Search for resonant HH production in the $b\bar{b}\gamma\gamma$ channel at ATLAS

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ATLAS Collaboration

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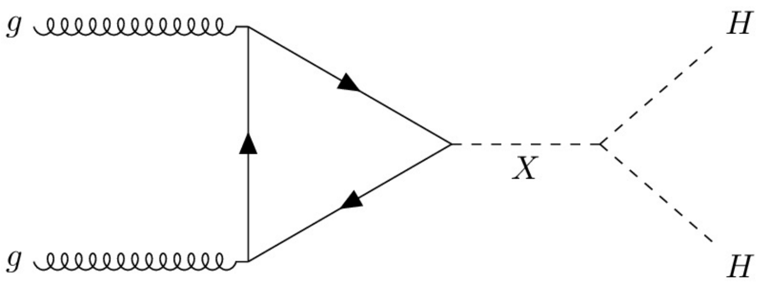
HDBS-2018-34

Physics Motivation

HH production is the simplest production mode sensitive to the Higgs boson self-coupling. The HH $\rightarrow bb\gamma\gamma$ channel allows to combine the high mass precision of the di-photon system to the important branching ratio of Higgs boson to b-quarks. The analysis is divided in two:

- Non-Resonant: search for SM HH production targeting two mechanisms, ggF and VBF.
- Resonant: search for narrow-width BSM $X \rightarrow HH$ (ggF mechanism), where $m_X \in [251{,}1000]$ GeV:
    - Leading channel in sensitivity for low resonances mass hypotheses.



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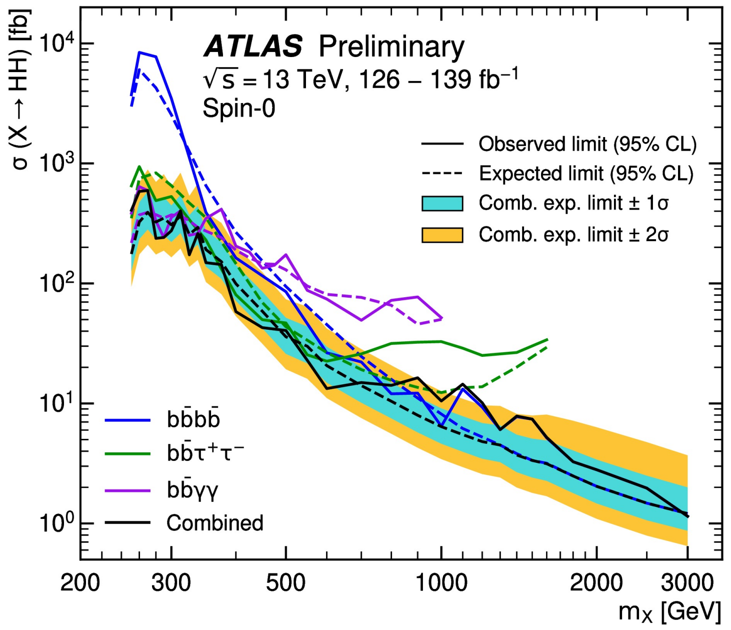

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Samples and selection criteria

Data and MC Samples

- Data: $139\ \mathrm{fb}^{-1}$ collected during Run 2.
- Signal Resonant ggF HH at LO with 22 mass points [251,1000] GeV.

Process	Generator	PDF set	Showering	Tune
Nonresonant ggF HH	POWHEG BOX v2 +FT	PDFLHC	PYTHIA 8.2	A14
Nonresonant VBF HH	MADGRAPH5_AMC@NLO	NNPDF3.0NLO	PYTHIA 8.2	A14
Resonant ggF HH	MADGRAPH5_AMC@NLO	NNPDF2.3LO	HERWIG 7.1.3	H7.1 - Default
ggF H	NNLOPS	PDFLHC	PYTHIA 8.2	AZNLO
VBF H	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
WH	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$qq \rightarrow ZH$	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$gg \rightarrow ZH$	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$t\bar{t}H$	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.2	A14
bbH	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.2	A14
tHq	MADGRAPH5_AMC@NLO	NNPDF3.0NLO	PYTHIA 8.2	A14
tHW	MADGRAPH5_AMC@NLO	NNPDF3.0NLO	PYTHIA 8.2	A14
$\gamma\gamma$+jets	SHERPA 2.2.4	NNPDF3.0NNLO	SHERPA 2.2.4	–
$t\bar{t}\gamma\gamma$	MADGRAPH5_AMC@NLO	NNPDF2.3LO	PYTHIA 8.2	–

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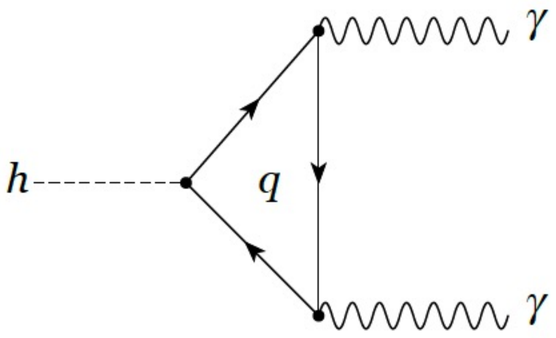
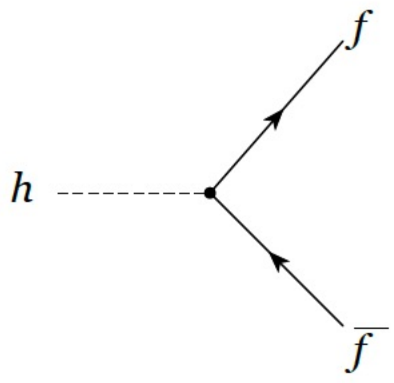
Selection criteria

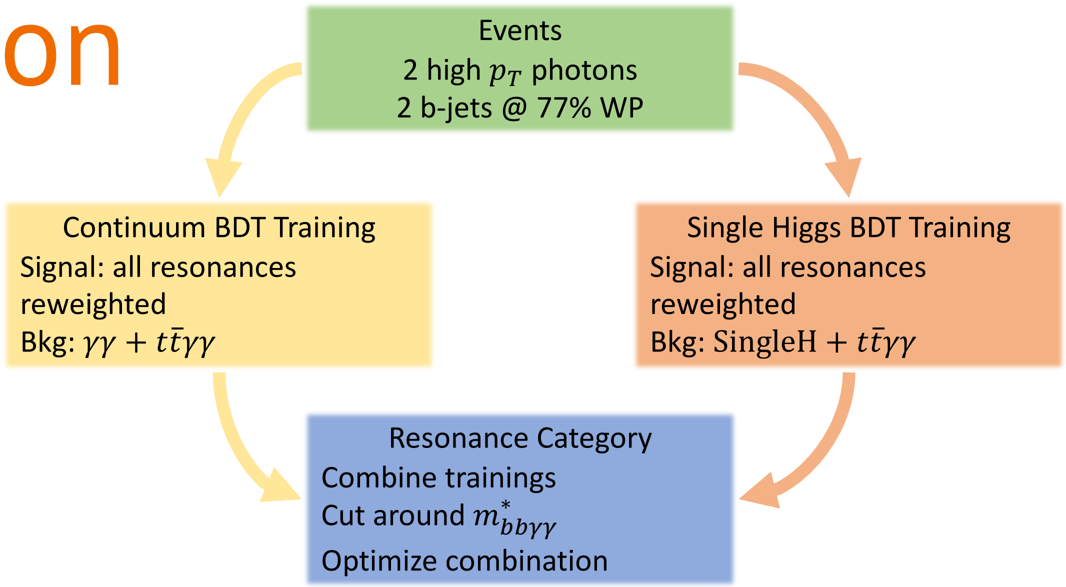
- Pre-selection (first selection criteria before further specific selection):
  - Two tight and isolated ID photons with $p_T/m_{\gamma\gamma} > 0.35\ (0.25)$ for the leading (subleading) photon. Lepton veto $N_l = 0$:
  - At least two central jets and less than 6 central jets with $p_T > 25$ GeV, $|\eta| < 2.5$, $|\gamma| < 4.4$.
  - Exactly 2 b-jet at 77% WP. The b-jets candidates are selected by ranking by the b-tag working point (WP). The algorithm used to determine the flavour of the jet is DL1r based.
- B-jets corrections are applied to correct semileptonic decay of b-hadron documented in HGam Performance Note (link).
- For further selection we require at least 0.8 background events in the window $123 < m_{\gamma\gamma} < 127$ GeV to be able to perform a fit in $m_{\gamma\gamma}$.

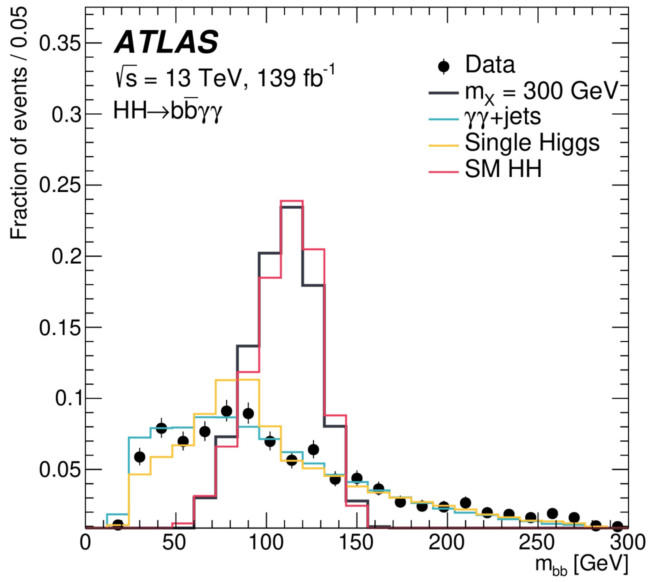




Resonant analysis selection

- A multivariable analysis (MVA) is used for the resonant analysis selection.
- Two BDTs are trained given the different nature of the backgrounds:
  - Diphoton continuum plus $tt\gamma\gamma$ which adds true photon information.
  - SH plus $tt\gamma\gamma$ which adds top and b-tagging information.
- A single BDT is trained for all the resonance masses.
- To make the BDT independent of the resonance mass input the signal is reweighted event by event to match $m^*_{b\bar{b}\gamma\gamma}$ background.





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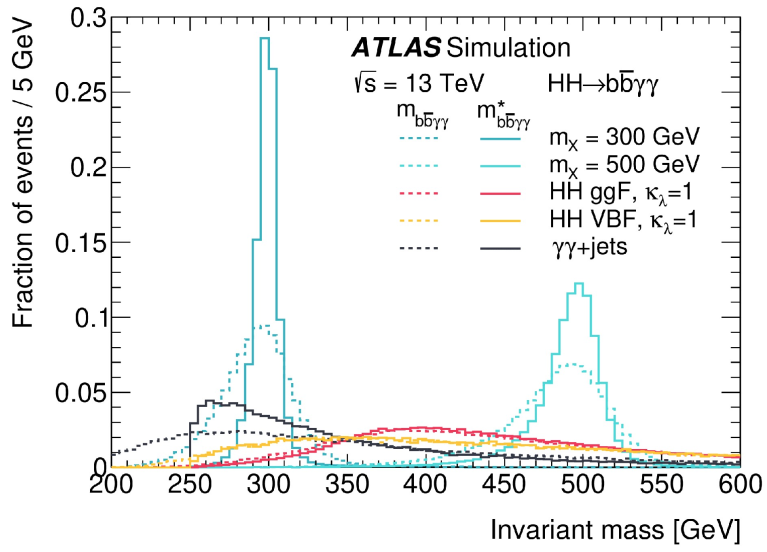
Resonant analysis selection

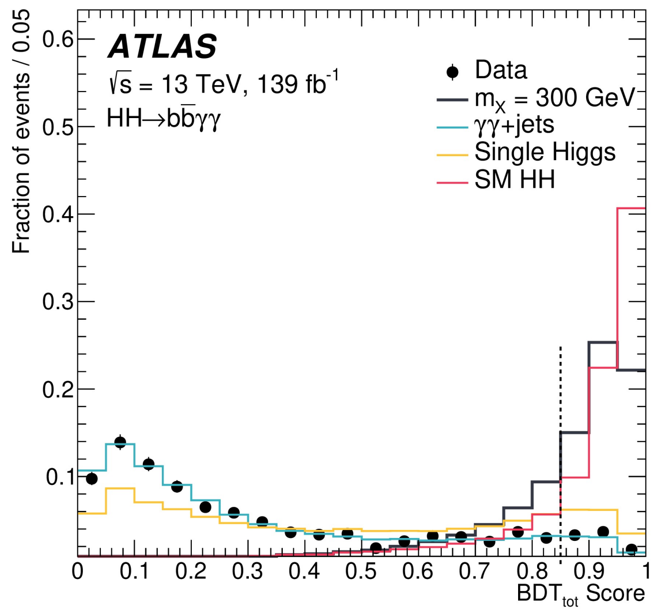
- The overall BDT score of an event is then obtained by combining both BDT scores in quadrature:

$$BDT_{tot} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \sqrt{C_1^2 \left(\frac{BDT_{\gamma\gamma} + 1}{2}\right)^2 + C_2^2 \left(\frac{BDT_{SingleH} + 1}{2}\right)^2}$$

- Further selection is applied around the m_x window:
  - Fitting $m^*_{b\bar{b}\gamma\gamma}$ using a CB function for each resonance obtaining the window $Mean \pm 2(4)RMS$ (900 and 1000 GeV).
- The coefficient C_1 ($C_2 = 1 - C_1$) and the BDT score is then scanned in a two step way:
  - Optimized selection for maximum binned Asimov's significance*.
  - Second scan to provide a common C_1 for all resonance masses at a maximum lost of a 5% from the maximum significance

$$*Z = \sqrt{2[(s+b)\ln(1+s/b) - s]}$$





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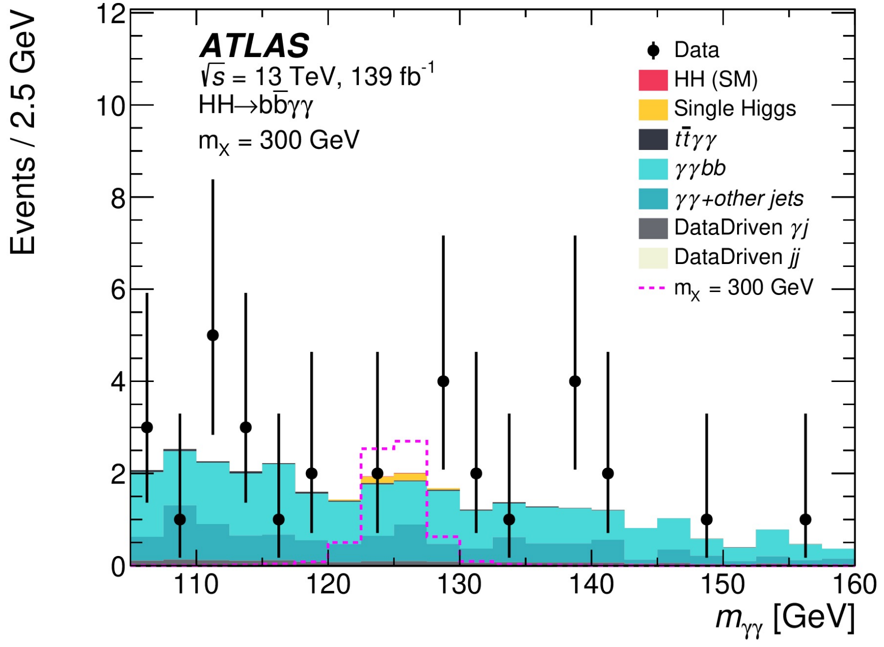
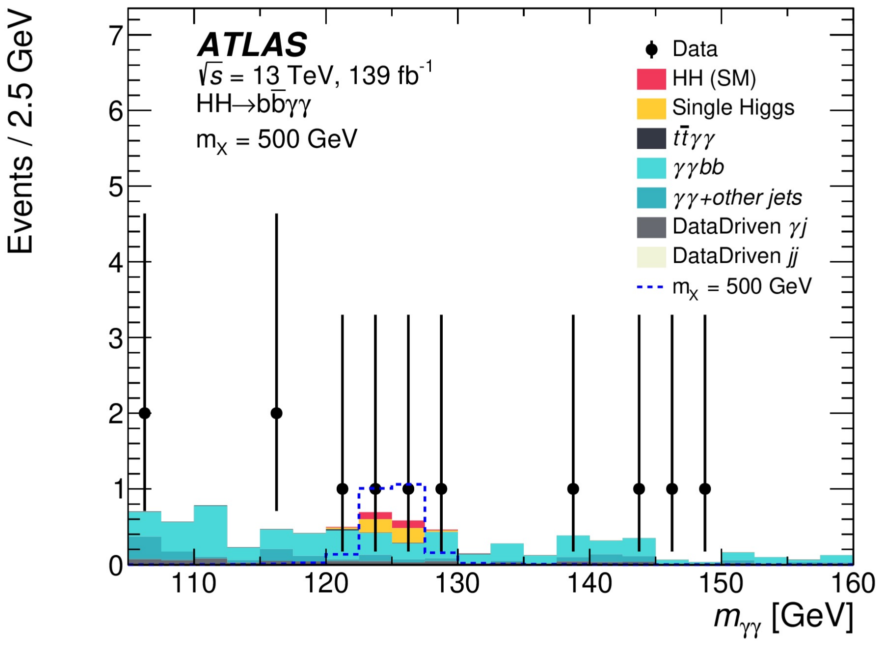
Resonant data / MC comparison

- Distribution of $m_{\gamma\gamma}$ at selection level for the resonance mass points of $m_X = 300, 500$ GeV. The data-derived fractions of non-resonant $\gamma\gamma, \gamma - jet$ and di-jet backgrounds are applied and the total background is normalized to the data sideband.
- Most of the background comes from continuum background.
- Signal shown is factorized by current limits.





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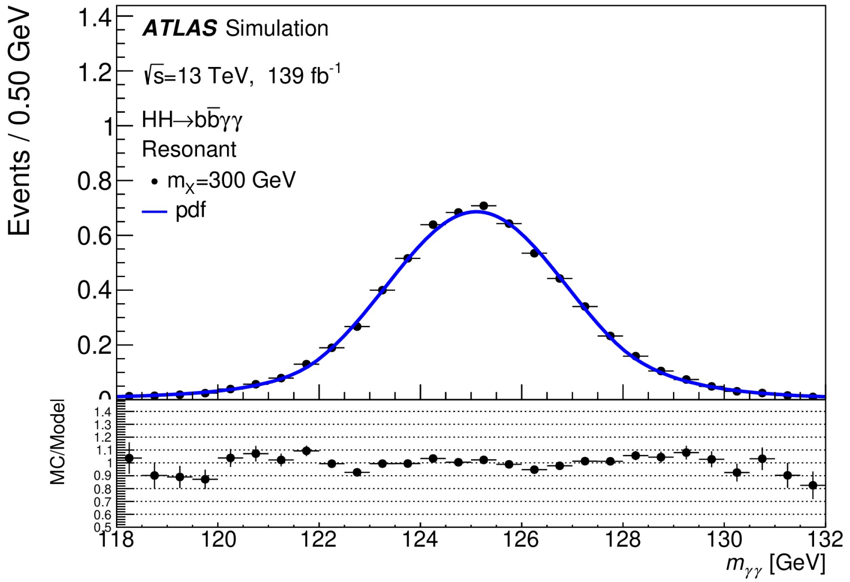
Signal and background modelling

Resonant signal modelling

- The $m_{\gamma\gamma}$ signal model are described by a double-sided Crystal Ball function.
- The same parameterized functions are used for both the single Higgs and di-Higgs boson processes since no statistical bias is found.
- This procedure is repeated for all resonance mass hypotheses.



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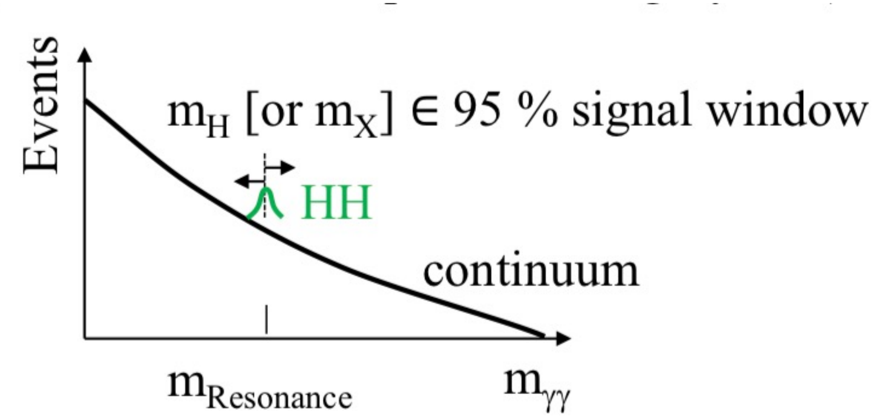
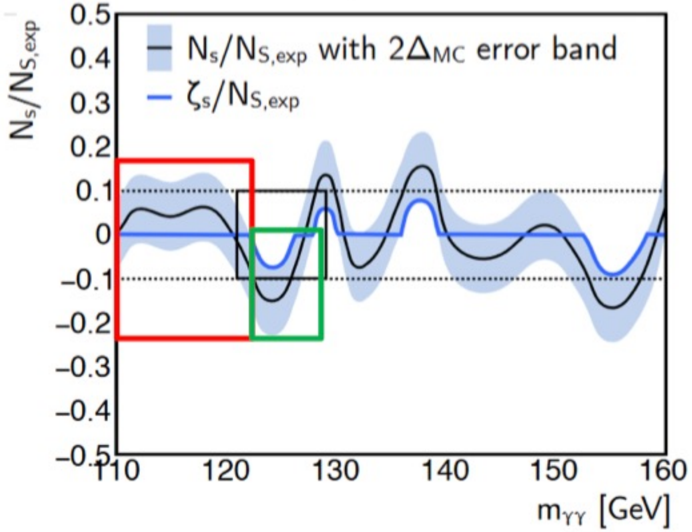
Background modelling

- For the background modelling we use the spurious signal test for any potential fake signal obtained from fitting the background distribution that describes signal plus background shape.
- The background is fitted with a signal plus background model and the fitted signal events is computed for different Higgs masses.
- The spurious signal N_{sp} is taken as the largest number of fitted signal events:
    - $|Max(N_{sp}/\sigma_{bkg})| < 20\%$
- For low statistic categories the criteria is relaxed to accommodate 2σ local statistical fluctuations (Δ_{MC}) in the background template:

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

- The background function is selected as an exponential function.





Systematics

Systematics

- Summary of dominant systematic uncertainties affecting expected yield and shape after the selection for both searches.
- Systemmatics are taken as the maximum across all resonances mass hypotheses.

		Relative impact of the systematic uncertainties [%]
Source	Type	Resonant analysis $m_X = 300$ GeV
Experimental		
Photon energy resolution	Norm. + Shape	0.6
Jet energy scale and resolution	Normalization	0.3
Flavor tagging	Normalization	0.2
Theoretical		
Factorization and renormalization scale	Normalization	< 0.2
Parton showering model	Norm. + Shape	2.6
Heavy-flavor content	Normalization	< 0.2
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	< 0.2
Spurious signal	Normalization	3.3

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Statistical Model

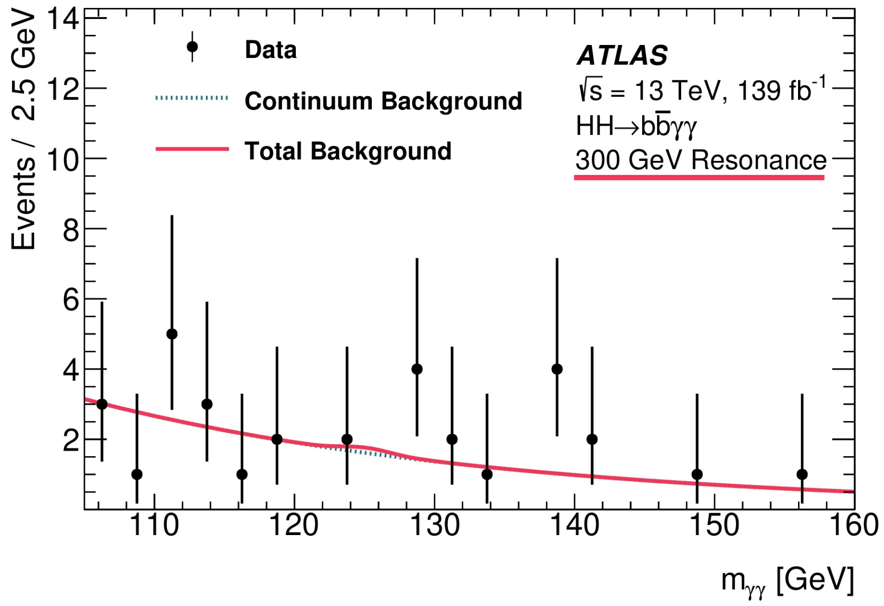
Statistical Model

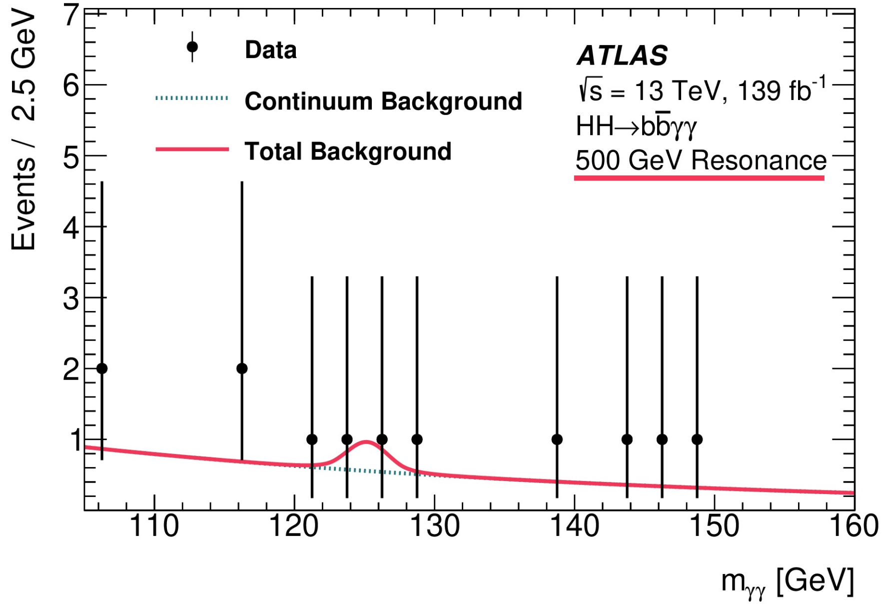
- The statistical results are obtained from a maximum likelihood fit of the $m_{\gamma\gamma}$ distribution in the range of $[105,160]$ GeV over all categories.
- The nominal single Higgs yields are fixed to values from simulation.
- The signal strength, non-resonant background shape parameters and the nuisance parameters, representing the systematic uncertainties, are free parameters in the fit.

Results

- Background only fit for two mass hypothesis.
- Number of data events in the $120 < m_{\gamma\gamma} < 130$ GeV. Values are obtained from a fit of the Asimov data set while the continuum background is obtained from fit of the data sideband.

	m_X = 300 GeV	m_X = 500 GeV
Continuum background	$5.5^{+1.3}_{-1.5}$	$1.6^{+0.6}_{-0.9}$
Single Higgs boson background	$0.34^{+0.14}_{-0.07}$	$0.40^{+0.18}_{-0.08}$
SM HH background	$0.021^{+0.005}_{-0.009}$	$0.20^{+0.09}_{-0.09}$
$X \rightarrow HH$ signal	$6.1^{+0.9}_{-0.8}$	$6.1^{+0.8}_{-0.6}$
Data	6	4





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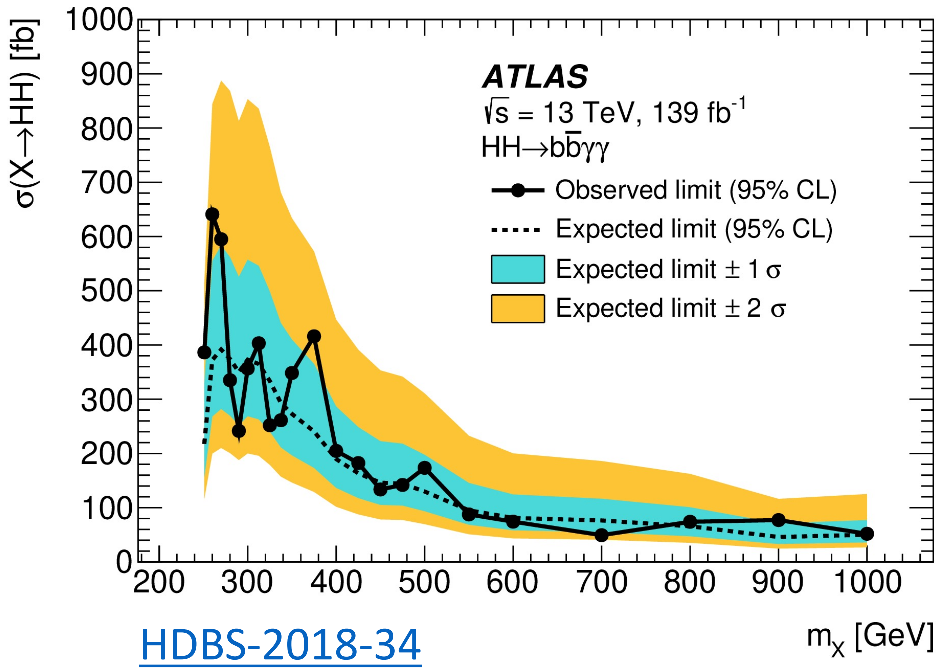
Results

- Observed and expected limit at 95% CL on the production cross section of a narrow-width scalar resonance X as a function of the mass m_X of the hypothetical scalar particle. **The observed (expected) upper limits are in the range 641-49 fb (392-46 fb)** depending of the mass hypothesis.
- The limit computed with $36\ \mathrm{fb}^{-1}$ can be seen in the right as a comparison to the new limit with $139\ \mathrm{fb}^{-1}$.
- There is an **improvement of a factor 3** respect to the previous analysis depending of the m_X.



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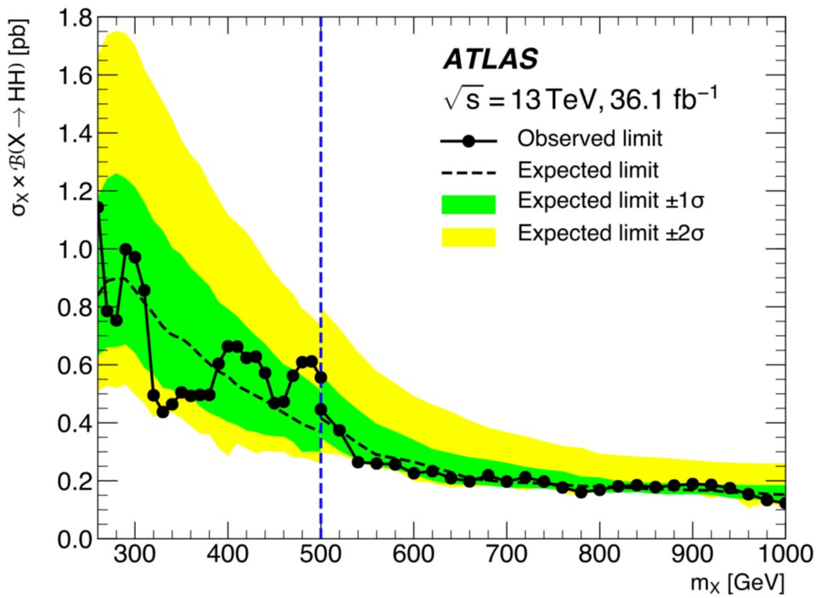

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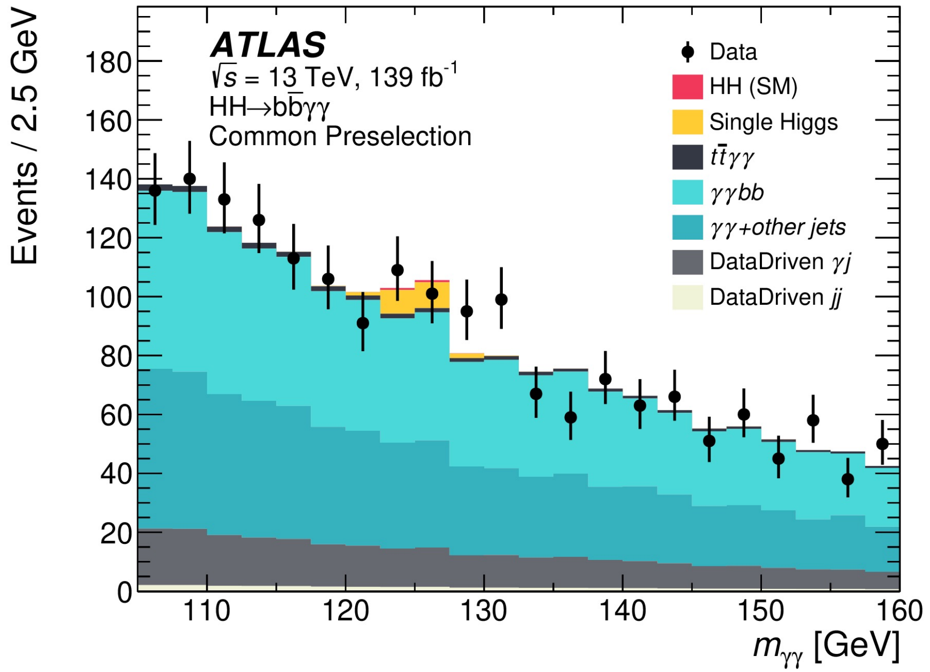
Conclusions

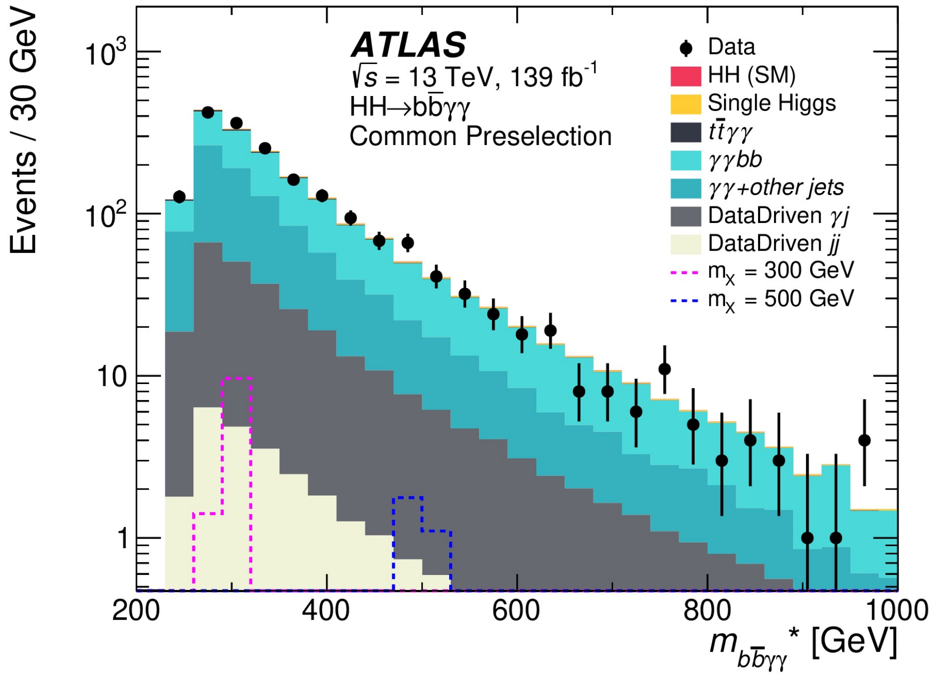
- Presented the resonant analysis for $HH \rightarrow bb\gamma\gamma$ final state with the full Run 2 data set.
- Leading channel for low resonances mass hypotheses.
- Up to a factor 3 improvement w.r.t the previous $36\ \mathrm{fb}^{-1}$ result.
- More details in the paper.

Back up

Data / MC Comparison

Distributions of $m_{\gamma\gamma}$ and $m^*_{b\bar{b}\gamma\gamma}$ for events satisfying the preselection criteria. The data-derived fractions of nonresonant $\gamma\gamma$, γ −jet and dijet background are applied and the total background is normalized to the data sideband. The scalar resonance signal is scaled to a total production cross section σ(pp → X → HH) = 370 fb for m_X = 300 GeV or σ(pp → X → HH) = 67 fb for m_X = 500 GeV.





Selection criteria details

- Pre-selection (first selection criteria before further specific selection):
  - Two tight and isolated ID photons with $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$. ${}^{p_T}/_{m_{\gamma\gamma}} > 0.35$ (0.25) for the leading (subleading) photon. The isolation requirement $topoEtCone20 < 0.065\ x\ p_T$ and $p_T cone20 < 0.05\ x\ p_T$.
  - Lepton veto $N_l = 0$:
    - Electrons: $p_T > 10$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$, Medium LH ID, $|d_0 significance| < 5$, $|\Delta Z_0 sin\theta| < 0.5$ mm. Isolation criteria $topoEtCone20 < 0.02\ x\ p_T$ and $p_T cone20 < 0.15\ x\ p_T$.
    - Muons: $p_T > 10$ GeV, $|\eta| < 2.7$, Medium ID, $|d_0 significance| < 3$, $|\Delta Z_0 sin\theta| < 0.5$ mm. GradientLoose isolation.
  - At least two AntiKt4EMPFlow central jets and less than 6 central jets with $p_T > 25$ GeV, $|\eta| < 2.5$, $|\gamma| < 4.4$, JetVertexFraction (JVT) tight.
  - Exactly 2 b-jet at 77% WP. The b-jets candidates are selected by ranking by the b-tag working point (WP) they pass and tie breaking by p_T. The algorithm used to determine the flavour of the jet is DL1r based in a deep neural network (RNNIP).
- B-jets corrections are applied to correct semileptonic decay of b-hadron documented in HGam Performance Note (link).
- For further selection we require at least 0.8 background events in the window $123 < m_{\gamma\gamma} < 127$ GeV to be able to perform a fit in $m_{\gamma\gamma}$.

Resonant cutflow for 300 GeV

Cuts	Yield	Efficiency [%]
All events	133.98	100.00
Pass trigger	91.84	68.55
Has Primary Vertex	91.84	68.54
2 loose photons	75.65	56.46
$e-\gamma$ ambiguity	75.61	56.44
Trigger match	68.40	51.05
Photons tight ID cut	58.67	43.79
Photons isolation cut	49.21	36.72
rel. p_T cuts	44.44	33.17
$m_{\gamma\gamma} \in [105, 160]$	44.42	33.15
$N_{lep} = 0$	44.20	32.99
$N_j \geq 2$	33.29	24.84
N_j central <6	33.05	24.67
2 b-jet with 77% WP	11.38	8.49
Di-Higgs invariant mass selection	9.80	7.52
$m_{\gamma\gamma} \in [120, 130]$ GeV	6.29	4.69

Resonant analysis training variables

Variable	Definition
Photon-related kinematic variables	
$p_{\mathrm{T}}^{\gamma\gamma}$, $y^{\gamma\gamma}$	Transverse momentum and rapidity of the diphoton system
$\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$	Azimuthal angle and ΔR between the two photons
Jet-related kinematic variables	
$m_{b\bar{b}}$, $p_{\mathrm{T}}^{b\bar{b}}$ and $y_{b\bar{b}}$	Invariant mass, transverse momentum and rapidity of the b-tagged jets system
$\Delta\phi_{b\bar{b}}$ and $\Delta R_{b\bar{b}}$	Azimuthal angle and ΔR between the two b-tagged jets
N_{jets} and $N_{b\text{-jets}}$	Number of jets and number of b-tagged jets
H_{T}	Scalar sum of the p_{T} of the jets in the event
Diphoton+dijet-related kinematic variables	
$m^{*}_{b\bar{b}\gamma\gamma}$	Invariant mass of the diphoton plus b-tagged jets system
$\Delta y_{\gamma\gamma,b\bar{b}}$, $\Delta\phi_{\gamma\gamma,b\bar{b}}$ and $\Delta R_{\gamma\gamma,b\bar{b}}$	Distance in rapidity, azimuthal angle and ΔR between the diphoton and the b-tagged jets system
Missing transverse momentum variables	
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum

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Resonant BDT Score cuts

m_X [GeV]	BDT threshold	Efficiency [%]
251	0.70	6.6
260	0.75	5.7
270	0.80	5.1
280	0.85	4.5
290	0.85	4.7
300	0.85	4.9
312.5	0.85	5.2
325	0.85	5.2
337.5	0.85	5.5
350	0.85	5.8
375	0.90	5.5
400	0.80	7.6
425	0.85	7.6
450	0.85	8.1
475	0.80	9.1
500	0.75	9.9
550	0.60	11.6
600	0.45	12.9
700	0.20	14.9
800	0.10	16.2
900	0.20	19.4
1000	0.05	20.0

Resonant MVA setup

- Two BDTs are trained for the first one (second one):
  - Even (Odd) entries are used as training
  - Odd (Even) numbers are used as testing
- Ntrees = 1000
- BoostType = Grad
- Shrinkage = 0.10
- BaggedSampleFraction = 0.5
- nCuts = 20
- MaxDepth = 5

Systematics

- MC systematics applied to signal and single Higgs:
  - Experimental systematics:
    - Pile-up modelling.
    - Diphoton trigger efficiency.
    - Photons: ID efficiency, isolation efficiency, energy scale, energy resolution.
    - Jets: energy scale, energy resolution, vertex tagger efficiency.
    - Flavour tagging efficiencies.
  - Theoretical systematics:
    - QCD scale uncertainties.
    - α_s.
    - Parton shower modelling.
    - Heavy-flavour uncertainty.
- Diphoton continuum is affected by spurious signal.