Search for HH in the bbγγ final state with the ATLAS detector

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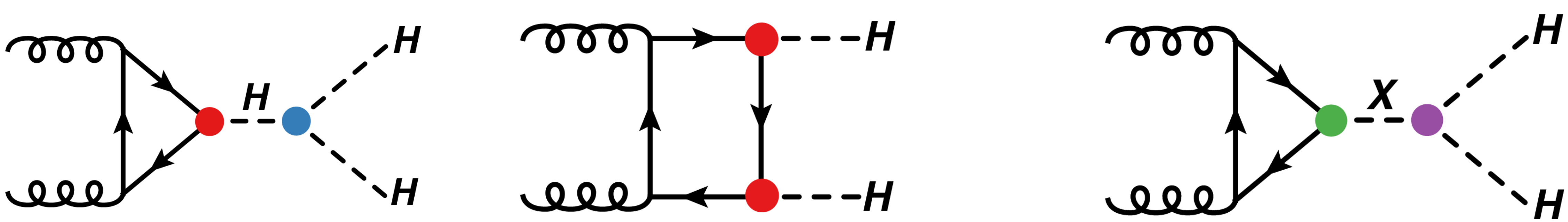
ATLAS EXPERIMENT

Introduction

- Higgs boson pair production is predicted in the SM and allows the possibility of measuring the Higgs boson self-coupling.
  - Destructive interference between diagrams results in a small cross section:
    σ = 31.05 fb at $\sqrt{s}$ = 13 TeV —> Not yet sensitive to this with the current LHC datasets.

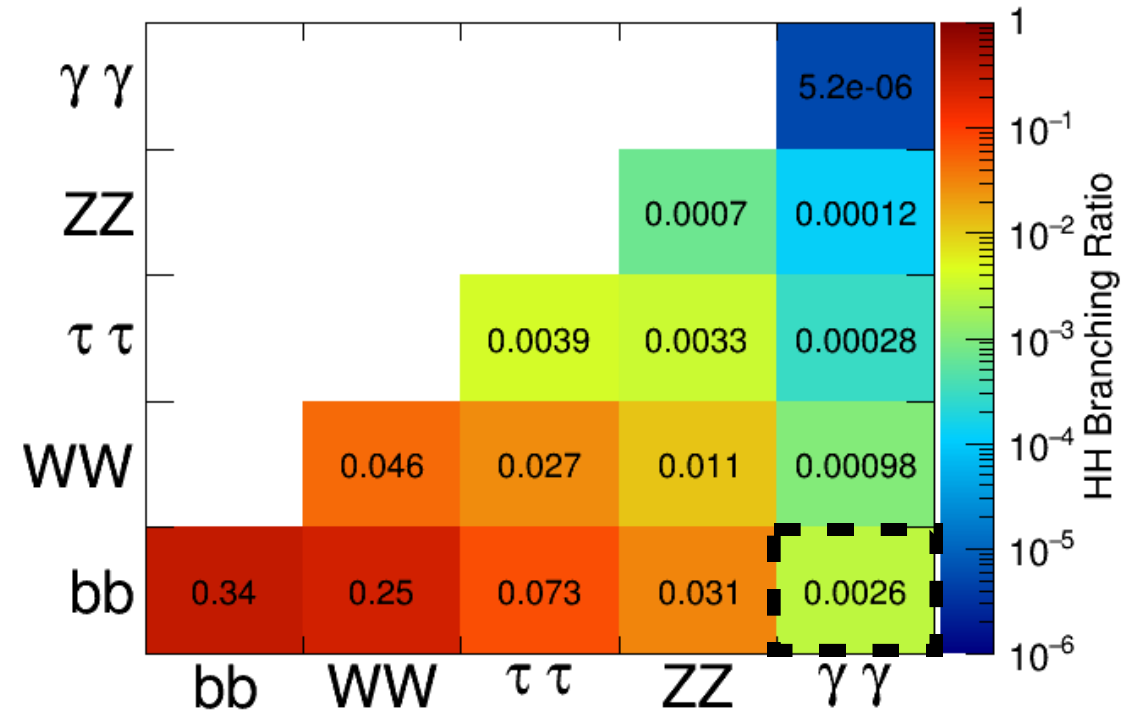


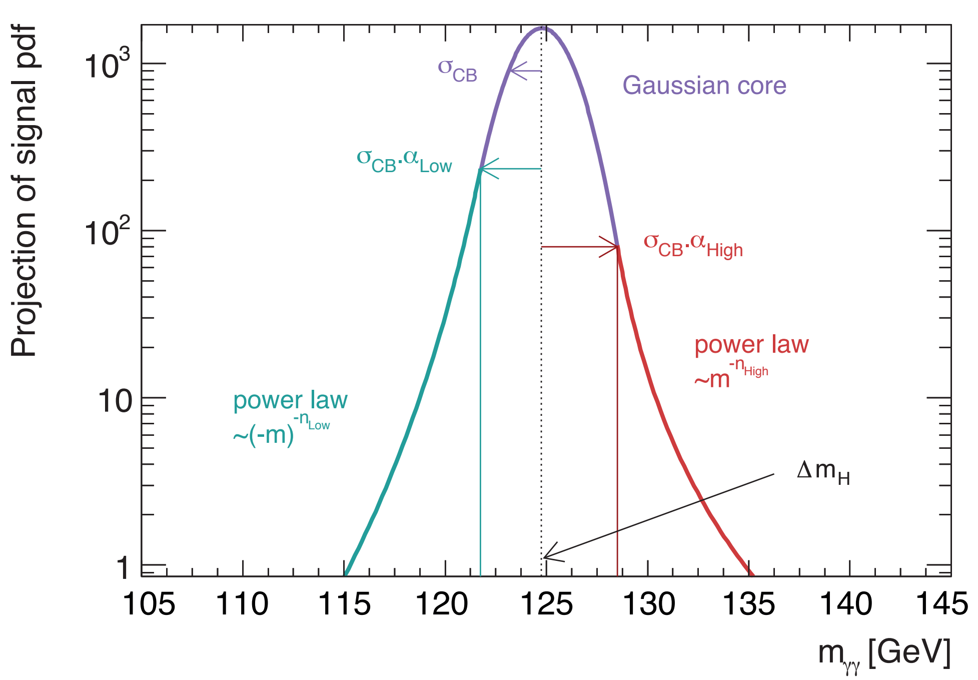
Standard Model **BSM**

- However, enhancements to non-resonant HH production can occur through an enhanced self-coupling ($\kappa_\lambda = \lambda_{HHH} / \lambda_{SM}$) or potentially BSM couplings (eg ttHH vertex).
- Various models also predict a new particle that can decay to pairs of Higgs bosons, referred to as resonant HH production.
- A search is performed for both resonant and non-resonant HH production in the $bb\gamma\gamma$ final state.

Motivation for bbγγ

- HH → bbγγ is one of the most attractive ways to study HH production:
- Branching ratio is ~ 130 times smaller than the largest HH → bbbb **but:**
  - Photon ID can effectively reject multi-jet backgrounds.
  - Efficient di-photon trigger gives high signal efficiency.
  - Excellent photon energy resolution gives a narrow H → γγ mass peak (σ_{CB} typically 1.6 GeV in ATLAS).





Data and MC samples

- Analysis uses 36.1 fb^{-1} of data collected by ATLAS in 2015 + 2016.
- **Signal MC samples:**

  Approximate NLO SM ($\kappa_\lambda = 1$) HH using MadGraph + Herwig.
  LO varied κ_λ HH using MadGraph + Pythia8 used to re-weight NLO sample for κ_λ interpretation.
  NLO BSM resonant HH using Madgraph + Herwig.

- **Background MC samples:**

  Single Higgs background: most important are ggF, ttH and ZH but all are considered.
  γγ + jets: used in the background decomposition and to guide the choice of functional form.

Process	Generator	Showering	PDF set	σ [fb]	Order of calculation of σ
Non-resonant SM HH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	33.41	NNLO+NNLL
Non-resonant BSM HH	MadGraph5_aMC@NLO	Pythia 8	NNPDF 2.3 LO	-	LO
Resonant BSM HH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	-	NLO
$\gamma\gamma$ plus jets	Sherpa	Sherpa	CT10 NLO	-	LO
ggH	Powheg-Box NNLOPS (r3080) [60]	Pythia 8	PDF4LHC15	48520	N^3LO(QCD)+NLO(EW)
VBF	Powheg-Box (r3052) [61]	Pythia	PDF4LHC15	3780	NNLO(QCD)+NLO(EW)
WH	Powheg-Box (r3133) [62]	Pythia	PDF4LHC15	1370	NNLO(QCD)+NLO(EW)
$q\bar{q} \to ZH$	Powheg-Box (r3133) [62]	Pythia 8	PDF4LHC15	760	NNLO(QCD)+NLO(EW
$t\bar{t}H$	MadGraph5_aMC@NLO	Pythia 8	NNPDF3.0	510	NLO(QCD)+NLO(EW)
$gg \to ZH$	Powheg-Box (r3133)	Pythia 8	PDF4LHC15	120	NLO+NLL(QCD)
$b\bar{b}H$	MadGraph5_aMC@NLO	Pythia	CT10 NLO	490	NNLO(5FS)+NLO(4FS)
t-channel tH	MadGraph5_aMC@NLO	Pythia 8	CT10 NLO	70	LO(4FS)
W-associated tH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	20	NLO(5FS)

Event selection

- $H \rightarrow \gamma\gamma$ event selection:
  Two tight ID and isolated photons with P_T / $m_{\gamma\gamma}$ > 0.35 (0.25) for the leading (subleading) photon.

  Events are then sorted into categories with exactly 2 b-tags or 1 b-tag.

  Two different selections are then used in the analysis:

- **Loose selection:**
  Used for resonant masses between 260 and 500 GeV and the κ_λ interpretation.

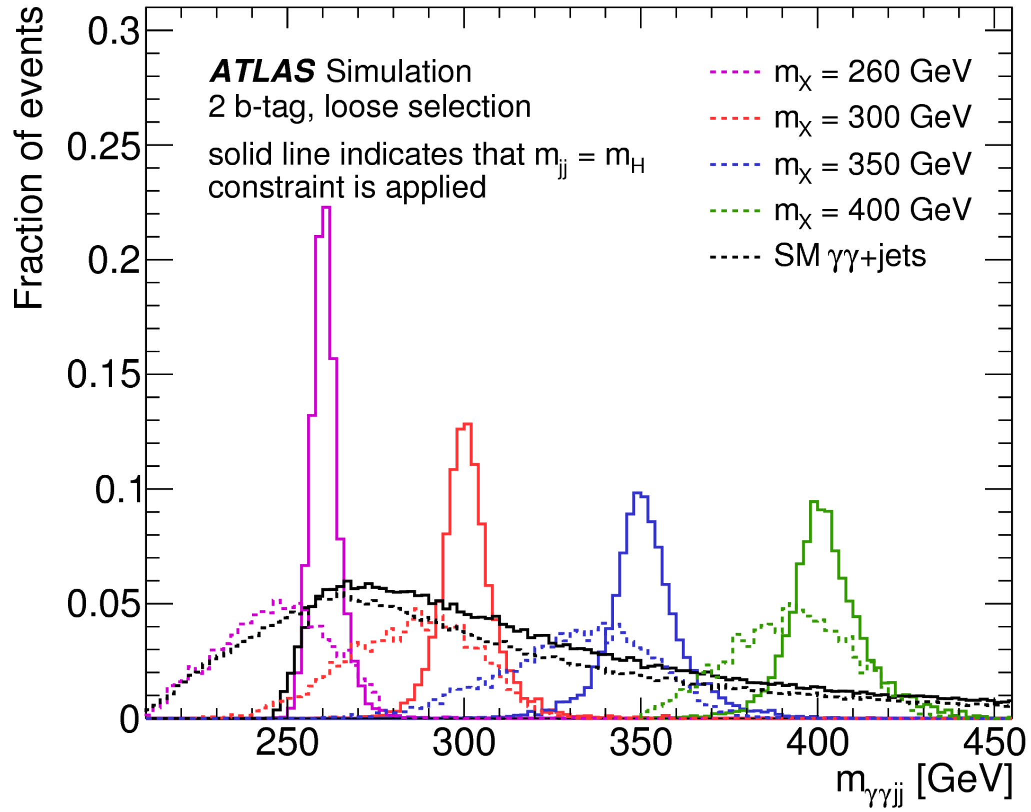
  jet P_T > 40 (25) GeV
  m_{bb} in the interval [80,140] GeV

  <u>Resonant analysis only:</u>
  $|m_{\gamma\gamma} - m_H| < 4.7$ GeV

- **Tight selection:**
  used for resonant masses between 500 GeV and 1 TeV and the limit on the SM cross-section.

  jet P_T > 100 (30) GeV
  m_{bb} in the interval [90,140] GeV

  <u>Resonant analysis only:</u>
  $|m_{\gamma\gamma} - m_H| < 4.3$ GeV



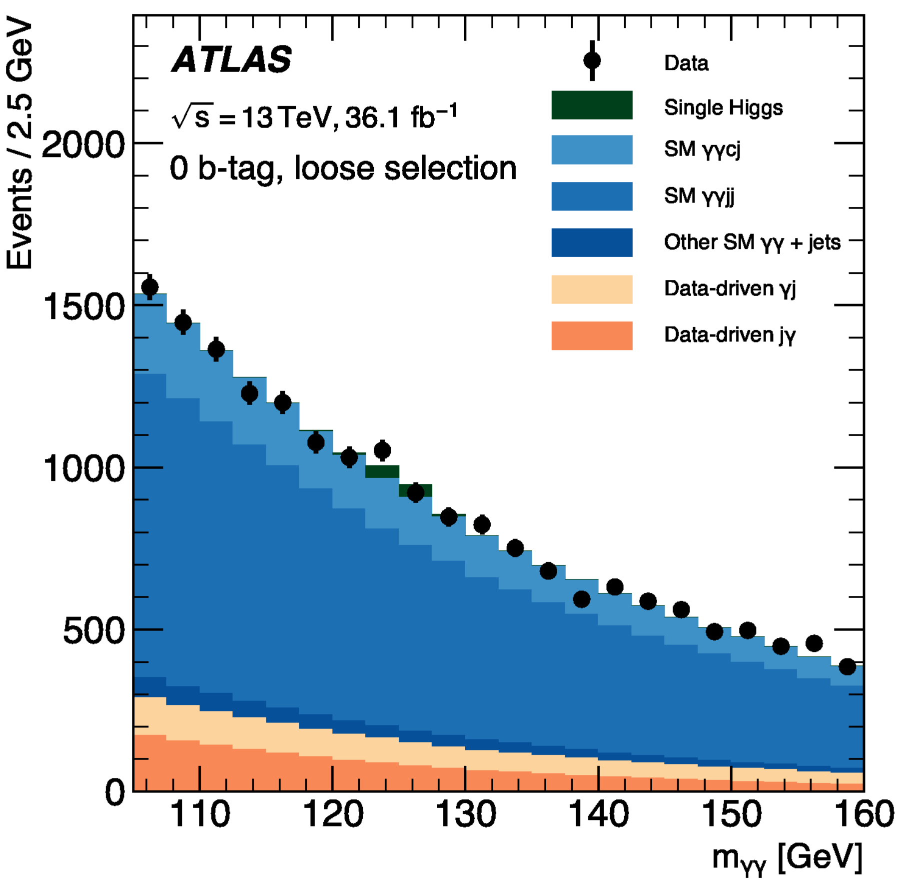
- <u>Resonant analysis only:</u>

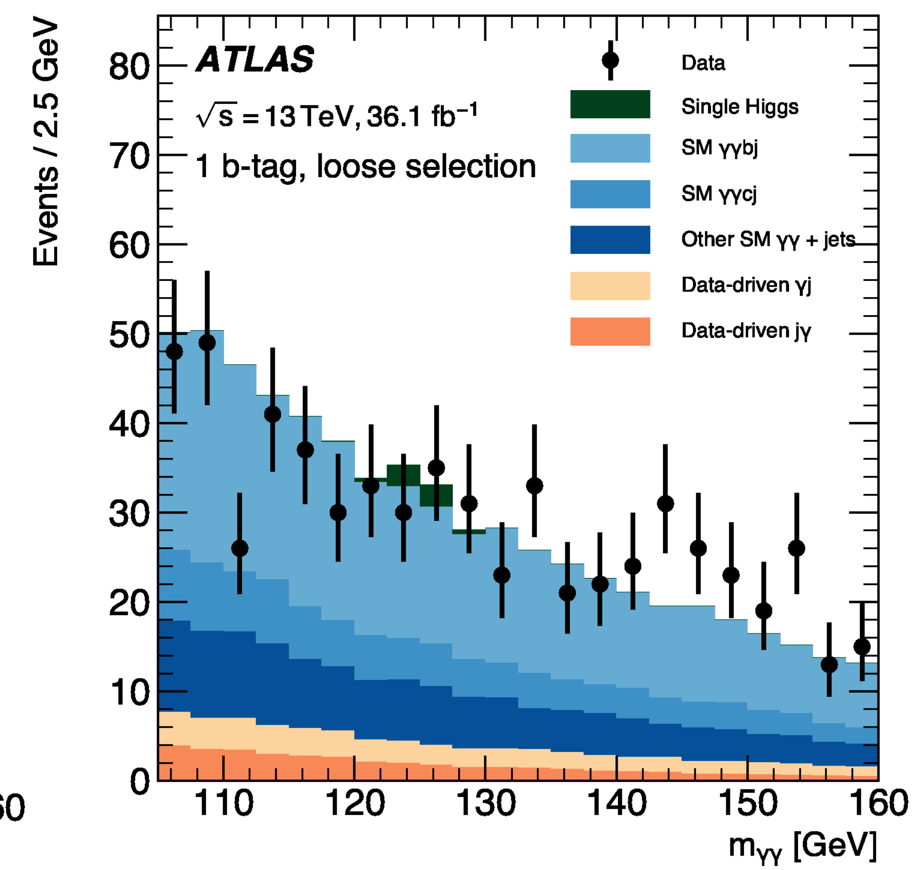
  The di-jet Higgs candidate 4-vector is rescaled such that its invariant mass is equal to 125 GeV

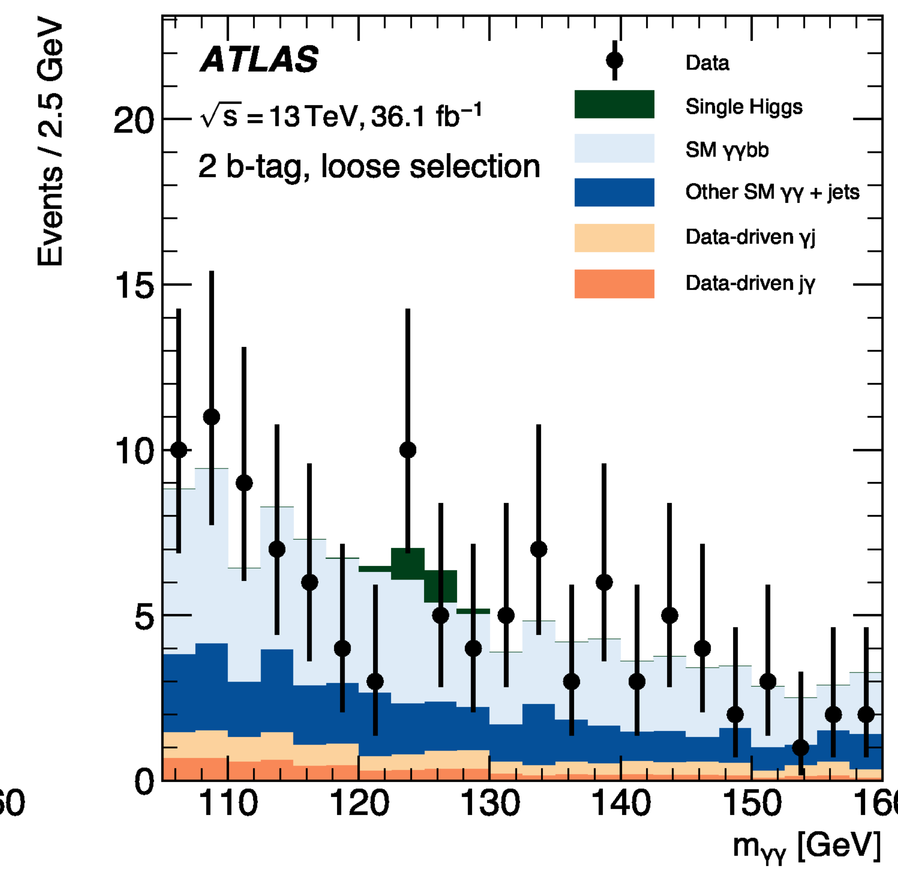
  Improves the $m_{\gamma\gamma bb}$ resolution, particularly at low m_X

Background decomposition

- Studied using a 2x2D sideband method where photon identification and isolation requirements are loosened.
- Flavour information extracted from the truth information in the Monte Carlo sample.
- In the 2-tag category which dominates the sensitivity, the background is mostly made up of the irreducible γγbb.



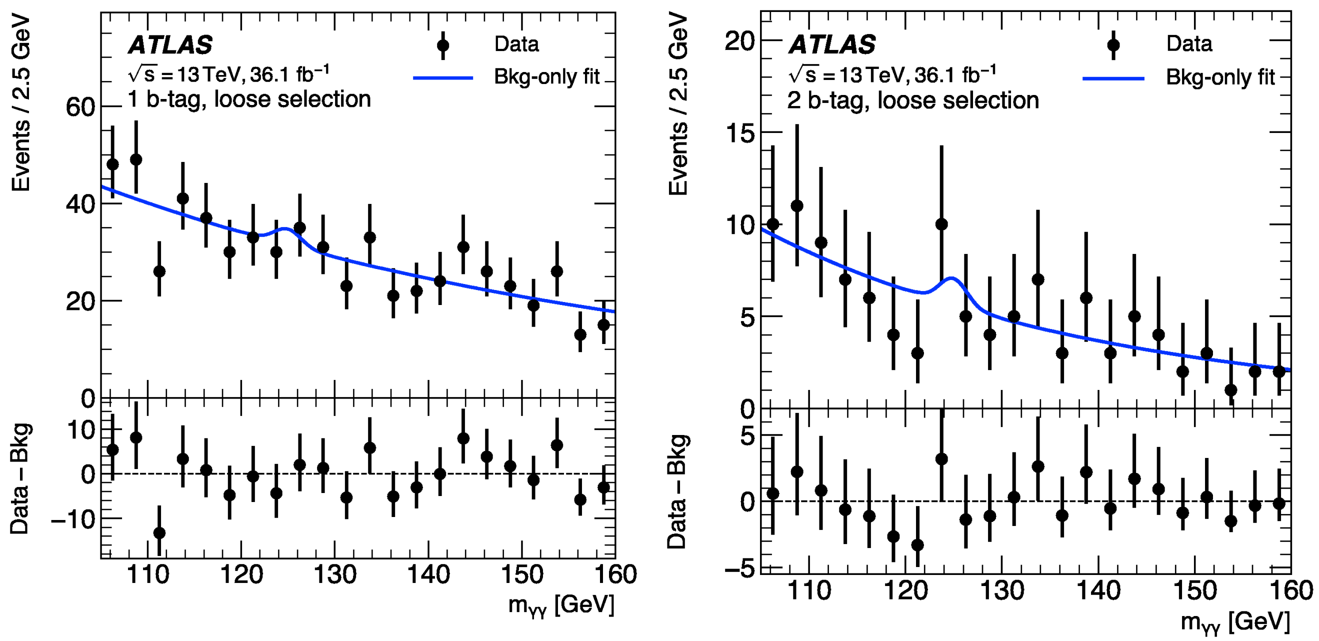




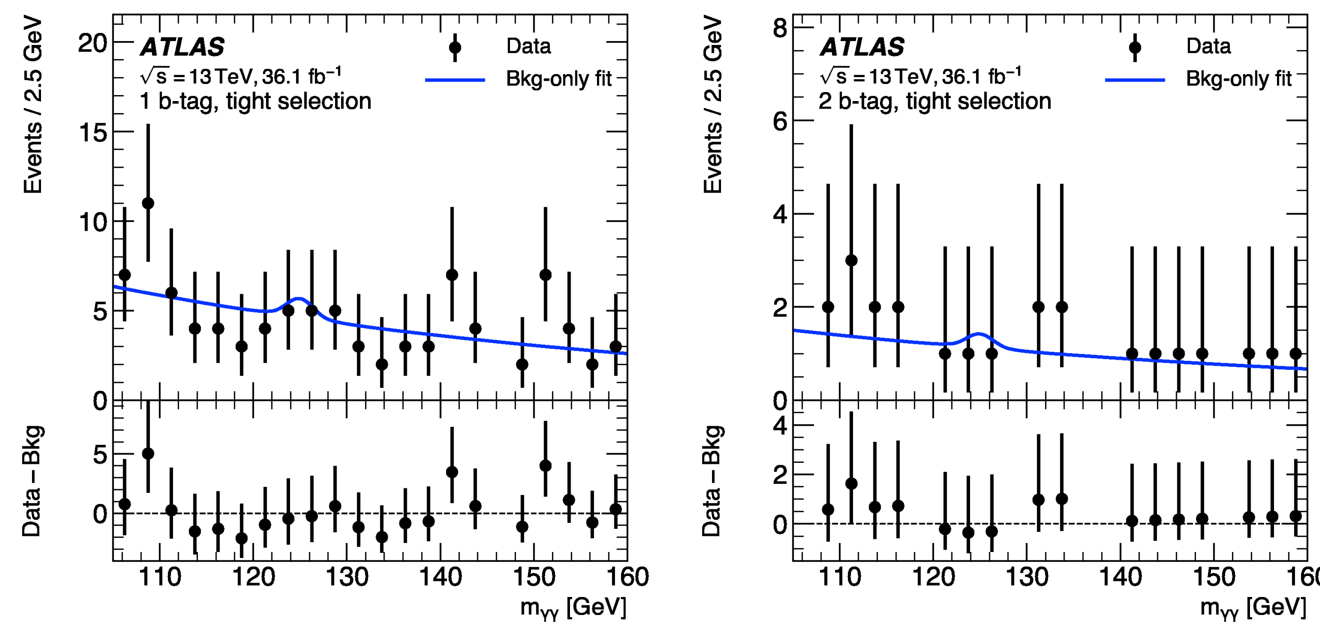
0-tag category used for cross checks only

Signal extraction (non-resonant)

- For the non-resonant analysis, the signal is extracted by performing a fit to the diphoton mass, $m_{\gamma\gamma}$ using a double-sided Crystal ball to model the signal and the single Higgs background and an exponential to model the continuum background.



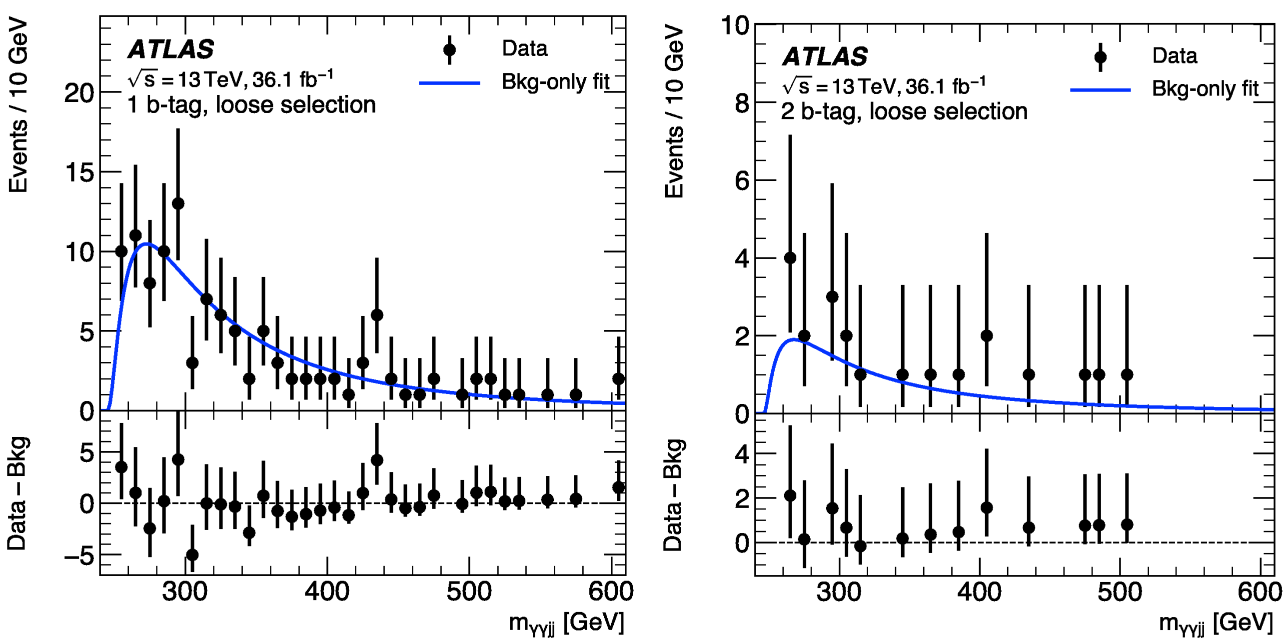
Loose selection
κ_λ analysis

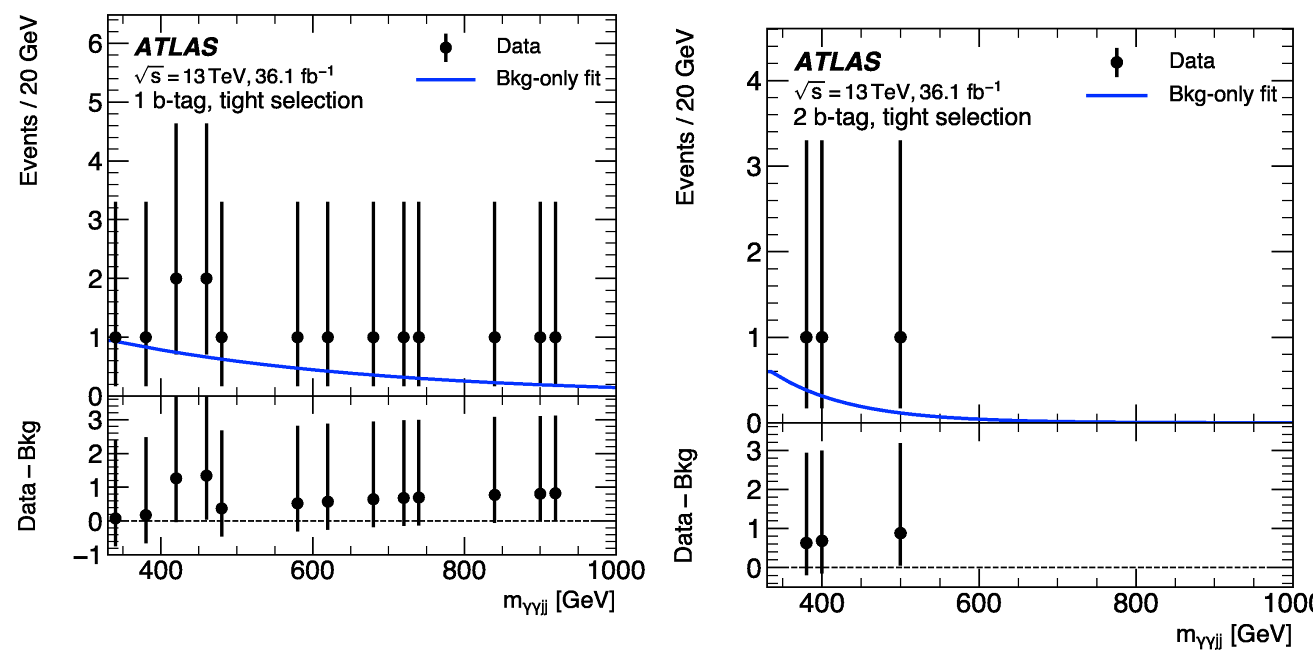


Tight selection
SM limit

Signal extraction (resonant)

- For the resonant analysis, the signal is extracted by performing a fit to the four-body mass, $m_{\gamma\gamma jj}$ using a Gaussian with exponential tails as signal model and a Novosibirsk (exponential) for the loose (tight) selection.





Loose selection
$M_X < 500$ GeV
($X \rightarrow HH \rightarrow bb\gamma\gamma$)

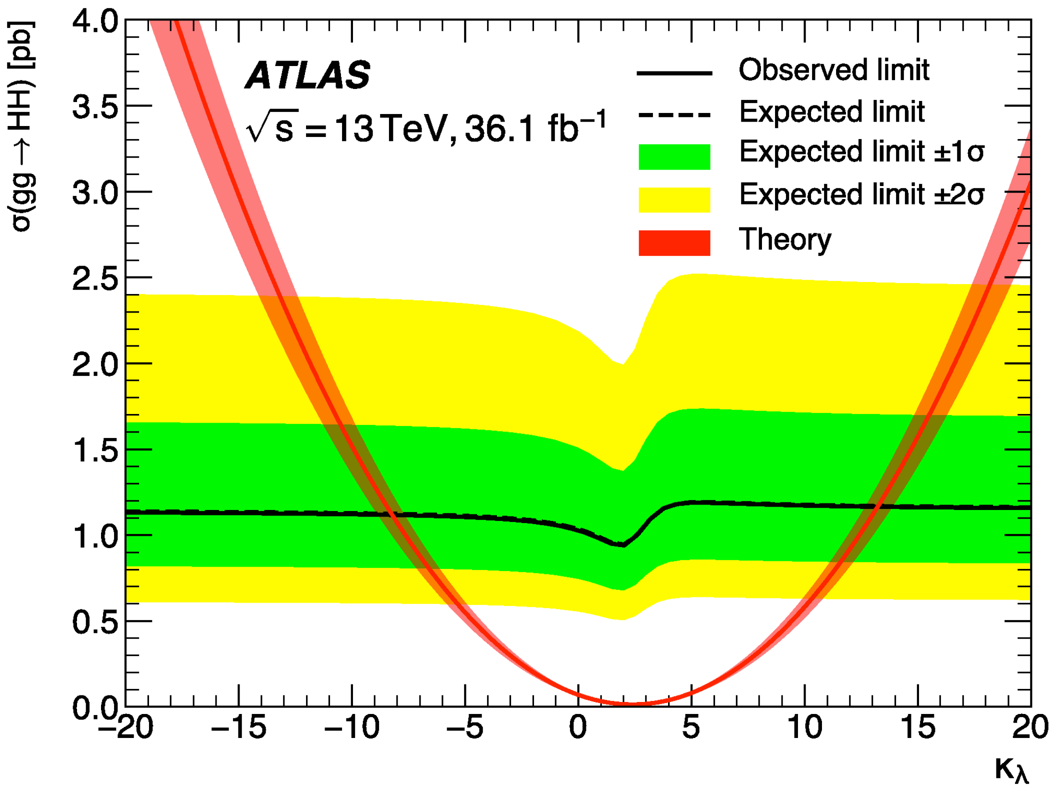
Tight selection
$M_X > 500$ GeV
($X \rightarrow HH \rightarrow bb\gamma\gamma$)

Results (non-resonant)

- Single Higgs backgrounds are fixed to their SM expectation in the fit.
- Limits on the SM HH cross-section at 95% CL:

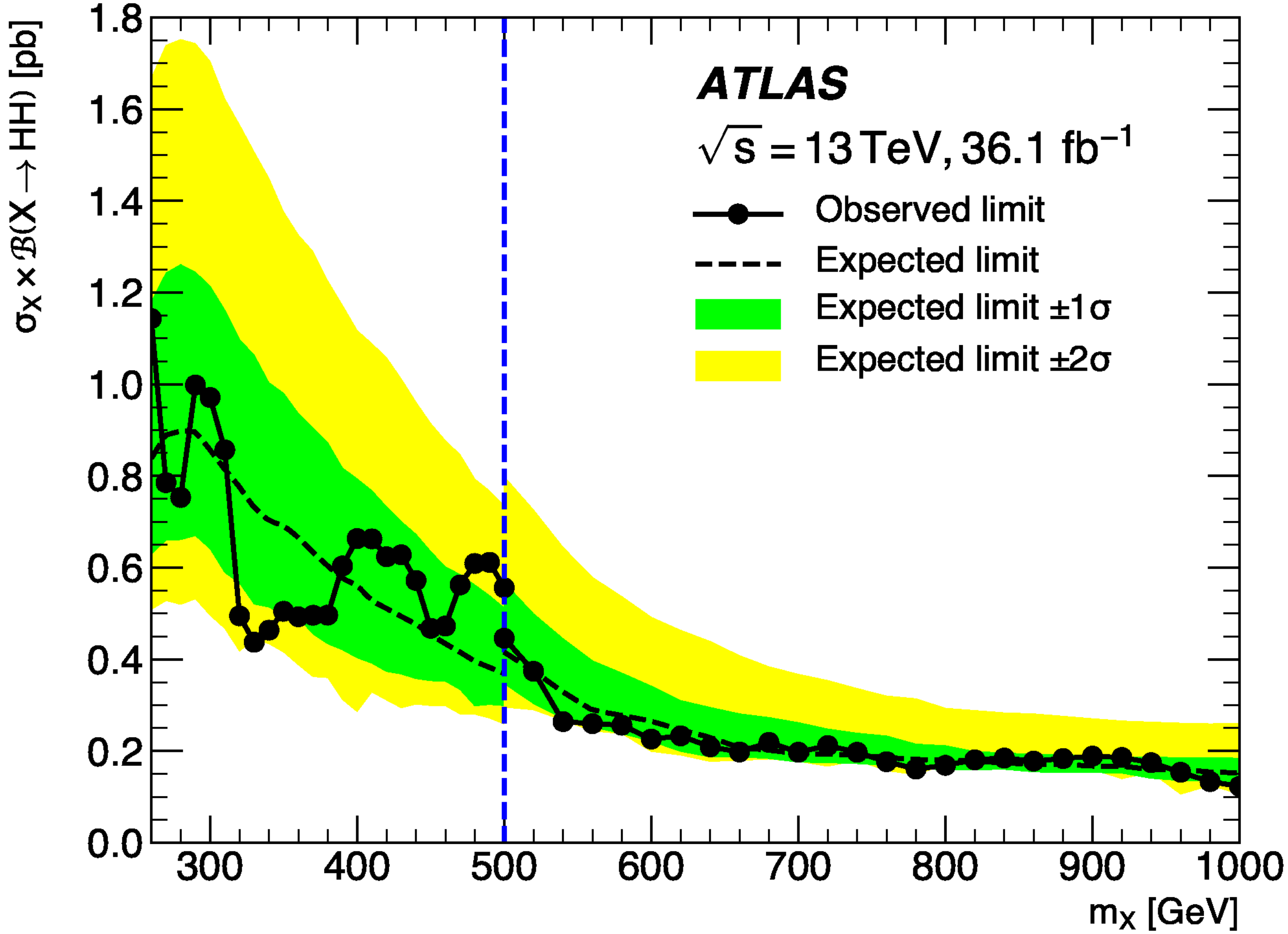
	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\to HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

- Selection efficiency parameterised as a function of κ_λ for the interpretation.
- κ_λ is observed (expected) to be constrained at 95% CL to $-8.2 < \kappa_\lambda < 13.2$ ($-8.3 < \kappa_\lambda < 13.2$).



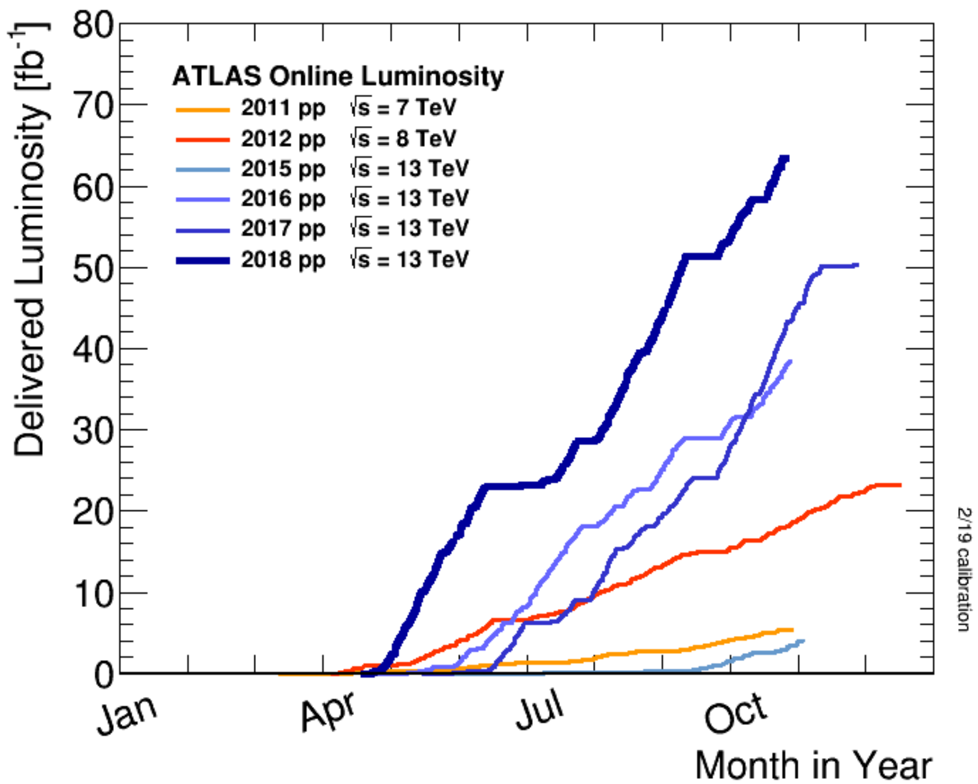
Results (resonant)

- Largest deviation from the background only hypothesis is 480 GeV (local significance of 1.2 σ). No significant excesses observed
- Observed limits vary from 1.1 pb at M_X = 260 GeV to 0.12 pb at M_X = 1 TeV.



Summary

- ATLAS has performed a search for HH in the bbγγ final state.
- No significant excesses observed in either the non-resonant or resonant search.
- Limits set in the non-resonant search:
  $\sigma_{HH} = 22 * \sigma_{SM}$
  Higgs boson self-coupling constrained to be in the interval $-8.2 < \kappa_{\lambda} < 13.2$
- Limits in the resonant search range between 1.1 pb to 0.12 pb for $260 < M_X < 1000$ GeV
- Looking forward, ATLAS has now collected ~ 140 fb^{-1} of data.
  HH → bbγγ is statistically limited so can expect large sensitivity increase with the full Run 2 data set.



Back-up

Systematic uncertainties

- Analysis is almost entirely statistically limited.
- The largest systematic uncertainties are:
  conservative 100% theory uncertainty on ggF + Heavy Flavour production.
  Photon ID, JES/JER and flavour tagging.

Source of systematic uncertainty		% effect relative to nominal in the 2-tag (1-tag) category: Non-resonant analysis				Resonant analysis: BSM HH			
		SM HH signal		Single-H bkg		Loose selection		Tight selection	
Luminosity		±2.1	(±2.1)	±2.1	(± 2.1)	±2.1	(±2.1)	±2.1	(±2.1)
Trigger		±0.4	(±0.4)	±0.4	(± 0.4)	±0.4	(±0.4)	±0.4	(±0.4)
Pile-up modelling		±3.2	(±1.3)	±2.0	(± 0.8)	±4.0	(±4.2)	±4.0	(±3.8)
Photon	identification	±2.5	(±2.4)	±1.7	(± 1.8)	±2.6	(±2.6)	±2.5	(±2.5)
	isolation	±0.8	(±0.8)	±0.8	(± 0.8)	±0.8	(±0.8)	±0.9	(±0.9)
	energy resolution	-		-		±1.0	(±1.3)	±1.8	(±1.2)
	energy scale	-		-		±0.9	(±3.0)	±0.9	(±2.4)
Jet	energy resolution	±1.5	(±2.2)	±2.9	(± 6.4)	±7.5	(±8.5)	±6.4	(±6.4)
	energy scale	±2.9	(±2.7)	±7.8	(± 5.6)	±3.0	(±3.3)	±2.3	(±3.4)
Flavour tagging	b-jets	±2.4	(±2.5)	±2.3	(± 1.4)	±3.4	(±2.6)	±2.5	(±2.6)
	c-jets	±0.1	(±1.0)	±1.8	(±11.6)	-		-	
	light-jets	<0.1	(±5.0)	±1.6	(± 2.2)	-		-	
Theory	PDF+α_S	±2.3	(±2.3)	±3.1	(± 3.3)	n/a		n/a	
	Scale	+4.3	(+4.3)	+4.9	(+ 5.3)	n/a		n/a	
		−6.0	(−6.0)	+7.0	(+ 8.0)	n/a		n/a	
	EFT	±5.0	(±5.0)	n/a		n/a		n/a	

HH Combination

- ATLAS HH Combination sets an upper limit on the SM HH cross section of 6.9 * SM (10.0 * SM expected) and constrains the Higgs boson self-coupling to $-5.0 < \kappa_\lambda < 12.0$.
- At present, $HH \rightarrow bb\gamma\gamma$ is the 3rd most sensitive channel to SM HH production and the most sensitive channel for large BSM κ_λ modifications.
- $HH \rightarrow bb\gamma\gamma$ with the best sensitivity to resonant masses less than 350 GeV.