SEARCHES FOR DI-HIGGS PRODUCTION WITH THE ATLAS DETECTOR.

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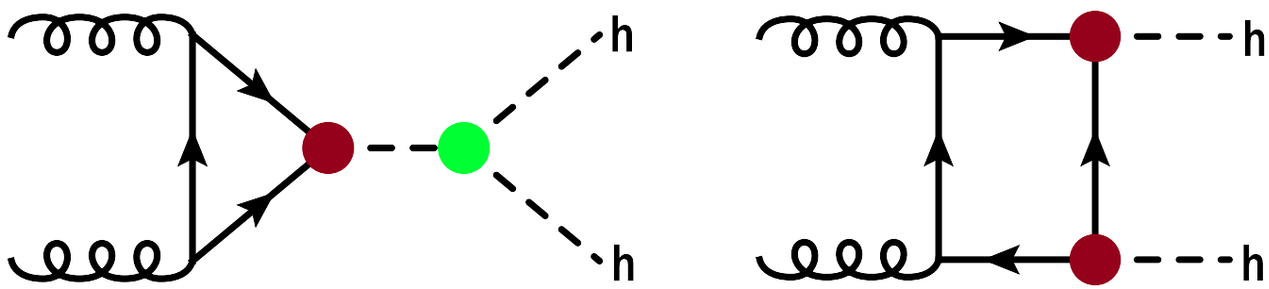
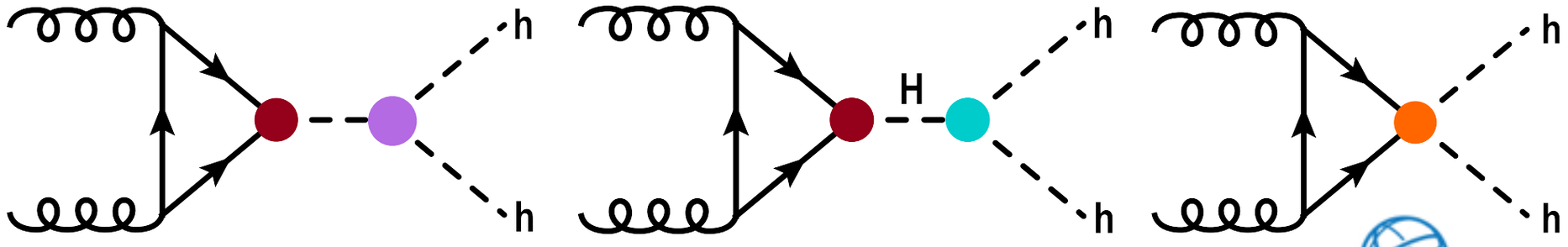
ATLAS EXPERIMENT

DI-HIGGS PRODUCTION

- **Standard Model:** small! σ(hh) = 33.41 fb @ 13 TeV
  - destructive interference between processes involving Higgs self-coupling and box-diagram with two tth vertices



- **Beyond the Standard Model:** possible enhancements?
  - enhanced self-coupling? resonant production via a heavy scalar? addition of a tthh vertex?



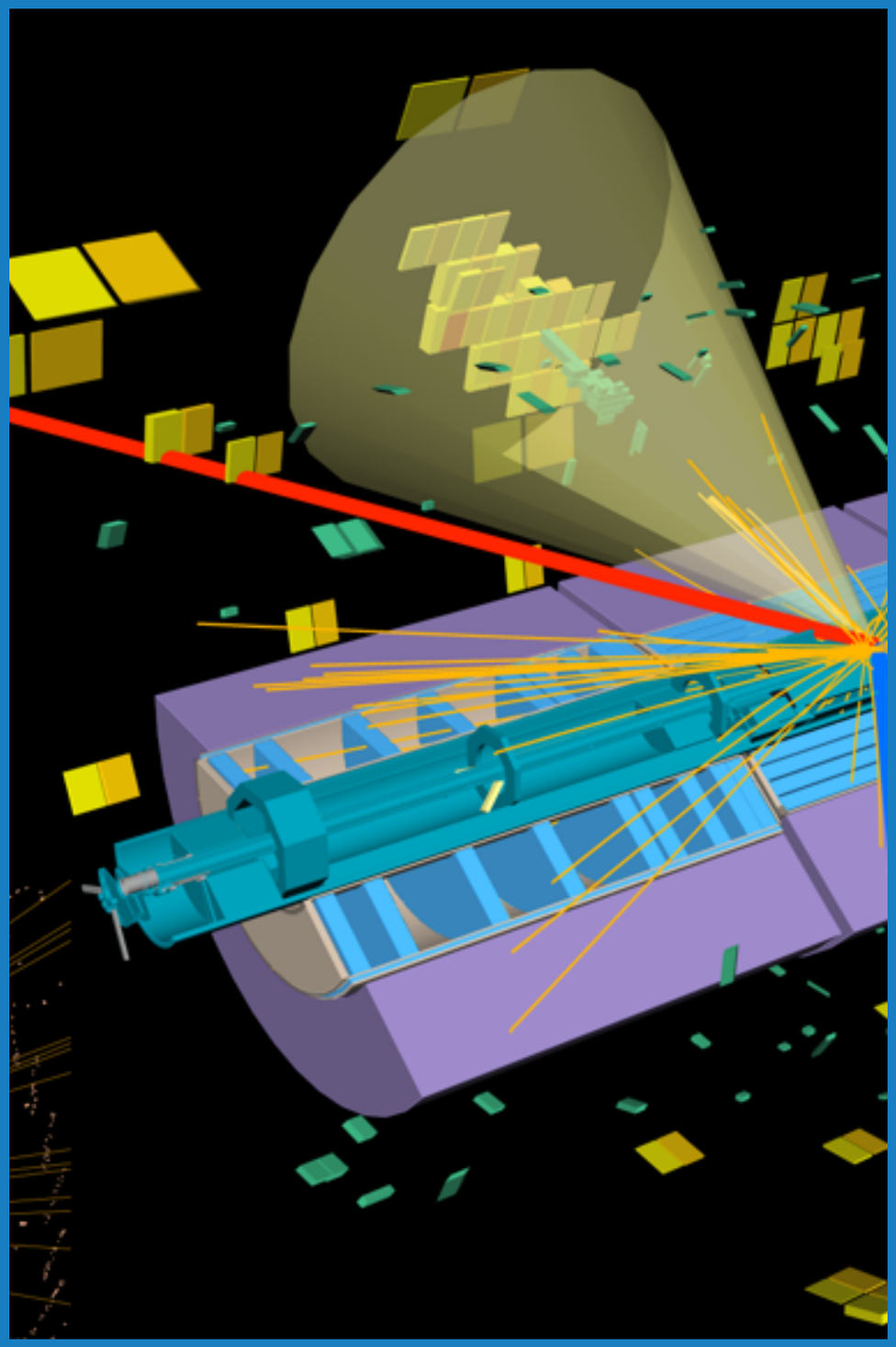
SEARCHES FOR DI-HIGGS PRODUCTION WITH ATLAS

- Run 1 combination (γγbb, γγWW, bbττ, bbbb)
- 13 TeV hh → γγWW
- 13 TeV hh → γγbb
- 13 TeV hh → bbbb
- Prospects at the HL-LHC

BR(hh → XXYY)

	bb	WW	gg	ττ	cc	ZZ	γγ	Zγ	μμ
bb	33%								
WW									
gg									
ττ	7%								
cc									
ZZ									
γγ	0.26%	0.1%							
Zγ									
μμ									

= di-Higgs channel covered by ATLAS



RUN 1 DI-HIGGS COMBINATION

ATLAS EXPERIMENT

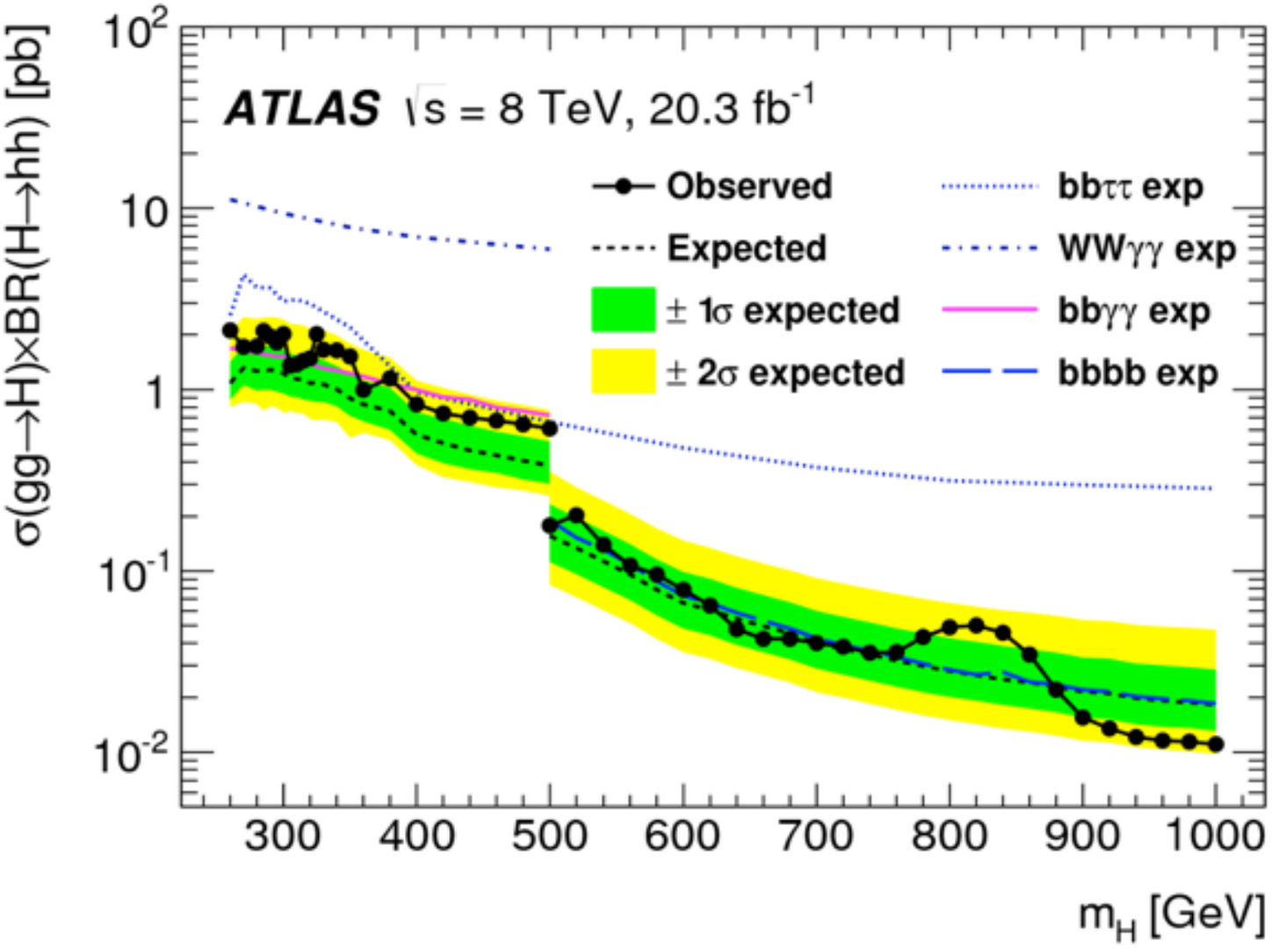
PHYS. REV. D 92, 092004 (2015)

- combination of Run 1 hh searches (γγbb, γγWW, bbττ, bbbb) in 20.3 fb^{-1} of 8 TeV data
- $\sigma(hh)_{SM}$ = 10.15 fb @ 8 TeV
- non-resonant combination:

0.69 pb (0.47 pb) observed (expected) → 70 (48) * σ/σ_{SM}

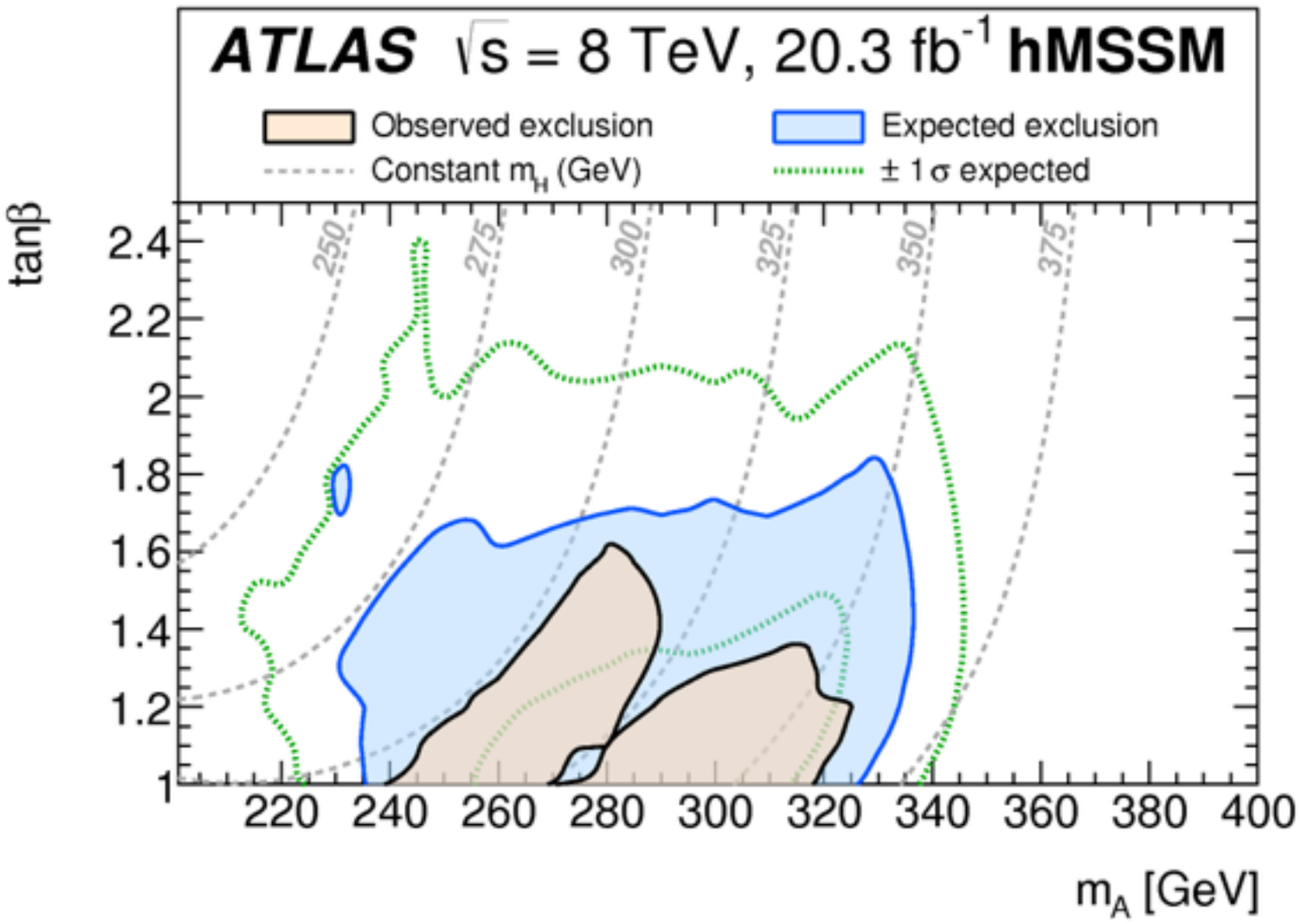
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

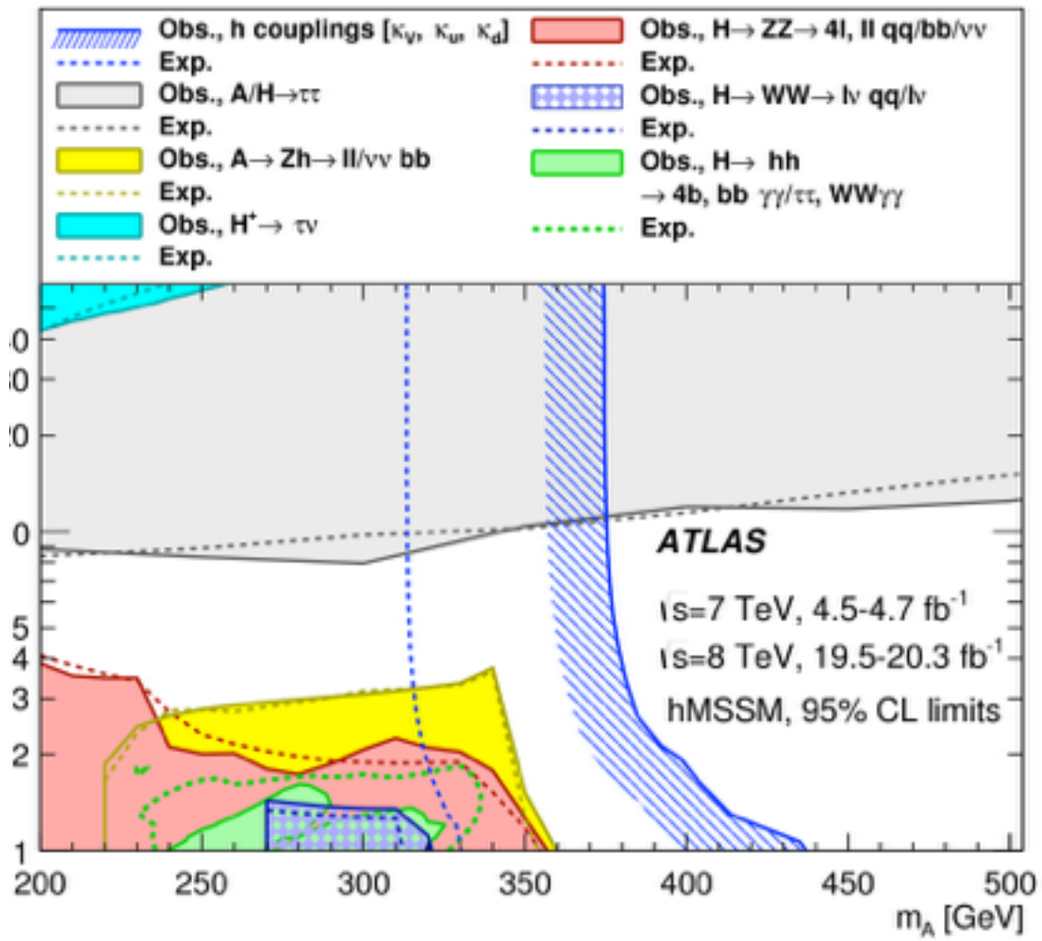
PHYS. REV. D 92, 092004 (2015)



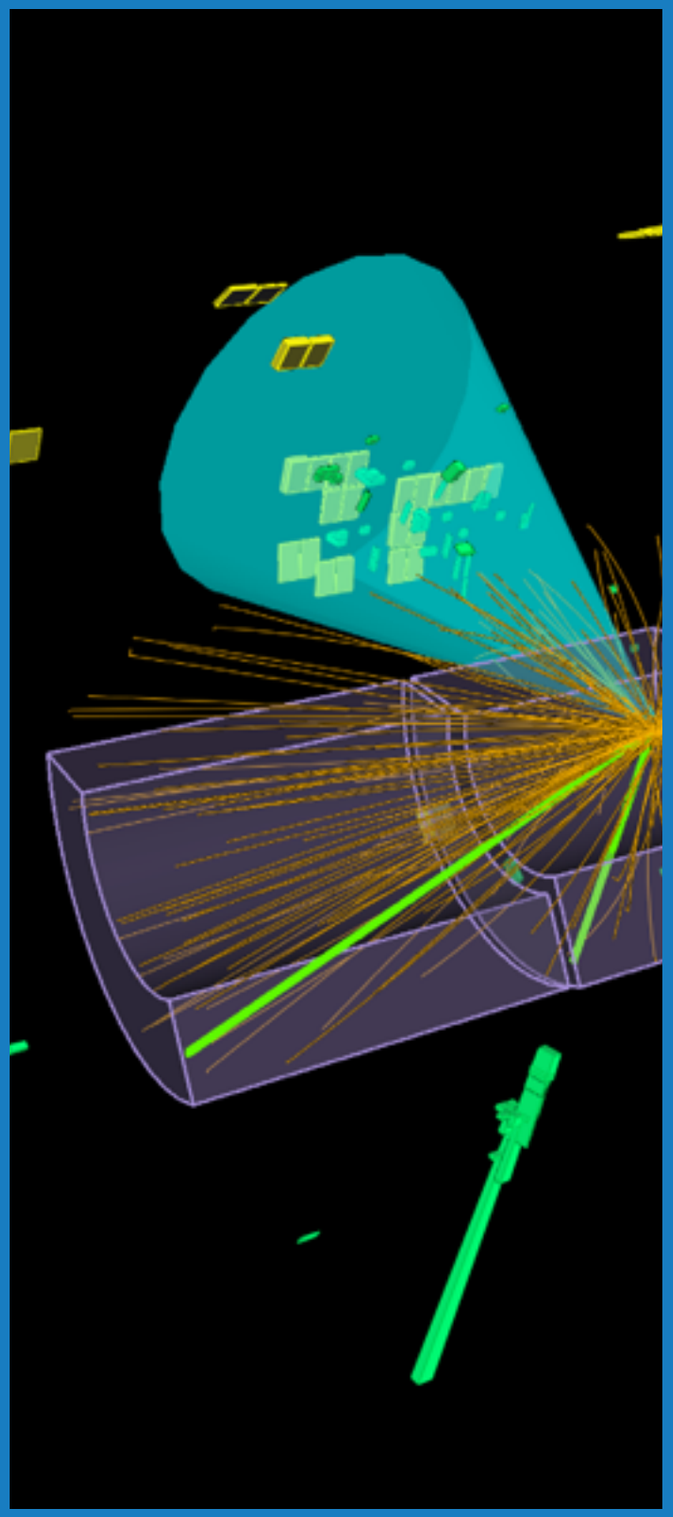
- observed (expected) limits on σ(H)*BR(H→hh) range from 2.1 (1.1) pb at 260 GeV to 0.011 (0.018) pb at 1000 GeV

PHYS. REV. D 92, 092004 (2015)





- di-Higgs combination is an input to the hMSSM summary plot (in green)

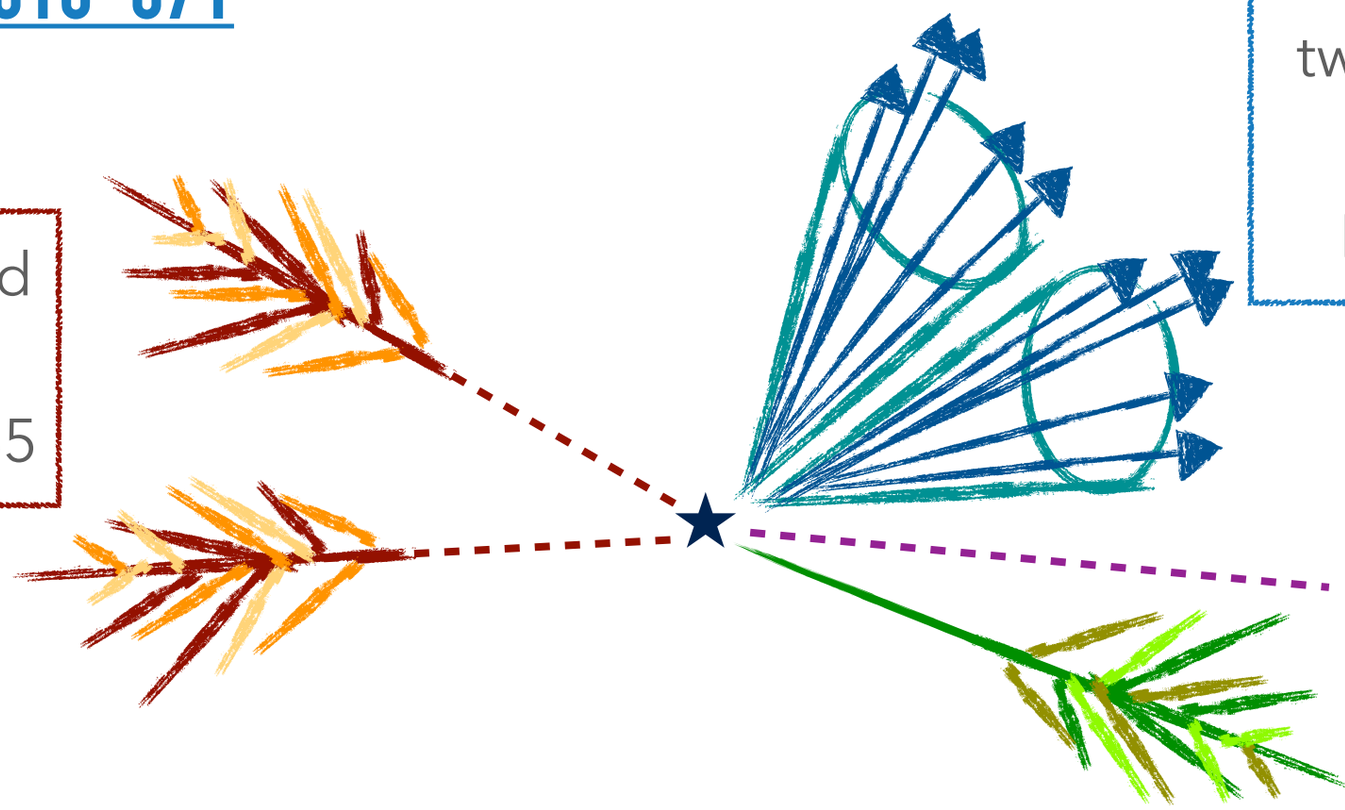


FINAL STATE WITH TWO PHOTONS AND TWO W BOSONS

ATLAS EXPERIMENT

ATLAS-CONF-2016-071

two tight, isolated photons
$p_T/m_{\gamma\gamma} > 0.25,0.35$



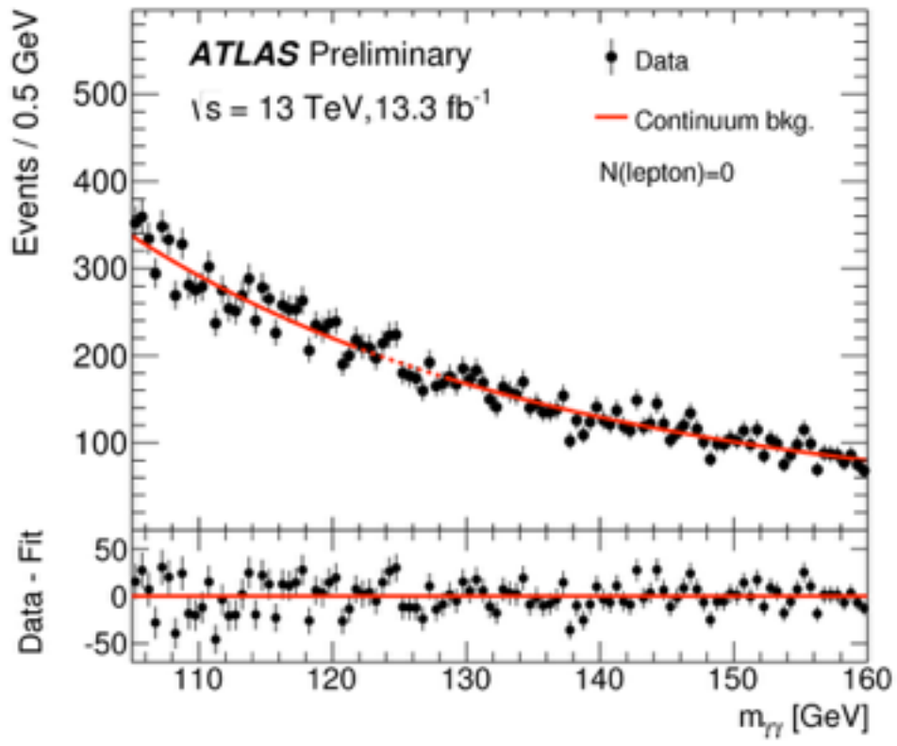
two jets (b-veto @ 70% eff.)
$p_T > 25$ GeV

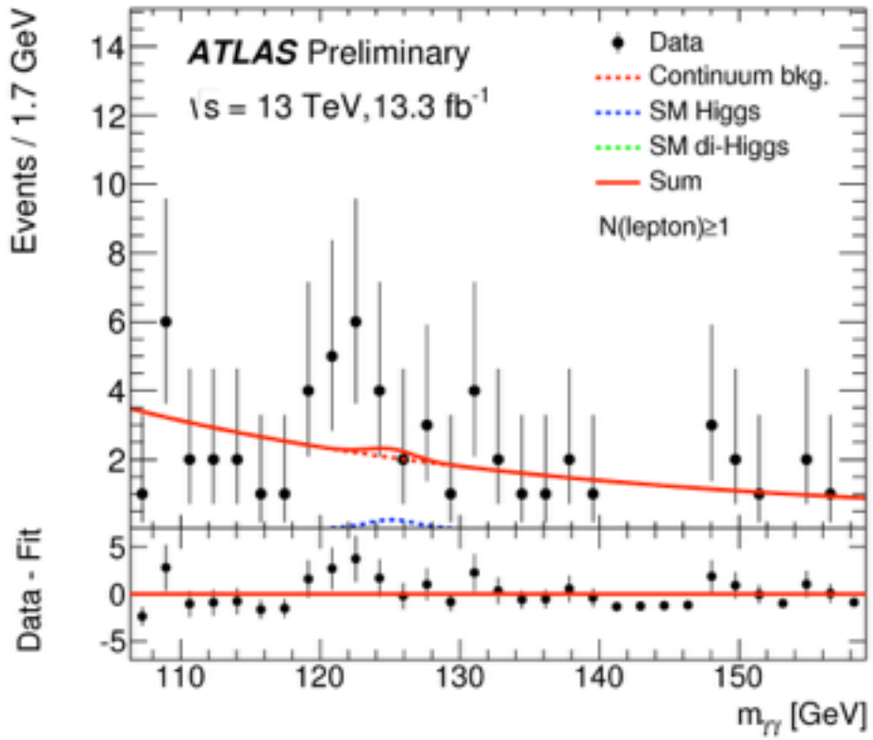
no MET requirement (does not improve result)

one lepton (e or μ)
$p_T > 10$ GeV

- search for non-resonant and resonant (260-500 GeV) hh production in 13.3 fb^{-1} of 13 TeV data
- BR(hh → γγWW) = 0.1%
- main backgrounds: SM Higgs (small, from MC), γγ/γj/jj continuum (large, data-driven)
- cut-and-count in signal region defined by: $m_{\gamma\gamma} \pm 3.4$ GeV

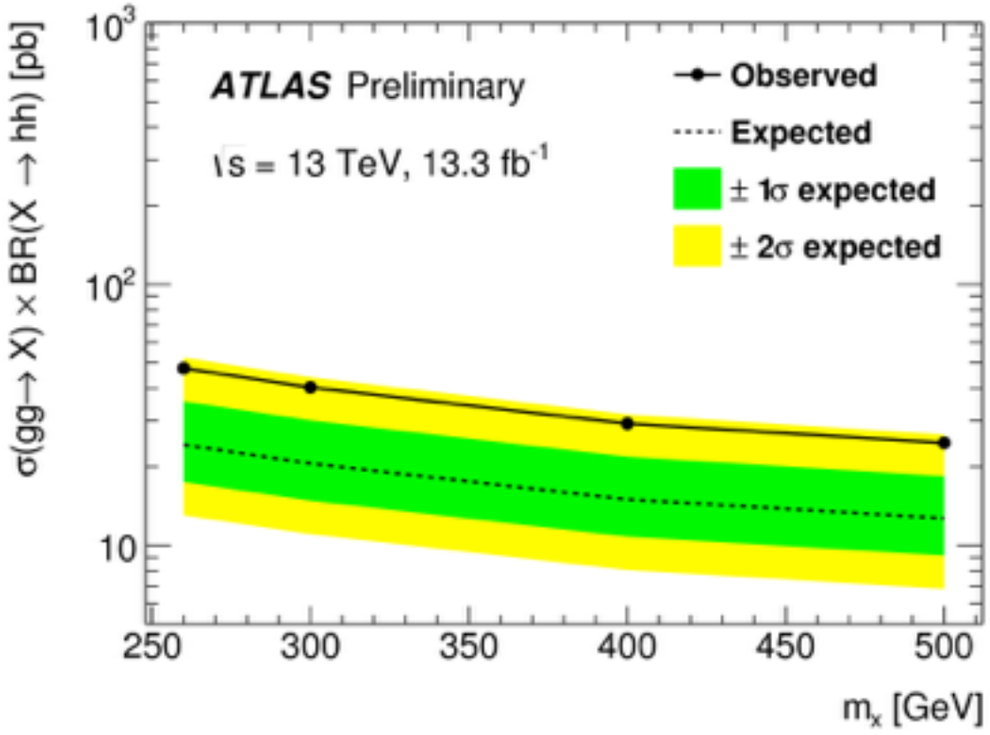
ATLAS-CONF-2016-071





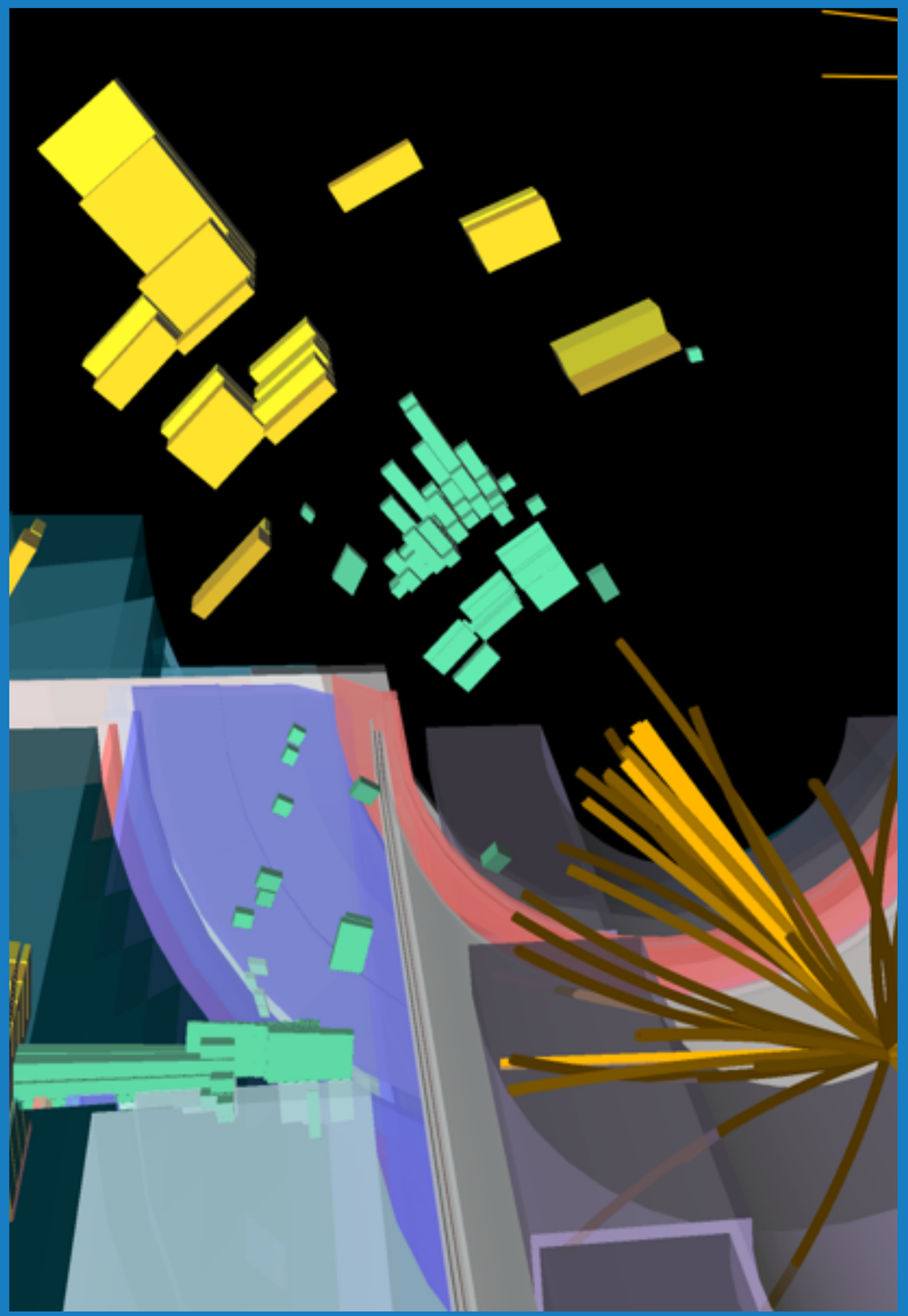
- estimate continuum background using data sidebands in m_{YY}
- due to low stats, fit m_{YY} in 0-lepton control region and transfer ε_{YY} to 1-lepton signal region
  - continuum background in SR: $n_{SR} = n_{SB} * (\varepsilon_{YY}/1-\varepsilon_{YY})$

ATLAS-CONF-2016-071



Process	Number of events	
Continuum background	7.26	± 1.23
SM single-Higgs	0.616	± 0.115
SM di-Higgs	0.0187	± 0.002 24
Observed		15

- the CL_S method and the asymptotic approximation are used to set limits on hh → γγWW
  - non-resonant: 25 pb (12.9 pb) observed (expected)
  - resonant: 47.7 to 24.7 pb (24.3 to12.7 pb) observed (expected)

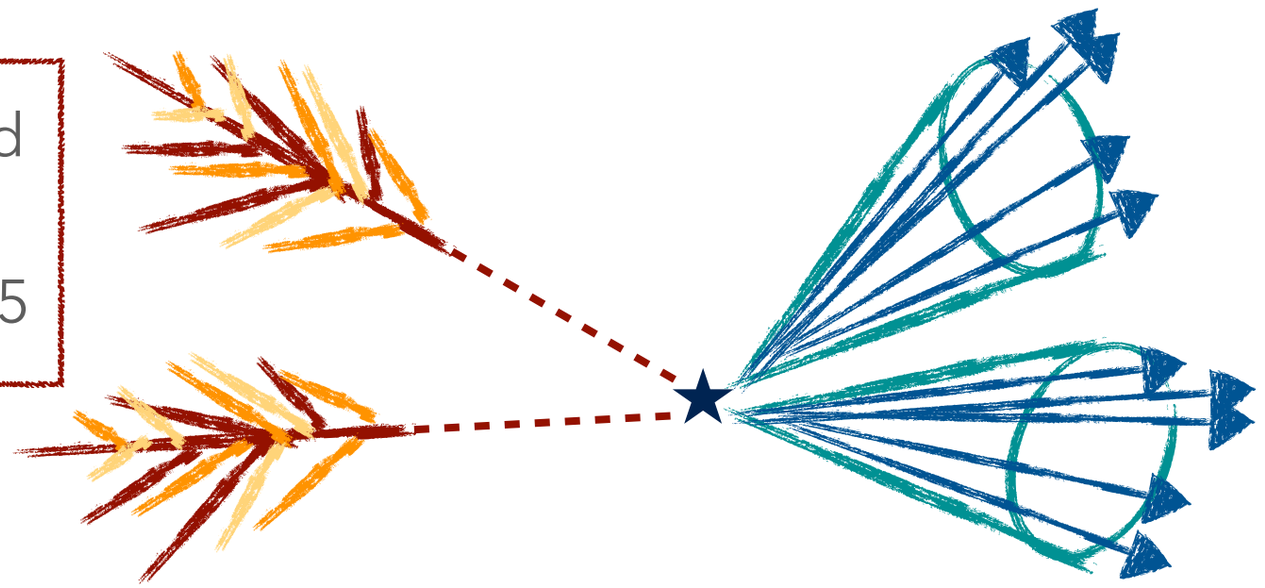


FINAL STATE WITH TWO PHOTONS AND TWO B-TAGGED JETS

ATLAS EXPERIMENT

ATLAS-CONF-2016-004

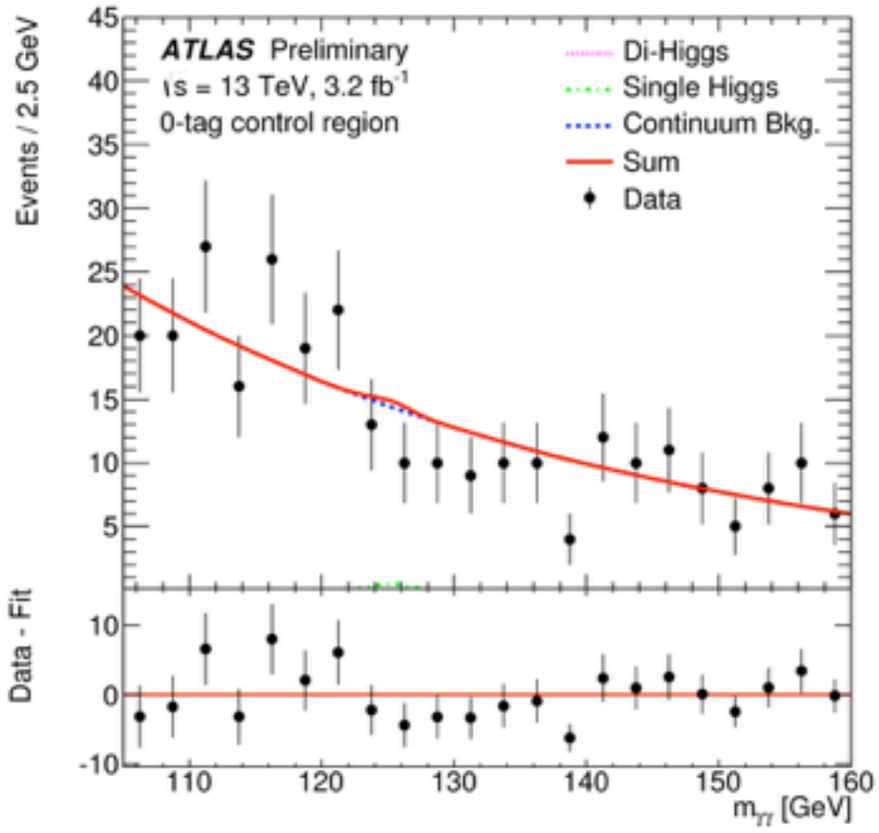
two tight, isolated photons
$p_T/m_{\gamma\gamma} > 0.25,0.35$

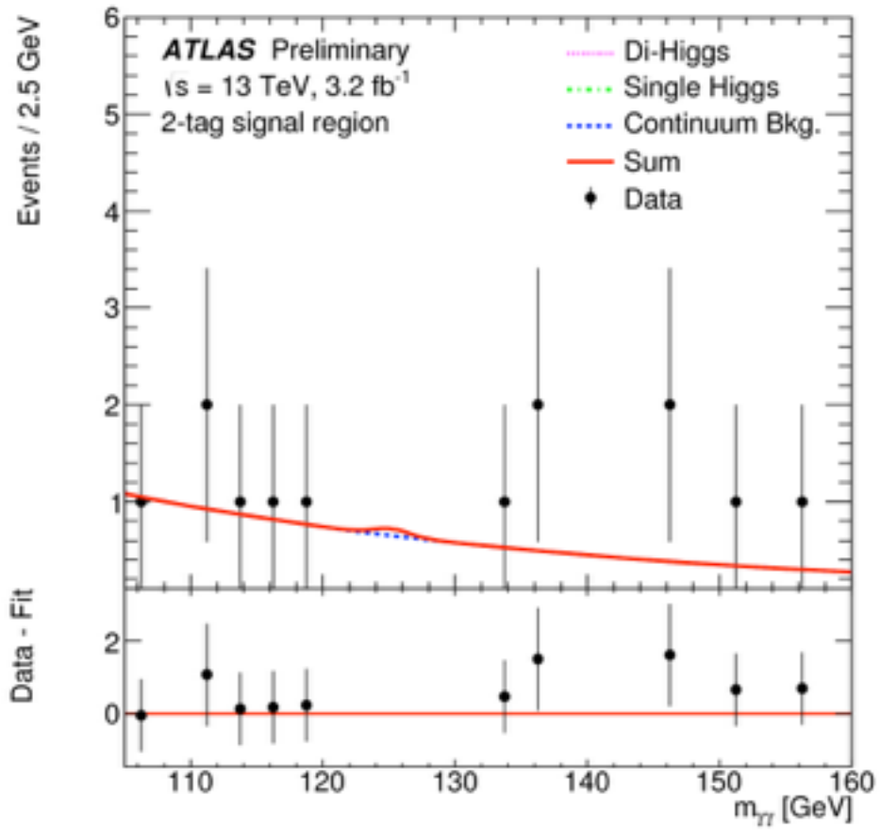


two b-tagged jets @ 85% efficiency

- search for non-resonant and resonant (275-400 GeV) hh production in 3.2 fb^{-1} of 13 TeV data
- BR(hh → γγbb) = 0.26%
- main backgrounds: SM Higgs (small, from MC), γγ/γj/jj continuum (large, data-driven)
- fit $m_{\gamma\gamma}$ (non-resonant search), cut-and-count (resonant search)

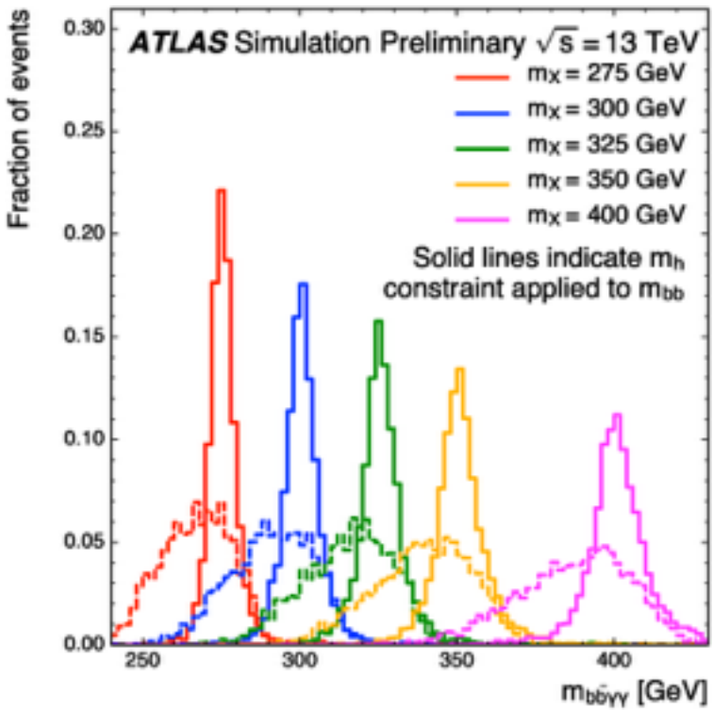
ATLAS-CONF-2016-004

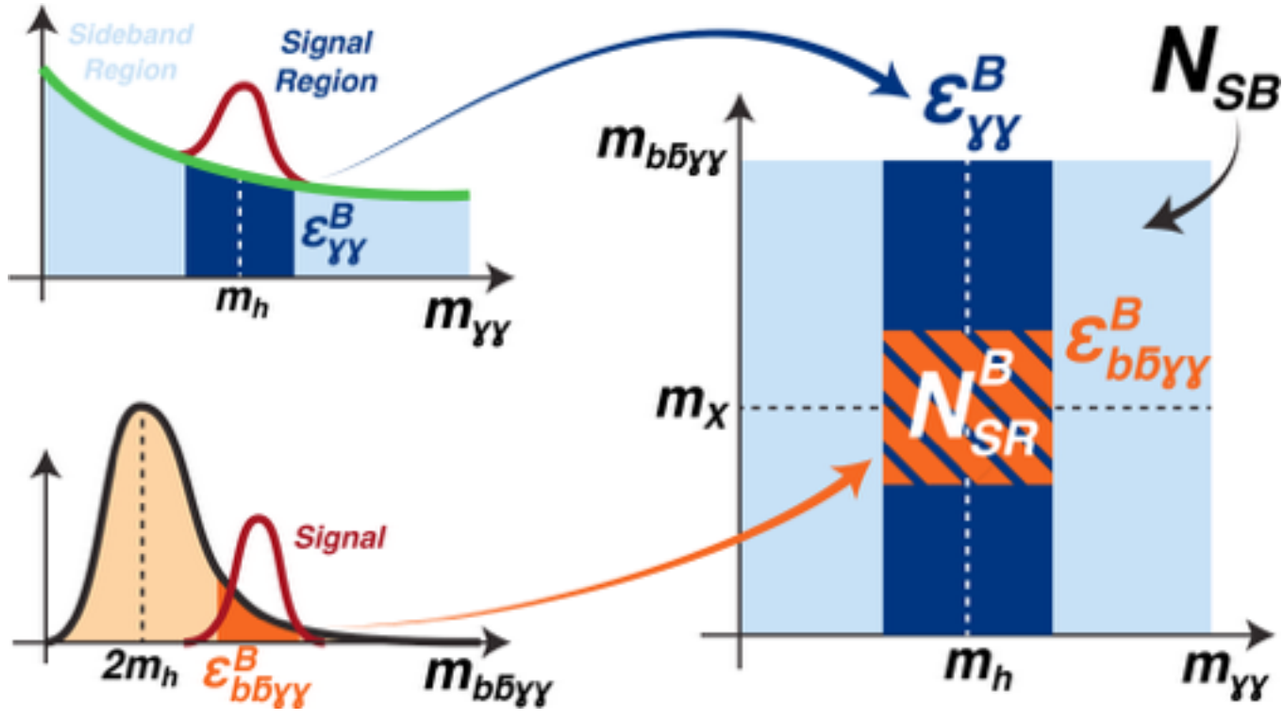




- non-resonant signal and background modeling:
  - signal and single Higgs background are fit with double-sided Crystal Ball function
  - γγ/γj/jj continuum: simultaneous fit in $m_{\gamma\gamma}$ for 0-tag CR and 2-tag SR

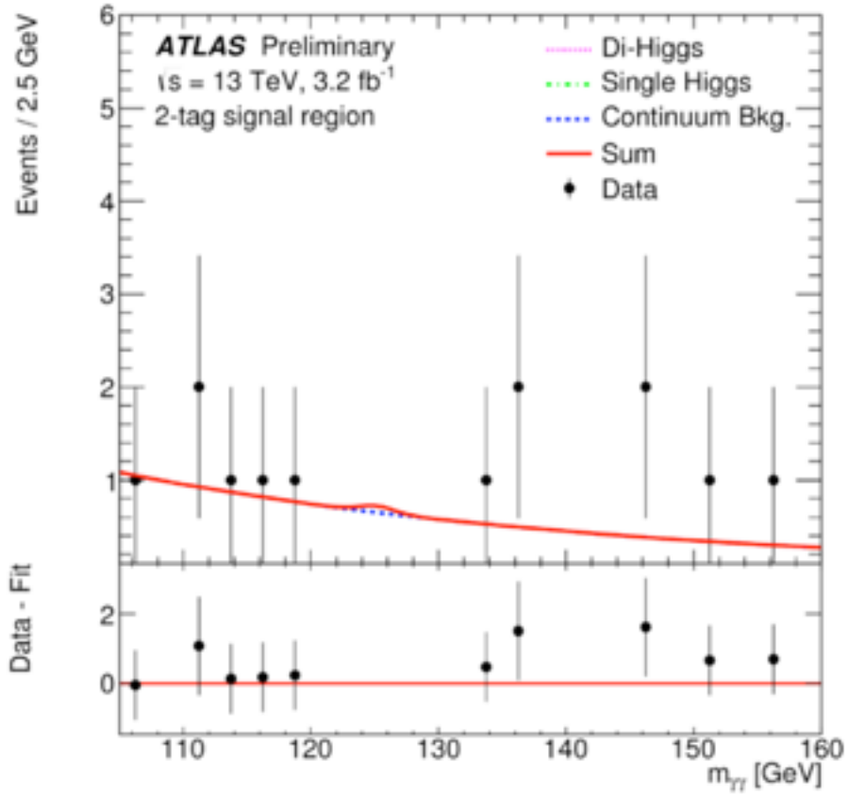
ATLAS-CONF-2016-004

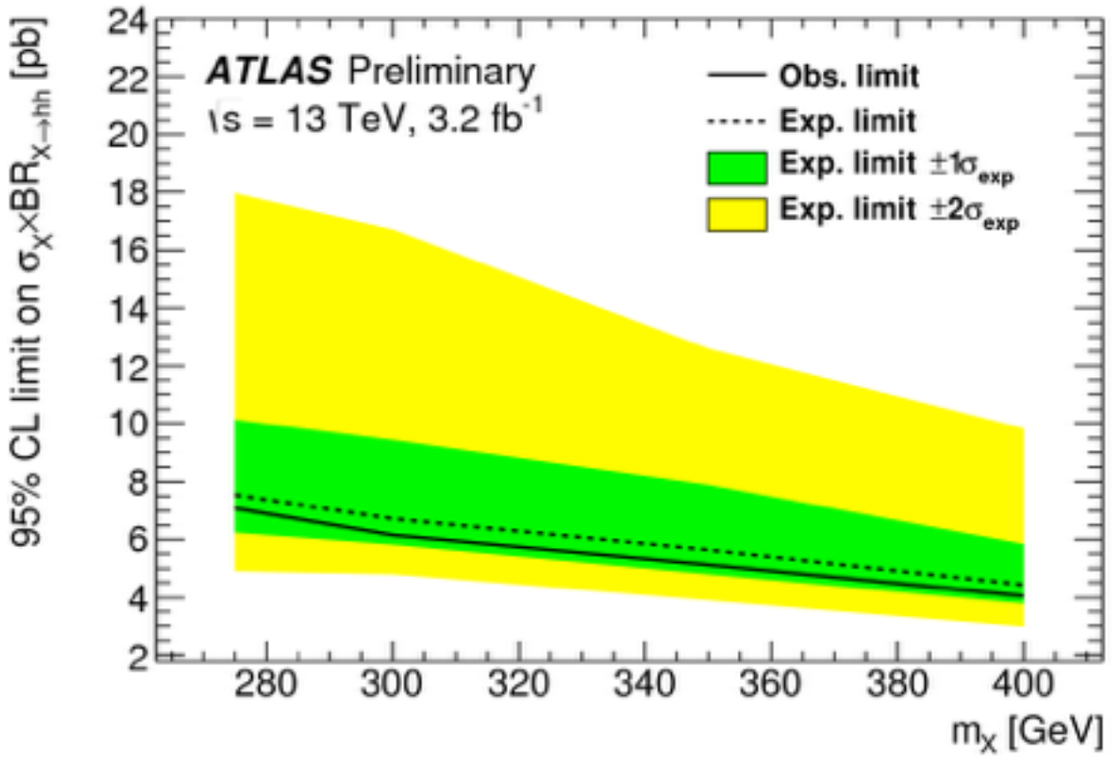




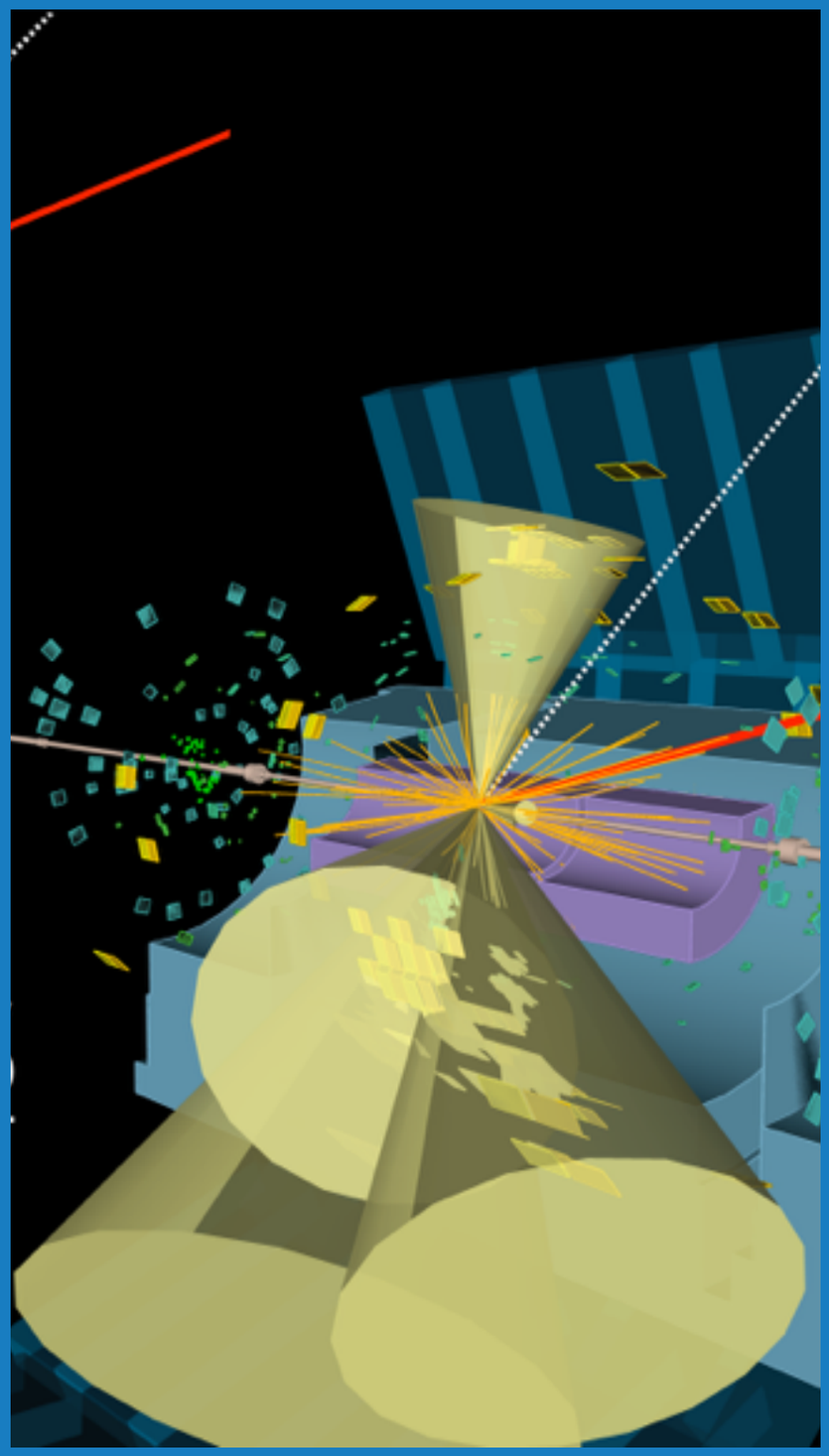
- resonant background modeling:
  - scale m_{bb} 4-vector to have $m_{bb} \equiv m_h$
  - fit $m_{\gamma\gamma}$ with an exponential function, $m_{\gamma\gamma bb}$ with a Landau function
  - cut and count – make cuts on $m_{\gamma\gamma}$ and $m_{\gamma\gamma bb}$ that keep 95% of signal ($n^B_{SR} = n_{SB} * (\varepsilon^B_{\gamma\gamma} / 1-\varepsilon^B_{\gamma\gamma}) * \varepsilon^B_{\gamma\gamma bb}$)

ATLAS-CONF-2016-004





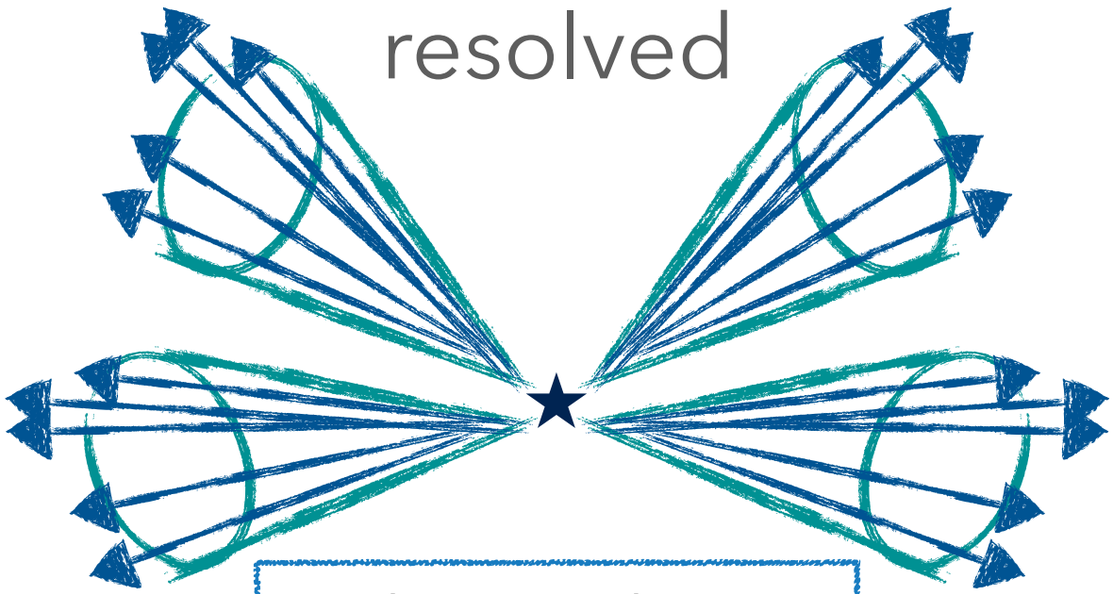
- no events in data in the signal region
- 95% CL upper limits (low stats – throw toys):
  - non-resonant: 3.9 pb (5.4 pb) observed (expected)
  - resonant: 7 to 4 pb (7.5 to 4.4 pb) observed (expected)



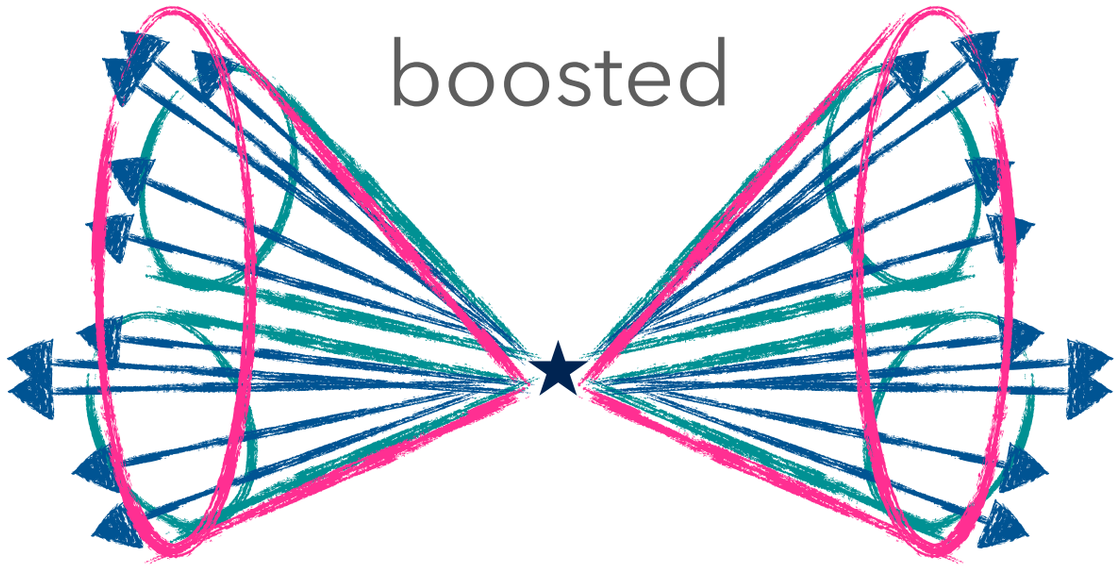
FINAL STATE WITH FOUR B-TAGGED JETS

ATLAS EXPERIMENT

ATLAS-CONF-2016-049



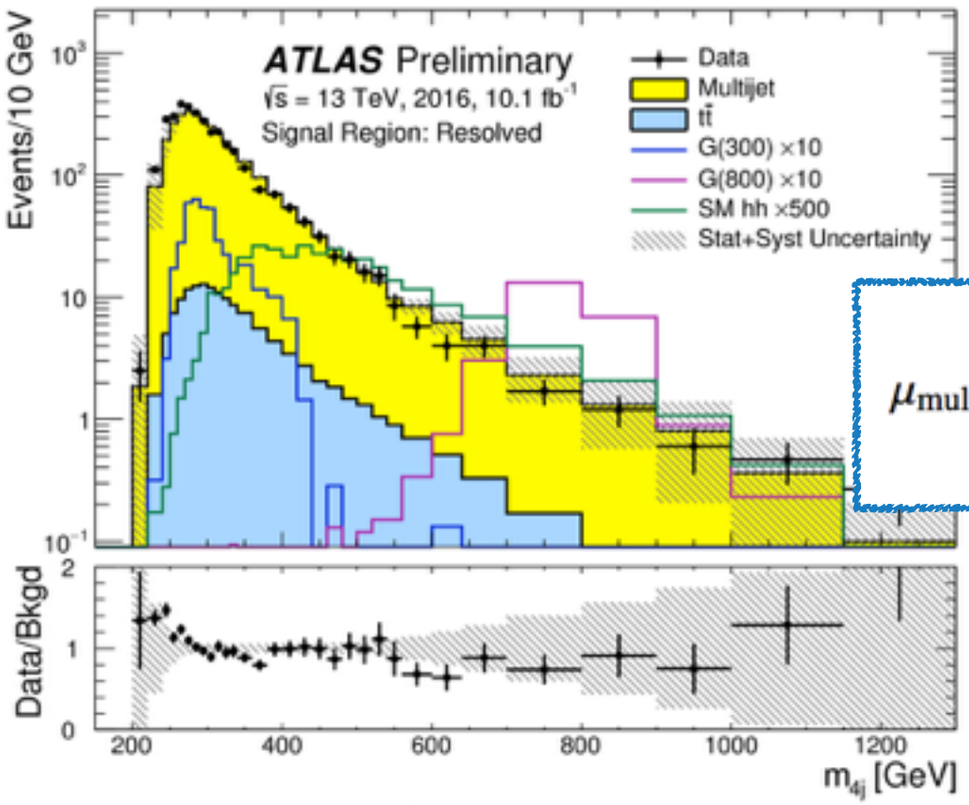
≥4 b-tagged jets @
70% efficiency
p_T > 30 GeV



≥2 large-R (1.0) jets
(≥1 (R=0.2, 70% eff.)
b-tagged jet in each)

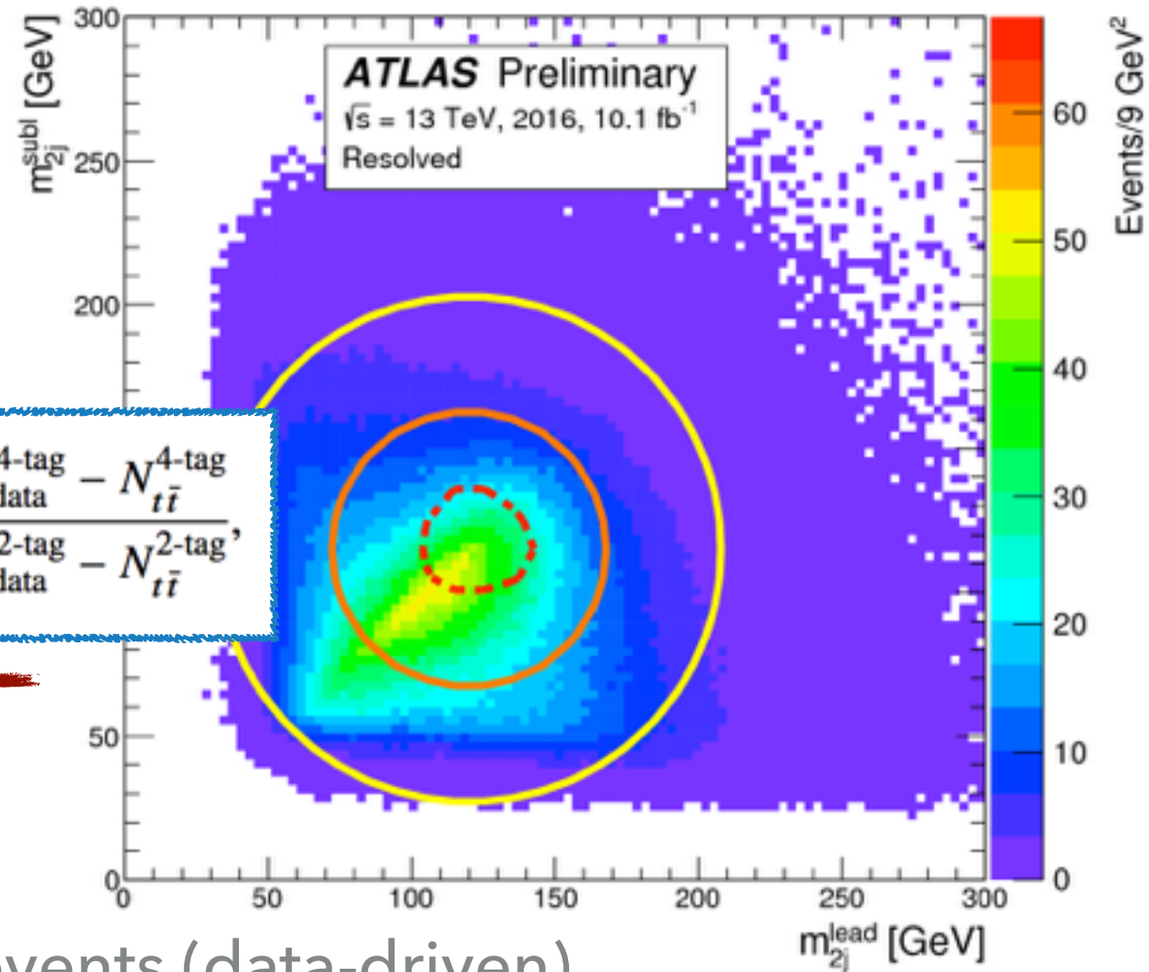
- search for non-resonant and resonant (300 - 3000 GeV) hh production in 13.3 fb^{-1} of 13 TeV data
- BR(hh → bbbb) = 33%
- main backgrounds: multi-jet (data-driven), ttbar (MC)

ATLAS-CONF-2016-049



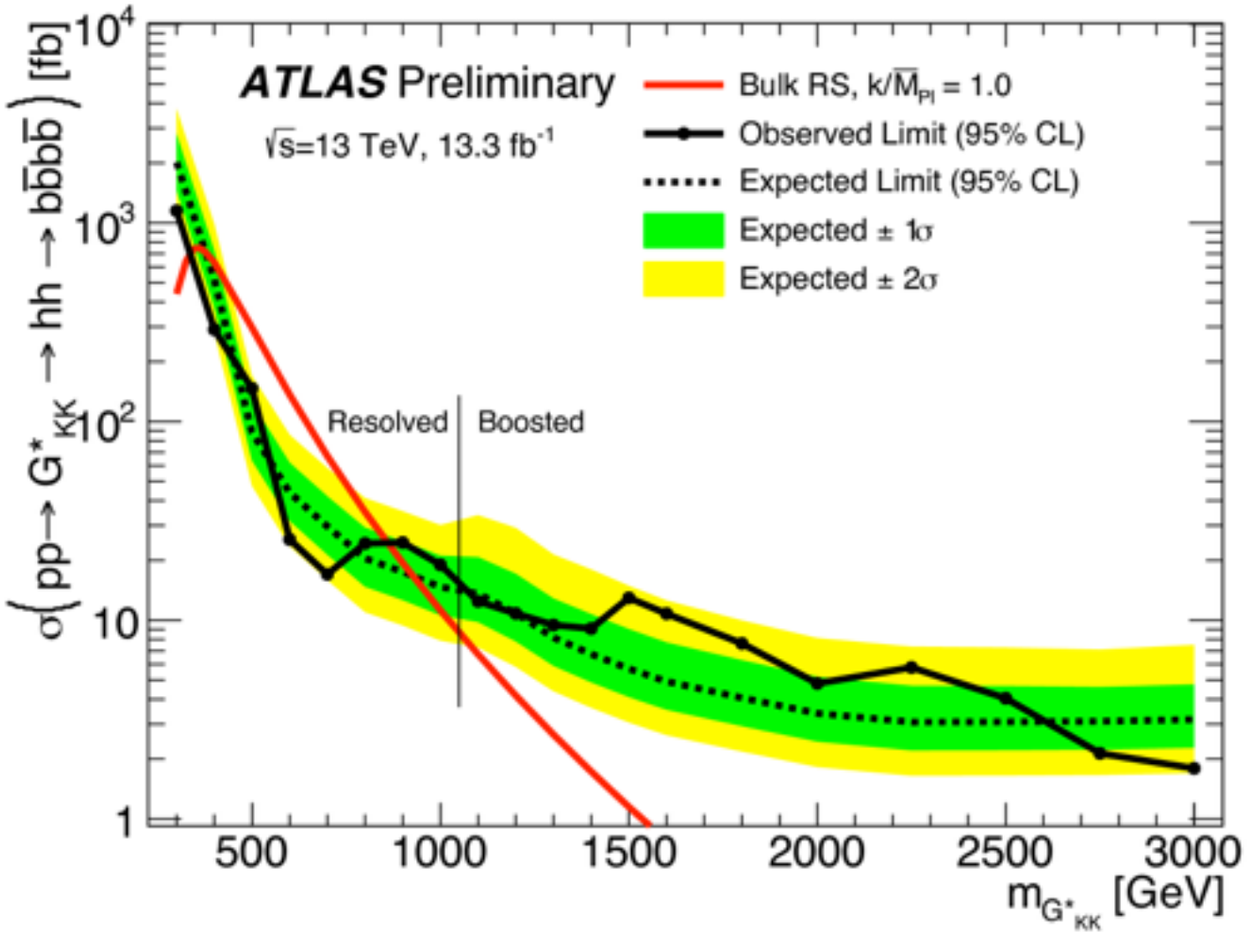
resolved

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

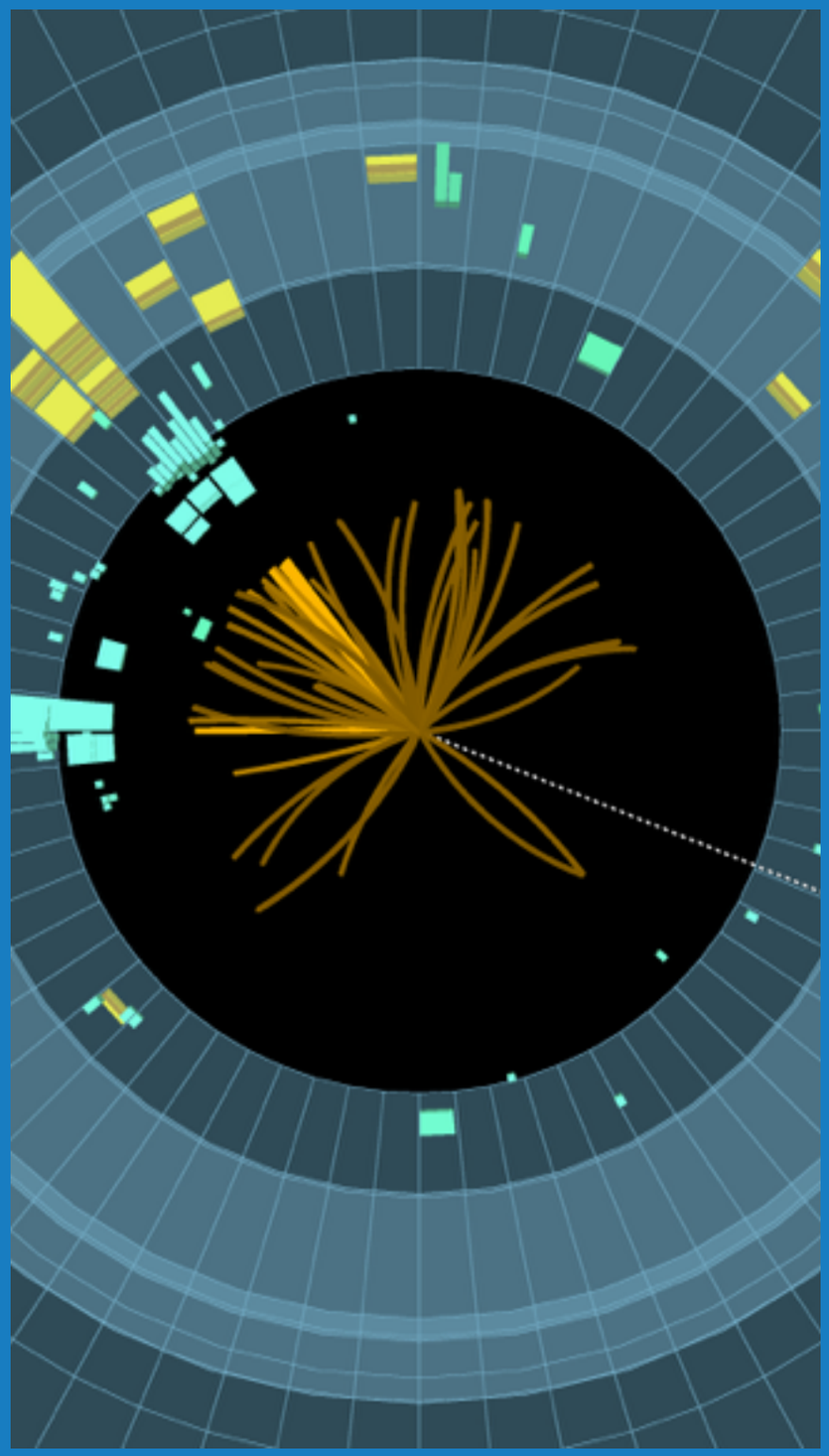


- ~95% of background is from multi-jet events (data-driven)
  - define signal, control, and sideband regions in 2-tag selection
  - multi-jet background is estimated in sidebands and reweighted to correct for differences between 2- and 4-tag selections
- similar method in boosted analysis using 0-tag data

ATLAS-CONF-2016-049



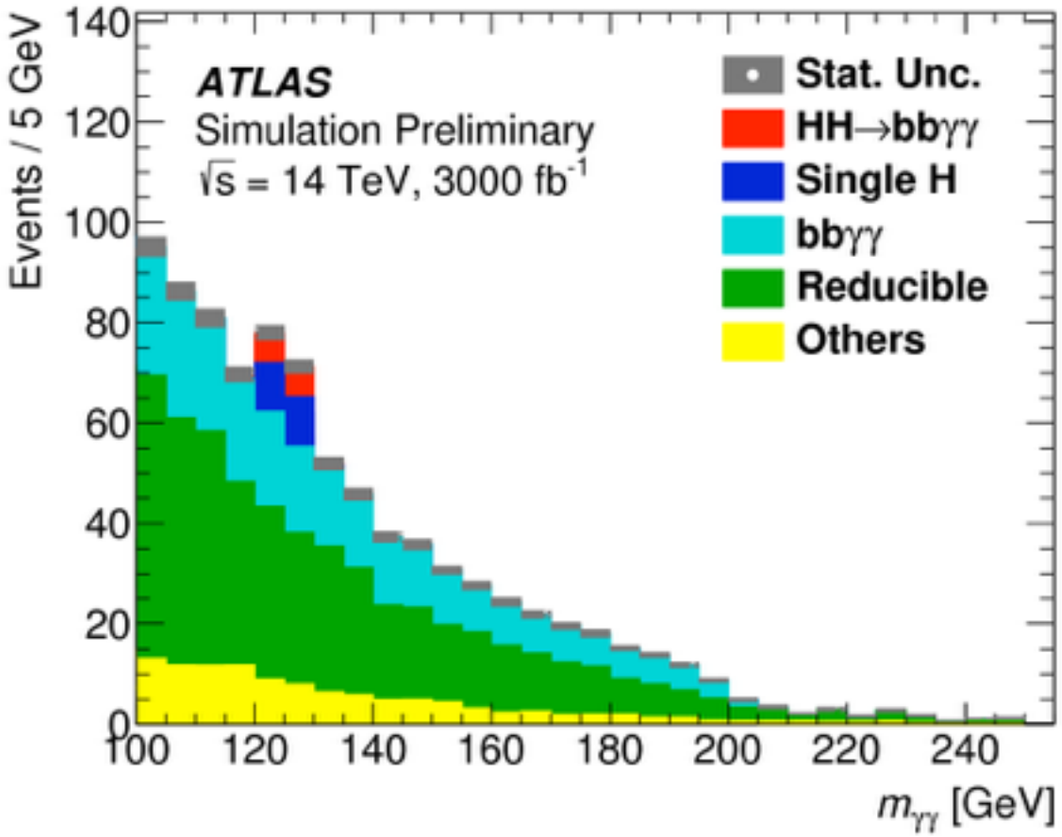
- resolved and boosted analyses are sensitive in different ranges
- 95% CL upper limits:
  - non-resonant: σ(hh→ bbbb) < 330 (430) fb observed (expected)
  - resonant: excluded from 1000 fb to 2 fb for $m_{G^*_{KK}}$ between 300 and 3000 GeV

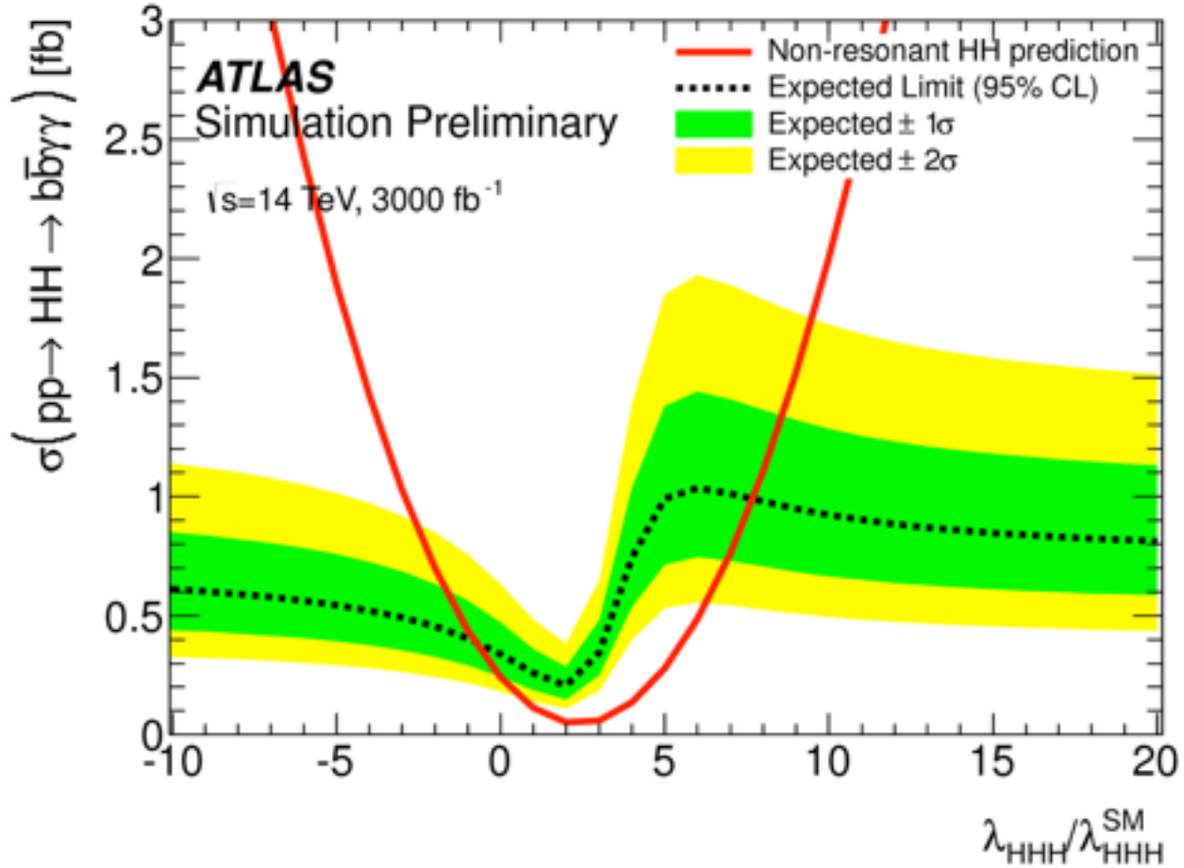


DI-HIGGS PROSPECTS FOR HL-LHC

ATLAS EXPERIMENT

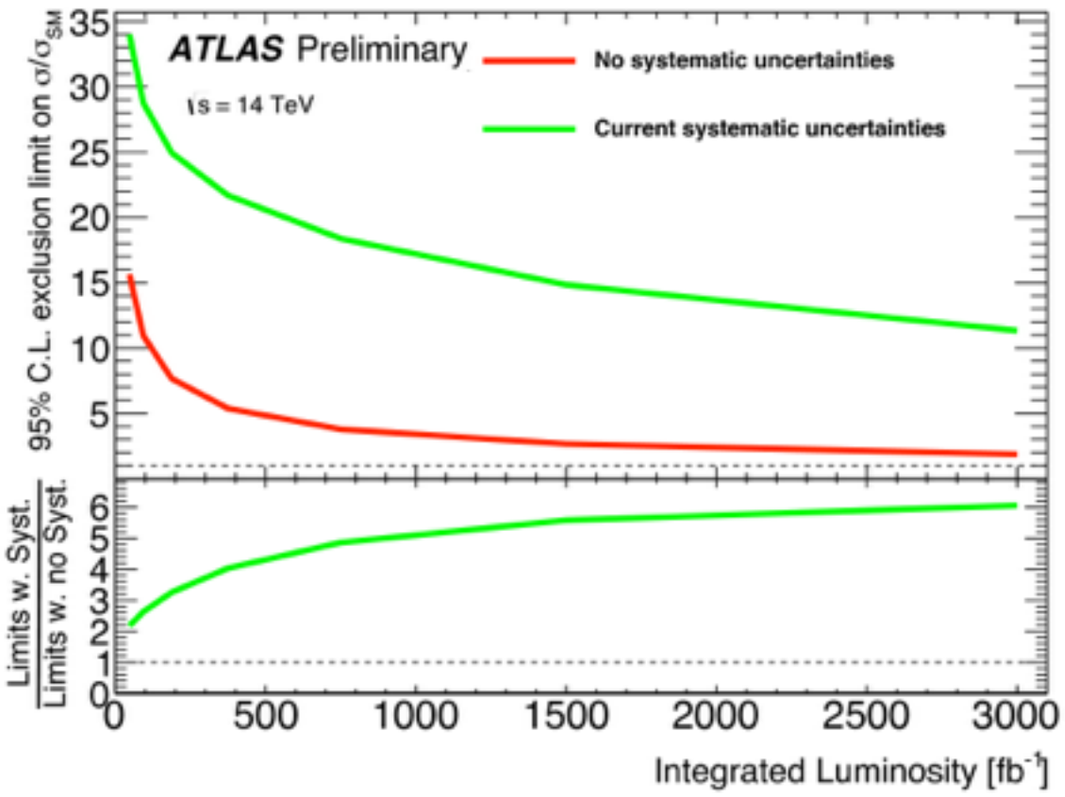
HH → YYBB @ HL-LHC (ATL-PHYS-PUB-2017-001)

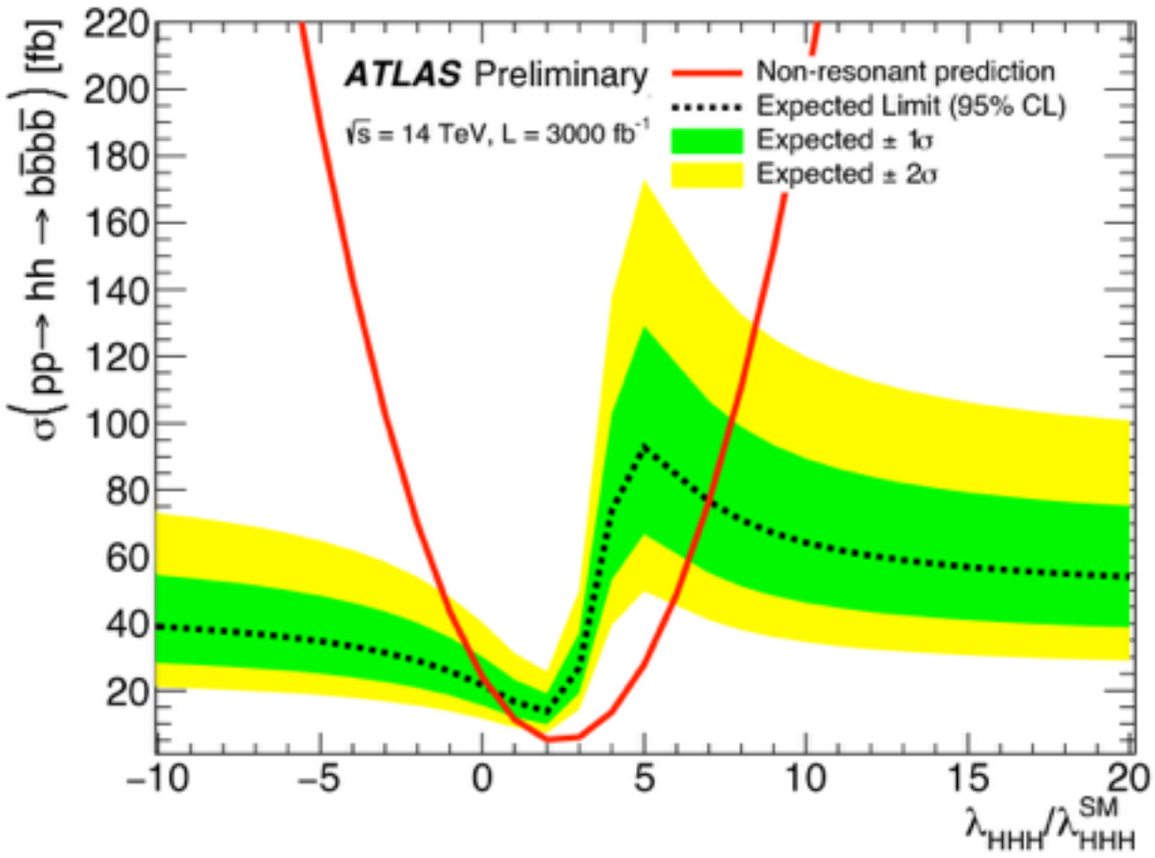




- set expected limits using truth-level MC for $\sqrt{s}$ = 14 TeV, $\int L$ = 3000 fb^{-1}
  - The truth-level objects are smeared according to predicted detector resolution at <μ> = 200
- expected significance for non-resonant SM hh → γγbb: 1.05σ
- limits on Higgs self-coupling: $-0.8 < \lambda/\lambda_{SM} < 7.7$

HH → BBBB @ HL-LHC (ATL-PHYS-PUB-2016-024)





- extrapolate current Run 2 results to $\sqrt{s}$ = 14 TeV, $\int L = 3000\ fb^{-1}$
- expected limit on non-resonant SM hh → bbbb: $1.5*\sigma_{SM}$
  - with current systematic uncertainties: $5.2*\sigma_{SM}$
- limits on Higgs self-coupling: $0.2 < \lambda/\lambda_{SM} < 7.0$ ($-3.5 < \lambda/\lambda_{SM} < 11$ syst)

SEARCHES FOR DI-HIGGS PRODUCTION WITH ATLAS

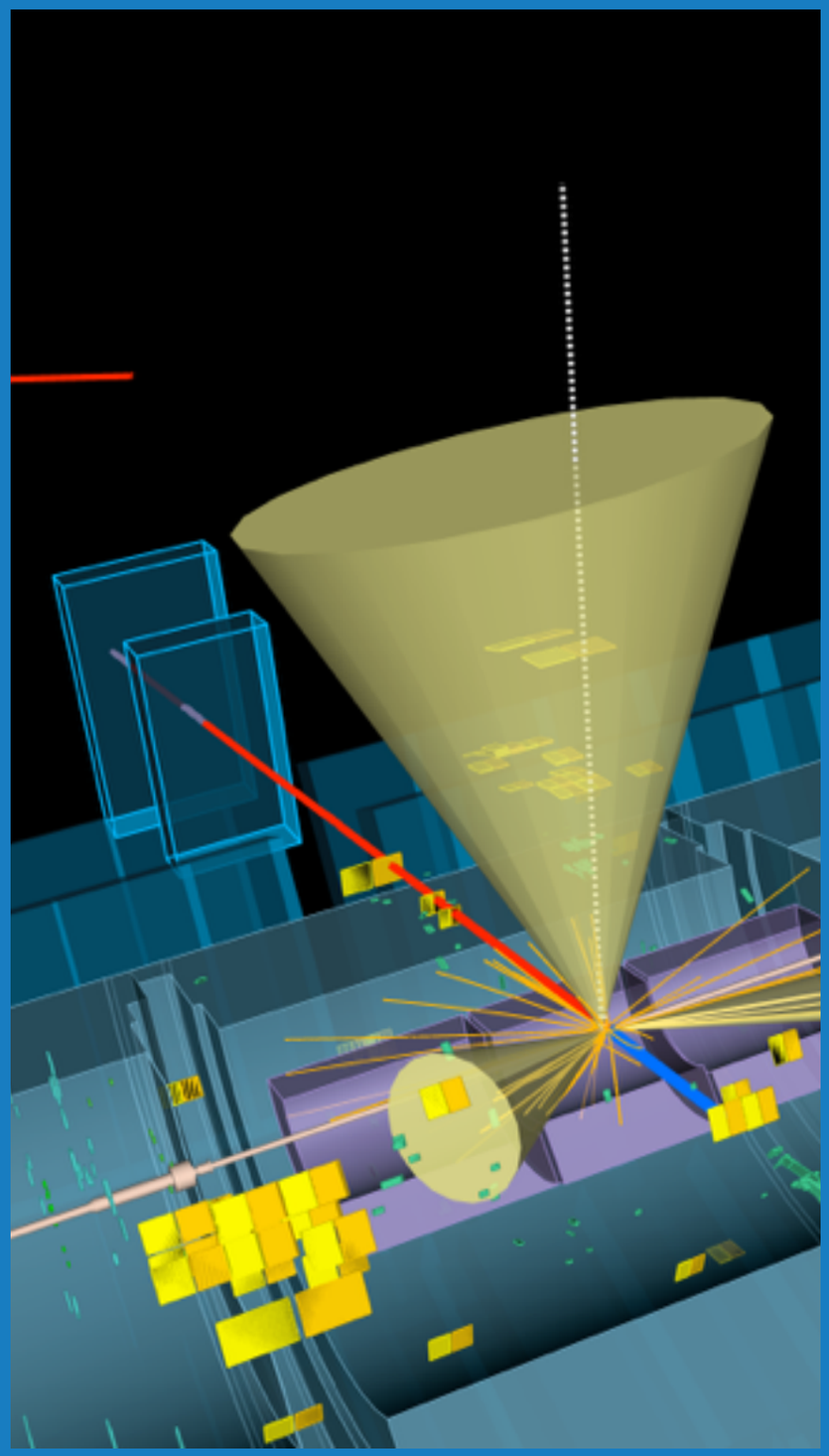
- wide variety of final states covered by ATLAS
- searches for non-resonant and resonant di-Higgs production
- stay tuned for results with 2015+2016 dataset (36.1 fb^{-1})

(including new final states!)

most recent non-resonant upper limits on $\sigma(hh)/\sigma(hh)_{SM}$

	γγbb	γγWW	bbττ	bbbb
σ/σ_{SM}	120	750	160	29
dataset	3.2 fb^{-1}, 13 TeV	13.3 fb^{-1}, 13 TeV	20.3 fb^{-1}, 8 TeV	13.3 fb^{-1}, 13 TeV

FOR MORE HIGGSES: HTTPS://TWIKI.CERN.CH/TWIKI/BIN/VIEW/ATLASPUBLIC/HIGGSPUBLICRESULTS



BACKUP SLIDES

ATLAS EXPERIMENT

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MC generators

Process	Event generator	PDF set	Cross section [pb]
	Background processes		
V+jets	ALPGEN + PYTHIA8	CTEQ6L1	normalized to data
Diboson: WW	POWHEG + PYTHIA8	CT10	55.4
Diboson: WZ	POWHEG + PYTHIA8	CT10	22.3
Diboson: ZZ	POWHEG + PYTHIA8	CT10	7.3
$t\bar{t}$	POWHEG + PYTHIA8	CT10	253
Single top: t-channel	ACERMC + PYTHIA8	CTEQ6L1	87.8
Single top: s-channel	POWHEG + PYTHIA8	CT10	5.6
Single top: Wt	POWHEG + PYTHIA8	CT10	22.0
$gg \to h$	POWHEG + PYTHIA8	CT10	19.2
$q\bar{q}' \to q\bar{q}' h$	POWHEG + PYTHIA8	CT10	1.6
$q\bar{q} \to Vh$	PYTHIA8	CTEQ6L1	1.1
$q\bar{q}/gg \to t\bar{t}h$	PYTHIA8	CTEQ6L1	0.13
	Signal processes		
Nonresonant $gg \to hh$	MADGRAPH5 + PYTHIA8	CTEQ6L1	0.0099
Resonant $gg \to H \to hh$	MADGRAPH5 + PYTHIA8	CTEQ6L1	model dependent

PHYS. REV. D 92, 092004 (2015)

analysis strategy and limits, per channel

hh	Nonresonant search		Resonant search		
final state	Categories	Discriminant	Categories	Discriminant	m_H [GeV]
$\gamma\gamma bb$	1	$m_{\gamma\gamma}$	1	event yields	260–500
$\gamma\gamma WW^*$	1	event yields	1	event yields	260–500
$b\bar{b}\tau\tau$	4	$m_{\tau\tau}$	4	$m_{bb\tau\tau}$	260–1000
$bbbb$	1	event yields	1	m_{bbbb}	500–1500

Nonresonant search		Resonant search			
		$m_H = 300$ GeV		$m_H = 600$ GeV	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
Background model	11	Background model	15	b-tagging	10
b-tagging	7.9	Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	9.9	h BR	6.3
h BR	5.8	Lepton and τ_{had}	6.9	Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	5.5
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	5.5	h BR	5.9	Luminosity	2.7
Luminosity	3.0	Luminosity	4.0	Background model	2.4
Total	16	Total	21	Total	14

PHYS. REV. D 92, 092004 (2015)

resonant limits, per mass point, per channel

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

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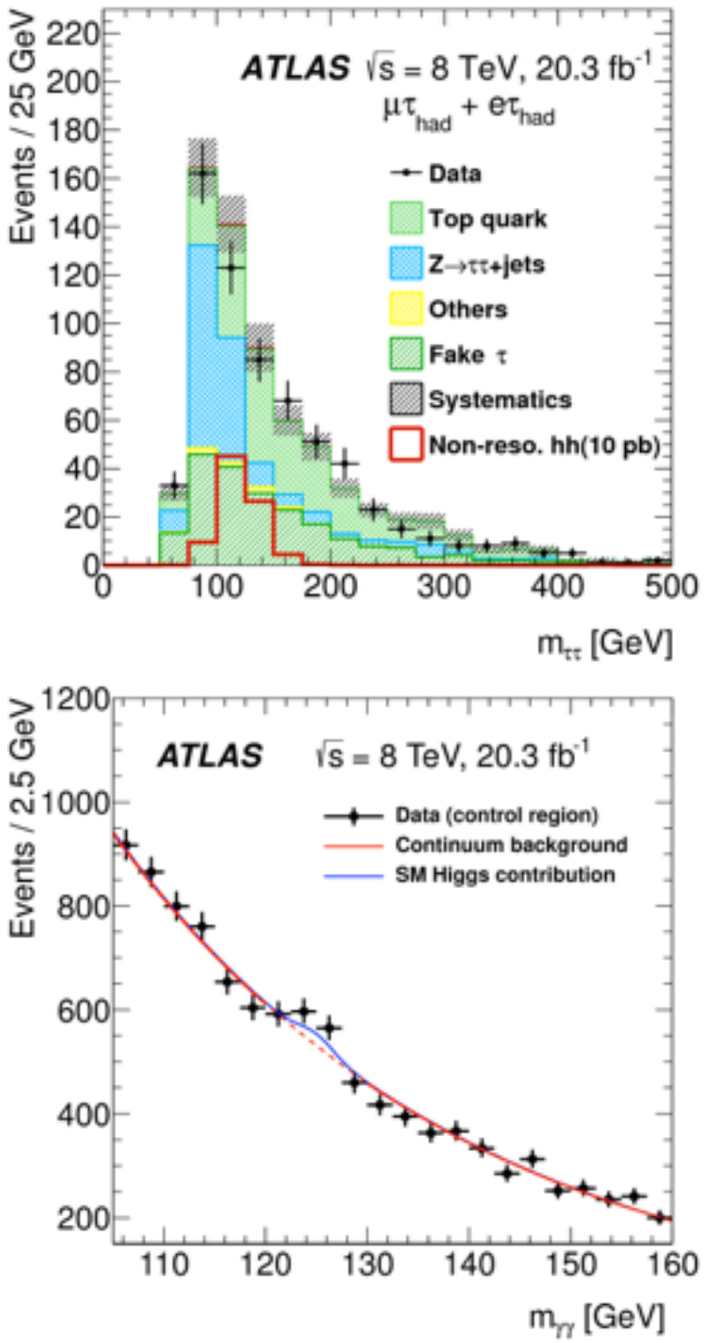
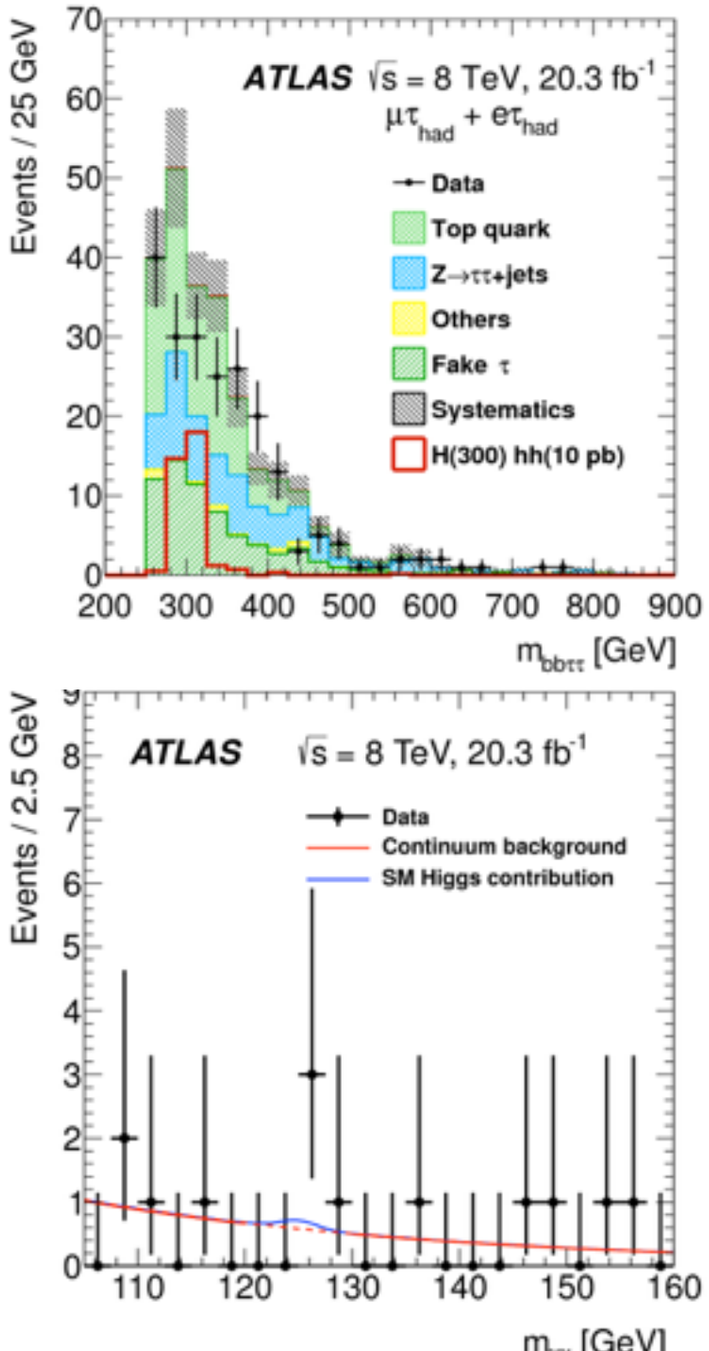
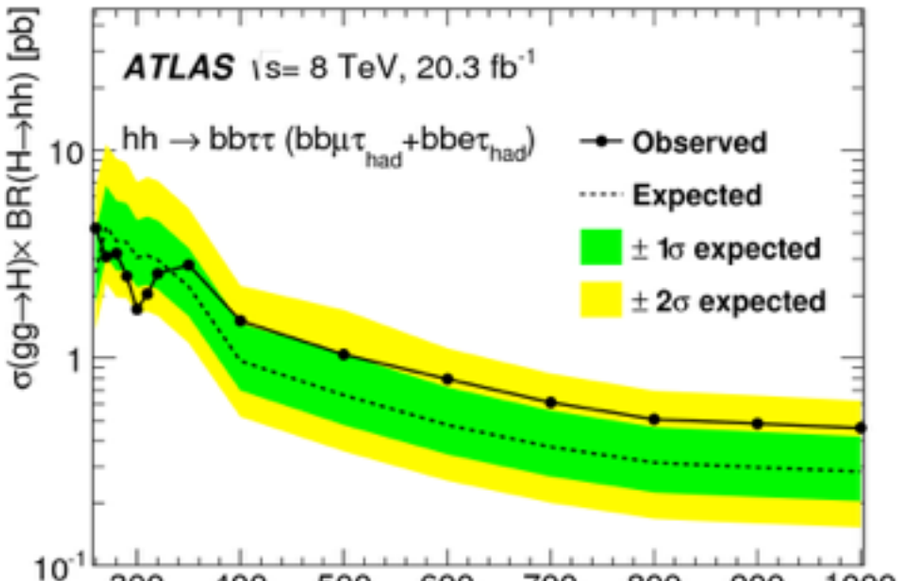
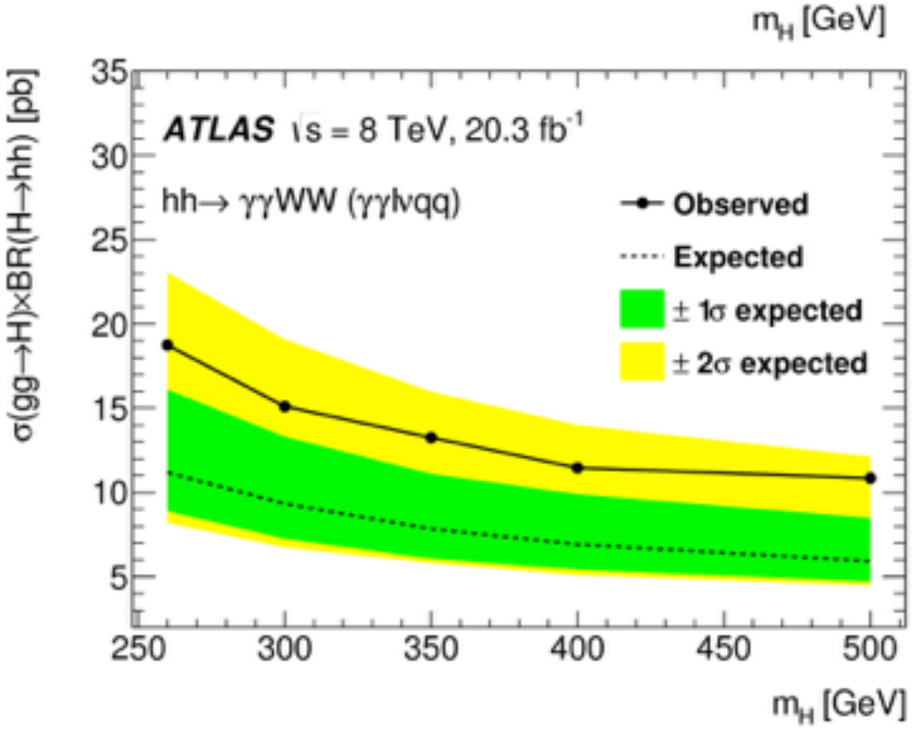
bbττ







YYWW

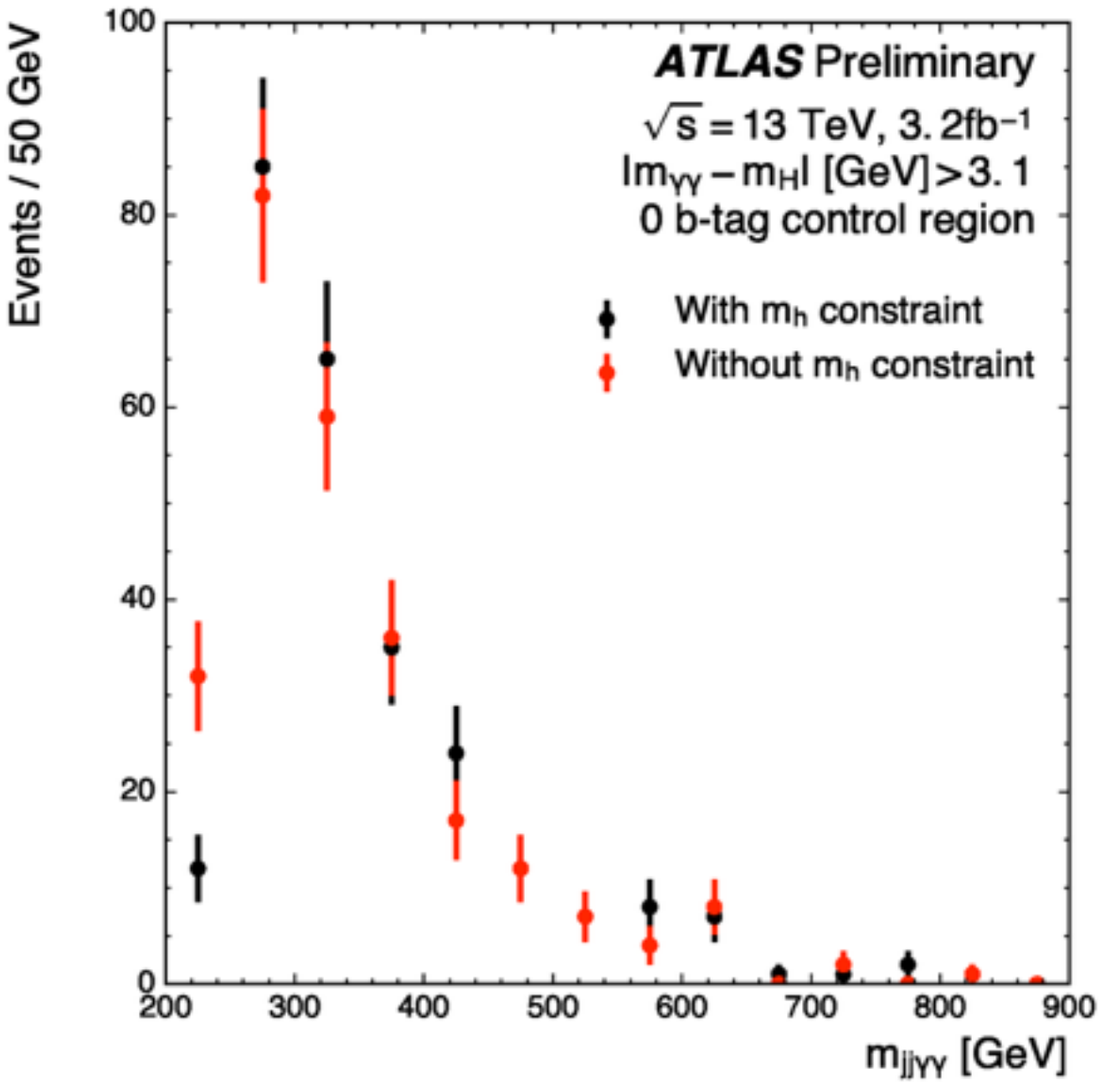


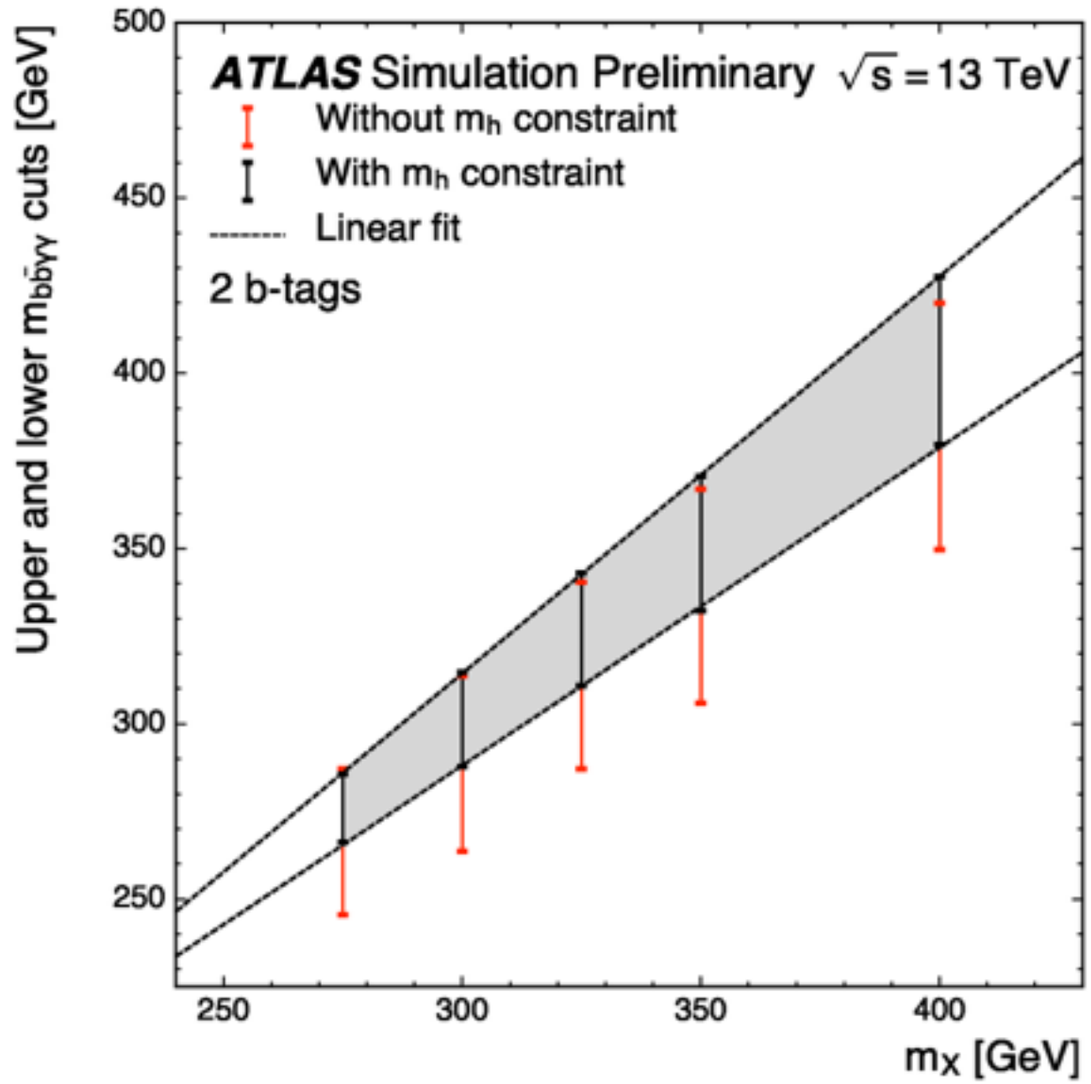
ATLAS-CONF-2016-071

systematic uncertainties

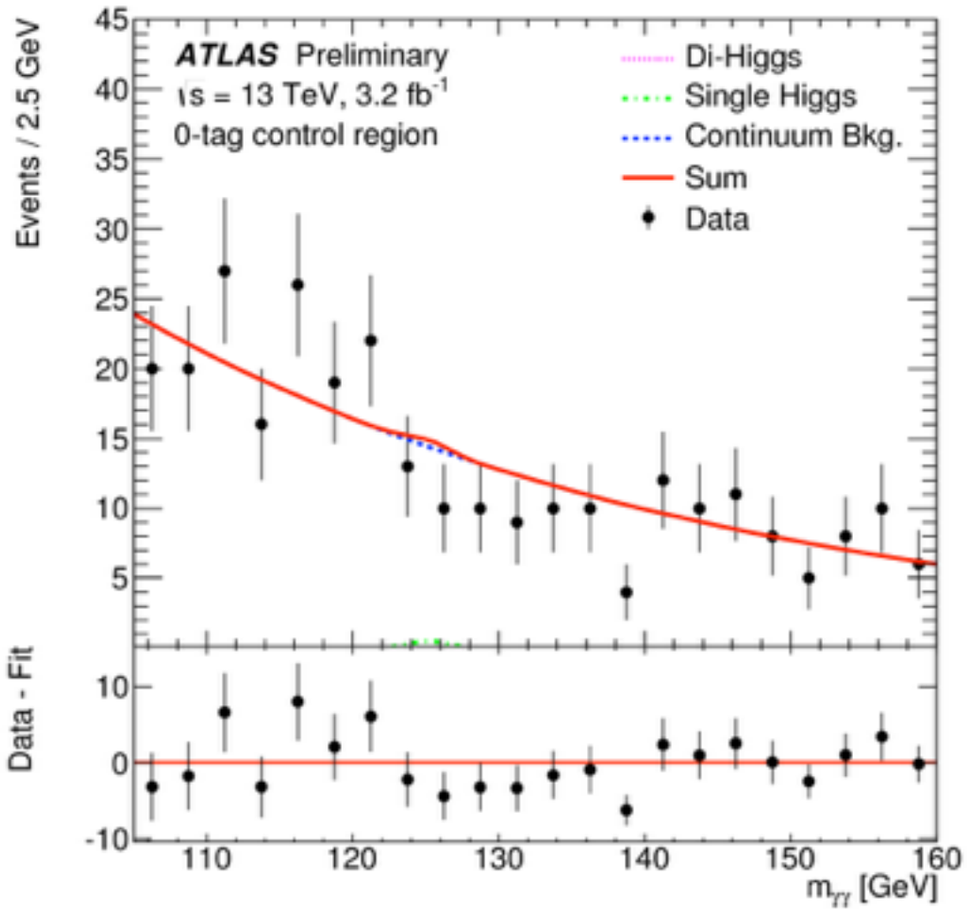
Source of uncertainties		Non-resonant hh	$X \to hh$	Single-h bkg	Cont. bkg
		All numbers are in %			
Luminosity 2015+2016		2.9	2.9	2.9	-
Trigger		0.4	0.4	0.4	-
Pileup re-weighting		0.8	0.2	1.8	-
Event statistics		2.0	1.8	2.7	14.7
Photon	energy resolution	2.0	1.8	1.2	-
	energy scale	4.2	4.1	1.6	-
	identification	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

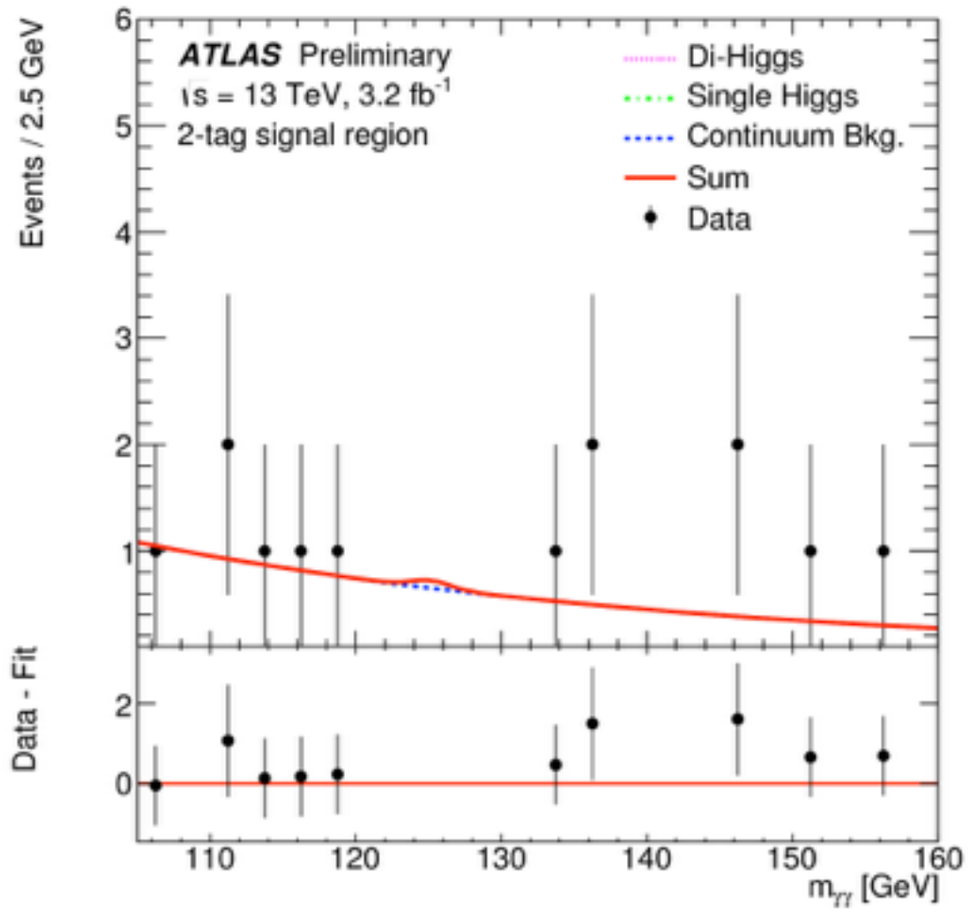
ATLAS-CONF-2016-004





ATLAS-CONF-2016-004





Process	0-tag	2-tag
Continuum background	35.8 ± 2.1	1.63 ± 0.30
SM single-Higgs	1.8 ± 1.5	0.14 ± 0.05
SM di-Higgs	<0.001	0.027 ± 0.006
Observed	27	0

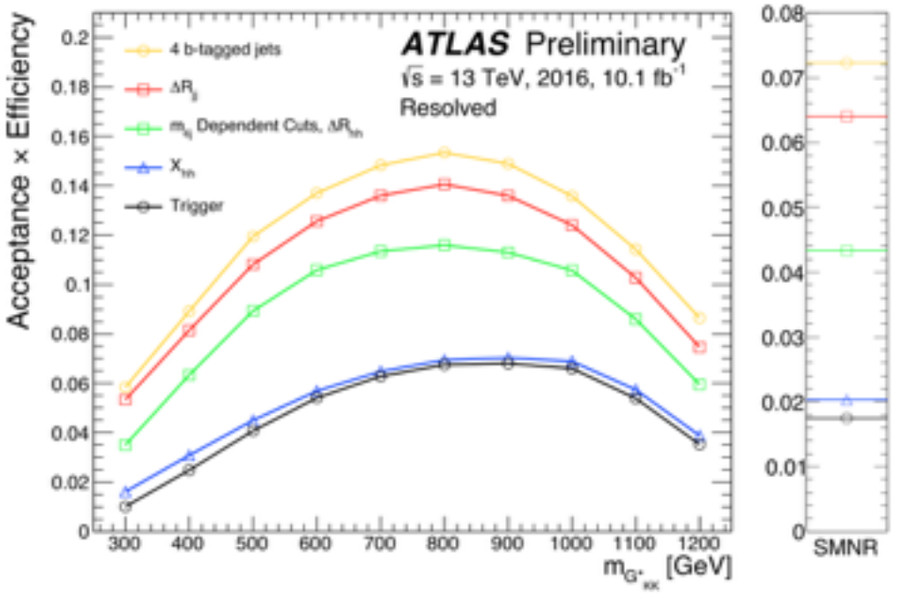
ATLAS-CONF-2016-004

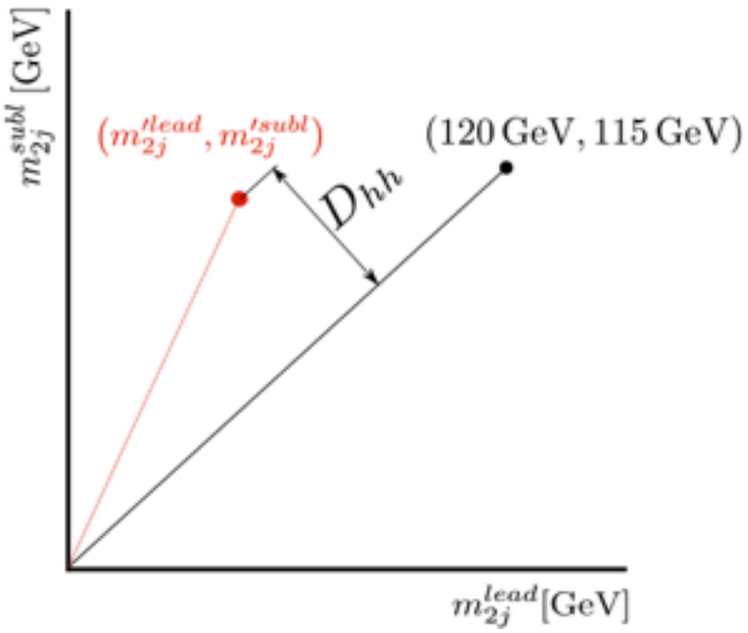
systematic uncertainties

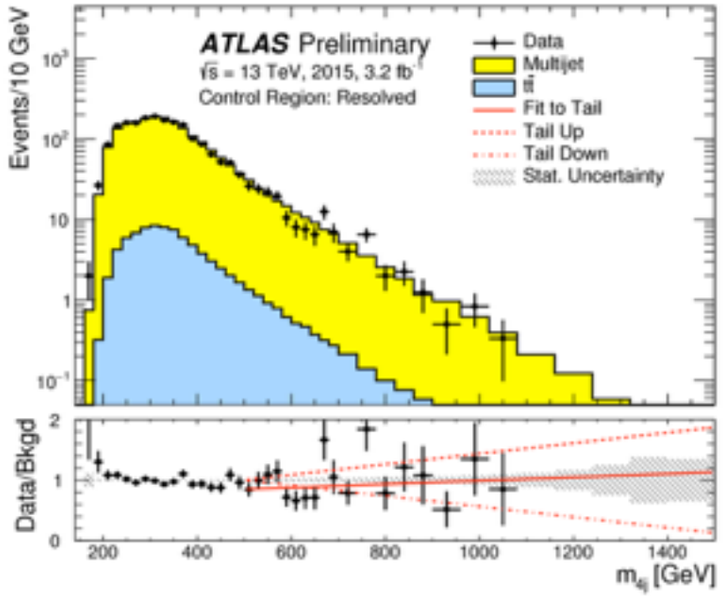
Source of systematic uncertainty		Impact in % on the search for di-Higgs production in non-resonant mode			Impact in % on the search for di-Higgs production in resonant mode		
		hh signal	Single-h bkg	Cont.	$X \to hh$ signal	SM $h+hh$ bkg	Cont.
Luminosity		±5.0	±5.0	-	±5.0	±5.0	-
Trigger		±0.4	±0.4	-	±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

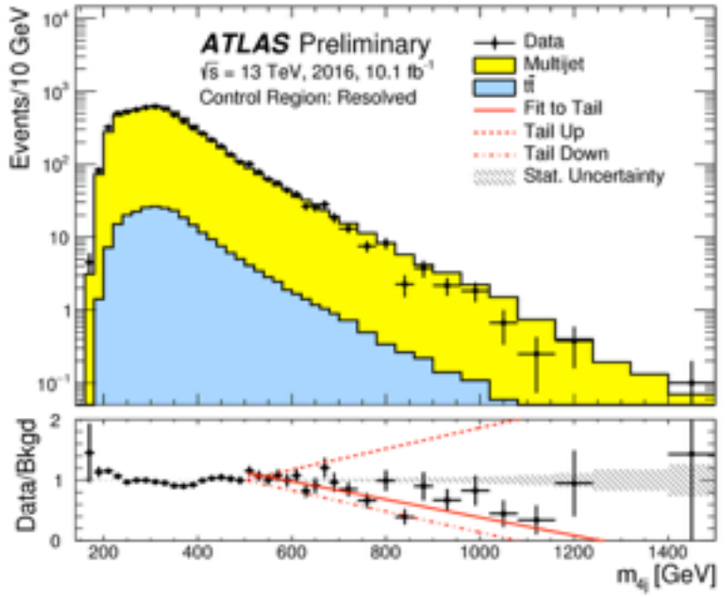
ATLAS-CONF-2016-049

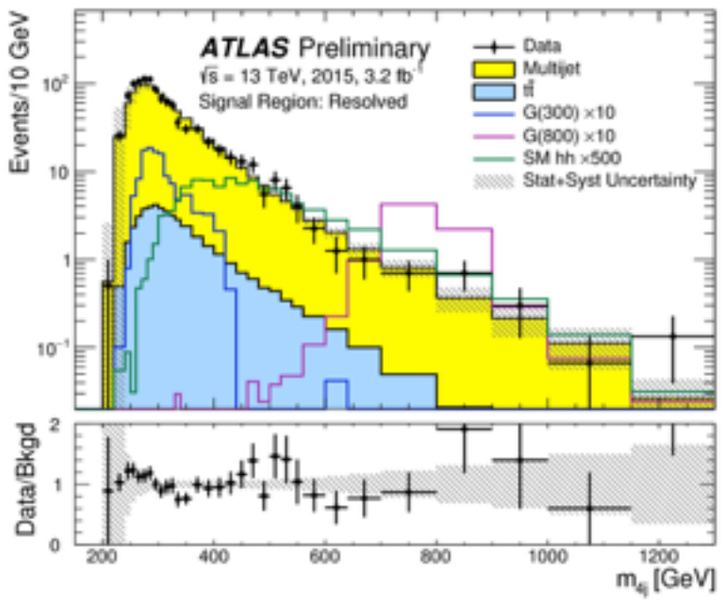
resolved analysis

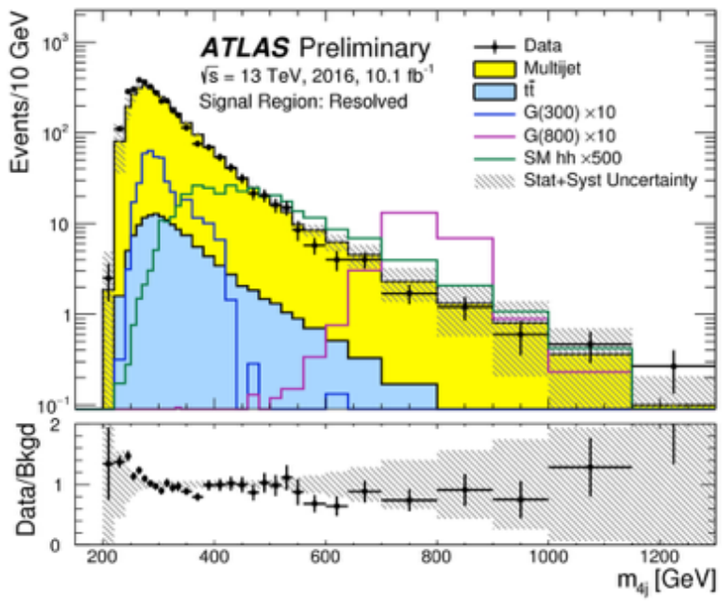






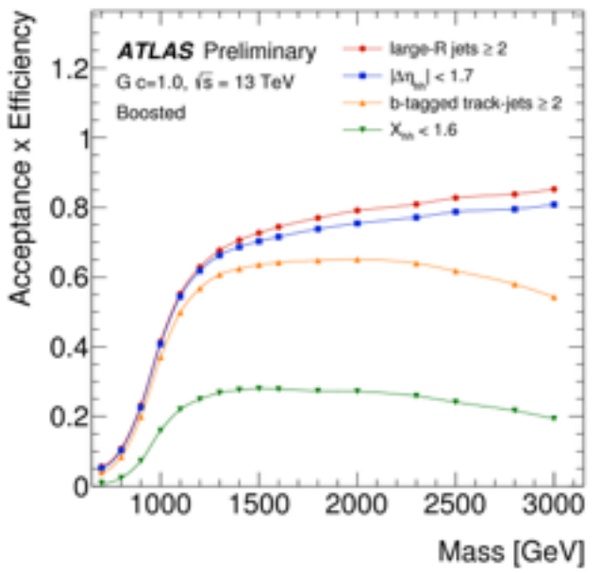


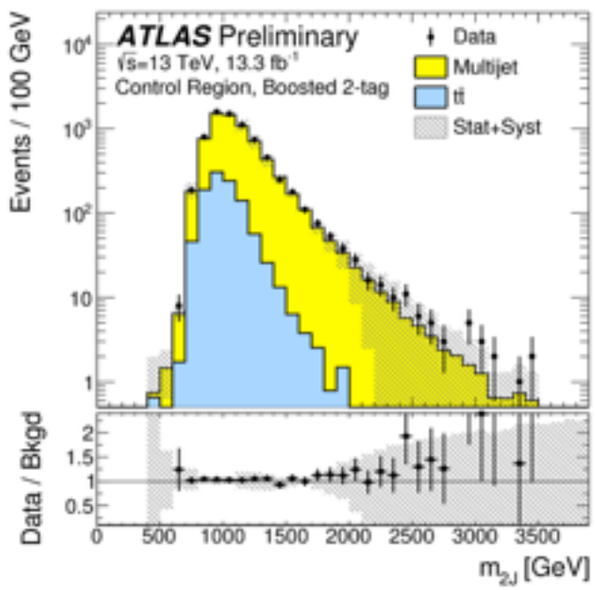


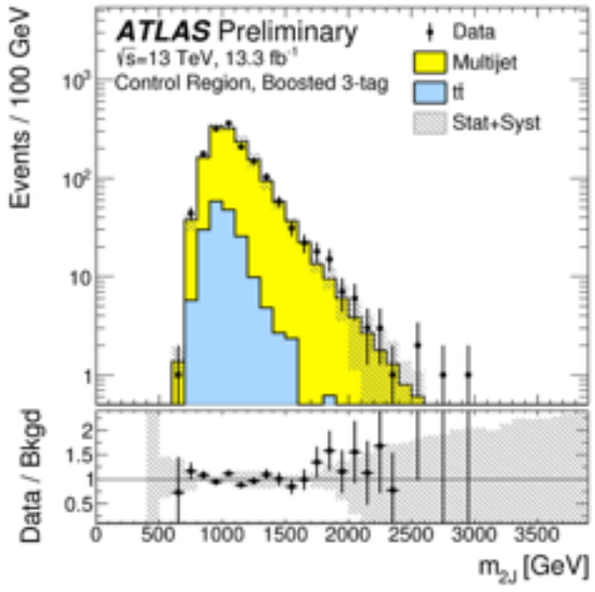


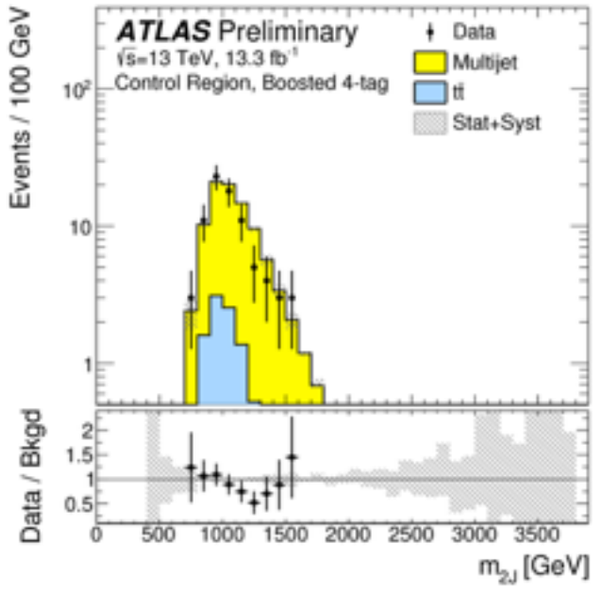
ATLAS-CONF-2016-049

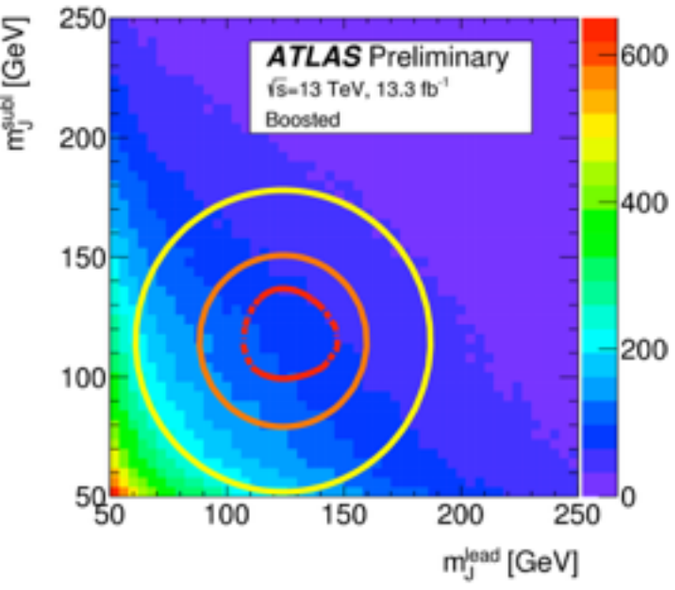
boosted analysis

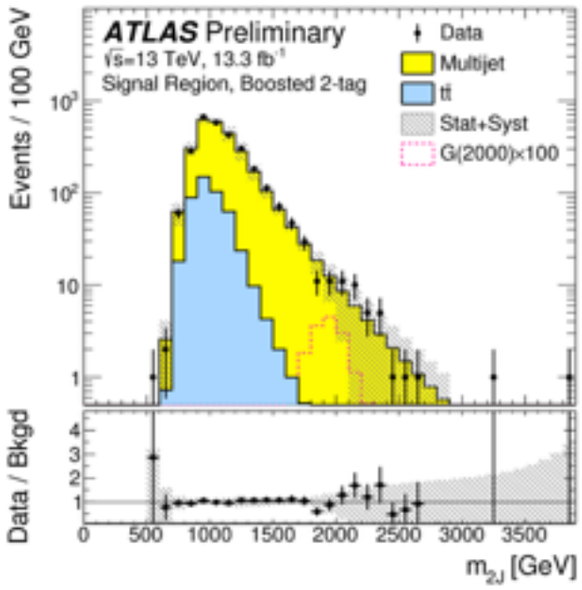


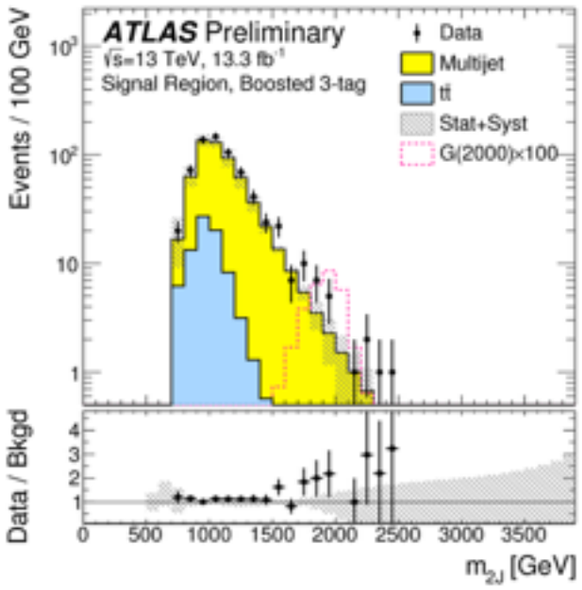


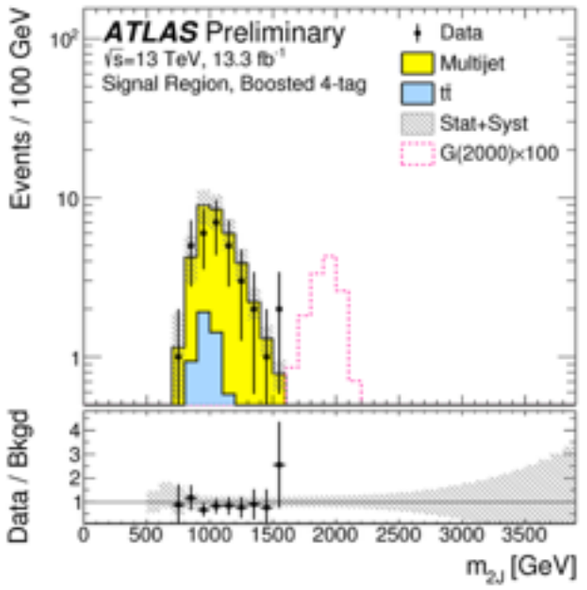












ATLAS-CONF-2016-049

resolved analysis

Sample	2015 Sideband	2015 Control Region	2016 Sideband	2016 Control Region
Multijet	4 196 ± 65	3 861 ± 86	13 080 ± 120	12 430 ± 160
$t\bar{t}$	103 ± 6	159 ± 15	332 ± 18	546 ± 38
Total	4 300 ± 66	4 021 ± 88	13 410 ± 120	12 970 ± 110
Data	4 300	3 995	13 413	12 752

Source	2015 Background	2015 SM hh	2015 G^*_{KK} (800 GeV)	2016 Background	2016 SM hh	2016 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

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), $k/\bar{M}_{\mathrm{Pl}} = 1$	8 ± 3	24 ± 8

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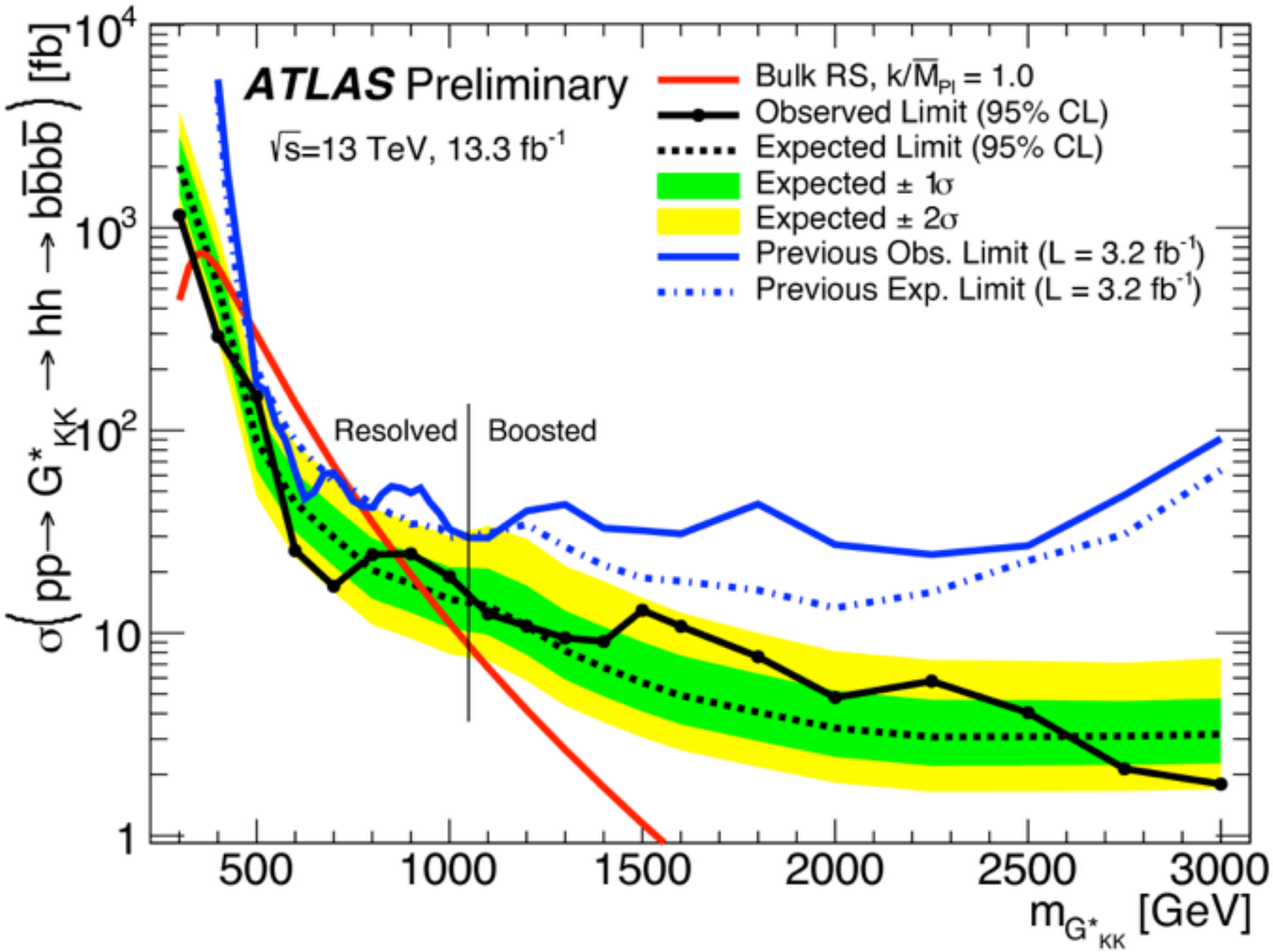
boosted analysis

	2-tag-split		3-tag		4-tag	
Sample	Sideband	Control Reg.	Sideband	Control Reg.	Sideband	Control Reg.
Multijet	$19\,400 \pm 200$	$5\,917 \pm 62$	$4\,294 \pm 89$	$1\,318 \pm 27$	258 ± 22	84.3 ± 7.1
$t\bar{t}$	$3\,860 \pm 160$	$1\,038 \pm 45$	720 ± 68	189 ± 19	36 ± 16	10.1 ± 4.5
Total	$23\,260 \pm 160$	$6\,954 \pm 52$	$5\,014 \pm 73$	$1\,507 \pm 24$	294 ± 17	94.4 ± 5.8
Data	23 277	7 200	5 007	1 529	291	81

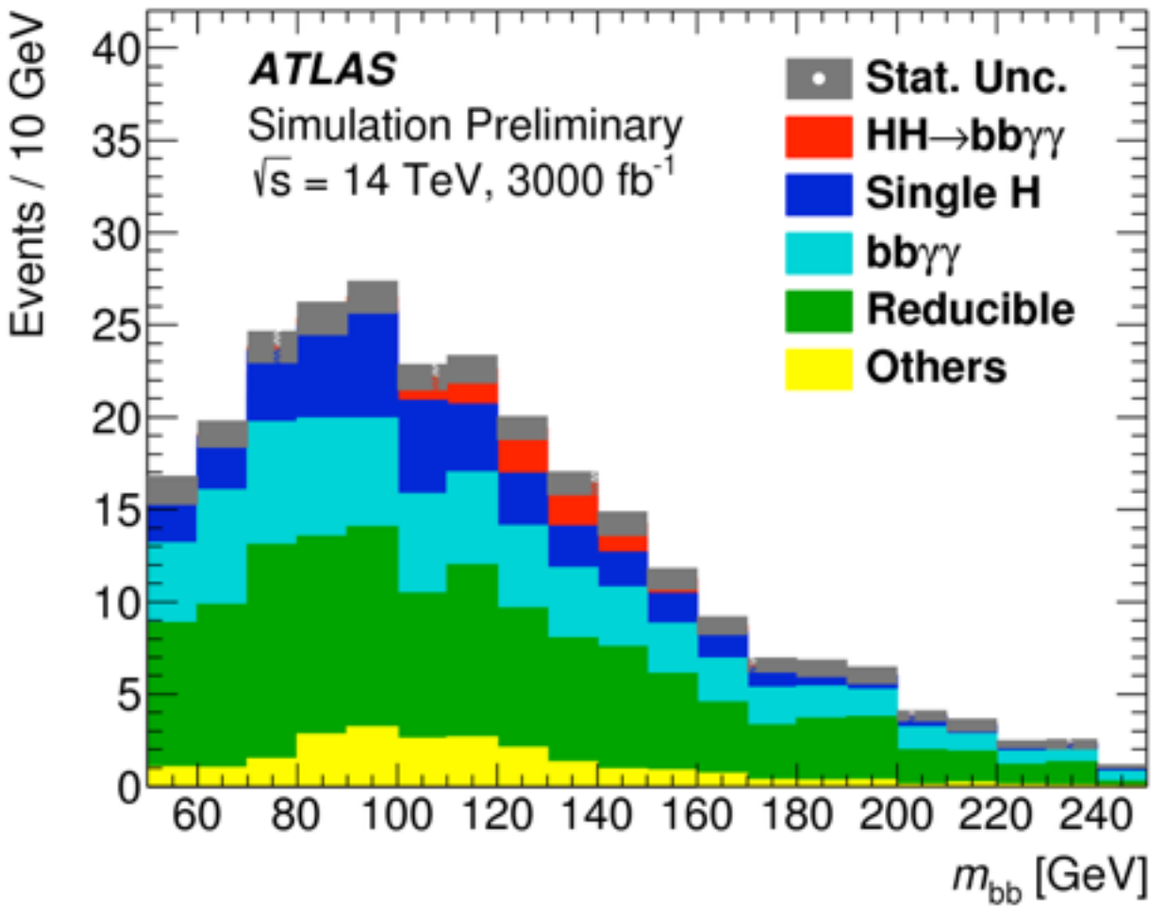
	2-tag-split		3-tag		4-tag	
Source	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)
Luminosity	-	2.9	-	2.9	-	2.9
JER	-	0.1	-	0.1	-	0.3
JMR	-	12	-	12	-	12
JES/JMS	-	4.5	-	4.2	-	3.3
b-tagging	-	58	-	15	-	38
Theoretical	-	2.7	-	2.3	-	2.4
Bkg Estimate	4.4	-	4.6	-	21	-
Statistical	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

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

ATLAS-CONF-2016-049



HH → YYBB @ HL-LHC (ATL-PHYS-PUB-2017-001)



signal and bkg event yield

Categorisation	Barrel-barrel	Other
$H(\to b\bar{b})H(\to\gamma\gamma), \lambda/\lambda^{SM}=1$	7.309 ± 0.025	2.235 ± 0.016
$t\bar{t}H(\to\gamma\gamma)$	5.89 ± 0.13	1.98 ± 0.08
$ZH(\to\gamma\gamma)$	3.42 ± 0.17	1.56 ± 0.06
$b\bar{b}H(\to\gamma\gamma)$	0.106 ± 0.011	0.042 ± 0.005
$ggH(\to\gamma\gamma)$	1.96 ± 0.29	0.78 ± 0.19
$bb\gamma\gamma$	12.4 ± 0.4	9.4 ± 0.5
$c\bar{c}\gamma\gamma$	5.70 ± 0.31	2.77 ± 0.34
$jj\gamma\gamma$	2.2 ± 0.5	1.84 ± 0.32
$b\bar{b}j\gamma$	11.8 ± 0.8	10.8 ± 0.8
$c\bar{c}j\gamma$	2.5 ± 0.7	0.7 ± 0.4
$b\bar{b}jj$	3.3 ± 0.7	2.05 ± 0.33
$Z(\to b\bar{b})\gamma\gamma$	1.21 ± 0.10	0.85 ± 0.10
$t\bar{t}\gamma(\geq 1\text{lepton})$	3.80 ± 0.34	1.36 ± 0.14
$t\bar{t}(\geq 1\text{lepton})$	0.80 ± 0.28	1.6 ± 0.4
Total background	55.1 ± 1.6	35.7 ± 1.3
Significance	0.984 ± 0.018	0.373 ± 0.017
Combined significance	1.052 ± 0.026	

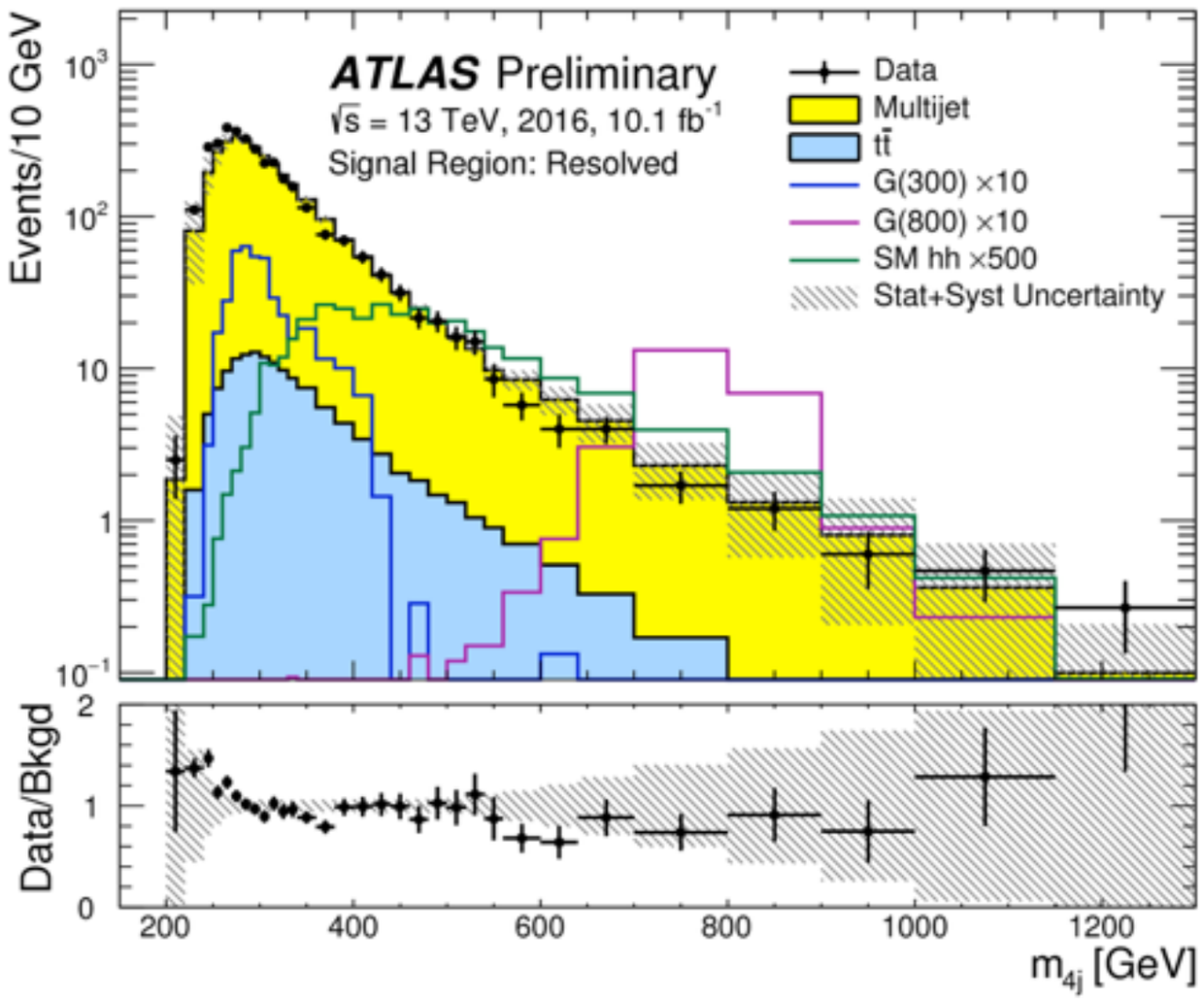
HH → YYBB @ HL-LHC (ATL-PHYS-PUB-2017-001)

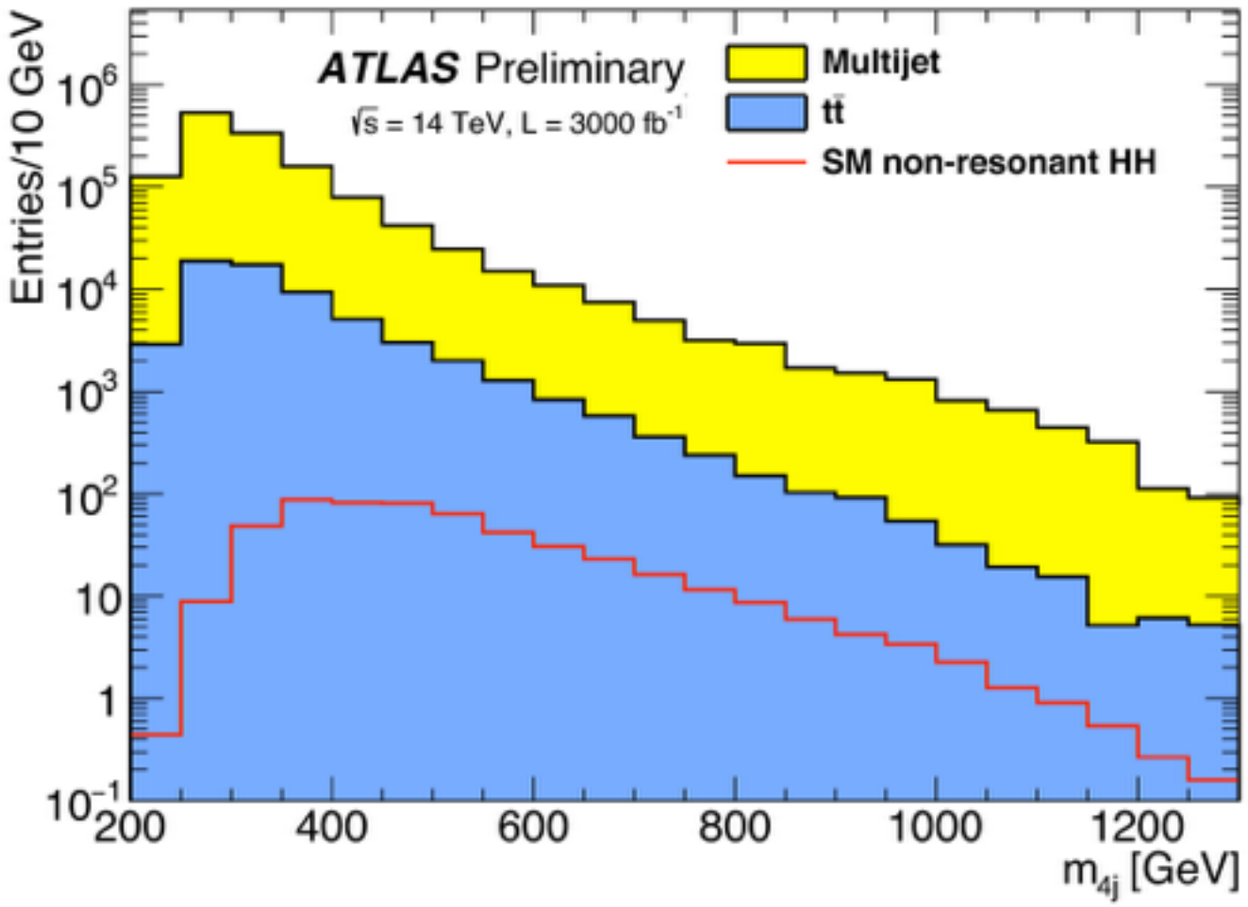
Process	Generator	$\sigma \cdot BR$ [fb]	Order QCD	Equivalent Lumi. [fb^{-1}]
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 1$	MadGraph5/Pythia 8	0.11	NNLO	5.5×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 0$	MadGraph5/Pythia 8	0.23	NNLO	1.3×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 2$	MadGraph5/Pythia 8	0.05	NNLO	6.1×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 10$	MadGraph5/Pythia 8	1.81	NNLO	0.2×10^6
$ggF(\gamma\gamma)$	Powheg-Box/Pythia 6	1.2×10^2	NNNLO	8.1×10^3
$t\bar{t}H(\gamma\gamma)$	Pythia 8	1.40	NLO	7.1×10^4
$ZH(\gamma\gamma)$	Pythia 8	2.24	NLO	4.4×10^4
$b\bar{b}H(\gamma\gamma)$	Pythia 8	1.26	NLO	4.2×10^6
$b\bar{b}\gamma\gamma$	MadGraph5/Pythia 8	1.4×10^2	LO	1.8×10^4
$c\bar{c}\gamma\gamma$	MadGraph5/Pythia 8	1.1×10^3	LO	3070
$jj\gamma\gamma$	MadGraph5/Pythia 8	1.6×10^4	LO	2460
$b\bar{b}j\gamma$	MadGraph5/Pythia 8	3.8×10^5	LO	130
$c\bar{c}j\gamma$	MadGraph5/Pythia 8	1.1×10^6	LO	36
$b\bar{b}jj$	MadGraph5/Pythia 8	4.6×10^8	LO	0.005
$Z(\rightarrow b\bar{b})\gamma\gamma$	MadGraph5/Pythia 8	5.07	LO	2.0×10^4
$t\bar{t}(\geq 1\text{lepton})$	Powheg-Box/Pythia 6	5.3×10^5	NNLO	5.7×10^2
$t\bar{t}\gamma(\geq 1\text{lepton})$	MadGraph5/Pythia 8	5.0×10^3	NLO	2×10^3

HH → YYBB @ HL-LHC (ATL-PHYS-PUB-2017-001)

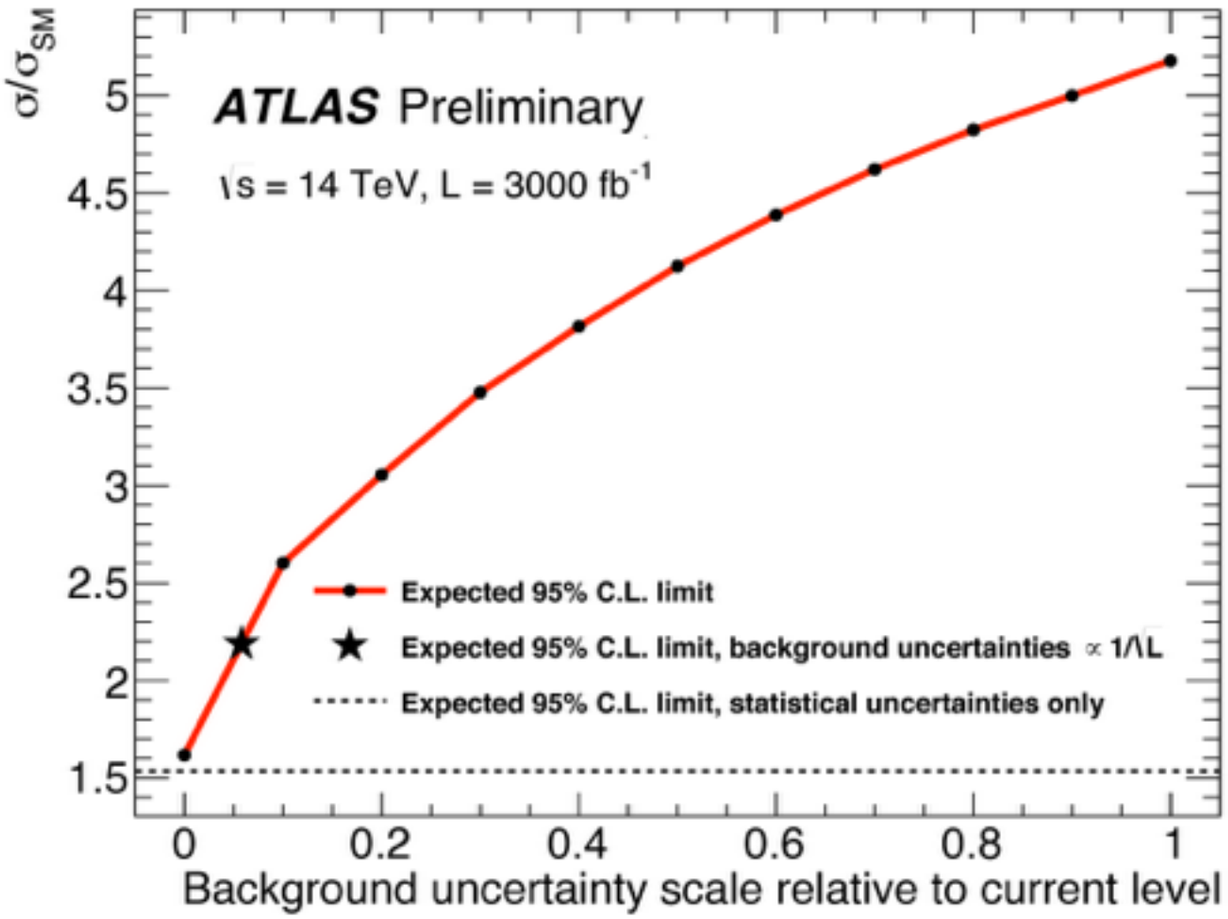
Event Selection Criteria
≥ 2 isolated photons, with $p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$
≥ 2 jets identified as b-jets with leading/subleading $p_{\mathrm{T}} > 40/30$ GeV, $\lvert\eta\rvert$¡2.4
< 6 jets with $p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 2.5$
No isolated leptons with $p_{\mathrm{T}} > 25$ GeV, $\lvert\eta\rvert < 2.5$
$0.4 < \Delta R_{b\bar{b}} < 2.0, 0.4 < \Delta R_{\gamma\gamma} < 2.0, 0.4 < \Delta R_{\gamma jet}$
$122 < m_{\gamma\gamma} < 128$ GeV, $100 < m_{b\bar{b}} < 150$ GeV
$p_{\mathrm{T}}^{\gamma\gamma}$, $p_{\mathrm{T}}^{b\bar{b}} > 80$ GeV

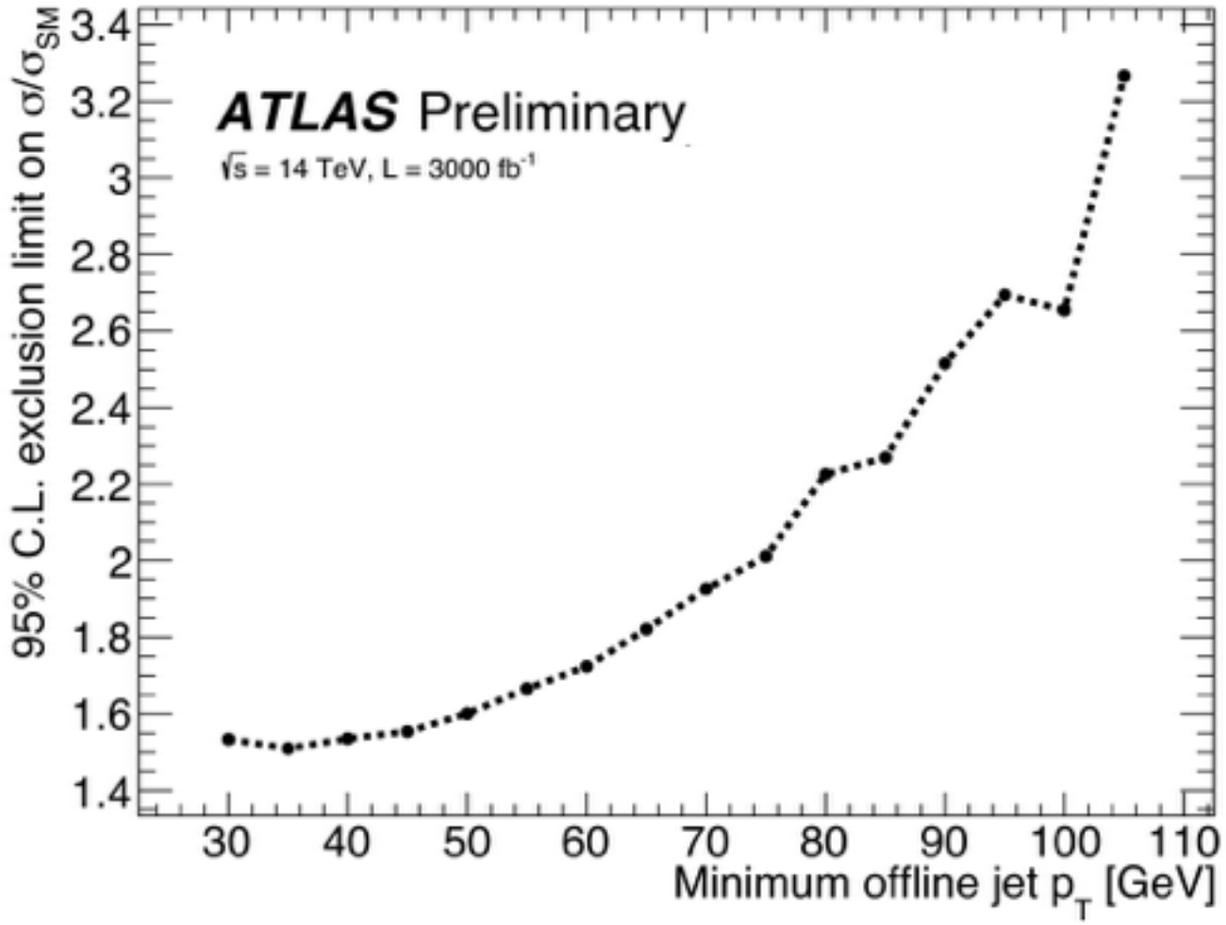
HH → BBBB @ HL-LHC (ATL-PHYS-PUB-2016-024)





HH → BBBB @ HL-LHC (ATL-PHYS-PUB-2016-024)





HH → BBBB @ HL-LHC (ATL-PHYS-PUB-2016-024)

Jet Threshold [GeV]	Background Systematics	σ/σ_{SM} 95% Exclusion	$\lambda_{HHH}/\lambda^{SM}_{HHH}$ Lower Limit	$\lambda_{HHH}/\lambda^{SM}_{HHH}$ Upper Limit
30 GeV	Negligible	1.5	0.2	7
30 GeV	Current	5.2	-3.5	11
75 GeV	Negligible	2.0	-3.4	12
75 GeV	Current	11.5	-7.4	14