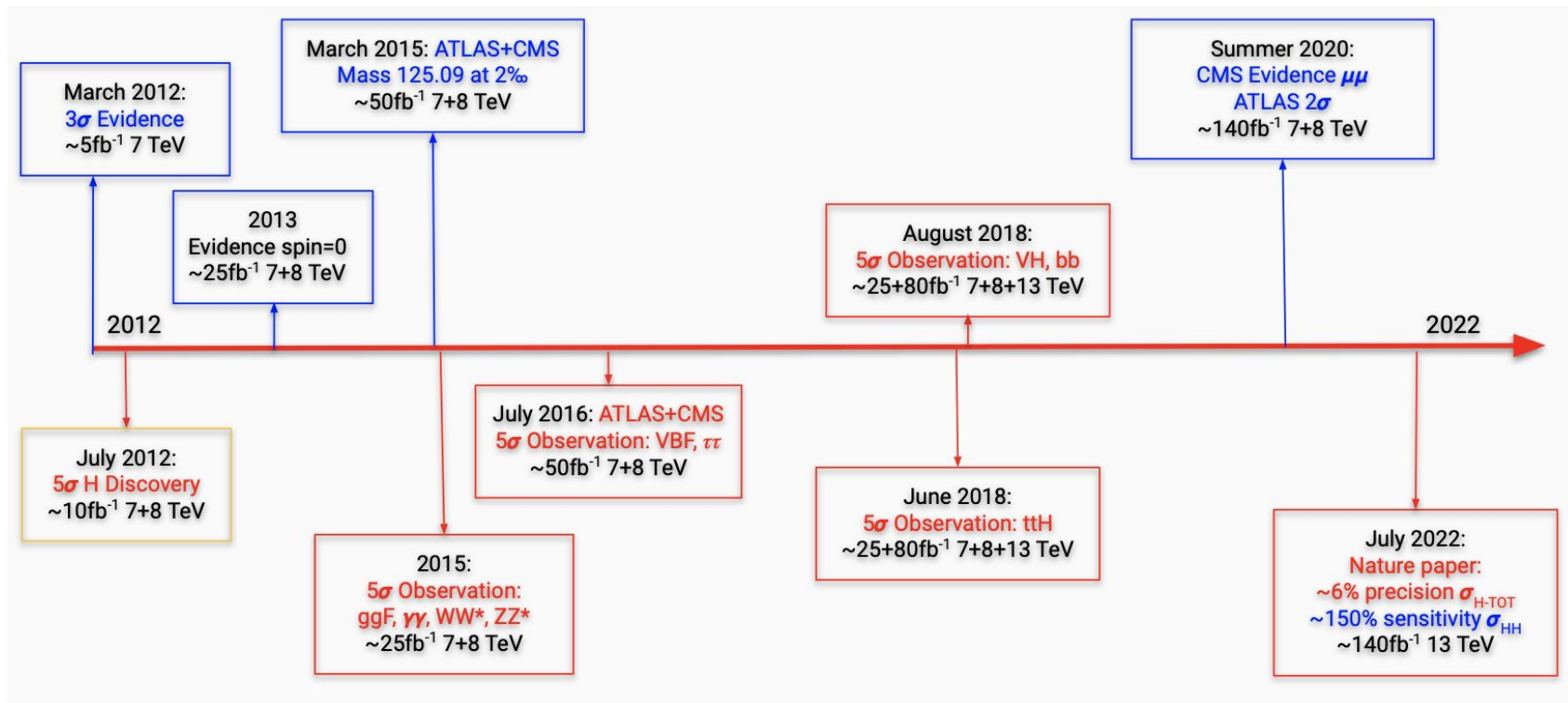
Cosmological observations



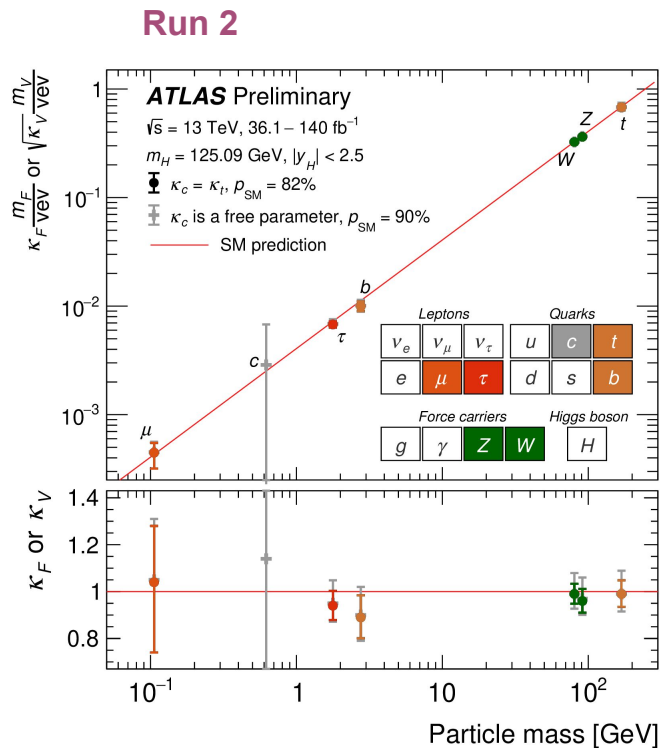
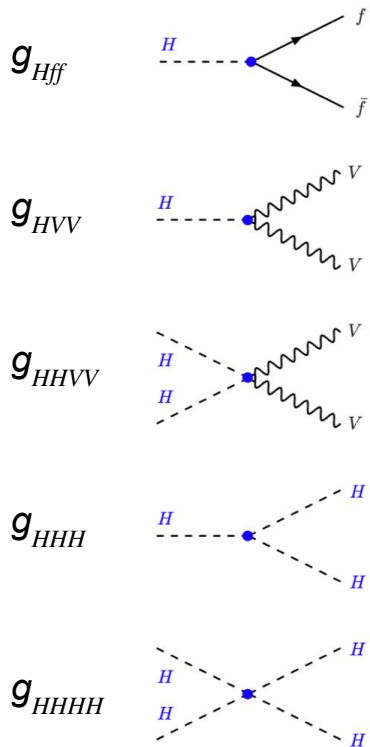
- **Mass pattern and mixing angles** not explained
 - Masses expand in > 5 orders of magnitude!
 - No reason for only three generations of fermions
- **No mass term for the neutrinos in the SM Lagrangian** (observed experimentally in the neutrino oscillations)

Higgs sector in the first decade after discovery

A new era in particle physics and cosmology



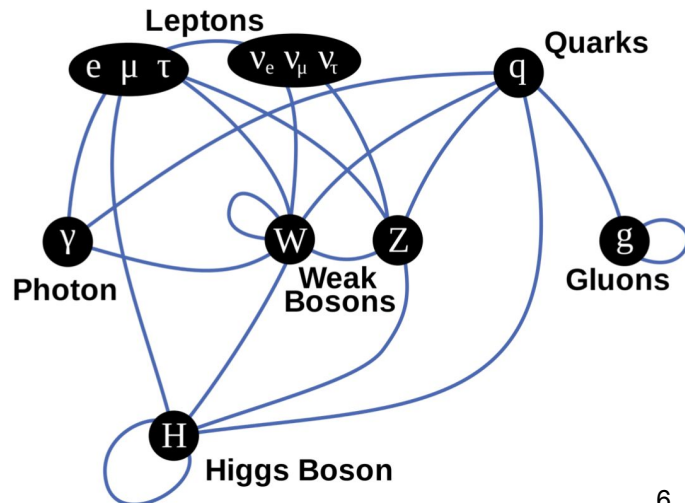
Higgs boson - couplings



[ATLAS-CONF-2025-006](#)

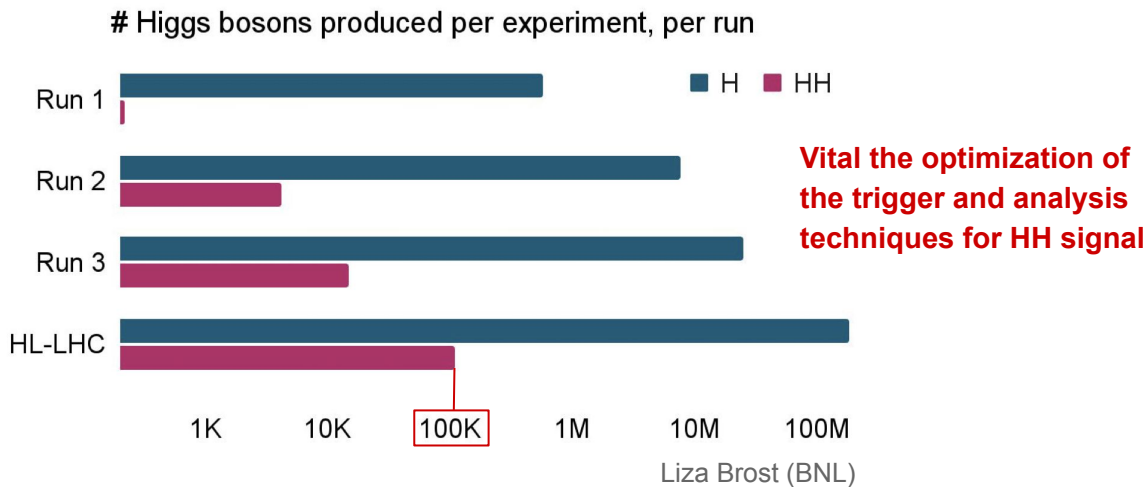
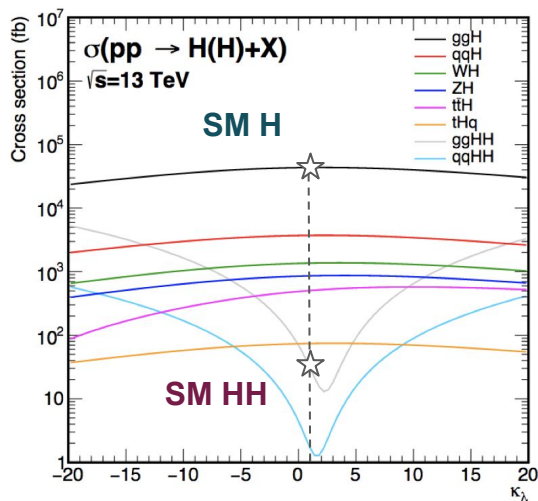
Most of the Higgs boson couplings well established, but still remaining & expected at the HL-LHC:

- $H \rightarrow \mu\mu, Z\gamma$ couplings at 3% and 7%
- Charm Yukawa coupling of 1.5xSM
- Higgs boson self-coupling at 30%



DiHiggs production - not observed experimentally (yet)

DiHiggs production x1000 smaller than single Higgs production in the Standard Model



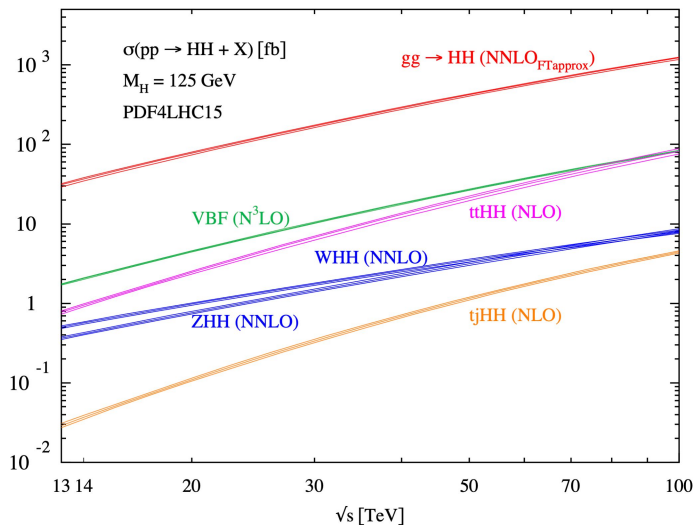
Higgs sector as a portal to new physics BSM:

- **Loop corrections** including new particles
- **Anomalous couplings** between the Higgs boson and other Standard Model particles
- **New resonances** $X \rightarrow HH$ (motivated by BSM theories)

DiHiggs production mechanisms

- Main diHiggs production modes at hadron colliders:
 - **ggF HH**: gluon-gluon fusion, dominant production mechanism (> 90%)
 - **VBF HH**: vector-boson fusion, second largest production mechanism ($qq \rightarrow HHqq$)
 - **VHH**: double Higgs-strahlung, associated production of HH with a W or Z boson
 - **ttHH**: double Higgs bremsstrahlung off top quarks, associated production of HH with top quark pairs

Cross sections in fb, HH white paper ([arXiv:1910.00012](https://arxiv.org/abs/1910.00012))



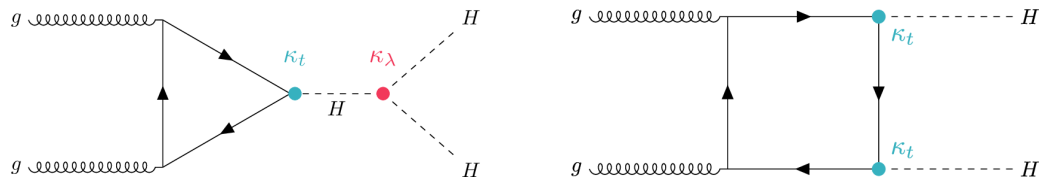
$\sqrt{s}$	13 TeV	14 TeV
ggF HH	$31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$	$36.69^{+2.1\%}_{-4.9\%} \pm 3.0\%$
VBF HH	$1.73^{+0.03\%}_{-0.04\%} \pm 2.1\%$	$2.05^{+0.03\%}_{-0.04\%} \pm 2.1\%$
ZHH	$0.363^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.415^{+3.5\%}_{-2.7\%} \pm 1.8\%$
$W^+ HH$	$0.329^{+0.32\%}_{-0.41\%} \pm 2.2\%$	$0.369^{+0.33\%}_{-0.39\%} \pm 2.1\%$
$W^- HH$	$0.173^{+1.2\%}_{-1.3\%} \pm 2.8\%$	$0.198^{+1.2\%}_{-1.3\%} \pm 2.7\%$
$t\bar{t}HH$	$0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$	$0.949^{+1.7\%}_{-3.1\%} \pm 3.1\%$
$t j HH$	$0.0289^{+5.5\%}_{-3.6\%} \pm 4.7\%$	$0.0367^{+4.2\%}_{-1.8\%} \pm 4.6\%$

Superseded by [LHCHWG Report 5](#)

SM DiHiggs production

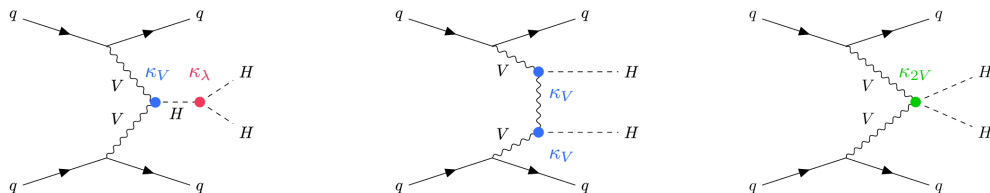
ggF HH

(dominant production $\sim 90\%$)



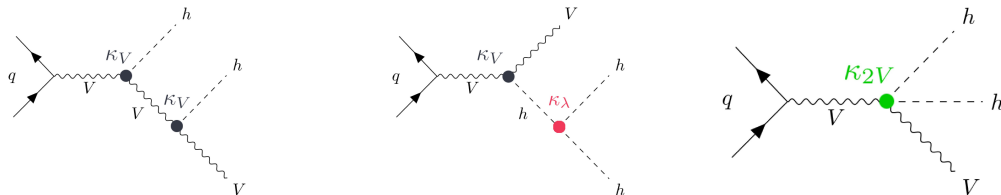
VBF HH

(subdominant production $\sim 5\%$)



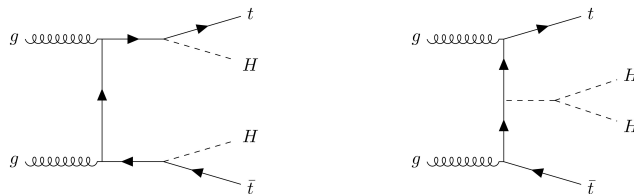
VHH

(rare production $\sim 2.5\%$)



ttHH

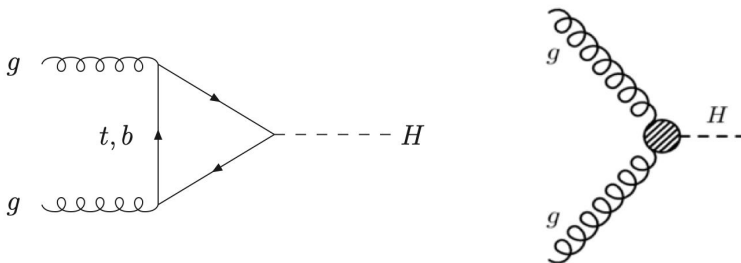
(rare production $\sim 2\%$)



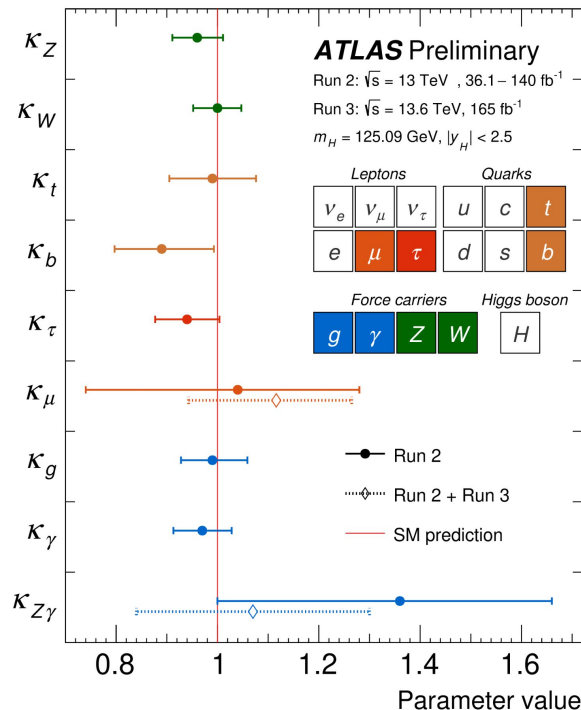
Looking at deviations from the Standard Model

Kappa framework

- Parametrization of possible deviations of the Higgs boson couplings from the SM
- **Coupling modifiers κ_i** are introduced for the Higgs couplings to other particles with the SM hypothesis corresponding to 1
 - **resolved parametrization:** expressed as a function of other modifiers
 - **effective parametrization:** considered as independent parameters in the fit, also introduced to describe effective Higgs interactions with gluons (Hgg), photons ($H\gamma\gamma$) and the combined interaction with a photon and a Z boson ($HZ\gamma$)



[ATLAS-CONF-2025-006](#)



Looking at deviations from the Standard Model

Higgs Effective Field Theory (HEFT)

- In the HEFT Lagrangian, ggF HH production described at LO by 5 relevant operators and their associated **Wilson coefficients** c_i

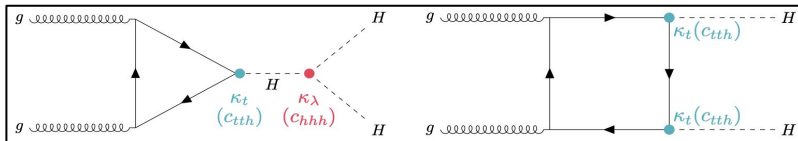
$$C_{hhhh}, C_{tth}, C_{tthh}, C_{ggh}, C_{gghh}$$

$$C_{hhhh} = \kappa_\lambda$$

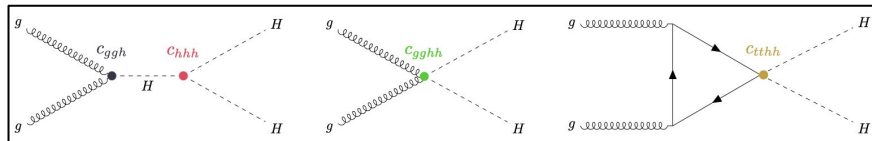
$$C_{tth} = \kappa_t$$

$$\text{In the SM } C_{ggh} = C_{gghh} = C_{tthh} = 0$$

SM diagrams

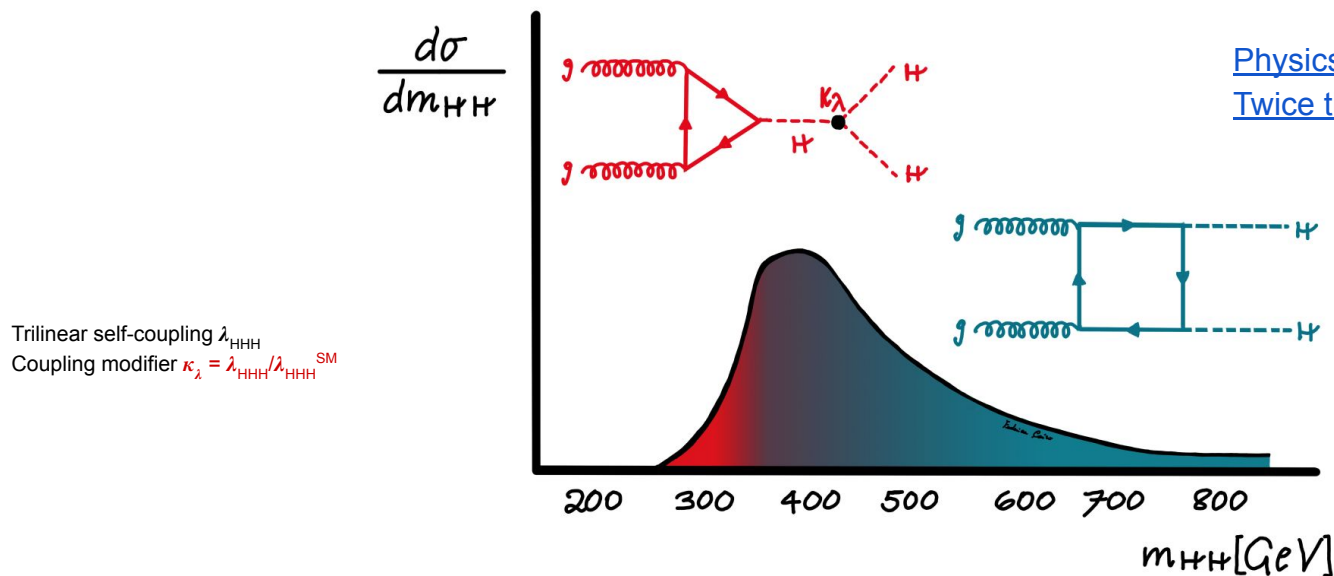


non-SM HEFT diagrams

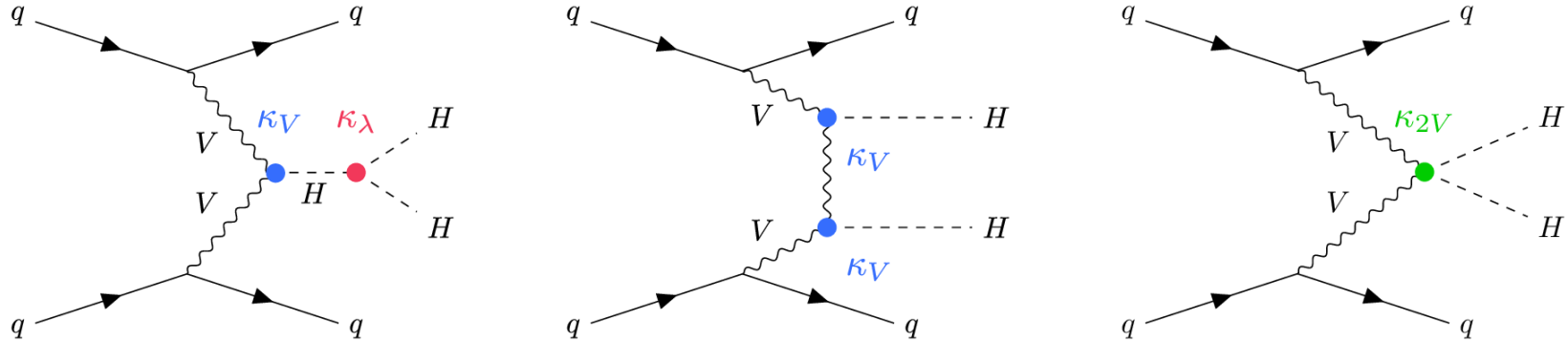


SM HH production: ggF

- **Destructive interference** between the triangle and box diagrams
- Only the **triangle diagram** includes the **Higgs boson self-coupling**, and it contributes mainly to the production of Higgs pairs at low mass
- m_{HH} cut in 350 GeV typically used in the $HH \rightarrow b\bar{b}\gamma\gamma$ and $HH \rightarrow b\bar{b}\tau\tau$ channels to increase sensitivity in κ_λ
- $HH \rightarrow b\bar{b}\gamma\gamma$ is the most powerful decay channel in the important low-mass region



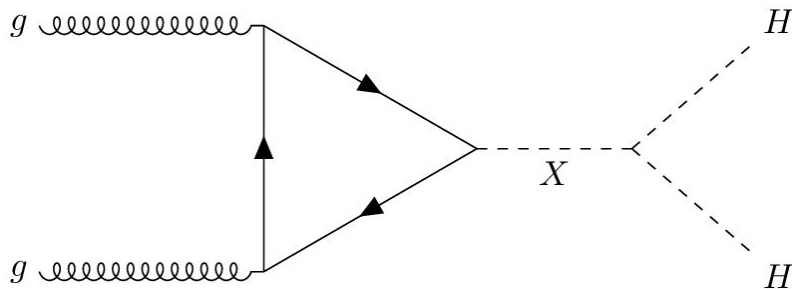
SM HH production: VBF



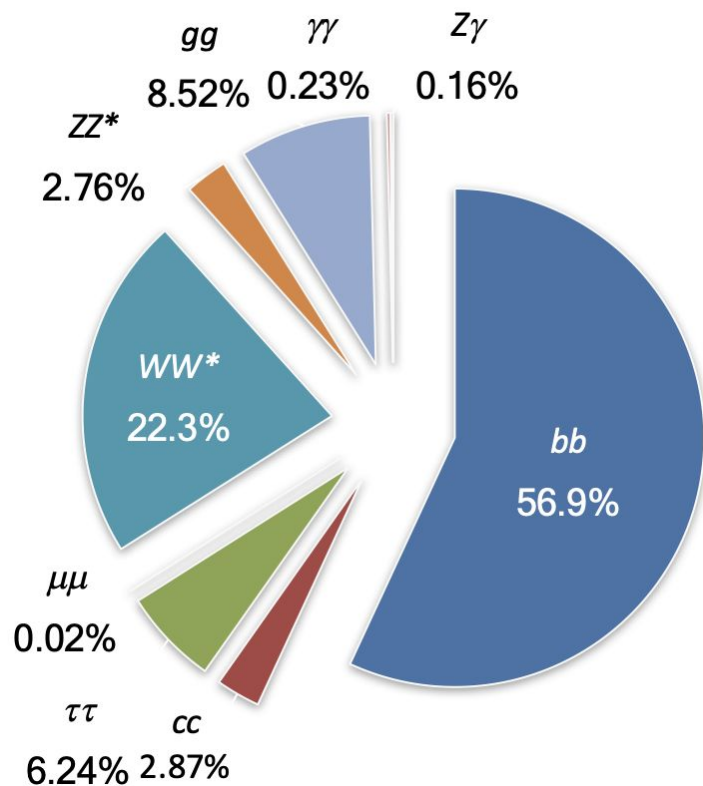
- VBF HH production mode sensitive to both κ_λ and κ_{2V}
- VBF production cross-section depends critically on the value of κ_{2V} due to **destructive interference between the two right diagrams**, a value of $\kappa_{2V} = 0$ would lead to a cross-section of 15 x SM prediction
- Higgs bosons produced in **non-SM κ_{2V} scenarios are expected to be more energetic** and more central in the detector on average relative to the SM $\kappa_{2V} = 1$, resulting in higher acceptances and selection efficiencies

BSM HH production

- **HH non-resonant production ($pp \rightarrow HH$)** enhancements can originate from:
 - Loop corrections involving new particles
 - Through non-SM couplings between the Higgs boson and other SM particles
 - Through alteration of the trilinear self-coupling $\lambda_{HHH} \rightarrow$ limits derived on the Higgs boson trilinear coupling modifier: $\kappa_\lambda = \lambda_{HHH} / \lambda_{SM\ HHH}$
- Searching for **HH resonant production ($pp \rightarrow X \rightarrow HH$)** well motivated by different BSM theories (Two Higgs Doublet Model, MSSM, Randall-Sundrum model of warped extra dimensions, etc.)



HH decay channels



Very rich set of final states

Most relevant channels: $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$

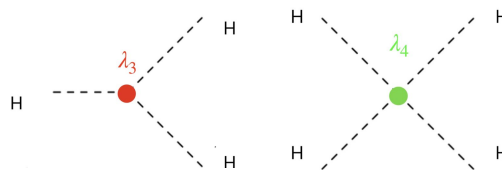
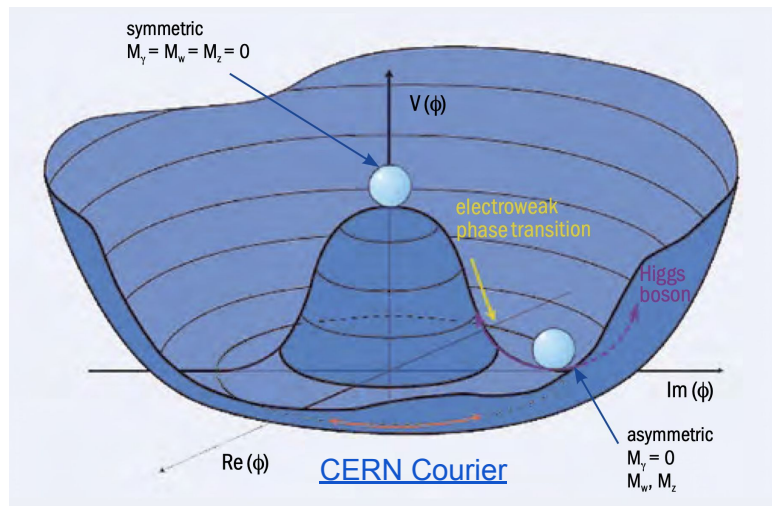
	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

Why the Higgs boson self-coupling is so important?

Higgs potential

$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 = \underbrace{\frac{1}{2} m_h^2 h^2}_{\text{Mass term}} + \underbrace{\lambda_3 h^3}_{\text{Higgs trilinear self-coupling}} + \underbrace{\lambda_4 h^4}_{\text{Higgs quartic self-coupling}}$$

Transition of the Higgs field to the minimum responsible for the electroweak symmetry breaking mechanism



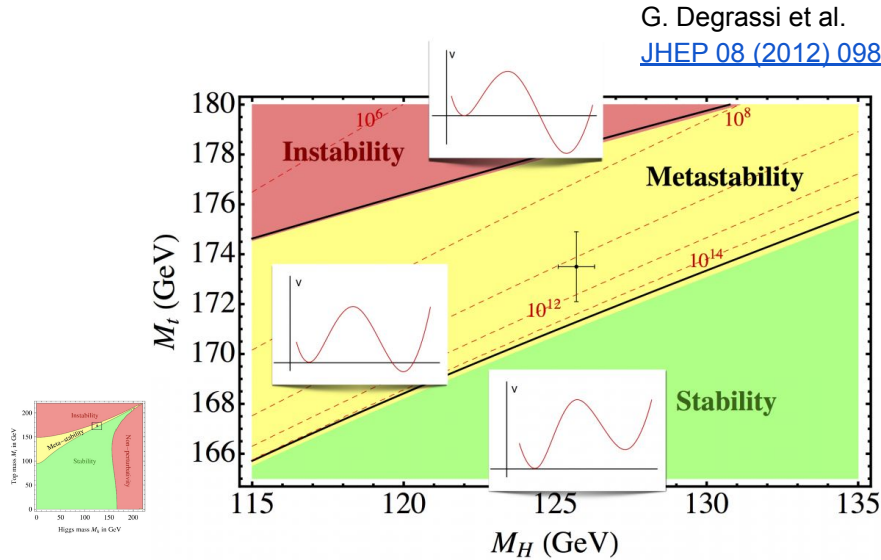
The Higgs field has different vacuum states:

At high energy (**false vacuum**) → unstable local maximum

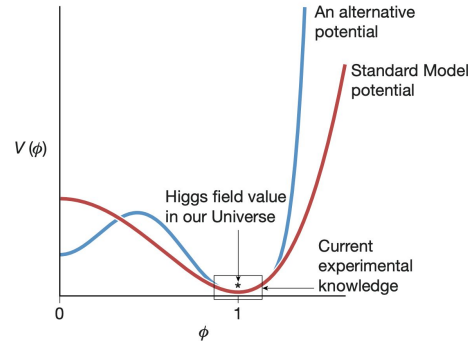
At low energy (**true vacuum**) → current universe

Higgs potential - vacuum stability of the universe

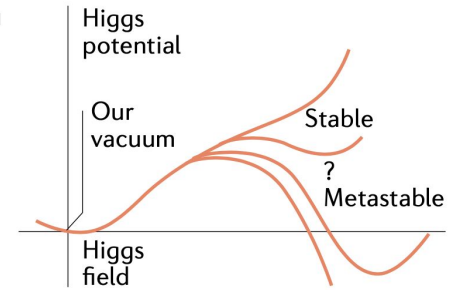
- The Standard Model could have a second “true” minimum (metastability of the universe)
- If there is a deeper minimum, transition can happen via quantum tunnelling



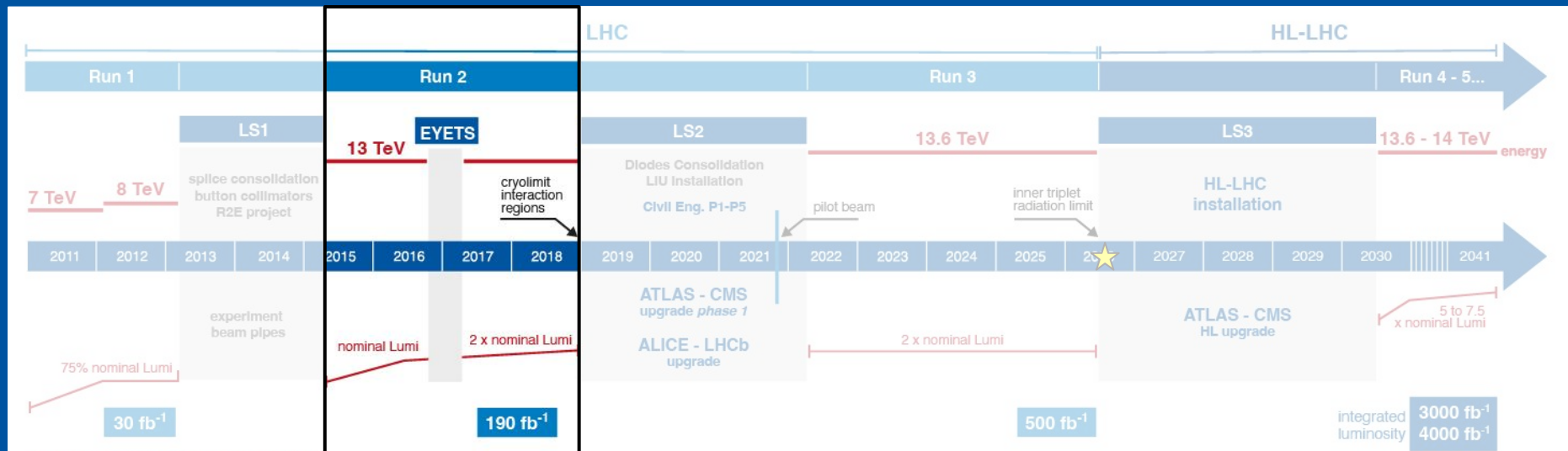
G. Salam, L-T Wang, G. Zanderighi
[Nature 607, 41–47 \(2022\)](#)



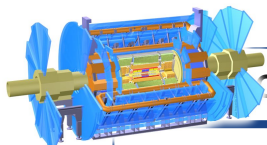
S. Bass, A. De Roeck, M. Kado
[Nature 3, 608–624 \(2021\)](#)



DiHiggs searches in Run 2



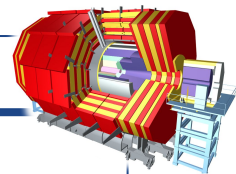
DiHiggs searches - Legacy Run 2 results



Channel	Run 2 (126-140 fb ⁻¹)
HH → bbll + E _{T,miss}	JHEP 02 (2024) 037
HH → Multilepton	JHEP 08 (2024) 164
HH → bbbb res ggF+VBF boosted VBF	PRD 108 (2023) 052003 PLB 858 (2024) 139007
HH → bbγγ	JHEP 01 (2024) 066
HH → bbττ	PRD 110 (2024) 032012
Combination	PRL 133 (2024) 101801

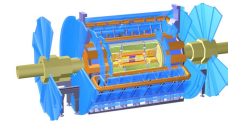
ATLAS + CMS Comb.	arXiv:2602.23991 NEW
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Orthogonality of the event selections ensured to be able to combine the results

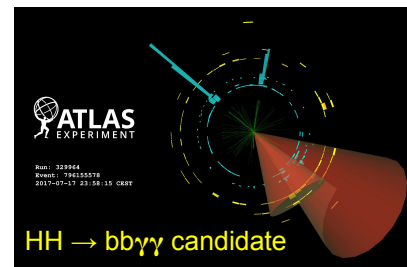
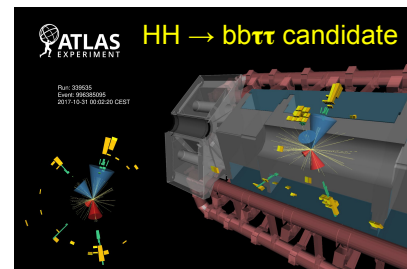
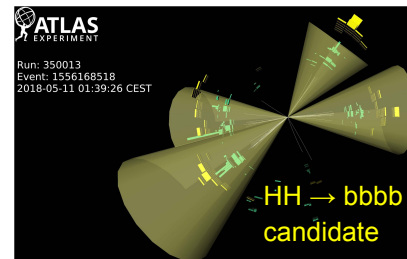


Channel	Run 2 (138 fb ⁻¹)
HH → WWγγ	-
HH → bbZZ, 4l	JHEP 06 (2023) 130
HH → γγττ	JHEP 05 (2026) 186
HH → Multilepton	JHEP 07 (2023) 095
HH → bbWW	JHEP 07 (2024) 293
HH → bbγγ	JHEP 03 (2021) 257
HH → bbττ	PLB 842 (2023) 137531
resolved HH → bbbb boosted VHH	PRL 129 (2022) 081802 PRL 131 (2023) 041803 JHEP 10 (2024) 061
Combination	arXiv:2510.07527

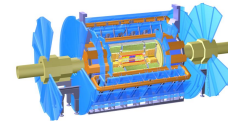
ATLAS Run 2 HH combination



- Most sensitive channels:
 - $HH \rightarrow bbbb$ largest BR (34%), affected by the overwhelming QCD background
 - $HH \rightarrow b\bar{b}\tau\tau$ BR (7.3%), compromise between signal yield & background contamination
 - $HH \rightarrow b\bar{b}\gamma\gamma$ small BR (0.26%), clean experimental signature, good resolution
- New channels included (4% sensitivity increase):
 - $HH \rightarrow \text{Multilepton}$
 $bbZZ^* / VV^*VV^* / VV^*\tau\tau / \tau\tau\tau\tau / \gamma\gamma VV^* / \gamma\gamma\tau\tau$ where $V = W, Z$ with BR of 6.5%
 - $HH \rightarrow b\bar{b}\ell\ell + E_{T,\text{miss}}$
 $bb + WW^* / ZZ^* / \tau^+\tau^-$ where $\ell = e, \mu$ with BR of 2.9%
- **Final discriminating variables** can be the **diHiggs invariant mass**, the **diphoton invariant mass** or **multivariate classifiers** used to separate signal from background

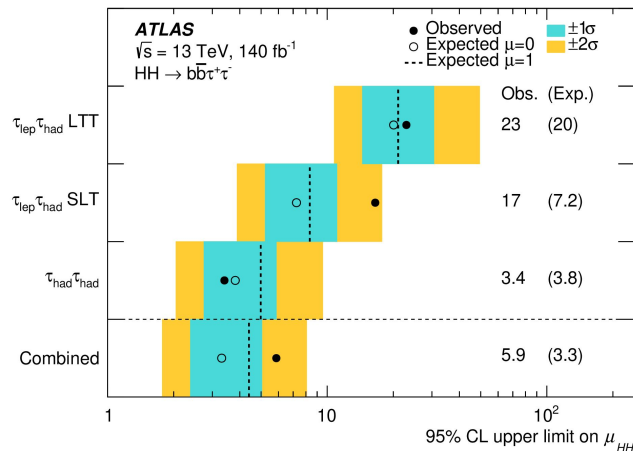
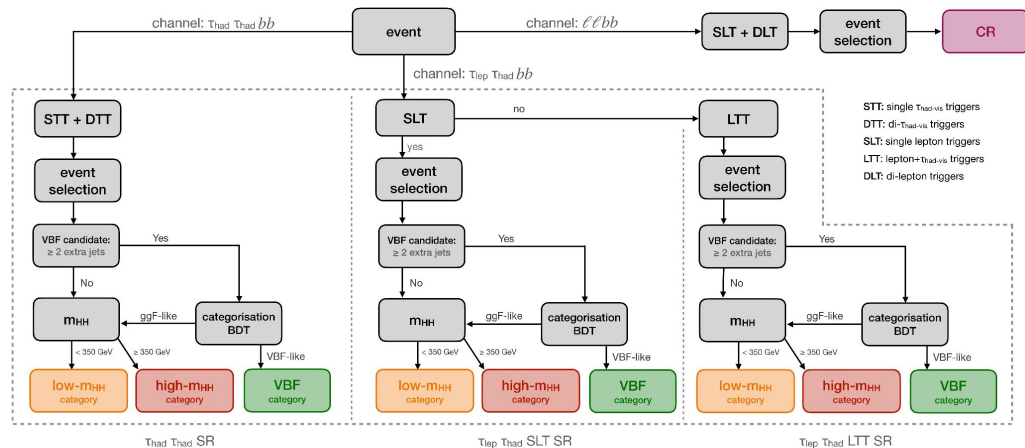
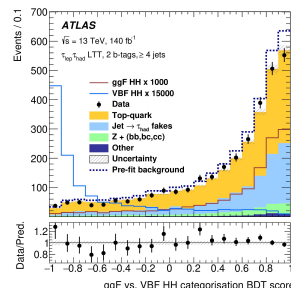
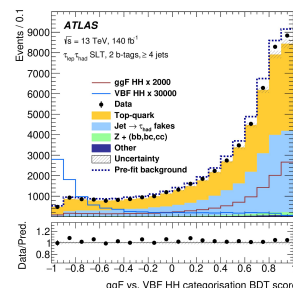
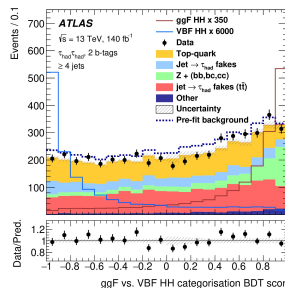


ATLAS Run 2 HH $\rightarrow$ $bb\tau\tau$

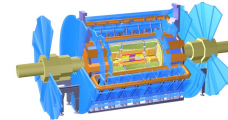


PRD 110 (2024) 032012

- **9 categories** defined:
 - 1 had-had and 2 lep-had (trigger dependent)
 - low $m_{HH} < 350$ GeV, high $m_{HH} > 350$ GeV and VBF
- BDTs to separate ggF from VBF production
- **Main backgrounds:** $t\bar{t}$, Z + hf jets and fake τ_{had} contribution
- **Limit:** 5.9 x SM prediction



ATLAS Run 2 HH $\rightarrow$ $b\bar{b}\gamma\gamma$

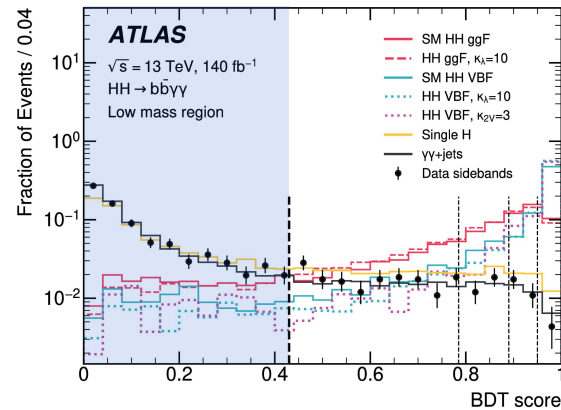
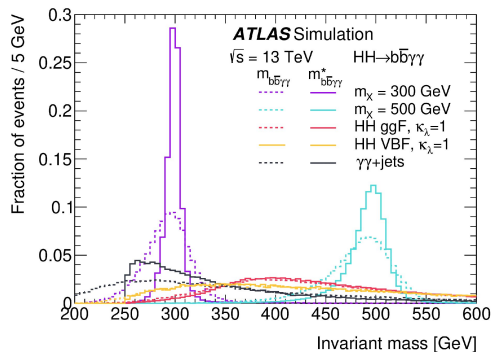


JHEP 01 (2024) 066

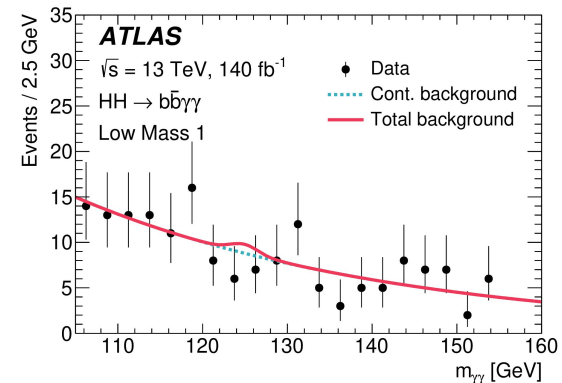
- 7 categories defined based on BDT score and the four-body invariant mass:

$$m_{b\bar{b}\gamma\gamma}^* = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125 \text{ GeV}) - (m_{\gamma\gamma} - 125 \text{ GeV})$$

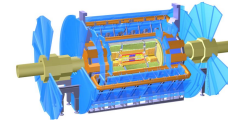
Category	Selection criteria
High Mass 1	$m_{b\bar{b}\gamma\gamma}^* \geq 350 \text{ GeV}$, BDT score $\in [0.545, 0.830]$
High Mass 2	$m_{b\bar{b}\gamma\gamma}^* \geq 350 \text{ GeV}$, BDT score $\in [0.830, 0.905]$
High Mass 3	$m_{b\bar{b}\gamma\gamma}^* \geq 350 \text{ GeV}$, BDT score $\in [0.905, 1.000]$
Low Mass 1	$m_{b\bar{b}\gamma\gamma}^* < 350 \text{ GeV}$, BDT score $\in [0.430, 0.785]$
Low Mass 2	$m_{b\bar{b}\gamma\gamma}^* < 350 \text{ GeV}$, BDT score $\in [0.785, 0.890]$
Low Mass 3	$m_{b\bar{b}\gamma\gamma}^* < 350 \text{ GeV}$, BDT score $\in [0.890, 0.950]$
Low Mass 4	$m_{b\bar{b}\gamma\gamma}^* < 350 \text{ GeV}$, BDT score $\in [0.950, 1.000]$



- Main backgrounds: $\gamma\gamma$ + jets and $H \rightarrow \gamma\gamma$
- Signal Region: $120 < m_{\gamma\gamma} < 130 \text{ GeV}$
- Side Bands: $105 < m_{\gamma\gamma} < 120 \text{ GeV}$, $130 < m_{\gamma\gamma} < 160 \text{ GeV}$
- $m_{\gamma\gamma}$ discriminant parametrization:
 - Double-sided Crystal Ball function for HH signal and single H background
 - Exponential for background (normalized to SBs)
- Limit: 4.0 x SM prediction

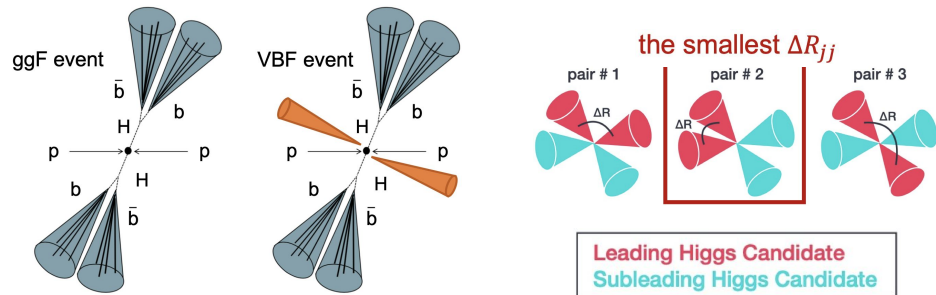


ATLAS Run 2 HH $\rightarrow$ bbbb



PRD 108 (2023) 052003

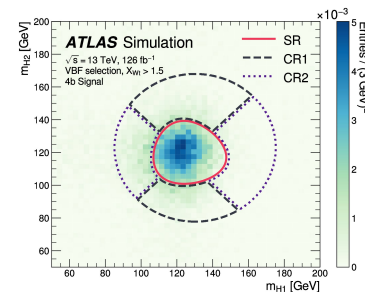
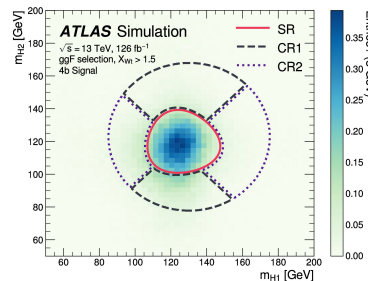
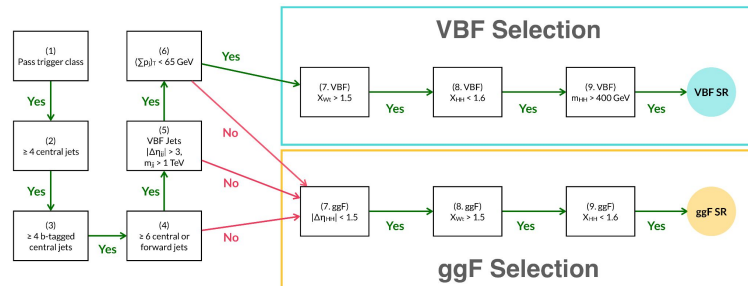
- Two orthogonal regions targeting ggF and VBF



- Main backgrounds: multijet ($\sim 90\%$) and $t\bar{t}$ ($\sim 10\%$)
- Suppress multijet and $t\bar{t}$ using $|\Delta\eta_{HH}| < 1.5$ and top veto variable $\chi_{Wt} > 1.5$
- Signal Region using an ellipse in the mass plane $X_{HH} < 1.6$:

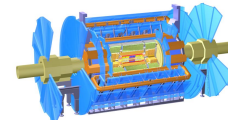
$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124 \text{ GeV}}{0.1 m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117 \text{ GeV}}{0.1 m_{H2}}\right)^2}$$

- Final discriminant: m_{HH} distribution
- Limit: 5.4 x SM prediction, $0.0 < \kappa_{2V} < 2.1$ at the 95% CL



	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
μ_{ggF}	5.5	4.4	5.9	8.2	12.4	19.6
μ_{VBF}	130	70	100	130	190	280
$\mu_{\text{ggF+VBF}}$	5.4	4.3	5.8	8.1	12.2	19.1

ATLAS Run 2 HH $\rightarrow$ bbbb VBF boosted regime

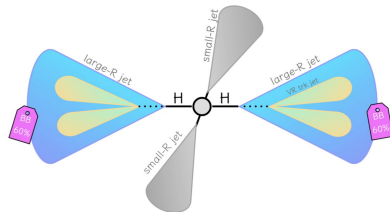


PLB 858 (2024) 139007

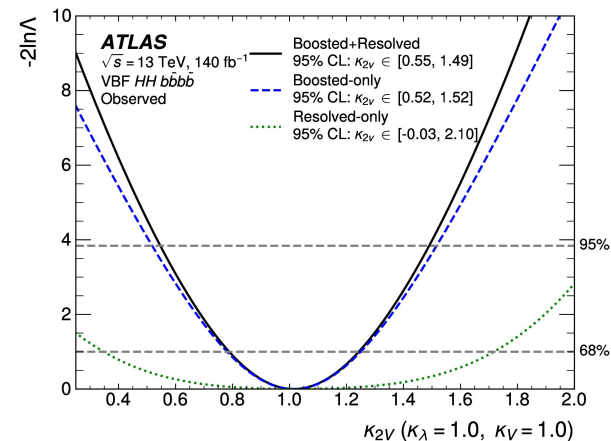
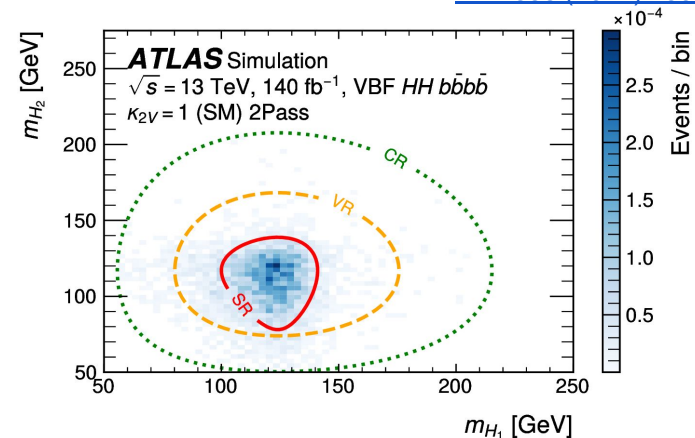
- Search for non-resonant and resonant VBF $HH \rightarrow bbbb$ production

- Boosted regime reconstruction:**

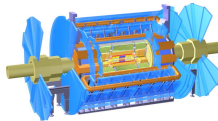
- HH system reconstructed with **2 large- R ($R = 1.0$) jets**
- VBF signature from 2 resolved small- R ($R = 0.4$) jets



- Data-driven background estimation
- Signal Region defined using an ellipse in the mass-plane
- BDT selection for further discrimination between signal & background
- To maximise the sensitivity to the κ_{2V} parameter, combined result with the VBF $HH \rightarrow bbbb$ resolved analysis [[PRD 108 \(2023\) 052003](#)]
- Constraint on $0.55 < \kappa_{2V} < 1.49$ at the 95% CL, $\kappa_{2V} = 0$ excluded with a significance of 3.8σ



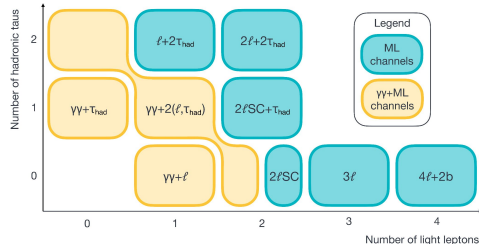
ATLAS Run 2 HH → Multilepton



- $HH \rightarrow bbZZ^* / VV^*VV^* / VV^*\tau^+\tau^- / \tau^+\tau^-\tau^+\tau^- / \gamma\gamma VV^* / \gamma\gamma\tau^+\tau^-$ (6.5% BR)

- **Two main categories:**

- **$\gamma\gamma$ + ML channel** (Diphoton plus multilepton): 3 sub-channels
- **ML channel** (light leptons and hadronic taus): 6 sub-channels



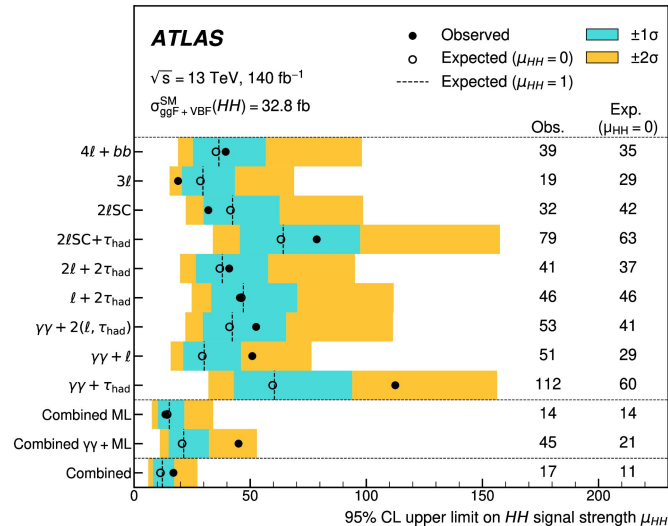
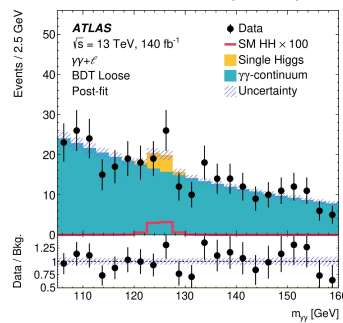
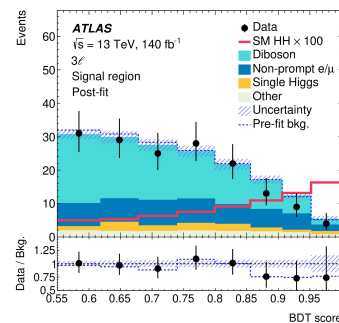
- **Dominant backgrounds:**

- For the $\gamma\gamma$ + ML channel is non-resonant $\gamma\gamma$ production
- For the ML channel is diboson production

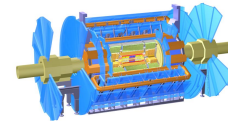
- **Final discriminant:**

- $m_{\gamma\gamma}$ distribution used in each $\gamma\gamma$ + ML SR
- BDT output score distribution used in each ML SR

- **Limit: 17 x SM prediction**

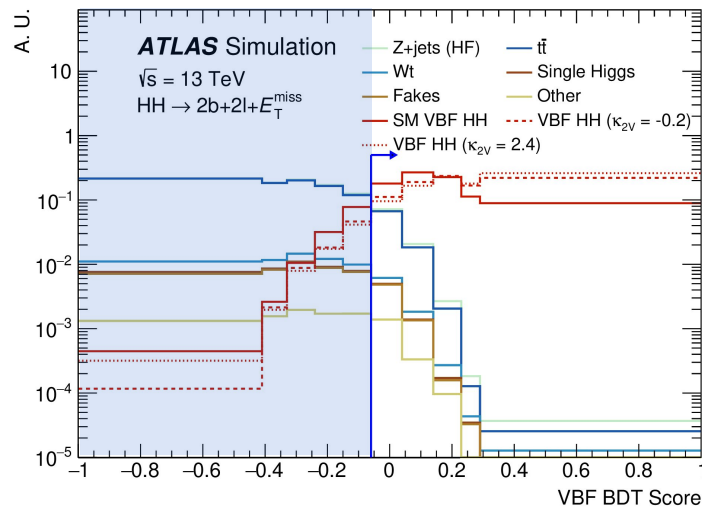
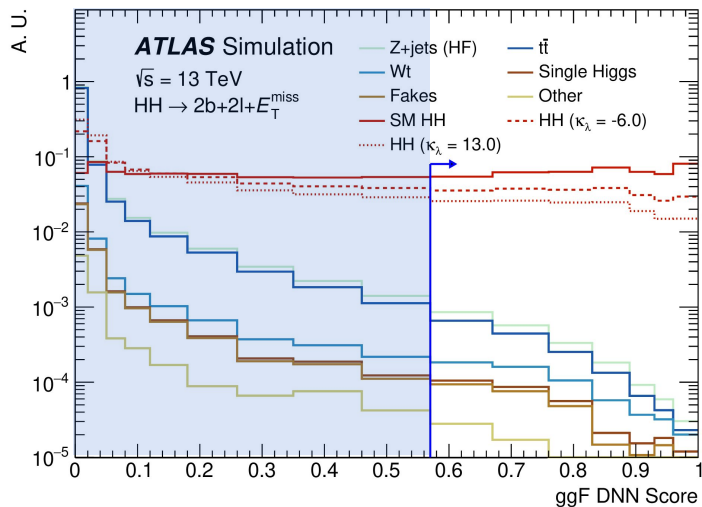


ATLAS Run 2 HH $\rightarrow$ $bb\ell\ell + E_{T,\text{miss}}$

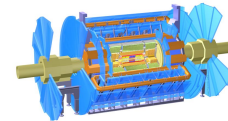


JHEP 02 (2024) 037

- $HH \rightarrow bb + WW^* / ZZ^* / \tau^+\tau^- \rightarrow bb + \ell\ell + \text{neutrinos}$ (2.9% BR)
- **Dominant backgrounds:** $t\bar{t}$, single top, Z + heavy flavour jets
- MVA selection to separate signal from background:
 - DNN to classify events in ggF
 - BDT to classify events in VBF (due to low stat)
- **Limit: 9.7 x SM prediction**



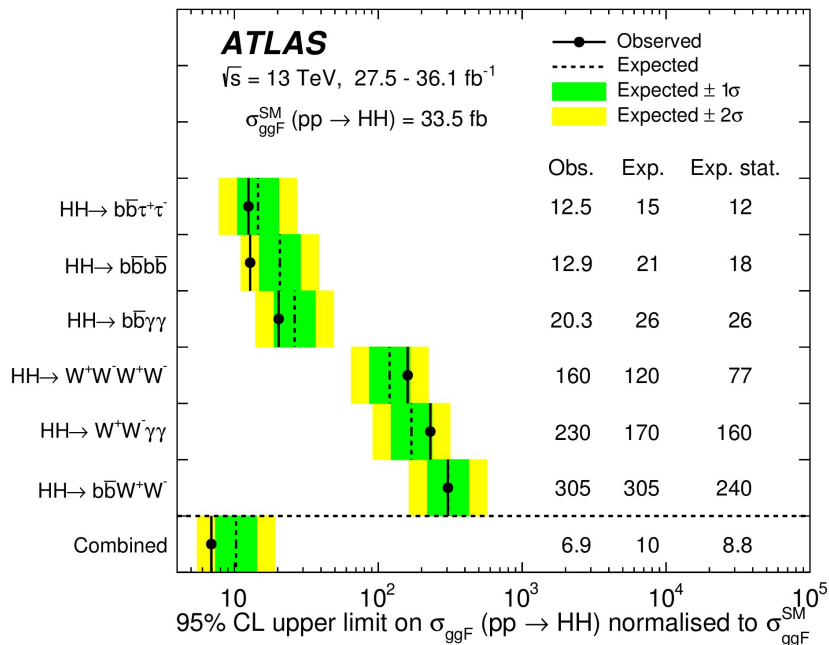
ATLAS Run 2 HH Combination



Combination of channels to achieve ultimate sensitivity

First batch (2015-2016)

36 fb⁻¹ [PLB 800 (2020) 135103]



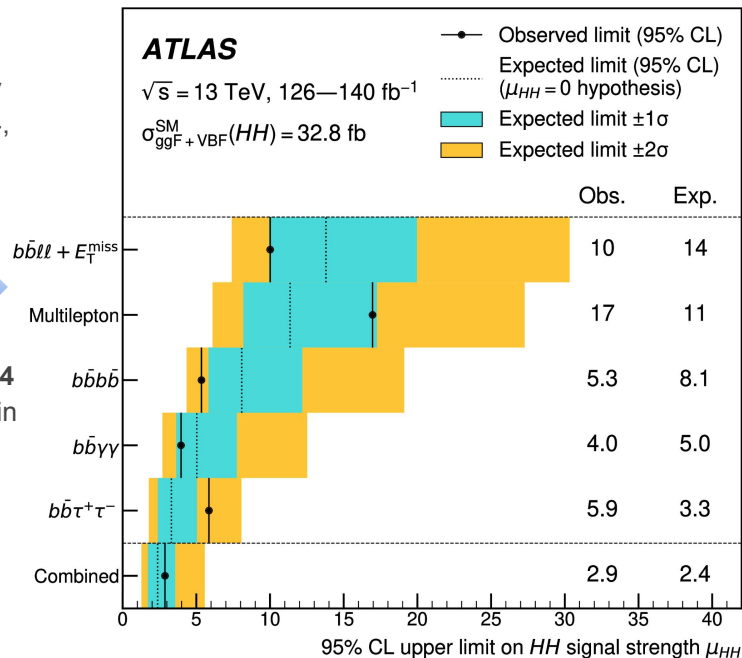
Obs. (exp.) 95% CL limit: 6.9 (10) x SM prediction

Integrated luminosity
increase by a factor 4,
leading to an
improvement of a
factor 2

Expected limits
improved by a **factor 4**
due to improvements in
analysis techniques

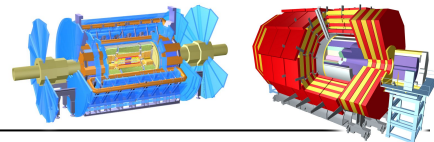
Second batch (2015-2018)

140 fb⁻¹ [PRL 133 (2024) 101801]



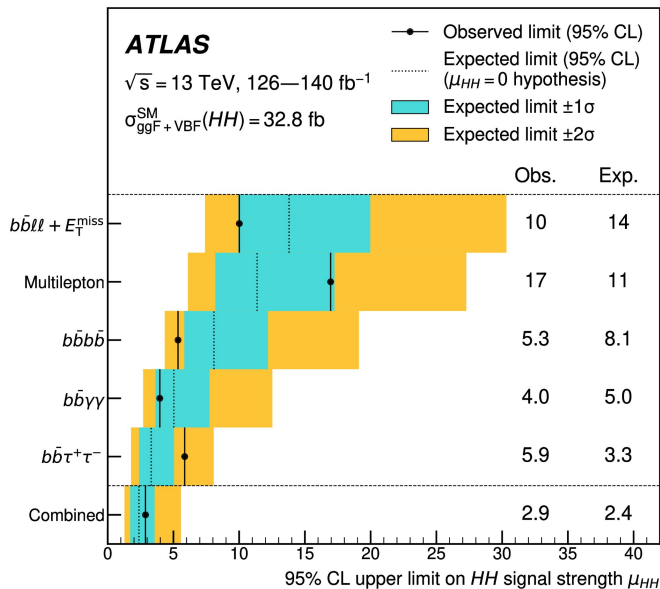
Obs. (exp.) 95% CL limit: 2.9 (2.4) x SM prediction 27

ATLAS+CMS Run 2 HH Combination

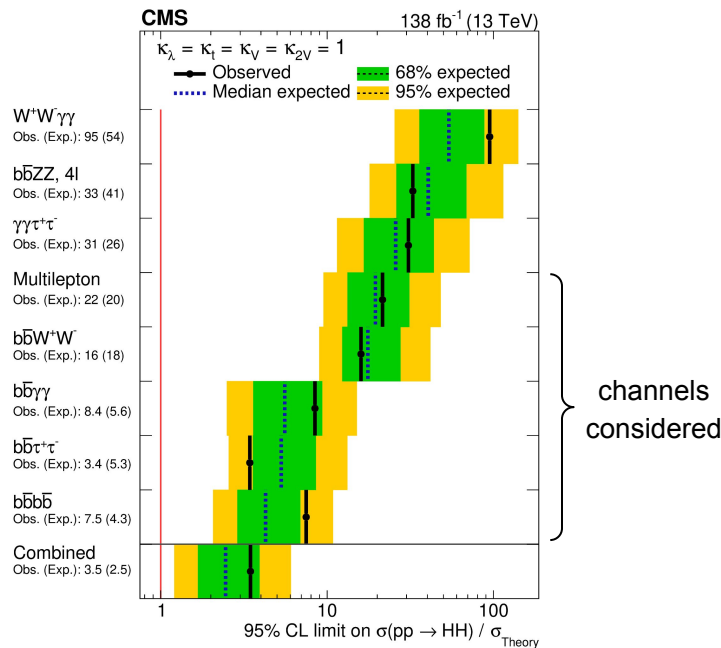


- All the ATLAS channels and the strongest channels from CMS included in the combination
- Missing CMS channels have an effect of $< 1\%$ on the κ_λ results

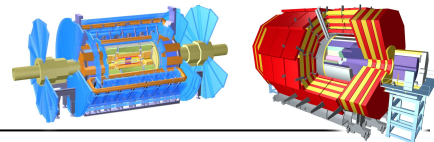
ATLAS [[PRL 133 \(2024\) 101801](#)]



CMS [[arXiv:2510.07527](#)]



ATLAS+CMS Run 2 HH Combination



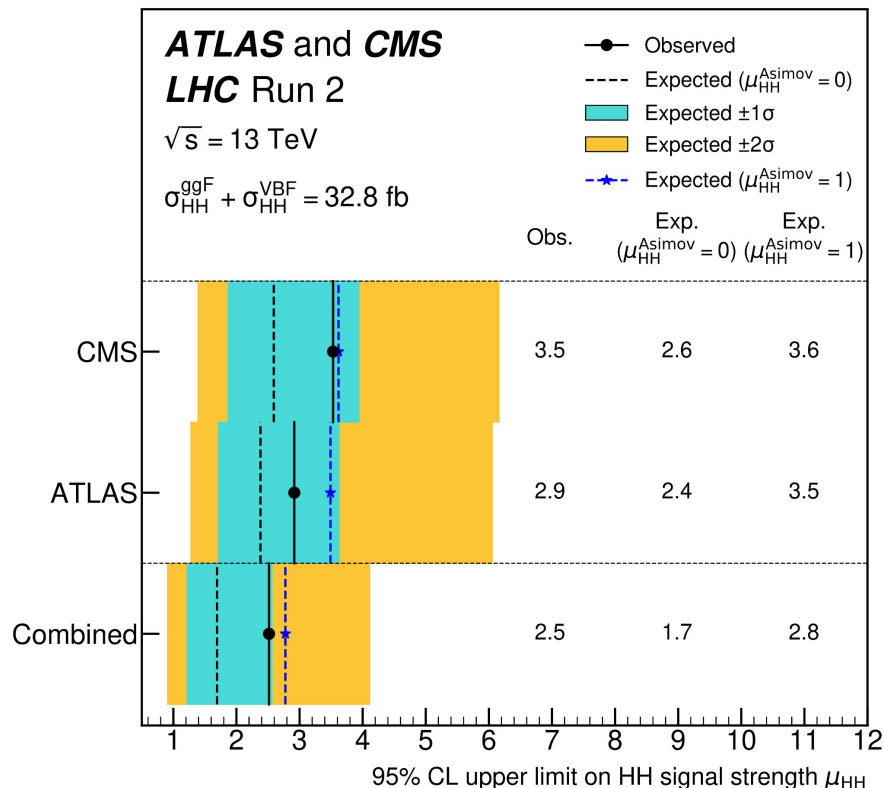
[arXiv:2602.23991](https://arxiv.org/abs/2602.23991)

- **Expected ggF+VBF 95% CL upper limit reach 1.7**
(~30% improvement compared to ATLAS results)
- **Observed (expected) significance of 1.1σ (1.3σ)** for the SM HH signal
- Combined best-fit signal strength for HH production:

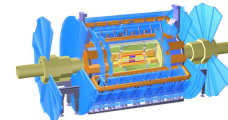
$$\hat{\mu}_{\text{HH}} = 0.8^{+0.9}_{-0.7} = 0.8^{+0.7}_{-0.6}(\text{stat.})^{+0.4}_{-0.2}(\text{theory})^{+0.3}_{-0.3}(\text{exp.})$$

$$\hat{\mu}_{\text{HH}}^{\text{exp}} = 1.0^{+0.9}_{-0.8} = 1.0^{+0.7}_{-0.6}(\text{stat.})^{+0.5}_{-0.3}(\text{theory})^{+0.3}_{-0.3}(\text{exp.})$$

- Statistical uncertainty dominates, theoretical one is also sizable
- Leading theoretical uncertainties from the ggF HH signal normalization from the choice of the renormalization scheme and top quark mass scale



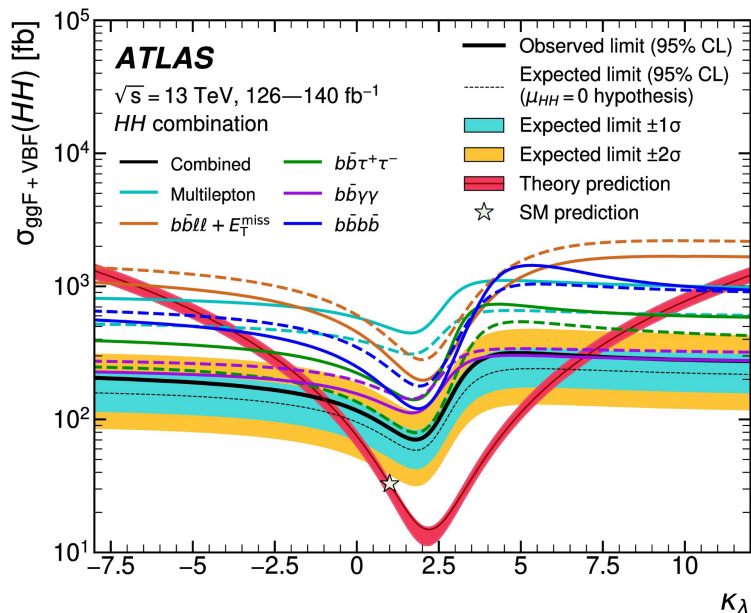
ATLAS Run 2 HH combination



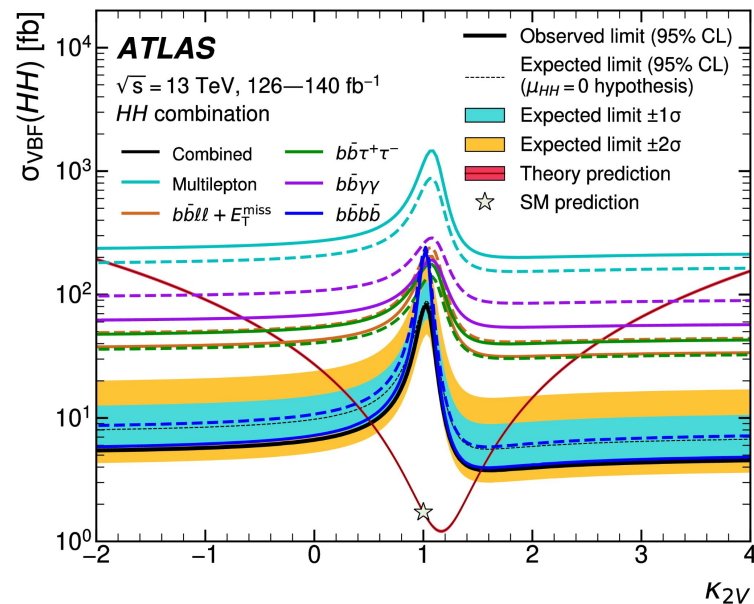
PRL 133 (2024) 101801

- Constraints on κ_λ dominated by $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ with access to low m_{HH} , while on κ_{2V} dominated by the boosted hadronic signatures (bbbb)
- Results obtained assuming no HH signal

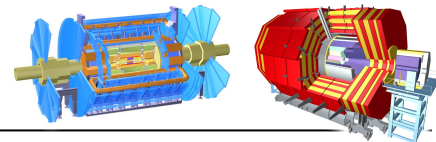
$$-0.4 < \kappa_\lambda < 6.3 \quad (-1.9 < \kappa_\lambda < 7.6)$$



$$0.1 < \kappa_{2V} < 2.0 \quad (0.0 < \kappa_{2V} < 2.1)$$



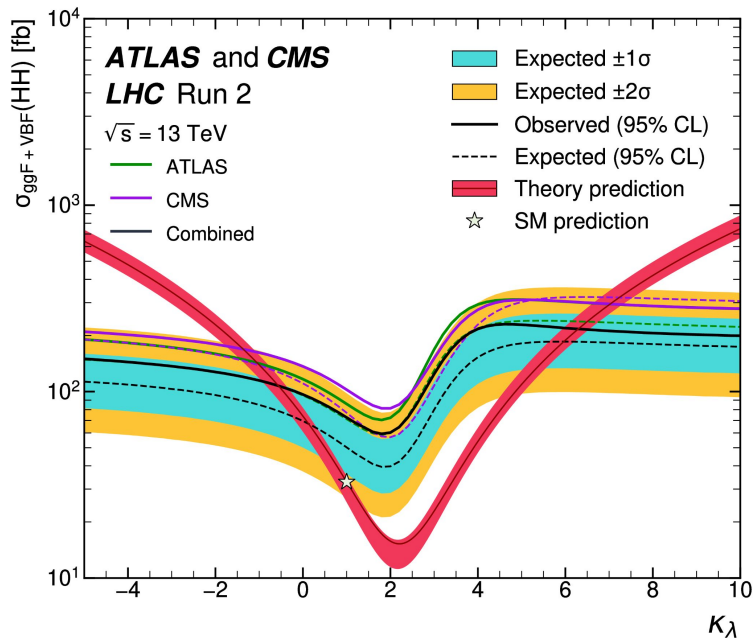
ATLAS+CMS Run 2 HH Combination



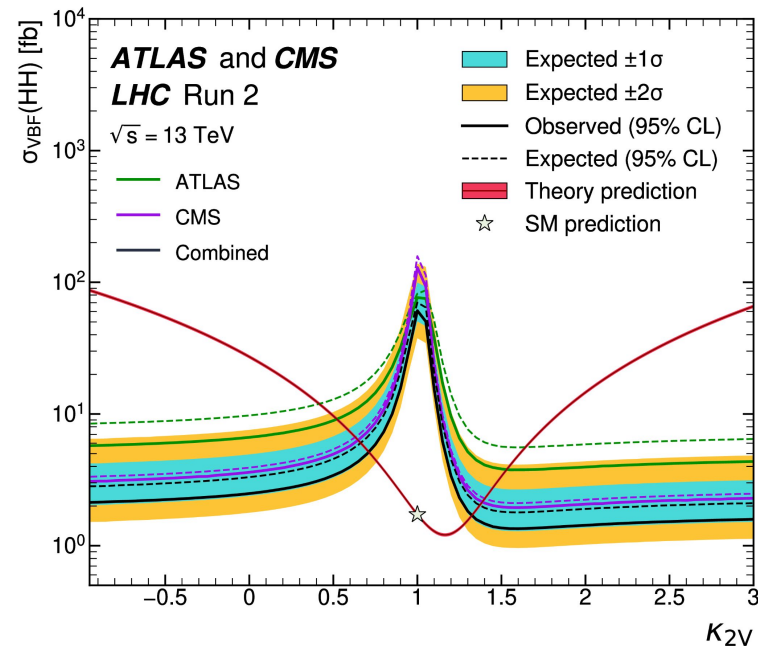
[arXiv:2602.23991](https://arxiv.org/abs/2602.23991)

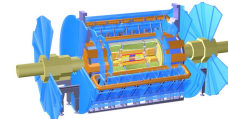
- Results of the combination compatible with the SM and represent the **most comprehensive and most sensitive constraints on HH production to date**
- Results obtained assuming no HH signal

$$-0.71 < \kappa_\lambda < 6.1 \quad (-1.3 < \kappa_\lambda < 6.7)$$



$$0.73 < \kappa_{2V} < 1.3 \quad (0.66 < \kappa_{2V} < 1.4)$$





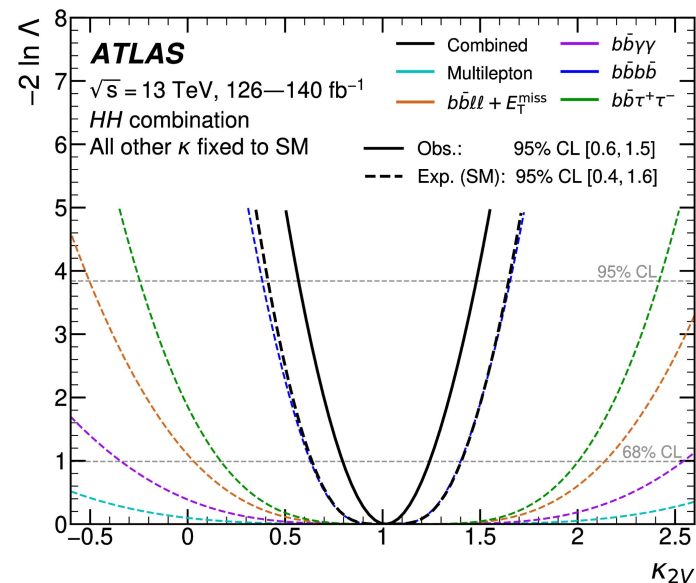
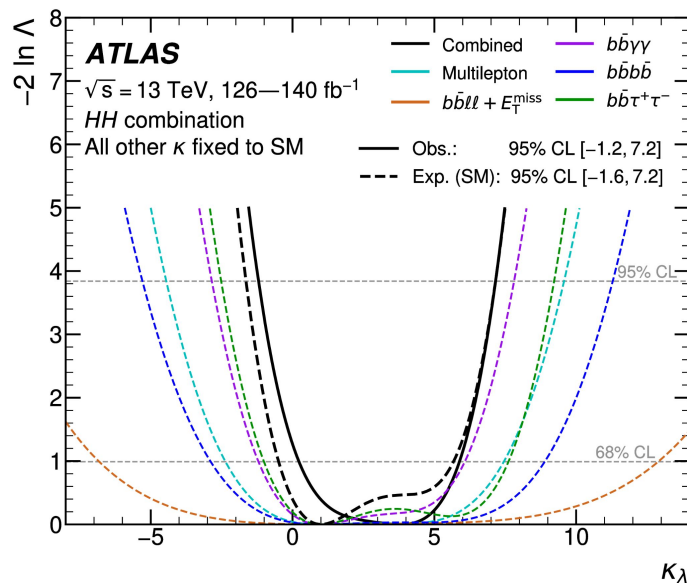
- Negative log-likelihood scans for the Higgs boson self-coupling modifier κ_λ and quartic $HHVV$ coupling modifier κ_{2V}
- Best constraint on κ_λ provided by $HH \rightarrow b\bar{b}\gamma\gamma$ and on κ_{2V} by $HH \rightarrow b\bar{b}b\bar{b}$** (mainly due to the boosted VBF channel)

$$-1.2 < \kappa_\lambda < 7.2 \text{ (observed)}$$

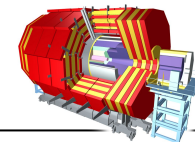
$$-1.6 < \kappa_\lambda < 7.2 \text{ (expected)}$$

$$0.6 < \kappa_{2V} < 1.5 \text{ (observed)}$$

$$0.4 < \kappa_{2V} < 1.6 \text{ (expected)}$$



CMS Run 2 HH combination



[arXiv:2510.07527](https://arxiv.org/abs/2510.07527)

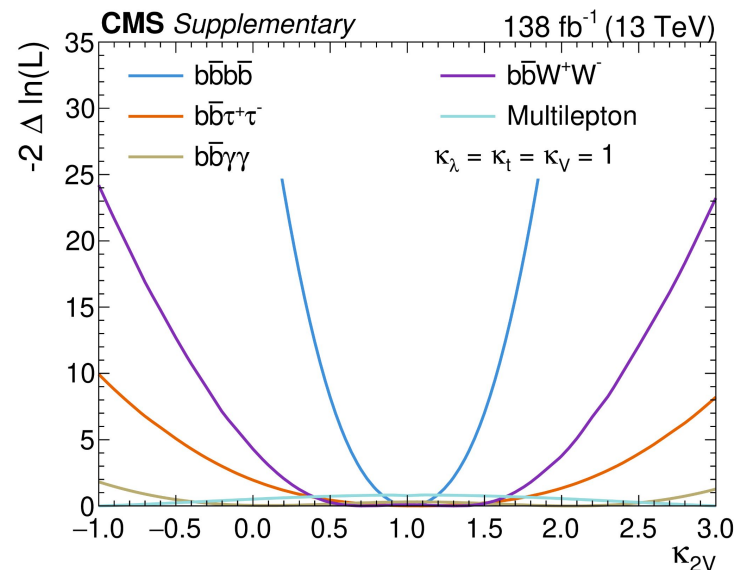
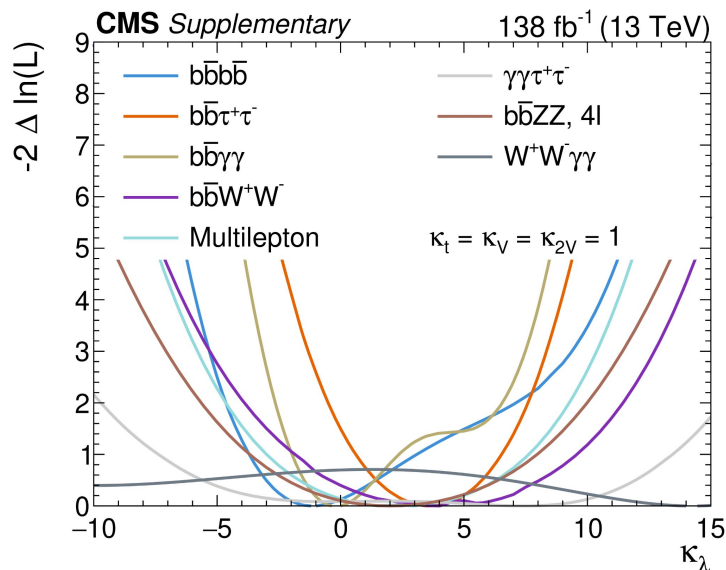
- Negative log-likelihood scans for the Higgs boson self-coupling modifier κ_λ and quartic $HHVV$ coupling modifier κ_{2V}
- The value of $\kappa_{2V} = 0$ excluded with a significance of 6.6σ

$$-1.35 < \kappa_\lambda < 6.37 \text{ (observed)}$$

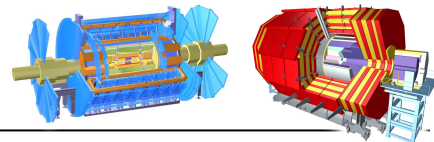
$$-2.24 < \kappa_\lambda < 7.89 \text{ (expected)}$$

$$0.64 < \kappa_{2V} < 1.40 \text{ (observed)}$$

$$0.62 < \kappa_{2V} < 1.41 \text{ (expected)}$$



ATLAS+CMS Run 2 HH Combination

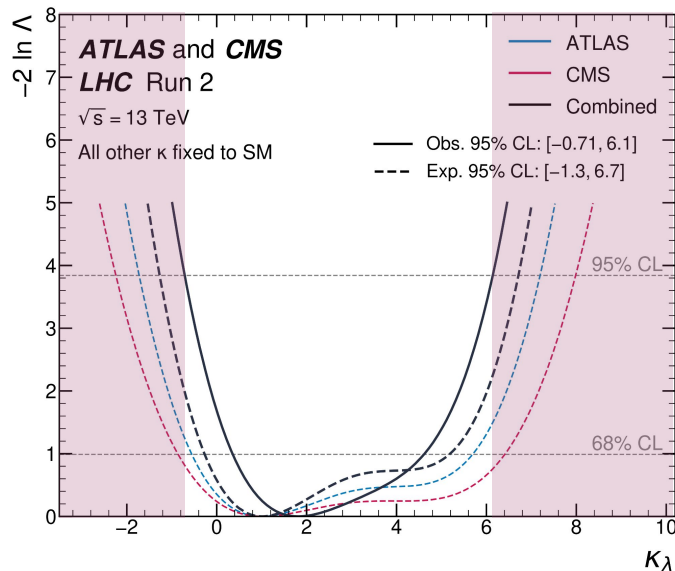


[arXiv:2602.23991](https://arxiv.org/abs/2602.23991)

- Difference between the ATLAS and CMS CL intervals arises from the sensitivities of these channels in each experiment
- **Improve the sensitivity by 10% on κ_λ and 8% on κ_{2V} with respect to the best constraints to date**

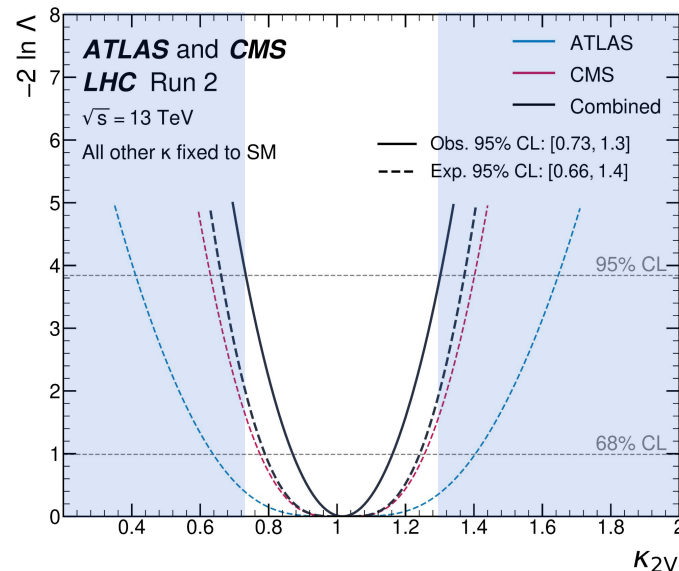
$$-0.71 < \kappa_\lambda < 6.1 \text{ (observed)}$$

$$-1.3 < \kappa_\lambda < 6.7 \text{ (expected)}$$

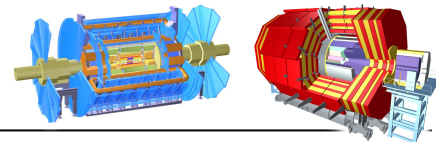


$$0.73 < \kappa_{2V} < 1.3 \text{ (observed)}$$

$$0.66 < \kappa_{2V} < 1.4 \text{ (expected)}$$

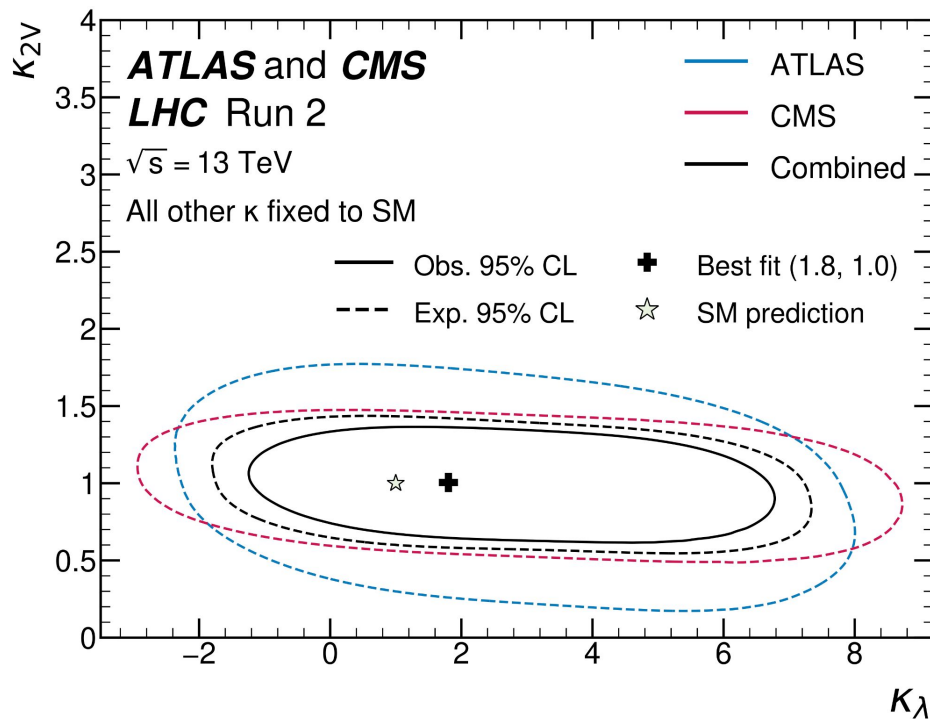


ATLAS+CMS Run 2 HH Combination



[arXiv:2602.23991](https://arxiv.org/abs/2602.23991)

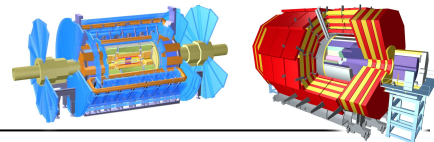
- 95% CL contours for the simultaneous scan of the profile likelihood as a function of κ_λ and κ_{2V}
- Best-fit point corresponds to 1.8 for κ_λ and 1.0 for κ_{2V} , compatible with SM prediction



Reaching the ultimate precision

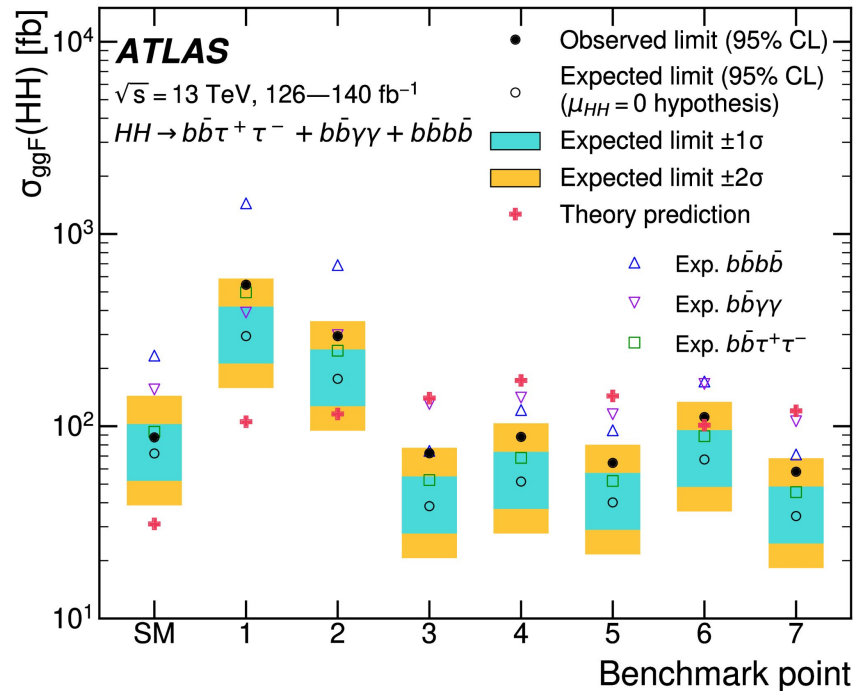
	Channel	Details	Expected			Observed		
			μ_{HH}	κ_λ	κ_{2V}	μ_{HH}	κ_λ	κ_{2V}
ATLAS	bbbb		< 8.1	[−5.3, 12]	[0.38, 1.7]	< 5.4	[−3.4, 11]	[0.55, 1.5]
	bb $\tau\tau$		< 3.3	[−2.6, 9.2]	[−0.24, 2.4]	< 5.8	[−3.3, 9.1]	[−0.51, 2.7]
	bb $\gamma\gamma$		< 5.2	[−3.0, 7.9]	[−1.1, 3.3]	< 4.1	[−1.6, 7.0]	[−0.48, 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]

HEFT interpretations



- Interpretation of the results in the **Higgs Effective Field Theory (HEFT)** from ATLAS [[PRL 133 \(2024\) 101801](#)] and CMS [[arXiv:2510.07527](#)]
- ATLAS results:
 - Benchmark definition updated accommodating bounds from single Higgs ([arXiv:2304.01968](#))
 - The VBF HH process is neglected for these results
 - Upper limits on the $\sigma_{\text{ggF } HH}$ for 7 HEFT benchmarks
 - Benchmark points 3, 4, 5 and 7 excluded

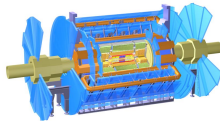
benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$\sigma_{\text{NLO}}[\text{fb}]$ at 13 TeV
SM	1	1	0	0	0	27.02
1	5.11	1.10	0	0	0	88.39
2	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0	93.79
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	120.93
4	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$	151.19
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$	124.12
6	-0.68	0.90	$-\frac{1}{6}$	$\frac{1}{2}$	$\frac{1}{4}$	85.23
7	-0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$	88.12



DiHiggs searches in Run 3



Major improvements in Run 3

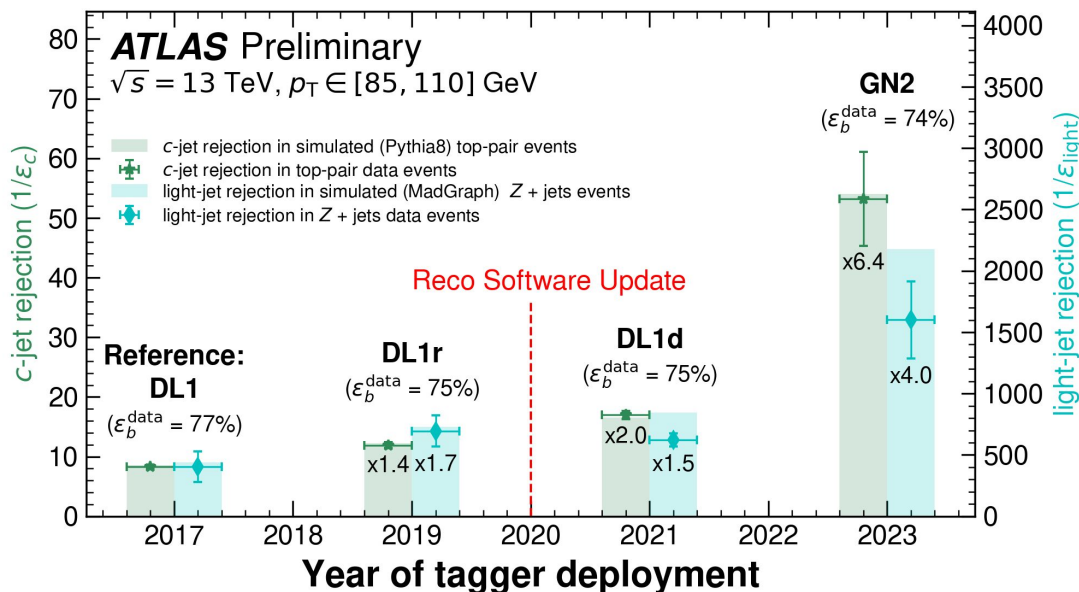


Room for improvements in the hadronic final states

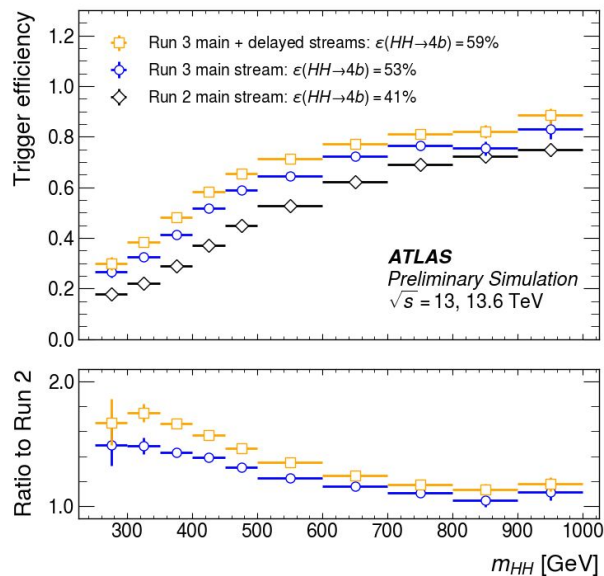
Run 3 bringing latest improvements in online and offline object reconstruction, identification and overall performance

Major updates in **b-tagging** and new **triggers** in Run 3

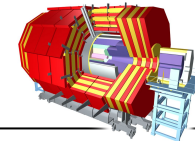
[FTAG-2023-07](#), [Nature Commun. 17 \(2026\) 541](#)



[BJetTriggerPublicResults](#)

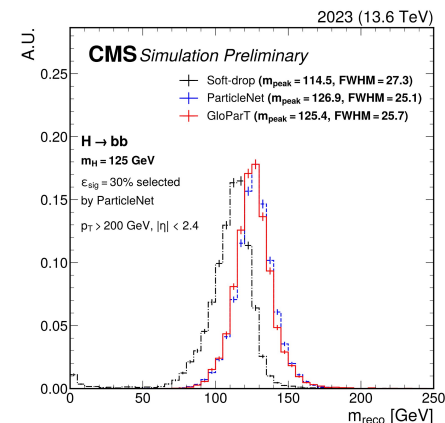
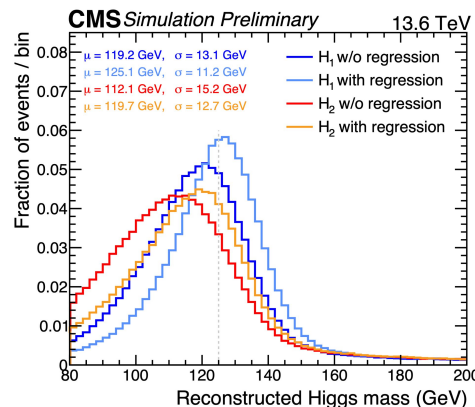
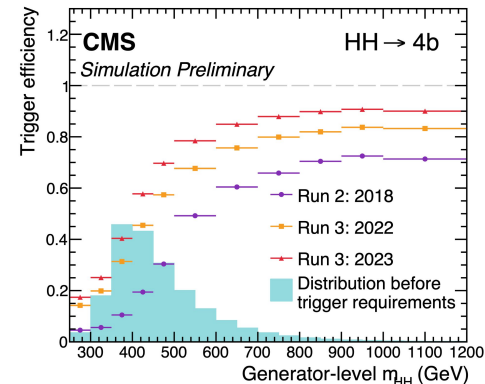
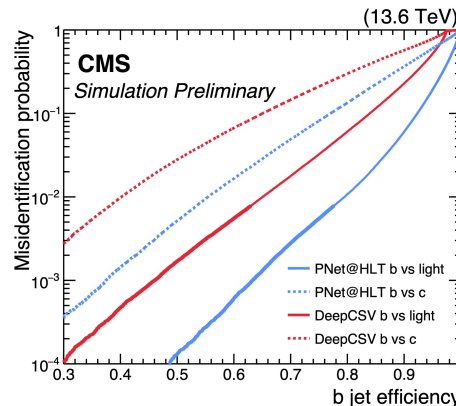


Major improvements in Run 3

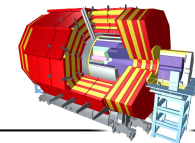


CMS-PAS-HIG-24-010

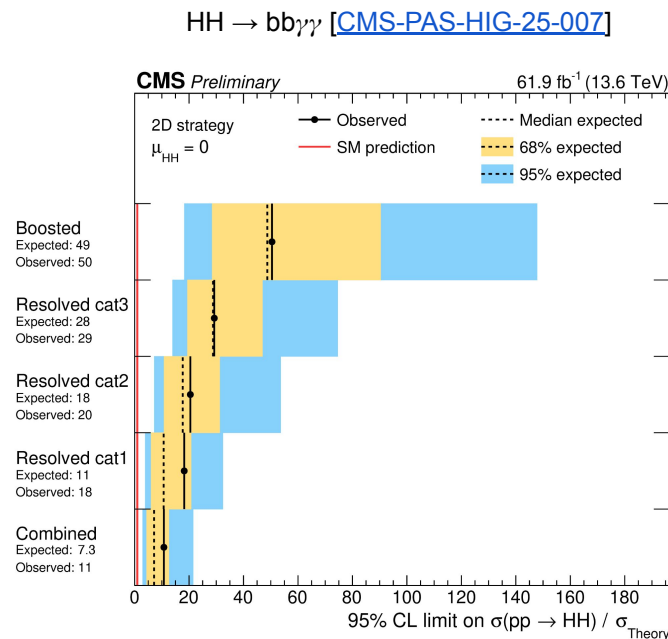
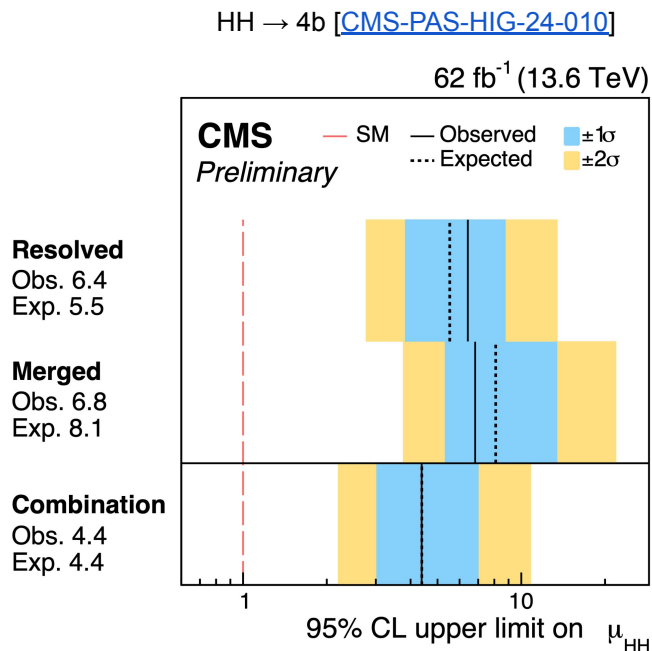
- **New triggers** providing > factor 2 absolute $HH \rightarrow 4b$ trigger efficiency
- Run 3 PNET@HLT algorithm compared to the best-performing algorithm at HLT in Run 2 (DEEPCSV)
- **Jet p_T regression**: novel approach to jet p_T reconstruction where a single algorithm simultaneously performs the jet flavour identification and estimates a jet p_T correction
- Jet paring and dijet mass resolution improved



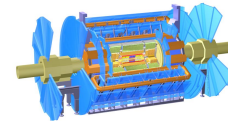
CMS HH $\rightarrow$ bbbb, bb $\gamma\gamma$ partial Run 3 (2022-23)



- **Early Run 3 limits** with 62 fb⁻¹ of data already **competitive to full Run 2** with 138 fb⁻¹ of data in key channels
- Major Run 3 improvements: triggers, b-tagging, regression, and advanced ML

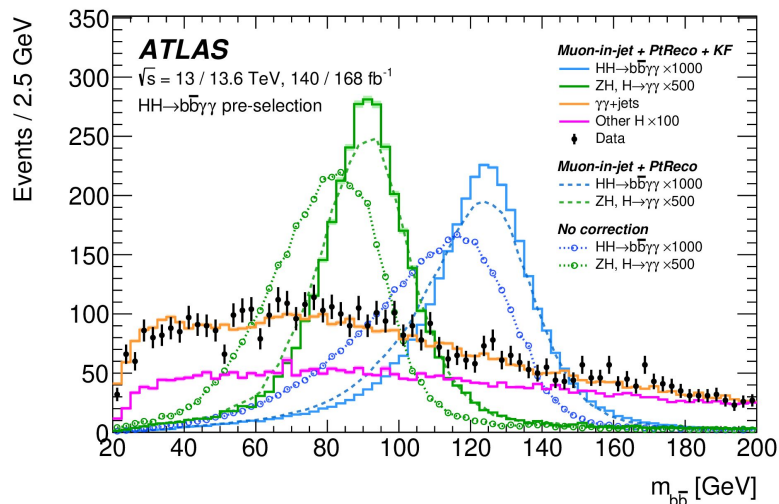


ATLAS HH $\rightarrow$ $b\bar{b}\gamma\gamma$ Run 2 + partial Run 3 (2022-24)

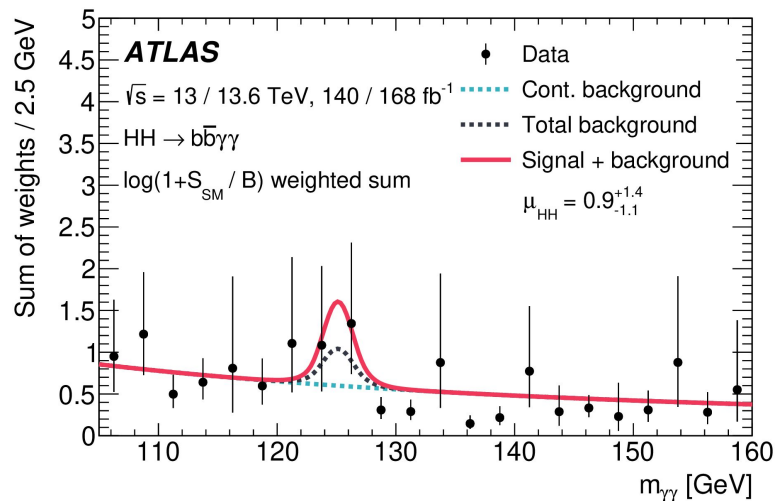


[PLB 876 \(2026\) 140280](#)

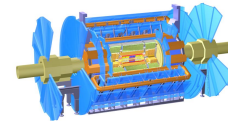
- First ATLAS result using **> 300 fb⁻¹ of data**
- First HH result to reach **1 σ expected significance**
- Unbinned maximum likelihood fit over 14 category yields (7 regions x 2 run periods)
- Limits ($\kappa_\lambda \in [-1.6, 6.6]$) **competitive with the Run 2 ATLAS legacy HH combination** ($\kappa_\lambda \in [-1.2, 7.2]$)



Diphoton invariant mass distribution summed over all categories and the two data-taking periods

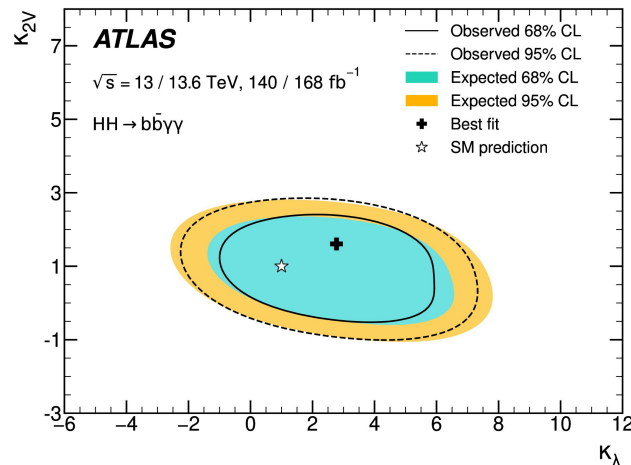
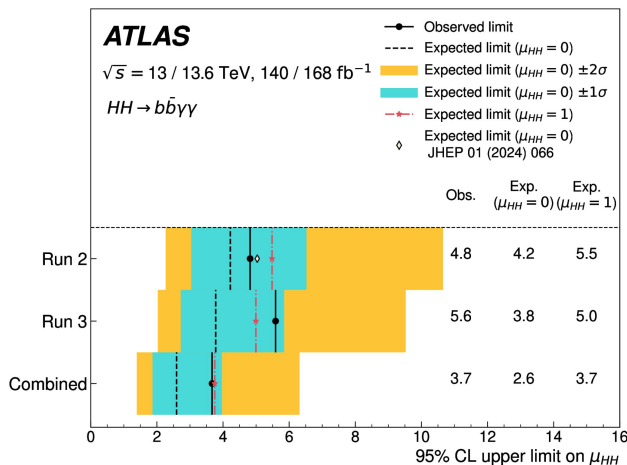
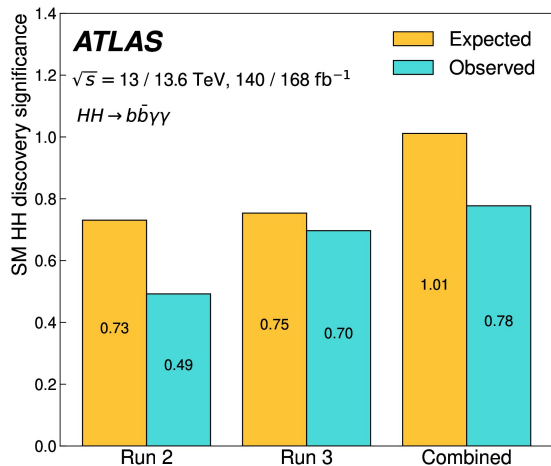


ATLAS HH $\rightarrow$ $b\bar{b}\gamma\gamma$ Run 2 + partial Run 3 (2022-24)

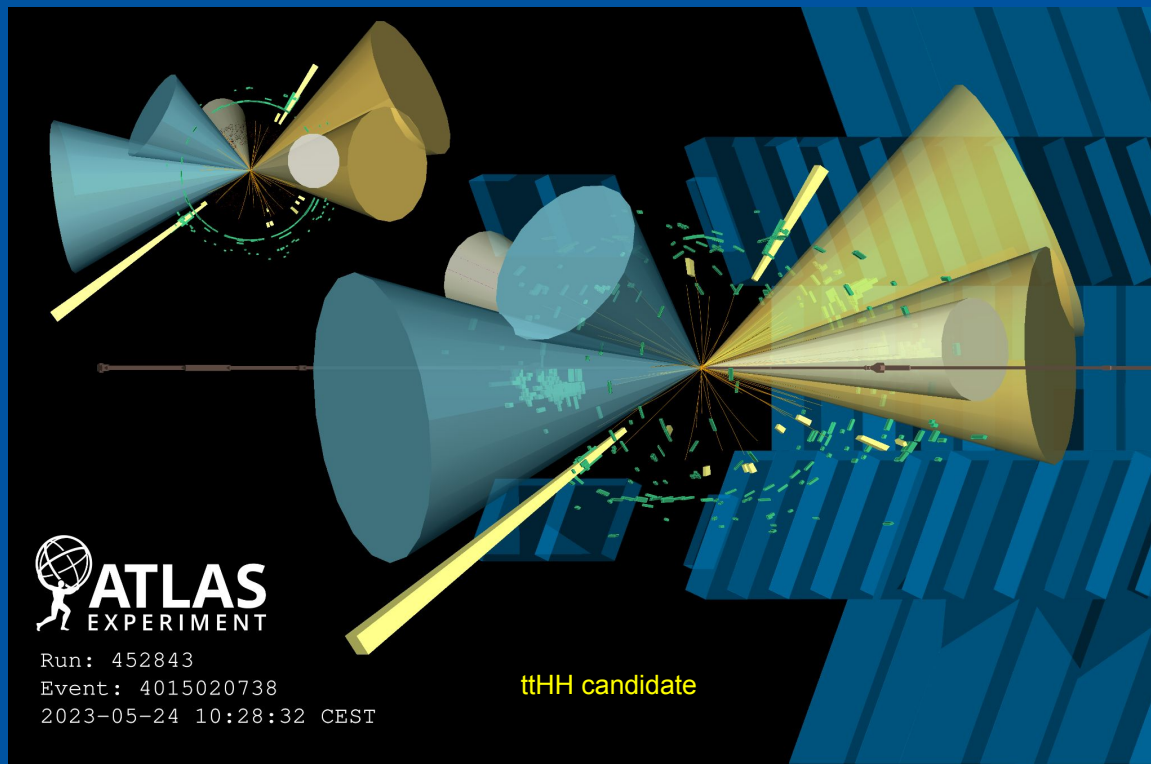


PLB 876 (2026) 140280

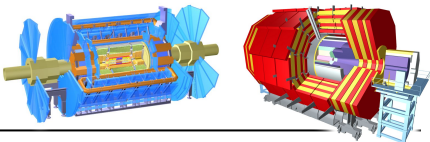
- First ATLAS result using $> 300 \text{ fb}^{-1}$ of data
- First HH result to reach 1σ expected significance
- Unbinned maximum likelihood fit over 14 category yields (7 regions x 2 run periods)
- Limits ($\kappa_\lambda \in [-1.6, 6.6]$) competitive with the Run 2 ATLAS legacy HH combination ($\kappa_\lambda \in [-1.2, 7.2]$)



Exploring an uncharted territory

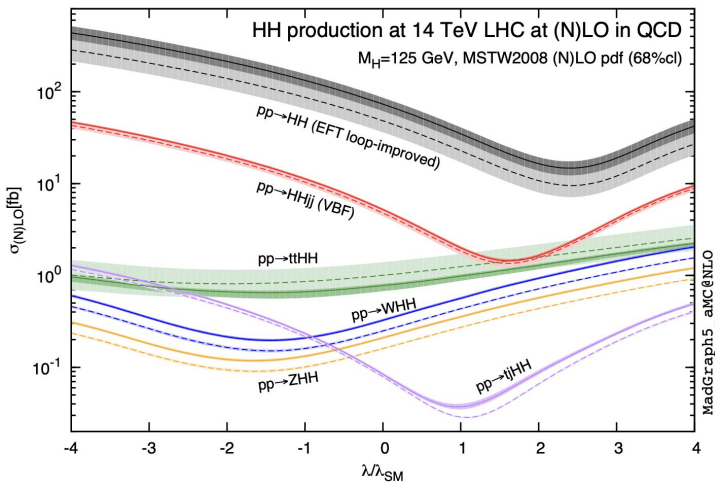


Even more complex: VHH

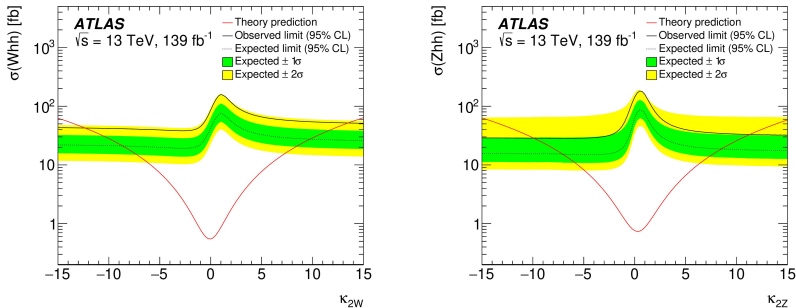


- **First searches for VHH production at the LHC**, both in the $V(HH \rightarrow 4b)$ channel using Run 2 data:
 - ATLAS [\[EPJC 83 \(2023\) 519\]](#)
 - CMS [\[JHEP 10 \(2024\) 061\]](#)
- **Constructive interference** yields an increasing Vhh cross section as κ_λ increases ($0 < \kappa_\lambda < 4$), while ggF and VBF channels are close to their minimum, complementary channel, with cleaner signal when choosing V-leptonic decay
- **Decomposing κ_{2W} and κ_{2Z} couplings separately**

[PLB 732 \(2014\) 142](#)



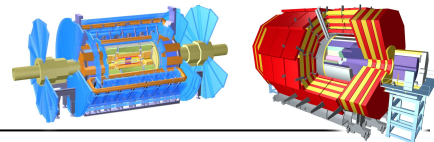
[EPJC 83 \(2023\) 519](#)



[JHEP 10 \(2024\) 061](#)

	κ_λ	κ_{2V}	κ_V	κ_{2Z}	κ_{2W}
Observed	(-37.7, 37.2)	(-12.2, 13.5)	(-3.7, 3.8)	(-17.4, 18.5)	(-14.0, 15.4)
Expected	(-30.1, 28.9)	(-7.2, 8.9)	(-3.1, 3.1)	(-10.5, 11.6)	(-10.2, 11.6)

Even more complex: ttHH

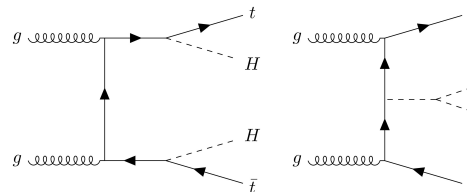


- **First searches for ttHH production at the LHC:**

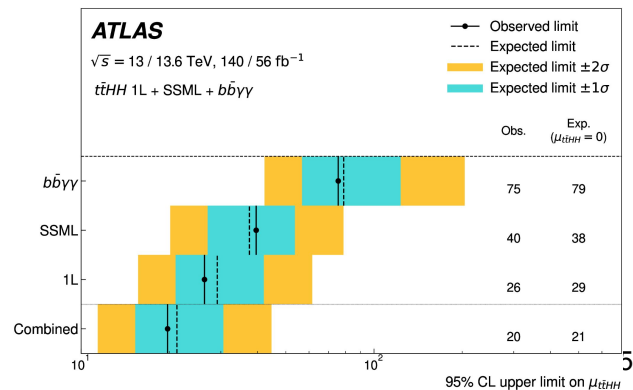
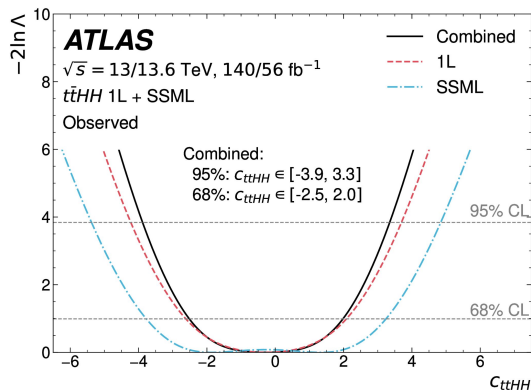
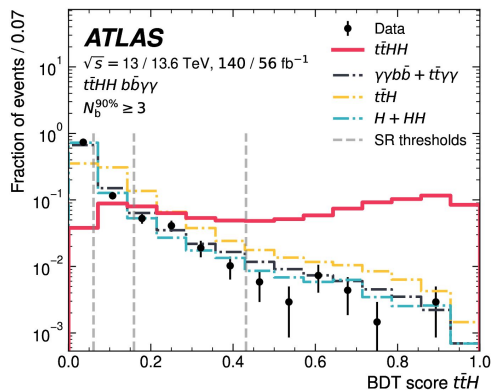
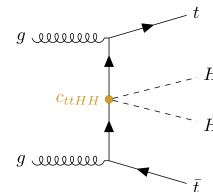
- CMS in the $\gamma\gamma+X$ channel using Run 2 data [[CMS-PAS-HIG-23-004](#)]
- ATLAS in the $t\bar{t}(HH \rightarrow 4b)$, $t\bar{t}HH \rightarrow \text{Multilepton}$ and $t\bar{t}(HH \rightarrow b\bar{b}\gamma\gamma)$ using Run 2 + partial Run 3 (2022-23) data [[arXiv:2603.13113](#)]

- Not have destructive interference terms at LO
- In the SM, ~ 3000 ttHH events at the HL-LHC
- Cross section increases faster with energy (future colliders)
- First observation of ttH in 2018, our background today

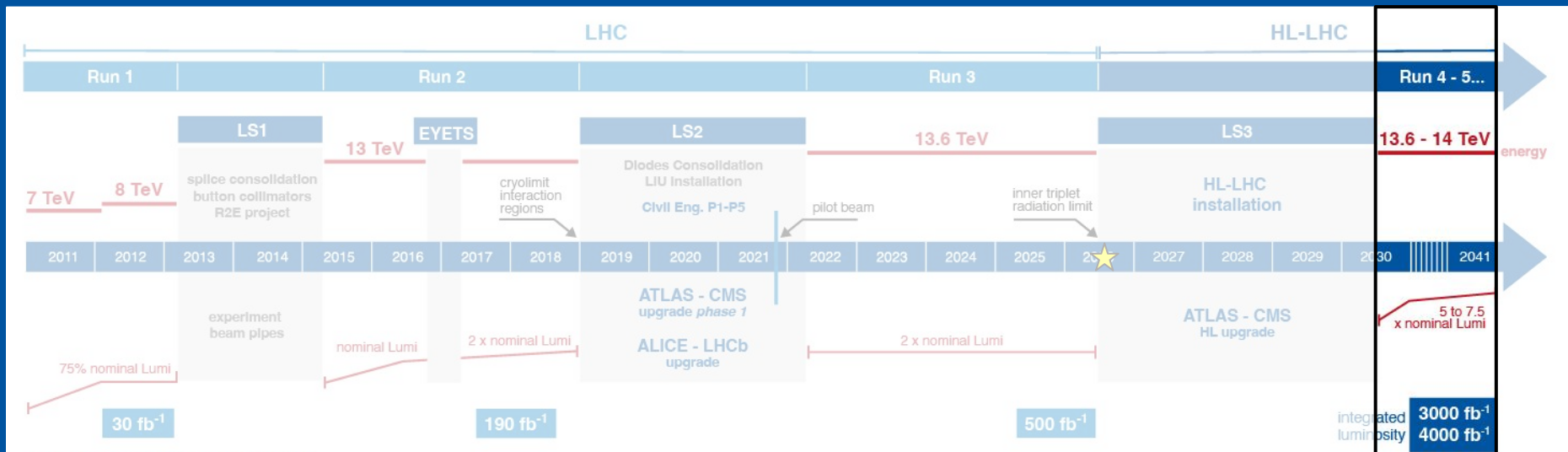
SM diagrams



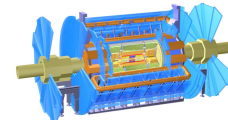
non-SM LO diagram in HEFT



DiHiggs projections at the HL-LHC

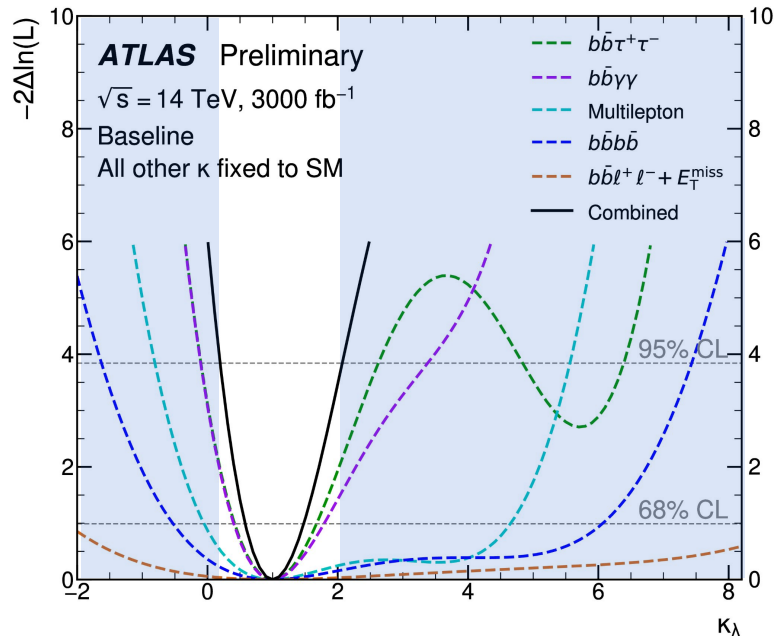
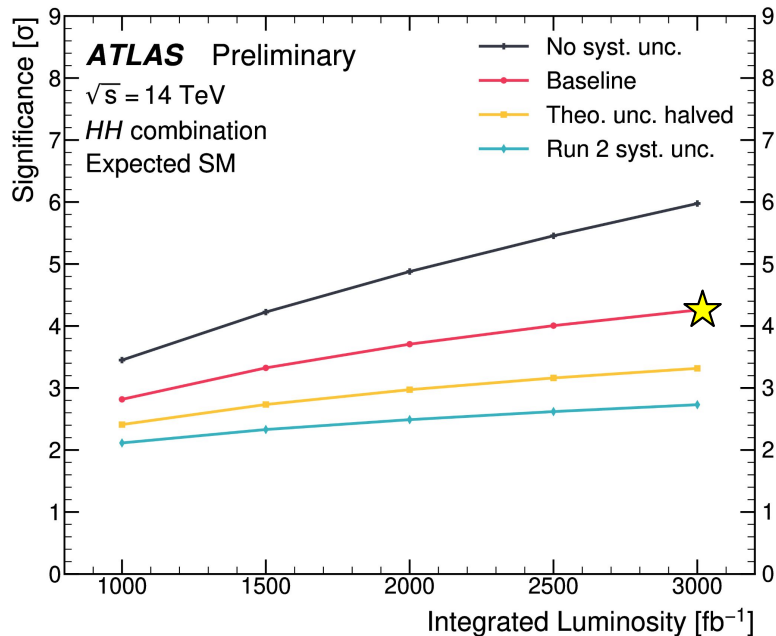


ATLAS HH projections at the HL-LHC

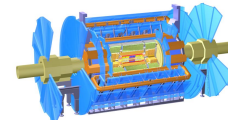


ATL-PHYS-PUB-2025-006

- Extrapolation to HL-LHC based on Run 2 searches assuming 3000 fb⁻¹:
 $HH \rightarrow b\bar{b}\gamma\gamma$, $HH \rightarrow b\bar{b}\tau\tau$, $HH \rightarrow b\bar{b}b\bar{b}$, $HH \rightarrow$ Multilepton, $HH \rightarrow b\bar{b}l\bar{l} + E_{T,\text{miss}}$
- Baseline** scenario assuming most experimental and theory systematics reduced by the luminosity scaling or halved
- 4.26 σ discovery significance and $\kappa_\lambda = 1.0^{+0.48}_{-0.42}$**



ATLAS HH projections at the HL-LHC

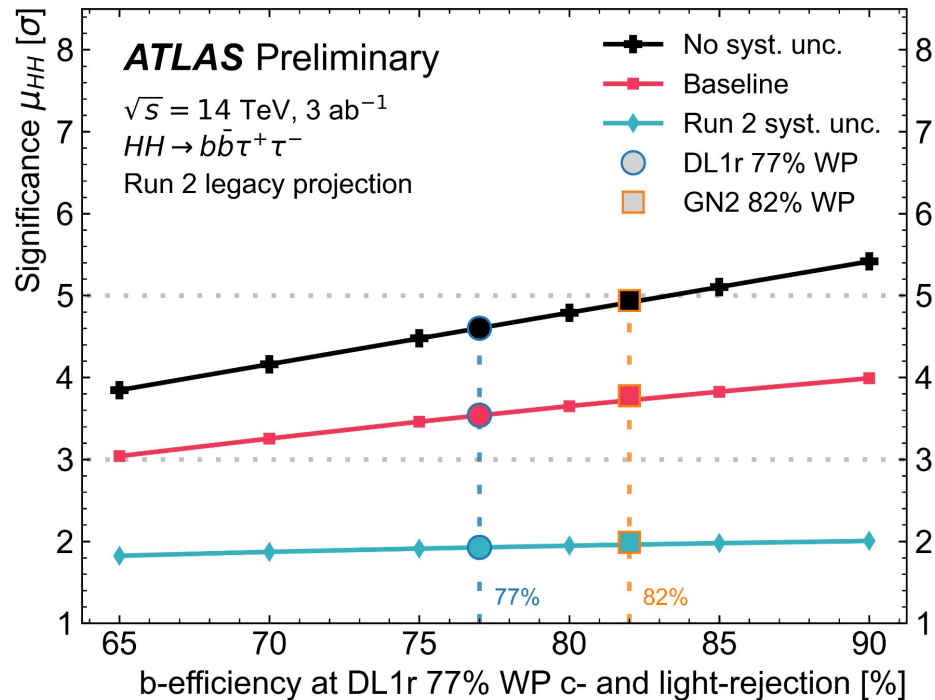


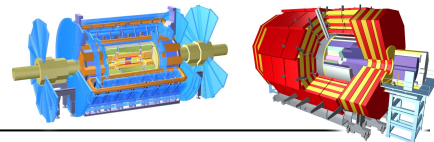
[ATL-PHYS-PUB-2024-016](#)

New generation of b-taggers in $HH \rightarrow b\bar{b}\tau^+\tau^-$

DL1r 77% WP $\rightarrow$ GN2 82% WP

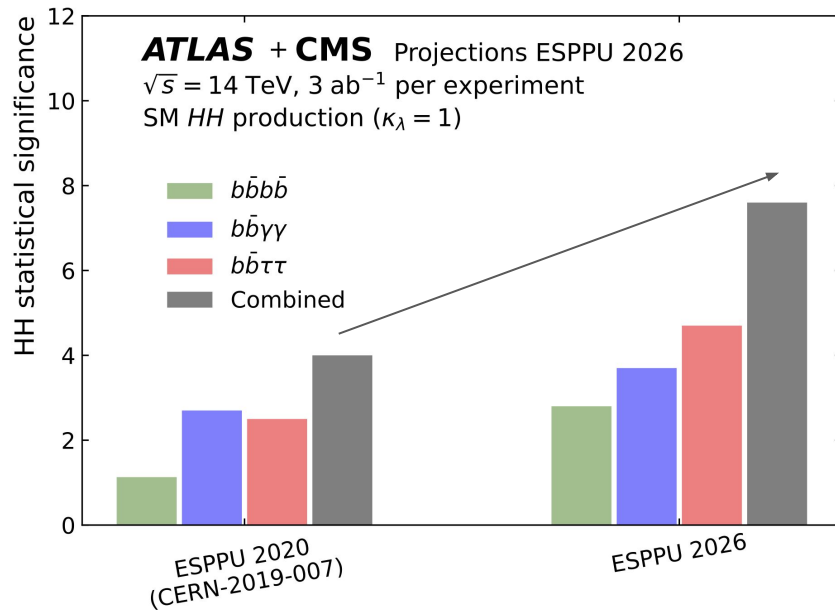
Extremely dependent on improvements on reconstruction and analysis techniques!



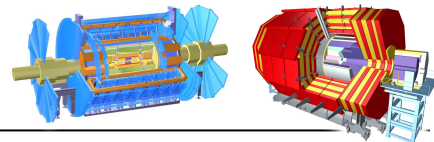


ESPPU 2026

- Observation of the SM di-Higgs boson production with a **significance** $> 5\sigma$ with 2000 fb^{-1}
- Increase in significance **from 4σ in ESPPU 2020 to $> 7\sigma$ in ESPPU 2026** with 3000 fb^{-1}
- Measurement of the Higgs boson trilinear self-coupling λ_3 with a **precision** $> 30\%$



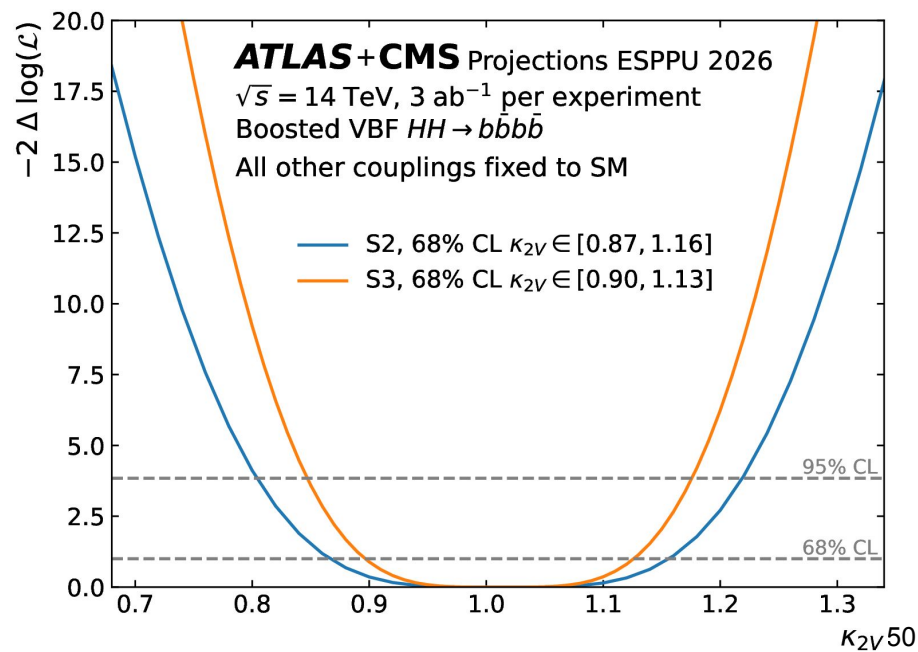
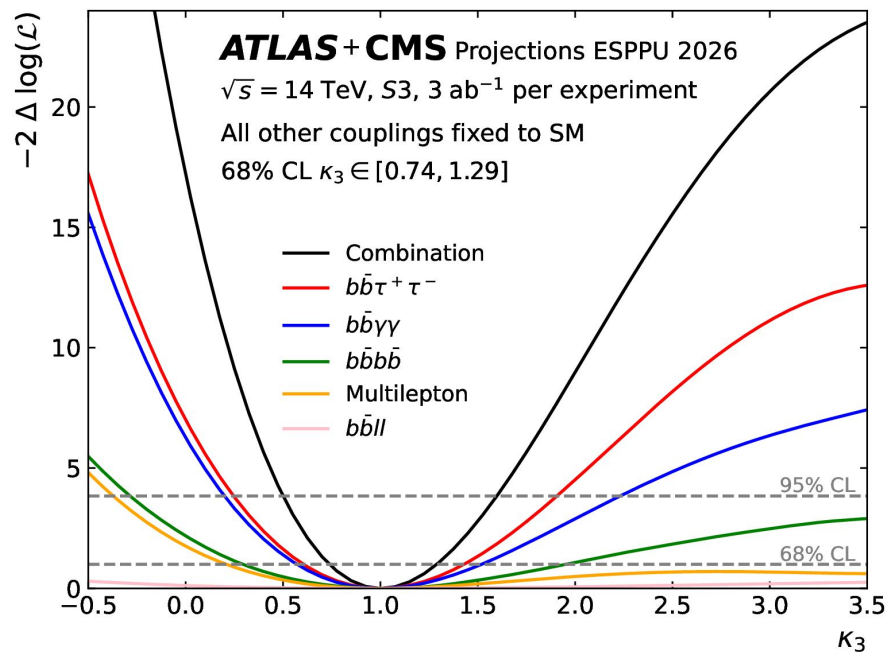
ATLAS+CMS HH projections at the HL-LHC



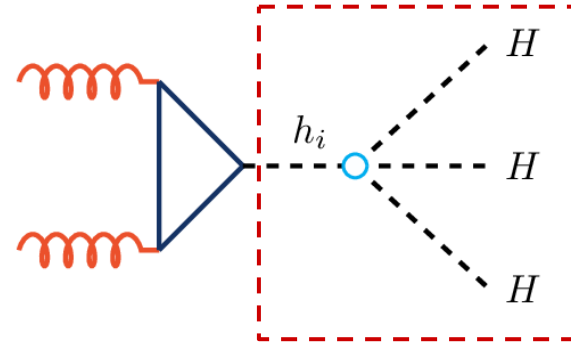
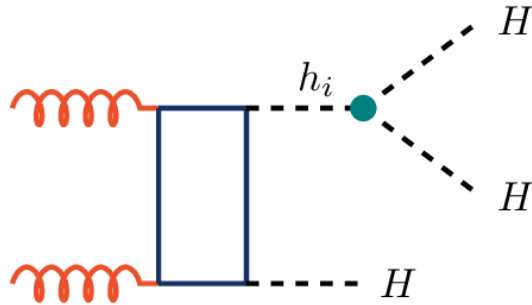
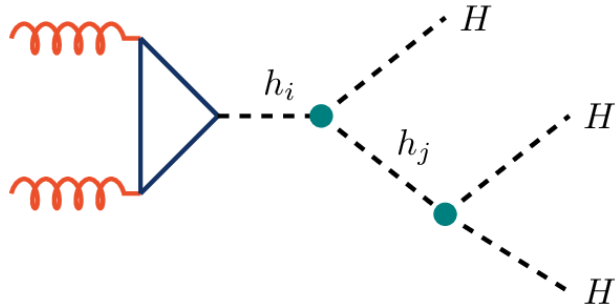
[arXiv:2504.00672](https://arxiv.org/abs/2504.00672)

ESPPU 2026

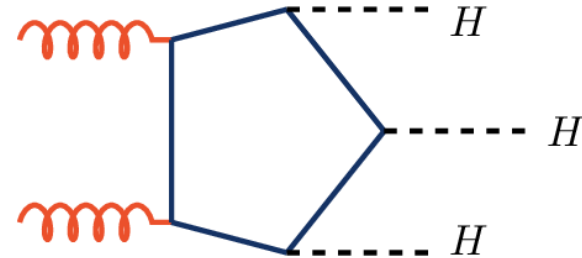
- First scenario (S2) assumes reduced systematic uncertainties and theoretical uncertainties halved
- Second scenario (S3) evaluates the impact of recent improvements in specific object reconstruction relative to S2



Search for HHH production

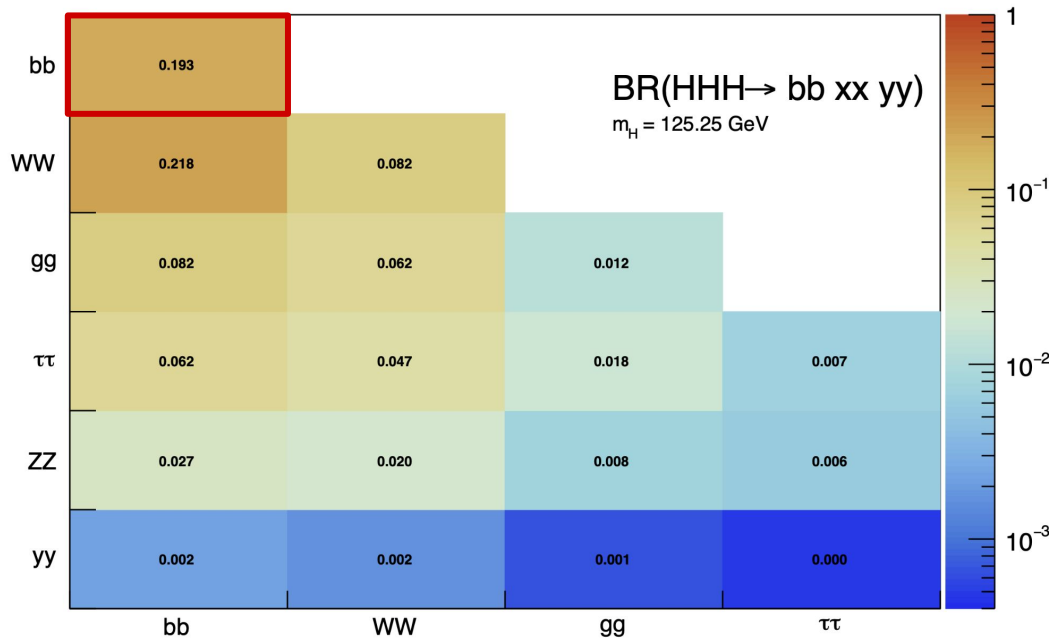


For $h_i = H$, Higgs quartic self-coupling



Search for HHH production

HHH white paper [\[EPJC 84 \(2024\) 1183\]](#)



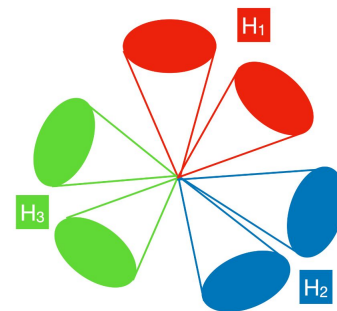
$$\sigma_{\text{HHH, SM}} = 0.079^{+0.012}_{-0.013} \text{ fb at NNLO QCD @ 13 TeV}$$

(extrapolated from cross section at $\sqrt{s} = 14$ TeV from [JHEP 03 \(2020\) 155](#))

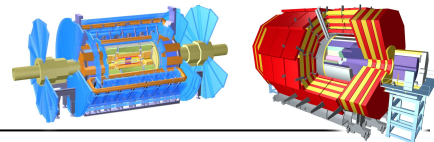
Largest BR: $HHH \rightarrow 6b$

$$\text{BR}(H \rightarrow bb)^3 = 0.193$$

Faint signal, extremely challenging



HHH searches in Run 2



ATLAS HHH $\rightarrow$ 6b [PRD 111 (2025) 032006]

Limit: 760 (750) x SM HHH $\rightarrow$ 6b prediction

corresponding to 59 (59) fb

$-230 < \kappa_4 < 240$ at 95% CL

CMS HHH $\rightarrow$ 6b [CMS-PAS-HIG-24-012]

Limit: 588 (572) x SM HHH $\rightarrow$ 6b prediction

corresponding to 44 (43) fb

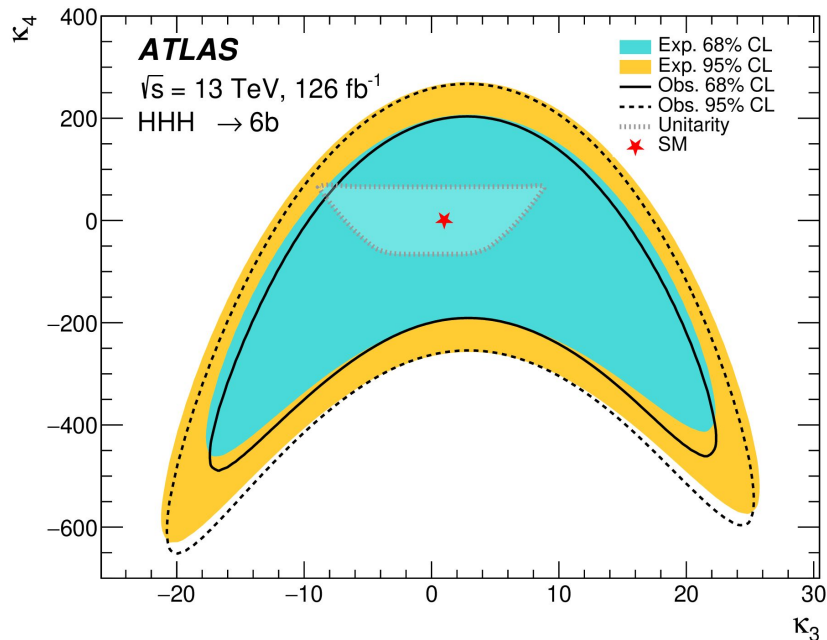
$-190 < \kappa_4 < 190$ at 95% CL

CMS HHH $\rightarrow$ 4b2 γ [CMS-PAS-HIG-24-015]

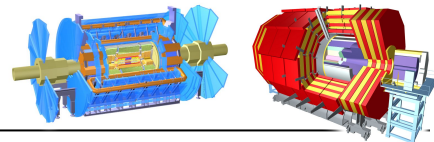
Limit: 3400 (2086) x SM HHH $\rightarrow$ 4b2 γ prediction

corresponding to 0.56 (0.35) fb

$-533 < \kappa_4 < 541$ at 95% CL



HHH searches in Run 2



ATLAS HHH $\rightarrow$ 6b [[PRD 111 \(2025\) 032006](#)]

Limit: 760 (750) x SM HHH $\rightarrow$ 6b prediction

corresponding to 59 (59) fb

$-230 < \kappa_4 < 240$ at 95% CL

CMS HHH $\rightarrow$ 6b [[CMS-PAS-HIG-24-012](#)]

Limit: 588 (572) x SM HHH $\rightarrow$ 6b prediction

corresponding to 44 (43) fb

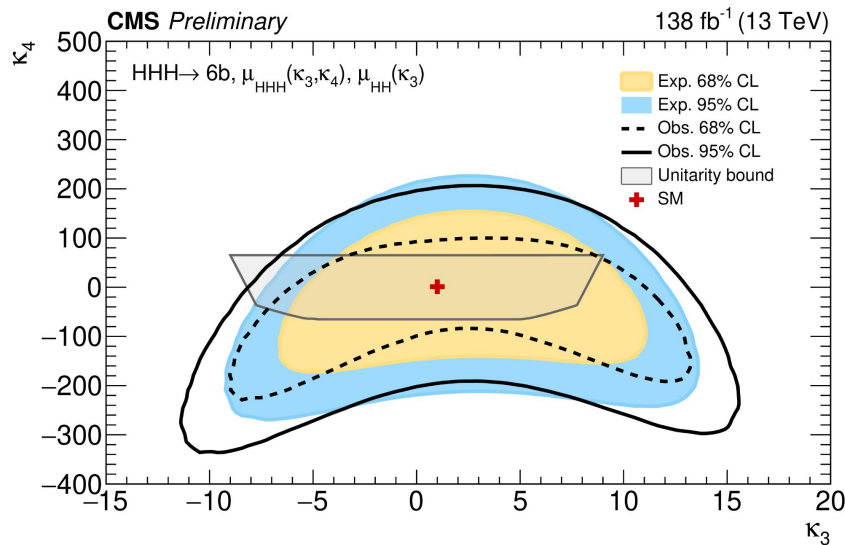
$-190 < \kappa_4 < 190$ at 95% CL

CMS HHH $\rightarrow$ 4b2 γ [[CMS-PAS-HIG-24-015](#)]

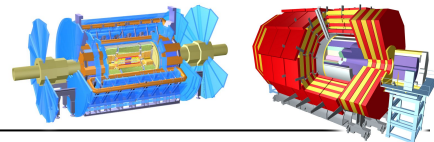
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HHH searches in Run 2



ATLAS HHH $\rightarrow$ 6b [PRD 111 (2025) 032006]

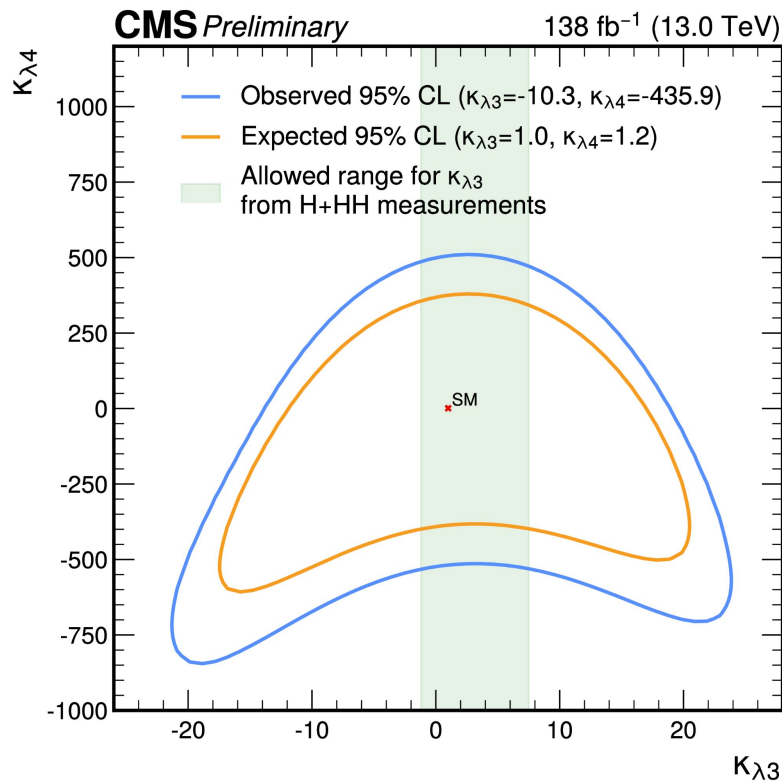
Limit: 760 (750) x SM HHH $\rightarrow$ 6b prediction
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CMS HHH $\rightarrow$ 6b [CMS-PAS-HIG-24-012]

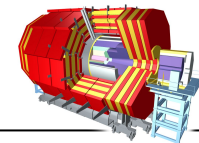
Limit: 588 (572) x SM HHH $\rightarrow$ 6b prediction
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CMS HHH $\rightarrow$ 4b2 γ [CMS-PAS-HIG-24-015]

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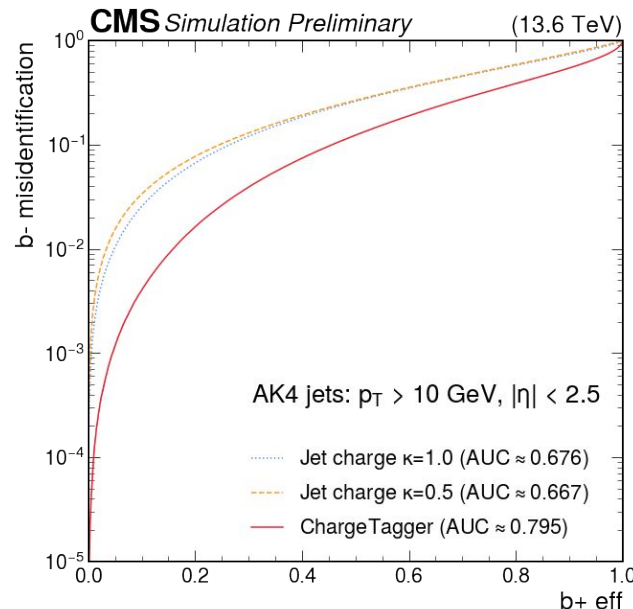
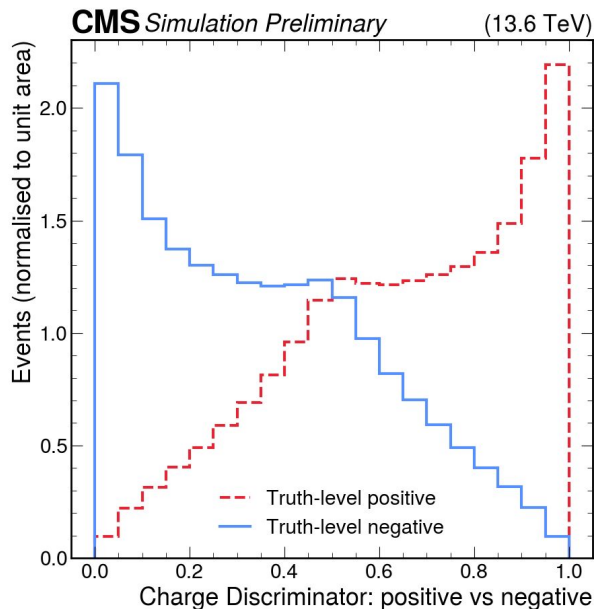
Hot-off-the-press b-tagging techniques



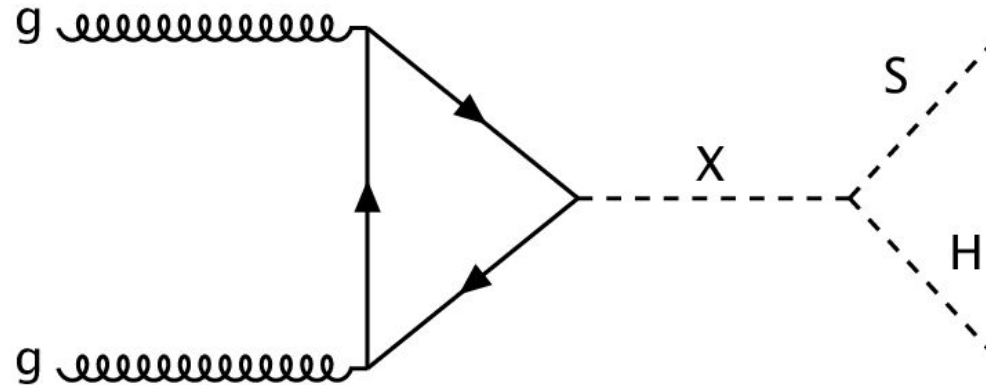
[CMS-DP-2025-071](#)

New CMS jet-charge tagging technique:

- HHH extremely challenging, need advanced tools
- CMS developed a first inclusive jet-charge tagger at the LHC to improve HHH ($\text{HHH} \rightarrow \mathbf{6b}$ and $\text{HHH} \rightarrow \mathbf{4b+X}$)
- Performance: 70% accuracy on b-jets (30% mis-identified anti-b-jets)



Search for Higgs cascade decays



Extended Higgs sector models

- The current experimental precision does not exclude that H may have a small mixing with additional scalar bosons, and may be part of an extended Higgs sector
- Many BSM theories predict such an extended Higgs sector

Extended Higgs sector models:

2HDM

Two Higgs Doublet Model

One of the simplest extensions of the SM, extended with an additional complex scalar doublet, resulting in **5 physical Higgs bosons**:

- 2 neutral CP even (H and H_2)
- 1 neutral CP odd (A)
- 2 charged (H^+ , H^-)

TRSM

Two-real-scalar-singlet extension of the Standard Model

Extension resulting in **3 physical Higgs bosons** (CP even neutral scalars), one corresponding to the SM Higgs boson

$$pp \rightarrow h_i \rightarrow h_j h_k$$

NMSSM

Next-to-Minimal Supersymmetric extension of the Standard Model

Extends the two doublet fields of the MSSM by a complex superfield

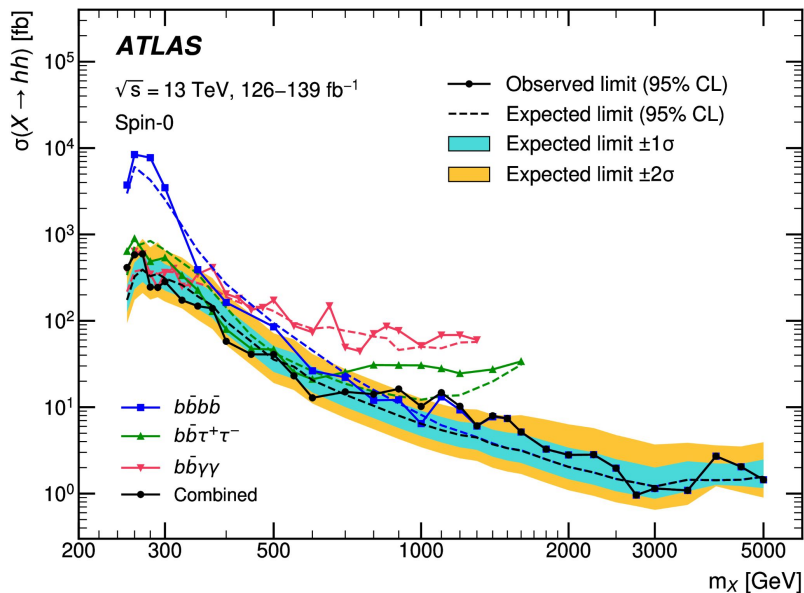
7 physical Higgs bosons:

- 3 CP even (H_1 , H_2 , H_3)
- 2 CP odd (A_1 , A_2)
- 2 charged (H^+ , H^-)

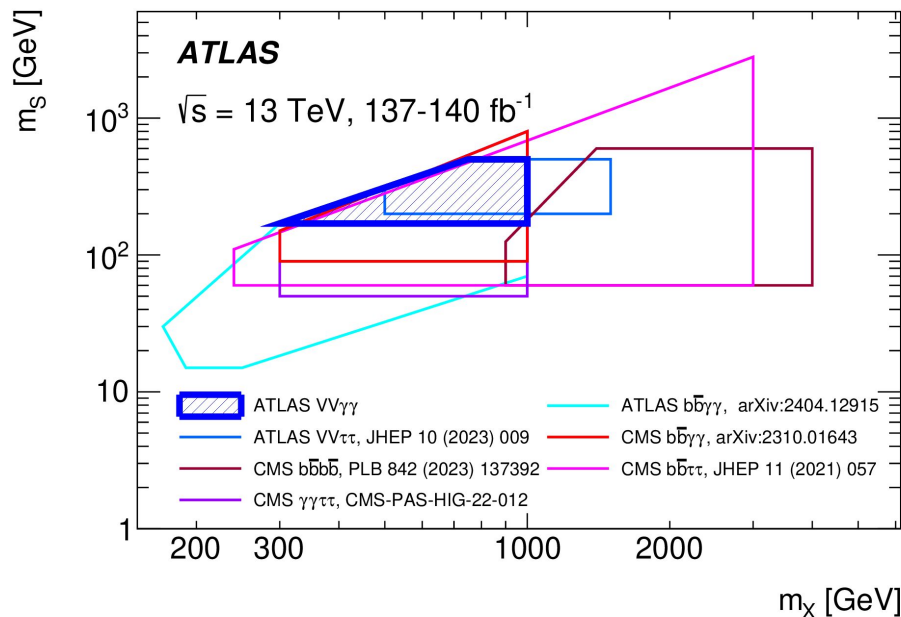
State-of-the-art $X \rightarrow HH / SH$

- Search for resonant production in ATLAS and CMS using the full Run 2 data
- Wealth of results targeting a huge phase space

$X \rightarrow HH$ [[PRL 132 \(2024\) 231801](#)]

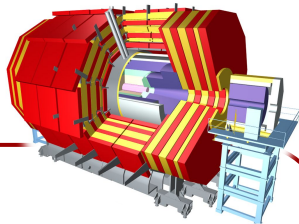


$X \rightarrow SH$ [[JHEP 11 \(2024\) 047](#)]



Search for Higgs cascade decays $X \rightarrow SH$ in Run 2

- Search for two additional scalar bosons X and S under the condition $m_X > m_S + m_H$, the decay $X \rightarrow SH$ is kinematically allowed
- Narrow width approximation, no interference effects with non-resonant production considered
- New ATLAS and CMS searches using the full Run 2 data



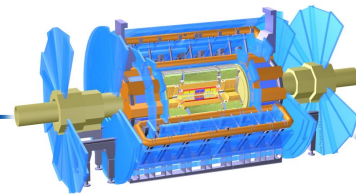
CMS

$X \rightarrow S(\rightarrow bb)H(\rightarrow bb)$ [[PLB 842 \(2023\) 137392](#)]

$X \rightarrow S(\rightarrow bb)H(\rightarrow \tau\tau)$ [[JHEP 11 \(2021\) 057](#)]

$X \rightarrow S(\rightarrow bb)H(\rightarrow \gamma\gamma)$ [[JHEP 05 \(2024\) 316](#)]

Combination [[Phys. Rept. 1115 \(2025\) 368](#)]



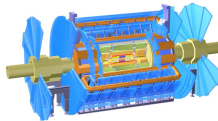
ATLAS

$X \rightarrow S(\rightarrow VV)H(\rightarrow \tau\tau)$ [[JHEP 10 \(2023\) 009](#)]

$X \rightarrow S(\rightarrow VV)H(\rightarrow \gamma\gamma)$ [[JHEP 10 \(2024\) 104](#)]

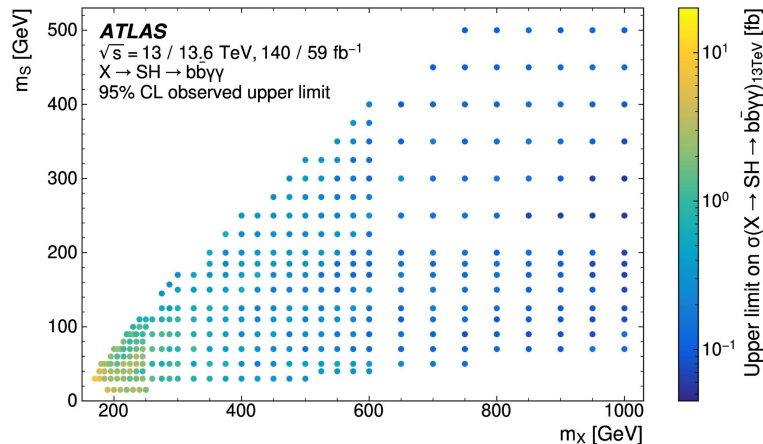
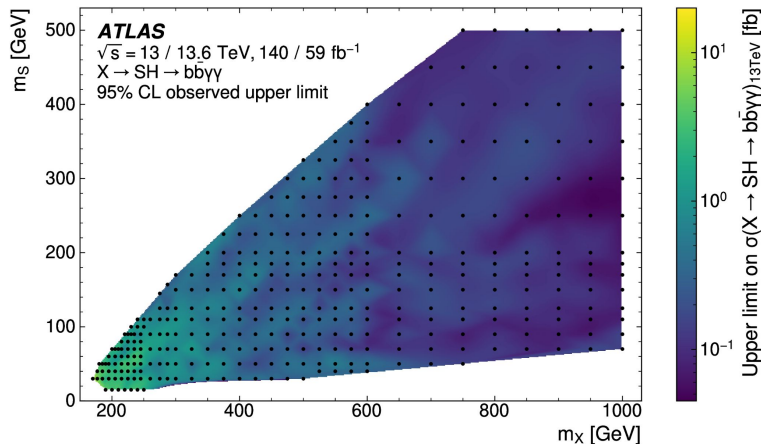
$X \rightarrow S(\rightarrow bb)H(\rightarrow \gamma\gamma)$ [[JHEP 11 \(2024\) 047](#)]

ATLAS X $\rightarrow$ SH $\rightarrow$ $bb\gamma\gamma$ Run 2 + partial Run 3 (2022-23)

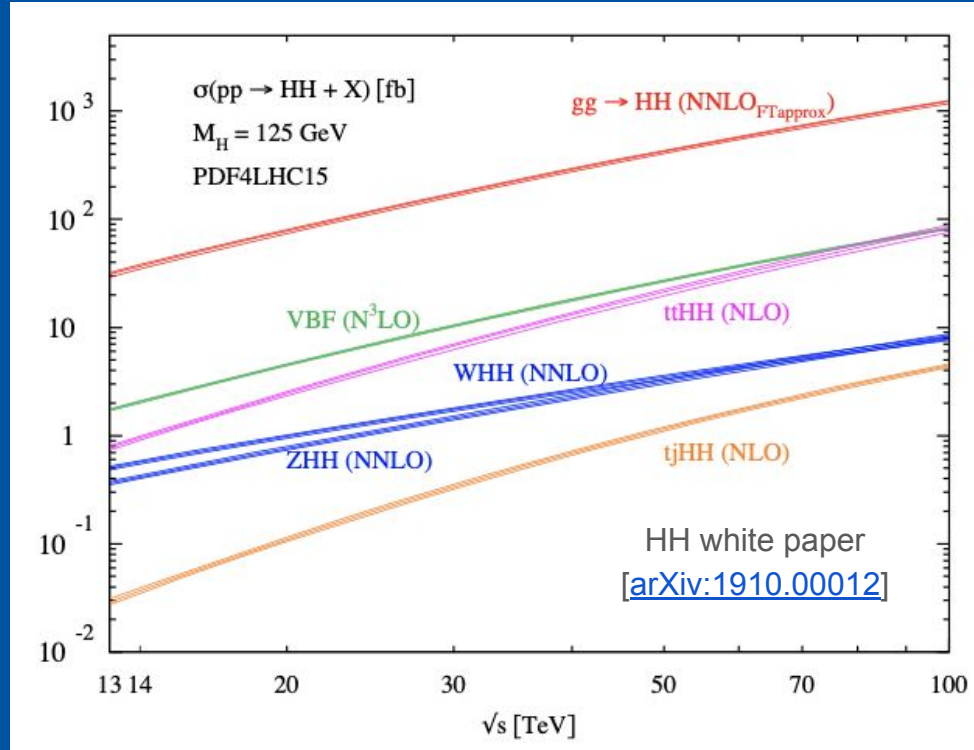


[PLB 877 \(2026\) 140425](#)

- Limits on $X \rightarrow S(\rightarrow bb)H(\rightarrow \gamma\gamma)$ production ranging from **9 to 0.06 fb using Run 2 + partial Run 3** (2022-2023) data, compared to limits from **39 to 0.06 fb with only Run 2**
- Two categories to reconstruct S candidates: 2 b-tagged region and 1 b-tagged region (boosted topology)
- Discriminant based on a parameterised neural network (PNN)
- Improvements include new generation of taggers (**from DL1r to GN2**) and a narrower $H \rightarrow \gamma\gamma$ mass window (**from 120-130 GeV to 122.5-127.5 GeV**)



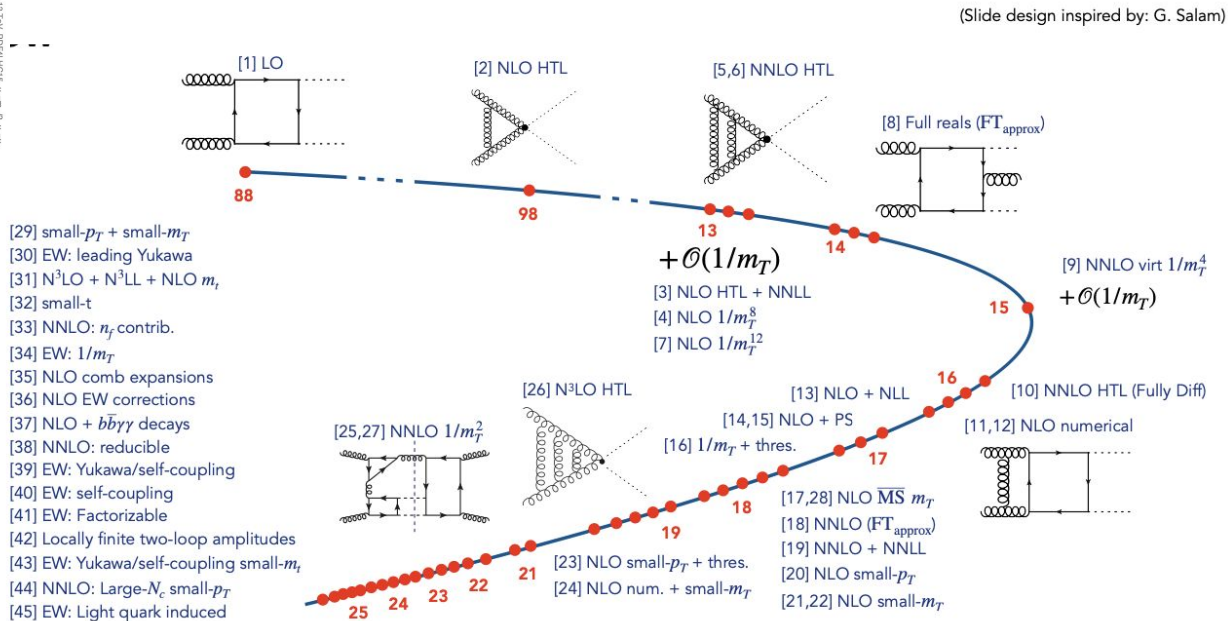
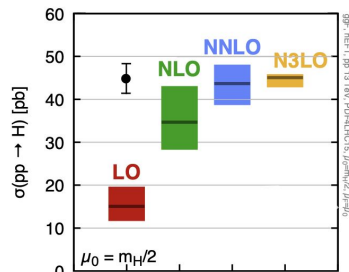
LHC Higgs Working Group



- LHC Higgs WG
 - Twiki page: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG>
 - Mailing list: lhc-higgs@cern.ch
 - WG1: Higgs cross-sections and branching ratios
 - WG2: Higgs properties
 - WG3: BSM Higgs
 - WG4: di-Higgs and multi-Higgs
 - Twiki page: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGHH>
 - Mailing list: lhc-higgs-hh@cern.ch
 - New HHH subgroup created in December 2024
 - Mailing list: lhc-higgs-hhh@cern.ch
 - General assembly at CERN on 18-20 Nov 2026: <https://indico.cern.ch/event/1675595/>

- Four CERN Yellow Reports have been completed:
 1. Inclusive Observables ([CERN-2011-002](#))
 2. Differential Distributions ([CERN-2012-002](#))
 3. Higgs Properties ([CERN-2013-004](#))
 4. Deciphering the Nature of the Higgs Sector ([CERN-2017-002](#))
- CERN ~~Yellow~~ LHCHWG Report 5:
 - Focus on physics goals and recommendations for LHC Run 4, submitted by the LHCHWG on SciPost
 - WG4 focus on theory predictions for HH cross sections (ggF HH, VBF HH, VHH) to reflect the major updates achieved since YR4 and the [HH White Paper](#) (2019) with refined calculations and more reliable uncertainty estimates

NNLO and N3LO revolution



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke 16; [13] Ferrara, Pires 16; [14] Heinrich, Jones, Kerner, Luisoni, Vryonidou 17; [15] Jones, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degraßi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, Jones, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degraßi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Ajith, Shao 22; [32] Davies, Mishima, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser 23; [34] Davies, Schönwald, Steinhauser, Zhang 23; [35] Bagnaschi, Degraßi, Gröber 23; [36] Bi, Huang, Huang, Ma Yu 23 [37] Li, Si, Wang, Zhang, Zhao 24; [38] Davies, Schönwald, Steinhauser, Vitti 24; [39] Heinrich, Jones, Kerner, Stone, Vestner [40] Li, Si, Wang, Zhang, Zhao 24; [41] Davies, Schönwald, Steinhauser, Zhang 24; [42] C. Anastasiou, J. Karlen, G. Sterman, A. Venkata 24; [43] Davies, Schönwald, Steinhauser, Zhang 25; [44] Davies, Schönwald, Steinhauser 25; [45] Bonetti, Rendler, Bobadilla 25;

- **WG4 first wave of contributions** structured as follows:
 - ggF HH production ([LHCHWG-INT-2026-001](#))
 - ggF+VBF HH NLO EW corrections and dependence on κ_3 and κ_4 ([LHCHWG-2025-015](#), [arXiv:2601.13248](#))
 - VBF HH MC simulation tools ([LHCHWG-2025-012](#), [arXiv:2511.02488](#))
 - VBF HH and VHH production ([LHCHWG-2026-001](#), [arXiv:2603.02764](#))
- **WG4 second wave of contributions** in the pipeline:
 - NMSSMScanner ([LHCHWG-2026-002](#), [arXiv:2604.25009](#))
 - BSM benchmarks, resonant HH production and interference effects
 - HEFT/SMEFT
 - HHH
- First round of contributions and recommendations being included in [SciPost series](#)
- Recommendations provided at $\sqrt{s} = 13, 13.6, 14$ TeV for different m_H values
- Update recommendations in WG4 twiki to summarize state-of-the-art calculations (more dynamic)
- Contributions being prepared and wrapped up for the second round!

$m_H = 125.09$ GeV [ATLAS+CMS Run 1, [PRL 114 \(2015\) 191803](#)]

$m_H = 125.38$ GeV [CMS Run 1 + 2016, [PLB 805 \(2020\) 135425](#)]

Higgs Boson Pair Production via Gluon Fusion: Higher-Order Corrections and Theoretical Uncertainties

[LHCHWG-INT-2026-001](#)

QCD corrections:

- Full NLO QCD + PS [Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke]
- Full NLO with m_t & m_H [Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira, Streicher]
- Amplitude expansion with small p_{TH} , small m_t [Bagnaschi, Bonciani, Degrossi, Giardino, Gröber]
- Full NLO with ggxy [Davies, Schönwald, Steinhauser, Stremmer]
- NNLO FTapprox [Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli]
- NNLO+PS with GENEVA [Alioli, Marinelli, Napoletano]
- NNLO with full m_t dependence [Davies, Schönwald, Steinhauser, Vitti]
- N3LO in the HTL [Chen, Chen, Dai, Li, Li, Shao, Wang]
- N3LO + N3LL in the HTL [A H, Shao]
- Partial m_t effects [A H, Chen, Chen, Dai, Li, Li, Shao, Wang]

Top-quark mass effects:

- m_t scheme and scale uncertainties at NLO [Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira, Streicher]
- m_t log resummation [Jaskiewicz, Jones, Szafron, Ulrich]

EW corrections:

- Full NLO EW [Bi, Huang, Huang, Ma, Yu] + separate contributions

SM ggF HH production

Contributions from 33 institutions,
comprehensive summary of results

See [M. Bonetti talk at the LHCHWG 2025](#)

[Mühlleitner, Schlenk, Spira] [Davies, Schönwald, Steinhauser, Zhang]
[Davies, Schönwald, Steinhauser, Zhang] [Heinrich, Jones, Kerner, Stone, Vestner]
[Bonetti, Rendler, Torres Bobadilla]
[Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Spira]
[Bonetti, Heinrich, Rendler, Torres Bobadilla]

Higgs Boson Pair Production via Gluon Fusion: Higher-Order Corrections and Theoretical Uncertainties

[LHCHWG-INT-2026-001](#)

- New HH cross section recommendations finalized (combination of NNLO F_Tapprox, the current recommendation):

$$\sigma_{\text{rec.}}(\sqrt{s}) = \sigma_{\text{NNLO}_{\text{F}_T\text{approx}}}(\sqrt{s}) \times K_3(\sqrt{s}) \times K_{\text{EW}}(\sqrt{s}) \quad \text{with} \quad K_3 = \left(\frac{\text{N}^3\text{LO} + \text{N}^3\text{LL HTL}}{\text{NNLO HTL}} \right) \quad \text{and} \quad K_{\text{EW}} = \frac{\sigma_{\text{NLO EW}}}{\sigma_{\text{LO}}}$$

- PDF set: PDF4LHC21_40 (uncertainty from the NNLO_F_Tapprox prediction)
- PDF uncertainty computed as cross-check using MSHT20xNNPDF40_aN3LO_qed & MSHT20xNNPDF40_NNLO_qed:

$$\Delta_{\text{NNLO}}^{\text{MHOU}} = \left| \frac{\sigma_{\text{N}^3\text{LO-PDF}}^{\text{N}^3\text{LO}} - \sigma_{\text{NNLO-PDF}}^{\text{N}^3\text{LO}}}{\sigma_{\text{N}^3\text{LO-PDF}}^{\text{N}^3\text{LO}}} \right|$$

- Central renormalization/factorization scales: $\mu_R = \mu_F = M_{\text{HH}}/2$
- Scale uncertainties: 7-point variations by a factor of 0.5, 1, 2 around the central scale, excluding (0.5, 2) and (2, 0.5)
- Top quark mass scheme uncertainty assigned to the definition of the virtual top quark mass entering the top Yukawa coupling and the propagators following [Phys. Rev. D 103 \(2021\) 056002](#)

Higgs Boson Pair Production via Gluon Fusion: Higher-Order Corrections and Theoretical Uncertainties

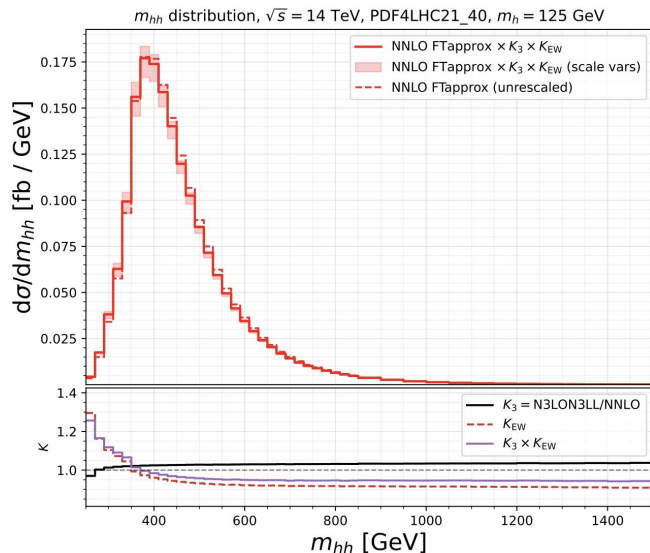
LHCHWG-INT-2026-001

- Final recommended inclusive total cross sections for ggF HH for $m_H = 125$ GeV

$\sqrt{s}$ [TeV]	13	13.6	14
$\sigma_{\text{rec.}}$ [fb]	30.40	33.62	35.81
$\pm$ PDF unc. [%]	1.96	1.92	1.89
$\pm \alpha_s$ unc. [%]	1.51	1.49	1.47
$\pm$ PDF + α_s unc. [%]	2.47	2.43	2.39
QCD scale unc. [%]	+2.11 -4.98	+2.07 -4.85	+2.01 -4.78
m_t scheme unc. [%]	+5 -16	+5 -16	+5 -16
$\pm$ THU [%]	0.14	0.19	0.21
Scale + THU + m_t scheme unc. [%]	+7.25 -21.12	+7.26 -21.04	+7.22 -20.99

- Scaling by $\sigma_{\text{NLO}}(m_h)/\sigma_{\text{NLO}}(125 \text{ GeV})$ computed with ggxy for other m_H

m_h [GeV]	$\sigma_{\text{rec.}}$ [fb]		
	$\sqrt{s} = 13 \text{ TeV}$	$\sqrt{s} = 13.6 \text{ TeV}$	$\sqrt{s} = 14 \text{ TeV}$
124.8	30.48	33.68	35.90
125	30.40	33.62	35.81
125.2	30.29	33.54	35.68



LHCHWG Report 5: VBF HH production

Electroweak Higgs boson pair production: Updated inclusive cross sections

Ramona Gröber, Alexander Karlberg, Mathieu Pellen,
Gioia Sacchi and Michael Spira

[LHCHWG-2026-001](#), [arXiv:2603.02764](#)

- Inclusive predictions obtained with PROVBFHH and RECOLA+MOCANLO
- Cross section with anomalous trilinear Higgs self-coupling obtained by PROVBFHH without NLO EW corrections

$$\mu = \sqrt{\frac{m_h}{2} \sqrt{\left(\frac{m_h}{2}\right)^2 + p_{T,hh}^2}} \quad \sigma_{\text{N3LO QCD} \times \text{NLO EW}}^{\text{VBF}} = \sigma_{\text{N3LO QCD}}^{\text{VBF}} \left(1 + \frac{\delta_{\text{NLO EW}}^{\text{VBF}}}{\sigma_{\text{LO}}^{\text{vbf}}}\right)$$

$\sqrt{s}$ [TeV]	m_h [GeV]	σ [fb] SM
13	125	$1.687^{+0.05\%}_{-0.04\%} \pm 2.7\%$
	125.09	$1.684^{+0.05\%}_{-0.04\%} \pm 2.7\%$
	125.38	$1.676^{+0.05\%}_{-0.04\%} \pm 2.8\%$
13.6	125	$1.874^{+0.05\%}_{-0.03\%} \pm 2.7\%$
	125.09	$1.870^{+0.05\%}_{-0.03\%} \pm 2.7\%$
	125.38	$1.861^{+0.05\%}_{-0.03\%} \pm 2.7\%$
14	125	$2.005^{+0.05\%}_{-0.03\%} \pm 2.7\%$
	125.09	$2.001^{+0.05\%}_{-0.03\%} \pm 2.7\%$
	125.38	$1.992^{+0.05\%}_{-0.03\%} \pm 2.7\%$

$\sqrt{s}$ [TeV]	m_h [GeV]	σ [fb] SM	σ [fb] $\kappa_\lambda = 0$	σ [fb] $\kappa_\lambda = 2$	σ [fb] $\kappa_\lambda = 3$
13	125	$1.742^{+0.04\%}_{-0.03\%} \pm 2.7\%$	$4.543^{+0.02\%}_{-0.01\%} \pm 2.6\%$	$1.443^{+0.06\%}_{-0.04\%} \pm 2.7\%$	$3.647^{+0.04\%}_{-0.00\%} \pm 2.5\%$
	125.09	$1.739^{+0.04\%}_{-0.03\%} \pm 2.7\%$	$4.540^{+0.02\%}_{-0.01\%} \pm 2.6\%$	$1.442^{+0.06\%}_{-0.04\%} \pm 2.7\%$	$3.648^{+0.04\%}_{-0.00\%} \pm 2.5\%$
	125.38	$1.731^{+0.04\%}_{-0.03\%} \pm 2.7\%$	$4.528^{+0.02\%}_{-0.01\%} \pm 2.6\%$	$1.440^{+0.06\%}_{-0.04\%} \pm 2.7\%$	$3.652^{+0.04\%}_{-0.00\%} \pm 2.5\%$
13.6	125	$1.938^{+0.03\%}_{-0.03\%} \pm 2.7\%$	$5.019^{+0.02\%}_{-0.01\%} \pm 2.5\%$	$1.606^{+0.05\%}_{-0.04\%} \pm 2.7\%$	$4.022^{+0.04\%}_{-0.00\%} \pm 2.5\%$
	125.09	$1.936^{+0.03\%}_{-0.03\%} \pm 2.7\%$	$5.015^{+0.02\%}_{-0.01\%} \pm 2.5\%$	$1.605^{+0.05\%}_{-0.04\%} \pm 2.7\%$	$4.023^{+0.04\%}_{-0.00\%} \pm 2.5\%$
	125.38	$1.927^{+0.03\%}_{-0.03\%} \pm 2.7\%$	$5.002^{+0.02\%}_{-0.01\%} \pm 2.5\%$	$1.602^{+0.05\%}_{-0.04\%} \pm 2.7\%$	$4.028^{+0.04\%}_{-0.00\%} \pm 2.5\%$
14	125	$2.075^{+0.03\%}_{-0.02\%} \pm 2.7\%$	$5.347^{+0.02\%}_{-0.01\%} \pm 2.5\%$	$1.719^{+0.05\%}_{-0.03\%} \pm 2.7\%$	$4.281^{+0.04\%}_{-0.00\%} \pm 2.5\%$
	125.09	$2.072^{+0.03\%}_{-0.02\%} \pm 2.7\%$	$5.342^{+0.02\%}_{-0.01\%} \pm 2.5\%$	$1.719^{+0.05\%}_{-0.03\%} \pm 2.7\%$	$4.282^{+0.04\%}_{-0.00\%} \pm 2.5\%$
	125.38	$2.027^{+0.03\%}_{-0.02\%} \pm 2.7\%$	$5.329^{+0.02\%}_{-0.01\%} \pm 2.5\%$	$1.715^{+0.05\%}_{-0.03\%} \pm 2.7\%$	$4.287^{+0.04\%}_{-0.00\%} \pm 2.5\%$

LHCHWG Report 5: VHH production

Electroweak Higgs boson pair production: Updated inclusive cross sections

Ramona Gröber, Alexander Karlberg, Mathieu Pellen,
Gioia Sacchi and Michael Spira

[LHCHWG-2026-001](#), [arXiv:2603.02764](#)

Updated cross sections wrt YR4 based on [JHEP 04 \(2013\) 151](#)
using PDF4LHC21 and $\mu_R = \mu_F = M_{Vhh}$

$\sqrt{s}$ [TeV]	m_h [GeV]	σ [fb] SM	σ [fb] $\kappa_\lambda = 0$	σ [fb] $\kappa_\lambda = 2$	σ [fb] $\kappa_\lambda = 3$
13	125	$0.366^{+3.3\%}_{-2.6\%} \pm 2.0\%$	$0.232^{+5.1\%}_{-4.0\%} \pm 1.9\%$	$0.561^{+2.2\%}_{-1.8\%} \pm 2.0\%$	$0.819^{+1.5\%}_{-1.3\%} \pm 2.0\%$
13	125.09	$0.365^{+3.3\%}_{-2.6\%} \pm 2.0\%$	$0.232^{+5.1\%}_{-4.0\%} \pm 1.9\%$	$0.560^{+2.2\%}_{-1.8\%} \pm 2.0\%$	$0.818^{+1.5\%}_{-1.3\%} \pm 2.0\%$
13	125.38	$0.362^{+3.3\%}_{-2.6\%} \pm 2.0\%$	$0.230^{+5.1\%}_{-4.0\%} \pm 1.9\%$	$0.556^{+2.2\%}_{-1.8\%} \pm 2.0\%$	$0.813^{+1.5\%}_{-1.3\%} \pm 2.0\%$
13.6	125	$0.396^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.253^{+5.3\%}_{-4.1\%} \pm 1.9\%$	$0.607^{+2.2\%}_{-1.8\%} \pm 2.0\%$	$0.885^{+1.6\%}_{-1.3\%} \pm 2.0\%$
13.6	125.09	$0.396^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.252^{+5.3\%}_{-4.1\%} \pm 1.9\%$	$0.606^{+2.2\%}_{-1.8\%} \pm 2.0\%$	$0.883^{+1.6\%}_{-1.3\%} \pm 2.0\%$
13.6	125.38	$0.393^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.250^{+5.3\%}_{-4.1\%} \pm 1.9\%$	$0.602^{+2.2\%}_{-1.8\%} \pm 2.0\%$	$0.878^{+1.6\%}_{-1.3\%} \pm 2.0\%$
14	125	$0.417^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.267^{+5.3\%}_{-4.1\%} \pm 1.8\%$	$0.638^{+2.3\%}_{-1.9\%} \pm 1.9\%$	$0.929^{+1.6\%}_{-1.3\%} \pm 2.0\%$
14	125.09	$0.416^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.266^{+5.3\%}_{-4.1\%} \pm 1.8\%$	$0.637^{+2.3\%}_{-1.9\%} \pm 1.9\%$	$0.927^{+1.6\%}_{-1.3\%} \pm 2.0\%$
14	125.38	$0.413^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.264^{+5.3\%}_{-4.1\%} \pm 1.8\%$	$0.632^{+2.3\%}_{-1.8\%} \pm 1.9\%$	$0.922^{+1.6\%}_{-1.3\%} \pm 2.0\%$

ZHH at NNLO QCD

$\sqrt{s}$ [TeV]	m_h [GeV]	σ [fb] SM	σ [fb] $\kappa_\lambda = 0$	σ [fb] $\kappa_\lambda = 2$	σ [fb] $\kappa_\lambda = 3$
13	125	$0.334^{+0.34\%}_{-0.41\%} \pm 2.3\%$	$0.192^{+0.31\%}_{-0.42\%} \pm 2.4\%$	$0.549^{+0.37\%}_{-0.41\%} \pm 2.3\%$	$0.837^{+0.37\%}_{-0.41\%} \pm 2.3\%$
13	125.09	$0.333^{+0.34\%}_{-0.41\%} \pm 2.3\%$	$0.192^{+0.31\%}_{-0.42\%} \pm 2.4\%$	$0.548^{+0.37\%}_{-0.41\%} \pm 2.3\%$	$0.835^{+0.37\%}_{-0.41\%} \pm 2.3\%$
13	125.38	$0.331^{+0.34\%}_{-0.41\%} \pm 2.3\%$	$0.190^{+0.31\%}_{-0.42\%} \pm 2.4\%$	$0.544^{+0.37\%}_{-0.41\%} \pm 2.3\%$	$0.831^{+0.37\%}_{-0.41\%} \pm 2.3\%$
13.6	125	$0.358^{+0.36\%}_{-0.40\%} \pm 2.3\%$	$0.206^{+0.33\%}_{-0.41\%} \pm 2.3\%$	$0.588^{+0.38\%}_{-0.40\%} \pm 2.2\%$	$0.896^{+0.39\%}_{-0.40\%} \pm 2.2\%$
13.6	125.09	$0.357^{+0.36\%}_{-0.40\%} \pm 2.3\%$	$0.206^{+0.33\%}_{-0.41\%} \pm 2.3\%$	$0.587^{+0.38\%}_{-0.40\%} \pm 2.2\%$	$0.895^{+0.39\%}_{-0.40\%} \pm 2.2\%$
13.6	125.38	$0.355^{+0.36\%}_{-0.40\%} \pm 2.3\%$	$0.204^{+0.33\%}_{-0.41\%} \pm 2.3\%$	$0.583^{+0.38\%}_{-0.40\%} \pm 2.2\%$	$0.890^{+0.39\%}_{-0.40\%} \pm 2.2\%$
14	125	$0.374^{+0.37\%}_{-0.40\%} \pm 2.2\%$	$0.216^{+0.33\%}_{-0.40\%} \pm 2.3\%$	$0.614^{+0.39\%}_{-0.41\%} \pm 2.2\%$	$0.936^{+0.40\%}_{-0.41\%} \pm 2.2\%$
14	125.09	$0.373^{+0.37\%}_{-0.40\%} \pm 2.2\%$	$0.216^{+0.33\%}_{-0.40\%} \pm 2.3\%$	$0.613^{+0.39\%}_{-0.41\%} \pm 2.2\%$	$0.935^{+0.40\%}_{-0.41\%} \pm 2.2\%$
14	125.38	$0.371^{+0.37\%}_{-0.40\%} \pm 2.2\%$	$0.214^{+0.33\%}_{-0.40\%} \pm 2.3\%$	$0.610^{+0.39\%}_{-0.40\%} \pm 2.2\%$	$0.930^{+0.40\%}_{-0.41\%} \pm 2.2\%$

W*HH at NNLO QCD

$\sqrt{s}$ [TeV]	m_h [GeV]	σ [fb] SM	σ [fb] $\kappa_\lambda = 0$	σ [fb] $\kappa_\lambda = 2$	σ [fb] $\kappa_\lambda = 3$
13	125	$0.173^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.098^{+1.3\%}_{-1.3\%} \pm 2.6\%$	$0.286^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.437^{+1.3\%}_{-1.4\%} \pm 2.5\%$
13	125.09	$0.172^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.098^{+1.3\%}_{-1.3\%} \pm 2.6\%$	$0.285^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.436^{+1.3\%}_{-1.4\%} \pm 2.5\%$
13	125.38	$0.171^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.097^{+1.3\%}_{-1.3\%} \pm 2.6\%$	$0.283^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.433^{+1.3\%}_{-1.4\%} \pm 2.5\%$
13.6	125	$0.187^{+1.3\%}_{-1.4\%} \pm 2.5\%$	$0.106^{+1.3\%}_{-1.3\%} \pm 2.6\%$	$0.309^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.472^{+1.3\%}_{-1.4\%} \pm 2.4\%$
13.6	125.09	$0.187^{+1.3\%}_{-1.4\%} \pm 2.5\%$	$0.106^{+1.3\%}_{-1.3\%} \pm 2.6\%$	$0.309^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.472^{+1.3\%}_{-1.4\%} \pm 2.4\%$
13.6	125.38	$0.185^{+1.3\%}_{-1.4\%} \pm 2.5\%$	$0.105^{+1.3\%}_{-1.3\%} \pm 2.6\%$	$0.307^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.469^{+1.3\%}_{-1.4\%} \pm 2.4\%$
14	125	$0.197^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.112^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.325^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.497^{+1.3\%}_{-1.4\%} \pm 2.4\%$
14	125.09	$0.196^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.112^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.325^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.496^{+1.3\%}_{-1.4\%} \pm 2.4\%$
14	125.38	$0.195^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.111^{+1.3\%}_{-1.3\%} \pm 2.5\%$	$0.322^{+1.3\%}_{-1.4\%} \pm 2.4\%$	$0.493^{+1.3\%}_{-1.4\%} \pm 2.4\%$

W-HH at NNLO QCD

Summary

- Exploring the **energy frontier**, have acquired only the **~15% of the data** (500 of 3000 fb⁻¹)
- After the discovery of the Higgs boson, the **observation of the Higgs boson self-coupling is one of the main priorities of the LHC physics program (physics driver)**
- State-of-the-art diHiggs searches: legacy Run 2 results in ATLAS and CMS including combination, new results using partial Run 3 data, good agreement with SM expectations observed so far
- A 95% CL **upper limit of 2.5 x SM HH non-resonant production** (combining ATLAS+CMS)
- Run 3 analysis effort ongoing, it can be a game-changer for HH
- Vital the optimization of the trigger and analysis techniques to maximize the HH signal
- According to the projections, **5 σ observation of the SM HH production at the HL-LHC (2000 fb⁻¹)**
- A very exciting program ahead of us!

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