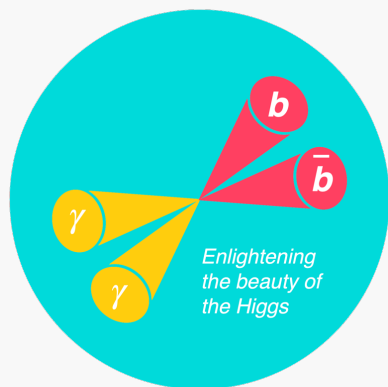




Studies of new Higgs boson interactions through nonresonant HH production in the $b\bar{b}\gamma\gamma$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Zihang Jia^{1,2} on behalf of the ATLAS collaboration

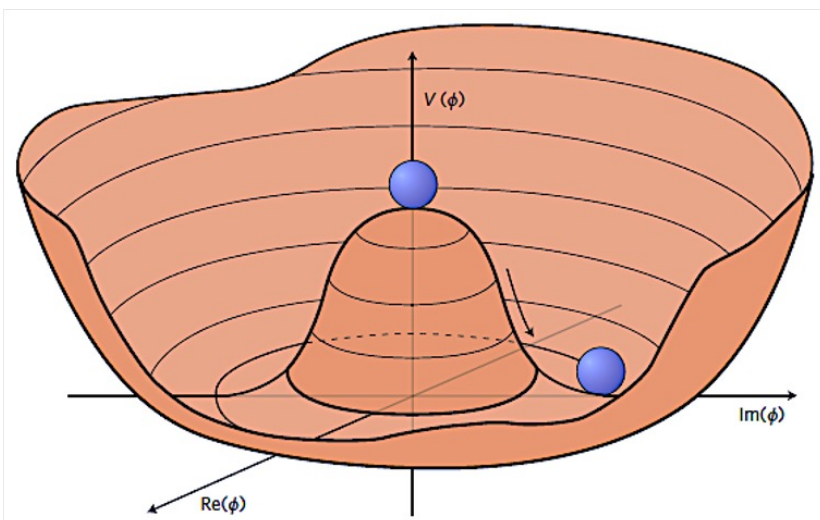
¹*Institute of High Energy Physics, Chinese Academy of Science*

²*Nanjing University*

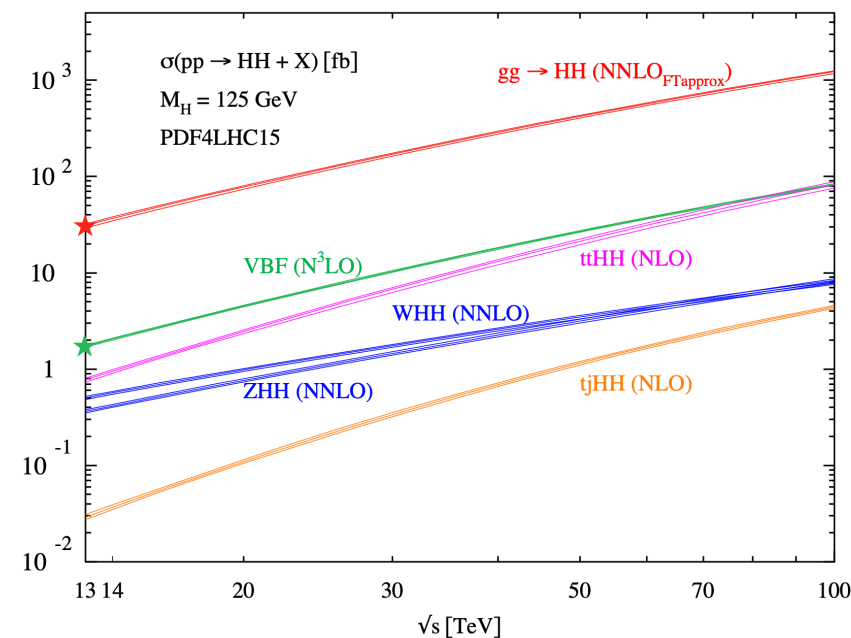
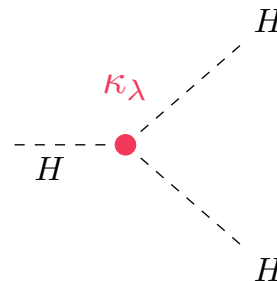
Introduction

- In the **Higgs sector**, couplings involving **multiple Higgs bosons** remain largely unconstrained experimentally
- **Higgs self-couplings** (λ) provide key information on the shape of the **Higgs potential** $V(h)$
- A direct probe of the **Higgs trilinear self-coupling** is possible via **Higgs boson pair (HH) production**

$$V(h) \sim \frac{1}{2} m_H^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \dots$$



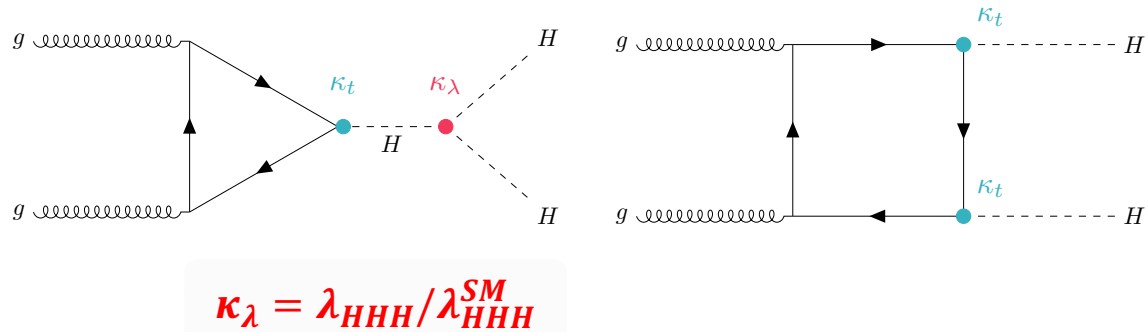
$$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$$



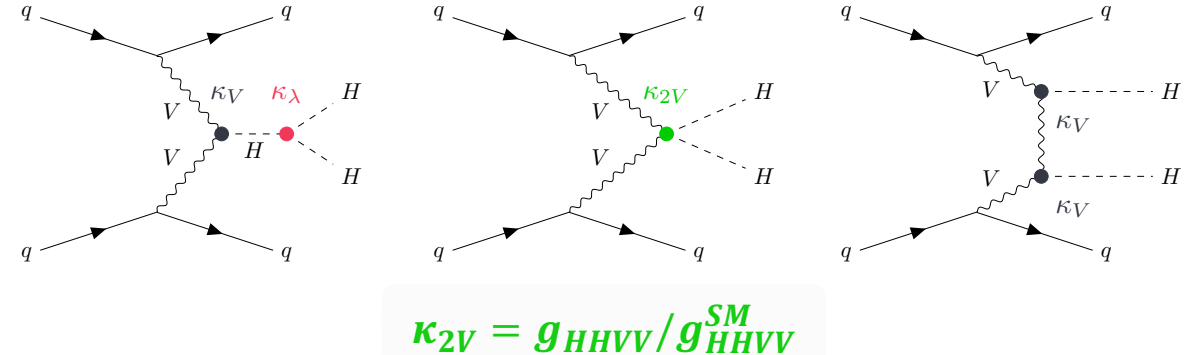
HH production

- **ggF HH production** drives the sensitivity to the Higgs trilinear self-coupling κ_λ
- **VBF HH production** provides **additional sensitivity to κ_λ** and has a unique sensitivity to the **quartic couplings between two Higgs bosons and two W or Z bosons κ_{2V}**
- Anomalous values of these couplings would point to **physics beyond the Standard Model (BSM)**

Gluon-gluon fusion (ggFHH) $\sigma_{\text{NNLO}} = 31.05 \text{ [fb]}^*$



Vector boson fusion (VBFHH) $\sigma_{\text{N3LO}} = 1.73 \text{ [fb]}^*$



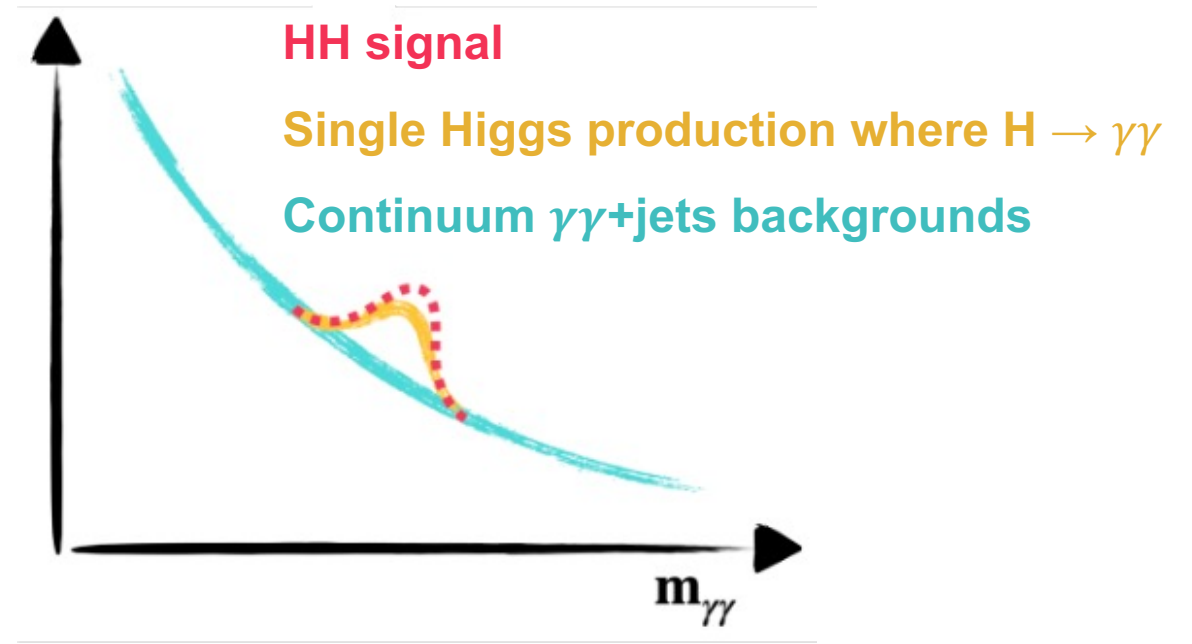
➤ 1000 times smaller than those of single-Higgs boson production in SM

*@13 TeV, $m_H = 125 \text{ GeV}$

$HH \rightarrow b\bar{b}\gamma\gamma$ analysis

- The $b\bar{b}\gamma\gamma$ final state is one of the most sensitive HH final states.
- $H \rightarrow b\bar{b}$ decay: high branching ratio
- $H \rightarrow \gamma\gamma$ decay: excellent photon trigger and $m_{\gamma\gamma}$ resolution, larger expected signal-to-background (S/B) ratio

	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%



Event selections: Pre-selections

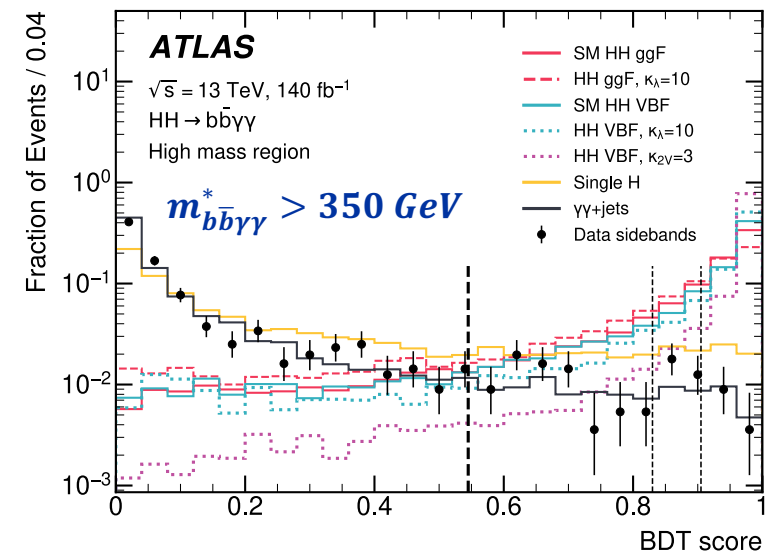
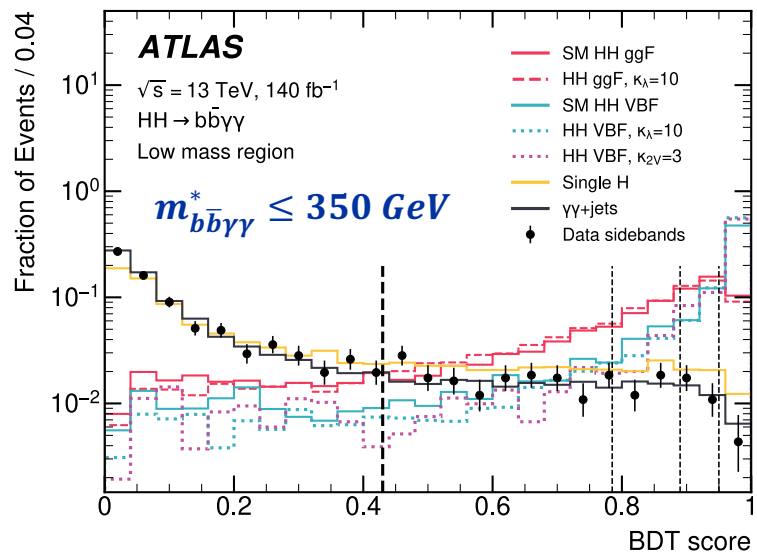
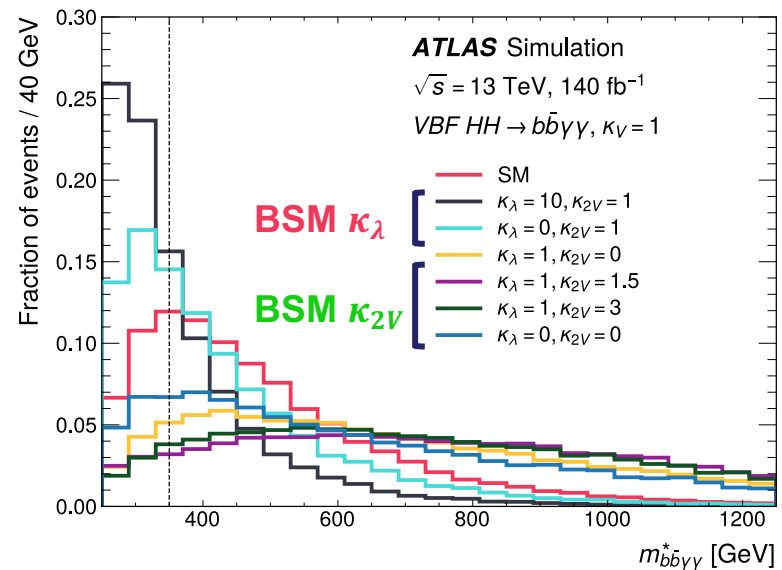
- **Triggers:** combination of di-photon and single photon ($\sim 0.1\%$ contribution) triggers
- Selections on **photons** and **jets** to identify $H \rightarrow \gamma\gamma$ and $H \rightarrow bb$ decays
- $t\bar{t}H(\gamma\gamma)$ is a major single Higgs background – can be reduced based on its final state topology

$H \rightarrow \gamma\gamma$ selection	$H \rightarrow bb$ selection	$t\bar{t}H$ reduction
• 2 tight and isolated photons • $\frac{p_T^{\gamma 1}(p_T^{\gamma 2})}{m_{\gamma\gamma}} > 0.35(0.25)$ • $m_{\gamma\gamma} \in [105, 160]$ GeV	• 2 b-jets @77% WP from DL1r tagger • μ-in-jet and p_T-reco* correction *undetected energies from neutrinos and out-of-cone effects	• $N_{lepton} = 0$ • $N_{central\ jets} < 6$

Improves the signal mass resolution due to the cancellation of detector resolution effects

Event selections: Categorization

- Mass regions:** define two mass regions based on **modified four-body invariant mass** $m_{b\bar{b}\gamma\gamma}^* = m_{b\bar{b}\gamma\gamma} - (m_{\gamma\gamma} - 125 \text{ GeV}) - (m_{b\bar{b}} - 125 \text{ GeV})$ to target HH signals with different κ_λ and κ_{2V} values
- Boosted decision tree (BDT) score:** in each mass region, a dedicated BDT discriminant is trained to distinguish HH signals from the continuum $\gamma\gamma$ background and single Higgs backgrounds



Event selections: Categorization BDT

- **BDT input variables:**

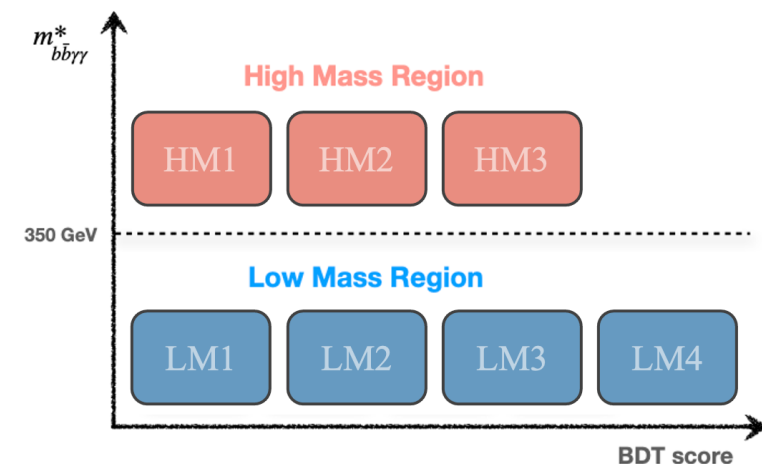
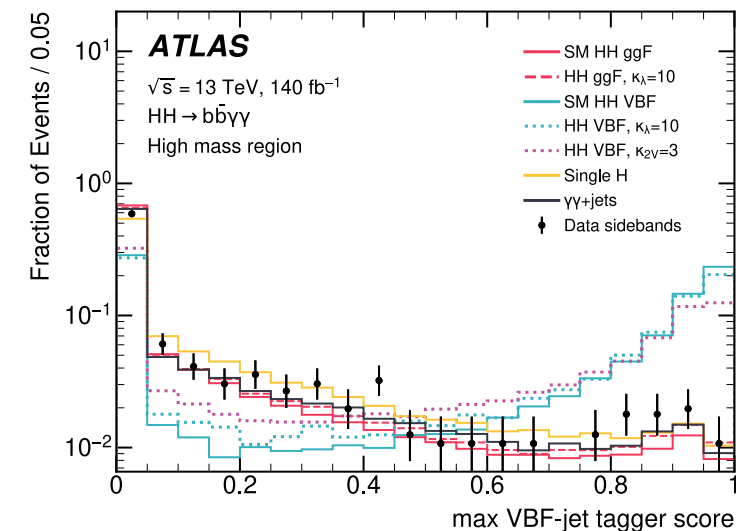
- Event-level kinematic quantities e.g. E_T^{miss} , $m_{b\bar{b}\gamma\gamma}^*$
- Kinematic properties of photons, b -jets and 2 additional jets

VBF jets (in VBF HH) identified by a BDT-based jet tagger

- **XGBoost hyperparameter optimization** based on number-counting

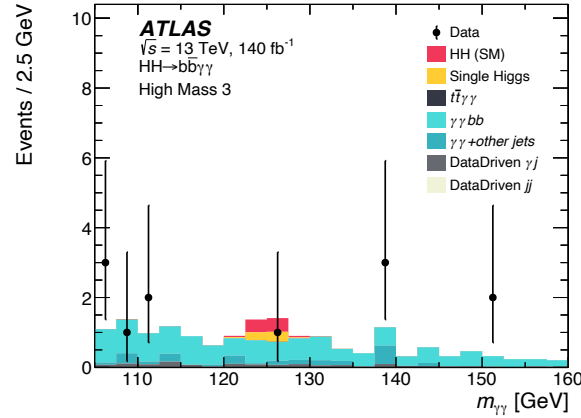
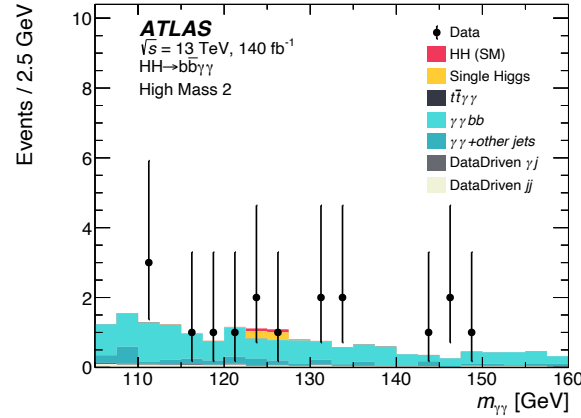
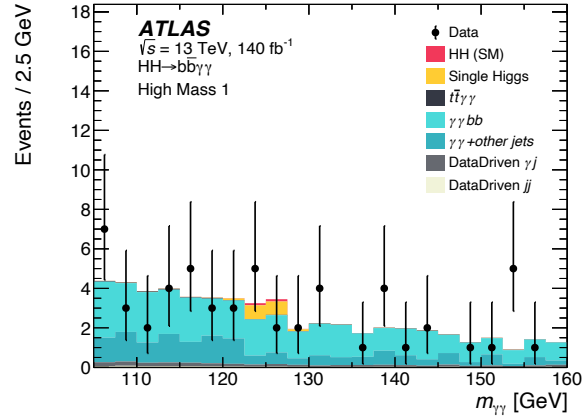
significance $Z = \sqrt{2 \cdot [(S + B) \cdot \ln(1 + S/B) - S]}$ as the evaluation metric to better correlate with the statistical results

- **Category boundaries** chosen by maximising the combined counting significance



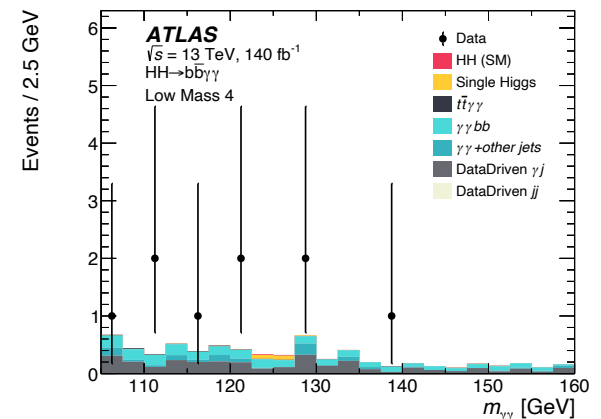
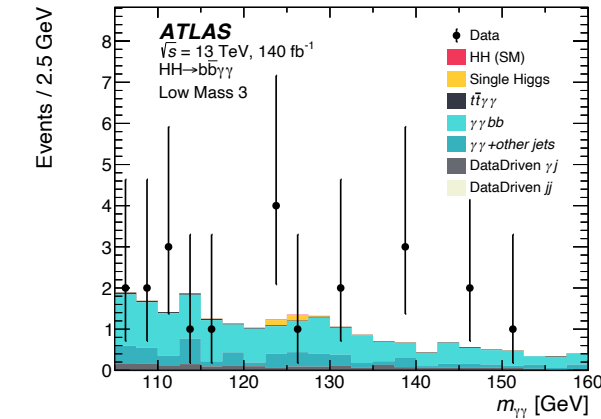
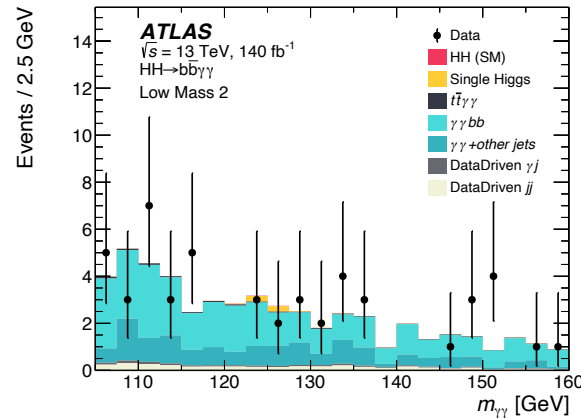
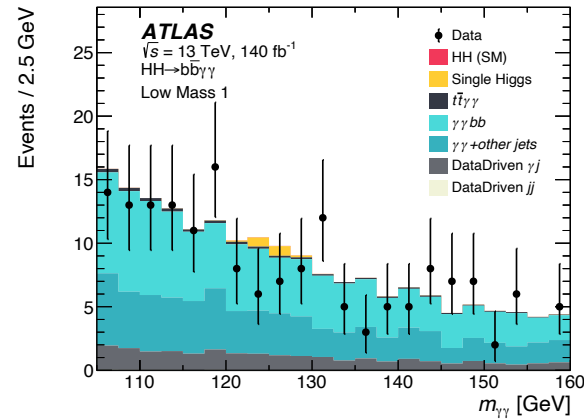
Data/MC comparison

- The agreement between data and MC in $m_{\gamma\gamma}$ spectrum for 7 categories.



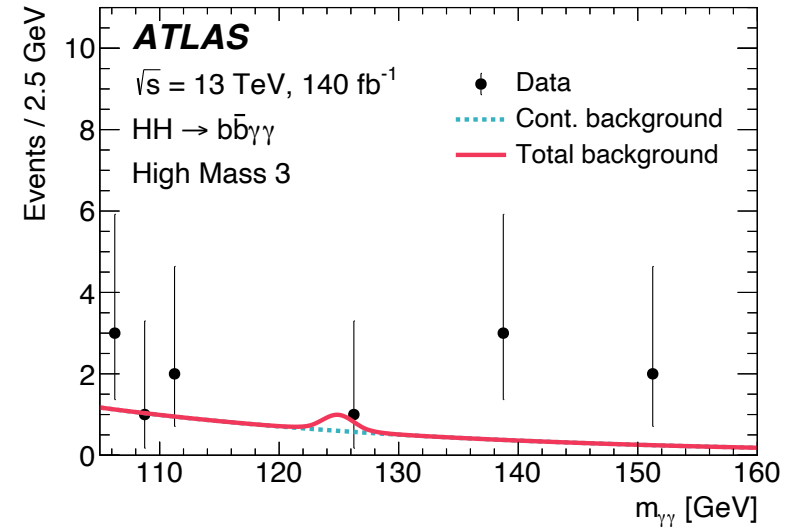
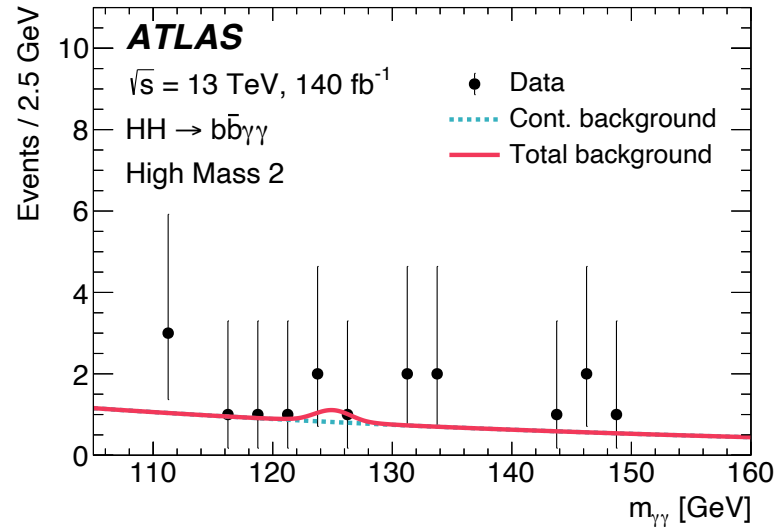
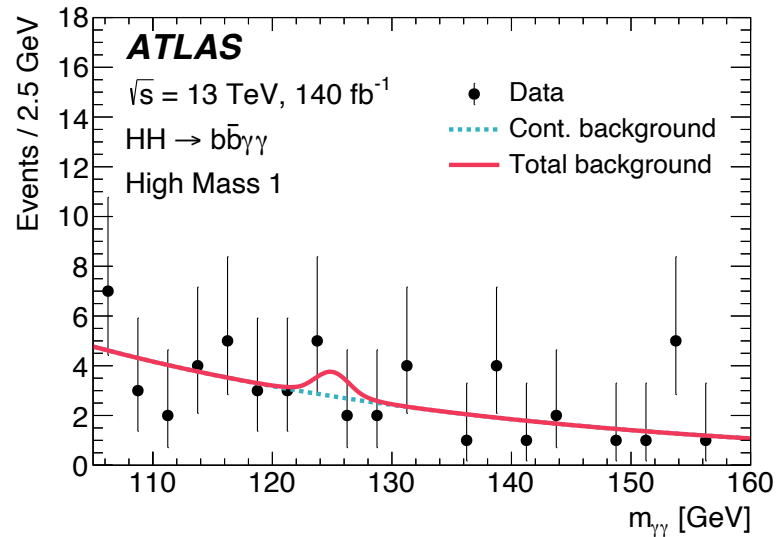
$\gamma\gamma$ +jets: jet flavor decomposition

$\gamma j/jj$: data-driven purities



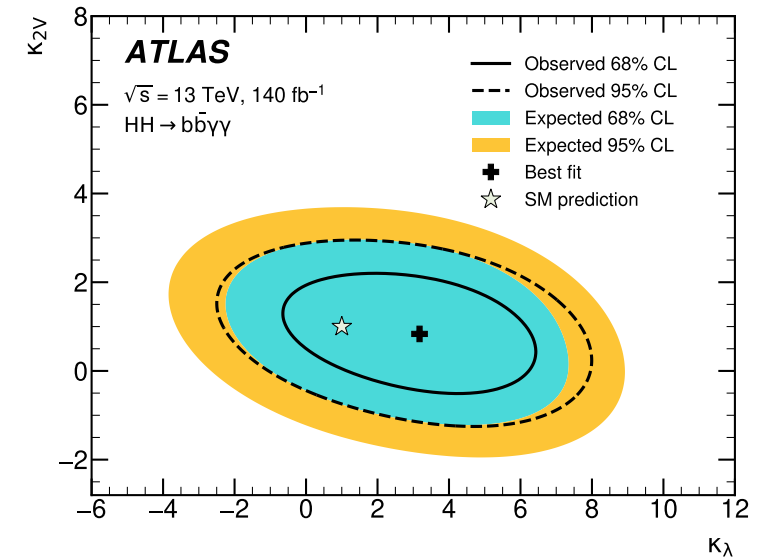
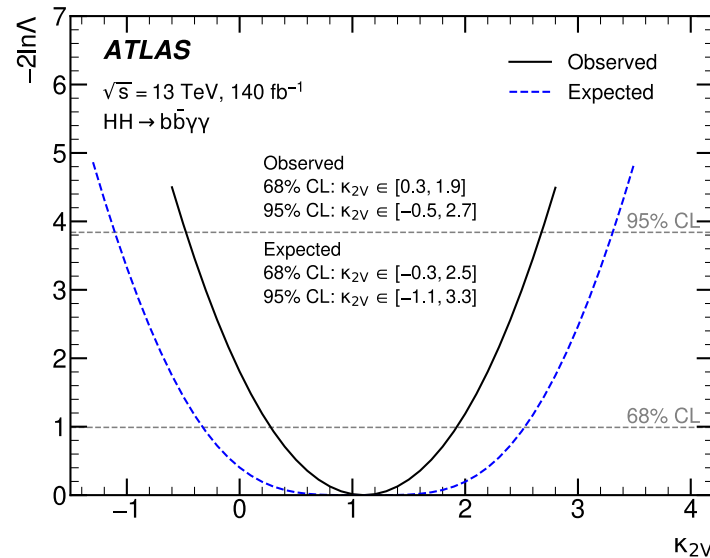
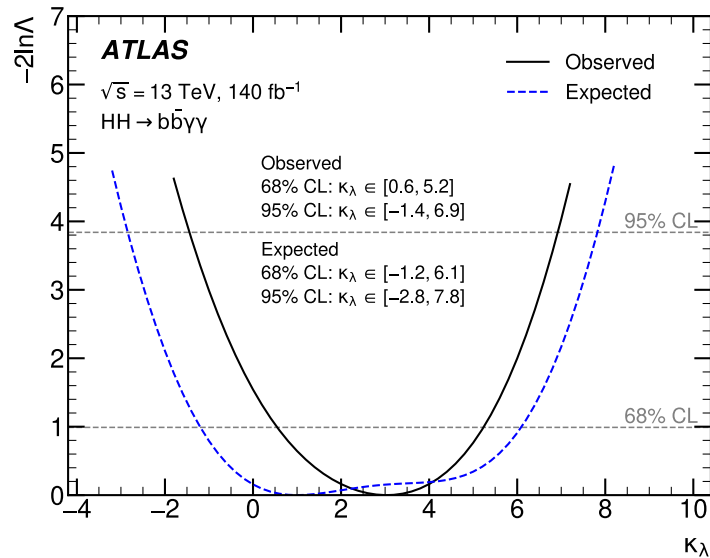
Signal Extraction

- The HH signals are extracted from an unbinned **maximum-likelihood fit to $m_{\gamma\gamma}$ spectrum** across all categories
- Signal model:** Double sided crystal ball function, derived from SM HH MC samples, shared with BSM HH and H
- Continuum background model:** Exponential function, normalization and shape parameters from fit to data



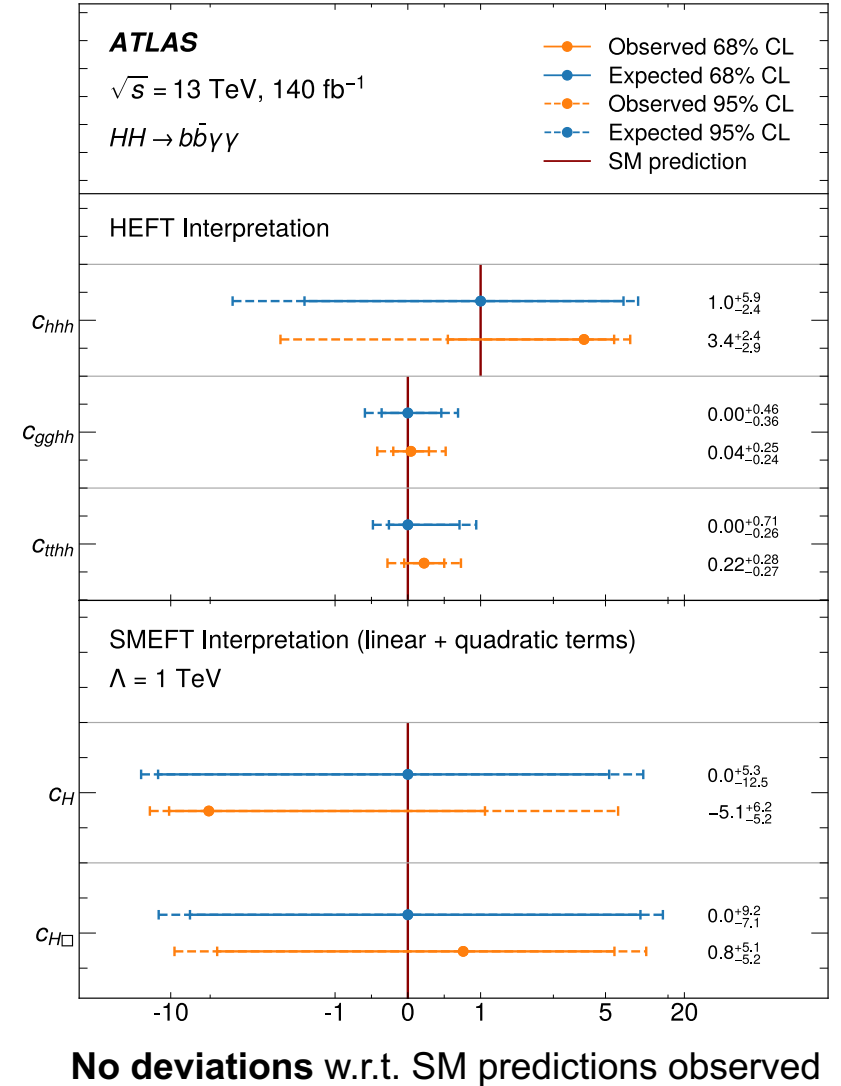
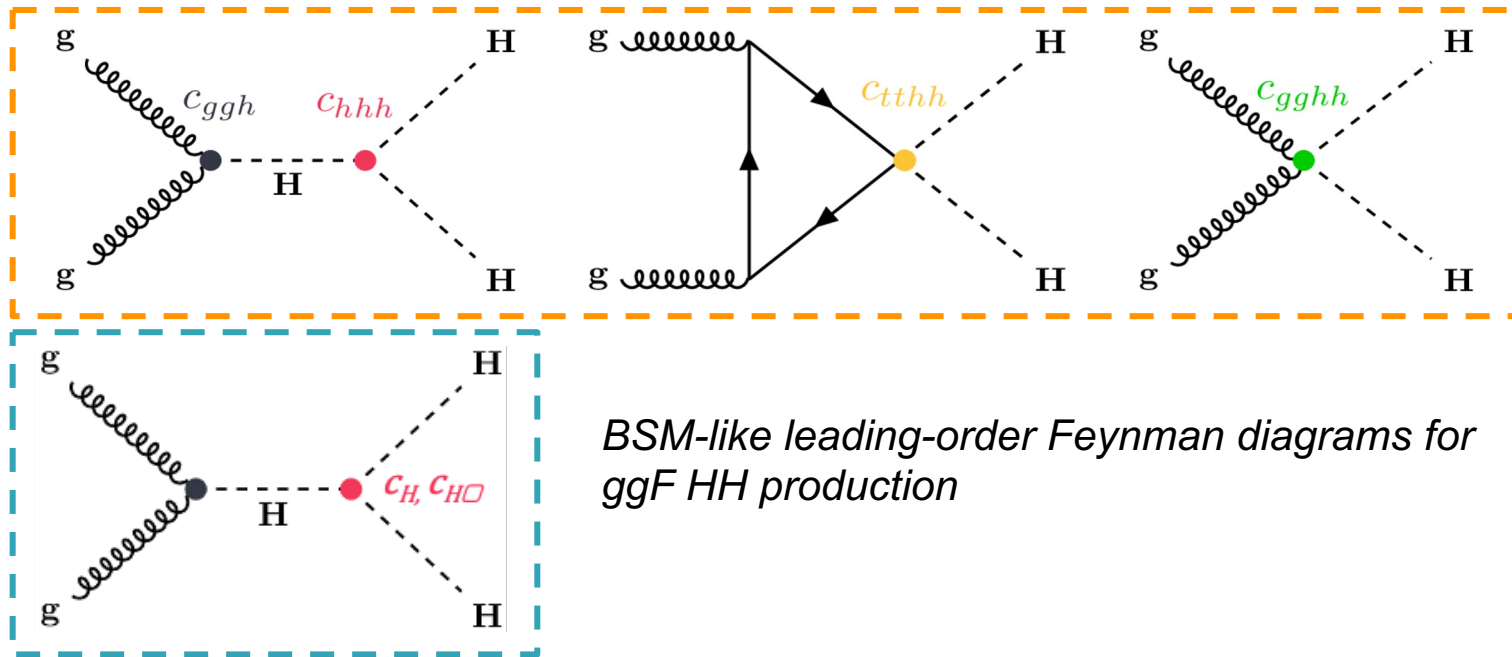
Results

- **No significant excess** over the expected background is observed
- Upper limit at 95% CL on HH production μ_{HH} : **4.0xSM** (obs), **5.0xSM** (exp)
- 1D and 2D constraints at 68% and 95% CL for κ_λ and κ_{2V} are evaluated via **profile log-likelihood scans**



EFT interpretations

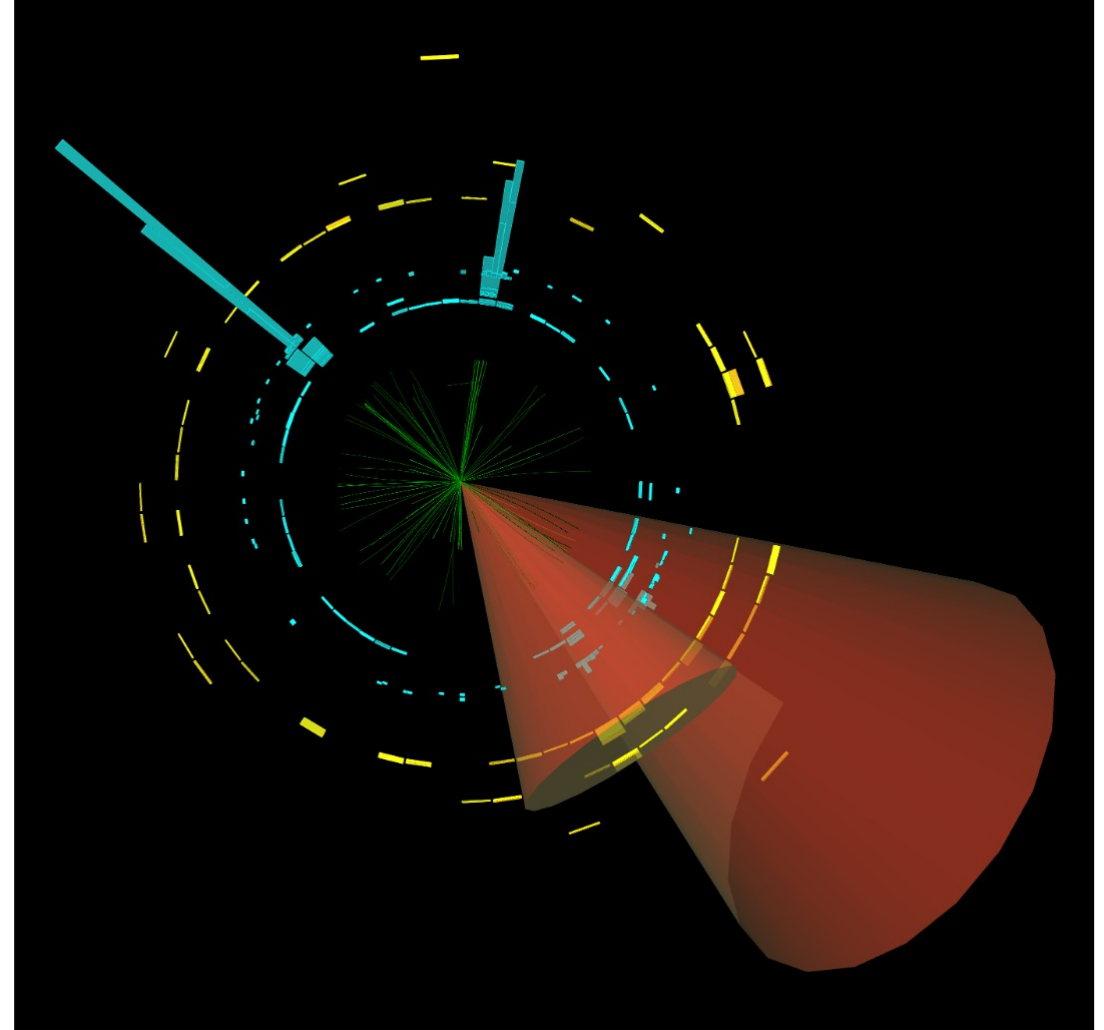
- The results are also interpreted in the context of **Higgs effective field theory (HEFT)** and **Standard Model effective field theory (SMEFT)**
- Set constraints on the Wilson coefficients of the operators describing **anomalous Higgs boson interactions**



Summary

Run 2 legacy search for *HH* production in *bbyy* final state

- **No excess** over the expected background was observed
- Constraints were placed for **coupling modifiers** κ_λ and κ_{2V}
- **Sizable improvements w.r.t previous publication**
 - Expected 95% CL μ_{HH} upper limit reduced by $\sim 12\%$
 - Expected confidence interval width for κ_λ reduced by $\sim 6\%$
 - Expected confidence interval width for κ_{2V} reduced by $\sim 17\%$
- **New features w.r.t previous publication**
 - Addition of **VBF HH signals** in event classification BDT
 - Dedicated **VBF-jet tagger** based on BDT
 - EFT interpretations** in HEFT and SMEFT frameworks



Thank you for your attention!

Back-up

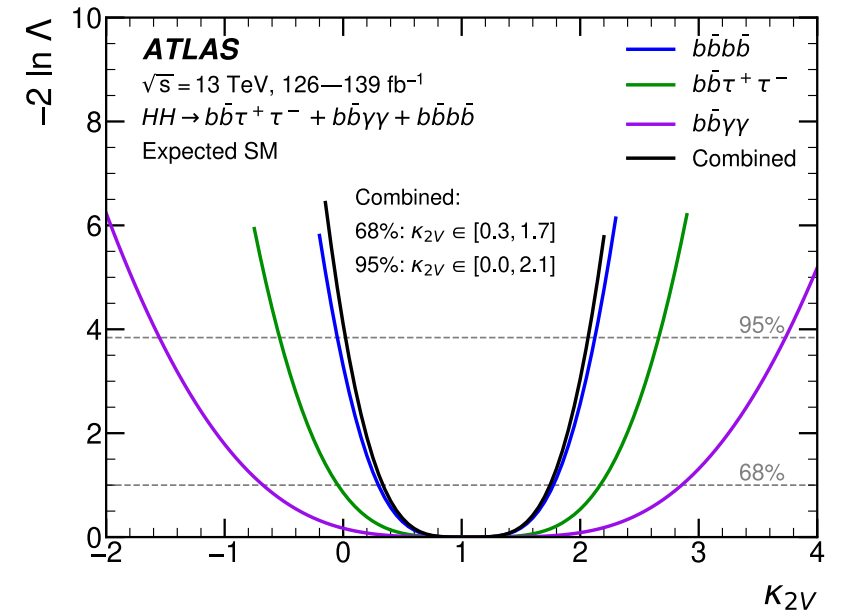
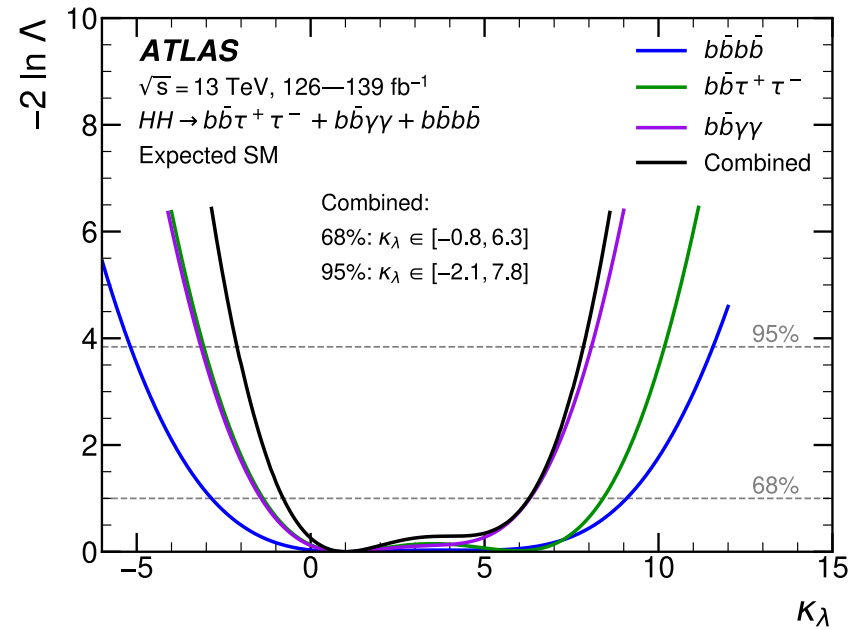
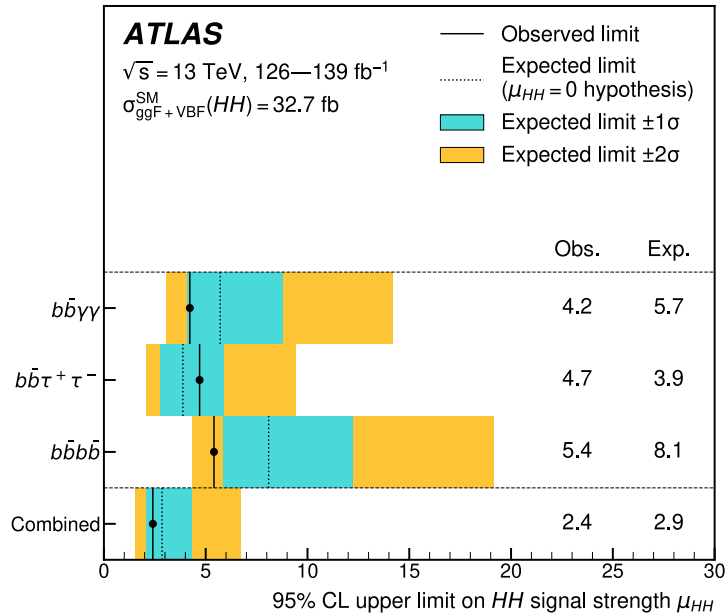
References

ATLAS $HH \rightarrow b\bar{b}\gamma\gamma$ Run 2: <https://arxiv.org/abs/2112.11876>

ATLAS $HH \rightarrow b\bar{b}\gamma\gamma$ Run 2 Legacy: <https://arxiv.org/abs/2310.12301>

ATLAS H+HH combination Run 2: <https://arxiv.org/abs/2211.01216>

HH combination



Samples

Data: full Run2 dataset, 140 fb^{-1}

MC Signals

- ggF HH at NLO using Powheg+Pythia8

$$\kappa_\lambda = 1, \kappa_\lambda = 10$$

- VBF HH at LO using MadGraph+Pythia8

$$(\kappa_\lambda, \kappa_{2V}, \kappa_V) = (1, 1, 1), 12 \text{ BSM samples}$$

	κ_λ	κ_{2V}	κ_V		κ_λ	κ_{2V}	κ_V
1	1	0	1	7	2	1	1
2	1	0.5	1	8	10	1	1
3	1	1.5	1	9	1	1	0.5
4	1	2	1	10	1	1	1.5
5	1	3	1	11	0	0	1
6	0	1	1	12	-5	1	0.5

MC Backgrounds

- Resonant Single Higgs:

ggH, VBFH, WH, qq→ZH, gg→ZH, ttH, tHjb, tWH, bbH

- Non-resonant:

Sherpa 2.2.4 $\gamma\gamma+0,1(\text{NLO}),2,3(\text{LO})$ partons, FastSim

Sherpa 2.2.12 $\gamma\gamma+bb$ produced with a b-jet filter, FullSim

- increased efficiency from generator-level requirements on the b -quarks, reduces the statistical uncertainty by 2

tt $\gamma\gamma$ using aMC@NLO+Pythia8

Samples

Process	Generator	PDF set	Showering	Tune	Accuracy	Order of σ calculation
ggF HH	POWHEG BOX v2	PDF4LHC15 _{NLO}	PYTHIA 8.2	A14	NLO	NNLO
VBF HH	MADGRAPH5_AMC@NLO	NNPDF3.0 _{NLO}	PYTHIA 8.2	A14	LO	N ³ LO
ggF H	NNLOPS	PDF4LHC15 _{NLO}	PYTHIA 8.2	AZNLO	NNLO	N ³ LO
VBF H	POWHEG BOX v2	PDF4LHC15 _{NLO}	PYTHIA 8.2	AZNLO	NLO	NNLO
WH	POWHEG BOX v2	PDF4LHC15 _{NLO}	PYTHIA 8.2	AZNLO	NLO	NNLO
$qq \rightarrow ZH$	POWHEG BOX v2	PDF4LHC15 _{NLO}	PYTHIA 8.2	AZNLO	NLO	NNLO
$gg \rightarrow ZH$	POWHEG BOX v2	PDF4LHC15 _{NLO}	PYTHIA 8.2	AZNLO	LO	NLO
$t\bar{t}H$	POWHEG BOX v2	NNPDF3.0 _{NLO}	PYTHIA 8.2	A14	NLO	NNLO
$b\bar{b}H$	POWHEG BOX v2	NNPDF3.0 _{NLO}	PYTHIA 8.2	A14	NLO	NNLO
tHq	MADGRAPH5_AMC@NLO	NNPDF3.0 _{NLO}	PYTHIA 8.2	A14	NLO	NLO
tHW	MADGRAPH5_AMC@NLO	NNPDF3.0 _{NLO}	PYTHIA 8.2	A14	NLO	NLO
$\gamma\gamma$ +jets	SHERPA 2.2.4	NNPDF3.0 _{NNLO}	SHERPA 2.2.4	–	–	–
$\gamma\gamma b\bar{b}$	SHERPA 2.2.12	NNPDF3.0 _{NNLO}	SHERPA 2.2.12	–	–	–
$t\bar{t}\gamma\gamma$	MADGRAPH5_AMC@NLO	NNPDF2.3 _{LO}	PYTHIA 8.2	A14	–	–

κ_λ and κ_{2V} parameterization

- Only a handful of signal HH MC samples are available with carefully selected values of coupling modifiers.
- Legacy analysis uses **linear combination method** for HH parameterization.
- BSM ggF basis is generated by a **κ_λ -reweighting** tool based on the particle-level invariant mass m_{HH}

$\sigma_{ggF}(HH)$ depends on $(\kappa_\lambda, \kappa_t)$

Basis: 3 reference samples

$(\kappa_\lambda, \kappa_t) = (0,1)$ reweighted from SM sample

$(\kappa_\lambda, \kappa_t) = (1,1)$ SM sample

$(\kappa_\lambda, \kappa_t) = (20,1)$ reweighted from $\kappa_\lambda = 10$ sample

$$\begin{aligned} \frac{d\sigma_{ggF}}{d\Phi}(\kappa_\lambda, \kappa_t) = & \kappa_t^2 \left[\left(\kappa_t^2 + \frac{\kappa_\lambda^2}{20} - \frac{399}{380} \kappa_\lambda \kappa_t \right) \times \frac{d\sigma_{ggF}}{d\Phi}(0,1) \right. \\ & + \left(\frac{40}{38} \kappa_\lambda \kappa_t - \frac{2}{38} \kappa_\lambda^2 \right) \times \frac{d\sigma_{ggF}}{d\Phi}(1,1) \\ & \left. + \left(\frac{\kappa_\lambda^2 - \kappa_\lambda \kappa_t}{380} \right) \times \frac{d\sigma_{ggF}}{d\Phi}(20,1) \right] \end{aligned}$$

$\sigma_{VBF}(HH)$ depends on $(\kappa_\lambda, \kappa_{2V}, \kappa_V)$

Basis: 6 available reference samples

$$\begin{aligned} \frac{d\sigma_{VBF}}{d\Phi}(\kappa_\lambda, \kappa_{2V}, \kappa_V) = & \left(\frac{68\kappa_{2V}^2}{135} - 4\kappa_{2V}\kappa_V^2 + \frac{20\kappa_{2V}\kappa_V\kappa_\lambda}{27} + \frac{772\kappa_V^4}{135} - \frac{56\kappa_V^3\kappa_\lambda}{27} + \frac{\kappa_V^2\kappa_\lambda^2}{9} \right) \times \frac{d\sigma_{VBF}}{d\Phi}(1,1,1) \\ & + \left(-\frac{4\kappa_{2V}^2}{5} + 4\kappa_{2V}\kappa_V^2 - \frac{16\kappa_V^4}{5} \right) \times \frac{d\sigma_{VBF}}{d\Phi}(1,1.5,1) \\ & + \left(\frac{11\kappa_{2V}^2}{60} + \frac{\kappa_{2V}\kappa_V^2}{3} - \frac{19\kappa_{2V}\kappa_V\kappa_\lambda}{4} - \frac{53\kappa_V^4}{30} - \frac{13\kappa_V^3\kappa_\lambda}{6} - \frac{\kappa_V^2\kappa_\lambda^2}{8} \right) \times \frac{d\sigma_{VBF}}{d\Phi}(2,1,1) \\ & + \left(-\frac{11\kappa_{2V}^2}{140} + \frac{11\kappa_{2V}\kappa_V\kappa_\lambda}{216} + \frac{13\kappa_V^4}{270} - \frac{5\kappa_V^3\kappa_\lambda}{54} + \frac{\kappa_V^2\kappa_\lambda^2}{72} \right) \times \frac{d\sigma_{VBF}}{d\Phi}(10,1,1) \\ & + \left(\frac{88\kappa_{2V}^2}{45} - \frac{16\kappa_{2V}\kappa_V^2}{3} + \frac{4\kappa_{2V}\kappa_V\kappa_\lambda}{9} + \frac{152\kappa_V^4}{45} - \frac{4\kappa_V^3\kappa_\lambda}{9} \right) \times \frac{d\sigma_{VBF}}{d\Phi}(1,1,0.5) \\ & + \left(\frac{8\kappa_{2V}^2}{45} - \frac{4\kappa_{2V}\kappa_V\kappa_\lambda}{9} - \frac{8\kappa_V^4}{45} + \frac{4\kappa_V^3\kappa_\lambda}{9} \right) \times \frac{d\sigma_{VBF}}{d\Phi}(-5,1,0.5) \end{aligned}$$

Input variables of event categorization BDTs

Variable	Definition
Photon candidates	
$p_T/m_{\gamma\gamma}$	Transverse momentum of each photon divided by the diphoton invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of each photons
$\Delta R(\gamma_1, \gamma_2)$	Angular distance between the two photons
<i>b</i> -jet candidates	
<i>b</i> -tag status	Tightest fixed <i>b</i> -tag working point (60%, 70%, 77%) that each jet passes
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of each jet
$p_T^{b\bar{b}}, \eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudorapidity and azimuthal angle of the two- <i>b</i> -jet system
$\Delta R(b_1, b_2)$	Angular distance between the two candidate <i>b</i> -jets
→ $m_{b\bar{b}}$	Invariant mass of the two candidate <i>b</i> -jets
Single topness	Variable used to identify $t \rightarrow Wb \rightarrow q\bar{q}'b$ decays. For the definition, see Eq.(??).
Other jets (only first two, if present, ranked by discrete <i>b</i> -tagging score)	
<i>b</i> -tag status	Tightest fixed <i>b</i> -tag working point (85% or none) that each jet passes
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of each jet
VBF-jet candidates	
$\Delta\eta(j_1, j_2), m_{jj}$	Pseudorapidity difference and invariant mass of the two jets
Event-level variables	
Transverse sphericity, planar flow, p_T balance	For the definitions, see Ref. , Ref. , and Eq. (??)
H_T	Scalar sum of the p_T of the jets in the event
E_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle
$m_{b\bar{b}\gamma\gamma}^*$	The 4-body invariant mass of the two photons and two candidate <i>b</i> -jets, $m_{b\bar{b}\gamma\gamma}^* = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125 \text{ GeV}) - (m_{\gamma\gamma} - 125 \text{ GeV})$

Input variables of VBF-jet tagger

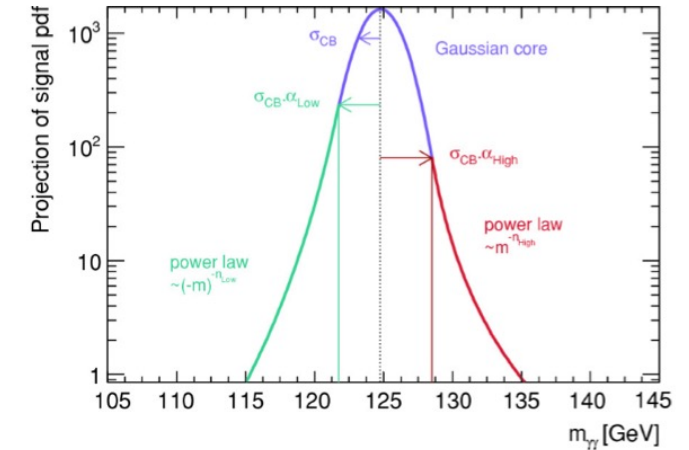
Variable	Definition
p_T^j and η^j	Transverse momentum and pseudorapidity of each of the VBF-jet candidates
$\Delta R(j, \gamma\gamma b\bar{b})$ and $\Delta\eta(j, \gamma\gamma b\bar{b})$	Angular and pseudorapidity separation between the VBF-jet candidates and the $\gamma\gamma b\bar{b}$ system
→ m_{jj} and $\Delta\eta(j, j)$	Invariant mass and pseudorapidity separation of the two VBF-jet candidates
$\Delta R(jj, \gamma\gamma b\bar{b})$ and $\Delta\eta(jj, \gamma\gamma b\bar{b})$	Angular and pseudorapidity separation between the VBF-jet candidate pair and the $\gamma\gamma b\bar{b}$ system
$p_T^{\gamma\gamma b\bar{b}jj}$, $\eta^{\gamma\gamma b\bar{b}jj}$, and $m_{\gamma\gamma b\bar{b}jj}$	Transverse momentum, pseudorapidity, and invariant mass of the system formed by the VBF-jet candidate pair, the two photons and the two b -tagged jets
H_T	Scalar sum of the p_T of the jets in the event

Yield table

	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
SM $HH(\kappa_\lambda = 1)$ signal	$0.26^{+0.03}_{-0.04}$	$0.194^{+0.021}_{-0.032}$	$0.84^{+0.10}_{-0.14}$	$0.048^{+0.007}_{-0.008}$	$0.038^{+0.004}_{-0.006}$	$0.039^{+0.004}_{-0.006}$	$0.032^{+0.004}_{-0.004}$
ggF	$0.25^{+0.03}_{-0.04}$	$0.188^{+0.021}_{-0.032}$	$0.81^{+0.10}_{-0.14}$	$0.046^{+0.007}_{-0.008}$	$0.036^{+0.004}_{-0.006}$	$0.037^{+0.004}_{-0.006}$	$0.025^{+0.004}_{-0.004}$
VBF $\times 10^3$	$7.9^{+0.6}_{-0.5}$	$5.3^{+0.5}_{-0.4}$	29^{+4}_{-3}	$1.98^{+0.28}_{-0.24}$	$1.71^{+0.16}_{-0.14}$	$1.96^{+0.21}_{-0.19}$	$7.4^{+0.6}_{-0.5}$
Alternative $HH(\kappa_\lambda = 10)$ signal	$2.5^{+0.4}_{-0.3}$	$1.81^{+0.25}_{-0.20}$	$6.2^{+0.8}_{-0.6}$	$5.0^{+1.2}_{-0.9}$	$3.8^{+0.7}_{-0.5}$	$3.7^{+0.7}_{-0.6}$	$3.6^{+0.4}_{-0.4}$
ggF	$2.3^{+0.4}_{-0.3}$	$1.64^{+0.25}_{-0.19}$	$4.9^{+0.8}_{-0.6}$	$4.7^{+1.0}_{-0.8}$	$3.6^{+0.7}_{-0.6}$	$3.3^{+0.7}_{-0.5}$	$2.04^{+0.34}_{-0.27}$
VBF	$0.231^{+0.019}_{-0.017}$	$0.170^{+0.019}_{-0.017}$	$1.29^{+0.15}_{-0.14}$	$0.28^{+0.20}_{-0.11}$	$0.23^{+0.23}_{-0.12}$	$0.36^{+0.10}_{-0.08}$	$1.57^{+0.17}_{-0.16}$
Alternative VBF $HH(\kappa_{2V} = 3)$ signal	$0.23^{+0.04}_{-0.04}$	$0.20^{+0.05}_{-0.04}$	$3.8^{+0.7}_{-0.6}$	$0.03^{+0.04}_{-0.02}$	$0.03^{+0.06}_{-0.02}$	$0.048^{+0.023}_{-0.015}$	$0.17^{+0.04}_{-0.03}$
Single Higgs boson background	$1.5^{+0.5}_{-0.3}$	$0.48^{+0.21}_{-0.10}$	$0.57^{+0.25}_{-0.14}$	$1.72^{+0.31}_{-0.19}$	$0.53^{+0.08}_{-0.06}$	$0.29^{+0.14}_{-0.07}$	$0.16^{+0.06}_{-0.03}$
ggF	$0.5^{+0.5}_{-0.2}$	$0.14^{+0.21}_{-0.09}$	$0.25^{+0.25}_{-0.12}$	$0.29^{+0.31}_{-0.15}$	$0.08^{+0.08}_{-0.04}$	$0.07^{+0.13}_{-0.06}$	$0.04^{+0.06}_{-0.03}$
$t\bar{t}H$	$0.302^{+0.034}_{-0.032}$	$0.069^{+0.009}_{-0.008}$	$0.063^{+0.008}_{-0.007}$	$0.77^{+0.09}_{-0.08}$	$0.214^{+0.029}_{-0.026}$	$0.100^{+0.012}_{-0.012}$	$0.048^{+0.005}_{-0.005}$
ZH	$0.61^{+0.06}_{-0.05}$	$0.174^{+0.020}_{-0.016}$	$0.188^{+0.035}_{-0.029}$	$0.49^{+0.05}_{-0.04}$	$0.149^{+0.028}_{-0.025}$	$0.069^{+0.033}_{-0.023}$	$0.028^{+0.010}_{-0.007}$
Rest	$0.17^{+0.08}_{-0.04}$	$0.089^{+0.030}_{-0.016}$	$0.07^{+0.04}_{-0.02}$	$0.181^{+0.030}_{-0.019}$	$0.089^{+0.016}_{-0.009}$	$0.046^{+0.007}_{-0.004}$	$0.039^{+0.008}_{-0.004}$
Continuum background	$11.3^{+1.5}_{-1.6}$	$3.2^{+0.8}_{-0.8}$	$2.8^{+0.8}_{-0.8}$	$37.2^{+2.9}_{-2.9}$	$10.8^{+1.5}_{-1.5}$	$4.4^{+0.9}_{-1.0}$	$1.1^{+0.5}_{-0.5}$
Total background	$12.8^{+1.6}_{-1.6}$	$3.7^{+0.9}_{-0.8}$	$3.4^{+0.8}_{-0.8}$	$38.9^{+2.9}_{-2.9}$	$11.3^{+1.5}_{-1.5}$	$4.7^{+0.9}_{-1.0}$	$1.3^{+0.5}_{-0.5}$
Data	12	4	1	29	8	5	4

Signal modeling

- The $m_{\gamma\gamma}$ shape for the HH signals and single Higgs backgrounds is modelled with a **double-sided crystal ball function** (DSCB).
- Shape parameters of the DSCB in each category are selected by an **unbinned fit** on the **SM ggF HH and VBF HH MC samples**.
- The resulting **signal model** in each category is **shared by the HH signals and single Higgs backgrounds**.



Impact of the systematic uncertainties

- Breakdown of the dominant systematic uncertainties in the **expected μ_{HH} upper limit at 95% CL**

Systematic uncertainty source	Relative impact [%]
Experimental	
Photon energy resolution	0.4
Photon energy scale	0.1
Flavour tagging	0.1
Theoretical	
Factorisation and renormalisation scale	4.8
$\mathcal{B}(H \rightarrow \gamma\gamma, b\bar{b})$	0.2
Parton showering model	0.2
Heavy-flavour content	0.1
Background model (spurious signal)	0.1

EFT interpretations

EFT interpretations for the Legacy $HH \rightarrow b\bar{b}\gamma\gamma$

In addition to interpreting the statistical results in terms of constraints on the coupling modifiers κ_λ and $\kappa_{2\gamma}$, the **Legacy $HH \rightarrow b\bar{b}\gamma\gamma$** analysis provides **1-dimensional** and **2-dimensional constraints** on **anomalous Higgs boson couplings** in the **EFT framework**!

➡ **Two EFT frameworks** are available in HH: ➡ **HEFT** and **SMEFT**!

HEFT

- Only minimal assumption are set in the scalar sector.
 - ➡ The observed Higgs boson is a singlet.
- In the HEFT framework, ggF HH production is affected by 5 Wilson coefficients and their operators.
 - ➡ c_{hhh} , c_{tth} , c_{ttth} , c_{ggh} and c_{gggh} .
 - SM-like HH couplings BSM-like HH couplings
- We would like to set limits on the HH cross-section for 7 HEFT benchmarks.

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



1-dimensional constraints on c_{tthh} and c_{gggh} and 2-dimensional likelihood scans in the (c_{hhh}, c_{gggh}) and (c_{hhh}, c_{tthh}) planes.
➡ The **parametrization** allows to vary **all HEFT couplings**.

SMEFT

- The observed Higgs boson is a complex doublet of the $SU(2)_L$ group. ➡ More **SM-like** description!
- We would like to set 1-dimensional constraints on 2 Wilson coefficients.

Wilson Coef.

$$C_H$$

$$C_{H\Box}$$

Operator

$$(\Phi^\dagger \Phi)^3$$

$$\partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$$



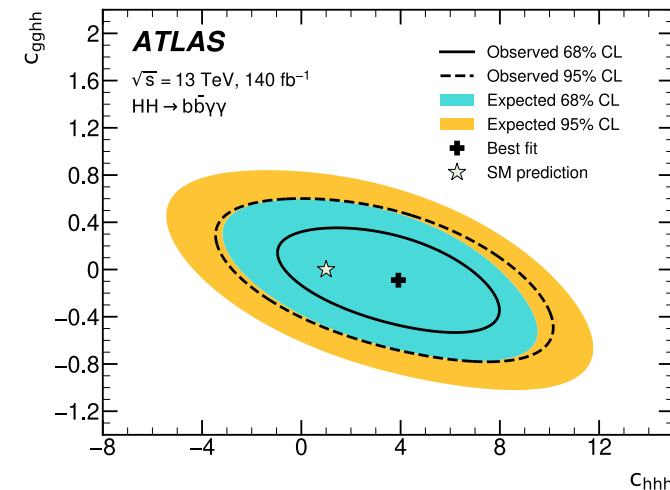
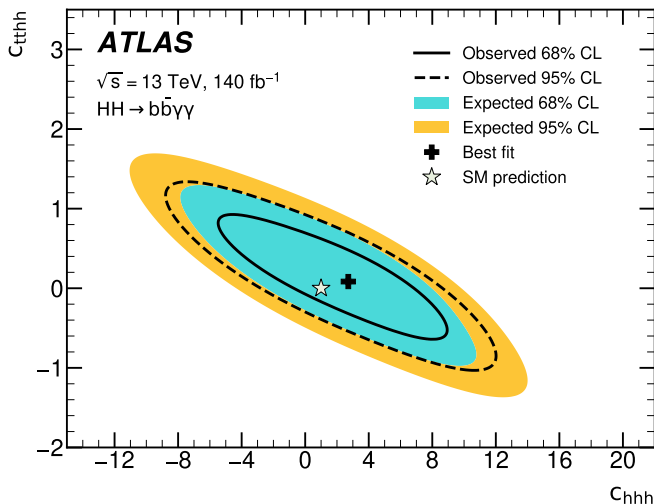
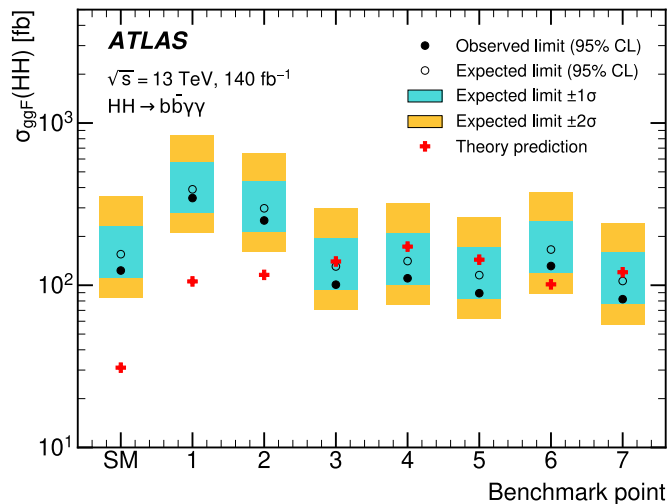
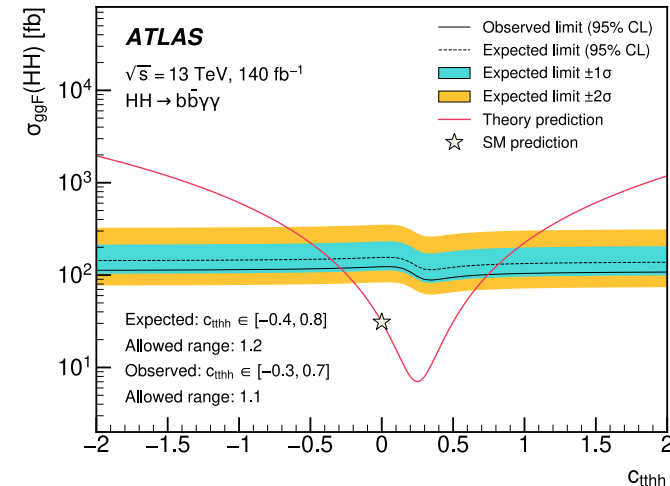
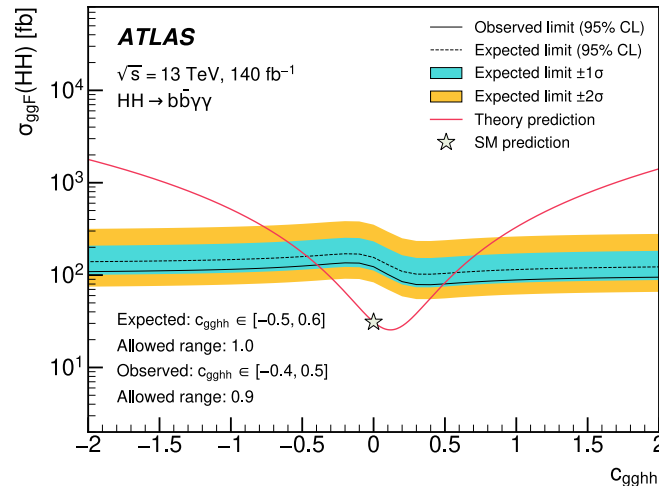
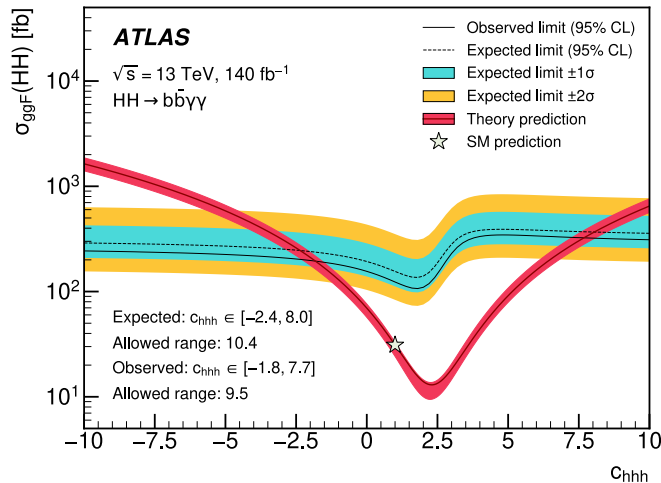
2-dimensional constraints on $(C_H, C_{H\Box})$!

- Both the HH and the single Higgs processes are parametrized as a function of C_H and $C_{H\Box}$, considering the **linear+quadratic** parametrization only.

One advantage of HEFT compared with SMEFT is that it provides a one-to-one relation between operators (and corresponding Wilson coefficients) and effective interactions, which allows single- and di-Higgs boson couplings to be separated, leading to simplified HH interpretations.

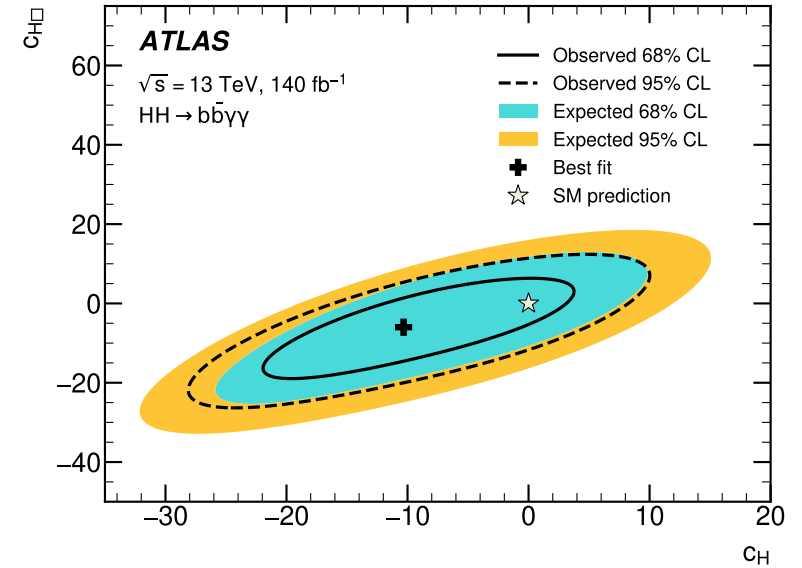
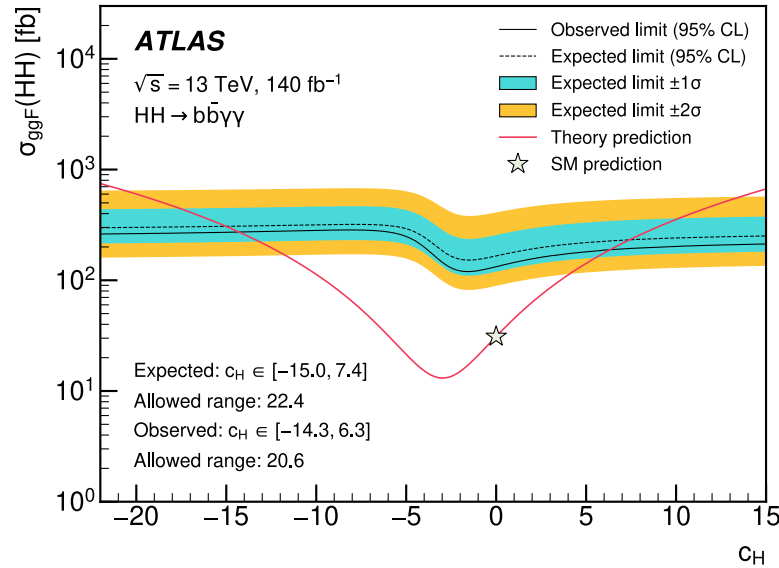
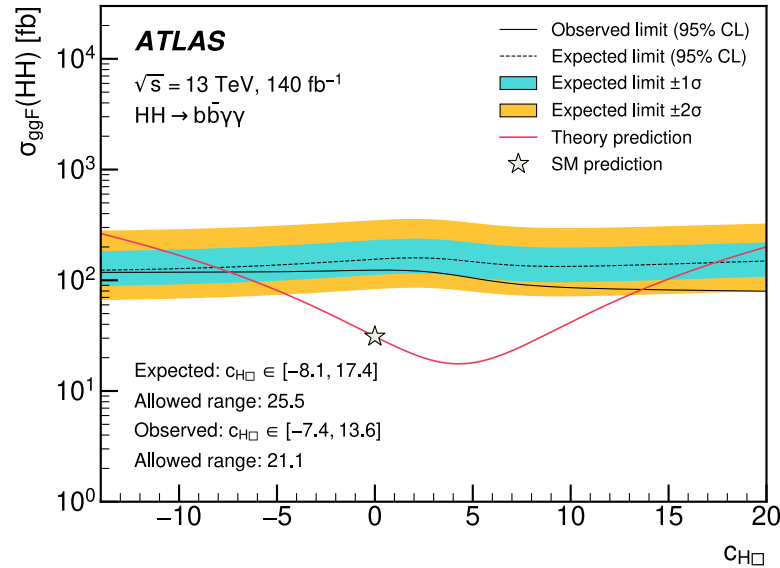
HEFT results

- Consider only ggF HH production
- HH signal reweighting: as a function of truth m_{hh}



SMEFT results

- Consider only ggF HH production
- Dependencies in H background
- Include relevant dimension-6 operators
- **HH signal reweighting:** as a function of truth m_{hh}
- **H background reweighting:** as a function of truth H p_T



Spurious signal

The spurious signal test

The **best functional form** for modeling the continuum background in each category is chosen as a **compromise** between having a **minimal number of degrees of freedom** and a **small bias**!



$\gamma\gamma$ +jets MC normalized to data sidebands!

➡ The chosen functional form has to pass the **(relaxed) spurious signal test**:

➡ • $|N_{sp}| < 10\% \cdot N_{S,exp}$

OR

• $|N_{sp}| < 20\% \cdot \sigma_{bkg}$

Expected signal yield according to the SM.

Stat. uncertainty on the fitted number of signal events on the bkg template.

➡ Measured by performing **S+B fits** on a **background-only template**!

- The number of signal events is extracted for different values of $m_H \in [123, 127]$ GeV with steps of 0.5 GeV.
- **Bias** (i.e. **spurious signal**) of the tested functional form $\equiv$ **largest signal yield** in the m_H window!

➡ If no function satisfies these conditions, the test is further **relaxed** by replacing N_{sp} with ζ_{sp} , where:

$$\zeta_{sp} = \begin{cases} N_{sp} + 2\Delta_{MC} & \text{if } N_{sp} + 2\Delta_{MC} < 0 \\ N_{sp} - 2\Delta_{MC} & \text{if } N_{sp} - 2\Delta_{MC} > 0 \\ 0 & \text{otherwise} \end{cases}$$

Local stat. fluctuations of the background template.

Spurious signal test results for the simple exponential and power-law functions.

Category	Function	N_{sp}	$\max(N_{sp}/\sigma_{bkg})$	$\max(\zeta_{sp})$ [%]	$\max(N_{sp}/S_{ref,SM})$ [%]	$\text{Prob}(\chi^2)$ [%]
SM_3	Exponential	0.451	28.8	0	56.1	2.55
	Power	0.505	32.2	0	63	2.51
SM_2	Power	-0.147	-10.3	0	-60.8	57.9
	Exponential	-0.188	-13.2	0	-77.7	55.2
SM_1	Power	-0.788	-30	-4.85	-306	8.91
	Exponential	-0.937	-35.7	-10.6	-365	7.03
BSM_4	Exponential	0.33	23	0	727	18.8
	Power	0.361	25.2	0	798	11.9
BSM_3	Exponential	1.1	48.1	4.11	2.75e+03	0.056
	Power	1.2	52.5	8.53	3.02e+03	0.04
BSM_2	Power	-0.137	5.41	0	446	21.9
	Exponential	-0.299	-11.5	0	-825	40.9
BSM_1	Exponential	0.649	10.3	0	1.36e+03	44
	Power	1.69	26.7	0	3.54e+03	31.9

Spurious signal: the maximum absolute value of the bias on the fitted signal yield in multiple signal+background fits to the background-only template

Criteria: smaller than 20% of the statistical uncertainty on the expected fitted signal yield plus twice the statistical uncertainty on the spurious signal itself.

Systematic uncertainties

Systematic uncertainties

The impact of each source of **systematic uncertainty** has to be quantified and included when performing the **statistical analysis**.

➡ The systematic uncertainties are **propagated** through the **full analysis workflow**!

➡ They may result in $\pm 1\sigma$ **variations** for the **expected yields** or the **shape parameters** for the signal HH and single Higgs processes!

		ggF HH	VBF HH	Single Higgs
Theory	Cross section and branching fraction	- BR($\gamma\gamma$) (2.9%) and BR(bb) (1.7%) - PDF + α_s (3%) - Scale + m_{top} (+6%_{-23%})	- BR($\gamma\gamma$) (2.9%) and BR(bb) (1.7%) - PDF + α_s (2.1%) - Scale (0.04%)	- BR($\gamma\gamma$) (2.9%) - Heavy Flavor uncertainty (100%, only for ggF, VBF, and WH)
	Acceptance	ggF HH parametrization	VBF HH parametrization	-
Exp.	Yields	Scale, PDF + α_s , Parton Shower - Pile-up modelling; - Di-photon trigger efficiency; - Photon identification and isolation efficiency; - Photon energy scale and resolution; - Jet energy scale and resolution; - Jet vertex tagger efficiency; - Flavour tagging efficiencies.		
	Shape	Photon energy scale, photon energy resolution.		

+

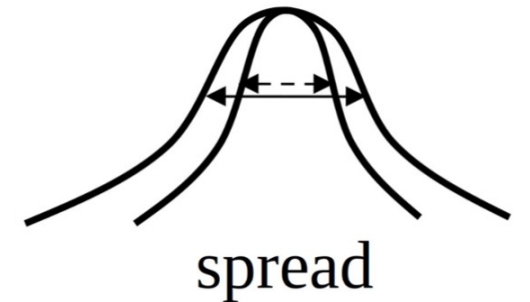
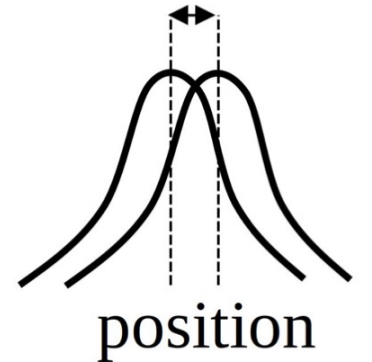
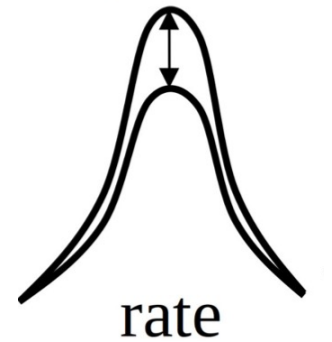
The **spurious signal**!

➡ Only source of uncertainty affecting the continuum background modeling.

- ➡ Related to the **particular choice** of the analytical **function** used for modelling the continuum background in each **analysis category**.
- Evaluated by performing a **signal + background fit** on a **MC-based background only template**, and extracting the **number of fitted signal events**.
- The main component of the spurious signal are **stat. fluctuations** in the background template!

➡ **Suppressed** in this analysis, thanks to the **new high-efficiency $\gamma\gamma + bb$ Sherpa 2.2.12 sample!**

➡ Selection efficiency $\times 40$ w.r.t. the older $\gamma\gamma + jets$ Sherpa 2.2.4 sample!

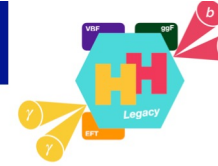


36

Statistical model

Statistical model

The **statistical results** are derived by performing an **unbinned maximum likelihood fit** to the $m_{\gamma\gamma}$ **distribution** in the invariant mass window $105 < m_{\gamma\gamma} < 160$ GeV.



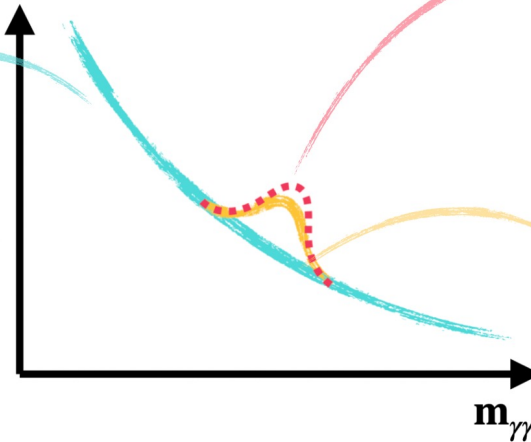
- The contributions of the **systematic uncertainties** are included in the fit as constrained NPs.
- The **normalization** and the **shape parameters** for **continuum** background are unconstrained and are **profiled on data**.
- The yields for the single Higgs background processes are fixed to their SM values.
- The **POIs** can be **either floated or fixed** in the fit. → Depending on the statistical interpretation!

Fit performed **simultaneously** over all the **analysis categories**!

→ The **HH signal strength** μ and the coupling modifiers κ_λ and κ_{2V} !

Continuum background

- The normalization and shape parameters are completely data-driven!
- The only systematic uncertainty related to the continuum bkg. modeling is the spurious signal.



di-Higgs signals

- Affected by the NPs from experimental and theoretical systematics.
- Depend from the the **POIs** μ , κ_λ , and κ_{2V} !

Single-Higgs background

- Affected by the NPs from experimental and theoretical systematics.
- Yields fixed to SM expectations.

Same strategy w.r.t. previous analysis

- Observed 95%CL μ_{HH} upper limit reduced by $\sim 5\%$
- Observed confidence interval width for κ_λ **increased by $\sim 5\%$**
- Observed confidence interval width for κ_{2V} reduced by $\sim 16\%$

The increase in the width of the observed κ_λ confidence interval arises from the fact that this new analysis favours larger, less negative values of the signal strength, corresponding to larger magnitudes of the coupling strength modifier κ_λ . The compatibility, considering only statistical uncertainties, between the allowed κ_λ interval at 95% CL from this study and that of Ref. [32] is evaluated using a bootstrap technique [99], based on the data events passing the selection of either the previous analysis, or that of the current one, or both. The compatibility between the two results is at the level of 0.3 standard deviations.

