ATLAS DI-HIGGS SEARCHES AT 13 TEV.

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[1] DESY

on behalf of the ATLAS Collaboration

LHC Discussion on Higgs, 9th May 2016

Why search for Higgs pairs?

SM motivation

Higgs self-coupling (λ_{hhh}): last unmeasured SM parameter

- Challenging target for the future
- Requires high luminosity and combination of channels

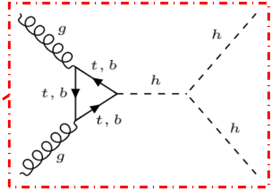
BSM motivation

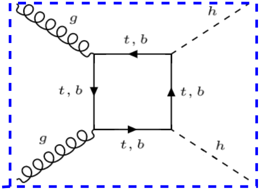
The Higgs boson at 125 GeV provides a new "standard candle"

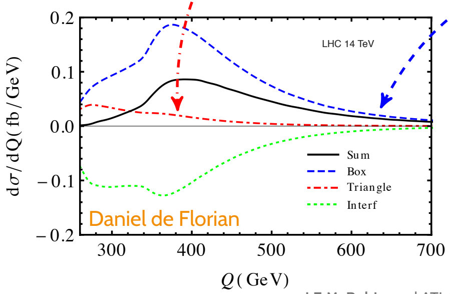
- Narrow resonance (smaller than experimental resolution)
- ...new opportunities for resonant and non-resonant searches

Interference between SM processes

SM di-Higgs observation difficult because triangle and box diagrams interfere destructively



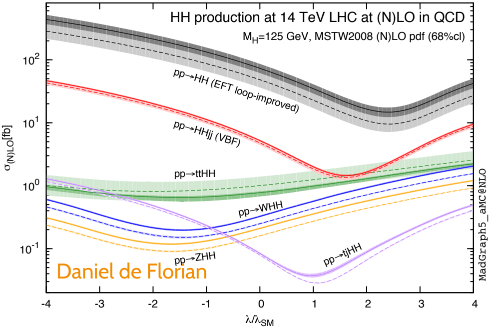


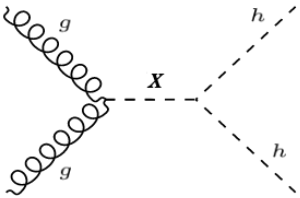


- Some signatures use high-p_{T} regime to reduce background
- ...also reduces sensitivity to self-coupling

BSM enhancements

- Cross section strongly dependent on λ_{hhh}
- Increased cross section if λ_{hhh} is far from λ_{SM}



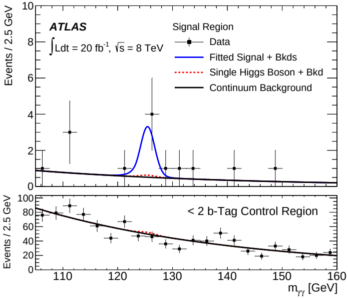


Many resonant BSM models

- Two Higgs doublet model
- Randall-Sundrum graviton
- SUSY (eg. stoponium)
- radions...

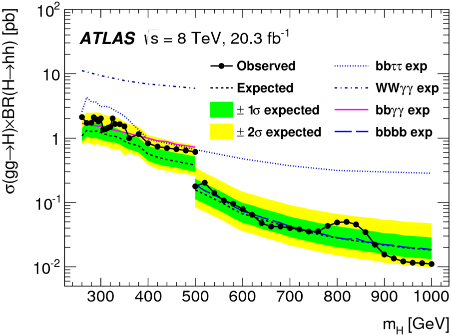
ATLAS Run 1 results

PRL 114, 081802 (2015), PRD 92, 092004 (2015)



- Run 1 $b\bar{b}\gamma\gamma$ (8 TeV)
- 5 (1.5) events obs. (exp.)
- Small (2.4σ) excess

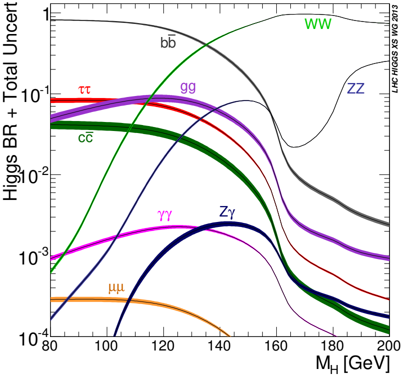
Combine: $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$, $WW\gamma\gamma$, $b\bar{b}\tau\tau$



- No significant excess seen in 8 TeV combination

ATLAS Run 2 searches

- Only two public ATLAS 13 TeV di-Higgs searches: $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$



$hh \to b\bar{b}b\bar{b}$ has highest BR ~ 0.34

Why $b\bar{b}\gamma\gamma$?

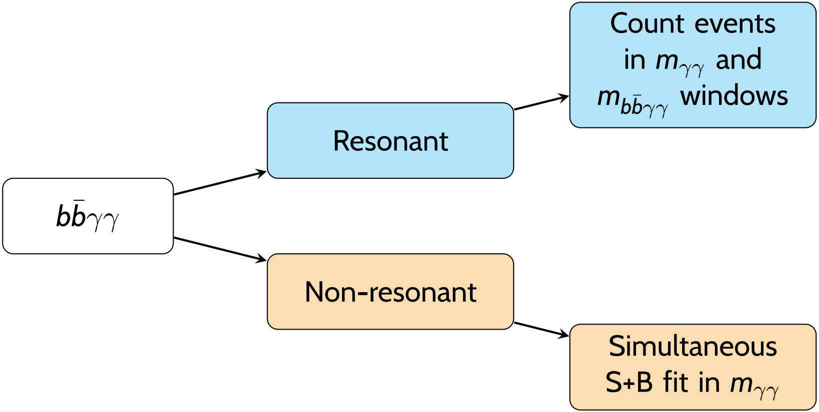
1. $h \to b\bar{b}$ BR ~ 0.57
2. Best m_H resolution in $h \to \gamma\gamma$
3. Easy to trigger on diphotons

- Other channels aiming for summer conferences or full 2016 dataset

Run 2 $b\bar{b}\gamma\gamma$ analysis

$b\bar{b}\gamma\gamma$ analysis categories

ATLAS_CONF_2016_004



Event selection and categorisation

- Two well-identified, isolated photons[1]
- Two anti-k_t R$=$0.4 jets[2]: $p_{\mathrm{T}}{}^{1(2)} > 55\ (35)$ GeV (add close-by muon 4-vectors)
- Recompute pileup rejection using diphoton vertex

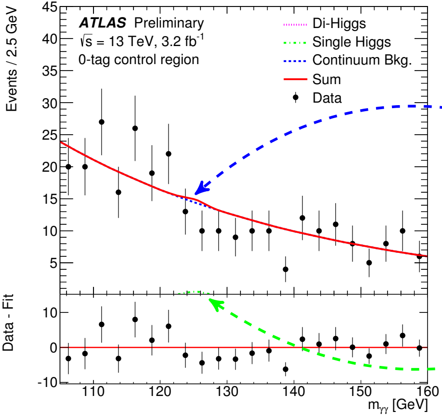
Jet categories

- 0 b-jet: control events
- 1 b-jet: not used (low purity for selecting correct jets)
- 2 b-jet: signal events
- 3+ b-jet: vetoed (orthogonality to $b\bar{b}b\bar{b}$)

[1] ATLAS-CONF-2015-060

[2] EPJC 75 (2015) 17

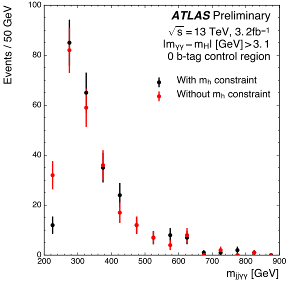
Non-resonant analysis



- Exponential fit to continuum background in 0-tag control region
- Use same exponential in 2-tag signal region; normalised to sidebands
- SM single-/di-Higgs also taken into account

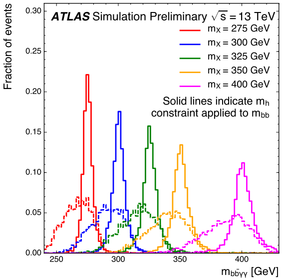
- Look for any excess on top of the predicted contributions

Resonant analysis

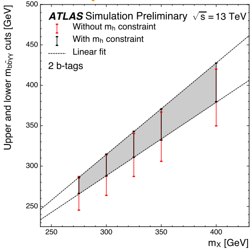


Start with requirement $|m_H - m_{\gamma\gamma}| < 2\sigma_{yy}$

- Constrain bb mass to m_H: improves resolution without biasing multijet bkg
- Use simulation to define 95% efficient $m_{b\bar{b}\gamma\gamma}$ windows

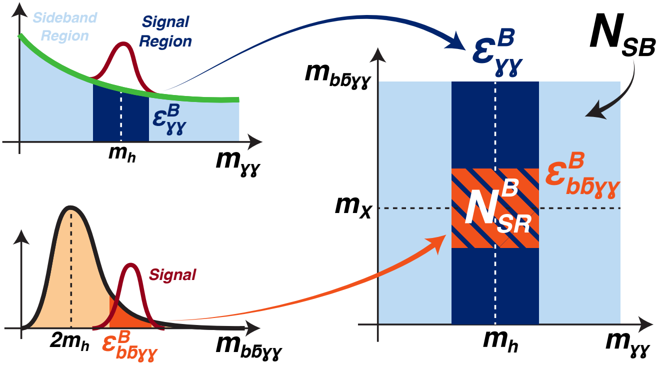


Count events inside defined signal region



Resonant analysis

Background contribution extrapolated from control regions



$$N^{SR}_{continuum} = N^{sideband}_{continuum} \times \frac{\mathcal{E}^{B}_{\gamma\gamma}}{1 - \mathcal{E}^{B}_{\gamma\gamma}} \mathcal{E}^{B}_{\gamma\gamma bb}$$

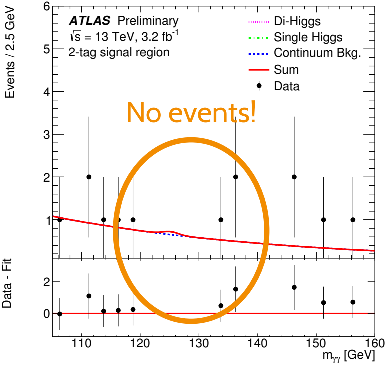
Non-resonant results

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

Inside $m_{\gamma\gamma}$ window around m_H

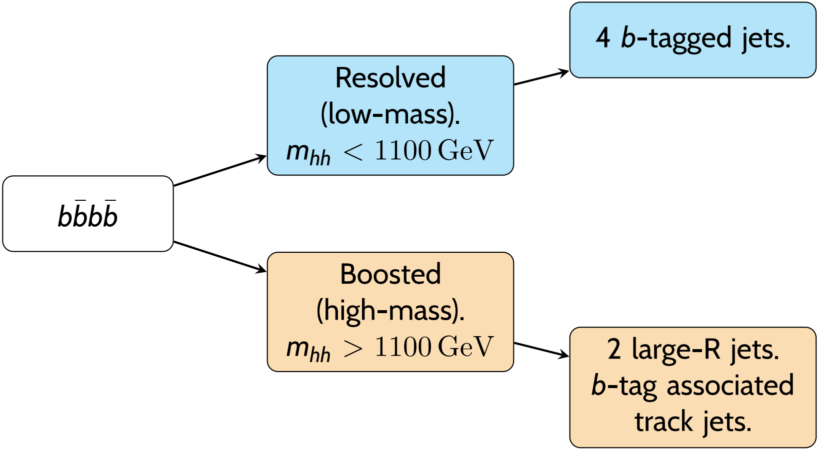
- 0-tag control: 27 (38) events obs. (exp.)
- 2-tag signal: 0 (2) events obs. (exp.)



- No events in the signal region $\rightarrow$ no events in resonant analysis
- Limits set on resonant and non-resonant production

Run 2 $b\bar{b}b\bar{b}$ analysis

$b\bar{b}b\bar{b}$ analysis categories



Event selection and categorisation

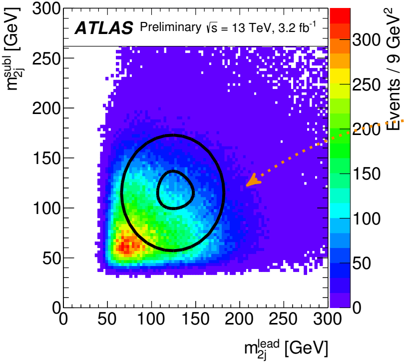
Resolved selection

- 4+ b-tagged anti-k_t R=0.4 jets (add close-by muon 4-vectors)
- Two dijet systems grouped in ΔR, requiring minimum $\Delta\eta$
- Low m_{4j}: $p_{\mathrm{T}}^{\mathrm{jj1(2)}} > 200\ (150)$ GeV
- High m_{4j}: $p_{\mathrm{T}}^{\mathrm{jj1(2)}} > 400\ (260)$ GeV

Boosted selection

- 2 anti-k_t R=1.0 jets (add close-by muon 4-vectors)
- Require $250 < p_{\mathrm{T}} < 1500$ GeV
- Ghost-associated track jets used for b-tagging
- Separate 3 b-tag and 4+ b-tag categories

- Kinematic veto reduces large $t\bar{t}$ background
- Residual contribution normalised to data in control region

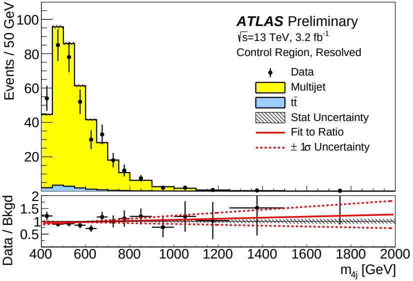


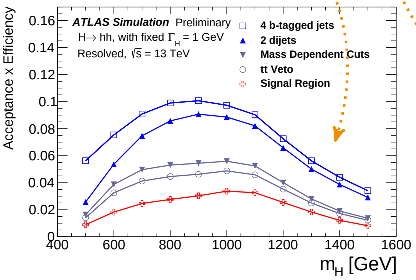
- Events with exactly 2 *b*-tagged jets $\rightarrow$ QCD background
- Take sideband region and reweight kinematics: p_T^{jj}, $\Delta R_{jj^{subl}}$, $\Delta R_{jj,jj}$
- Normalise to 4 *b*-tag sample and subtract

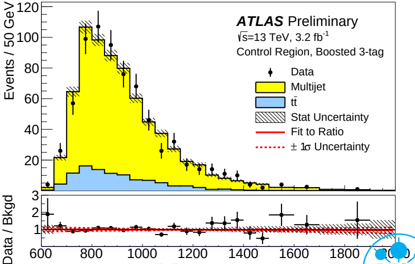
Similar procedure used for boosted analysis

Control regions

- Agreement in control regions
- Kinematic selection affects signal acceptance
- Calculated for each mass point in each model

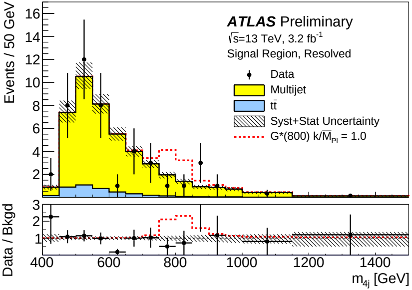


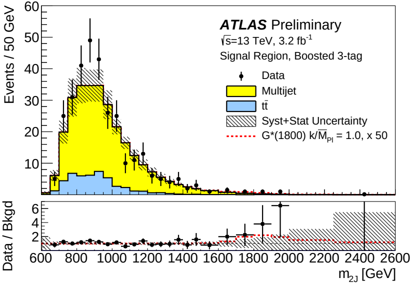




Signal regions

- Data agrees well with background-only prediction
- No significant excesses seen

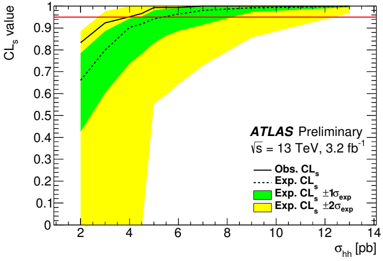




- Limits on non-resonant production plus graviton and heavy-Higgs models

Interpretation and limit-setting

$b\bar{b}\gamma\gamma$ limits

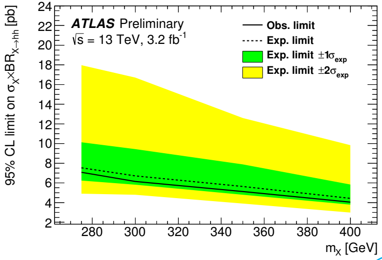


Non-resonant production:

- Set limits with CLs technique
- 3.9(5.4) pb obs. (exp.) limit

Resonant production:

- Use toys due to low number of expected events
- Observe 4.0–7.0 pb for resonance masses 275–400 GeV

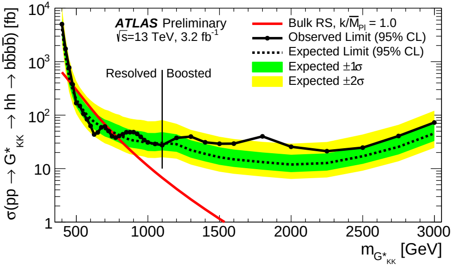


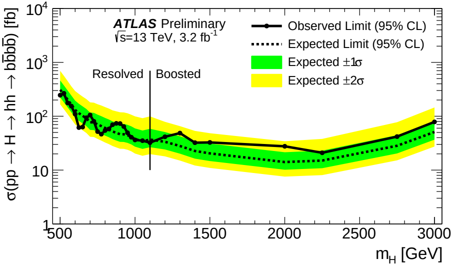
$b\bar{b}b\bar{b}$ limits

Non-resonant limit: 1.22 pb

Resonant: spin-2 RS Graviton

- $475 < m_{G^*_{KK}} < 785$ GeV $(k/\bar{M}_{Pl} = 1.0)$
- $m_{G^*_{KK}} < 980$ GeV $(k/\bar{M}_{Pl} = 2.0)$





Resonant: spin-0 heavy Higgs

- 95% CL limits 30–150 fb
- ...for resonance masses 500–3000 GeV

Conclusions

- ATLAS has released the first 13 TeV di-Higgs searches
- No significant excesses $\rightarrow$ set limits with 3.2 fb^{-1} of data

Non-resonant limits

$b\bar{b}\gamma\gamma$: 3.9 pb $b\bar{b}b\bar{b}$: 1.22 pb

Resonant limits

- $b\bar{b}\gamma\gamma$ in range 275–400 GeV on generic heavy resonances
- $b\bar{b}b\bar{b}$ in range 500–3000 GeV on RS-graviton and heavy Higgs

- Improved limits with respect to Run 1 in both channels
- 2016 should be an interesting year for di-Higgs searches
- More data is coming soon...stay tuned!

Backup

Full $b\bar{b}\gamma\gamma$ event/object selection

Objects	Selection
Photons	Tight ID, isolated, $\|\eta\| < 2.37$ $p_{\mathrm{T}\,1} > 0.35\, m_{\gamma\gamma}, p_{\mathrm{T}\,2} > 0.25\, m_{\gamma\gamma}$ $105 < m_{\gamma\gamma}$ [GeV] < 160
Jets	$p_{\mathrm{T}} > 25$ GeV, $\|\eta\| < 2.5$ $\|\mathrm{JVT}\| > 0.64$ ($p_{\mathrm{T}} < 50$ GeV, $\|\eta\| < 2.5$)
Muons	Medium ID $p_{\mathrm{T}} > 4$ GeV, $\|\eta\| < 2.5$ $\|d_0^{sig}\| < 3.0$, $\|z_0\| < 0.5$ mm
b-jets	MV2c20 85% *b*-jet muon correction ($\Delta R < 0.4$)
Remove objects overlapping with selected photons	
Signal/control (*b*)-jets	$p_{\mathrm{T}\,1} > 55$ GeV, $p_{\mathrm{T}\,2} > 35$ GeV $95 < m_{jj}$ [GeV] < 135

Count number of *b*-jets

- 0 *b*-tag category: control
- 1 *b*-tag category: not used
  (low purity of selecting correct jets)
- 2 *b*-tag category: signal
- 3 *b*-tag category: not used
  (remain orthogonal to 4*b* channel)

$b\bar{b}\gamma\gamma$ systematics

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

- Reduced from 86 nuisance parameters
- Resonant-mass-dependent systematics shown as range

$b\bar{b}b\bar{b}$ systematics: resolved

Source	Background	SM hh	G^*_{KK} (500 GeV) $\frac{k}{\bar{M}_{\mathrm{Pl}}} = 1$	G^*_{KK} (800 GeV) $\frac{k}{\bar{M}_{\mathrm{Pl}}} = 1$	G^*_{KK} (800 GeV) $\frac{k}{\bar{M}_{\mathrm{Pl}}} = 2$	H
Luminosity	–	5	5	5	5	5
JER	–	2	3	3	3	4
JES	–	12	14	5	4	6
b-tagging	–	18	15	26	27	26
Theoretical	–	13	2	3	3	3
Multijet	5	–	–	–	–	–
$t\bar{t}$	6	–	–	–	–	–
Total	8	26	21	28	28	28

- Systematic uncertainties in the signal region
- Expressed in percentage of background and signal yield

$b\bar{b}b\bar{b}$ systematics: boosted

Source	Background	G^*_{KK} $k/\bar{M}_{\mathrm{Pl}} = 1$	G^*_{KK} $k/\bar{M}_{\mathrm{Pl}} = 2$	H
Luminosity	-	5.0	5.0	5.0
3-tag				
JER	< 1	< 1	< 1	< 1
JES	2	< 1	< 1	< 1
JMR	1	12	12	11
JMS	5	14	13	17
b-tagging	1	23	22	23
Theoretical	-	3	3	3
Multijet Normalization	3	-	-	-
Statistical	2	1	1	1
Total	7	31	30	33
4-tag				
JER	< 1	< 1	< 1	< 1
JES	< 1	< 1	< 1	< 1
JMR	4	12	13	13
JMS	5	13	13	14
b-tagging	2	36	36	36
Theoretical	-	3	3	3
Multijet Normalization	14	-	-	-
Statistical	3	1	1	1
Total	15	42	42	43

- Systematic uncertainties in the signal region
- Expressed in percentage of background and signal yield