Non-resonant HH→bbγγ analysis with the ATLAS detector

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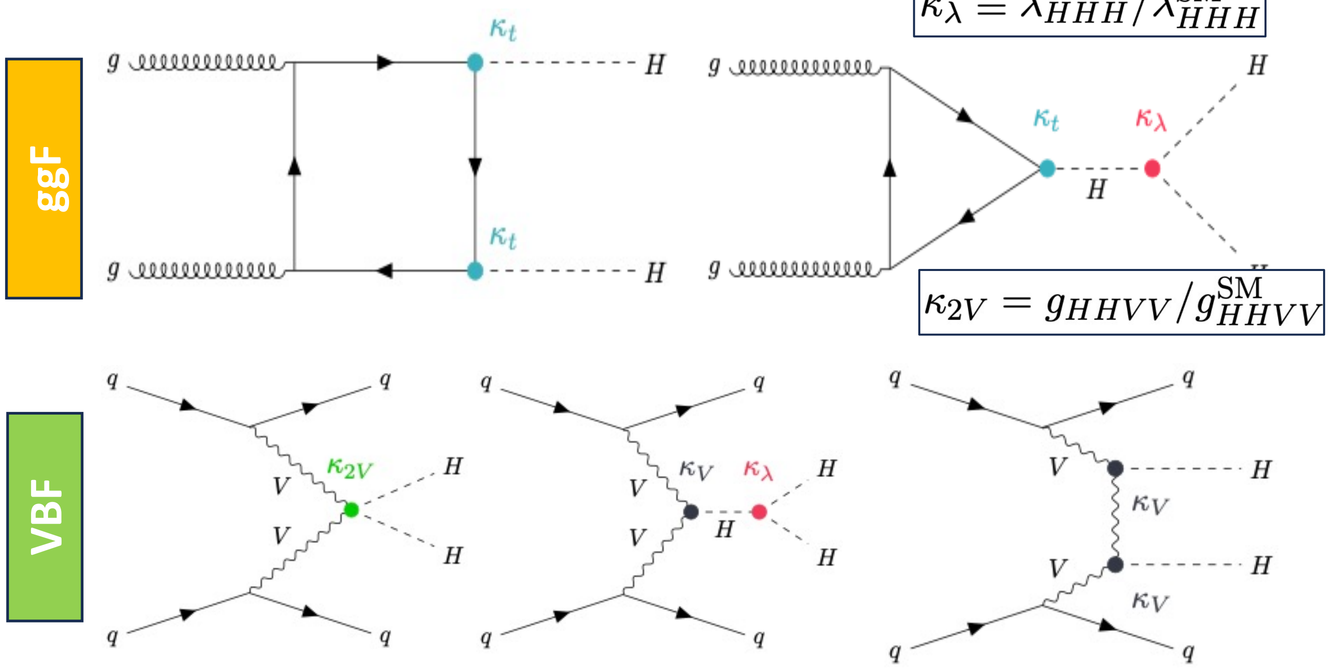
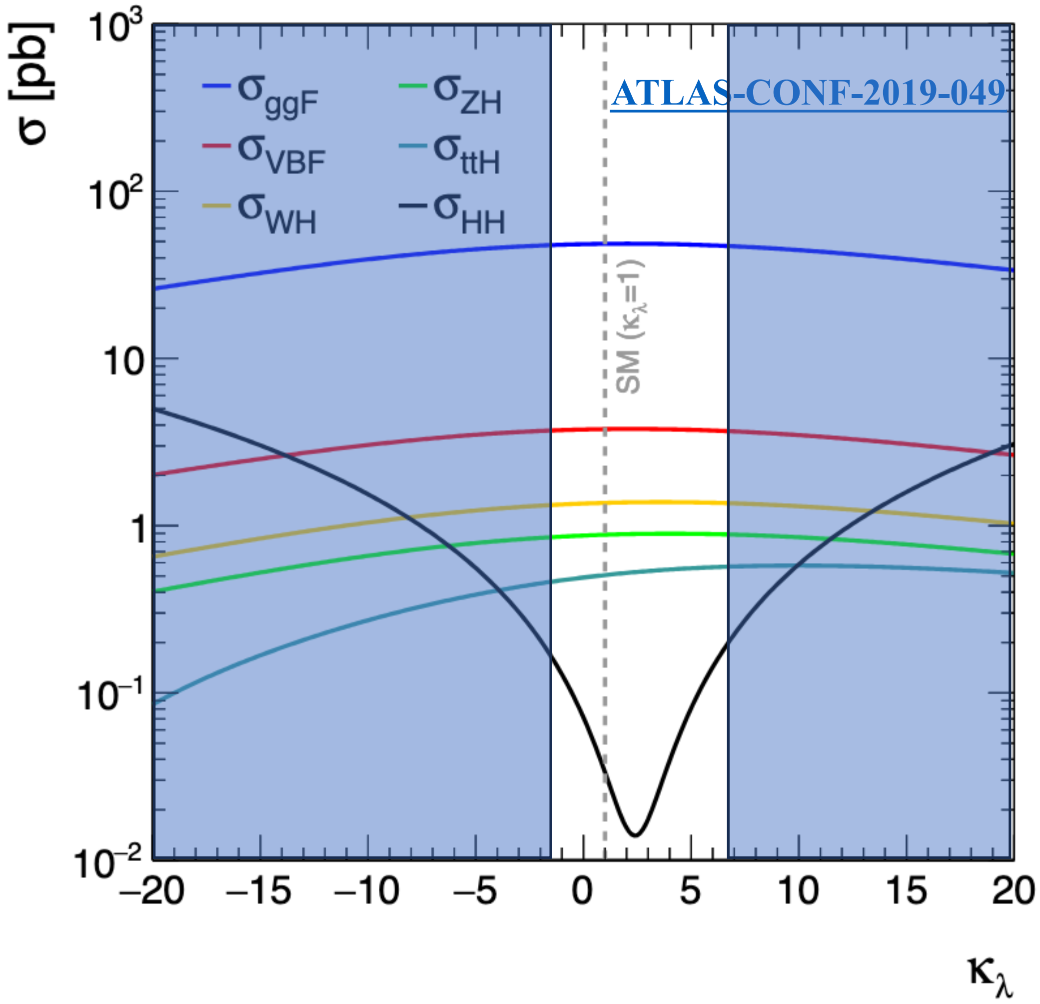
Why Di-Higgs?

- **Higgs pair production:**
  - Fundamental test of the **SM** – direct access to **Higgs self-coupling**
  - Route to search for **BSM**
    - New physics could affect the Higgs self-coupling (λ), and greatly impact the HH cross-section
  - An observed value of these coupling modifiers significantly different from unity would provide a proof of non-SM Higgs boson interactions

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

$$\kappa_{2V} = g_{HHVV}/g_{HHVV}^{SM}$$

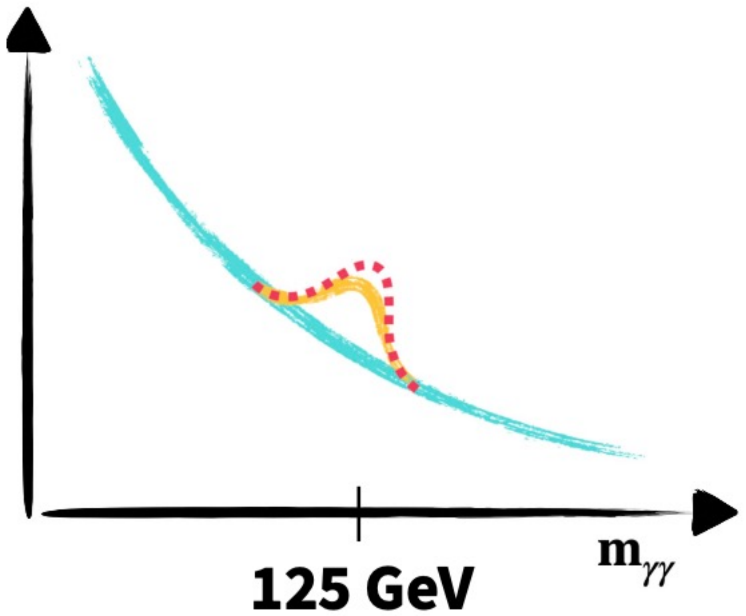




HH→bbγγ

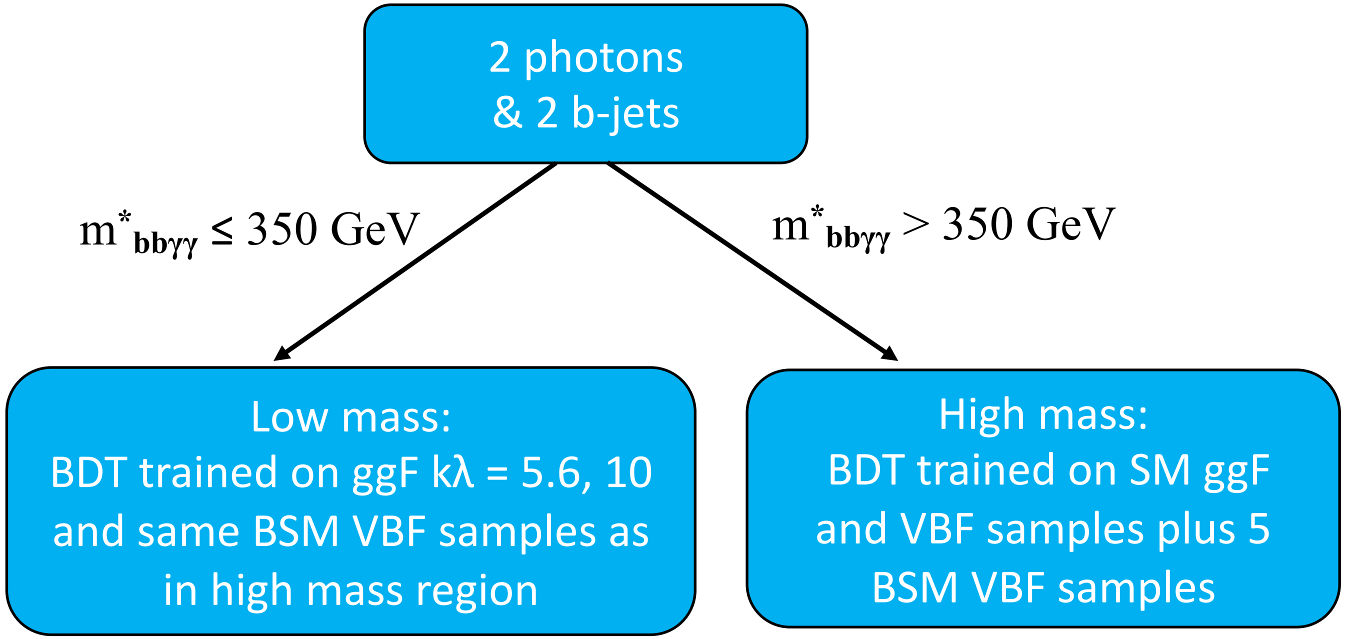
- **HH→bbγγ:**
  - Excellent trigger, reconstruction efficiency for photons at ATLAS. Excellent di-photon invariant mass resolution (1-2 GeV). Very **clean** final state
  - High **H→bb** branching ratio (59%) but challenging QCD environment
- **Published analyses with Run2 data:**
  - **Full Run 2**: [*Phys. Rev. D 106, 052001*]
  - ***Legacy Run 2***: [*JHEP01(2024)066*]
- **Three physics signatures:**
  - **HH (Signal)**
  - **H (Resonant background)**
  - **Continuum background**

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%



Strategy

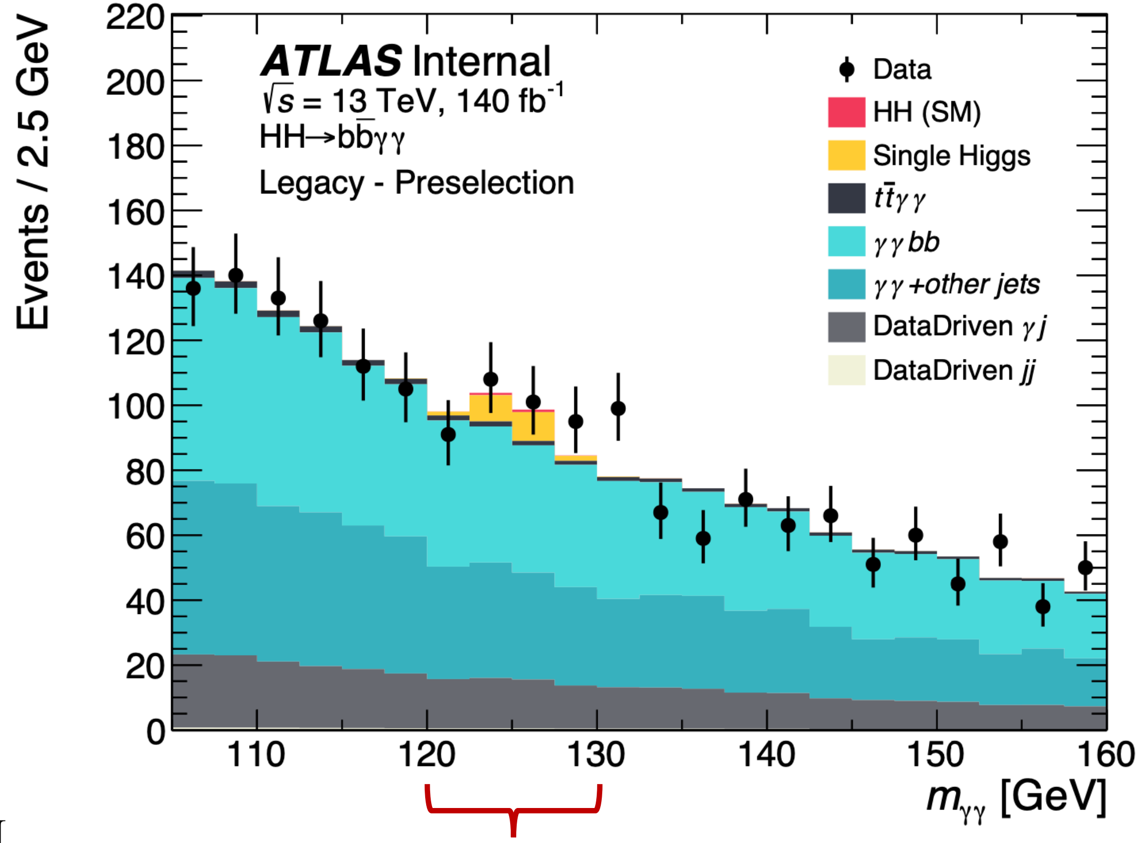
- Excellent di-photon mass resolution allows for signal extraction in $\mathbf{m}_{\gamma\gamma}$
- s/b in signal region after pre-selection is ~0.1%



- Split signal regions by $m^*_{bb\gamma\gamma}$ for sensitivity to SM and BSM HH.

$$m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{bb} - 125 \text{ GeV}) - (m_{\gamma\gamma} - 125 \text{ GeV})$$

- Train 2 BDTs to target each signal region.
  - Low mass: 4 categories
  - High mass: 3 categories



Signal region:
$m_{\gamma\gamma}$ = 120-130 GeV

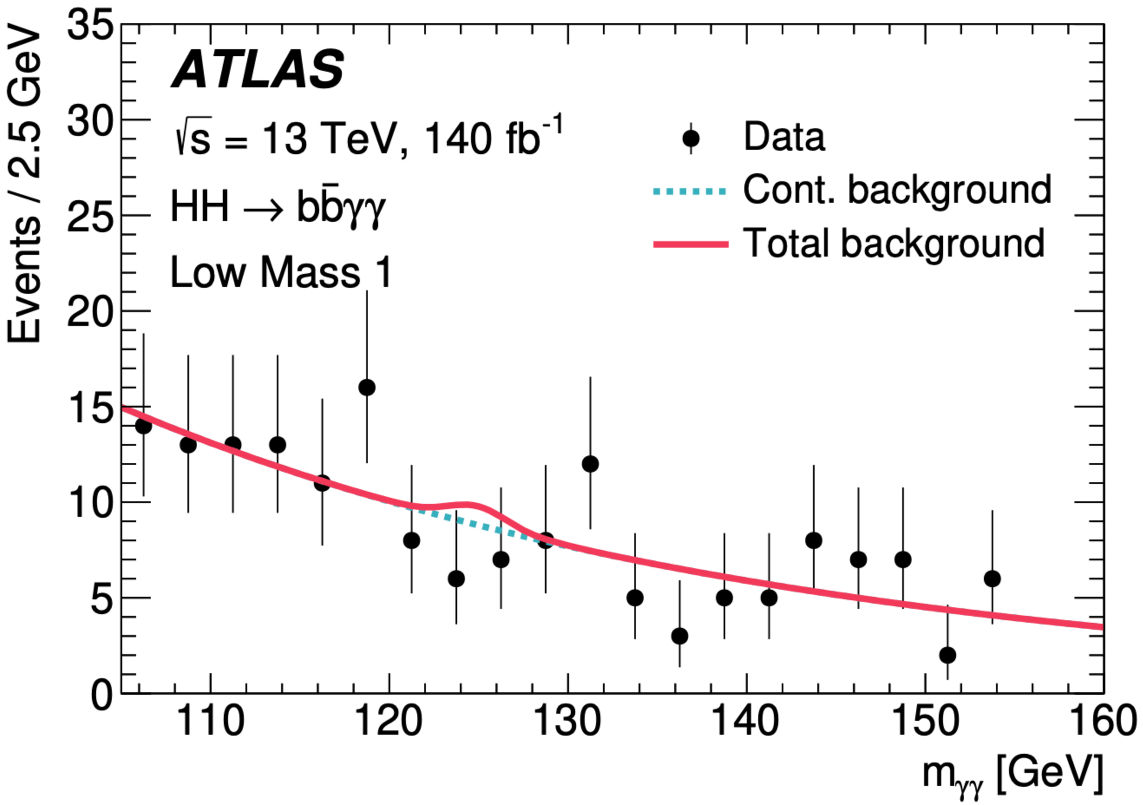
Signal Extraction

- Signal modeling
  - **Double-Sided Crystal Ball** Normalization and shape for HH signal and single Higgs background models determined from fits to Monte Carlo simulation.

- Background modeling
  - **Likelihood function** Shape chosen by fitting Monte Carlo simulation. Nomalized to the data sidebands where $\mathbf{m_{\gamma\gamma}}$ is between **105-120 & 130-160 GeV**

- **Spurious signal tests** performed to estimate bias introduced by choice of functional form.

- HH signal strength determined through maximum likelihood fit on $\mathbf{m_{\gamma\gamma}}$ **across all the BDT categories**



Background-only fit to the data

Systematic uncertainties

- Systematic uncertainties affect the **shape and normalisation of the diphoton invariant mass distributions** of the Higgs boson pair signal and single Higgs boson backgrounds
  - Computed separately for the ggF and VBF HH production modes and for single Higgs boson production modes
- The impact of the **systematic uncertainties** is small compared with that of the **statistical uncertainties**
  - Due to the **limited number of events** and **small signal-to-background ratio**
- **Dominant systematic uncertainties** in the expected μ_{HH} upper limit at 95% CL.

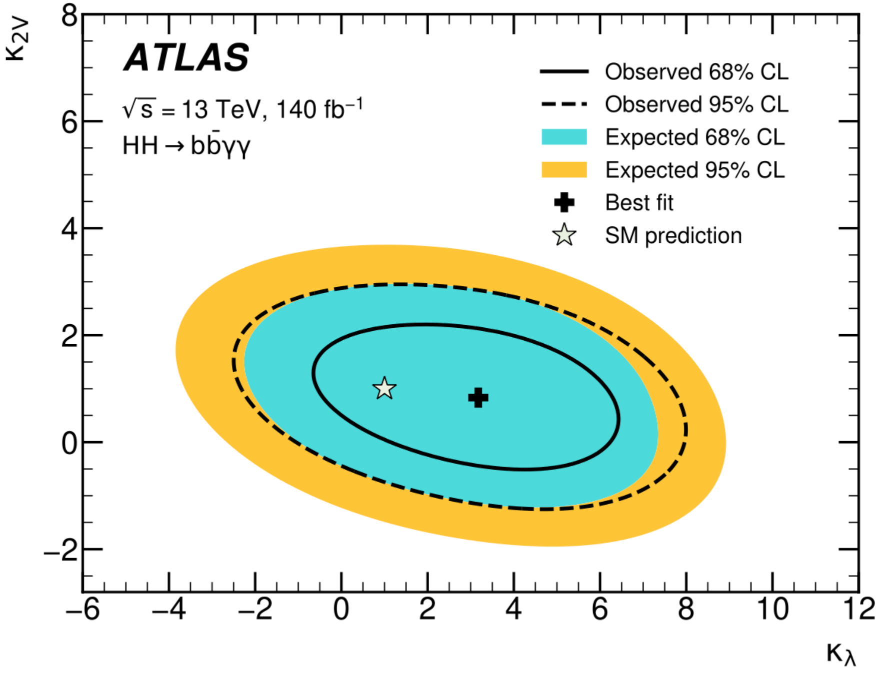
Systematic uncertainty source	Relative impact [%]
Experimental	
Photon energy resolution	0.4
Photon energy scale	0.1
Flavour tagging	0.1
Theoretical	
Factorisation and renormalisation scale	4.8
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	0.2
Parton showering model	0.2
Heavy-flavour content	0.1
Background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

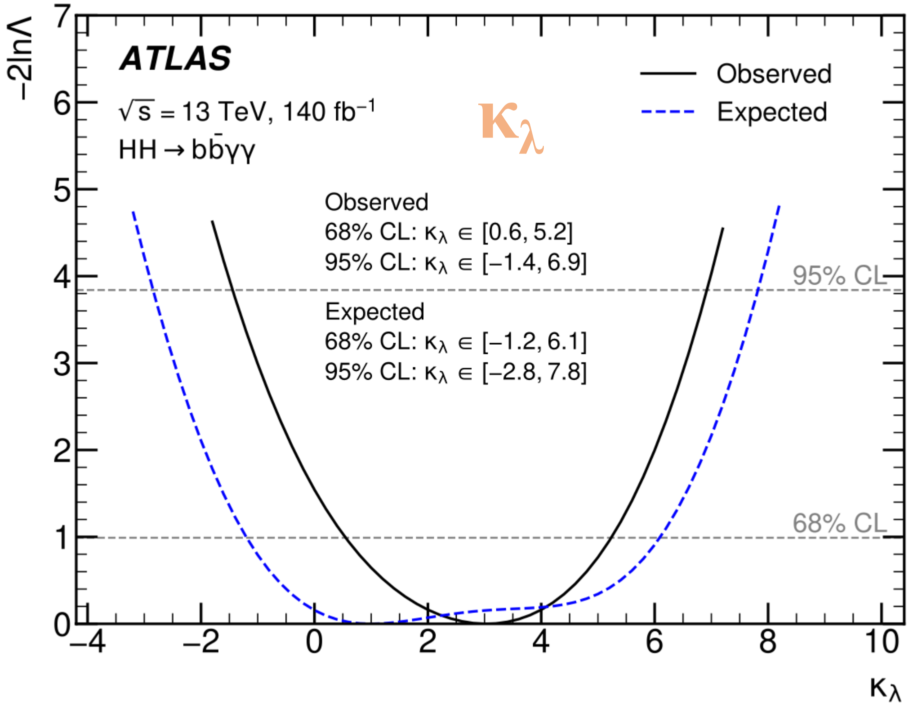
Results

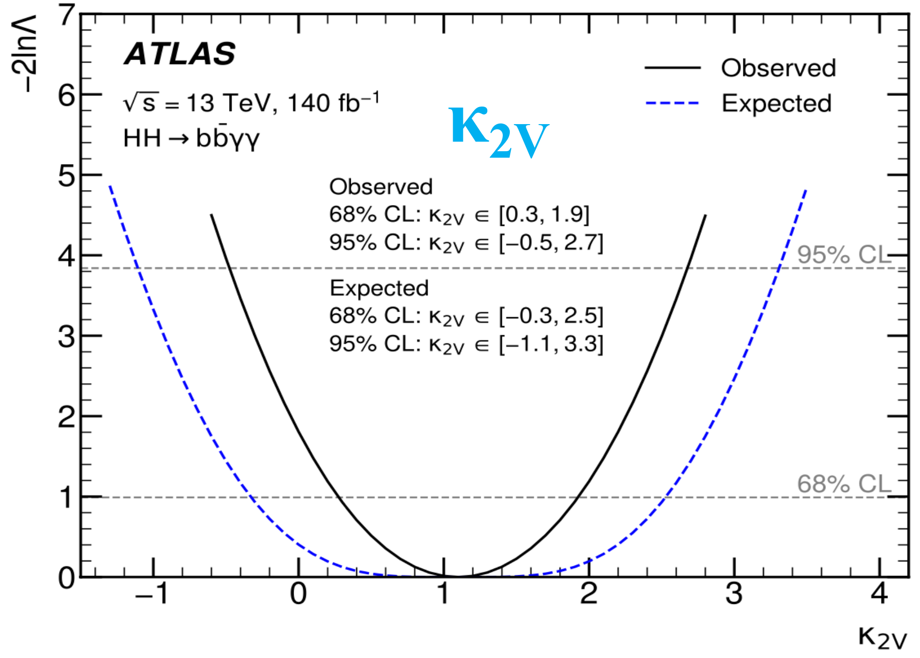
- No significant excess over the expected background was observed
- A 95% CL upper limit of 4.0 on the total HH production signal strength μ_{HH} is set

Statistial results	Upper limit	95% CL κ_λ constraint	95% CL κ_{2V} constraint
LegacyRun2	4.0	[-1.4, 6.9]	[-0.5, 2.7]

Likelihood contours

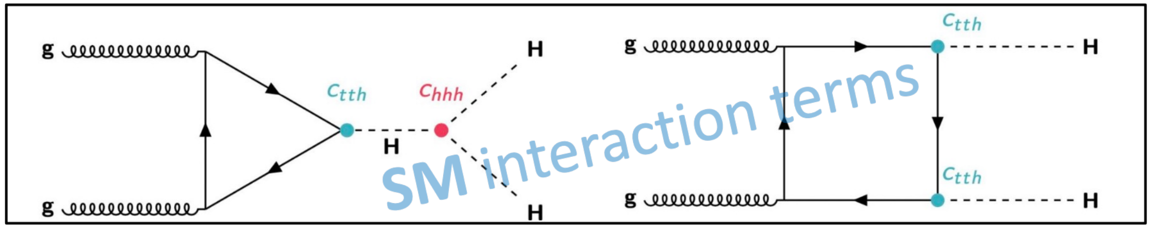


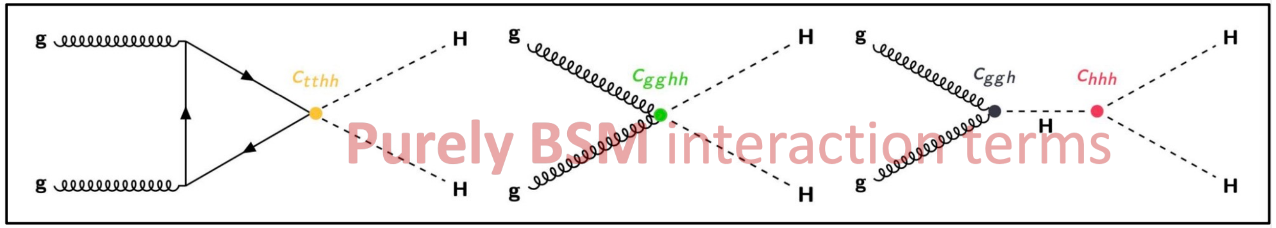




EFT inplementation: HEFT

- **HEFT** (Higgs Effective Field Theory)
  - Includes **five** couplings: c_{hhh} , c_{tth} , c_{ggh} , c_{gghh} , c_{tthh} . In SM, values are: (1, 1, 0, 0, 0)

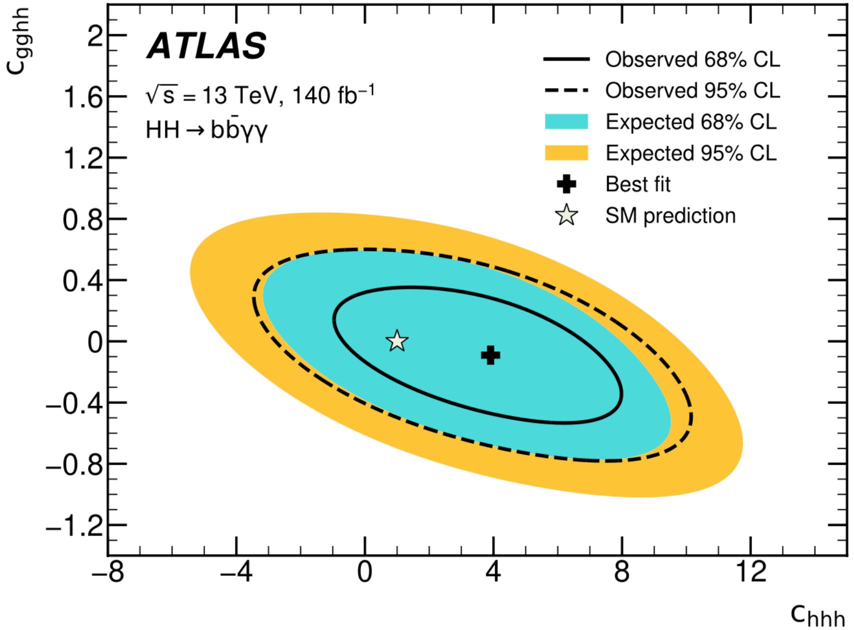


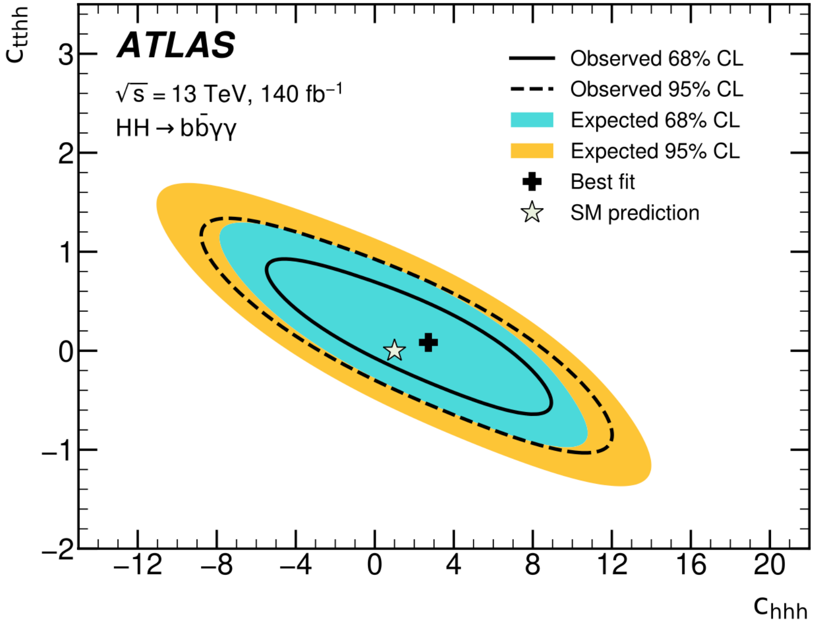


- Different parameterization used w.r.t κ_λ and κ_{2V} results
  - **HEFT results:** Use ratio of theory cross-sections between **SM point only** and point of interest in a given $\mathbf{m_{HH}}$ bin (weight for each bin)

- Results consider uncertainties from **reweighting, theory and PS.**

Likelihood contours

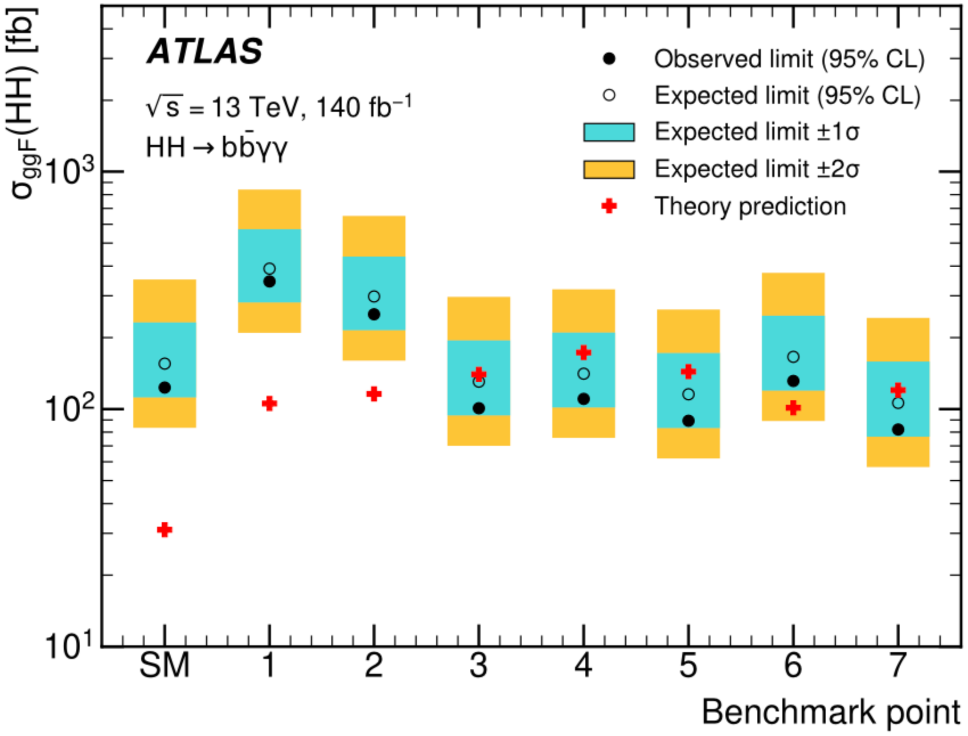




EFT inplementation: HEFT

- HEFT benchmark points (7) describe representative signal kinematics and m_{HH} shape features
  - Have sensitivities that can vary significantly between one point and another
- The resulting **upper limits** on the **Higgs boson pair production cross-section** through **gluon-gluon fusion**
  - Benchmark points 3, 5 and 7: sets upper limits similar to those set by the search for **HH→4b** events
  - The remaining benchmarks: have updated definitions compared to those in the **HH→4b** search
    - Can not be directly compared

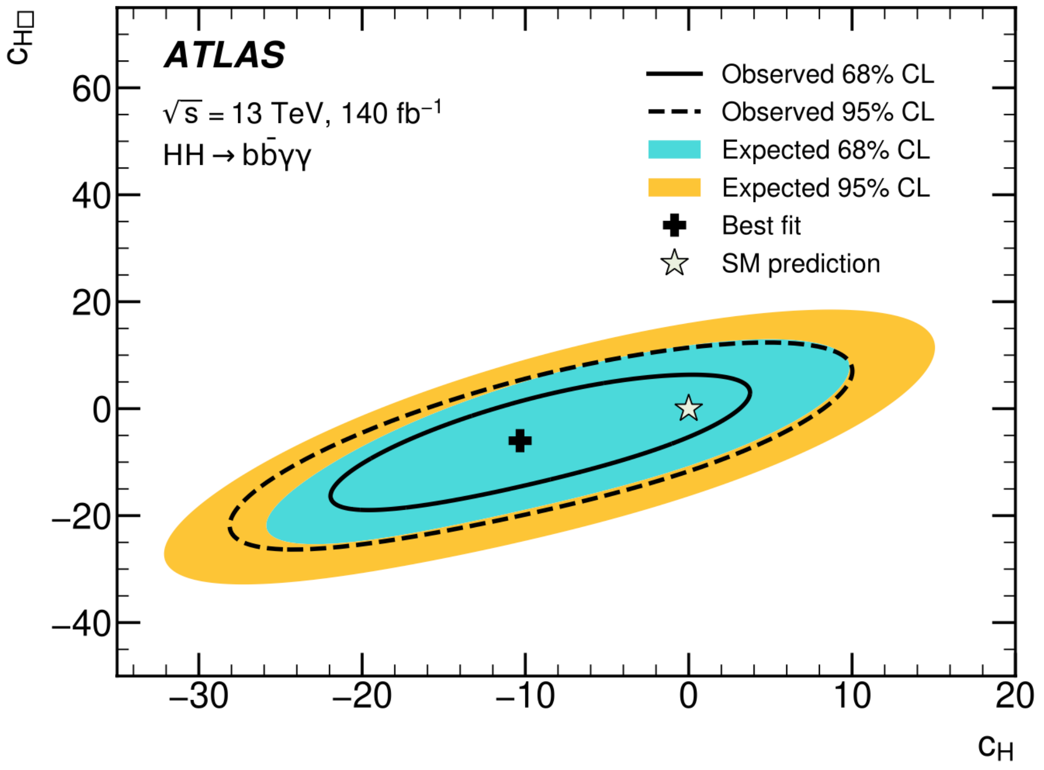
Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1.00	1.00	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	−1/3	0	1/6
3	2.21	1.05	1/2	1/2	−1/3
4	2.79	0.90	−1/3	−1/2	−1/6
5	3.95	1.17	1/6	−1/2	−1/3
6	−0.68	0.90	1/2	1/4	−1/6
7	−0.10	0.94	1/6	−1/6	1



EFT inplementation: SMEFT

- **SMEFT** (Standard Model Effective Field Theory)
  - Expansion of the SM Lagrangian with operators of dimension 6
  - Assumes an EW **doublet** for Higgs (HEFT assumes EW gauge **singlet**)
  - Includes 5 Wilson coefficients:
    - C_H , C_{HG}, C_{tH}, C_{tG}, $C_{H\Box}$
    - Some Wilson coefficients introduce dependencies, e.g. with **H production** (which does not happen in HEFT)
      - Need to model these properly
  - Strategy:
    - Estimate effects on HH cross section for variation of SMEFT parameters, and effects on uncertainties, to compute upper limits and likelihoods on different signal hypotheses
  - Additional points
    - Have both linear and quadratic terms in matrix element to consider
    - Trying to reweight from LO to NLO for more accurate results
    - Actively deriving **uncertainties** on the **signal** and the **background**

Wilson coefficient	95% CL Observed	95% CL Expected
c_H	$[-14.4,\ 6.2]$	$[-16.8,\ 9.7]$
$c_{H\Box}$	$[-\ 9.4, 10.2]$	$[-12.4, 13.7]$



Conclusions

- Performed the legacy ATLAS Run 2 results of **non-resonant $HH \rightarrow bb\gamma\gamma$ analysis**
  - **No significant excess** above the expected background was observed
- Looking forward for the **Run 2 + (Partial) Run 3 results**

Backup

Pre-selection

- A combination of di-photon and single-photon triggers are used to maximize the efficiency.
  - 2015+2016: `HTL_g35_loose_g25_loose`
  - 2017+2018: `HLT_g35_medium_g25_medium_L12EM20VH`

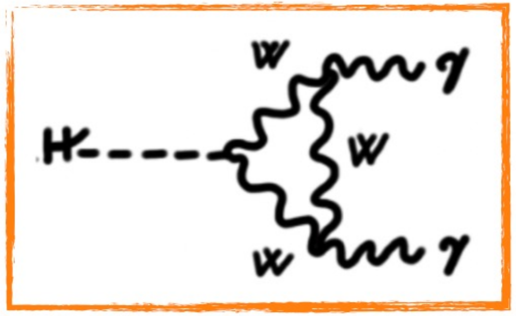
  ➡ Require two loose or medium photons with (sub-)leading $p_T > 35(25)$ GeV.

  - 2015: `HLT_g120_loose`
  - 2016+2017+2018: `HLT_g140_loose`

  } Require one loose photon with $p_T > 120$ or 140 GeV.

  ➡ More relevant for $H \to \gamma\gamma$ decays with highly boosted Higgs bosons, where the two photons cannot be resolved!

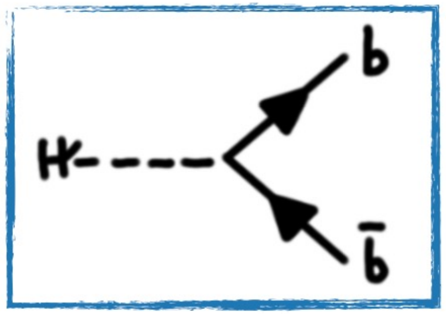
- **Pre-selection** requirements targeting the **signature** define the **signal region** of our analysis!



➡
- **Two** tight and isolated **photons**.
- (Sub-)Leading $p_T/m_{\gamma\gamma} > 0.35(0.25)$.
- Di-photon invariant mass window $105 < m_{\gamma\gamma} < 160$ GeV.

➕

- No leptons. ➡ **Suppress** ttH **background** where the **top decay chain** generates **electrons** and **muons**.
- Less than 6 central jets. ➡ **Suppress** ttH **background** where the **top decays hadronically**.



➡
- **Exactly two b-jets** passing the 77% efficiency WP for the DL1r b-tagging algorithm.

  ➡ This allows to preserve orthogonality with the $HH \to bbbb$ analysis!
- The b-jets candidates are selected by **ranking** them **by their b-tagging quantile** they pass and tie breaking by p_T.
- The μ-in-jet+`PtReco` (i.e. the `BJetCalibration`) ***b*-jet energy correction** is applied!

  ➡ The resolution on $\mathbf{m_{b\bar{b}}}$ for signal events improves of a factor of **22%**!

BDT training

- Input variables

- $p_T/m_{\gamma\gamma}$, η, ϕ of the 2 photons.
- $p_T/m_{\gamma\gamma}$, η, ϕ, b-tag quantile of the 2 b-jets.
- p_T^{bb}, η^{bb}, ϕ^{bb} and m_{bb}.
- H_T and single-topness χ_{Wt}.
- E_T^{miss} and ϕ^{MET}.

- $p_T/m_{\gamma\gamma}$, η, ϕ, b-tag score of the 3rd and 4th leading jets.

- 4-object invariant mass $m_{b\bar{b}\gamma\gamma}$.
- Distance between the 2 photons and between the 2 b-jets: $\Delta R(\gamma_1, \gamma_2)$ and $\Delta R(b_1, b_2)$.

- Invariant mass of the 2 VBF jets m_{jj} and $\Delta\eta(j_1, j_2)$.
- Event shape variables: transverse sphericity, planar flow, and p_T balance.

	Low Mass	High Mass
Signal	• ggF HH with $\kappa_\lambda = 5.6$ and $\kappa_\lambda = 10$ • VBF HH samples with **BSM** values for (κ_λ, κ_{2V}, κ_V).	• **SM ggF HH** • **SM + BSM VBF HH** samples
Background	• All single Higgs processes • γγ + ttγγ samples	• All single Higgs processes • γγ + ttγγ samples

Category	Mass region	BDT cuts
High Mass 1	$m^*_{b\bar{b}\gamma\gamma} > 350$ GeV	0.545 <BDT score< 0.830
High Mass 2	$m^*_{b\bar{b}\gamma\gamma} > 350$ GeV	0.830 <BDT score< 0.905
High Mass 3	$m^*_{b\bar{b}\gamma\gamma} > 350$ GeV	BDT score > 0.905
Low Mass 1	$m^*_{b\bar{b}\gamma\gamma} \leq 350$ GeV	0.430 <BDT score< 0.785
Low Mass 2	$m^*_{b\bar{b}\gamma\gamma} \leq 350$ GeV	0.785 <BDT score< 0.890
Low Mass 3	$m^*_{b\bar{b}\gamma\gamma} \leq 350$ GeV	0.890 <BDT score< 0.950
Low Mass 4	$m^*_{b\bar{b}\gamma\gamma} \leq 350$ GeV	BDT score > 0.950