Searches for Higgs pair production by the ATLAS collaboration

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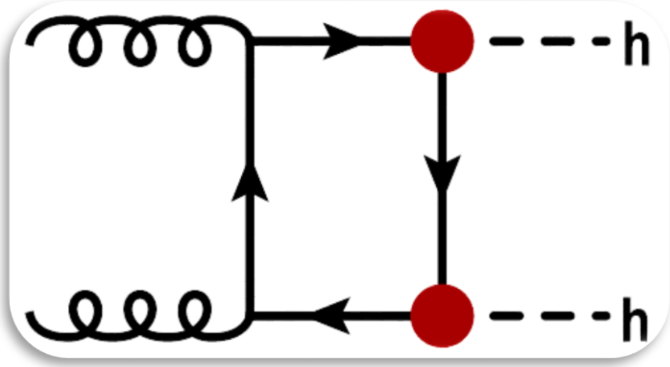
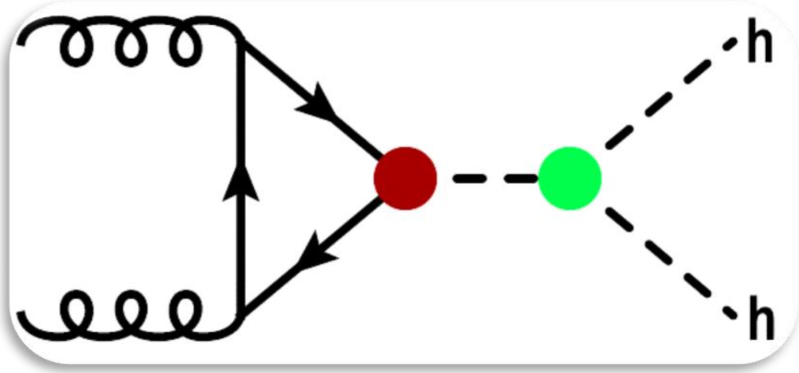
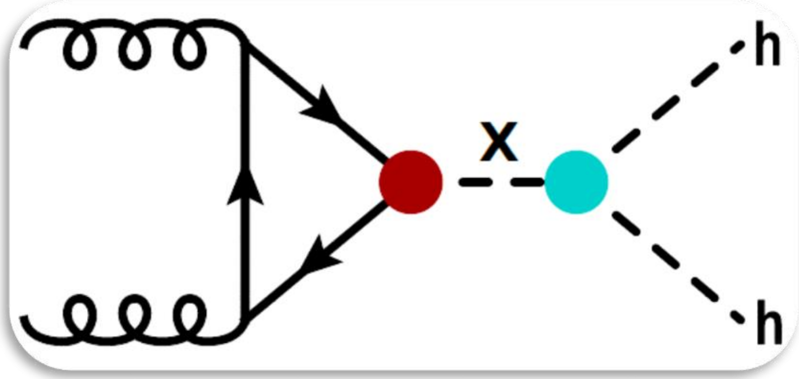
Motivation (theory)

- Higgs pair production has a very small cross section (10fb @ 8TeV, 33fb @ 13TeV) in SM with triangle and box destructive interference
- BSM can effectively enhance Higgs pair production
  - [**Non-resonance**]: altered Higgs self-coupling or ttH coupling
  - [**Resonance**]: BSM resonance decay, such as heavy Higgs and Kaluza-Klein graviton

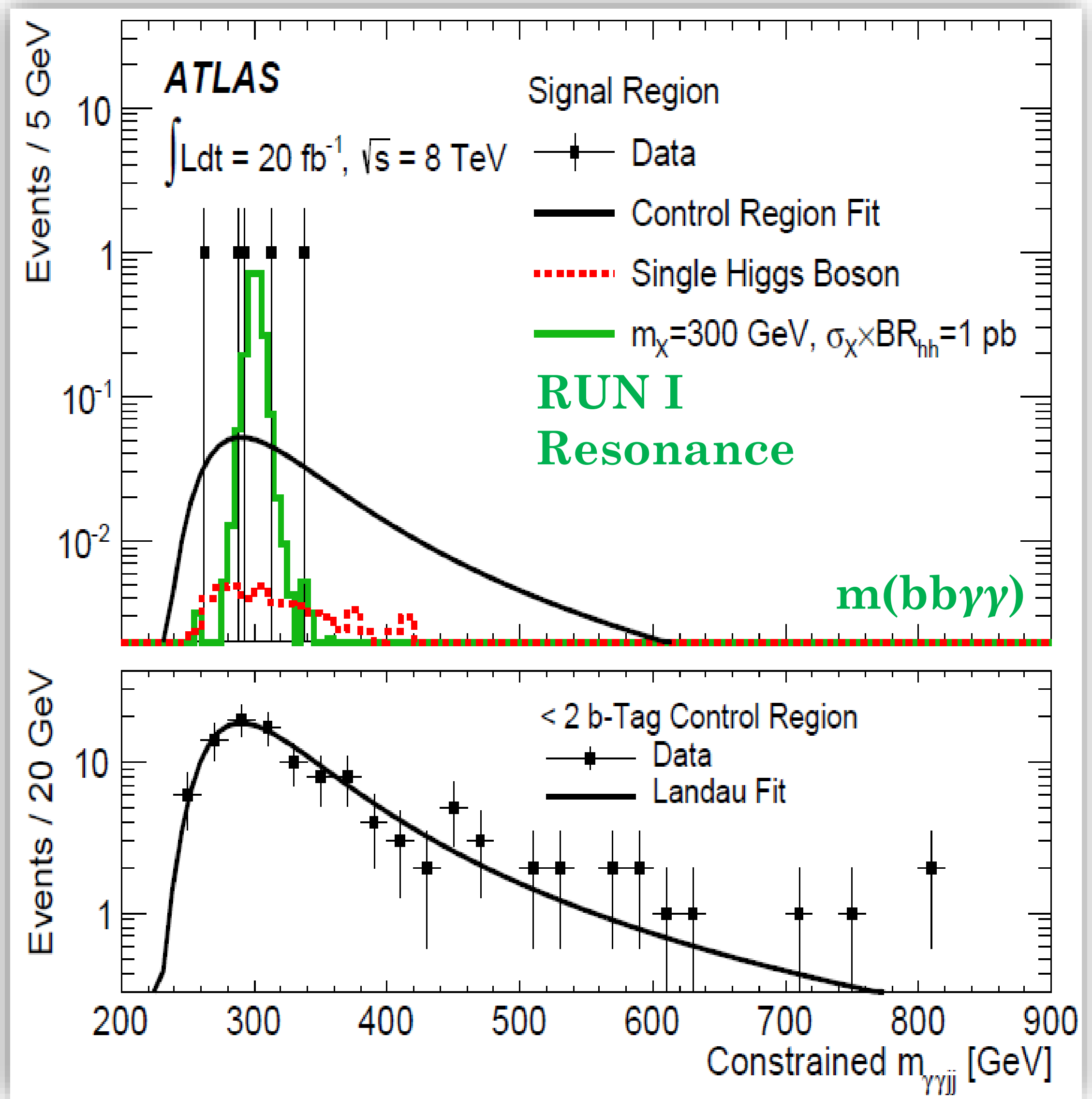






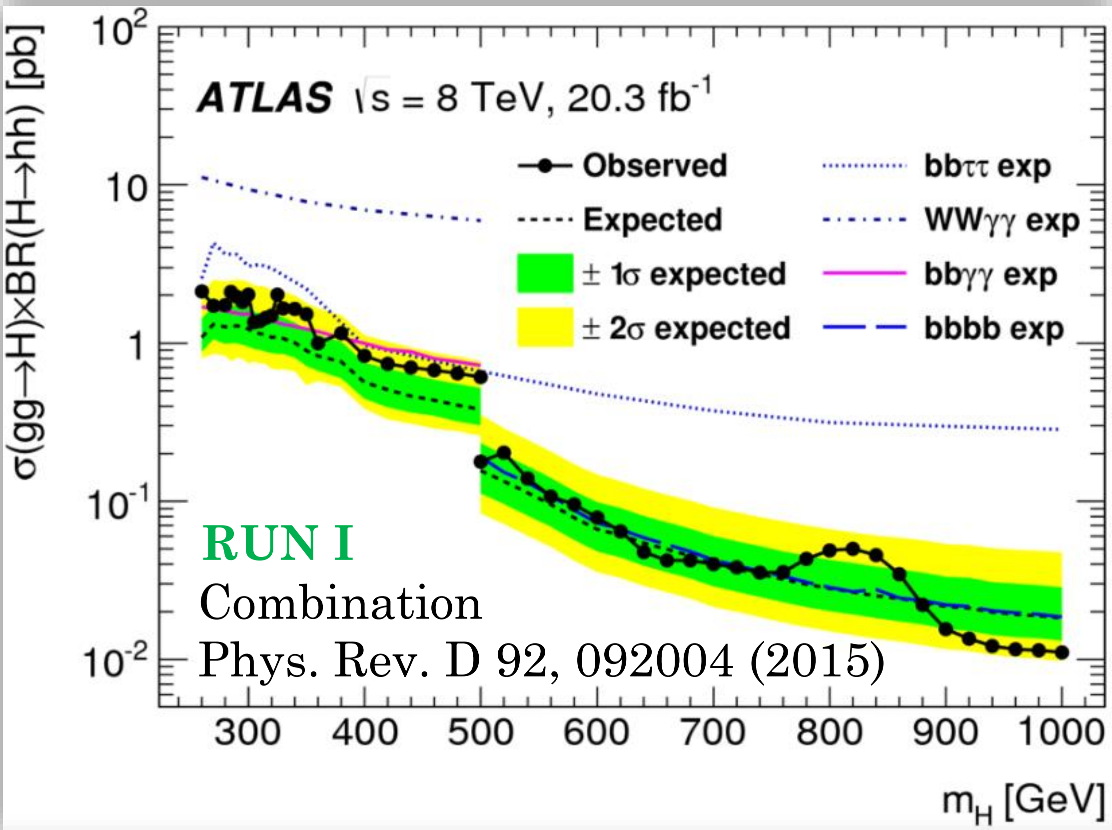
Motivation (experiment)

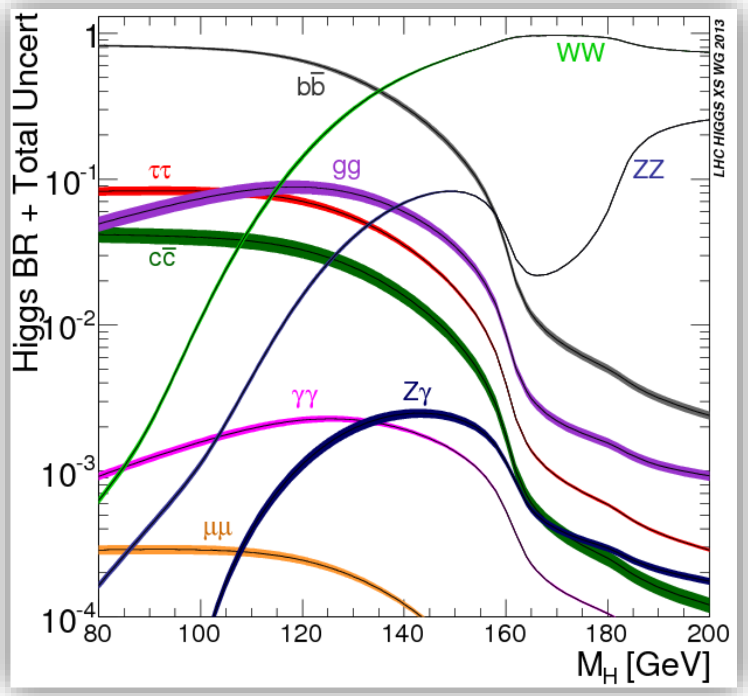
- There was an excess in data with the hh→$bb\gamma\gamma$ search in RUN I
- 5 events were found in signal region (1.5 events expected in backgrounds) ~ local 2.4σ
- Experimentally, it is extremely important to check this excess with RUN II early data



Final states

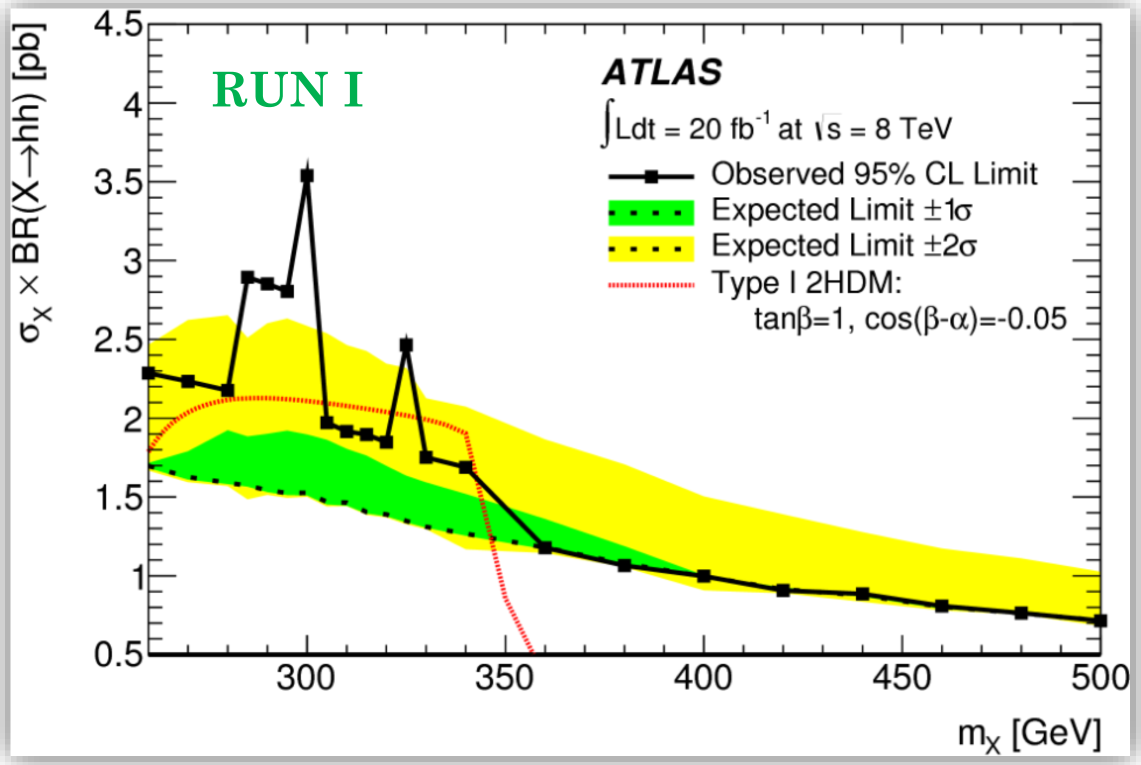
- One can look for Higgs pair via
  - *$bb\gamma\gamma$*, *$bbbb$*, *$bb\tau\tau$*, *$WW\gamma\gamma$* (done in RUN I)
  - and more in RUN II

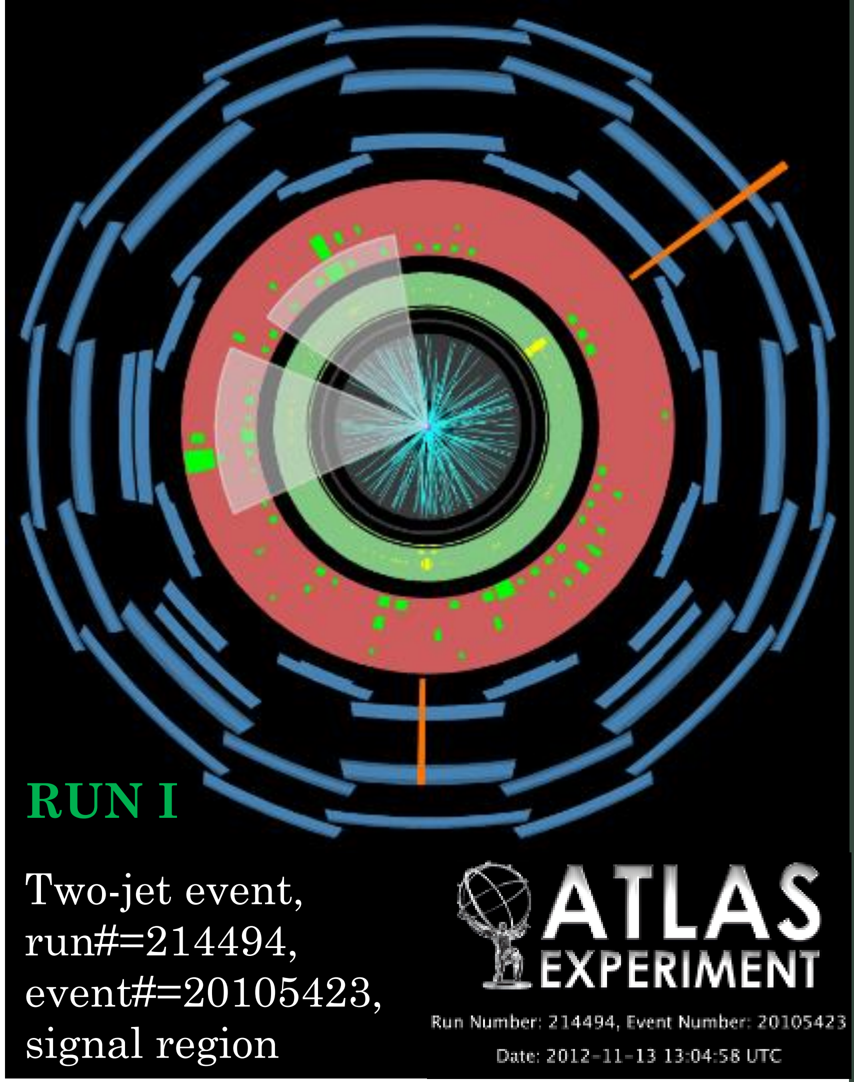




RUN I	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

RUN II so far: *$bb\gamma\gamma$* and *$bbbb$* (focus of this talk)





bbγγ

RUN I: Phys. Rev. Lett. 114, 081802 (2015);

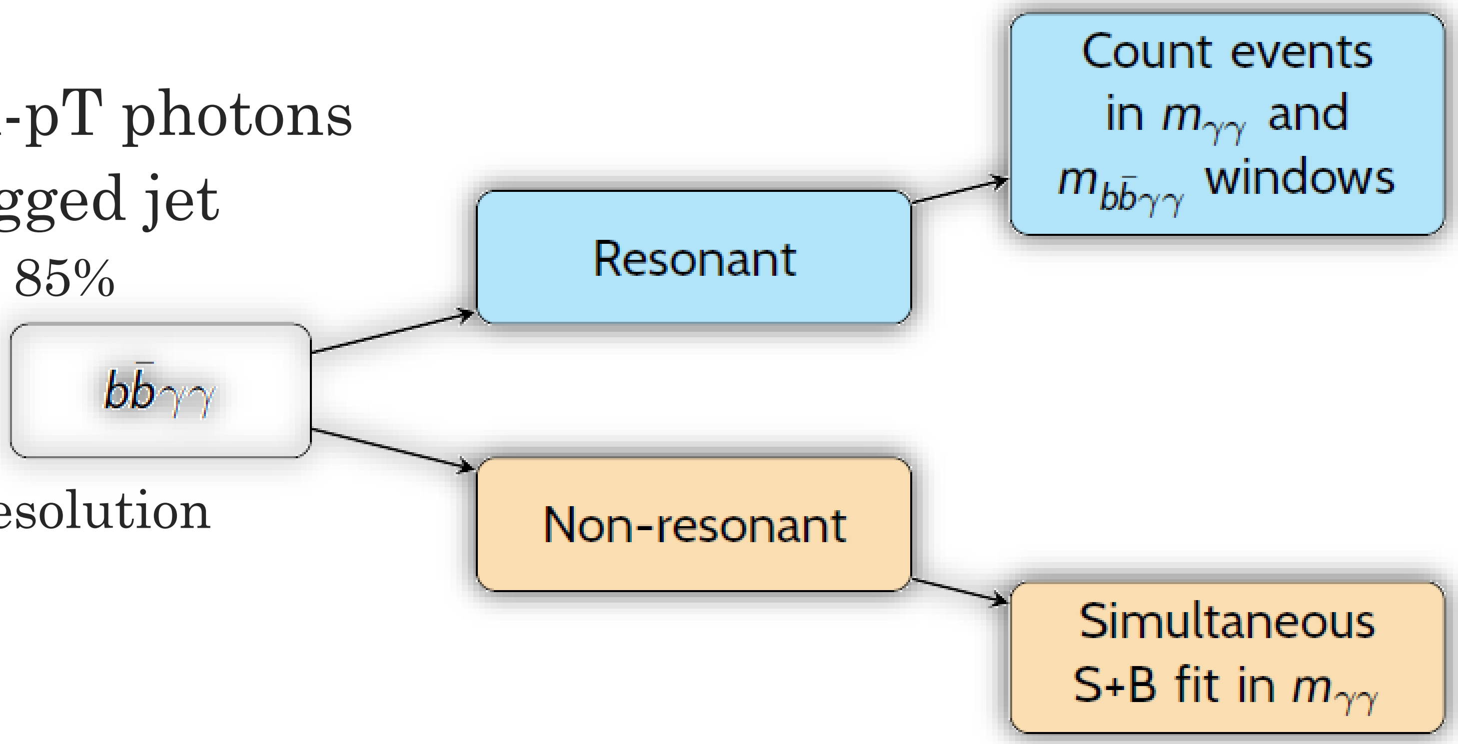
Phys. Rev. D 92, 092004 (2015) (combination)

RUN II: ATLAS-CONF-2016-004 (Moriond2016; talk RUN II only)

Signature and selection

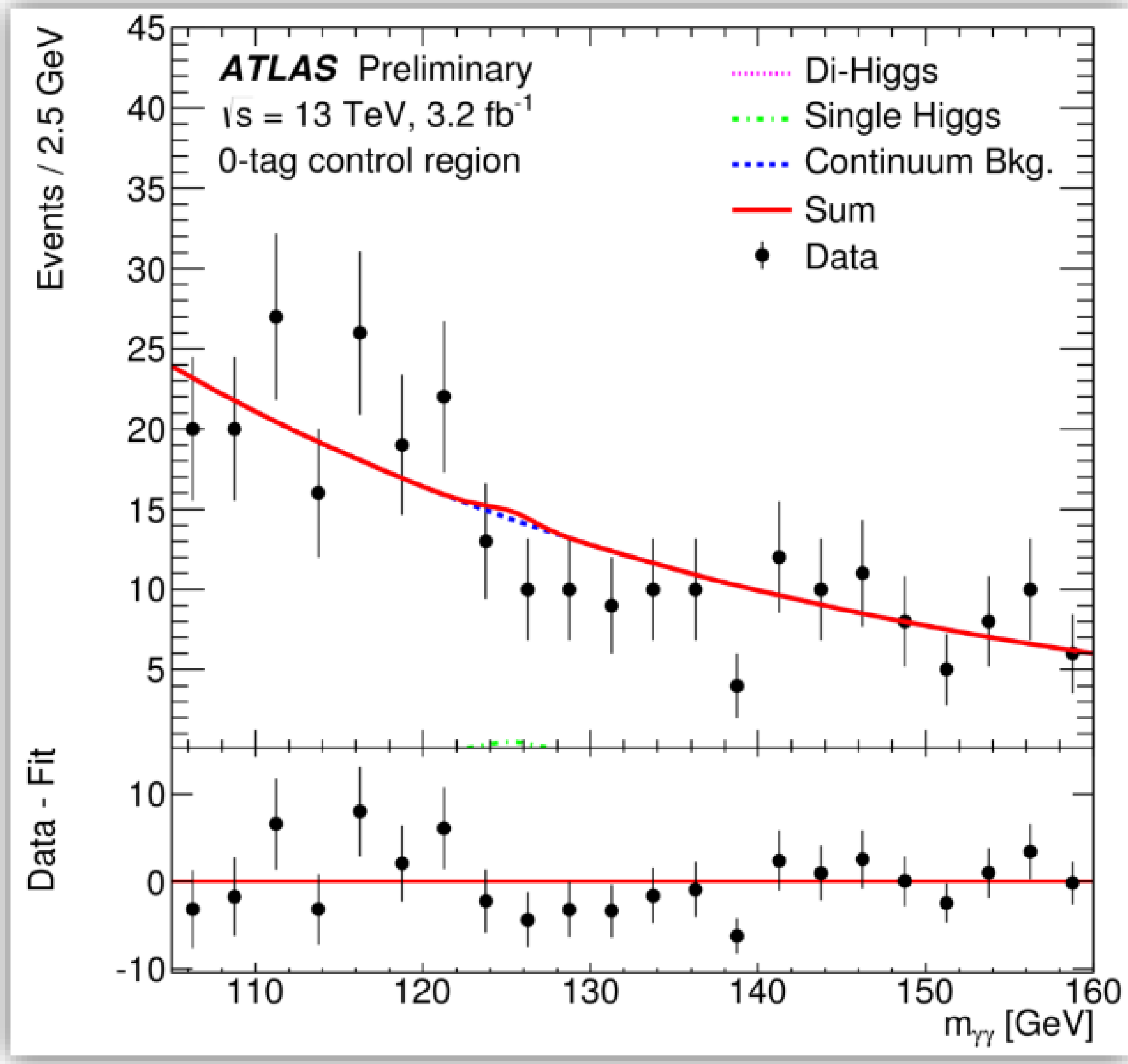
- Clean signature with
  - two bjets: largest branching ratio
  - two photons: best Higgs resolution
- Event selection
  - Diphoton trigger
  - Two isolated high-pT photons
  - Two high-pT b-tagged jet
    - With tag efficiency 85%
  - 125 constraint on
    - m(*bb*) or m(*jj*)
    - Improve m(*bbγγ*) resolution

2-tag category: signal region
0-tag category: control region



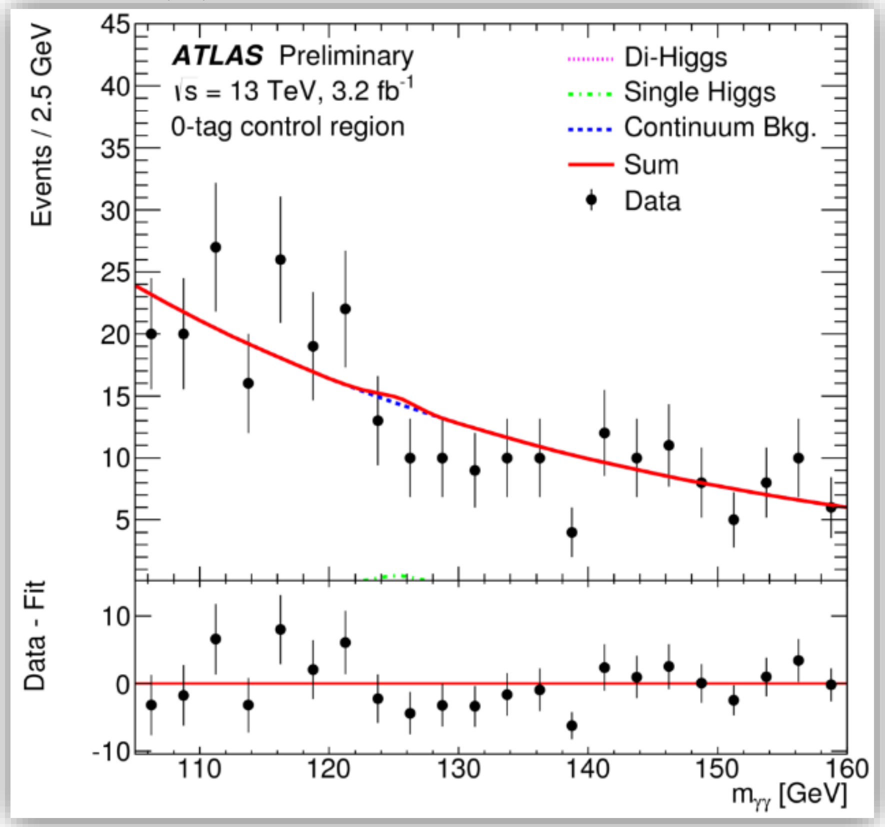
Non-resonant signal & background

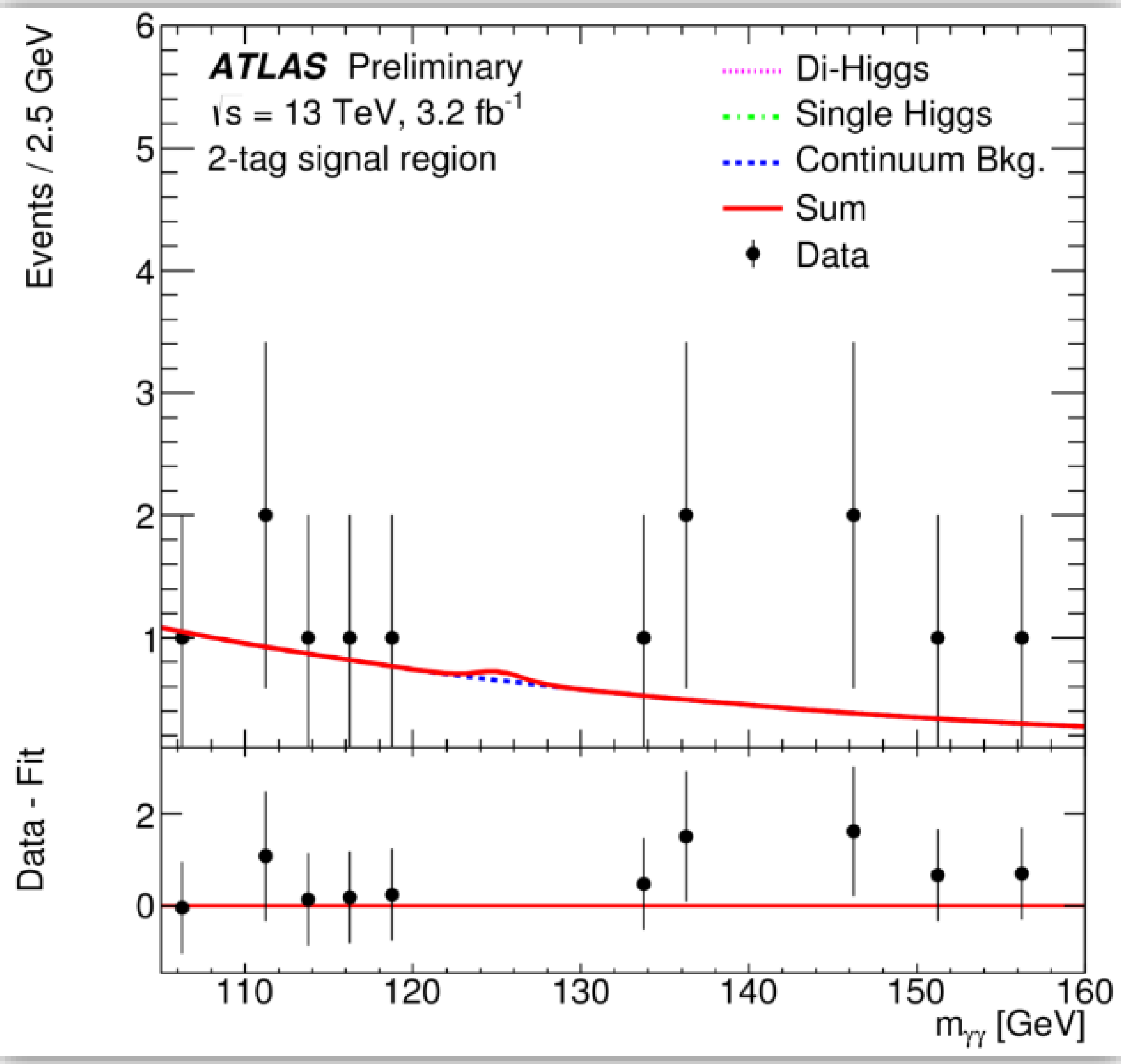
- Model signal with a double-sided crystal-ball function using MC
- Model continuum background with an exponential function fit in sideband
  - Background shape is determined in 0-tag region
- Use the determined signal/background shape in signal region
  - Background normalization is determined in 2-tag region



Non-resonant fit in signal region

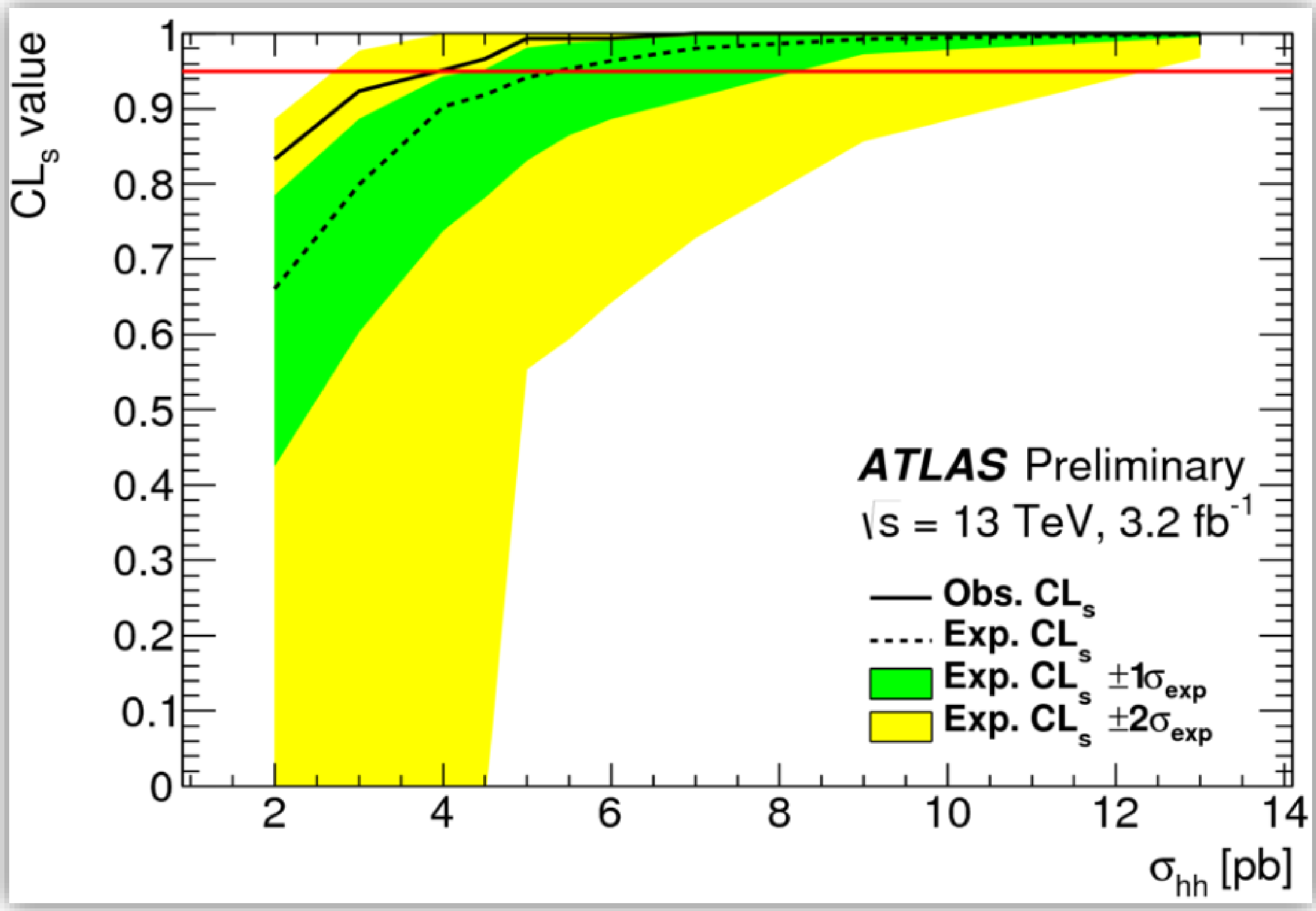
- Simultaneous S+B fit is performed along $m(\gamma\gamma)$





Non-resonant 95% CL upper limit on the Higgs pair production cross section

- Toys are used for statistical interpretation
- Expected limit is
- 5.4 pb
- Observed limit is
- 3.9 pb



Resonant strategy

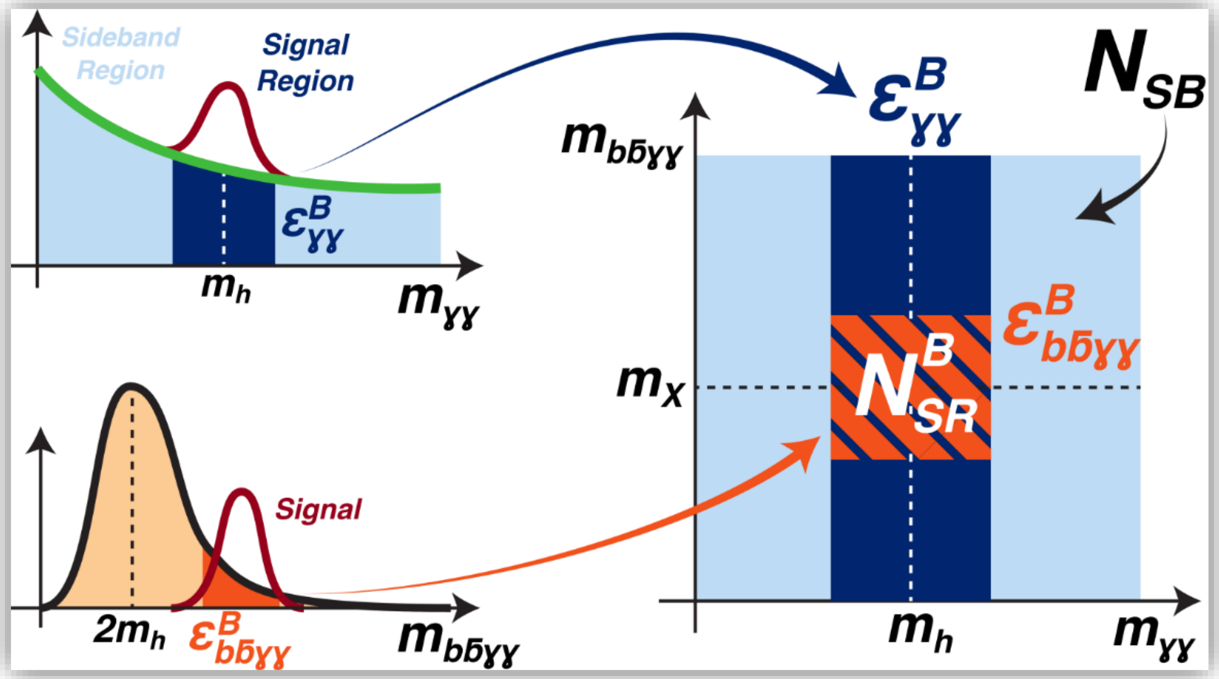
- Simply cut and count
- Windows on m($\gamma\gamma$) around Higgs mass and m($bb\gamma\gamma$) around heavy Higgs mass sequentially
- Background is estimated from sideband

$$|m_H - m_{\gamma\gamma}| < 2\sigma_{\gamma\gamma}$$

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

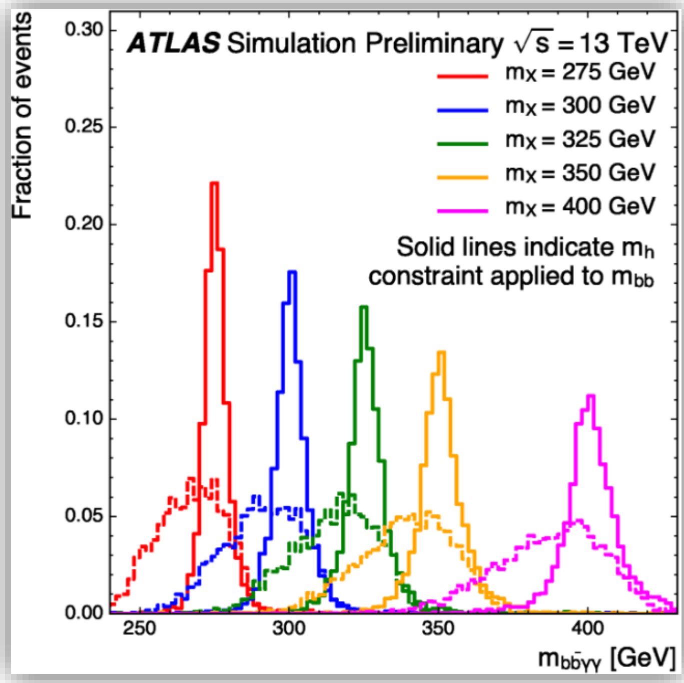
$\varepsilon(\gamma\gamma)$ is measured by fitting an exponential to m($\gamma\gamma$) with data in 0-tag region

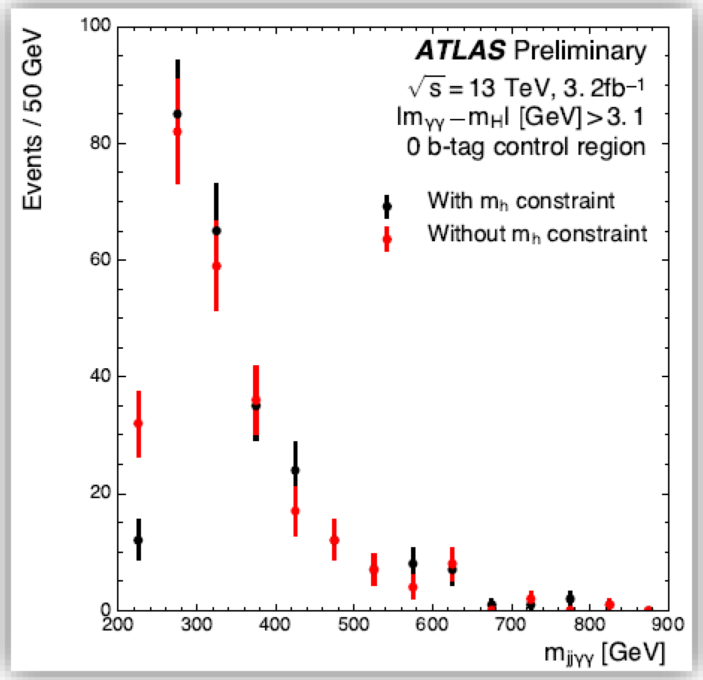
$\varepsilon(bb\gamma\gamma)$ is measured from m($jj\gamma\gamma$) with data in 0-tag region

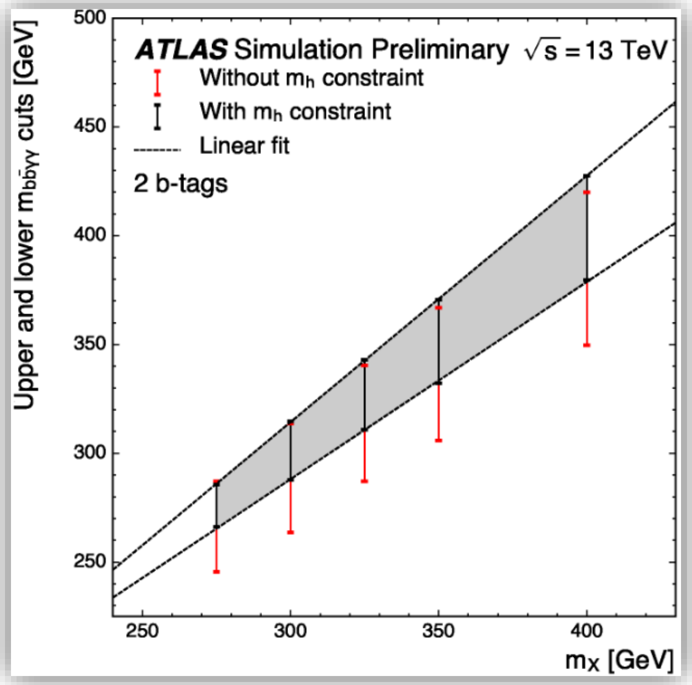


Improve m(*bbγγ*) resolution

- Rescale the four-momentum of the bb system by
  - A factor of m(h)/m(bb)
- This improves the m(bbγγ) resolution by 60% on average
- This does not strongly affect the shape or the normalization of the background







Resonant results

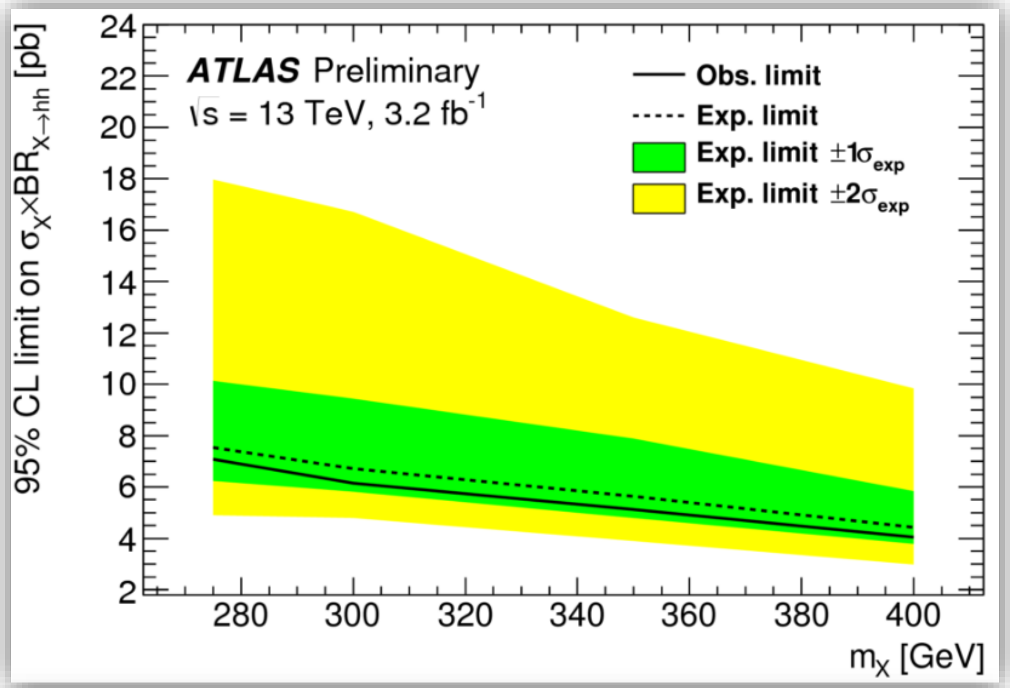
- There is no data observed in signal region

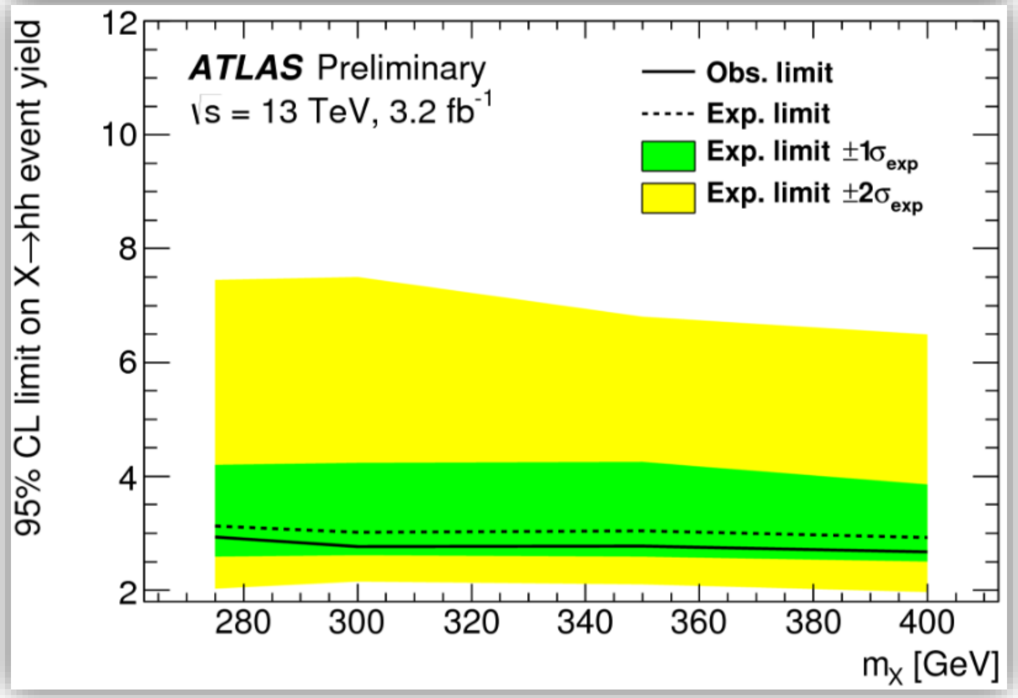
Process	0-tag	2-tag
Continuum background	35.8 ± 2.1	1.63 ± 0.30
SM single-Higgs	1.8 ± 1.5	0.14 ± 0.05
SM di-Higgs	<0.001	0.027 ± 0.006
Observed	27	0

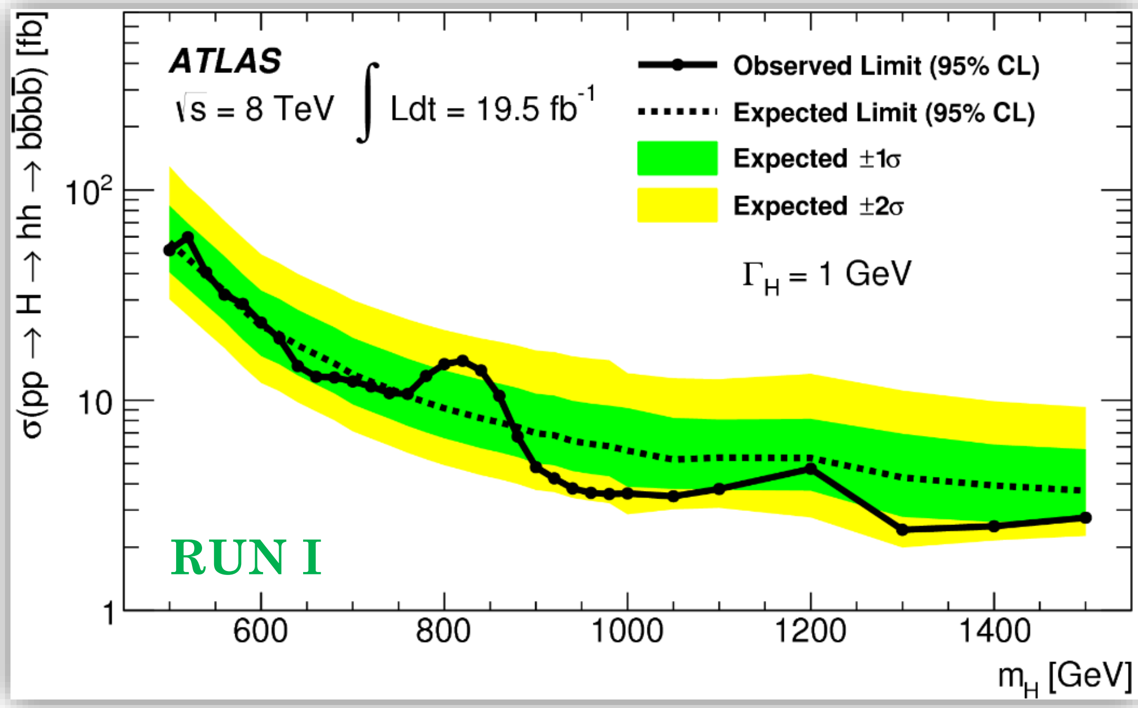
- This table shows the event yields in m($\gamma\gamma$) window, covering both resonant and non-resonant signal regions

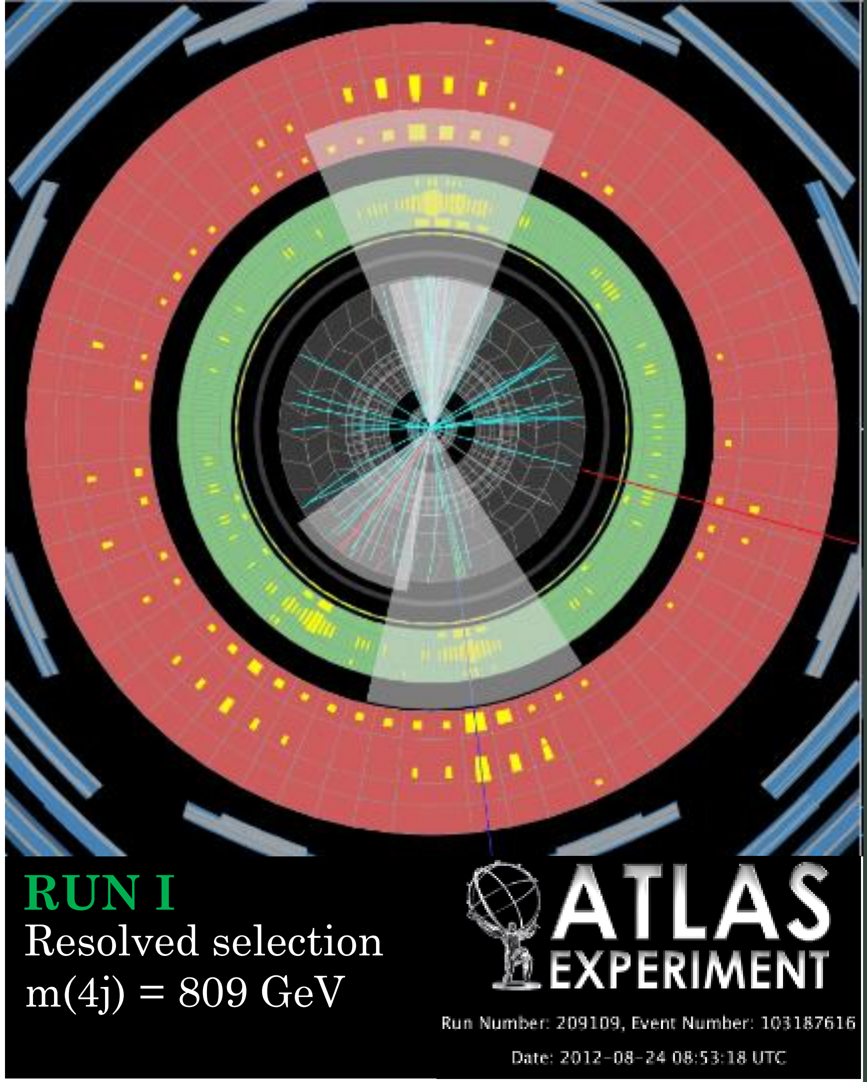
Resonant 95% CL upper limit on σ(ggH)*BR(H→hh)

- Toys are used for statistical interpretation due to low statistics
- Resonant search sets limits in range 275 GeV to 400 GeV
  - Expected range from
  - [7.5, 4.4] pb
  - Observed range from
  - [7.0, 4.0] pb
- The RUN II upper limits do not exclude RUN I results









bbbb

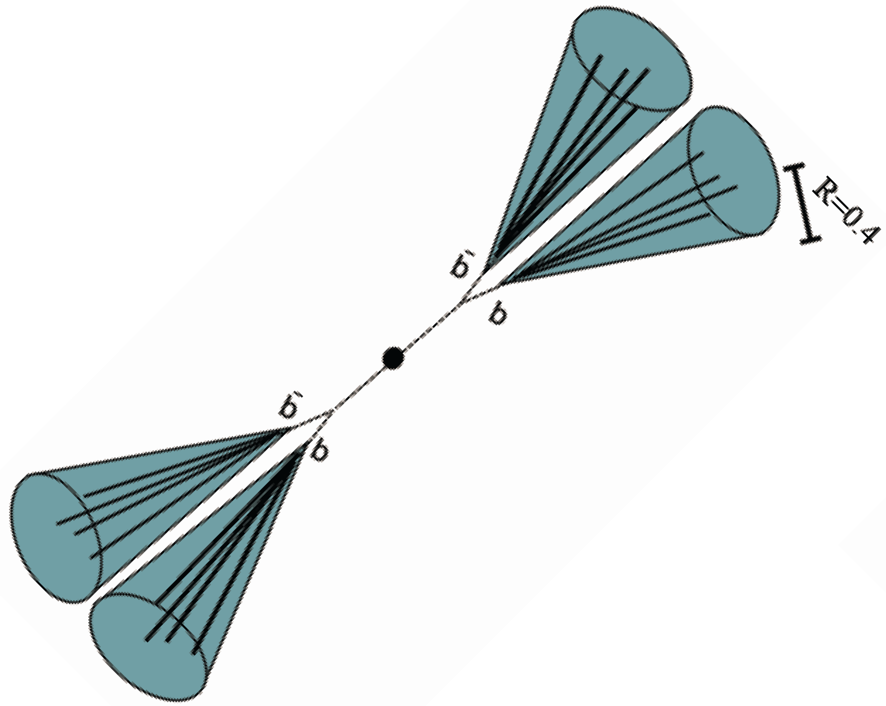
RUN I: Eur. Phys. J. C (2015) 75:412;

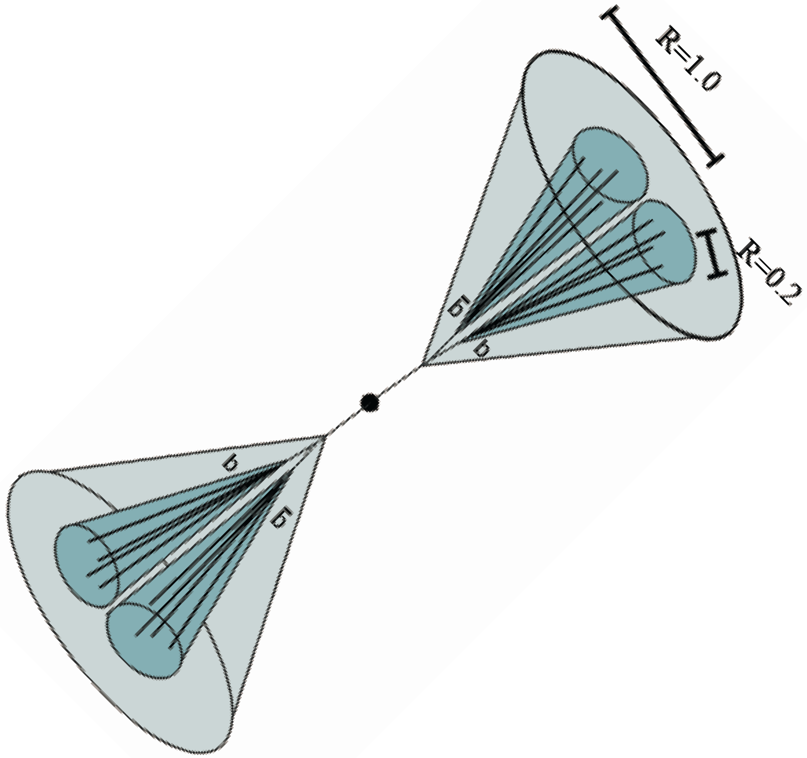
Phys. Rev. D 92, 092004 (2015) (combination)

RUN II: arXiv:1606.04782 [submitted to PRD] (discuss in this talk)

Signature

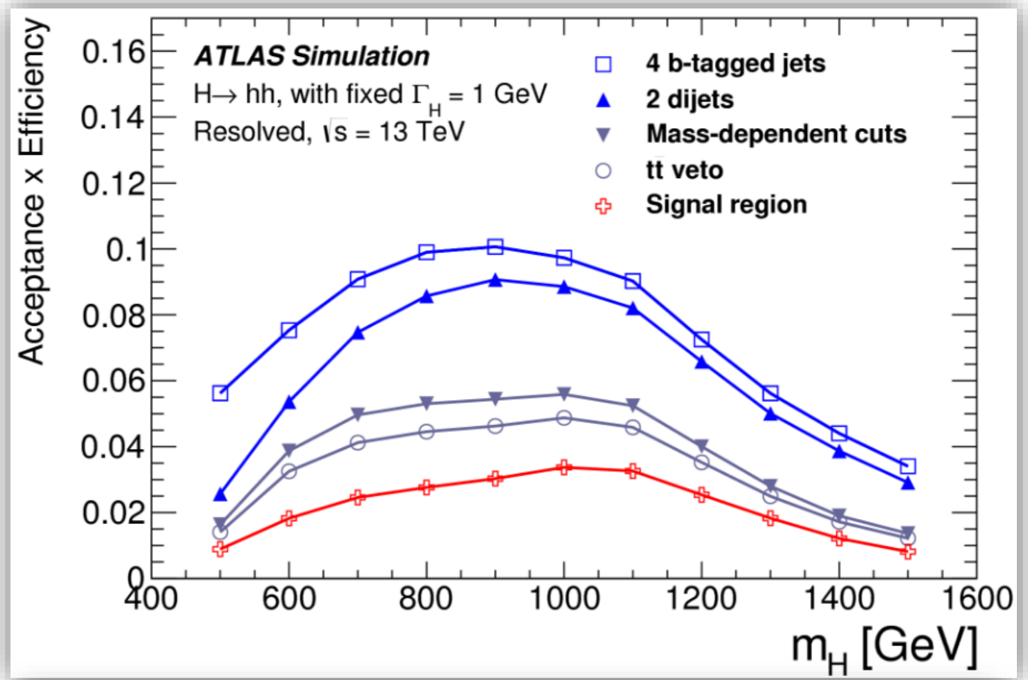
- Clear signature:
  - *bb* has largest branching ratio
  - Resolved analysis (400-1500GeV): 4 jets
  - Boosted analysis (800-3000GeV): 2 large-R jets

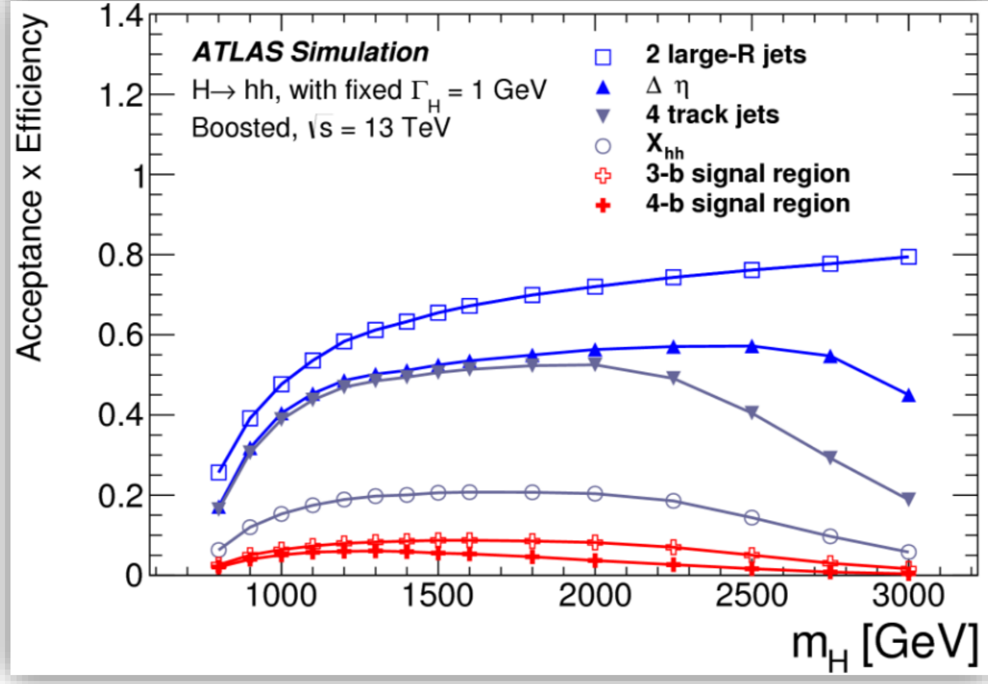




Event selection

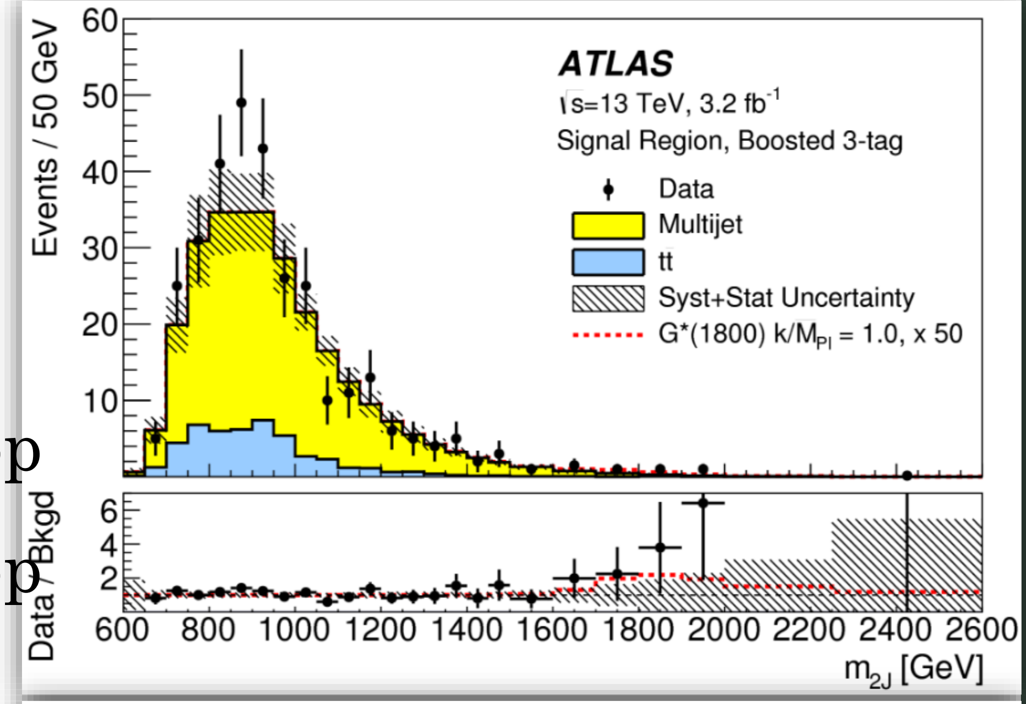
- **Resolved:**
- 4 b-tagged jets: Anti-kt 0.4, efficiency 70%
- Higgs candidates (2 dijets): ΔR(bb)<1.5, pT(dijet)>200(150)GeV
- Mass-dependent cut on dijet pT and Δη
- Top veto $X_{tt} = \sqrt{\left(\frac{m_W - 80.4\ \text{GeV}}{0.1\, m_W}\right)^2 + \left(\frac{m_t - 172.5\ \text{GeV}}{0.1\, m_t}\right)^2}$
- Constraints on dijet mass
- **Boosted:**
- 2 large-R jets: Anti-kt 1.0, trimmed
- Δη of two large R jets < 1.7
- Track jets associated to large R jets
- Constraints on dijet mass
- 3 or 4 b-tagged jets

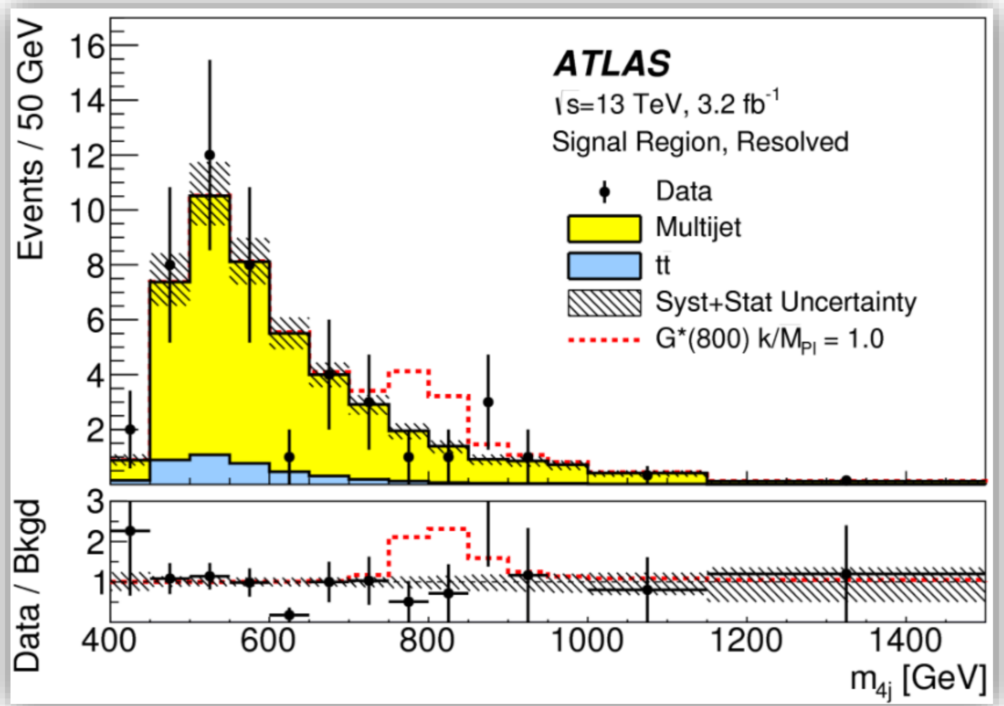


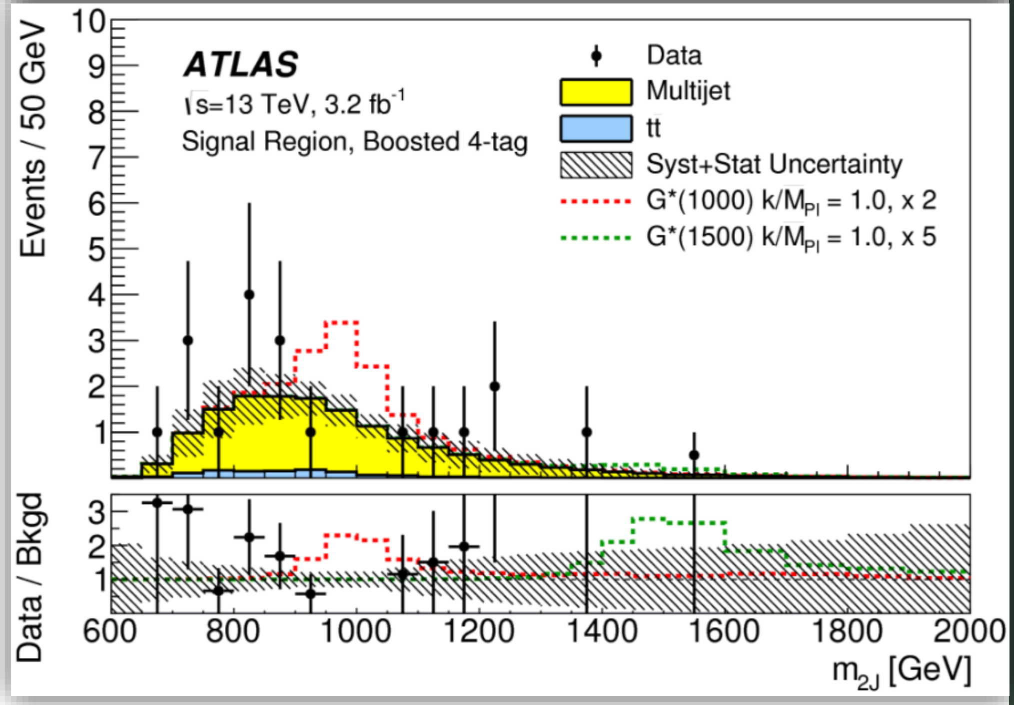


Backgrounds

- Resolved: 90% QCD, 10% top
- Boosted 3-tag: 80% QCD 20% top
- Boosted 4-tag: 90% QCD 10% top

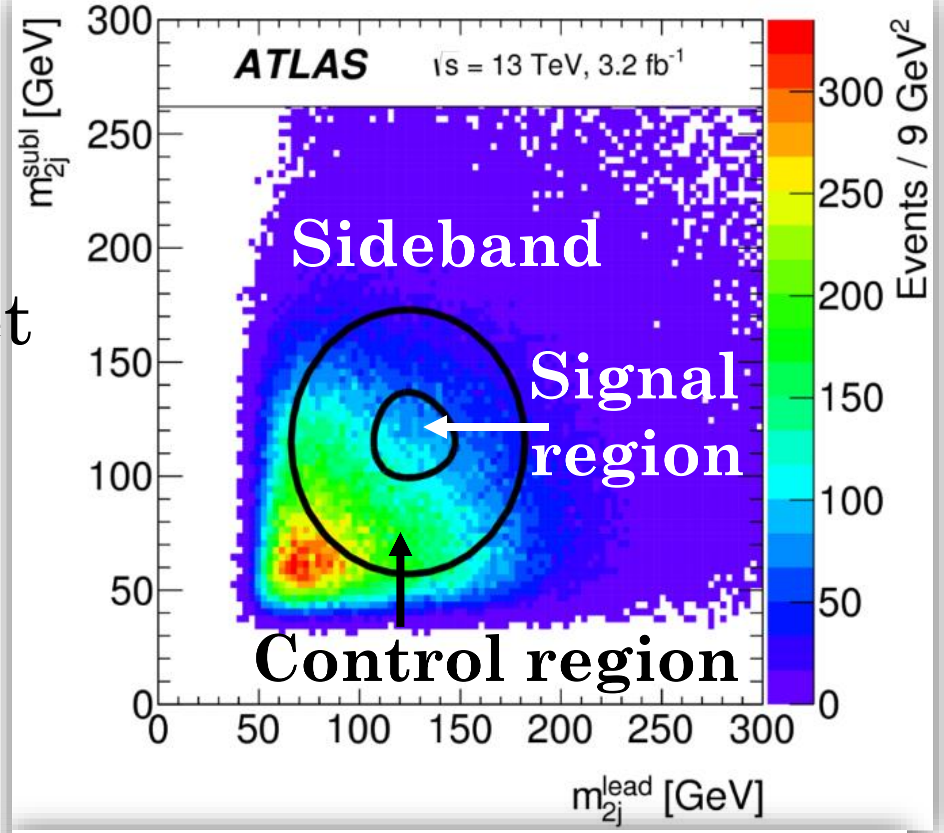


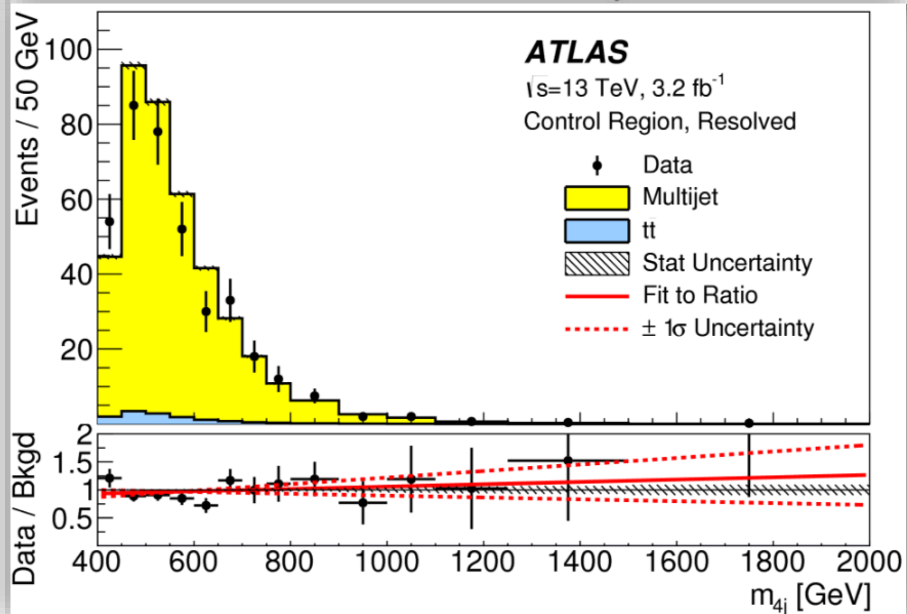




QCD (resolved)

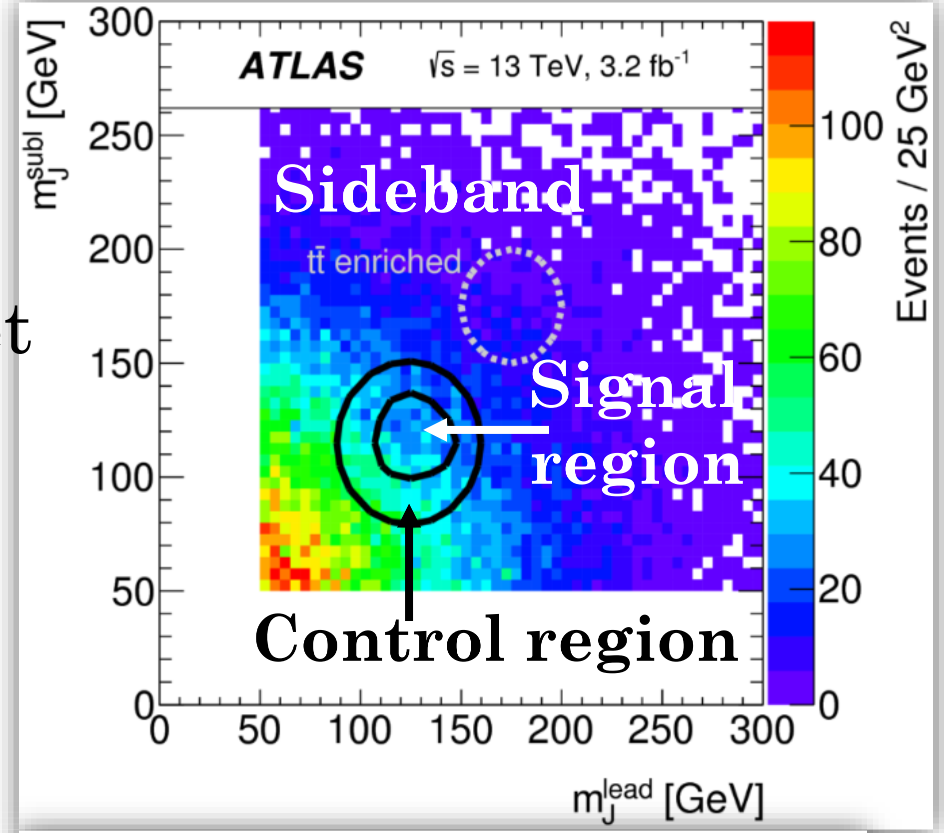
- 2-tag is used for QCD multijet modeling in 4-tag
- Sideband:
  - Correct the modeling
  - Determine the normalization
- Control region:
  - Validate the modeling and normalization
  - Estimate uncertainties
- Signal region:
  - Apply estimated QCD

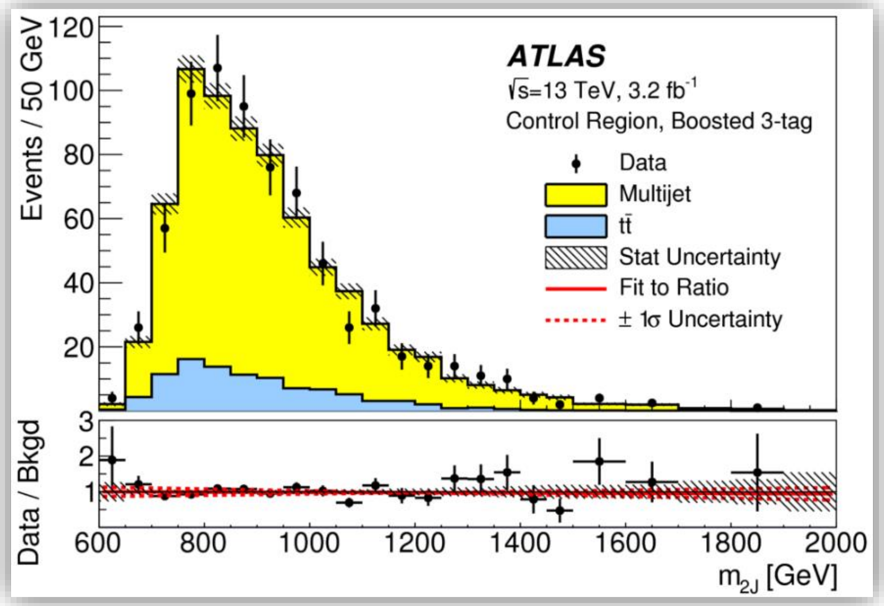


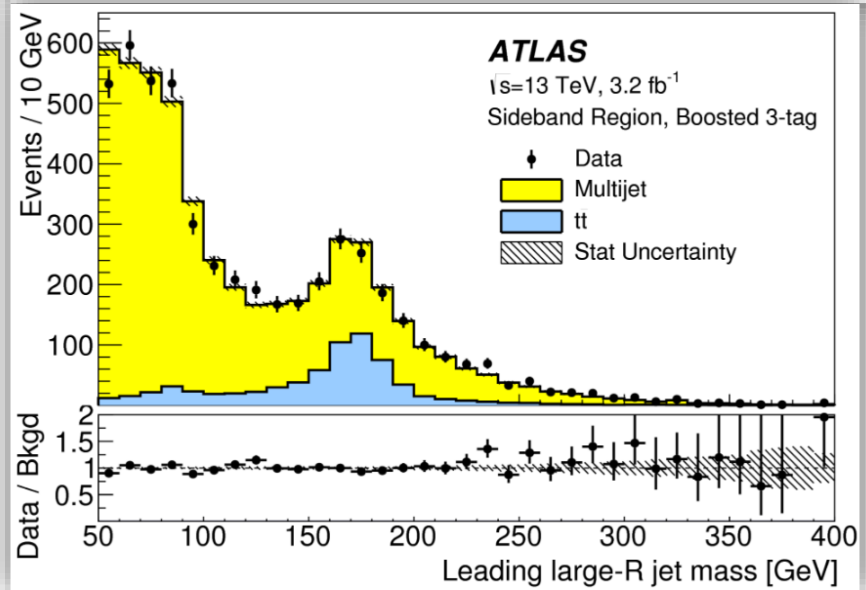


QCD (boosted)

- 2-tag is used for QCD multijet modeling in 3/4-tag
- Sideband: fit lead-jet mass to determine QCD and top
- Control region: validation







Event yields

Resolved

Sample	Signal Region Yield
Multijet	43.3 ± 2.3
$t\bar{t}$	4.3 ± 3.0
Z+jets	-
Total	47.6 ± 3.8
Data	46
SM hh	0.25 ± 0.07
G^*_{KK} (800 GeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	5.7 ± 1.5

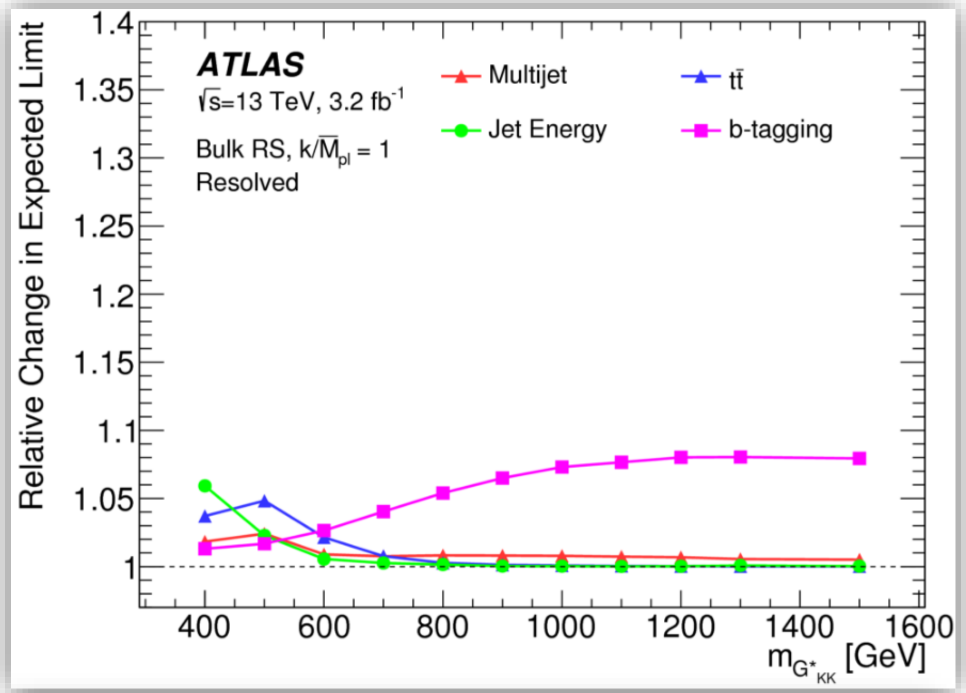
- Expected backgrounds agree will with observed data

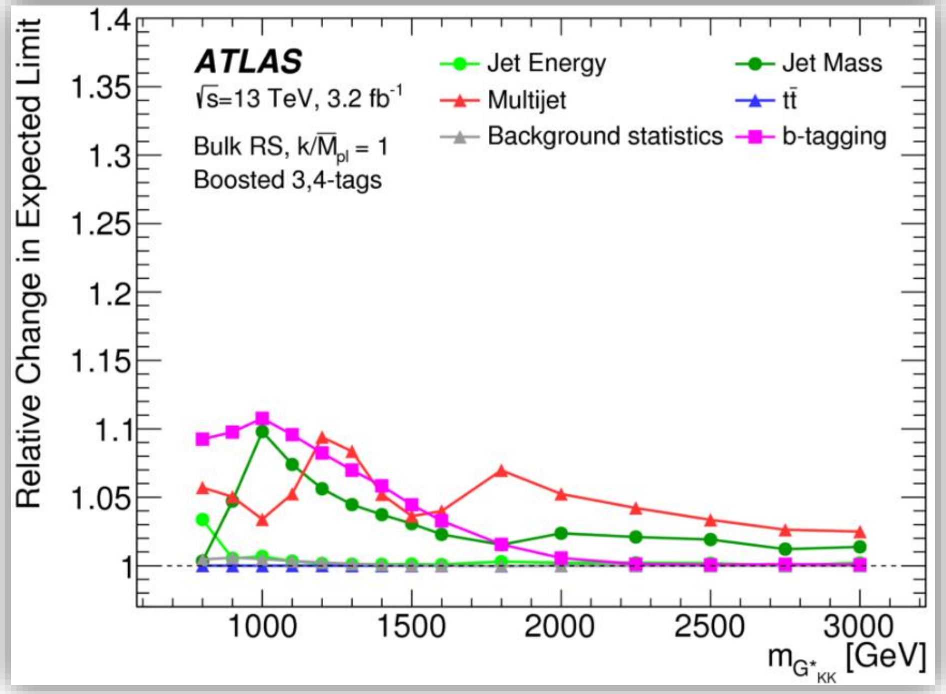
Boosted

Sample (3-tag)	Sideband Region	Control Region
Multijet	4328 ± 27	607 ± 10
$t\bar{t}$	683.5 ± 8.1	99.6 ± 3.1
Z+jets	31.8 ± 3.7	7.7 ± 1.8
Total	5043 ± 28	715± 11
Data	5043	724
Sample (4-tag)	Sideband Region	Control Region
Multijet	247.4 ± 1.5	34.7 ± 0.6
$t\bar{t}$	28.4 ± 1.5	5.1 ± 0.7
Z+jets	3.4 ± 1.2	0.6 ± 0.5
Total	279.2 ± 2.5	40.3 ± 1.0
Data	279	45

Impacts on limits

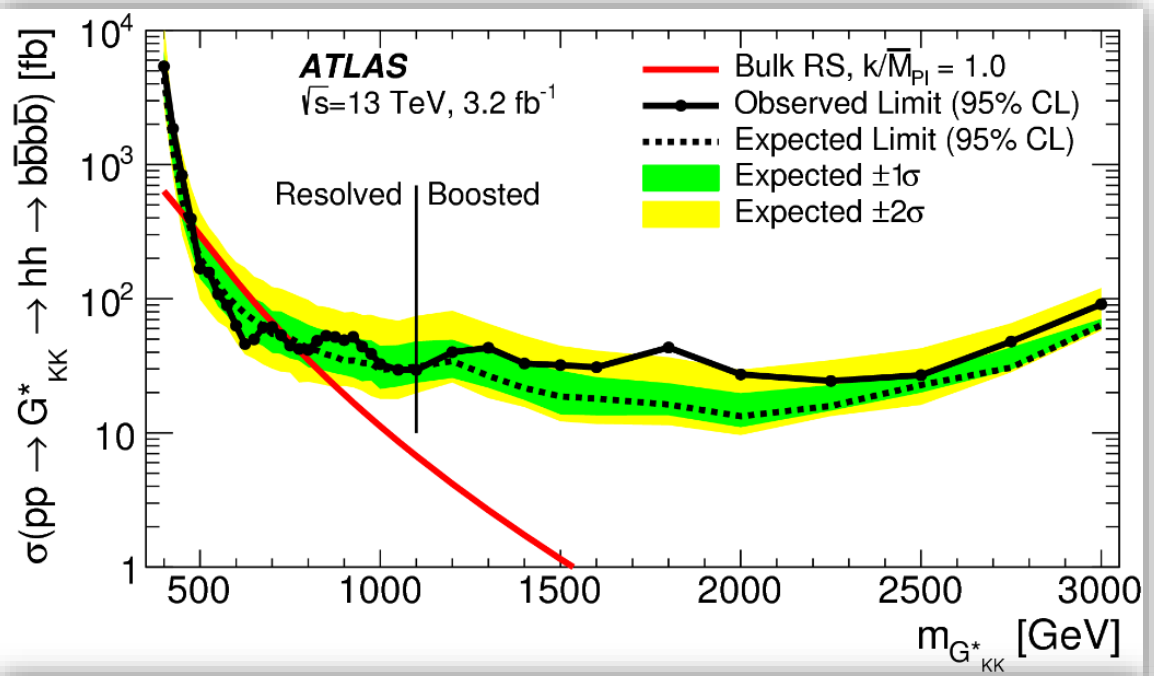
- The individual relative impact of systematic uncertainties on expected 95% confidence level exclusion limit
- B-tagging plays an important role in intermediate mass region
- Multijet dominates in high mass region

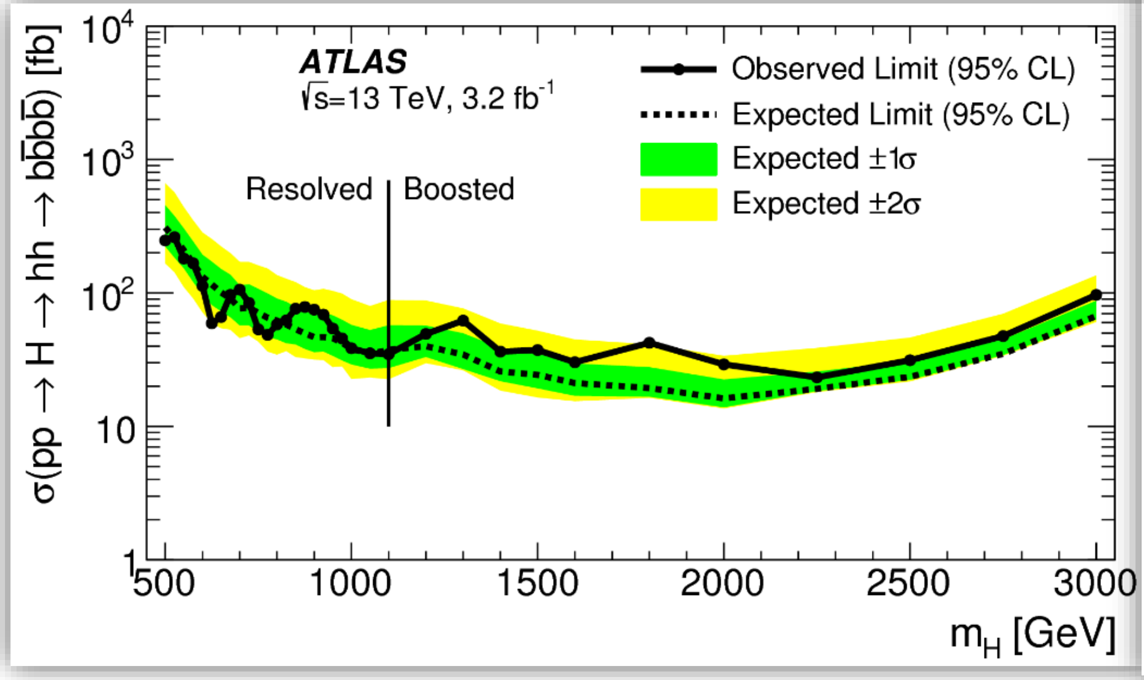


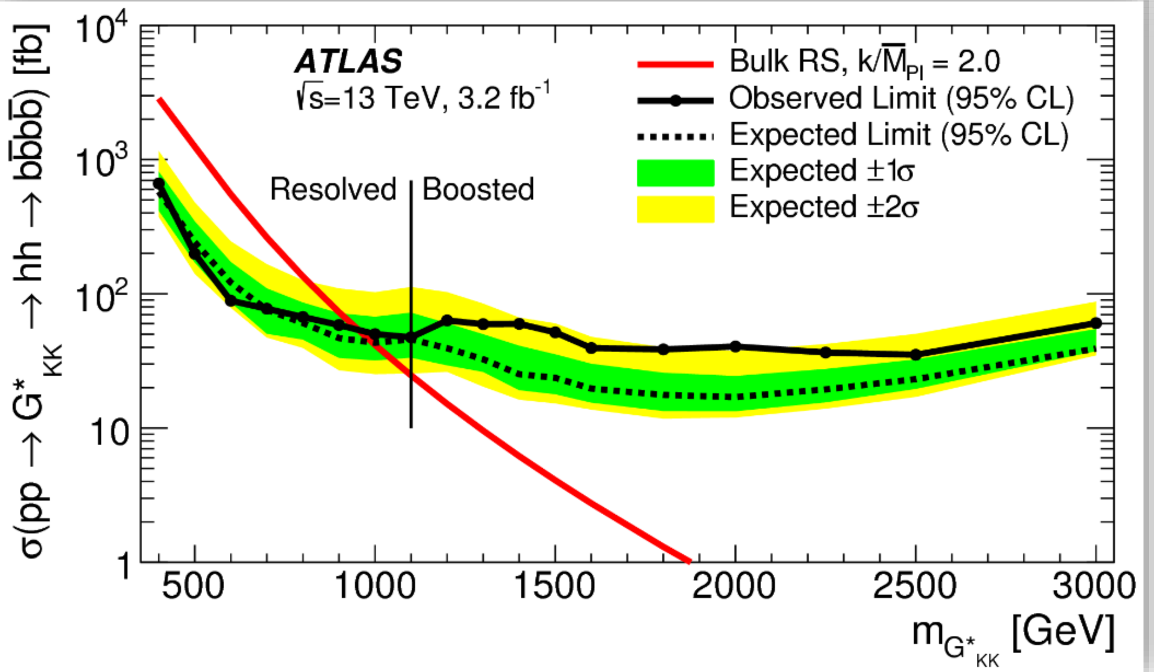


Results

- Upper limits on non-resonance is 1.22 pb
- Resolved has better sensitivity below 1.1TeV







Summary

- Higgs pair is an important decay if there are neutral resonances
- It would also provide the opportunity to probe Higgs self-coupling when more data is accumulated
- Higgs pair has been searched extensively during RUN I
- It will be explored with more interesting channels in RUN II, already seeing bb$\gamma\gamma$ and bbbb

Backup

Systematic uncertainties in $bb\gamma\gamma$

Source of systematic uncertainty		Impact in % on the search for diHiggs production in non-resonant mode			resonance 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	-	±25.0	±11.0
	$m_{b\bar{b}\gamma\gamma}$ modelling	-	-	-	-	-	±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

bbbb cuts

	Resolved	Boosted
Event preselection	≥ 4 jets with $p_{\mathrm{T}} > 40$ GeV, $\lvert\eta\rvert < 2.5$; ≥ 2 dijets with $p_{\mathrm{T}} > 200\,(150)$ GeV, $\Delta R < 1.5$, $p_{\mathrm{T}} > f(m_{4\mathrm{j}})$, $\lvert\Delta\eta\rvert < f'(m_{4\mathrm{j}})$	≥ 2 large-R jets with $350\,(250) < p_{\mathrm{T}} < 1500$ GeV, $\lvert\eta\rvert < 2.0$, $m_{\mathrm{J}} > 50$ GeV; ≥ 2 track jets associated to each large-R jet with $p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.5$, $\lvert\Delta\eta\rvert < 1.7$
Top veto	$X_{tt} < 3.2$	–
Tagging	4 b-tagged jets	3 or 4 b-tagged jets
Signal region (SR)	$X_{hh} < 1.6$	
Sideband region (SB)	Resolved: $\sqrt{(m_{2\mathrm{j}}^{\mathrm{lead}} - 124\,GeV)^2 + (m_{2\mathrm{j}}^{\mathrm{subl}} - 115\,GeV)^2} > 58\,GeV$ Boosted: $\sqrt{(m_{\mathrm{J}}^{\mathrm{lead}} - 124\,GeV)^2 + (m_{\mathrm{J}}^{\mathrm{subl}} - 115\,GeV)^2} > 36\,GeV$	
Control region (CR)	complementary to SR and SB	
Multijet normalization	scaled yields from 2-tag SR, scaling derived from 4-tag to 2-tag ratio in SB	scaled yields from 2-tag SR, scaling derived from 3(4)-tag to 2-tag fit to leading jet mass in SB
Multijet shape	derived from 2-tag SR	
$t\bar{t}$ normalization	scaled yields from $t\bar{t}$ CR, scaling derived from semileptonic $t\bar{t}$ events	scaled yields from MC simulation, scaling derived from 3(4)-tag to 2-tag fit to leading jet mass in SB
$t\bar{t}$ shape	derived from MC simulation	

Rate uncertainties in *bbbb* resolved

Source	Background	SM hh	G^*_{KK} (500 GeV) $\frac{k}{\overline{M}_{\mathrm{Pl}}} = 1$	G^*_{KK} (800 GeV) $\frac{k}{\overline{M}_{\mathrm{Pl}}} = 1$	G^*_{KK} (800 GeV) $\frac{k}{\overline{M}_{\mathrm{Pl}}} = 2$	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	–	9	2	3	3	3
Multijet	5	–	–	–	–	–
$t\bar{t}$	6	–	–	–	–	–
Total	8	24	21	28	28	28

Rate uncertainties in *bbbb* 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	3	–	–	–
Statistical	2	1	1	1
Total	7	31	30	33

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
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	14	–	–	–
Statistical	3	1	1	1
Total	15	42	42	43