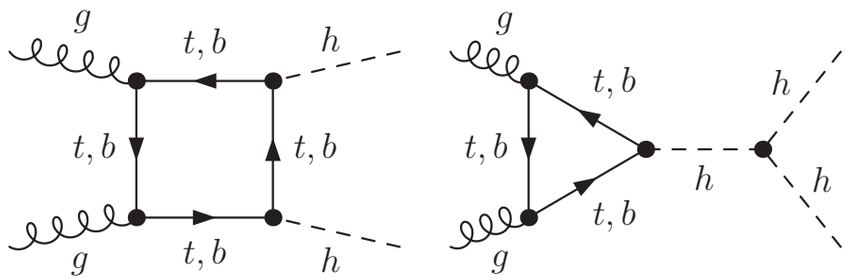
Search for di-Higgs Production with the ATLAS detector

Tülin Varol
Southern Methodist University
on behalf of the ATLAS Collaboration

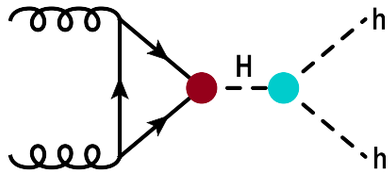
ICHEP2016, Chicago
August 3-10, 2016

Higgs Pair Production

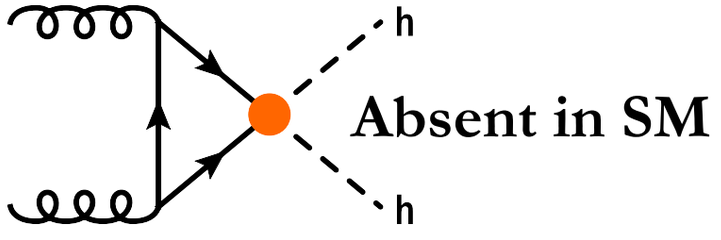
- **SM hh Production:**
  - Extremely small SM expectation due to destructive interference among diagrams
  - The SM hh cross-section at $\sqrt{s}$ =13 TeV is 37.9 fb (calculated at NNLO)
  - Important for measuring the Higgs self-coupling



- **BSM hh Production** - hh production significantly enhanced in many BSM models
  - **Resonant enhancements**



    - KK-graviton G^*_{KK} predicted in the bulk Randall-Sundrum model
    - 2HDM (i.e: The heavy neutral scalar H of two-Higgs-doublet models)…
  - **Non-resonant enhancements**
    - Activating tthh vertex, altering λ_{hhh}, etc..



Higgs Pair Searches with the ATLAS Detector

- ***In Run-II with 2015 and 2016 datasets (13.3 fb^{-1} of 13 TeV data)***
  - ***hh→bbbb (ATLAS-CONF-2016-049)***
  - ***hh→γγWW* (ATLAS-CONF-2016-071)***

- ***In Run-II only with 2015 dataset (3.2 fb^{-1} of 13 TeV data)***
  - ***hh→bbγγ (ATLAS-CONF-2016-004)***
  - ***hh→bbbb (ATLAS-CONF-2016-017)***

- ***In Run-I (20.3 fb^{-1} of 8 TeV data)***
  - ***hh→bbbb***
  - ***hh→bbγγ***
  - ***hh→bbττ***
  - ***hh→γγWW****

→ **Combined Analysis from Run-I**
arXiv:1509.04670v2

hh→bbbb Resolved Analysis

- *Large h→bb branching fraction*
- *High statistics control regions*
- *Suffers from large multi-jet background*

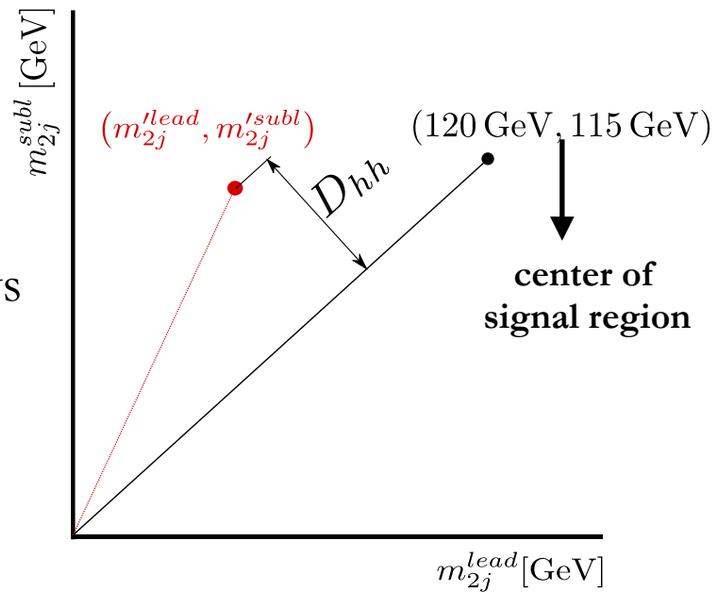
ATLAS-CONF-2016-049

- **Four anti-kt jets with R=0.4 selected**
  - Each b-tagged (70% working point),
  - With $p_T > 30$ GeV and $|\eta| < 2.5$

RESOLVED ANALYSIS

- *Optimised for non-resonant or low-mass hh systems*
- *Resolve all decay products*

- **Forming di-jets with selected jets**
  - Three possible ways to build two Higgs candidates out of the four jets
  - m_{4j}-dependent requirements applied on the Higgs candidate $\Delta R(j, j)$
  - Minimising the distance D_{hh}
  - (120 GeV, 115 GeV) - account for energy losses through semi-leptonic decays
    - Correspond to the median values of the narrowest intervals that contain 90% of the signal in simulation



- **Mass dependent cuts as a function of m_{4j} applied on the three variables**; Leading and sub-leading Higgs candidate p_T & $|\Delta\eta_{hh}|$

$$D_{hh} = \sqrt{\left(m_{2j}^{lead}\right)^2 + \left(m_{2j}^{subl}\right)^2}\left|\sin\left(\tan^{-1}\left(\frac{m_{2j}^{subl}}{m_{2j}^{lead}}\right) - \tan^{-1}\left(\frac{115}{120}\right)\right)\right|$$

- **Vetoing events with $\Delta R(h,h) < 1.5$**

hh→bbbb Resolved Analysis

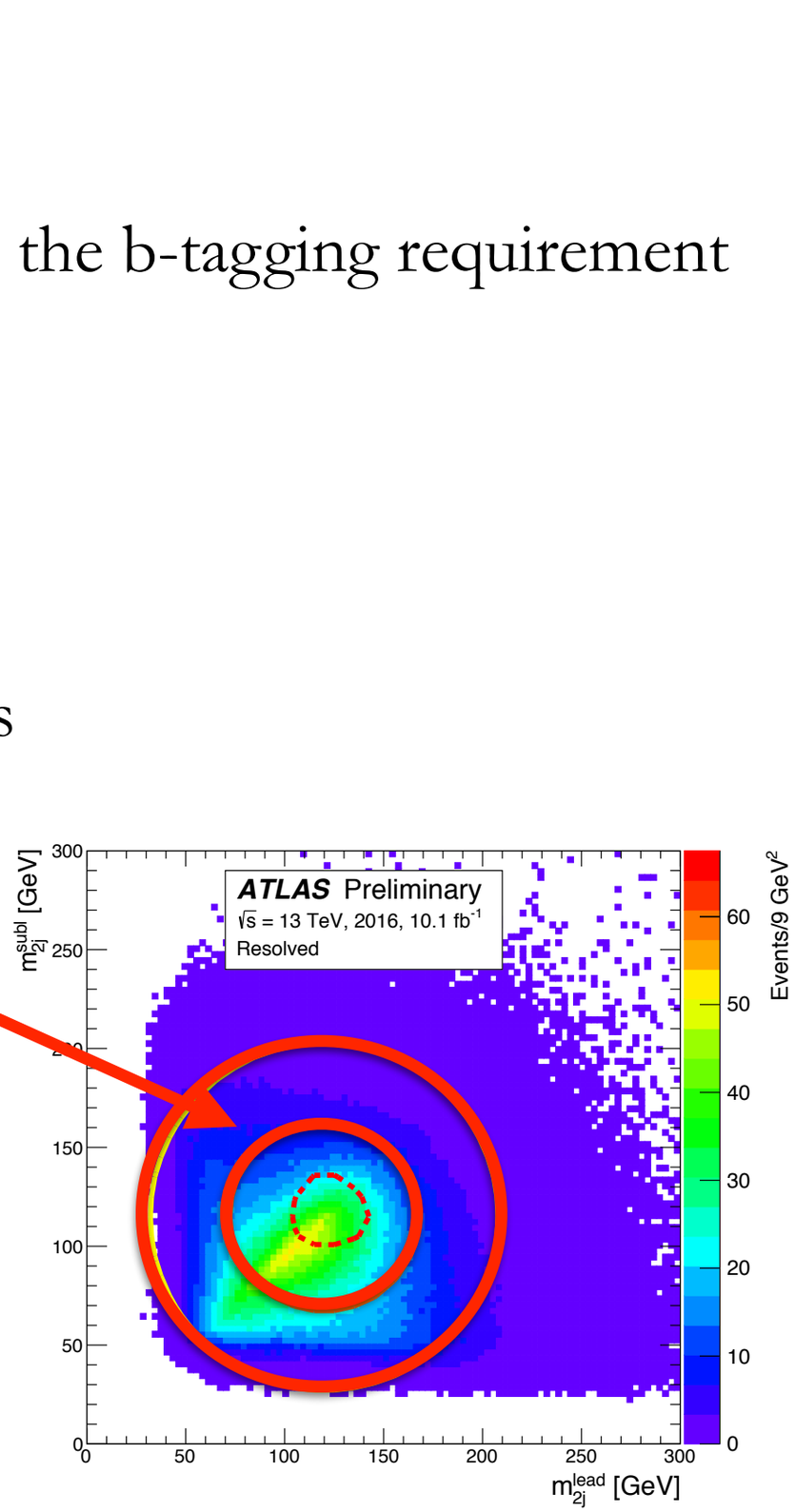
- **Backgrounds:**
  - 98% QCD multijet (data-driven)
    - **2-tag selection used:** Exactly two jets must pass the b-tagging requirement
  - 2% ttbar (taken from MC simulation)

hh→bbbb Resolved Analysis

- **Backgrounds:**
  - 98% QCD multijet (data-driven)
    - **2-tag selection used:** Exactly two jets must pass the b-tagging requirement
  - 2% ttbar (taken from MC simulation)

- **Side-Band Region**
  - Used to extrapolate to 4-tag SR by using 2-tag events

$$\mu_{\text{multijet}} = \frac{N^{\text{4-tag}}_{\text{Multijet}}}{N^{\text{2-tag}}_{\text{Multijet}}} = \frac{N^{\text{4-tag}}_{\text{data}} - N^{\text{4-tag}}_{t\bar{t}}}{N^{\text{2-tag}}_{\text{data}} - N^{\text{2-tag}}_{t\bar{t}}},$$

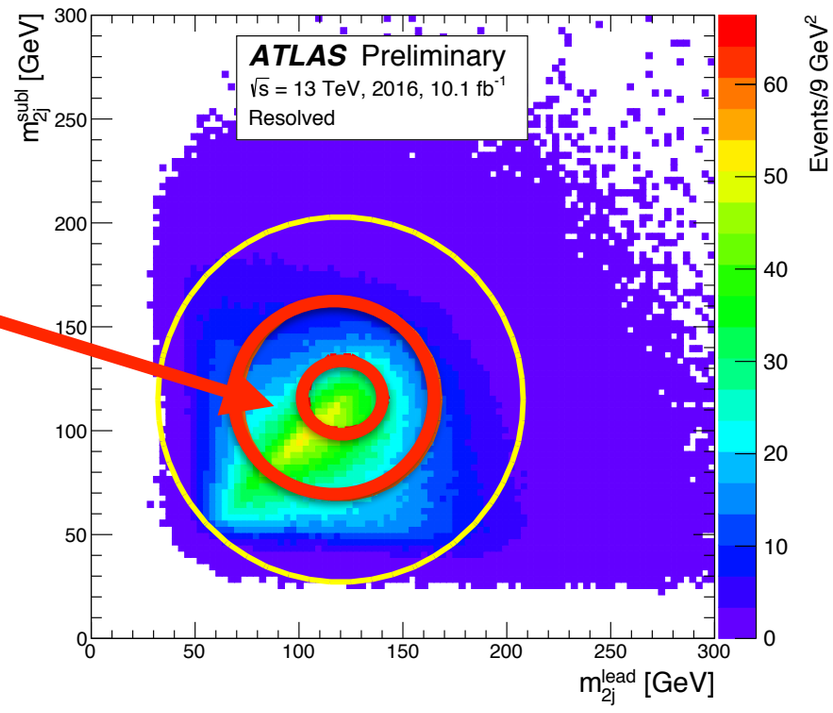


hh→bbbb Resolved Analysis

- **Backgrounds:**
  - 98% QCD multijet (data-driven)
    - **2-tag selection used:** Exactly two jets must pass the b-tagging requirement
  - 2% ttbar (taken from MC simulation)

- **Side-Band Region**
  - Used to extrapolate to 4-tag SR by using 2-tag events

- **Control Region**
  - Verify the QCD modelling
  - Assess systematics

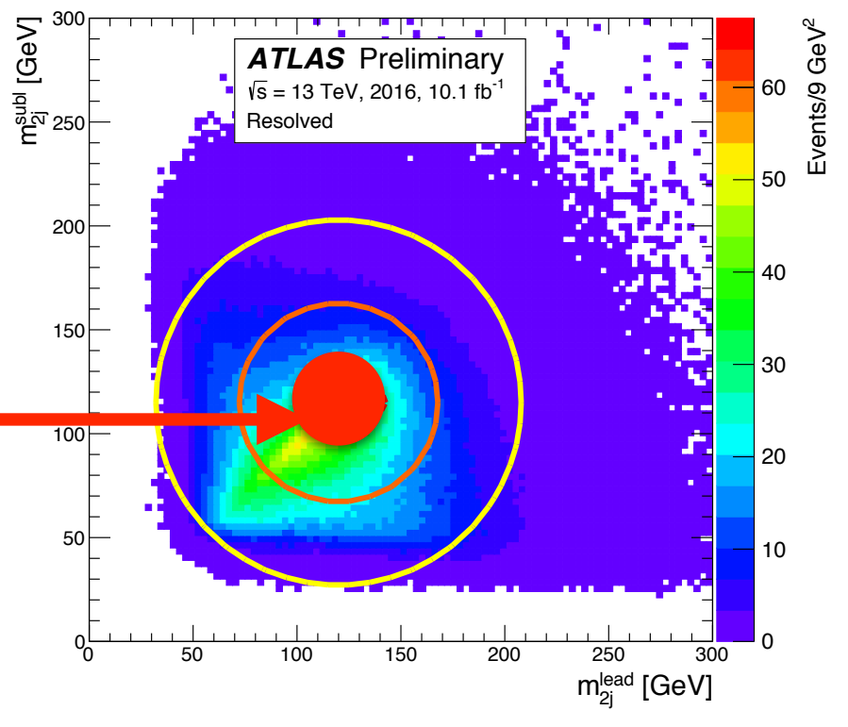


hh→bbbb Resolved Analysis

- **Backgrounds:**
  - 98% QCD multijet (data-driven)
    - **2-tag selection used:** Exactly two jets must pass the b-tagging requirement
  - 2% ttbar (taken from MC simulation)

- **Side-Band Region**
  - Used to extrapolate to 4-tag SR by using 2-tag events
- **Control Region**
  - Verify the QCD modelling
  - Assess systematics
- **Signal Region**
  - Final prediction

$$X_{hh} = \sqrt{\left(\frac{m_{2j}^{lead} - 120\ GeV}{0.1 m_{2j}^{lead}}\right)^2 + \left(\frac{m_{2j}^{subl} - 115\ GeV}{0.1 m_{2j}^{subl}}\right)^2} < 1.6$$



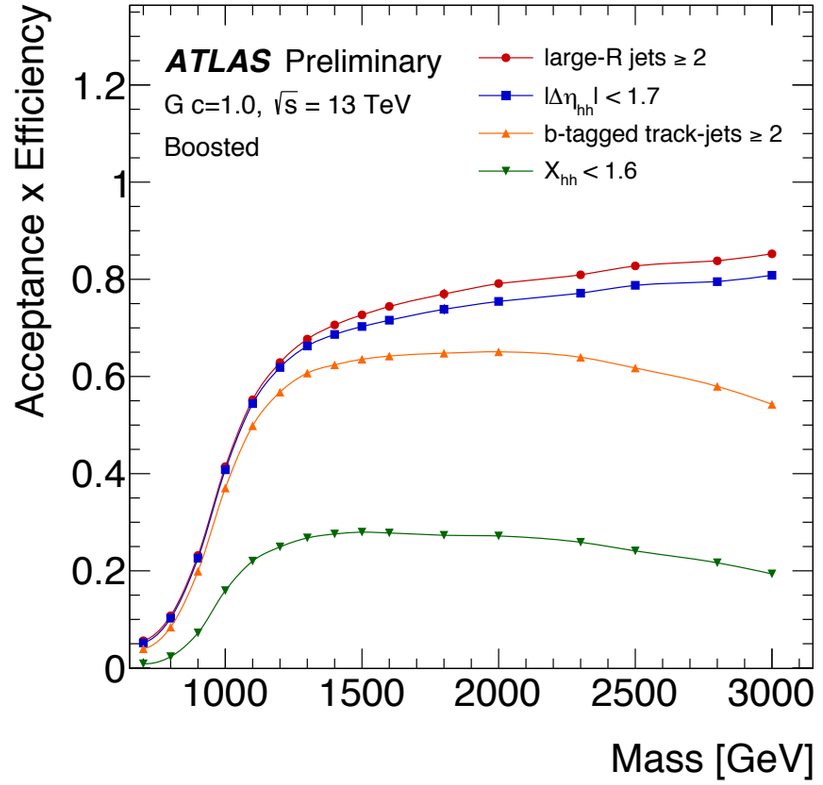
hh→bbbb Boosted Analysis

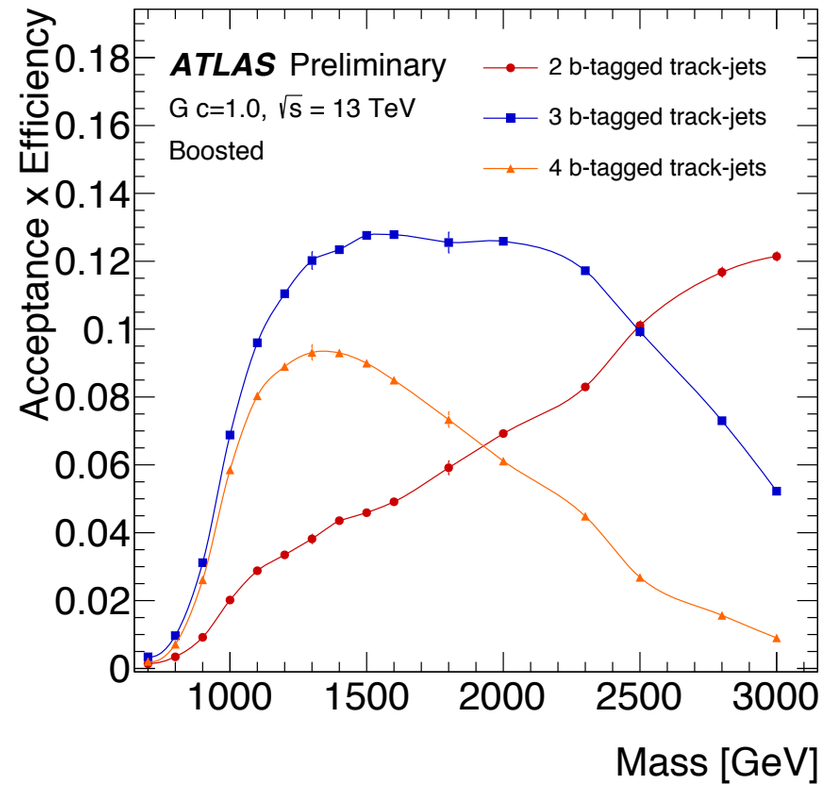
BOOSTED ANALYSIS

- ***Optimised for higher mass resonant hh systems characterised by higher-momentum Higgs bosons***
- ***The two b-jets cannot be resolved due to the high boost***
- ***Apply substructure techniques***

- **At least two anti-kt jets with R=1.0**
  - With $p_T > 250$ GeV, $|\eta| < 2.0$ and mass $m_J > 50$ GeV
  - $p_{T(lead\_J)} > 450$ GeV
  - $|\Delta\eta(J, J)| < 1.7$
- **At least one track jet (R=0.2) associated to the large jet**
  - b-tagged (77% working point) with $p_T > 10$ GeV and $|\eta| < 2.5$

- **Two-tag-split sample** - if exactly one such track jet associated to each Higgs candidate
- **Three-tag sample** - if one such track jet associated to one Higgs candidate and two track jets associated to the other Higgs candidate
- **Four-tag sample** - if two such track jets associated to each Higgs candidate





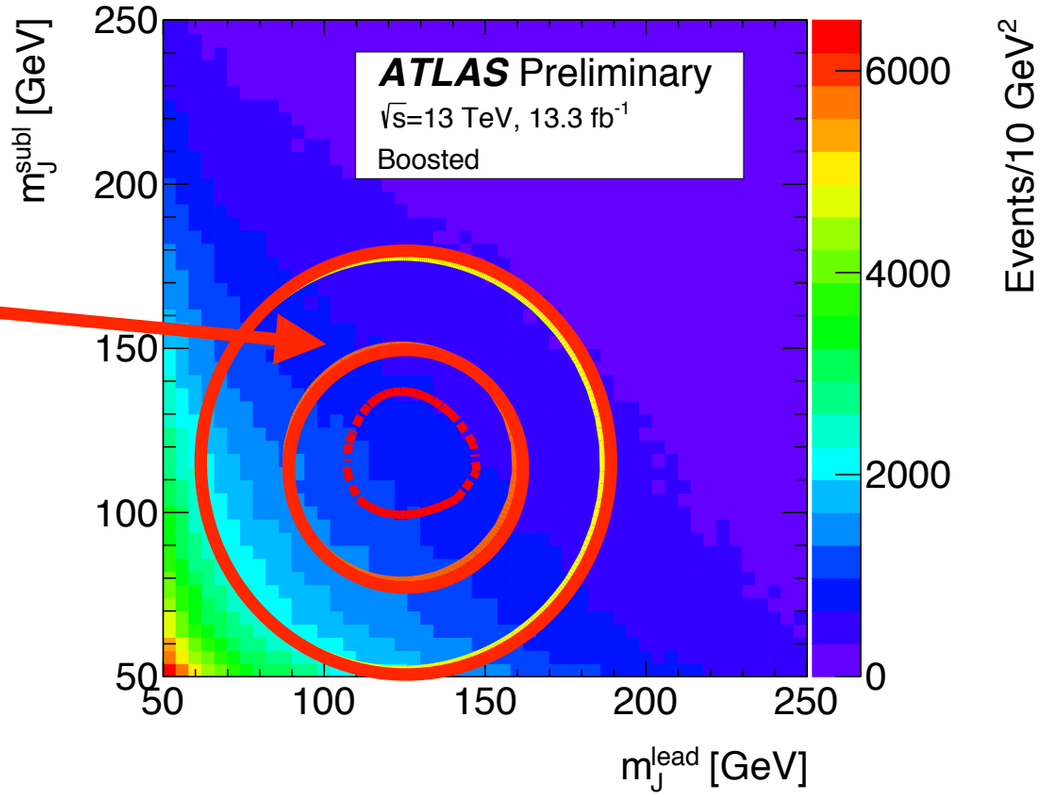
hh→bbbb Boosted Analysis

- **Backgrounds:**
  - 83-87% QCD multijet (data-driven, 0-tag selection (no associated b-tagged track jets) used)
  - Remainder from ttbar (data-driven, the m_{2J} shape from MC simulation)

hh→bbbb Boosted Analysis

- **Backgrounds:**
  - 83-87% QCD multijet (data-driven, 0-tag selection (no associated b-tagged track jets) used)
  - Remainder from ttbar (data-driven, the m_{2J} shape from MC simulation)

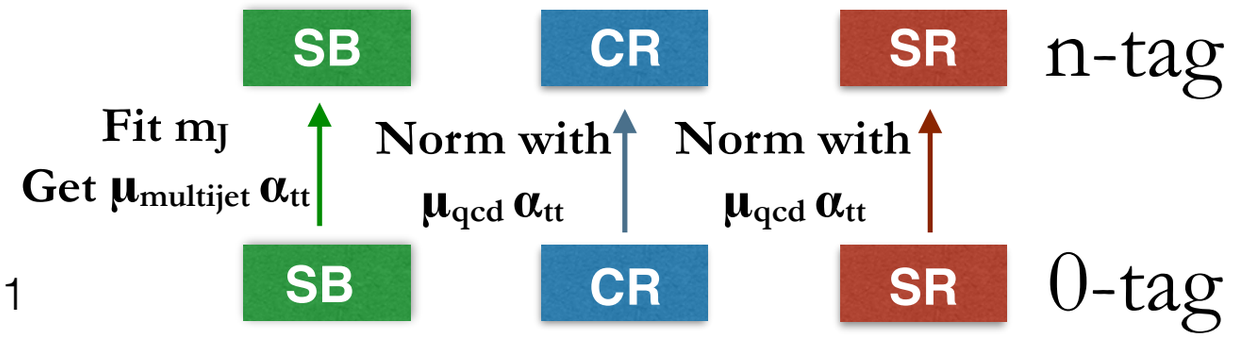
- **Side-Band Region**
  - Derive the normalisation of the multijet and ttbar background



$$N_{\text{bckgrd}}^{n-\text{tag}} = \mu_{\text{multijet}}^{n-\text{tag}} N_{\text{multijet}}^{0-\text{tag}} + \alpha_{t\bar{t}}^{n-\text{tag}} N_{t\bar{t}}^{n-\text{tag}}$$

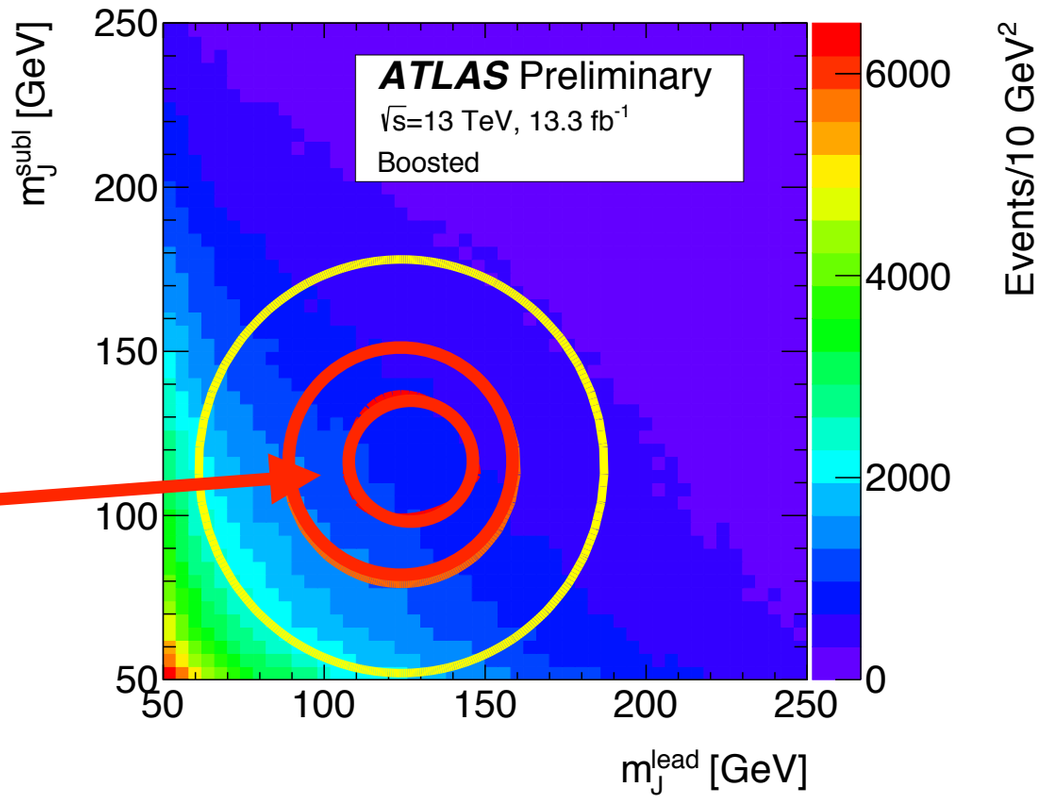
ratio of n-tag to 0-tag multijet event yields

a scale factor to correct the ttbar event yield estimated from the MC simulation



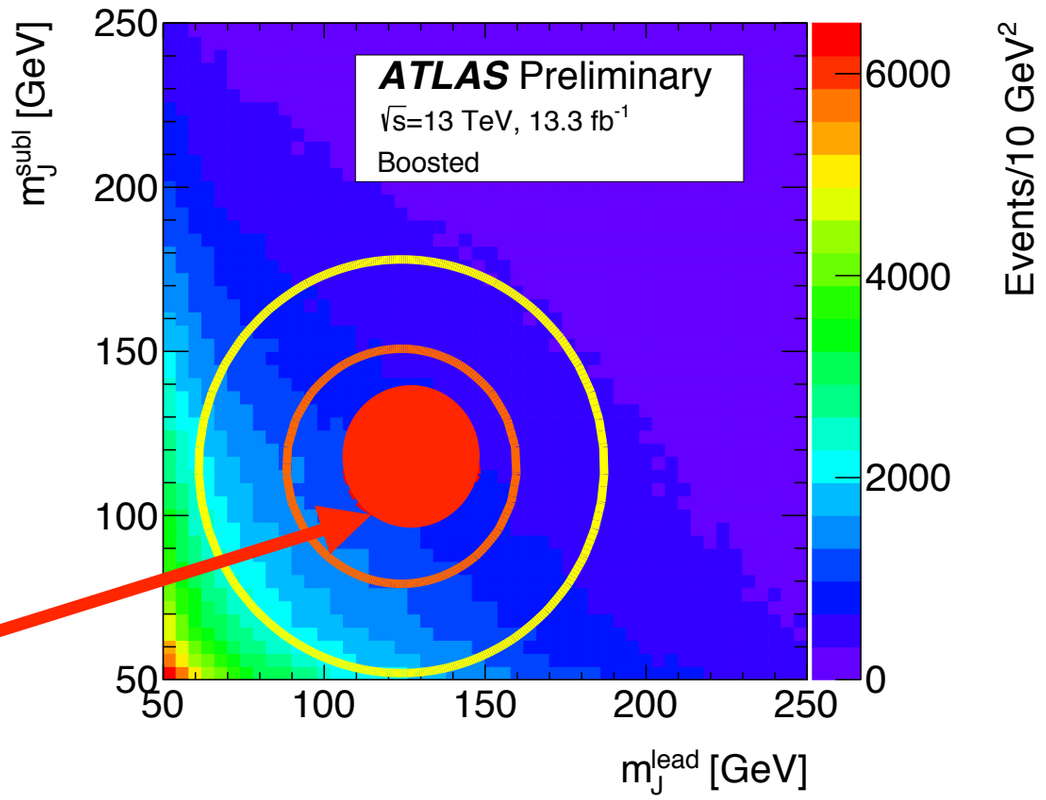
hh→bbbb Boosted Analysis

- **Backgrounds:**
  - 83-87% QCD multijet (data-driven, 0-tag selection (no associated b-tagged track jets) used)
  - Remainder from ttbar (data-driven, the m_{2J} shape from MC simulation)
- **Side-Band Region**
  - Derive the normalisation of the multijet and ttbar background
- **Control Region**
  - Verify the background models
  - Assign systematic uncertainties



hh→bbbb Boosted Analysis

- **Backgrounds:**
  - 83-87% QCD multijet (data-driven, 0-tag selection (no associated b-tagged track jets) used)
  - Remainder from ttbar (data-driven, the m_{2J} shape from MC simulation)
- **Side-Band Region:**
  - Derive the normalisation of the multijet and ttbar background
- **Control Region**
  - Verify the background models
  - Assign systematic uncertainties
- **Signal Region**
  - Final prediction



$$X_{hh} = \sqrt{\left(\frac{m_{\mathrm{J}}^{\mathrm{lead}} - 124\ \mathrm{GeV}}{0.1 m_{\mathrm{J}}^{\mathrm{lead}}}\right)^2 + \left(\frac{m_{\mathrm{J}}^{\mathrm{subl}} - 115\ \mathrm{GeV}}{0.1 m_{\mathrm{J}}^{\mathrm{subl}}}\right)^2} < 1.6$$

hh→bbbb Analysis: Combined Results

RESOLVED

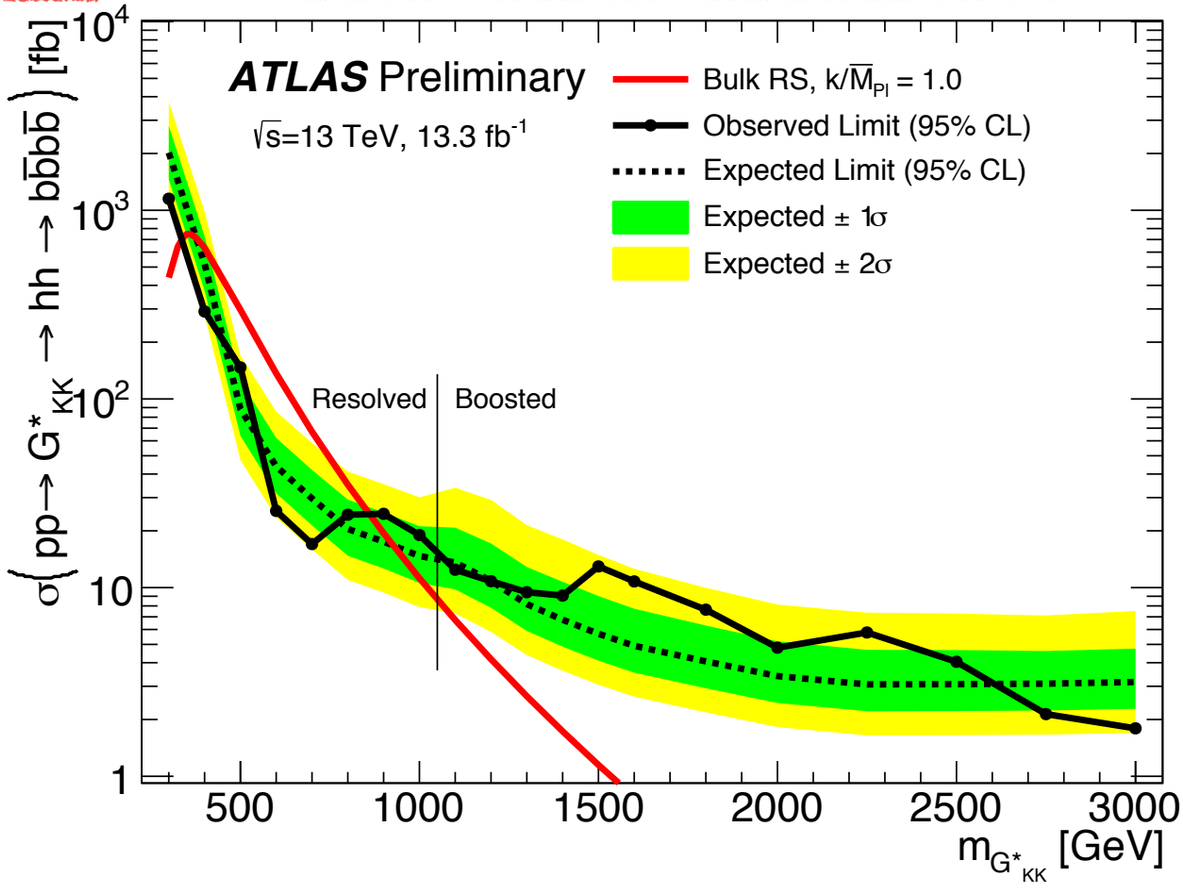
Sample	2015 Signal Region	2016 Signal Region
Multijet	1 131 ± 68	3 670 ± 200
$t\bar{t}$	57 ± 34	190 ± 110
Total	1 189 ± 76	3 860 ± 230
Data	1 231	3 990
SM hh	0.47 ± 0.12	1.5 ± 0.4
G^*_{KK} (800 GeV), $k/\bar{M}_{Pl} = 1$	8 ± 3	24 ± 8

BOOSTED

Sample	2-tag-split	3-tag	4-tag
Multijet	2 310 ± 240	515 ± 41	32.6 ± 7.6
$t\bar{t}$	460 ± 170	81 ± 37	5.7 ± 5.2
Total	2 770 ± 130	596 ± 39	38.3 ± 9.0
Data	2 813	671	32
G^*_{KK} (2 TeV), $k/\bar{M}_{Pl} = 1$	0.17 ± 0.10	0.31 ± 0.06	0.15 ± 0.06

Non-resonant Search:
Only in resolved analysis
$\sigma(pp\to hh\to bbbb) <$ 330 fb
(SM prediction = 11.3 fb)

Resonant Search:
In resolved & boosted analyses for $k/M_{Pl} = 1$
Limits on $\sigma(pp\to G^*_{KK}\to hh\to bbbb)$
1000 fb at $m(G^*_{KK}) = 300$ GeV
2.0 fb at $m(G^*_{KK}) = 3000$ GeV



$hh \to \gamma\gamma WW^*$ Analysis

- **Final state $\gamma\gamma l\nu qq'$**

ATLAS-CONF-2016-071

- **Events with two photons, at least two jets and no b-jet are selected**
- **105 GeV< $m_{\gamma\gamma}$ < 160 GeV**

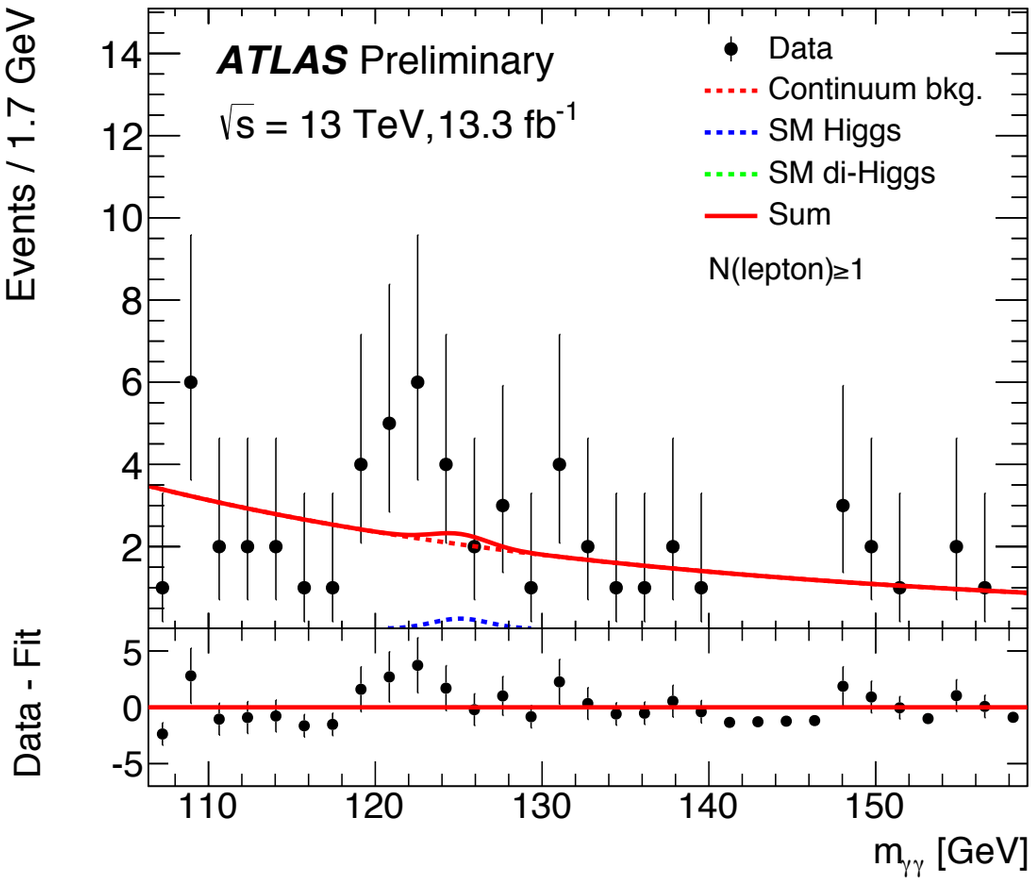
- ***Large $h \to WW$ branching fraction***
- ***Clean signature from $h \to \gamma\gamma$***

- **Signal Region:**
  - One lepton region - requiring at least one lepton
  - The diphoton mass $m_{\gamma\gamma}$ to be within a 2σ window of the Higgs boson mass ($\sigma_{\gamma\gamma}$ = 1.7 GeV)
- **Control Region**
  - Zero lepton region - requiring no lepton
- **Side-Band Region**
  - Reversing the tight mass window in either the one-lepton region or the zero-lepton region
  - Used for the data-driven estimation of the continuum diphoton background

selection efficiency of the tight mass window (13.64%)

$$N_{\mathrm{SR}}^{\mathrm{Continuum}} = N_{\mathrm{SB}}^{\mathrm{Continuum}} \times \frac{\epsilon_{\gamma\gamma}}{1-\epsilon_{\gamma\gamma}}$$

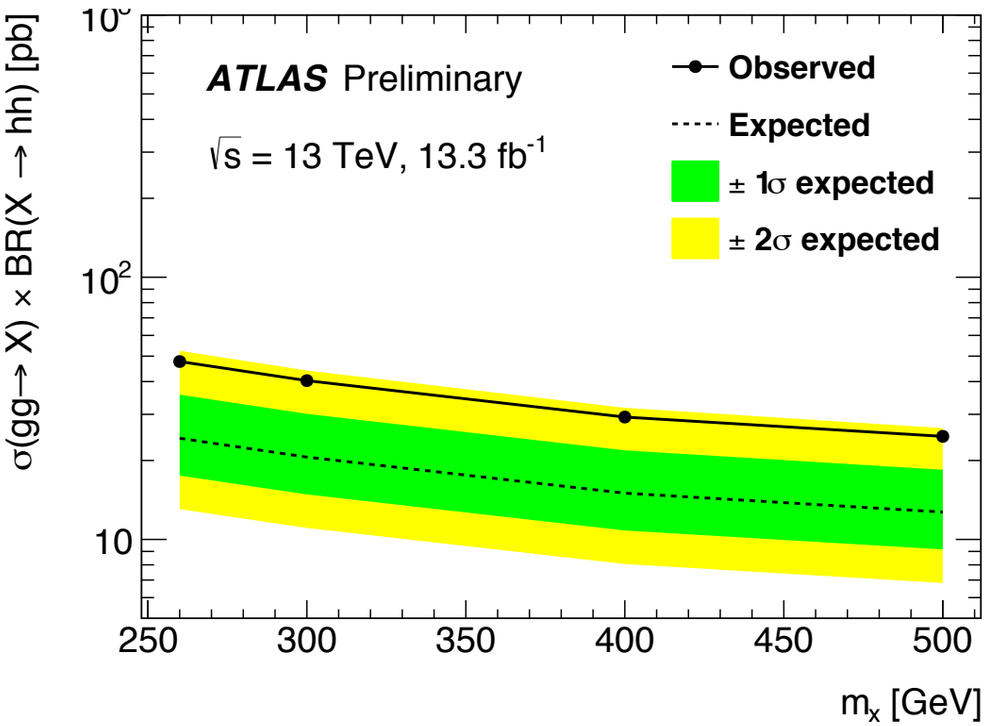
hh→γγWW* Analysis



Process	Number of events	
Continuum background	7.26	± 1.23
SM single-Higgs	0.616	± 0.115
SM di-Higgs	0.0187	± 0.00224
Observed	15	

Non-resonant Search:

σ(pp→hh) < 25.0 pb
(expected limit = 12.9 pb)



Resonant Search:

Limits on σ(pp→X→hh)
47.7 pb (expected 24.3 pb) at m_X= 260 GeV
24.7 pb (expected 12.7 pb) at m_X = 500 GeV

hh→bbγγ Analysis in Run II

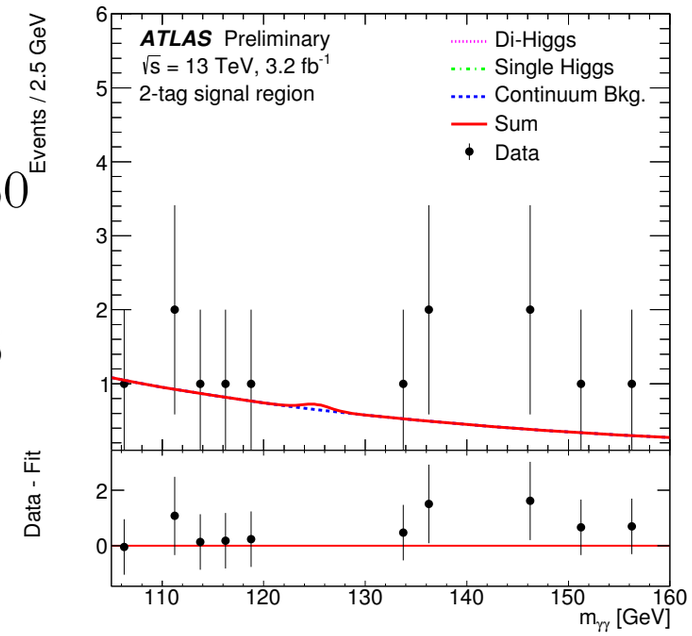
- **Event Selection:**
  - Following h→γγ analysis selection
  - Events with $105 < m_{\gamma\gamma}$ [GeV] < 160
  - 2 b-jets ($p_T > 55/35$ GeV)
  - Events with $95 < m_{bb}$ [GeV] < 135

- 2 b-tag category - **signal region**
- 0 b-tag category - **control region**

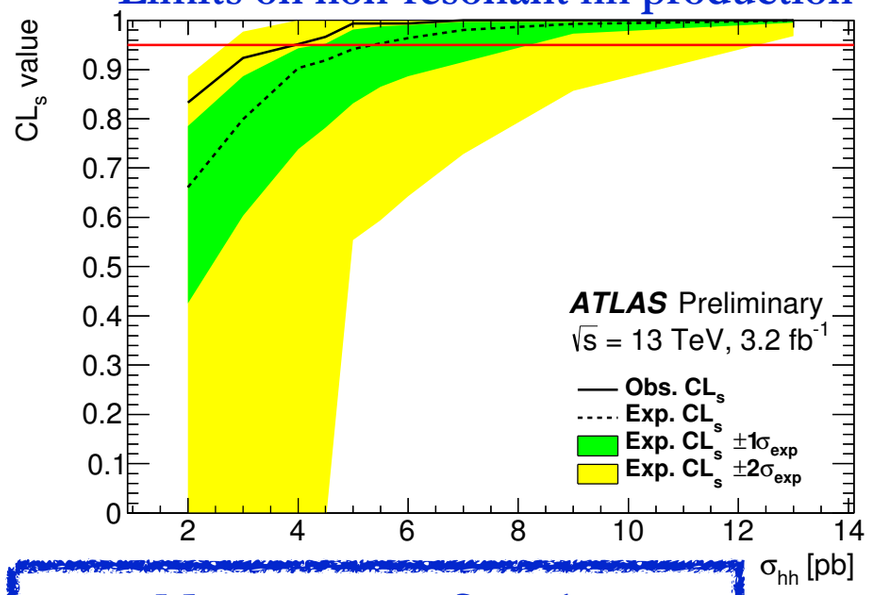
- **Non-Resonant Analysis:**
  - Simultaneous S+B fit to $m_{\gamma\gamma}$ in both SR and CR
    - $m_{\gamma\gamma}$ background fitted with exponential in CR
    - Single Higgs background and di-Higgs signal taken from MC

- **Resonant Analysis:**
  - Counting Approach
    - 2σ window cut on $m_{\gamma\gamma}$
    - Count in 95% efficiency $m_{bb\gamma\gamma}$ window
      - CR used to determine background efficiency

$$N_{SR}^{B} = N_{SB}\frac{\varepsilon_{m_{\gamma\gamma}}}{1-\varepsilon_{m_{\gamma\gamma}}}\varepsilon_{m_{b\bar{b}\gamma\gamma}}$$



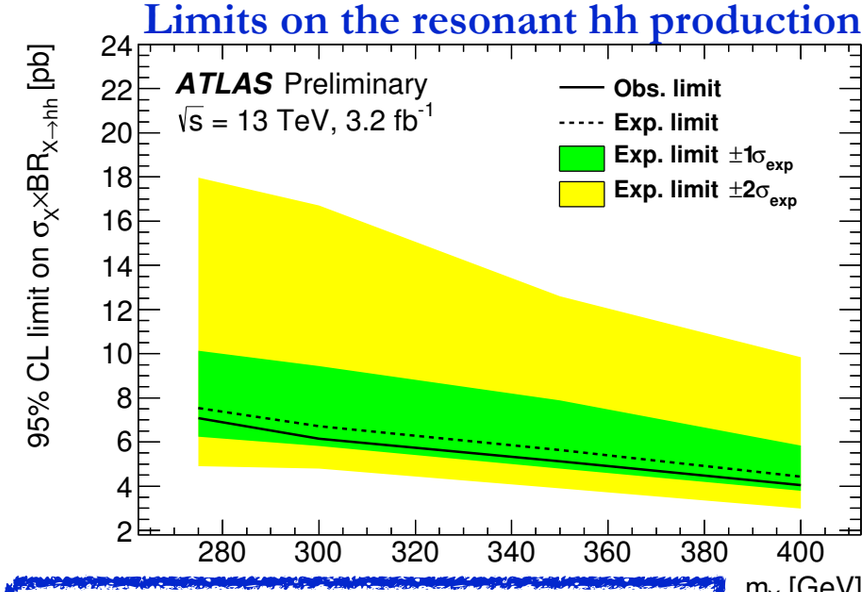
Limits on non-resonant hh production



Non-resonant Search:

σ(pp→hh) < 3.9 pb with SM BR
(expected limit = 5.4 pb)

Limits on the resonant hh production



Resonant Search:

Limits σ(pp→X→hh) with SM BR
7.0 pb at m_X = 275 GeV
4.3 pb at m_X = 400 GeV

Conclusion

- Higgs pair production searches performed in multiple final states with the ATLAS detector
- With Run-I data, **hh→bbbb, hh→bbγγ, hh→bbττ and hh→γγWW*** analyses are performed
- With Run-II data, **hh→bbbb, hh→γγWW* , hh→bbγγ** analyses are performed
- **No significant excess** observed

BACK UP

hh→bbbb Resolved Analysis: Systematic Uncertainties

	2015			2016		
Source	Background	SM hh	G^*_{KK} (800 GeV)	Background	SM hh	G^*_{KK} (800 GeV)
Luminosity	–	2.1	2.1	–	3.7	3.7
JER	–	5.7	3.3	–	5.4	3.5
JES	–	6.4	1.3	–	6.6	1.3
b-tagging	–	23	35	–	23	35
Theoretical	–	9.7	4.2	–	9.7	4.2
Multijet	5	–	–	5	–	–
$t\bar{t}$	58	–	–	58	–	–
Total	5.5	26	35	5.5	27	36

hh→bbbb Boosted Analysis: Systematic Uncertainties

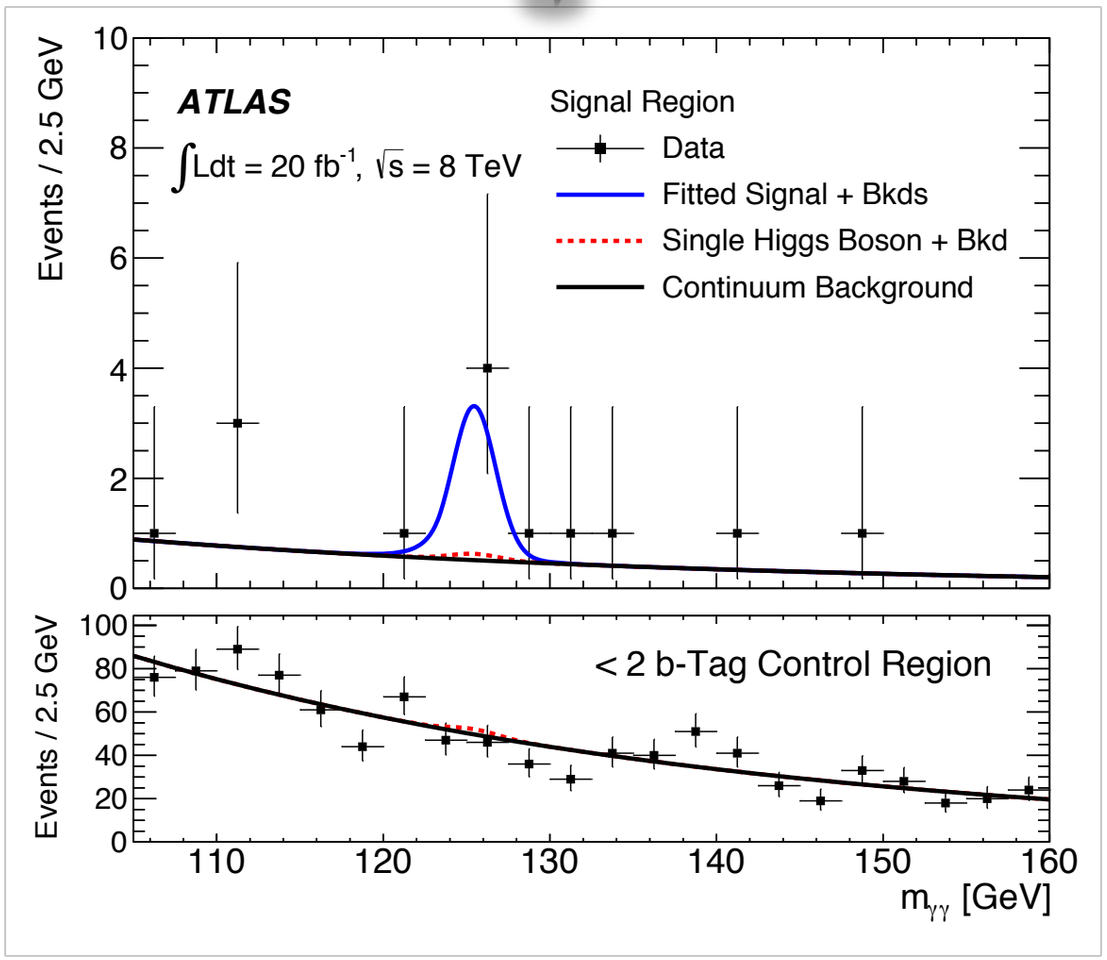
	2-tag-split		3-tag		4-tag	
Source	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)
Luminosity	-	2.9	-	2.9	-	2.9
JER	-	0.1	-	0.1	-	0.3
JMR	-	12	-	12	-	12
JES/JMS	-	4.5	-	4.2	-	3.3
b-tagging	-	58	-	15	-	38
Theoretical	-	2.7	-	2.3	-	2.4
Bkg Estimate	4.4	-	4.6	-	21	-
Statistical	0.5	1.4	1.1	1.0	1.2	1.3
$t\bar{t}$	1.6	-	4.7	-	10	-
Total Sys	4.7	59	6.6	20	24	40

hh→γγWW*: Systematic Uncertainties

Source of uncertainties		Non-resonant hh	$X \to hh$	Single-h bkg	Cont. bkg
		All numbers are in %			
Luminosity 2015+2016		2.9	2.9	2.9	-
Trigger		0.4	0.4	0.4	-
Pileup re-weighting		0.8	0.2	1.8	-
Event statistics		2.0	1.8	2.7	14.7
Photon	energy resolution	2.0	1.8	1.2	-
	energy scale	4.2	4.1	1.6	-
	identification	4.2	4.2	4.2	-
	isolation	1.0	1.0	1.1	-
Jet	energy resolution	0.8	0.2	8.0	-
	energy scale	3.5	3.5	5.2	-
b-tagging	b-jets	0.06	0.05	5.4	-
	c-jets	0.5	0.5	0.3	-
	light jets	0.4	0.4	0.4	-
	extrapolation	0.006	0.06	0.8	-
Lepton	electron	0.7	0.7	0.7	-
	muon	0.3	0.3	0.6	-
$\epsilon_{\gamma\gamma}$	lepton dependence	-	-	-	7.4
	background modelling	-	-	-	3.8
	sideband definition	-	-	-	1.2
	statistics on $\epsilon_{\gamma\gamma}$	-	-	-	1.3
Theory	PDF	(2.1)	-	2.2	-
	α_S	(2.3)	-	1.5	-
	scale	(6.0)	-	3.7	-
	HEFT	(5.0)	-	-	-
	jet multiplicity	-	-	12.5	-
	BR($h \to \gamma\gamma$)	2.1	2.1	2.1	-
	BR($h \to WW^*$)	1.5	1.5	1.5	-
Total		12.0	8.4	18.6	17.0

hh→bbγγ Analysis

- **Interesting modest excess in Run-I**
  - 20 fb^{-1} of data at $\sqrt{s}$=8 TeV used
  - Unbinned S+B fit
    - 1.5 background events expected
    - 5 events observed
    - 2.4σ from background-only hypothesis
- 95% C.L. upper limit on hh production of 2.2 pb (expected 1.0 pb)



- ***Excellent diphoton mass resolution***
- ***Relatively small background***
- ***Large h→bb branching fraction***
- ***Sensitive to lower mass resonances***

[Phys. Rev. Lett. 114, 081802 (2015)]

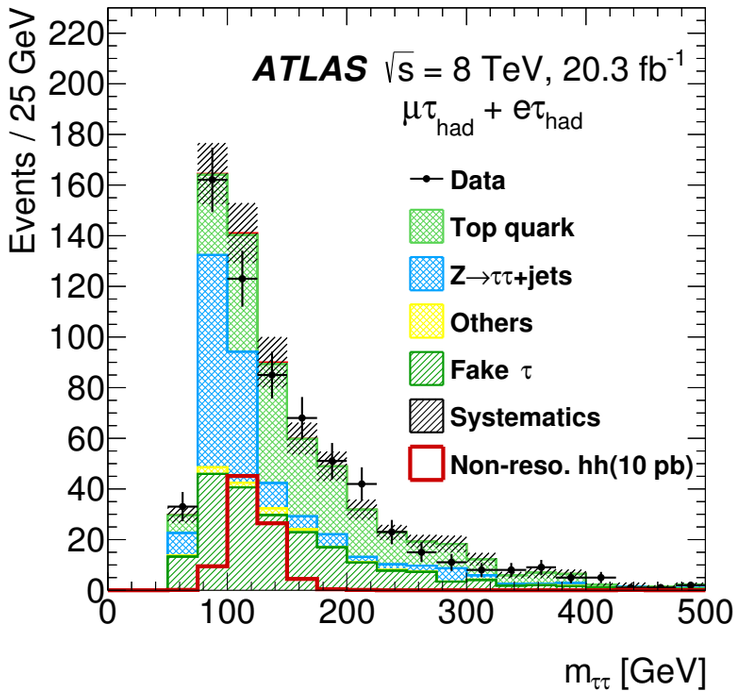
[ATLAS-CONF-2016-004]

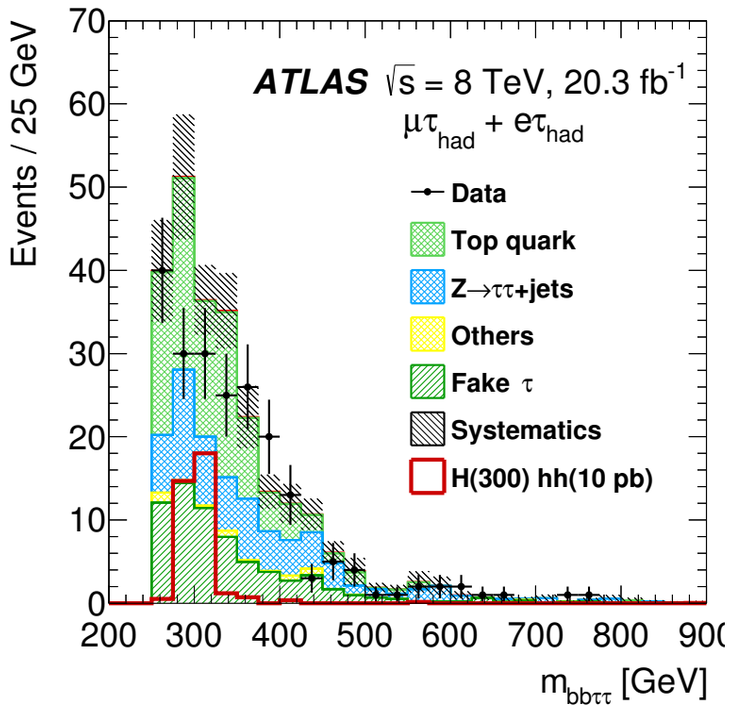
hh→bbγγ: Systematic Uncertainties

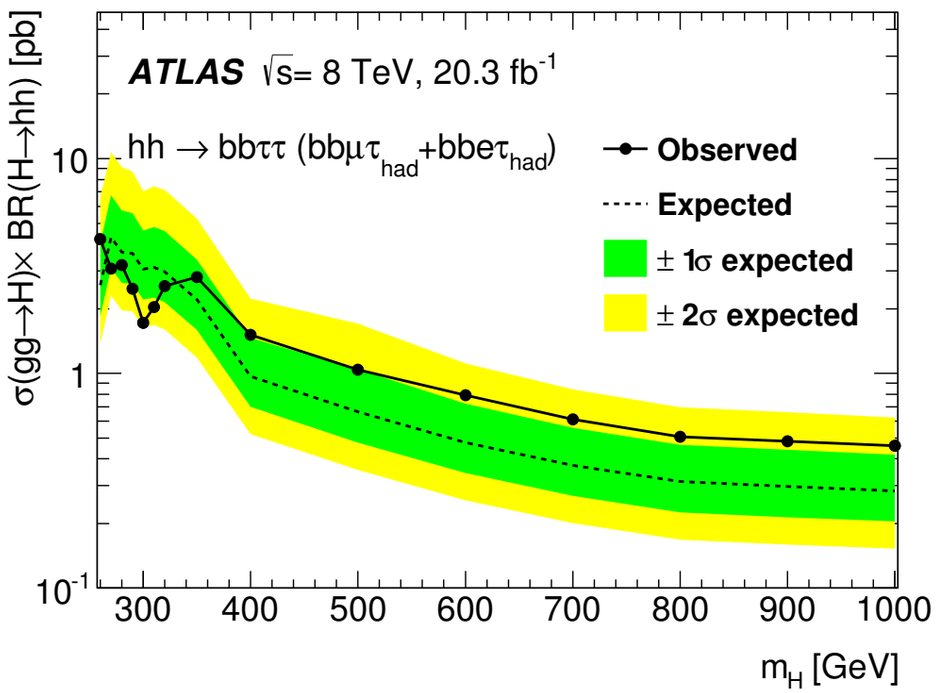
Source of systematic uncertainty		Impact in % on the search for di-Higgs production in non-resonant mode			resonant mode		
		hh signal	Single-h bkg	Cont.	$X\to hh$ signal	SM h+hh bkg	Cont.
Luminosity		±5.0	±5.0	-	±5.0	±5.0	-
Trigger		±0.4	±0.4	-	±0.4	±0.4	-
Pileup reweighting		±1.6	+2.4 / −0.4	-	±1.0	±2.3	-
Generated event statistics		±1.3	±16.8	-	±4.3	±12.6	-
Photon	energy resolution	+30 / −15	+30 / −15	-	+7.0 / −0.3	+0.0 / −3.8	-
	energy scale	±0.5	±0.5	-	+1.9 / −3.5	+2.8 / −3.0	-
	identification	±2.5	±2.5	-	±2.5	±2.5	-
	isolation	±3.4	±3.4	-	±3.9	±3.9	-
Jet	energy resolution	±2.7	±24	-	±9.1	±1.6–9.8	-
	energy scale	+1.3 / −1.1	±12	-	±12.1	±10.6	-
b-tagging	b-jets	±12.9	±10.0	-	±12.6	±12.6	-
	c-jets	±0.05	±4.1	-	±0.2	±3.0	-
	light-jets	±0.5	+3.9 / −4.6	-	±0.2	±0.5	-
	extrapolation	±5.1	±2.8	-	±5.2	±3.0	-
Shape	$m_{\gamma\gamma}$ modelling	-	-	±11	-	-	±11
	$m_{b\bar{b}\gamma\gamma}$ modelling	-	-	-	-	±25.0	±27–40
Theory	PDF+α_S	-	+6.8 / −6.6	-	-	+7.4 / −7.3	-
	Scale	-	+5.7 / −8.2	-	-	+6.9 / −10.9	-
	EFT	-	-	-	-	±5.7	-
Total		+34 / −22	+43 / −35	±11	+23 / −22	+36 / −35	±29–41

hh→bbττ in Run-I

- **One τ lepton is required to decay to e or μ, the other τ lepton decays to hadrons (τ_{had})**







- For **the non-resonant search**, the observed $m_{\tau\tau}$ distribution agrees well with that of the estimated background events: **σ(pp→hh) < 1.6 pb with SM BR (expected 1.3 pb)**
- For **the resonant search**, a small deficit with a local significance of ~2σ in the data relative to the background expectation at $m_{bb\tau\tau}$ ~300 GeV - Limits on **σ(pp→X→hh) with SM BR**
  - **4.2 pb (expected 2.6 pb) at m_X = 260 GeV**
  - **0.46 pb (expected 0.28 pb) at m_X = 1000 GeV**

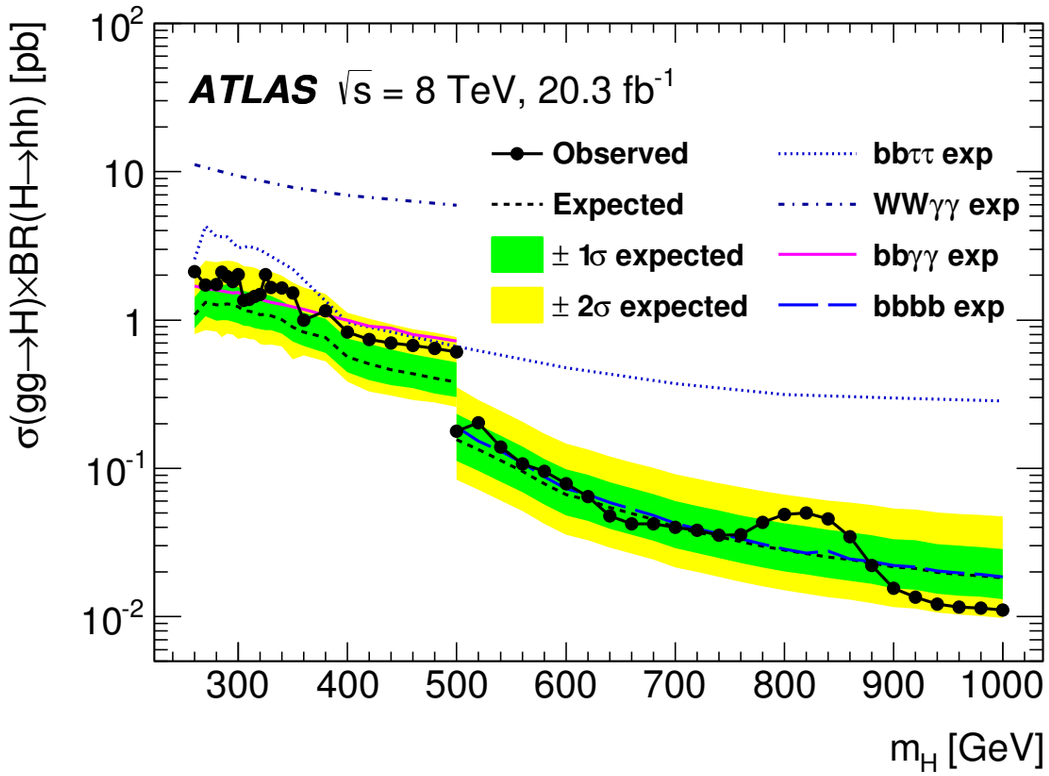
Combination of the hh Non-Resonant Analyses in Run-I

- Upper limits on the Higgs boson pair production cross section are derived **using the CLs method**
- For the combinations, **systematic uncertainties that affect two or more analyses** are modelled with **common nuisance parameters**

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

- These limits are to be compared with **the SM prediction of 9.9±1.3 fb**
- **The p-value** of compatibility of the combination with the SM hypothesis is 4.4%, equivalent to **1.7σ**

Combined Results for the Resonant Search in Run-I



m_H	Expected limit [pb]					Observed limit [pb]				
[GeV]	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
260	1.70	11.2	2.6	–	1.1	2.29	18.7	4.2	–	2.1
300	1.53	9.3	3.1	–	1.2	3.54	15.1	1.7	–	2.0
350	1.23	7.8	2.2	–	0.89	1.44	13.3	2.8	–	1.5
400	1.00	6.9	0.97	–	0.56	1.00	11.5	1.5	–	0.83
500	0.72	5.9	0.66	–	0.38	0.71	10.9	1.0	–	0.61
500	–	–	0.66	0.17	0.16	–	–	1.0	0.16	0.18
600	–	–	0.48	0.070	0.067	–	–	0.79	0.072	0.079
700	–	–	0.31	0.041	0.040	–	–	0.61	0.038	0.040
800	–	–	0.31	0.028	0.028	–	–	0.51	0.046	0.049
900	–	–	0.30	0.022	0.022	–	–	0.48	0.015	0.015
1000	–	–	0.28	0.018	0.018	–	–	0.46	0.011	0.011