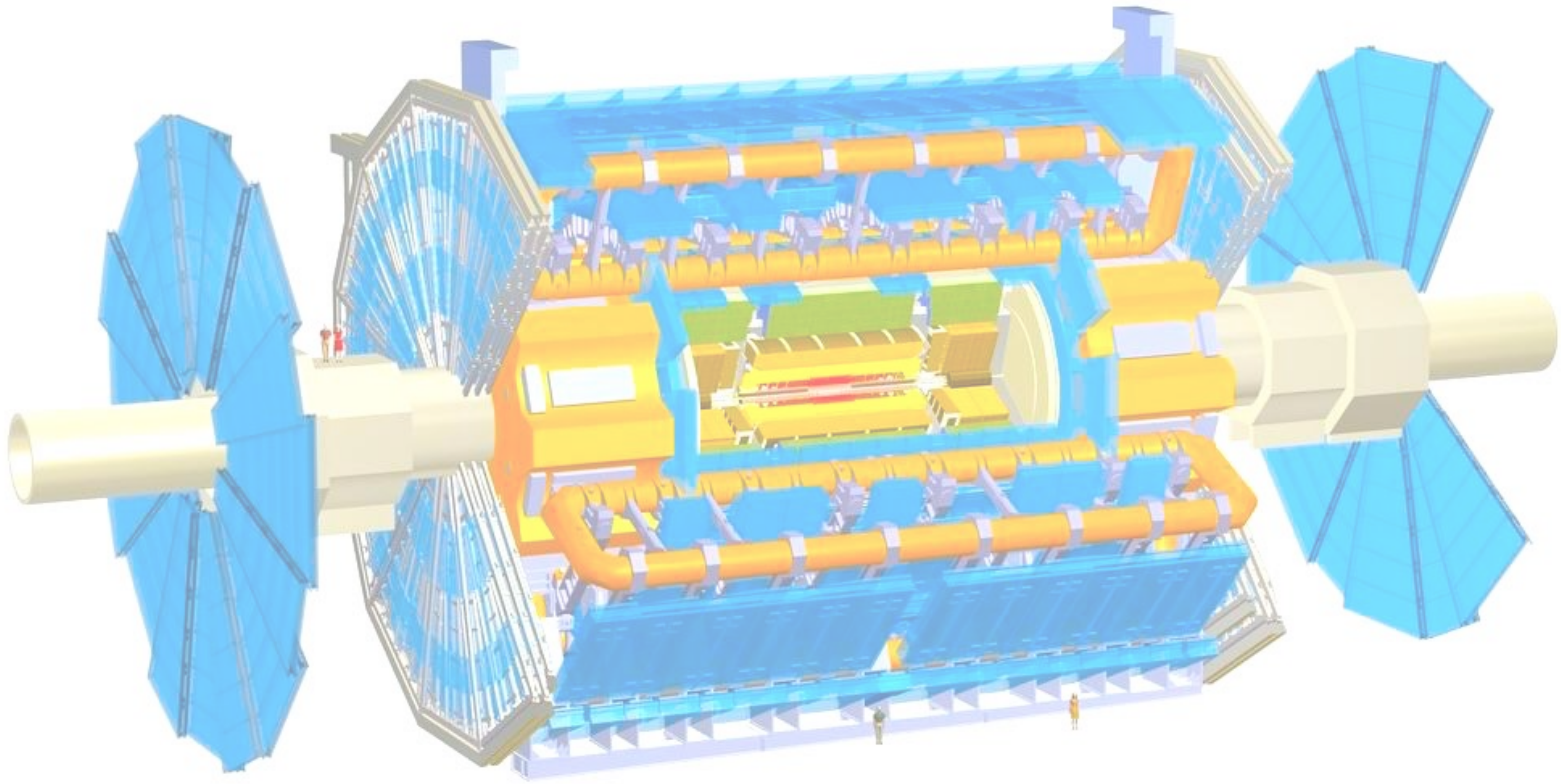
Search for di-Higgs production with the ATLAS detector



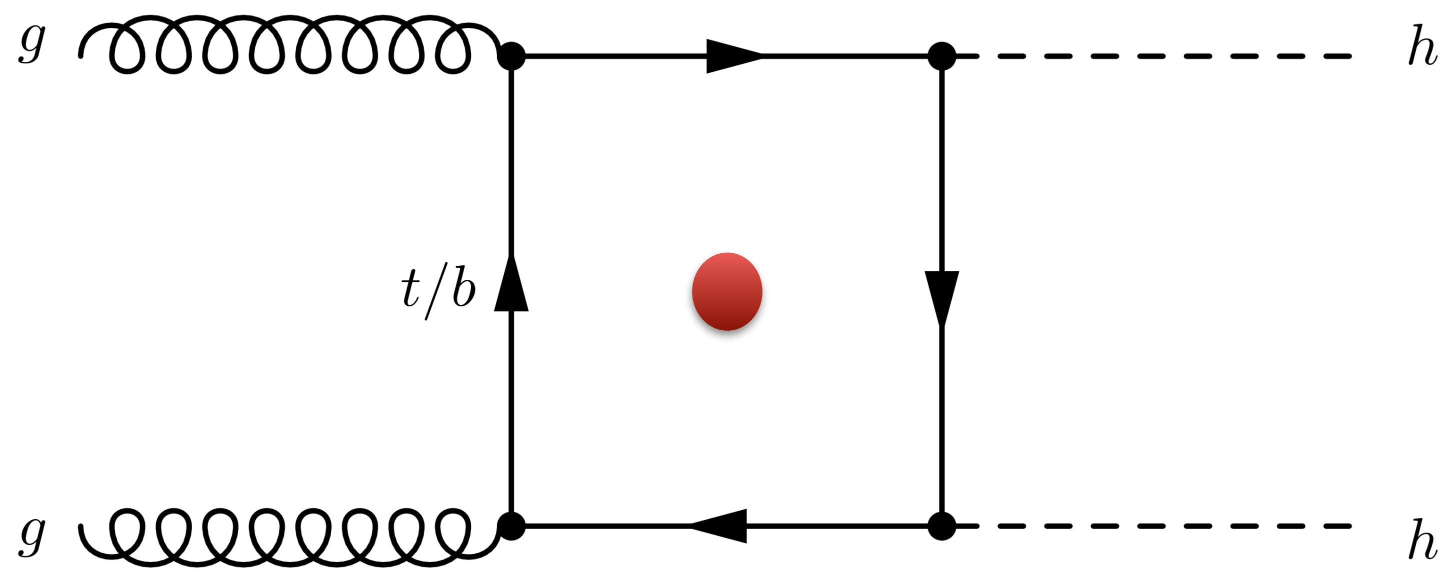
Tony(Baojia)Tong, Harvard University
on behalf of the ATLAS Collaboration
Higgs Coupling, SLAC, Nov. 9-12, 2016

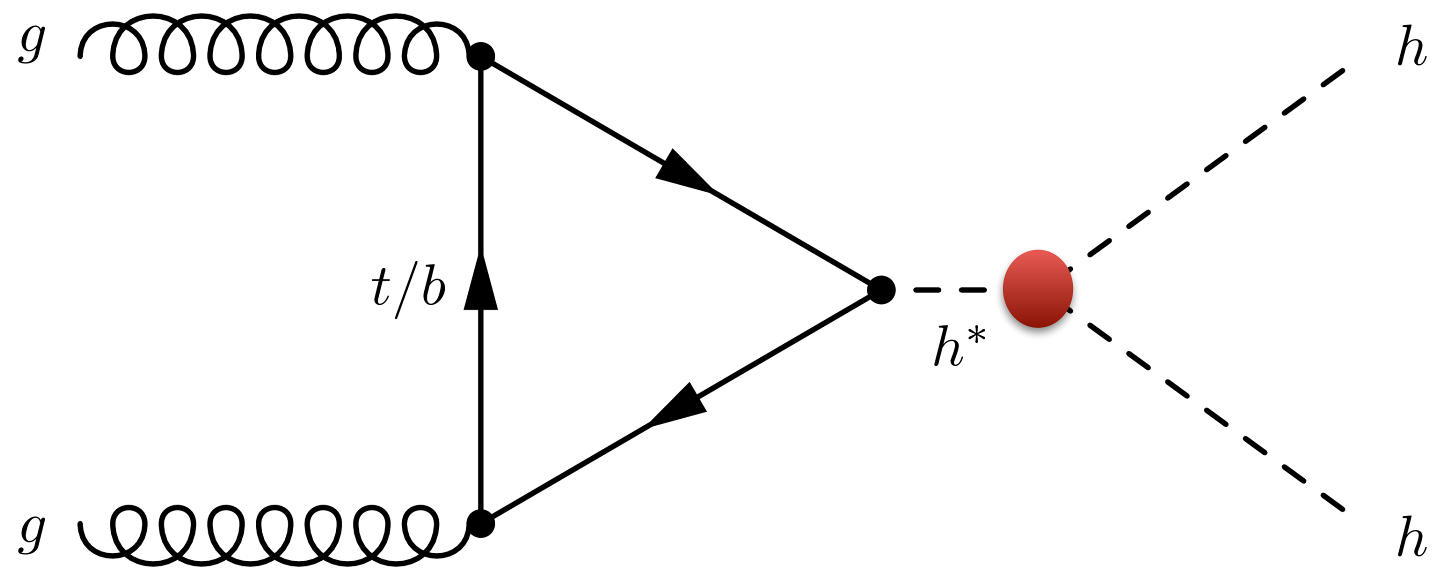
Di-Higgs production

- Cross section small in SM:
  - 8 TeV ~ 10 fb (NNLO)
  - 13 TeV ~ 38 fb (NNLO + NNLL)

Di-Higgs production

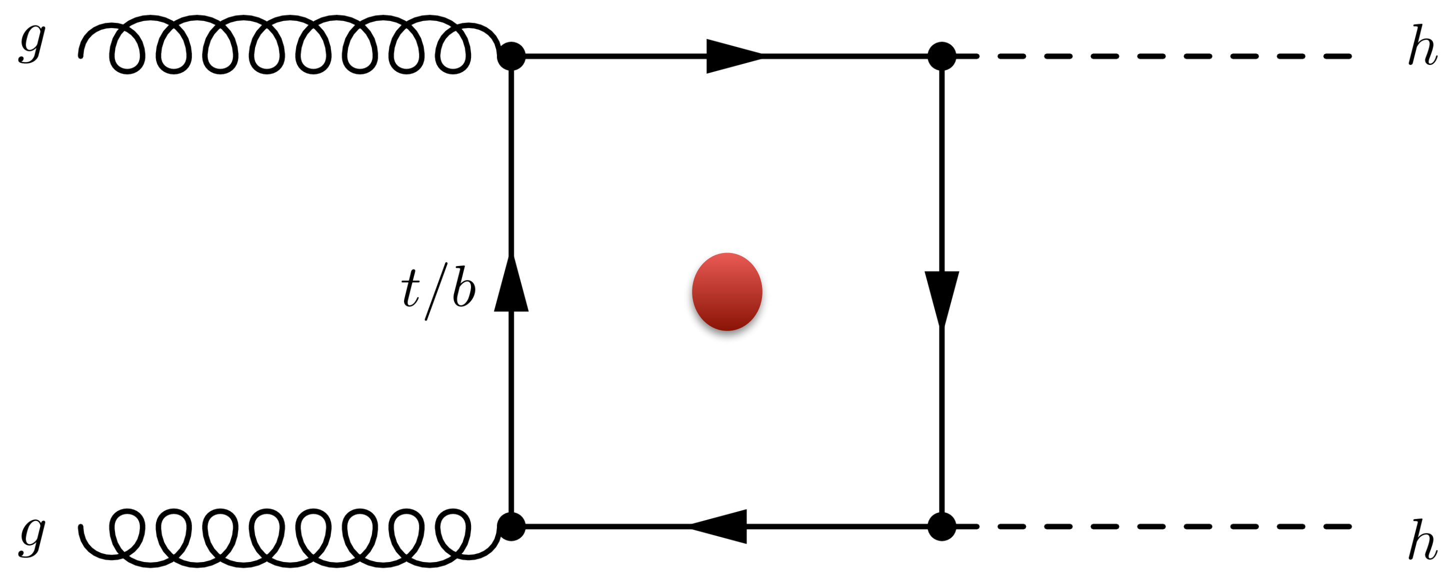
- Cross section small in SM:
    - 8 TeV ~ 10 fb (NNLO)
    - 13 TeV ~ 38 fb (NNLO + NNLL)
- Larger if BSM (●) physics exists
    - Non-resonant Examples
        - tthh, tth vertex modifications
        - λ_{hhh} triple-Higgs coupling

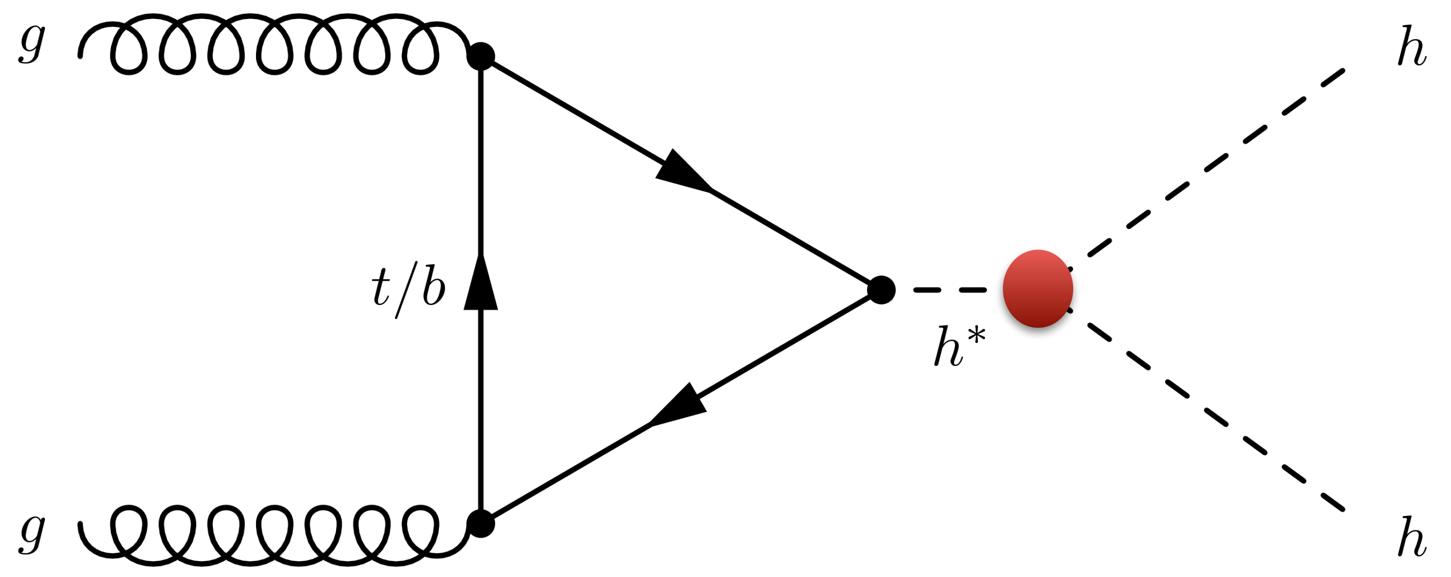


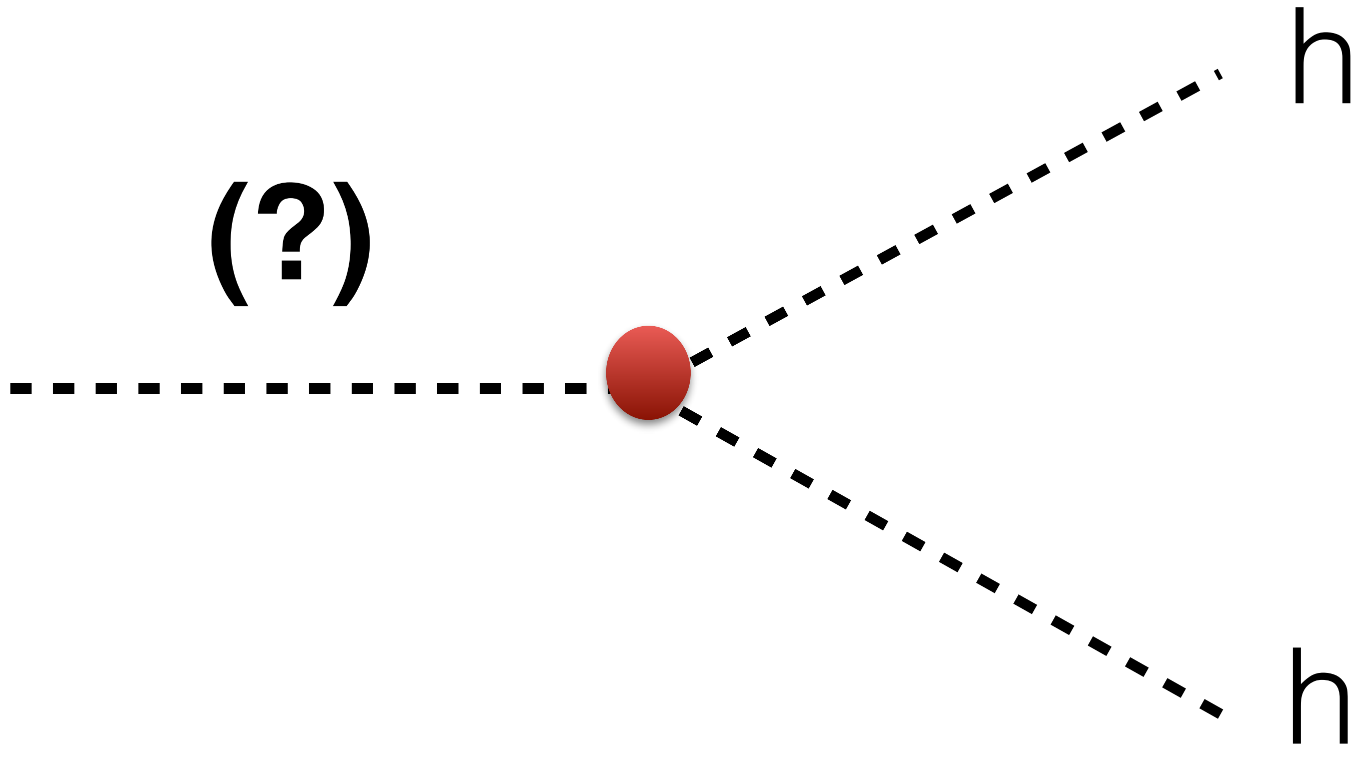


Di-Higgs production

- Cross section small in SM:
  - 8 TeV ~ 10 fb (NNLO)
  - 13 TeV ~ 38 fb (NNLO + NNLL)
- Larger if BSM (●) physics exists
  - Non-resonant Examples
    - tthh, tth vertex modifications
    - λ_{hhh} triple-Higgs coupling
  - Resonant Examples
    - KK Graviton
    - Heavy Higgs: 2HDM

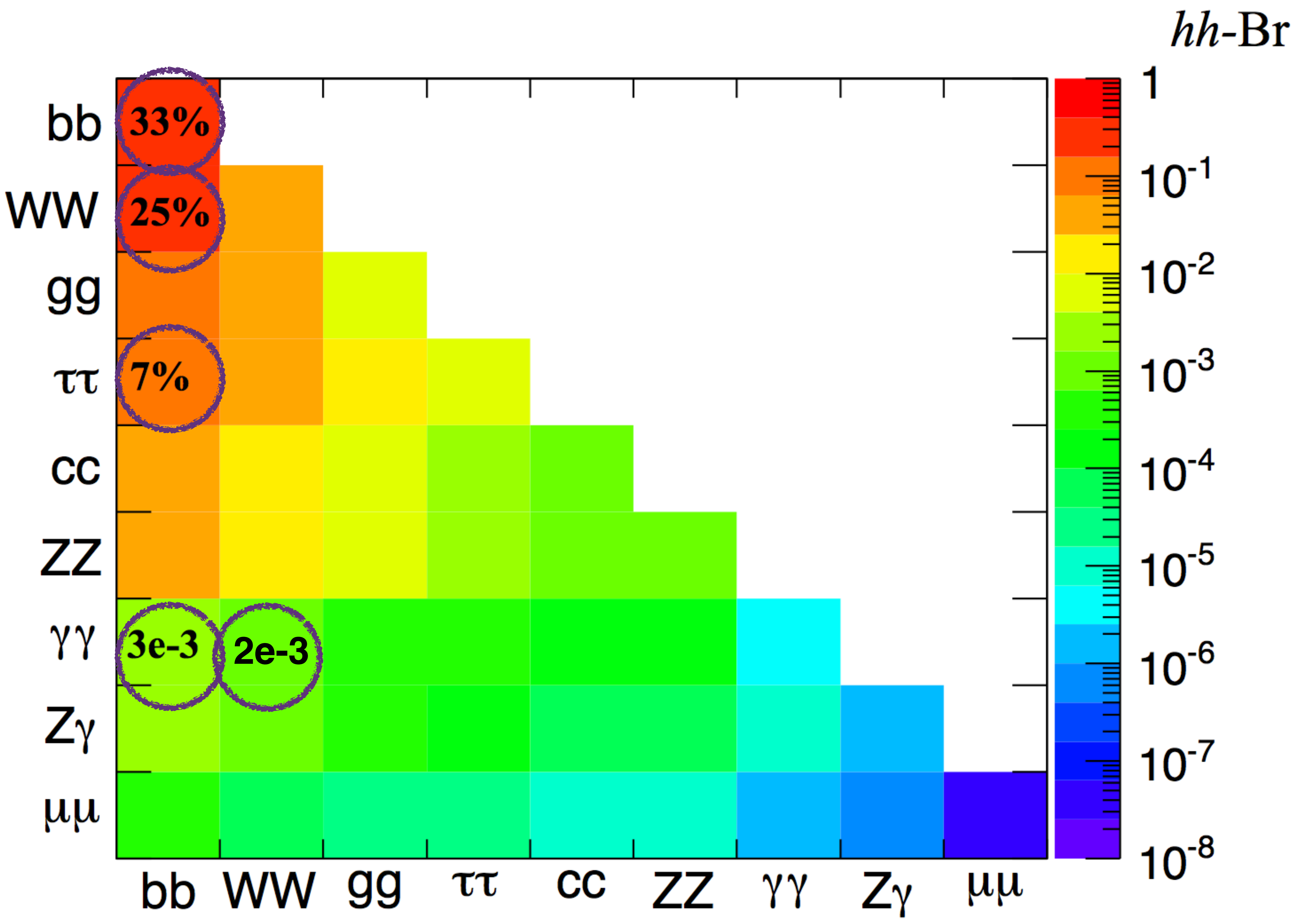






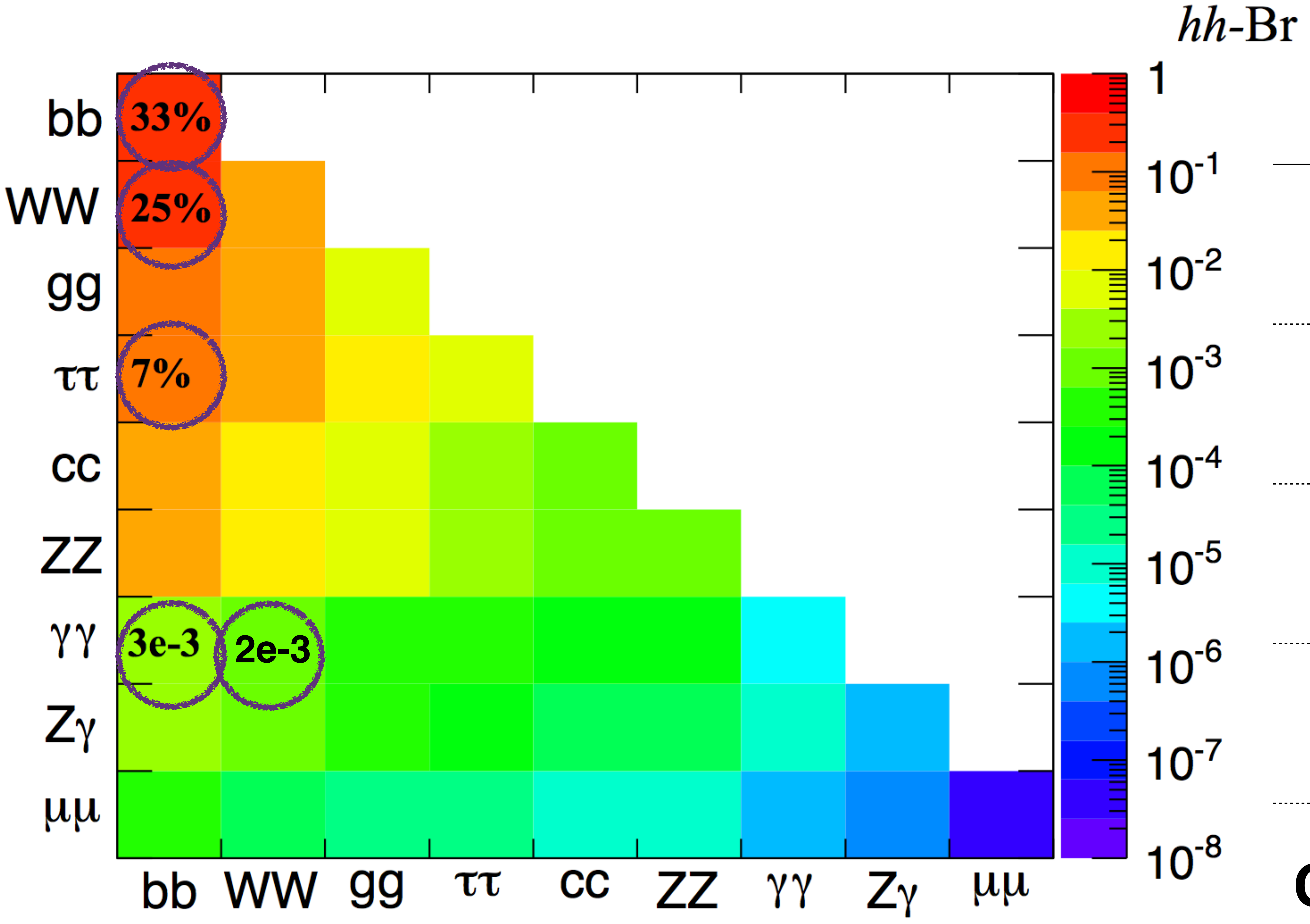
Di-Higgs decay

larger branching ratio—higher yield



Di-Higgs decay

larger branching ratio—higher yield



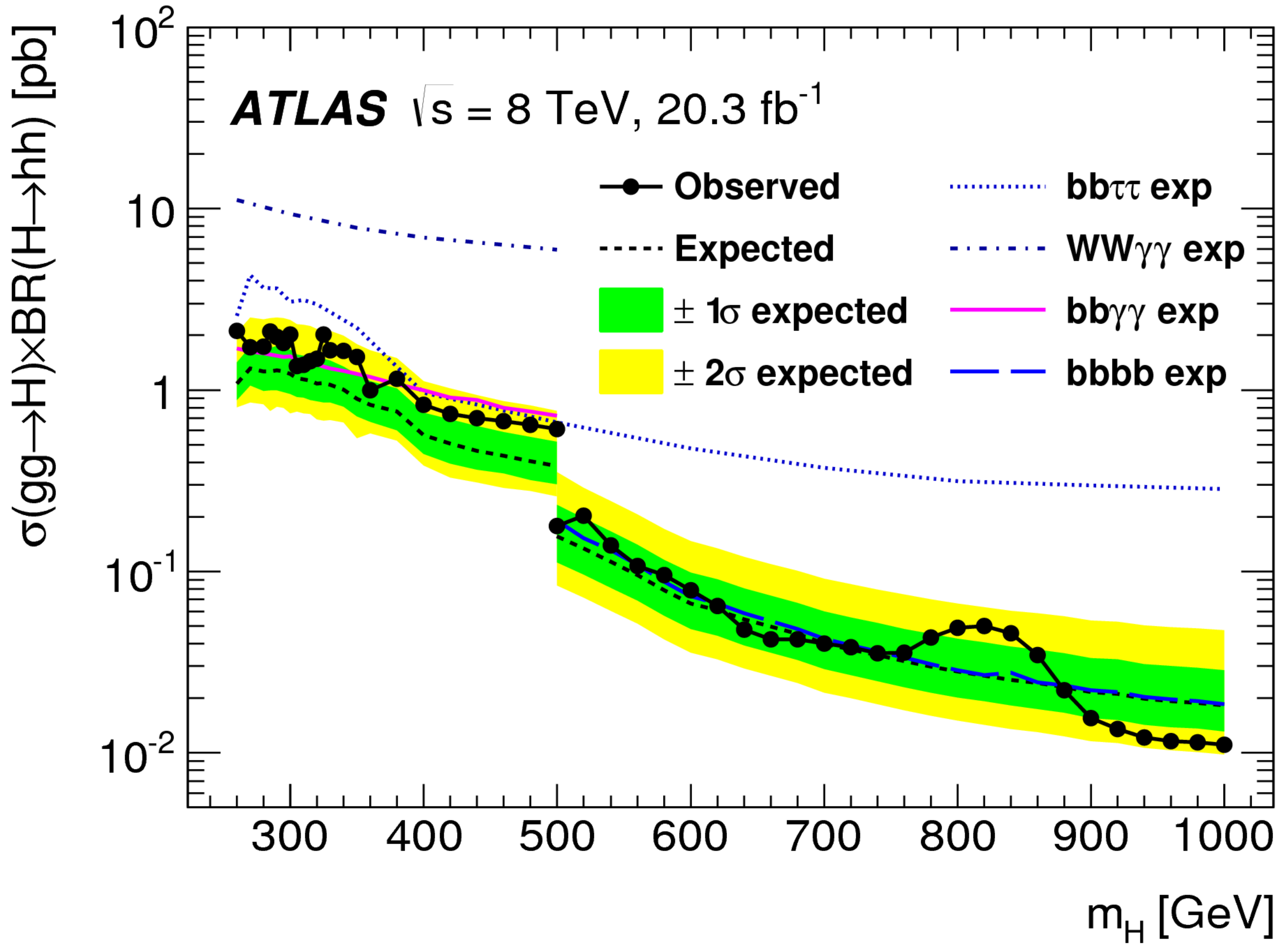
ATLAS Search Results (links)	8TeV, fb^{-1}	13TeV, fb^{-1}	HL-LHC
bbbb	20	3 / 13	prospect
$bb\tau\tau$	20		prospect
bbγγ	20	3	prospect
WW*γγ	20	13	
Combination	20		

Di-Higgs low mass searches

Phys. Rev. D 92, 092004 (2015)

- Mass range: 250 ~ 1000 GeV
  - Model: resonant, non-resonant
    - trigger efficiency
    - branching ratio

Run I Combined Limit

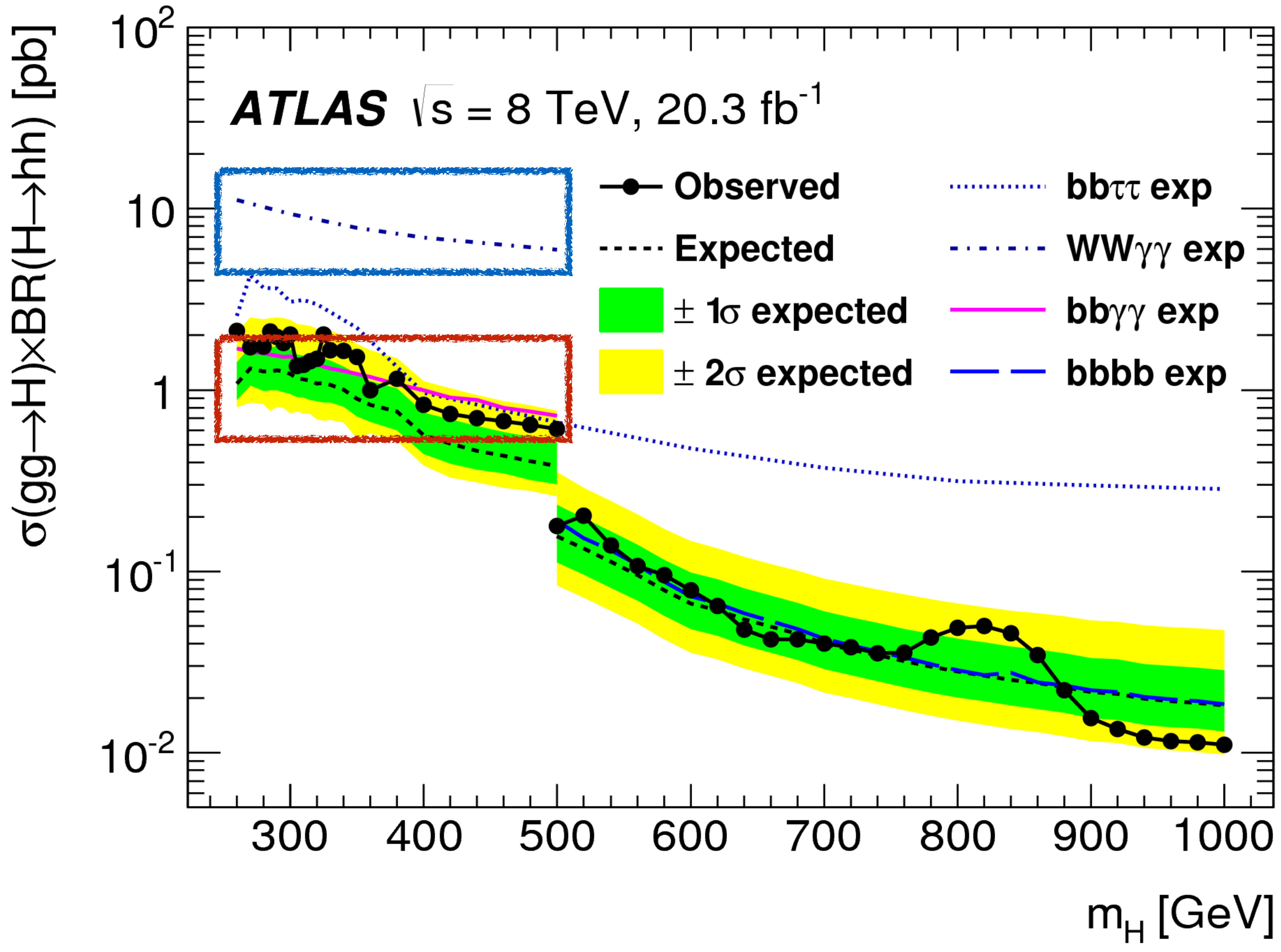


Di-Higgs low mass searches

Phys. Rev. D 92, 092004 (2015)

- Mass range: 250 ~ 1000 GeV
  - Model: resonant, non-resonant
    - trigger efficiency
    - branching ratio
  - Channels:
    - bbγγ, WW*γγ (250 ~ 500 GeV)

Run I Combined Limit

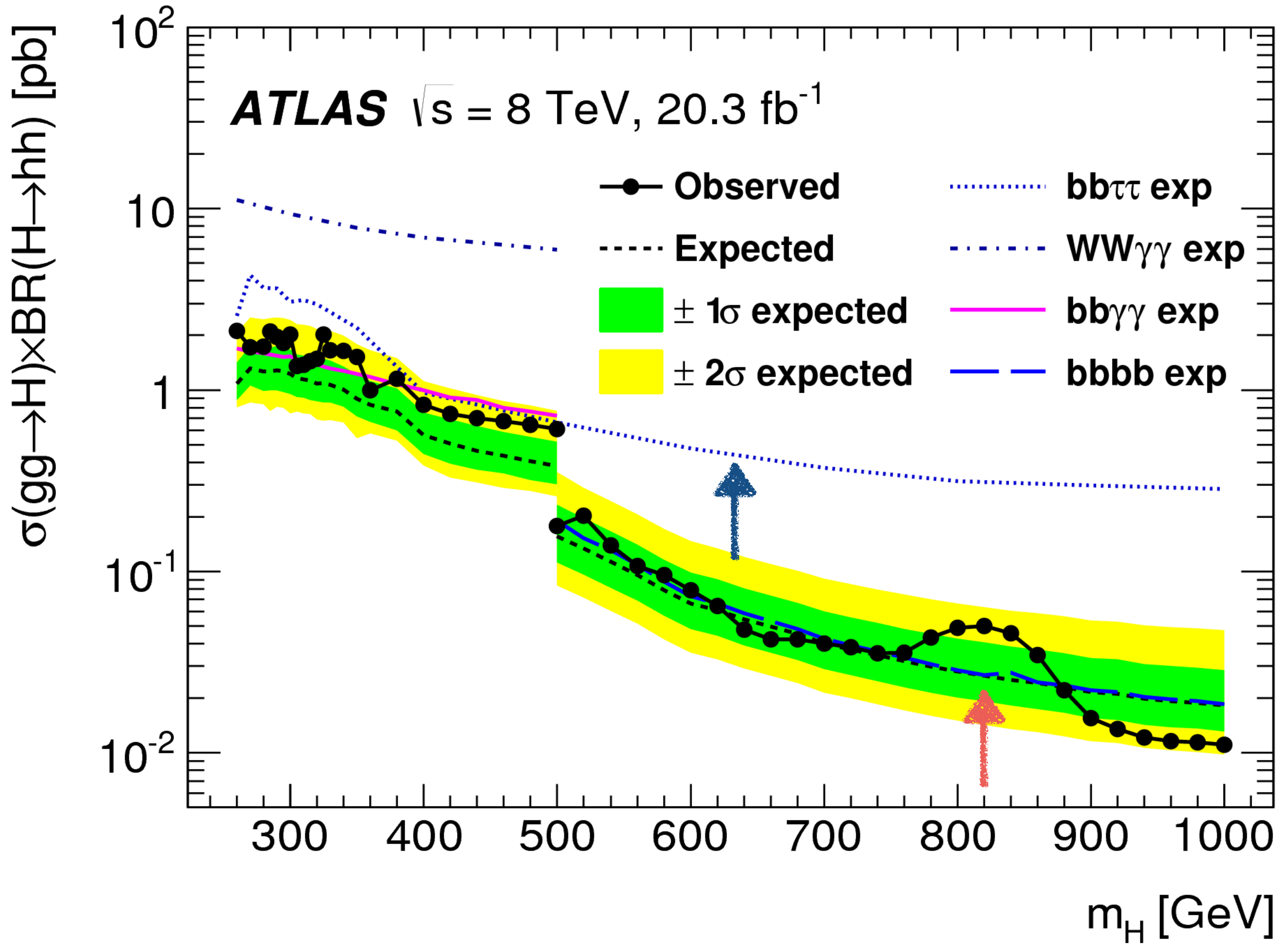


Di-Higgs low mass searches

Phys. Rev. D 92, 092004 (2015)

- Mass range: 250 ~ 1000 GeV
  - Model: resonant, non-resonant
    - trigger efficiency
    - branching ratio
  - Channels:
    - $bb\gamma\gamma$, $WW^*\gamma\gamma$ (250 ~ 500 GeV)
    - $bb\tau\tau$, bbbb (~ 1000 GeV)

Run I Combined Limit

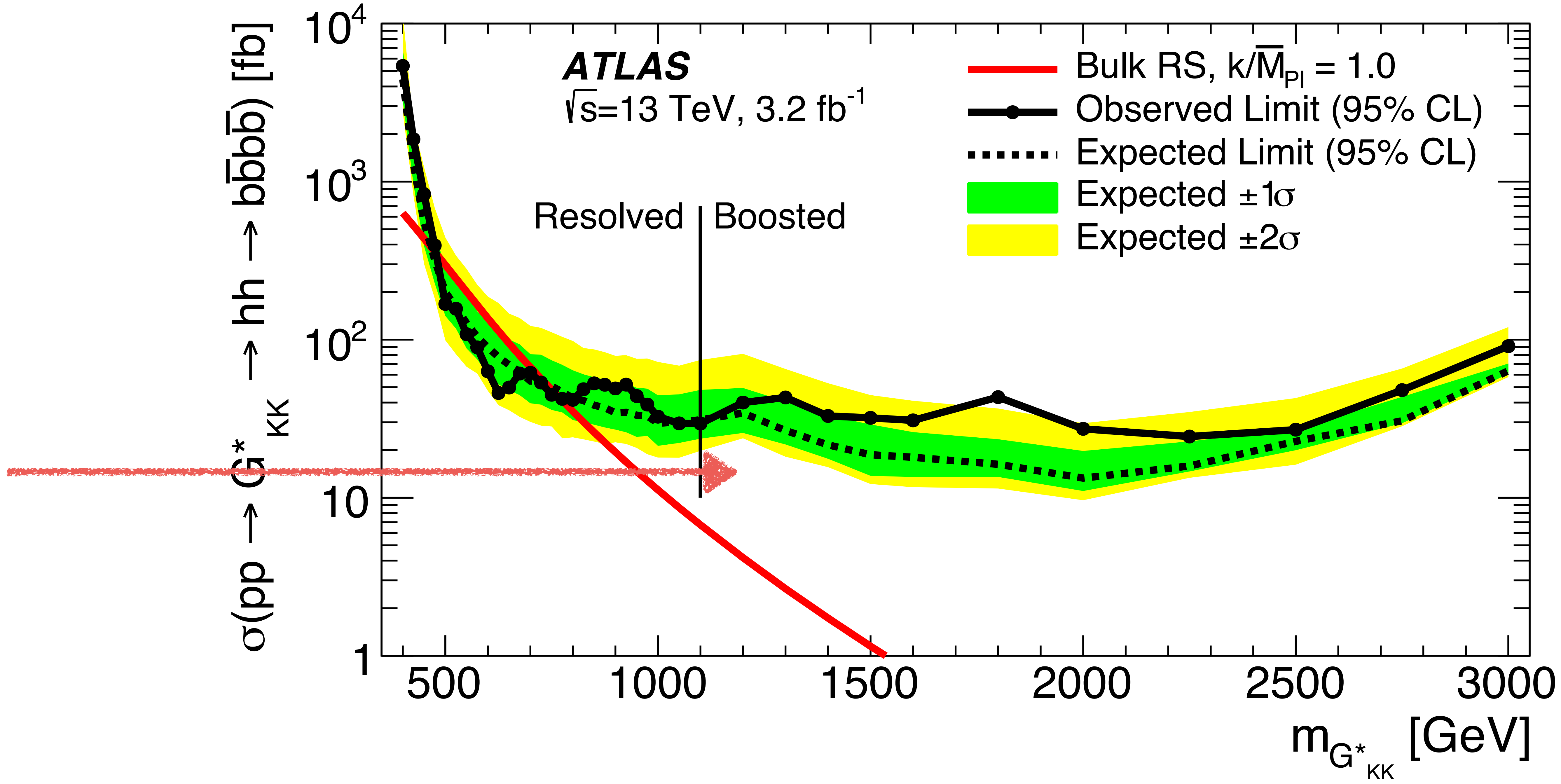


Di-Higgs high mass searches

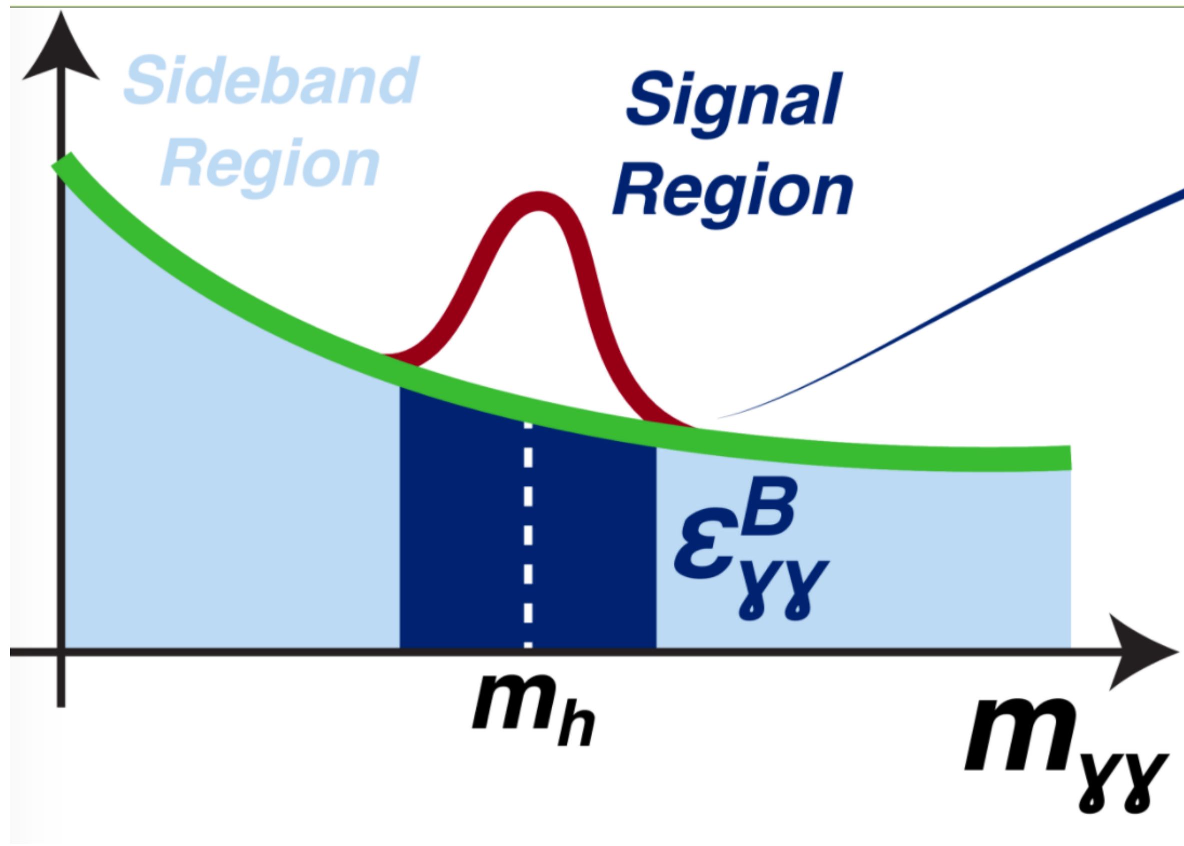
[Phys. Rev. D 94.052002 (2016)](https://doi.org/10.1103/PhysRevD.94.052002)

Run II 4b Limit, 3.2 fb^{-1}

- Mass range: 1000 ~ 3000 GeV
    - Model: resonant
        - standard objects merge
    - Channels:
        - bbbb, bb$\tau\tau$, bbWW*

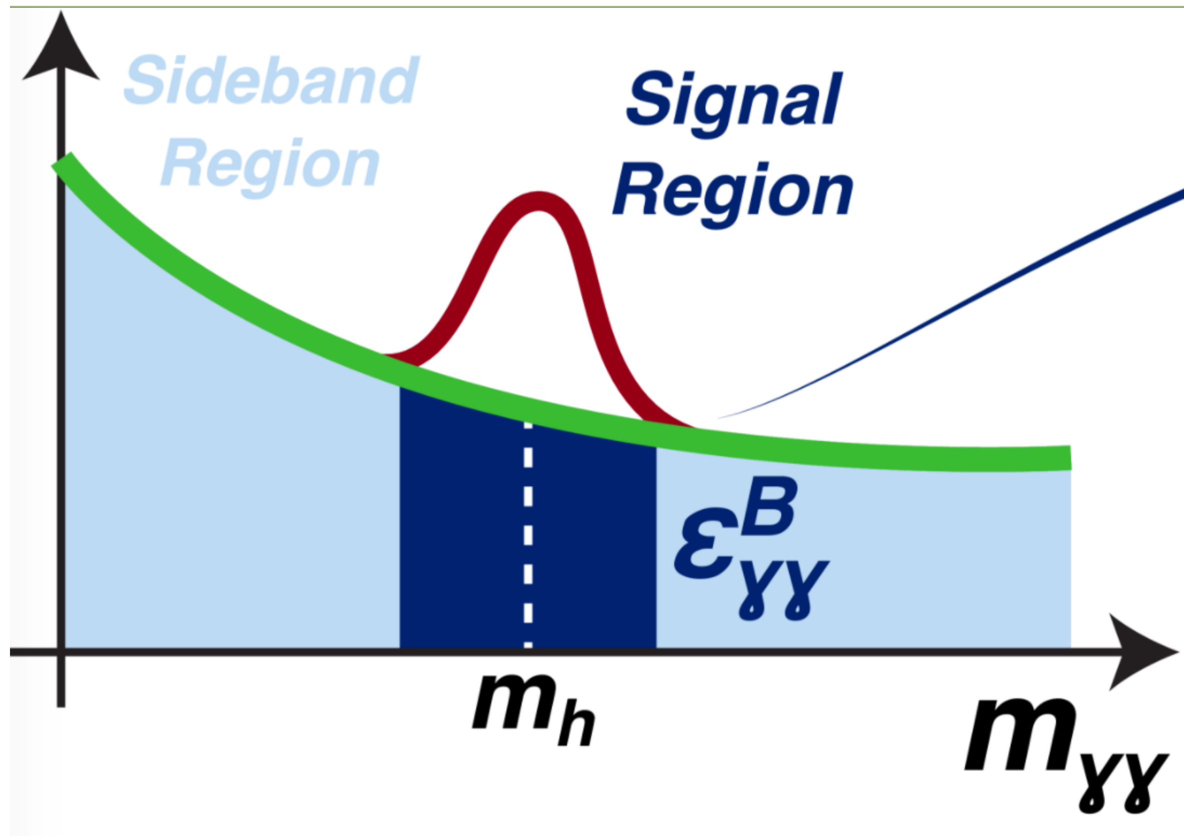


bbγγ and WW*γγ Selections



- Both built on top of SM $h\rightarrow\gamma\gamma$ selections—clean signature
- Both require 105 GeV < $m_{\gamma\gamma}$ < 160 GeV

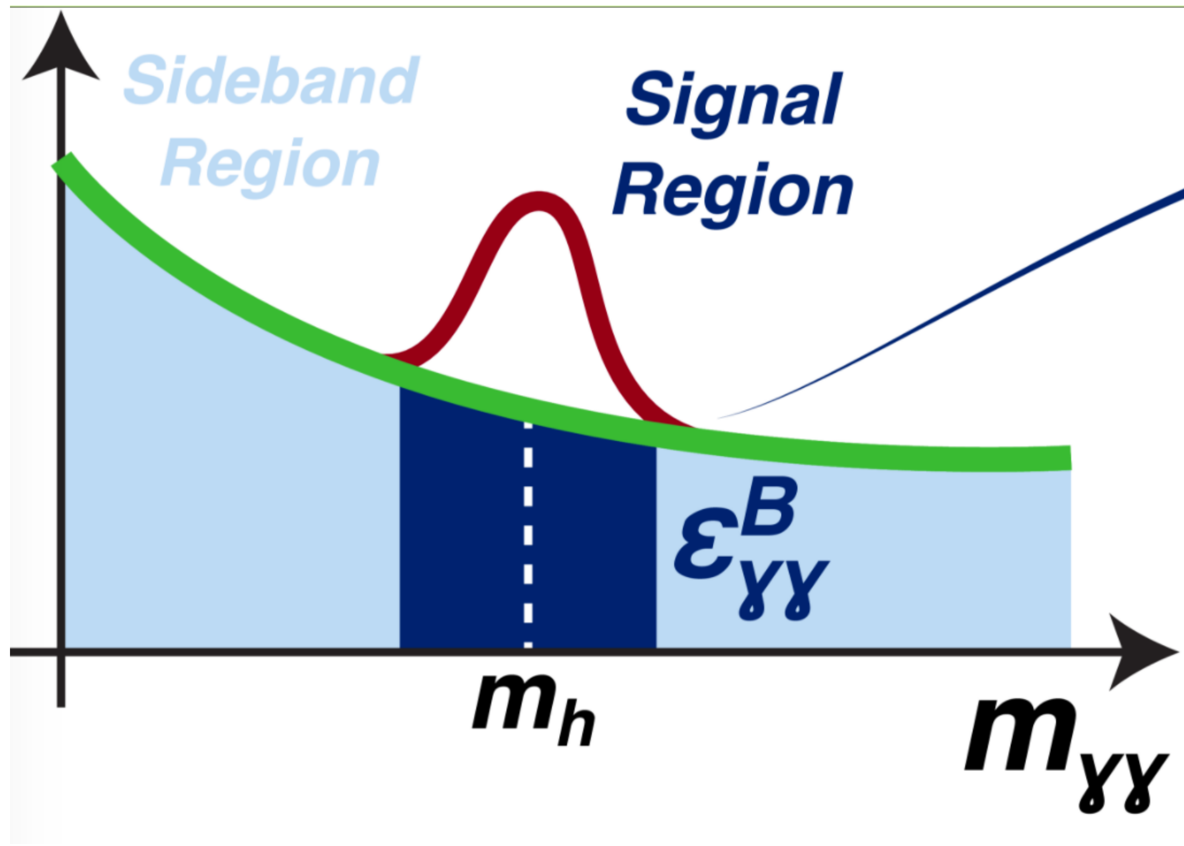
bbγγ and WW*γγ Selections



- Both built on top of SM h→γγ selections—clean signature
- Both require 105 GeV < $m_{\gamma\gamma}$ < 160 GeV

di-Higgs Decay/ Signal Regions	bbγγ		WW*γγ (semi-leptonic only)
Resonance	tighter mass window: 122 GeV < $m_{\gamma\gamma}$ < 128 GeV		
			2 jets, **1 lepton**
Non-resonance			same as resonance

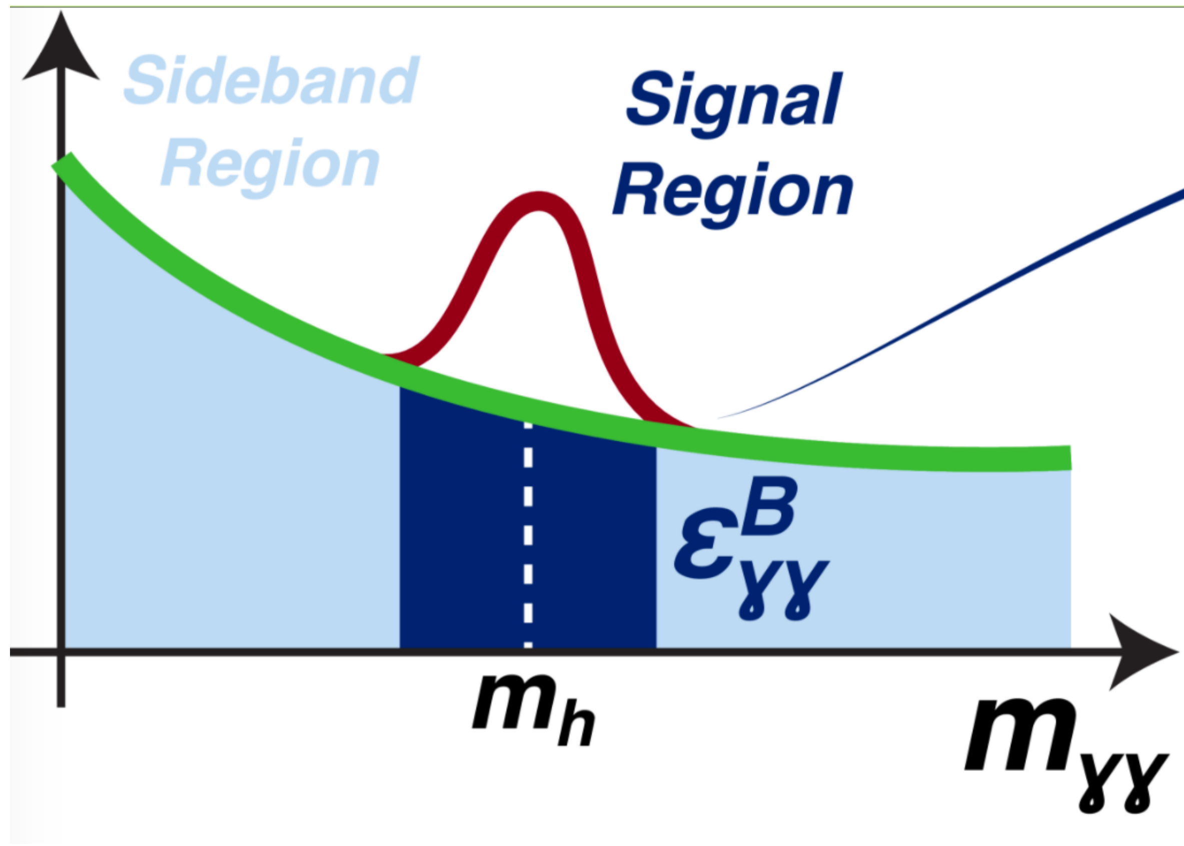
*bbγγ and WW*γγ Selections*



- Both built on top of SM $h \to \gamma\gamma$ selections—clean signature
- Both require 105 GeV < $m_{\gamma\gamma}$ < 160 GeV

di-Higgs Decay/ Signal Regions	**bbγγ**		**WW*γγ** (semi-leptonic only)
Resonance	tighter mass window: 122 GeV < $m_{\gamma\gamma}$ < 128 GeV		
	2 b-jets 95 GeV < m_{bb} < 135 GeV	mass window cuts on $m_{bb\gamma\gamma}$	2 jets, **1 lepton**
Non-resonance			same as resonance

bbγγ and WW*γγ Selections



- Both built on top of SM $h \rightarrow \gamma\gamma$ selections—clean signature
- Both require 105 GeV < $m_{\gamma\gamma}$ < 160 GeV

di-Higgs Decay/ Signal Regions	**bbγγ**		**WW*γγ** (semi-leptonic only)
Resonance	tighter mass window: 122 GeV < $m_{\gamma\gamma}$ < 128 GeV		
	2 b-jets 95 GeV < m_{bb} < 135 GeV	mass window cuts on $m_{bb\gamma\gamma}$	2 jets, **1 lepton**
Non-resonance		fit the full $m_{\gamma\gamma}$ without tighter mass window	same as resonance

*bbγγ and WW*γγ Signal Regions*

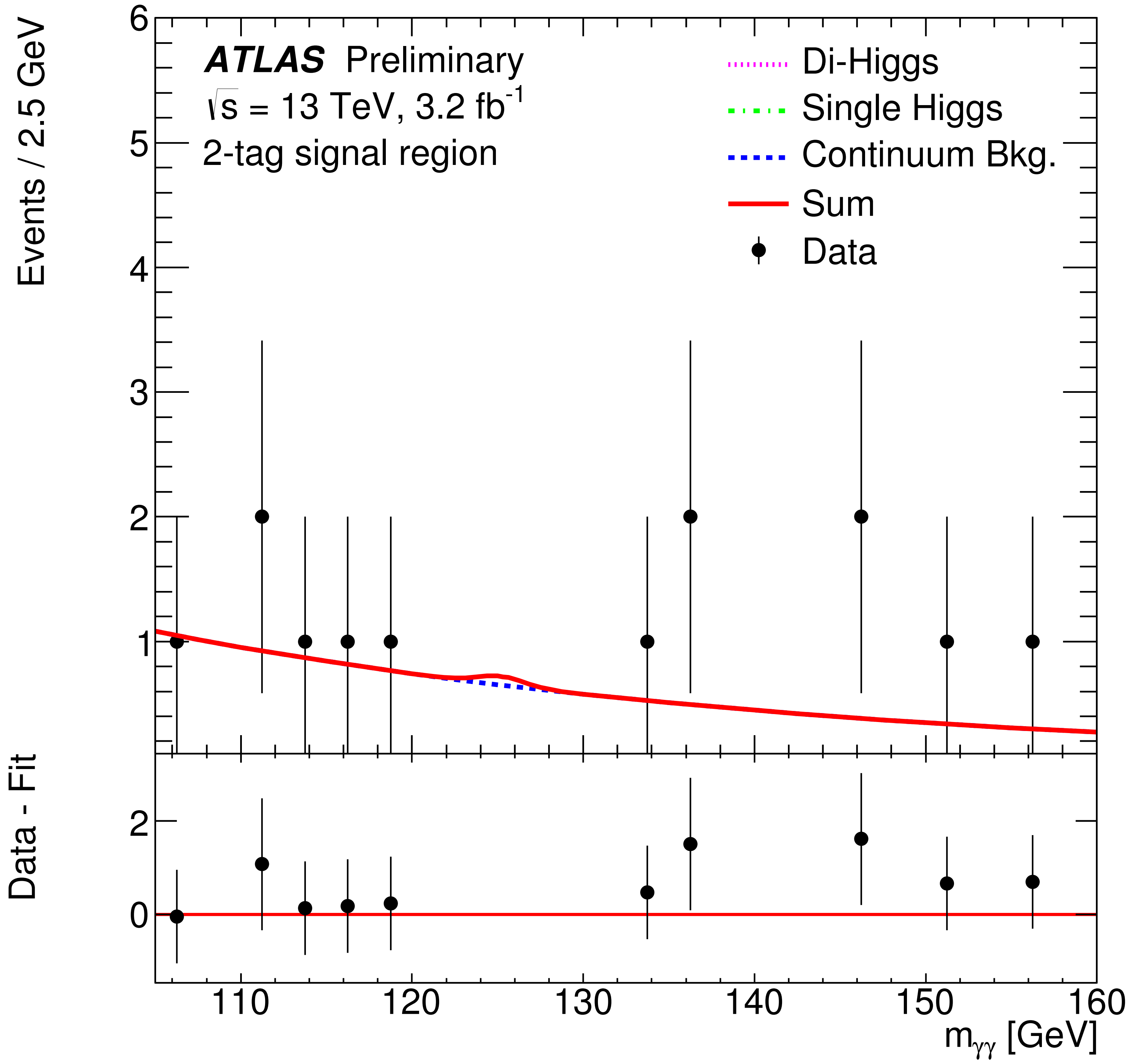
ATLAS-CONF-2016-004

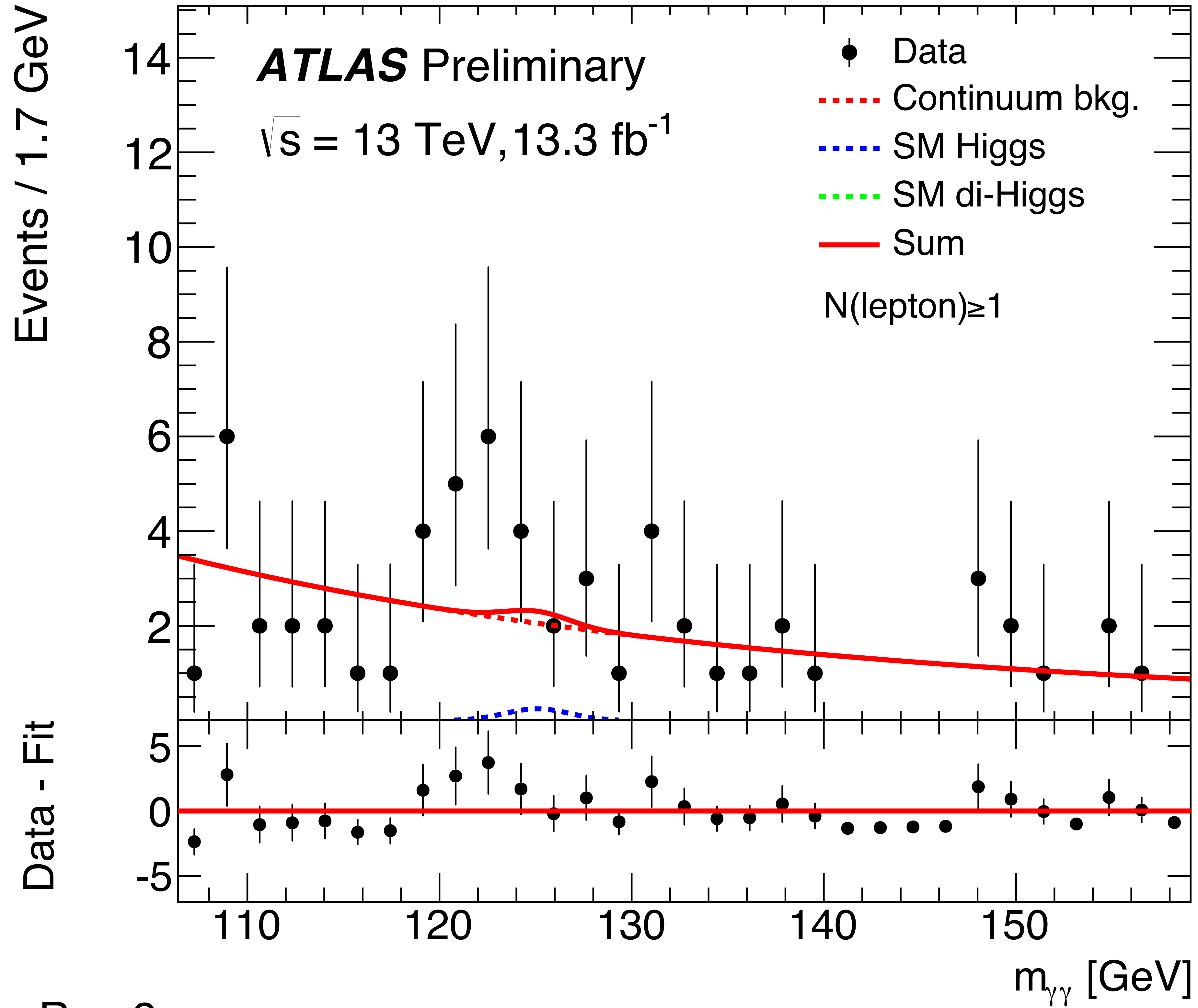
ATLAS-CONF-2016-071

bbγγ	3.2 fb^{-1}
Obs	0
Exp	1.6 ± 0.3

Yields are within the tight $m_{\gamma\gamma}$ window

WW*γγ	13.3 fb^{-1}
Obs	15
Exp	7.26 ± 1.23





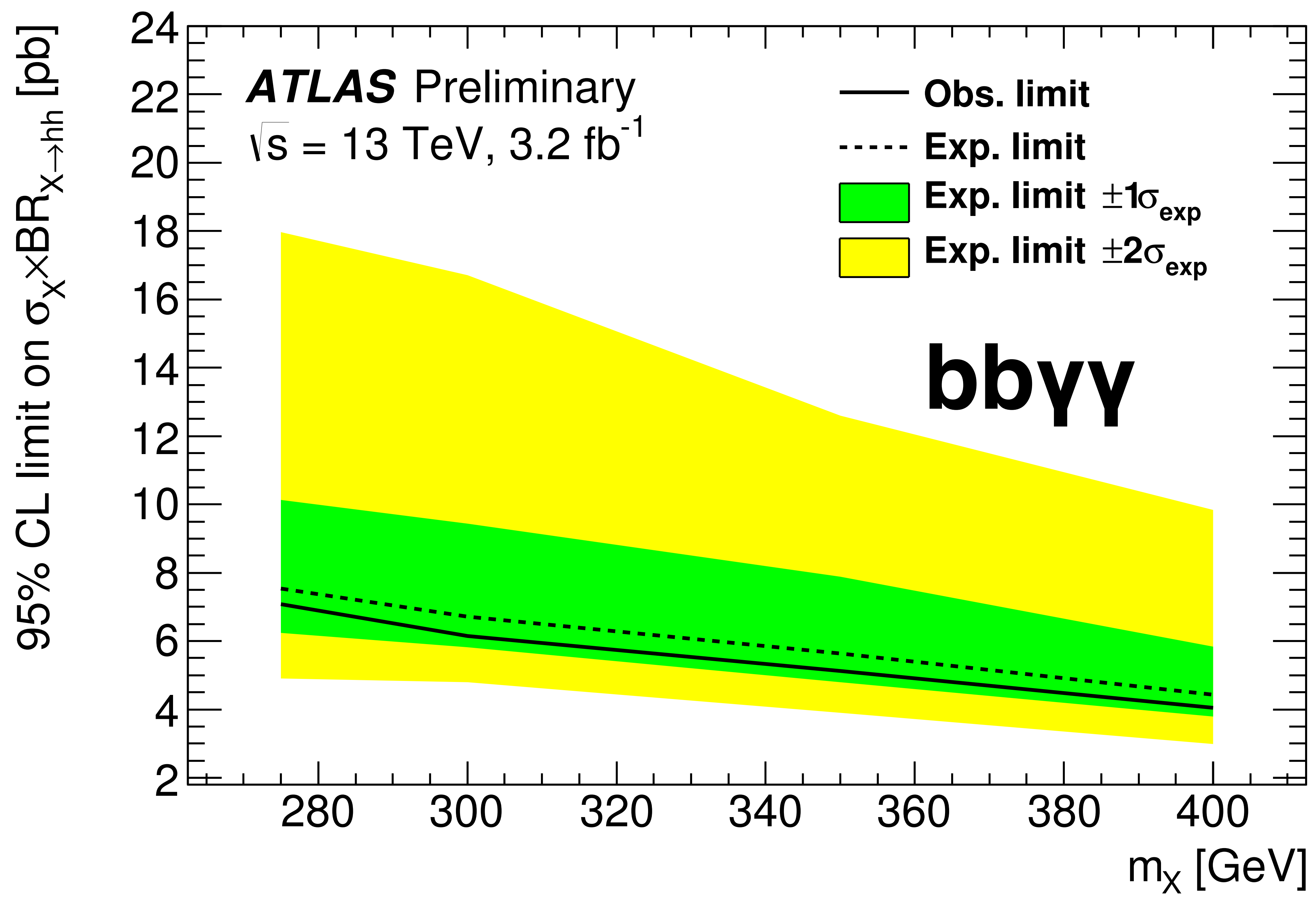
bbγγ observed an excess in Run-1, not confirmed by Run-2

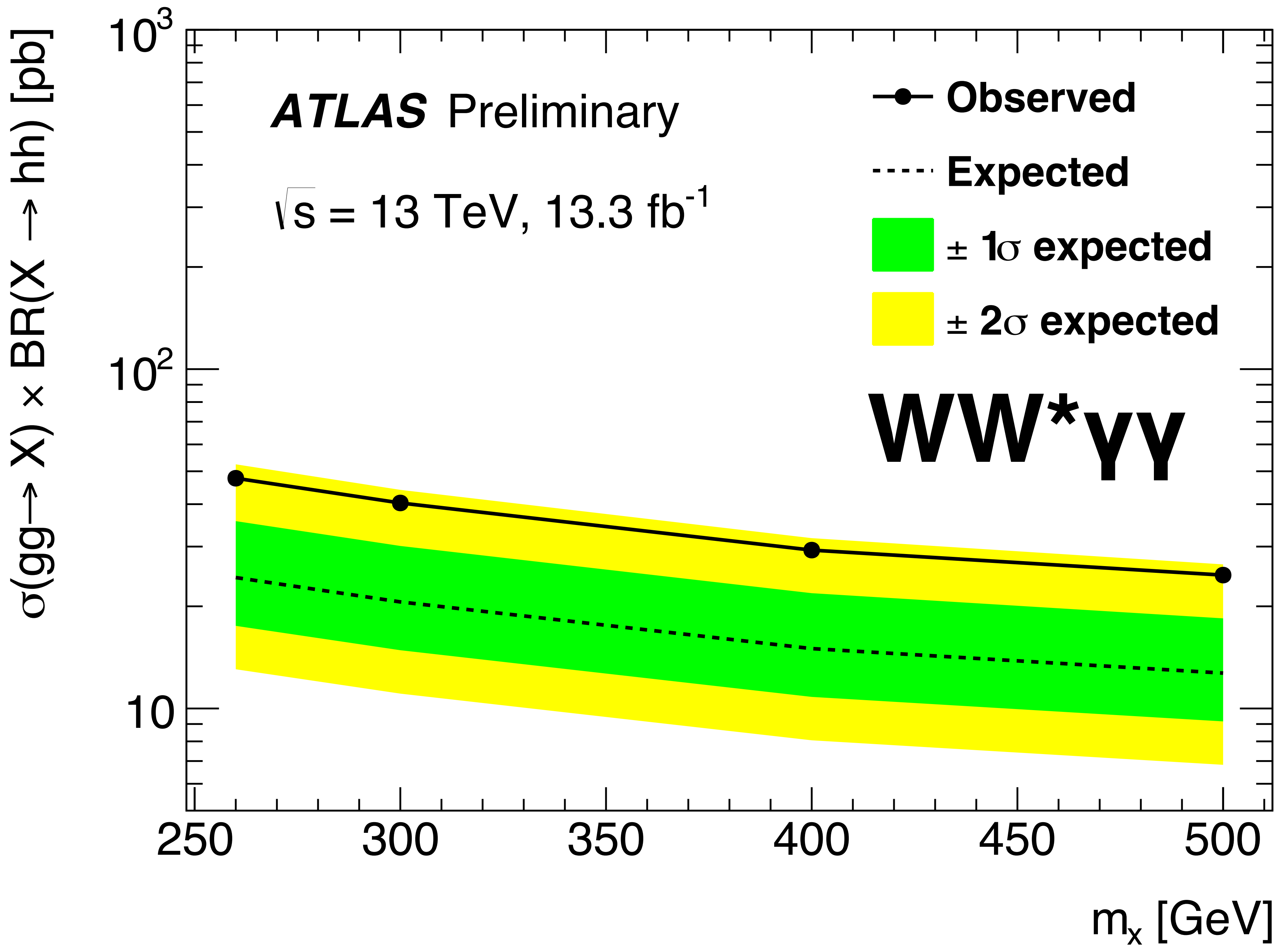
*bbγγ and WW*γγ Limits*

ATLAS-CONF-2016-004

ATLAS-CONF-2016-071

- No resonant excess observed
- Non-resonant hh limit:
  - bbγγ — **3.9 pb** (5.4 pb expected)
  - WW*γγ— **25 pb** (12.9 pb expected)

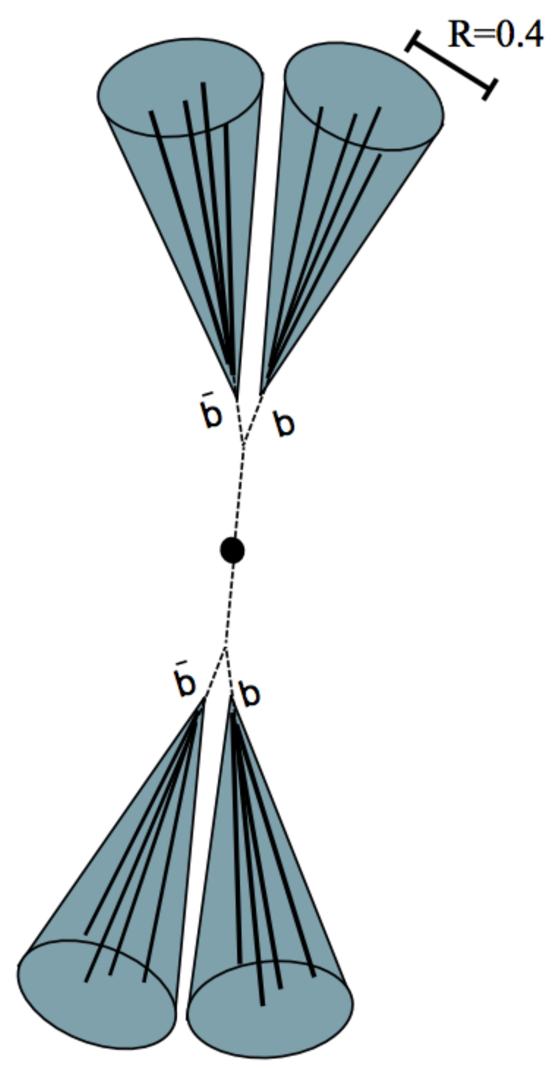




Jets Merging and the Two Channels

ATLAS-CONF-2016-049

- Standard resolved 4b jets for the low mass range

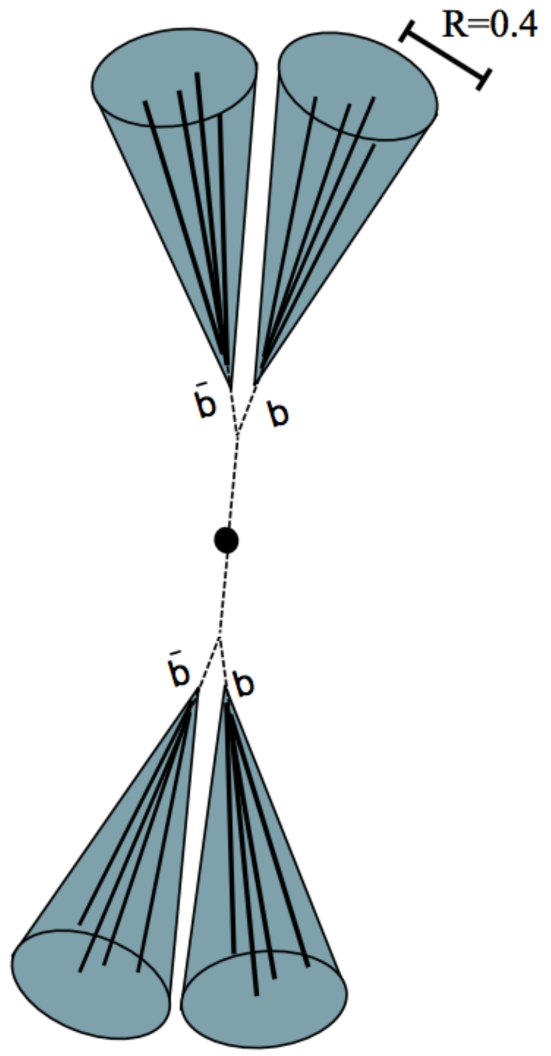


Objects/ Final State	Resolved (250–1100 GeV)	
Trigger	Mixed b Trigger	
Jets	Four **0.4** Anti-kt Jets	
pT cuts	Jet pT > **30** GeV	
B-tagging	70% WP on EM Jets	

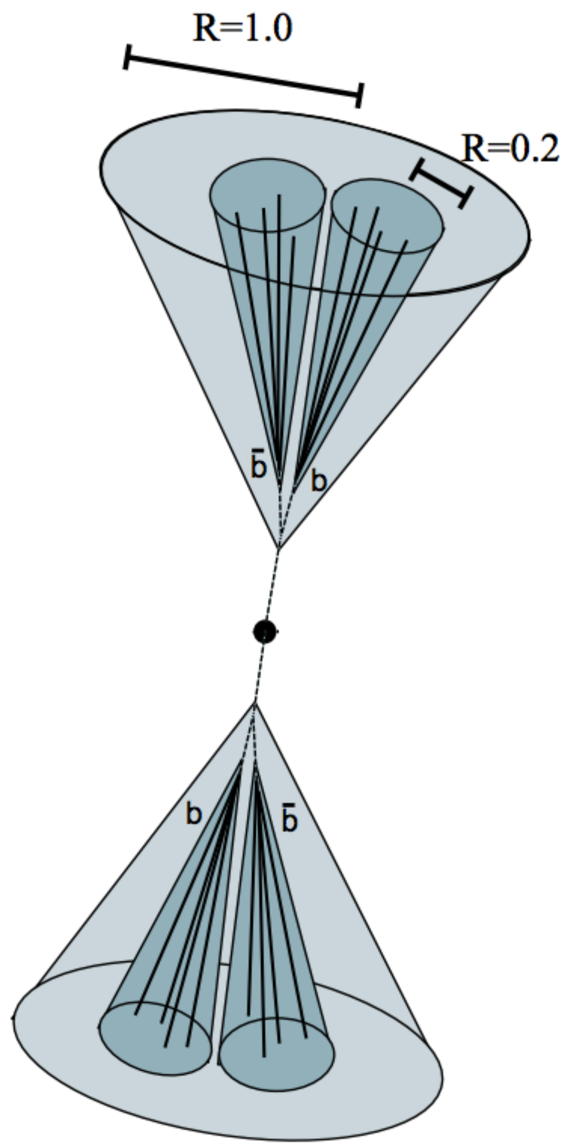
Jets Merging and the Two Channels

ATLAS-CONF-2016-049

- Standard resolved 4b jets for the low mass range
- **1.5 TeV** resonance → ~ 600 GeV p_T Higgs → ΔR_{bb} ~$2m_h/p_T$ ~ **0.4**



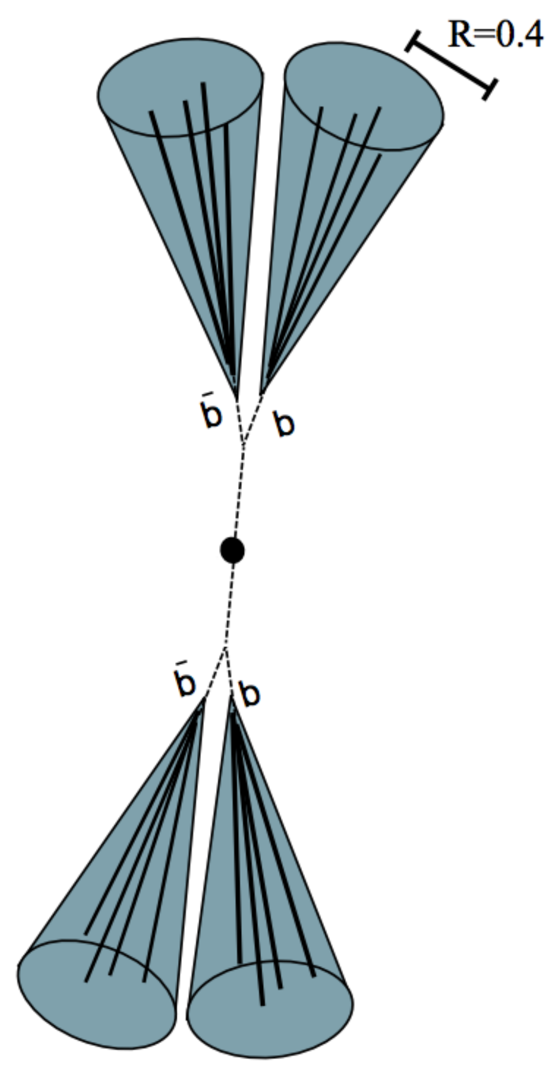
Objects/ Final State	Resolved (250–1100 GeV)	Boosted (1100-3000 GeV)
Trigger	Mixed b Trigger	
Jets	Four **0.4** Anti-kt Jets	
pT cuts	Jet pT > **30** GeV	
B-tagging	70% WP on EM Jets	



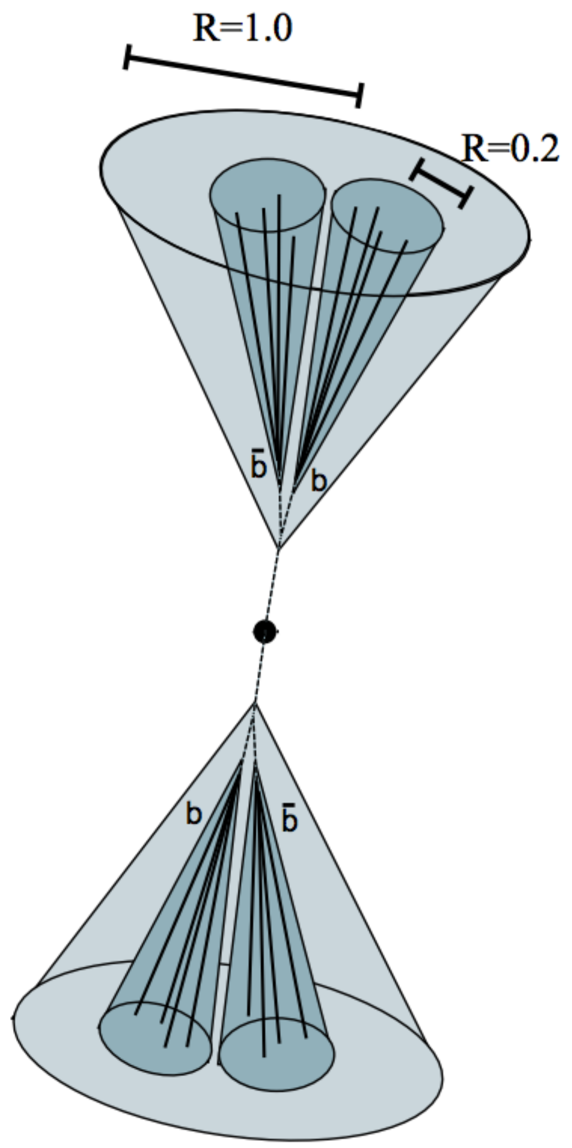
Jets Merging and the Two Channels

ATLAS-CONF-2016-049

- Standard resolved 4b jets for the low mass range
- **1.5 TeV** resonance → ~ 600 GeV p_T Higgs → ΔR_{bb} ~$2m_h/p_T$ ~ **0.4**



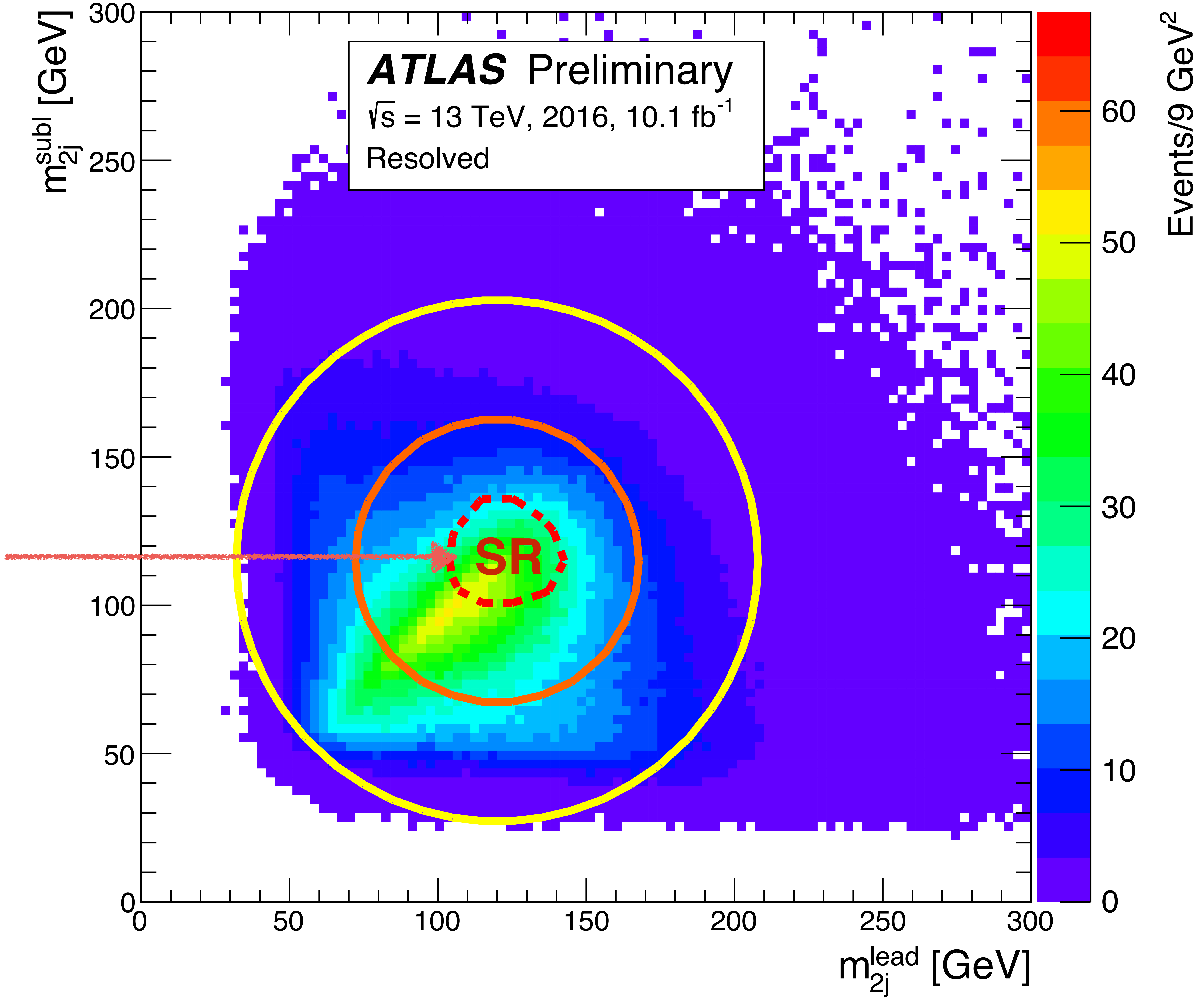
Objects/ Final State	Resolved (250–1100 GeV)	Boosted (1100-3000 GeV)
Trigger	Mixed b Trigger	Large R-jet Trigger
Jets	Four **0.4** Anti-kt Jets	Two **1.0** trimmed Anti-kt Jets
pT cuts	Jet pT > **30** GeV	Leading > **450** GeV Subleading > 250 GeV
B-tagging	70% WP on EM Jets	77% WP on Anti-kt R=**0.2** track jets



Two Higgs Mass Plane

ATLAS-CONF-2016-049

- **Signal Region** (SR):
  - "Circle" centered at h mass
  - Xhh < 1.6

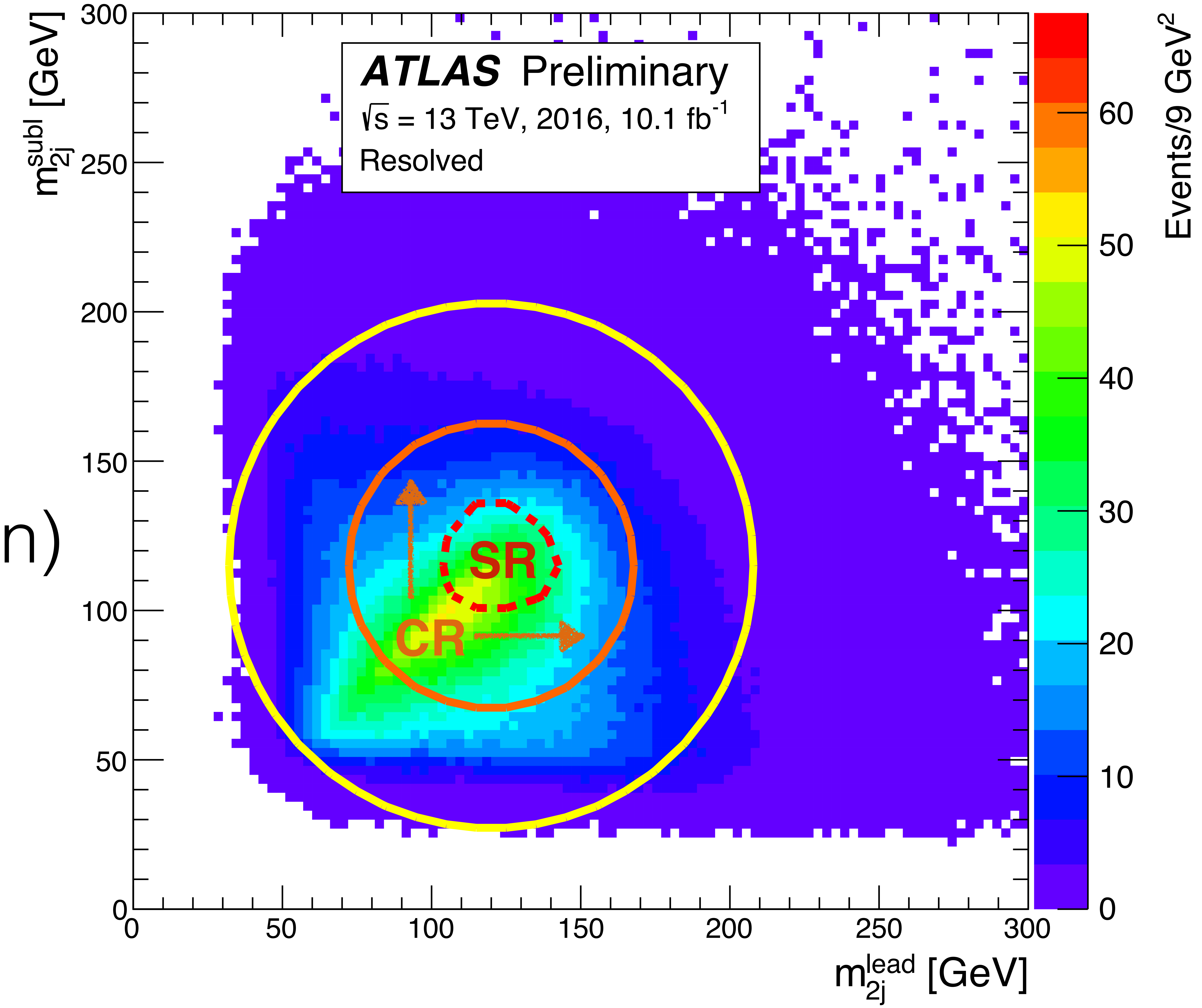


$$X_{hh} = \sqrt{\left(\frac{m_J^{\text{lead}} - 124\text{ GeV}}{\sigma\left(m_J^{\text{lead}}\right)}\right)^2 + \left(\frac{m_J^{\text{subl}} - 115\text{ GeV}}{\sigma\left(m_J^{\text{subl}}\right)}\right)^2}$$

Two Higgs Mass Plane

ATLAS-CONF-2016-049

- **Signal Region** (SR):
  - “Circle” centered at h mass
  - Xhh < 1.6
- **Control Region** (CR) :
  - Ring outside SR (for validation)



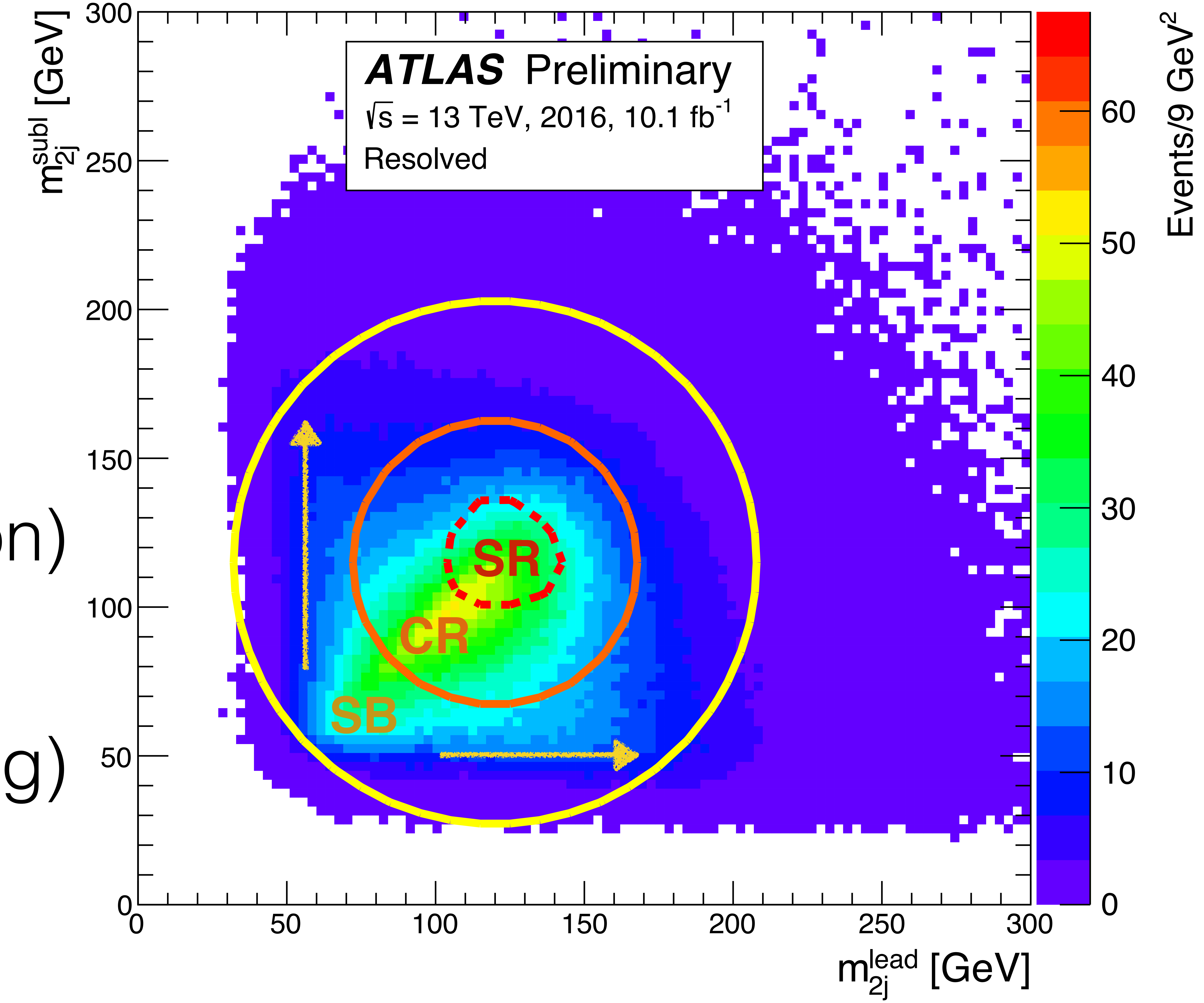
$$X_{hh} = \sqrt{\left(\frac{m_J^{lead} - 124\ \text{GeV}}{\sigma\left(m_J^{lead}\right)}\right)^2 + \left(\frac{m_J^{subl} - 115\ \text{GeV}}{\sigma\left(m_J^{subl}\right)}\right)^2}$$

Two Higgs Mass Plane

ATLAS-CONF-2016-049

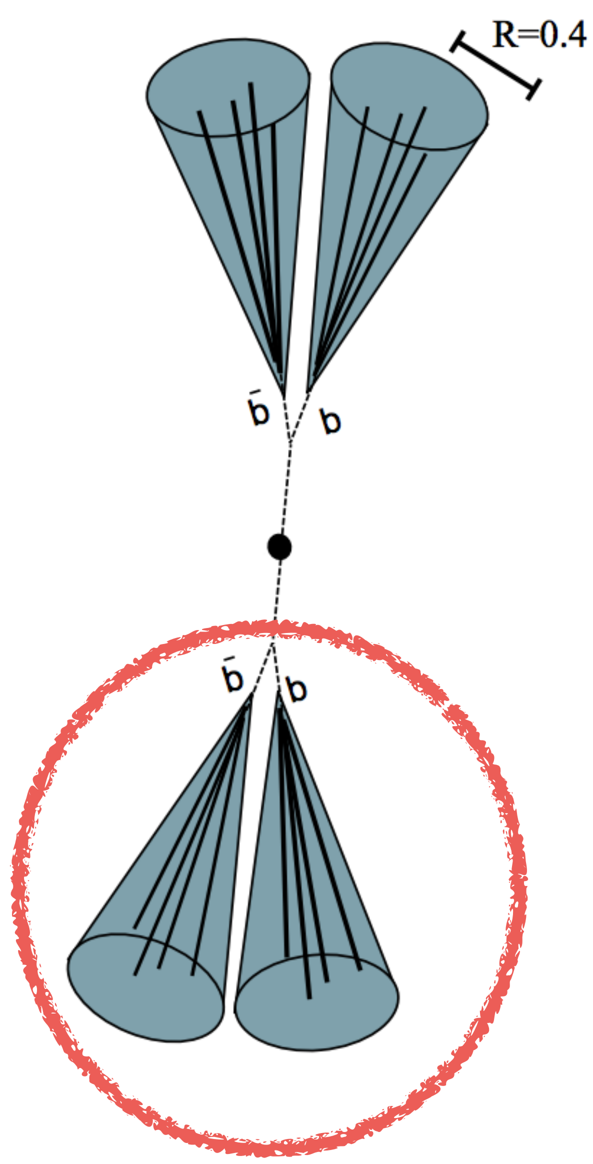
- **Signal Region** (SR):
  - "Circle" centered at h mass
  - Xhh < 1.6
- **Control Region** (CR) :
  - Ring outside SR (for validation)
- **Sideband** (SB)
  - Ring outside CR (for modeling)

$$X_{hh} = \sqrt{\left(\frac{m_J^{\text{lead}} - 124\text{ GeV}}{\sigma\left(m_J^{\text{lead}}\right)}\right)^2 + \left(\frac{m_J^{\text{subl}} - 115\text{ GeV}}{\sigma\left(m_J^{\text{subl}}\right)}\right)^2}$$

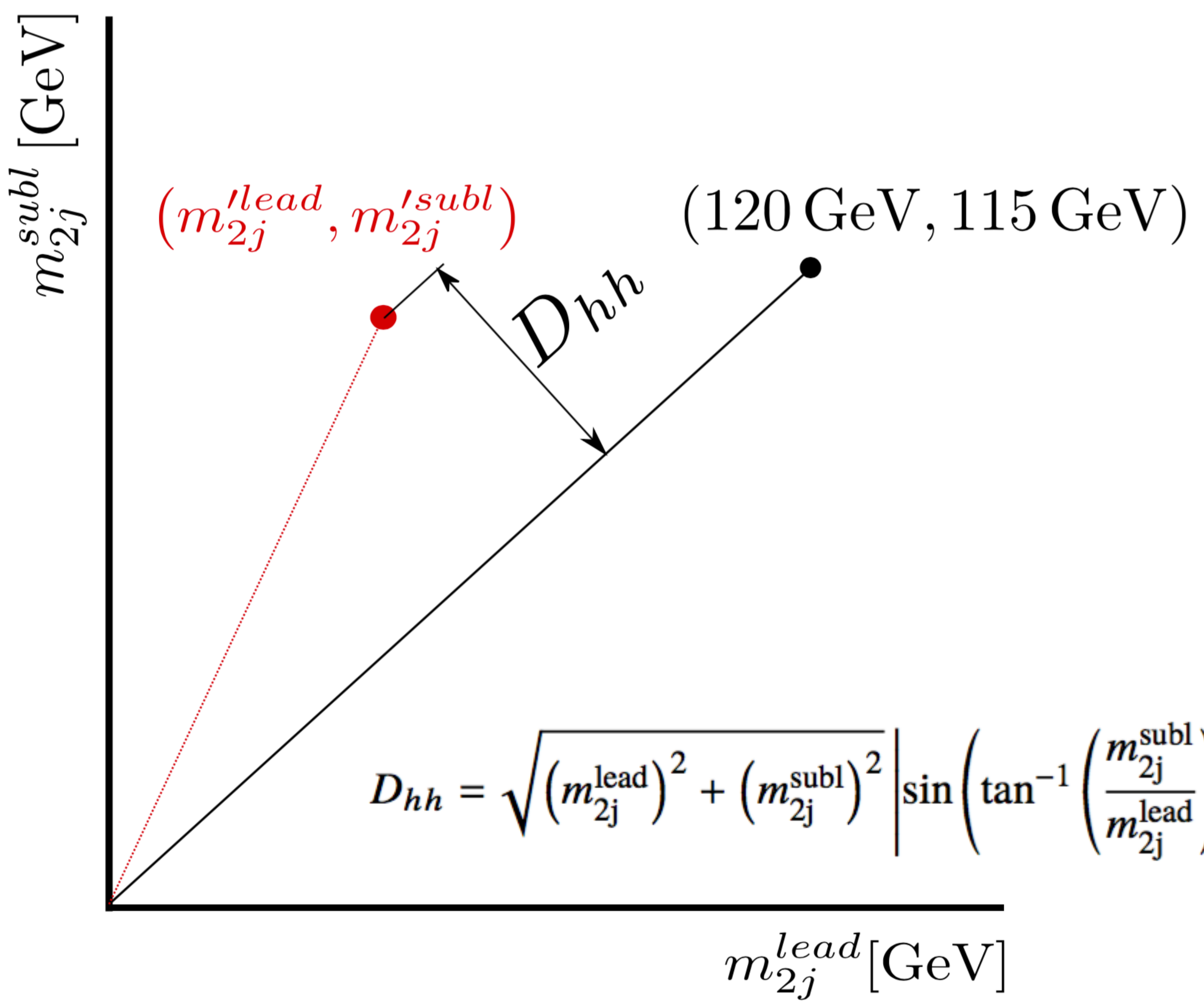


Jets Pair Combinatorics and Cuts

ATLAS-CONF-2016-049



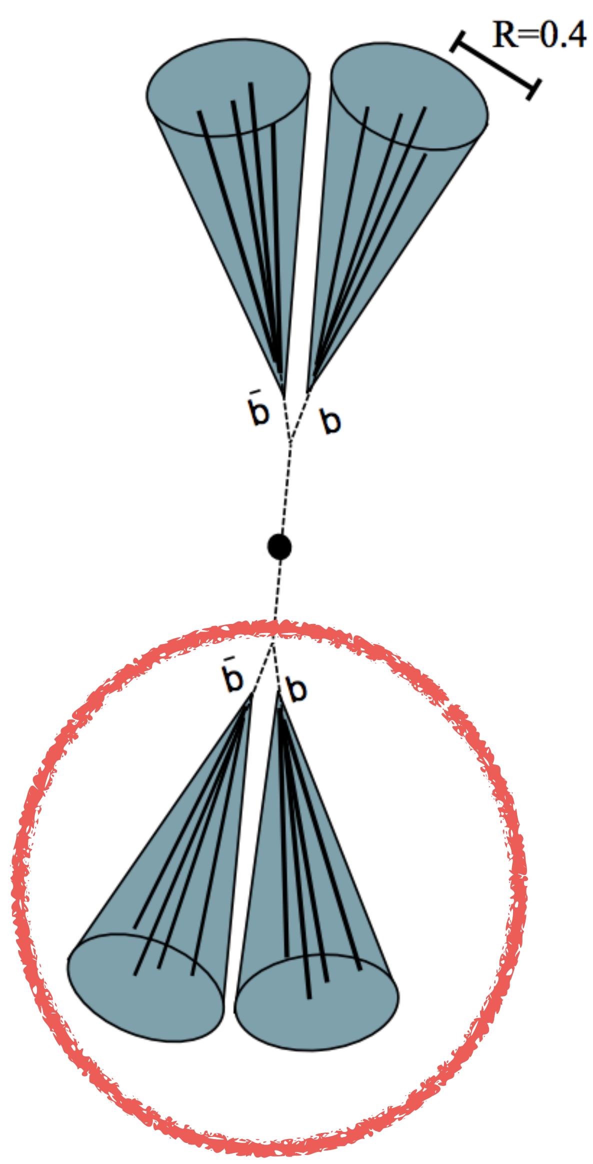
- Select hh pair that has the **minimal distance** to the diagonal line on the 2D mass plane
- m_{4j} dependent requirements on h **pT, eta, and dR$_{jj}$**



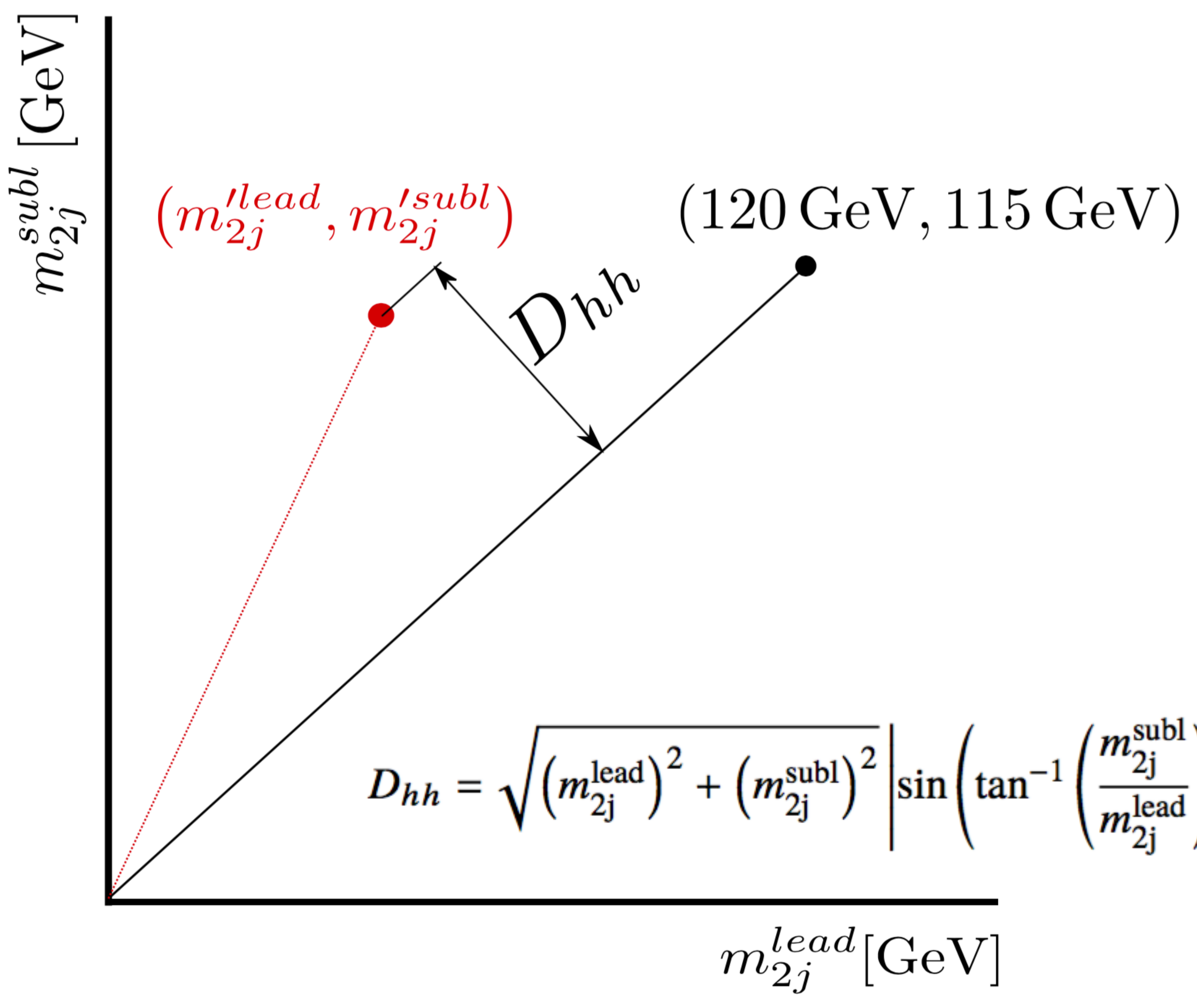
$$D_{hh} = \sqrt{\left(m_{2j}^{\mathrm{lead}}\right)^2 + \left(m_{2j}^{\mathrm{subl}}\right)^2}\left|\sin\left(\tan^{-1}\left(\frac{m_{2j}^{\mathrm{subl}}}{m_{2j}^{\mathrm{lead}}}\right) - \tan^{-1}\left(\frac{115}{120}\right)\right)\right|$$

Jets Pair Combinatorics and Cuts

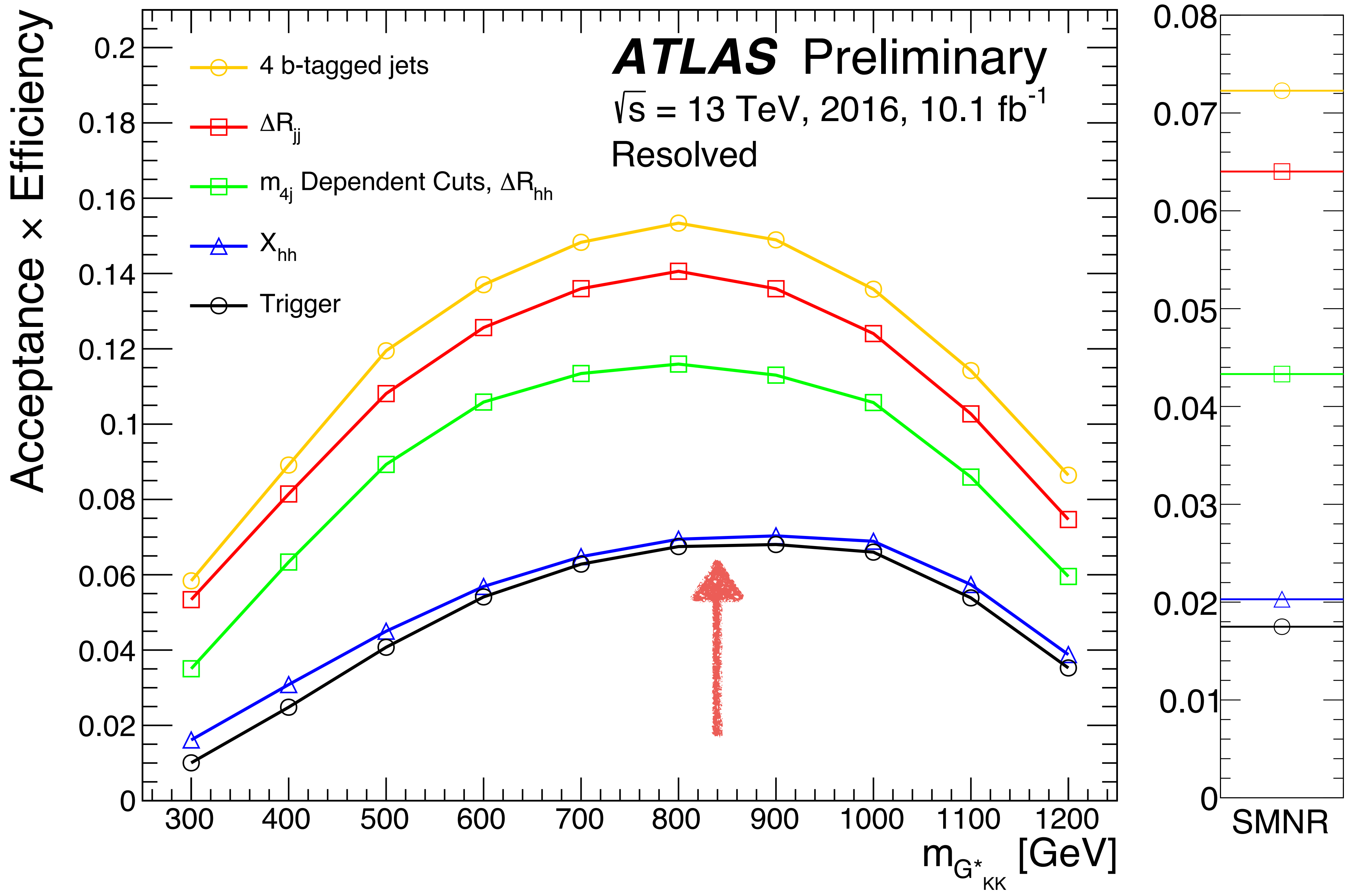
ATLAS-CONF-2016-049



- Select hh pair that has the **minimal distance** to the diagonal line on the 2D mass plane
- m_{4j} dependent requirements on h **pT, eta, and dR$_{jj}$**
- Good signal efficiency across **large** mass ranges



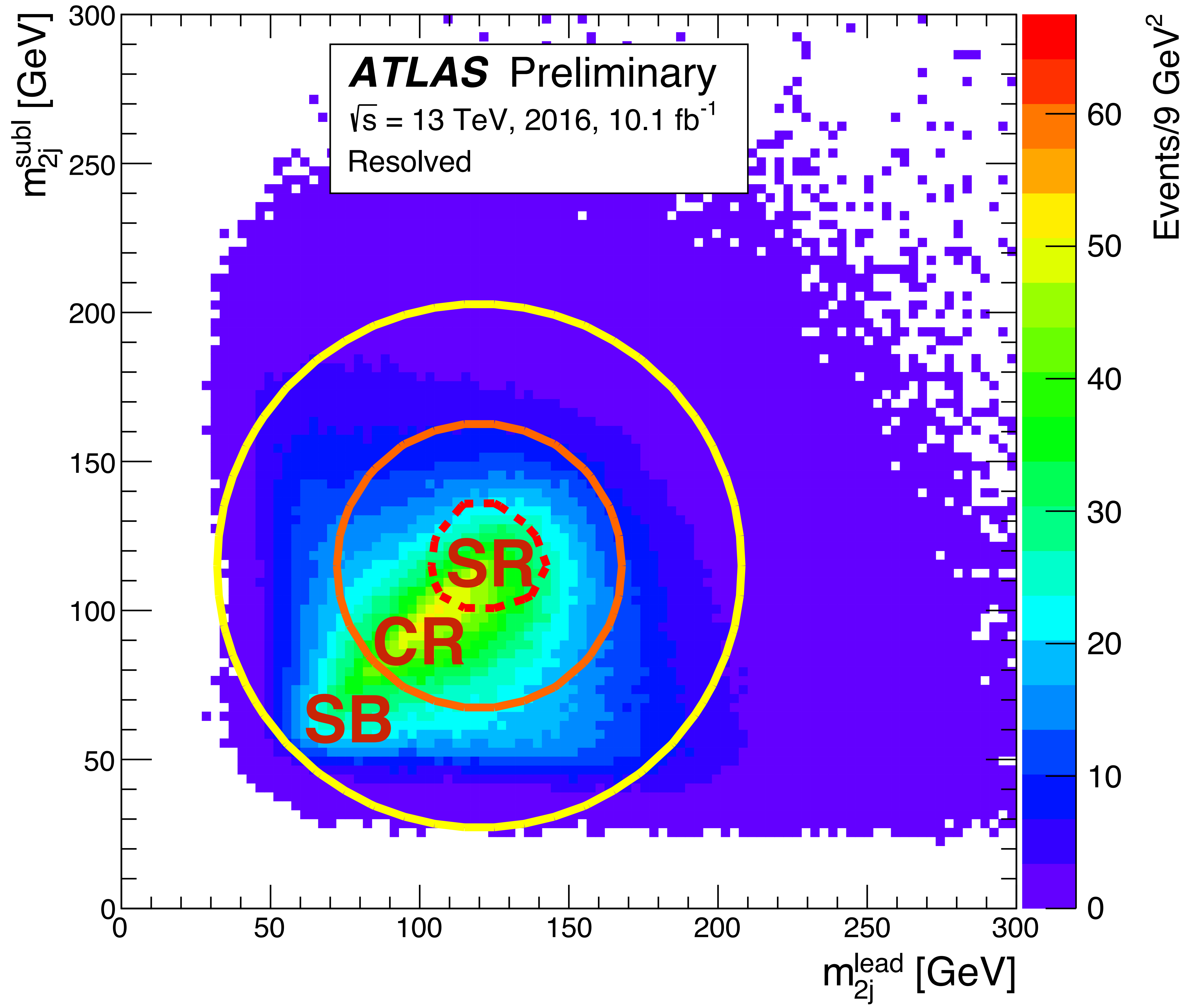
$$D_{hh} = \sqrt{\left(m_{2j}^{lead}\right)^2 + \left(m_{2j}^{subl}\right)^2} \left| \sin\left(\tan^{-1}\left(\frac{m_{2j}^{subl}}{m_{2j}^{lead}}\right) - \tan^{-1}\left(\frac{115}{120}\right)\right)\right|$$



Resolved 4b Background

ATLAS-CONF-2016-049

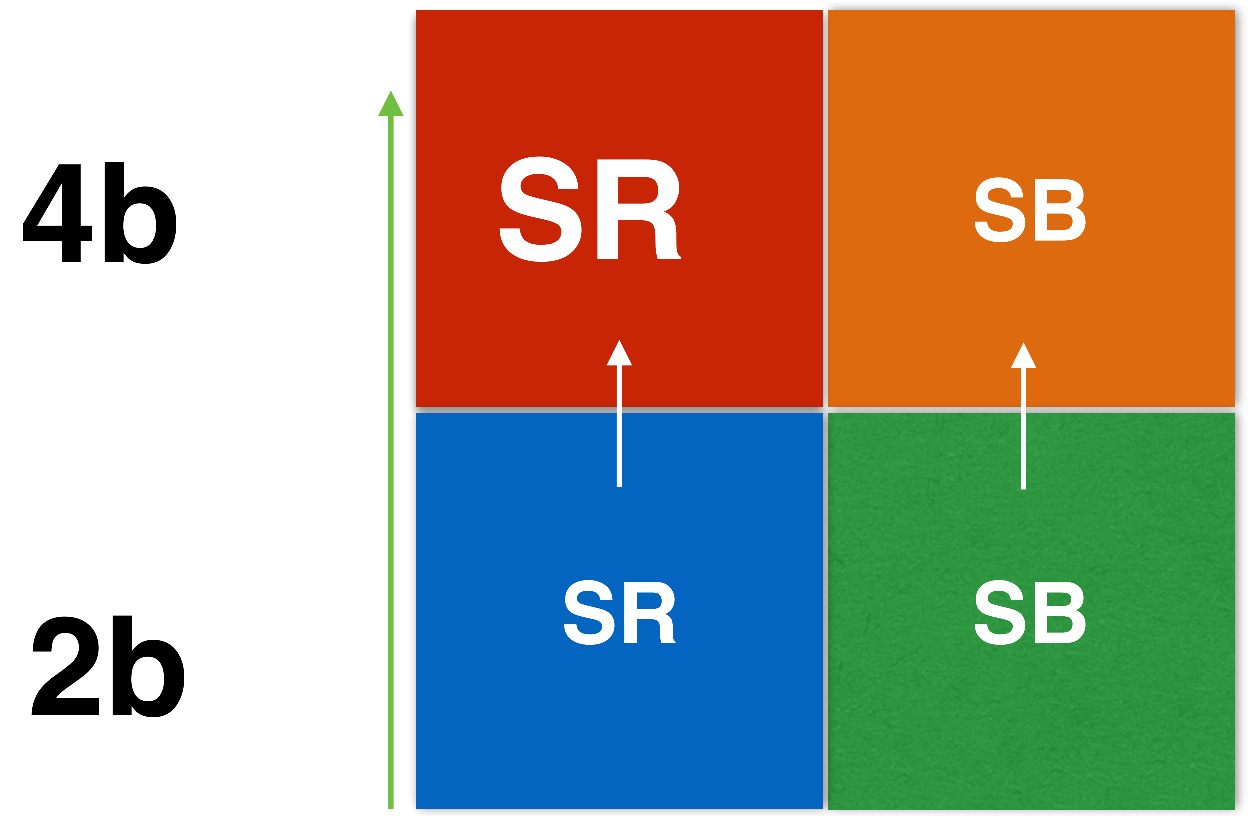
- Background:
  - 93% qcd—data driven
  - 7% ttbar—MC

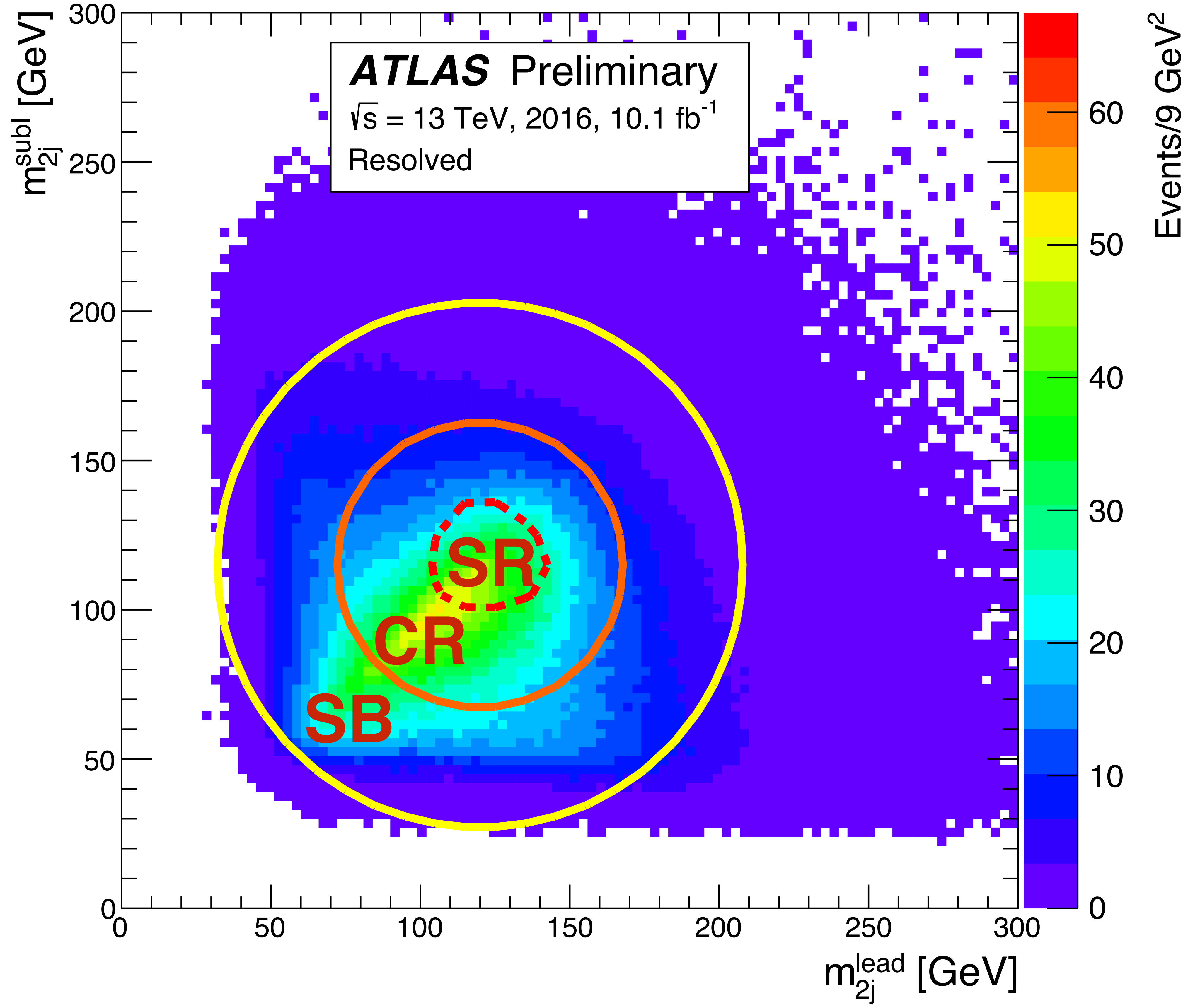


Resolved 4b Background

ATLAS-CONF-2016-049

- Background:
  - 93% qcd—data driven
  - 7% ttbar—MC





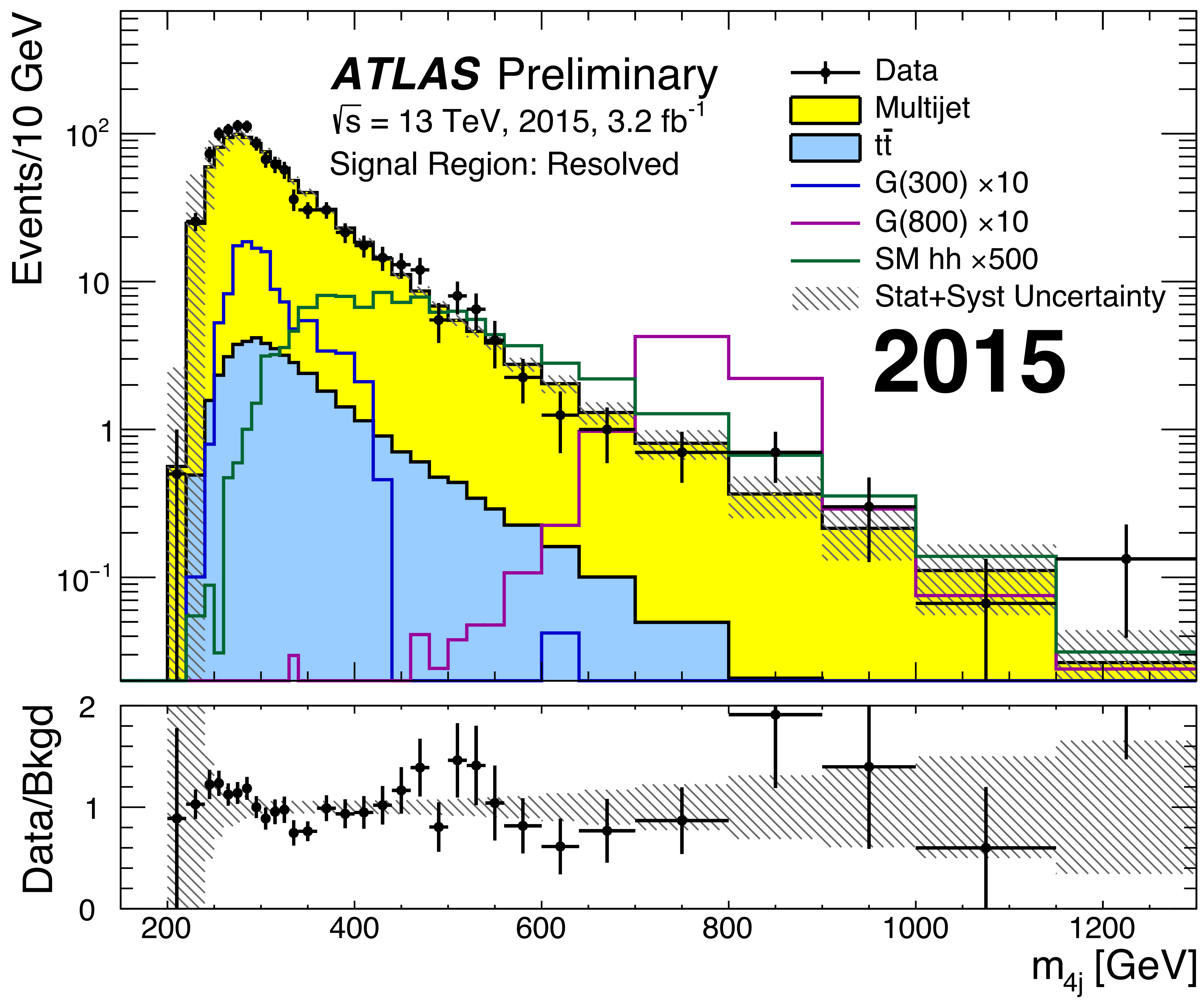
- Background **shape** estimation comes from 2Tag SB(sideband)/CR(control)/SR(signal) regions
- 2b inclusive sample is used to derive the **normalization** estimation in 4b

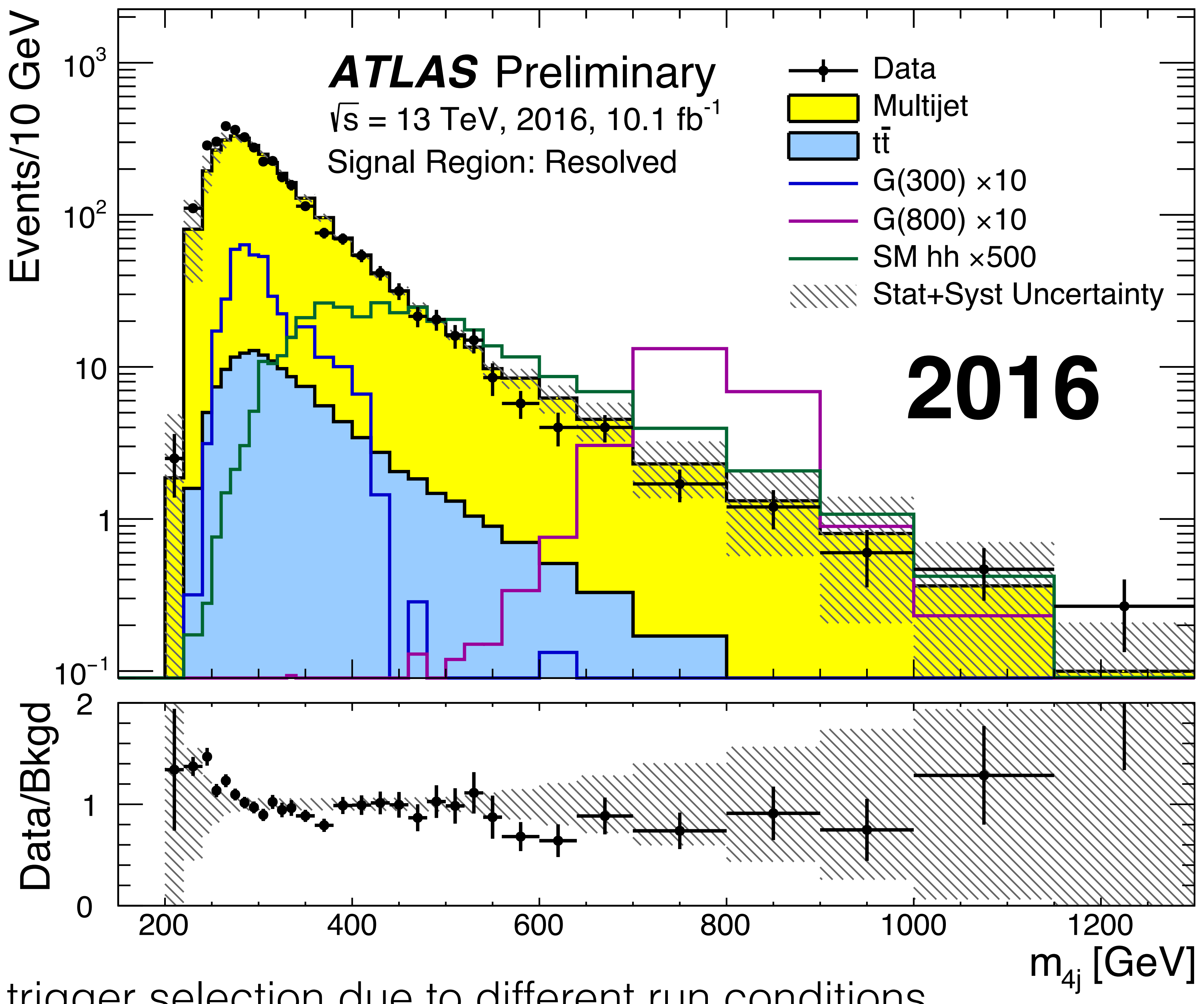
Signal Region: Resolved

ATLAS-CONF-2016-049

- Final discriminant: **four jets's invariant mass**; no significant excess observed

Data	2015	2016
Obs	**1231**	**3990**
Exp	1189 ± 76	3860 ± 230

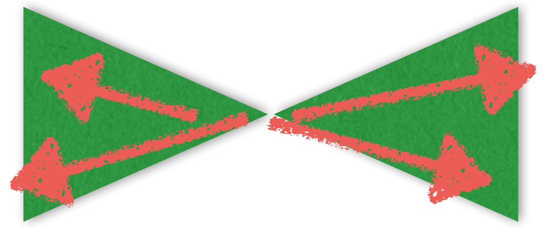
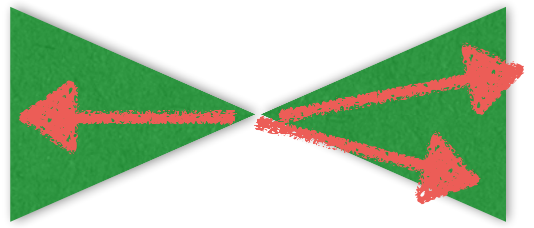


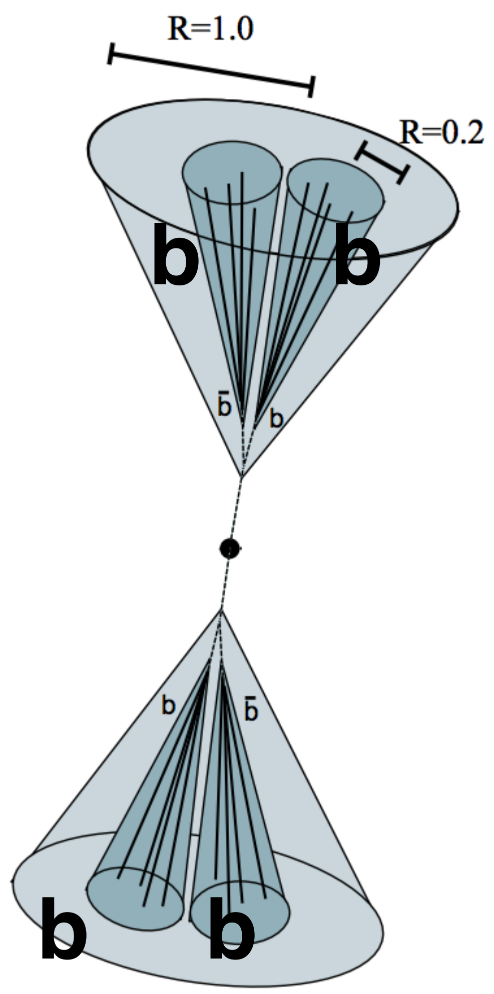


*2015 and 2016 have different trigger selection due to different run conditions

Track Jets Tagging and Signal Regions

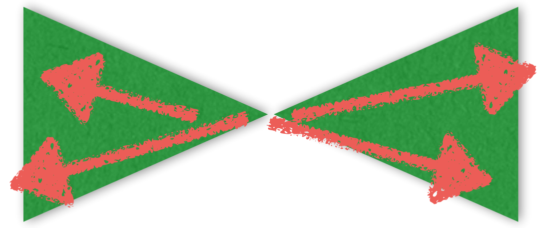
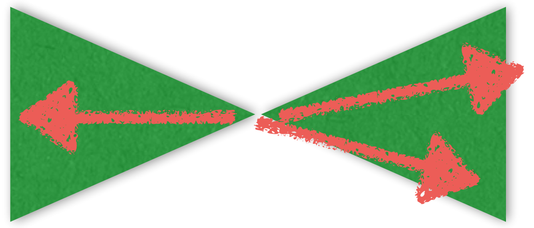
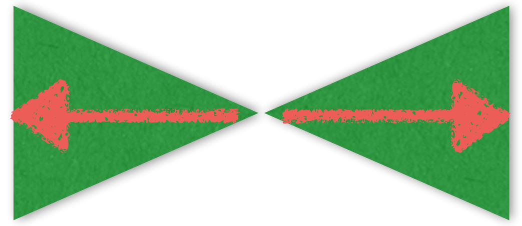
ATLAS-CONF-2016-049

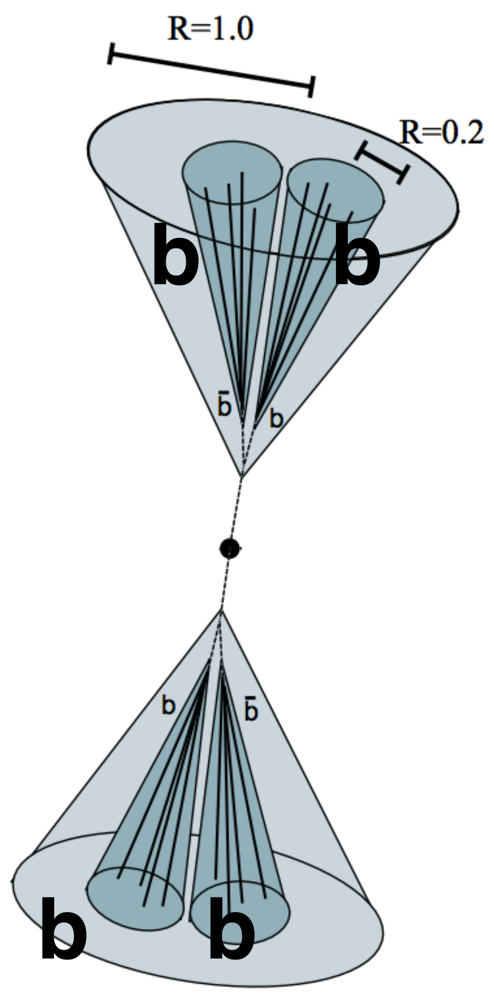
- 4Tag:  3Tag: (recover efficiency) 

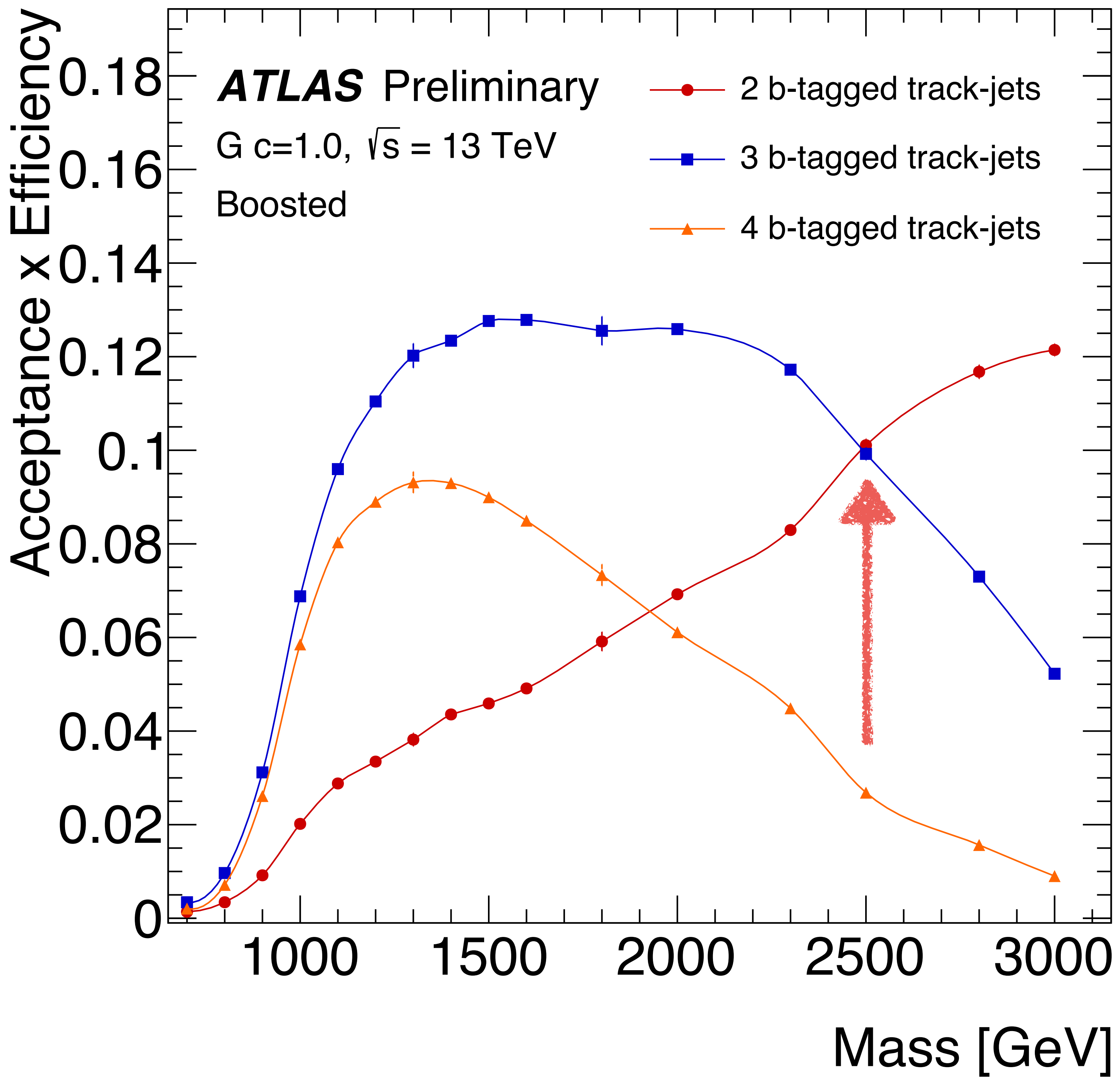


Track Jets Tagging and Signal Regions

ATLAS-CONF-2016-049

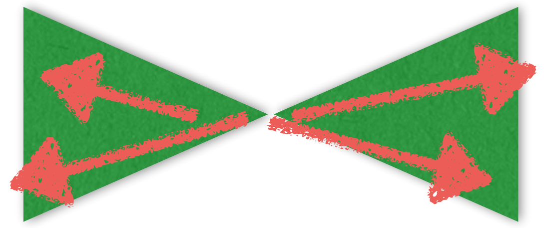
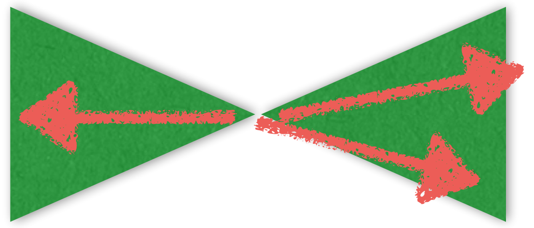
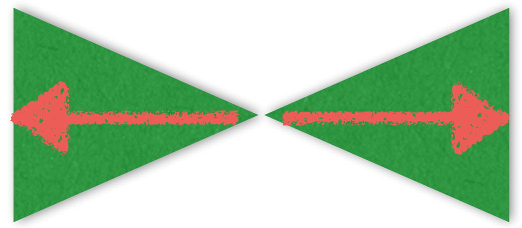
- 4Tag:  3Tag: (recover efficiency) 
- 2Tag Split: one b Tag in each large R jet 

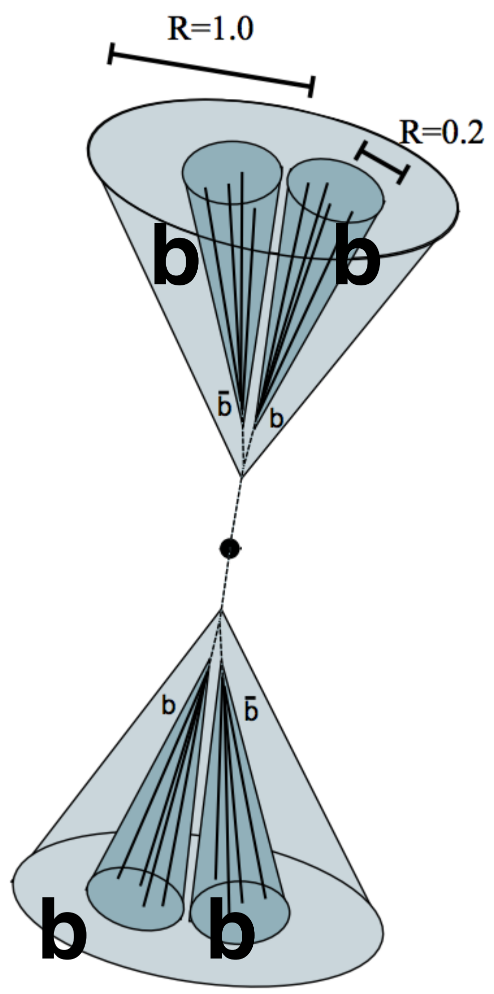


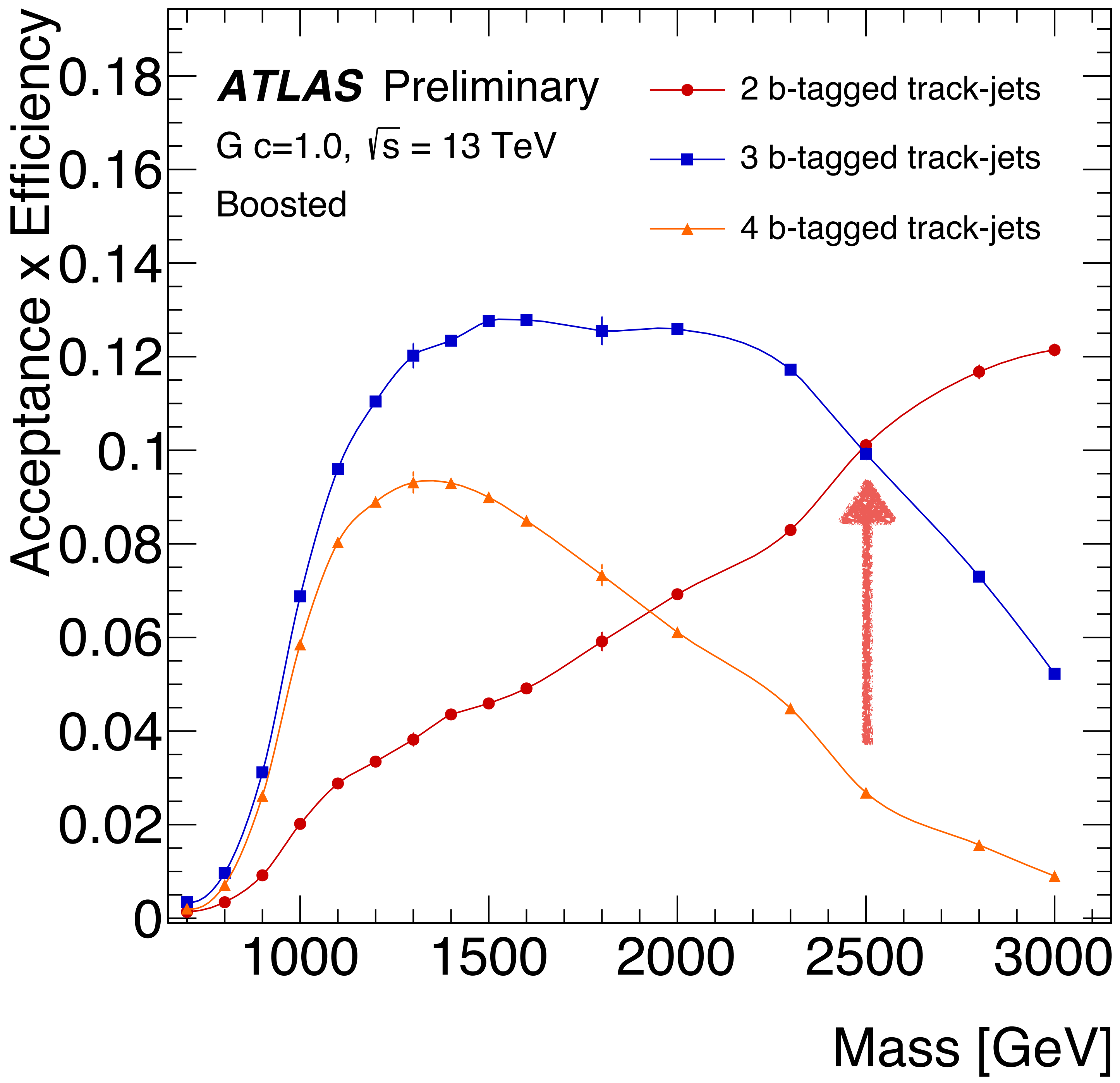


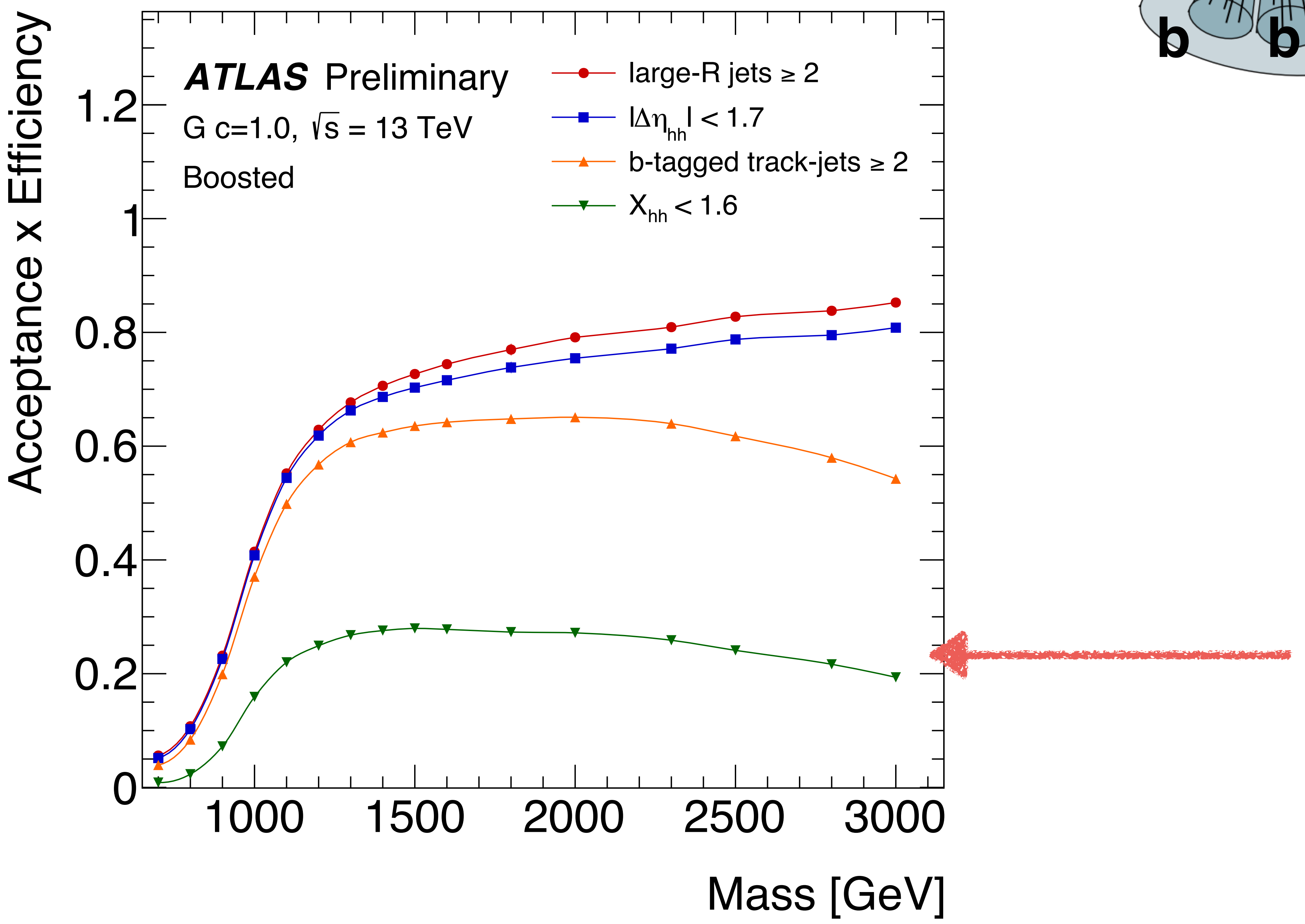
Track Jets Tagging and Signal Regions

ATLAS-CONF-2016-049

- 4Tag:  3Tag: (recover efficiency) 
- 2Tag Split: one b Tag in each large R jet 
- **Three** Signal Regions**: 4Tag, 3Tag and 2Tag Split**



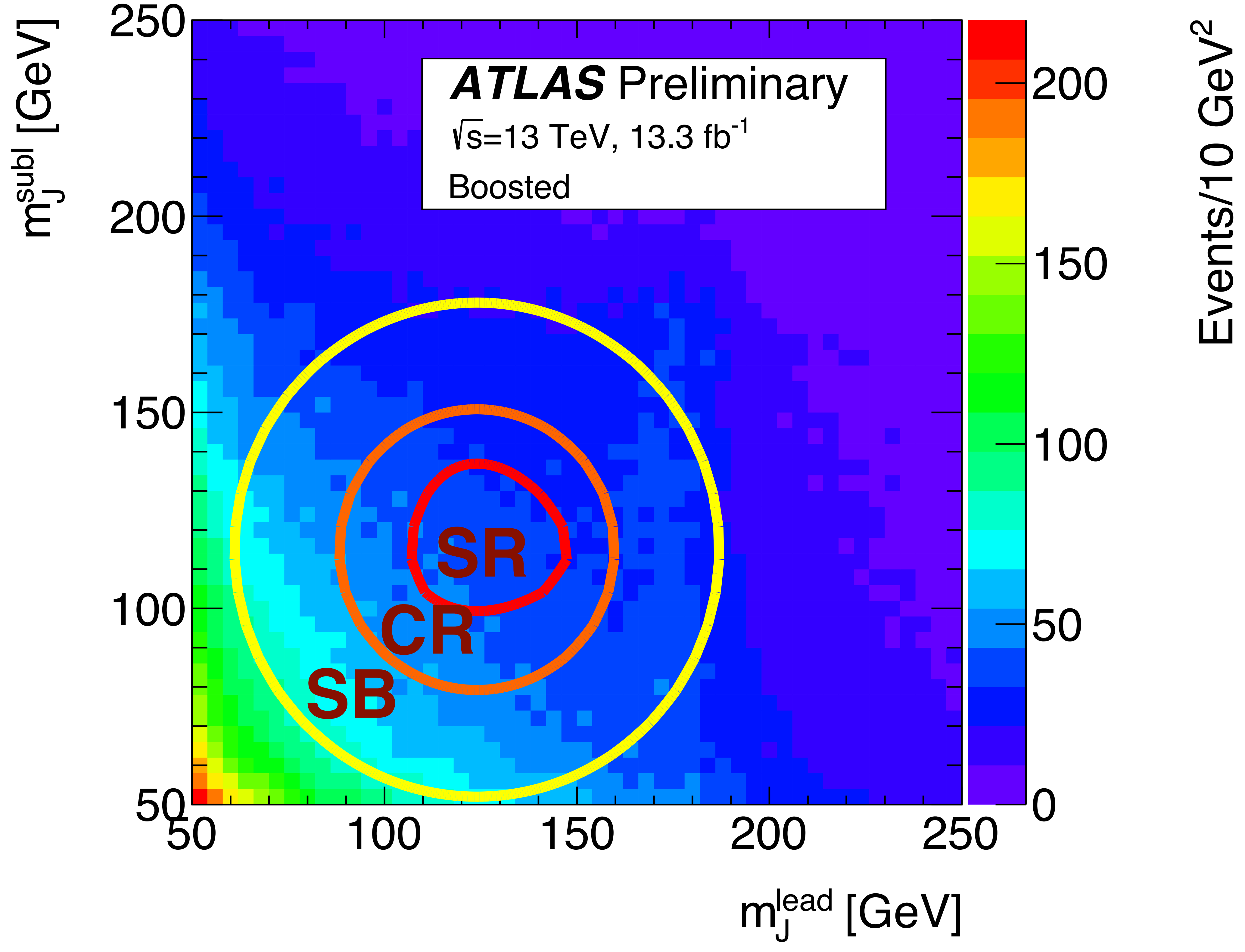




Boosted 4b Background

ATLAS-CONF-2016-049

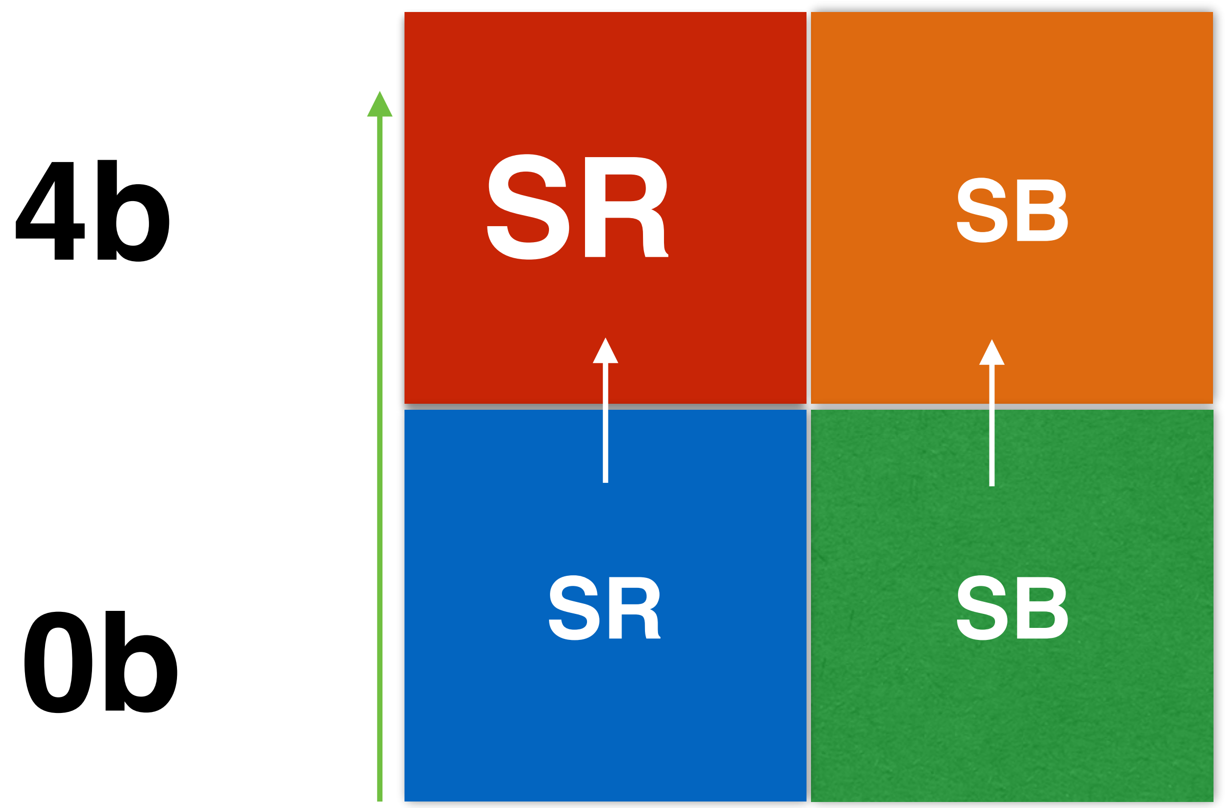
- Background:
  - 85% qcd—data driven
  - 15% ttbar—data driven

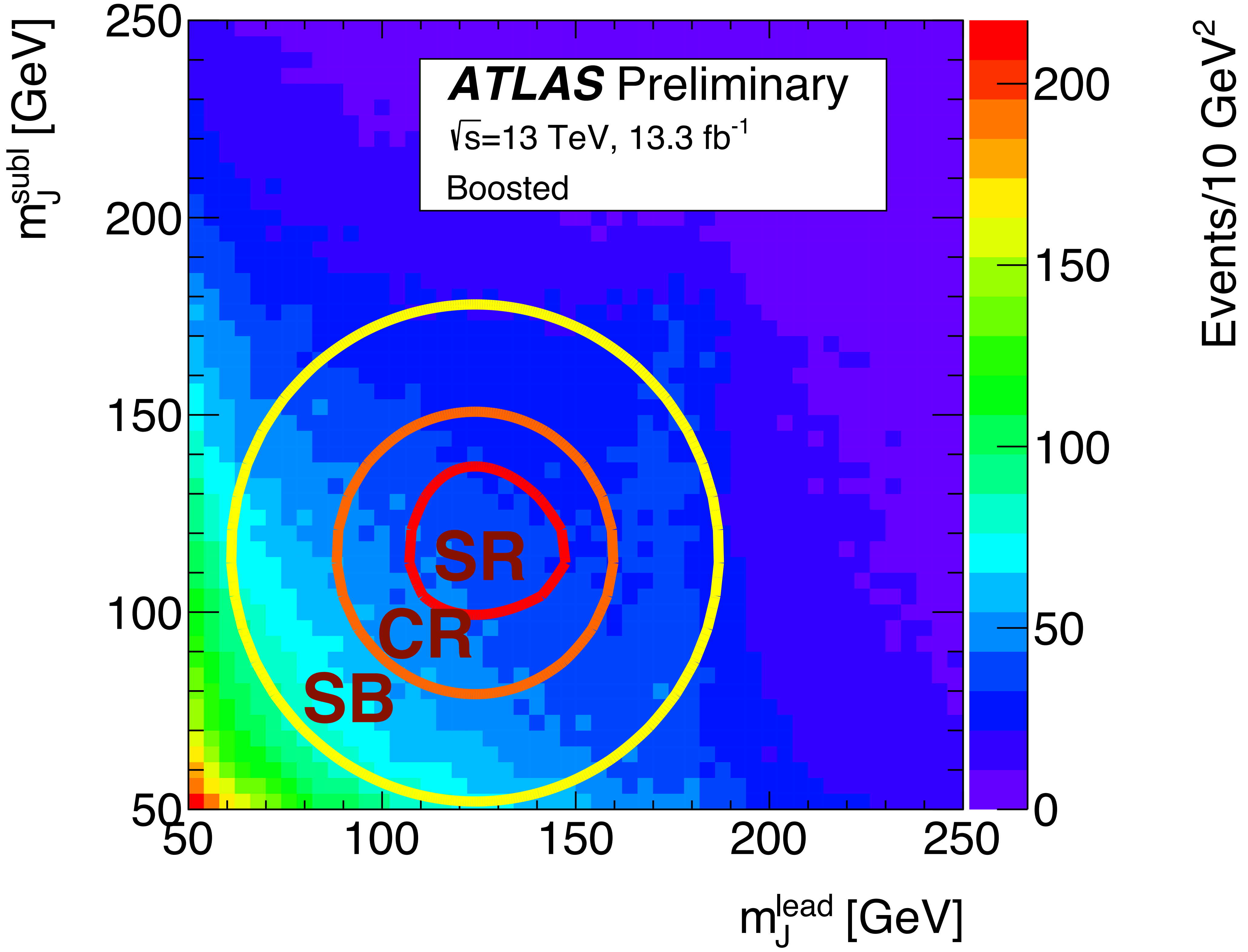


ATLAS-CONF-2016-049

Boosted 4b Background

- Background:
  - 85% qcd—data driven
  - 15% ttbar—data driven
- Background **shape** estimation comes from 0b SB(sideband)/CR(control)/SR(signal) regions
- Fit the leading jet mass in SB to extract ttbar and qcd **normalization** estimation comes from 0b to N(2, 3, 4)b



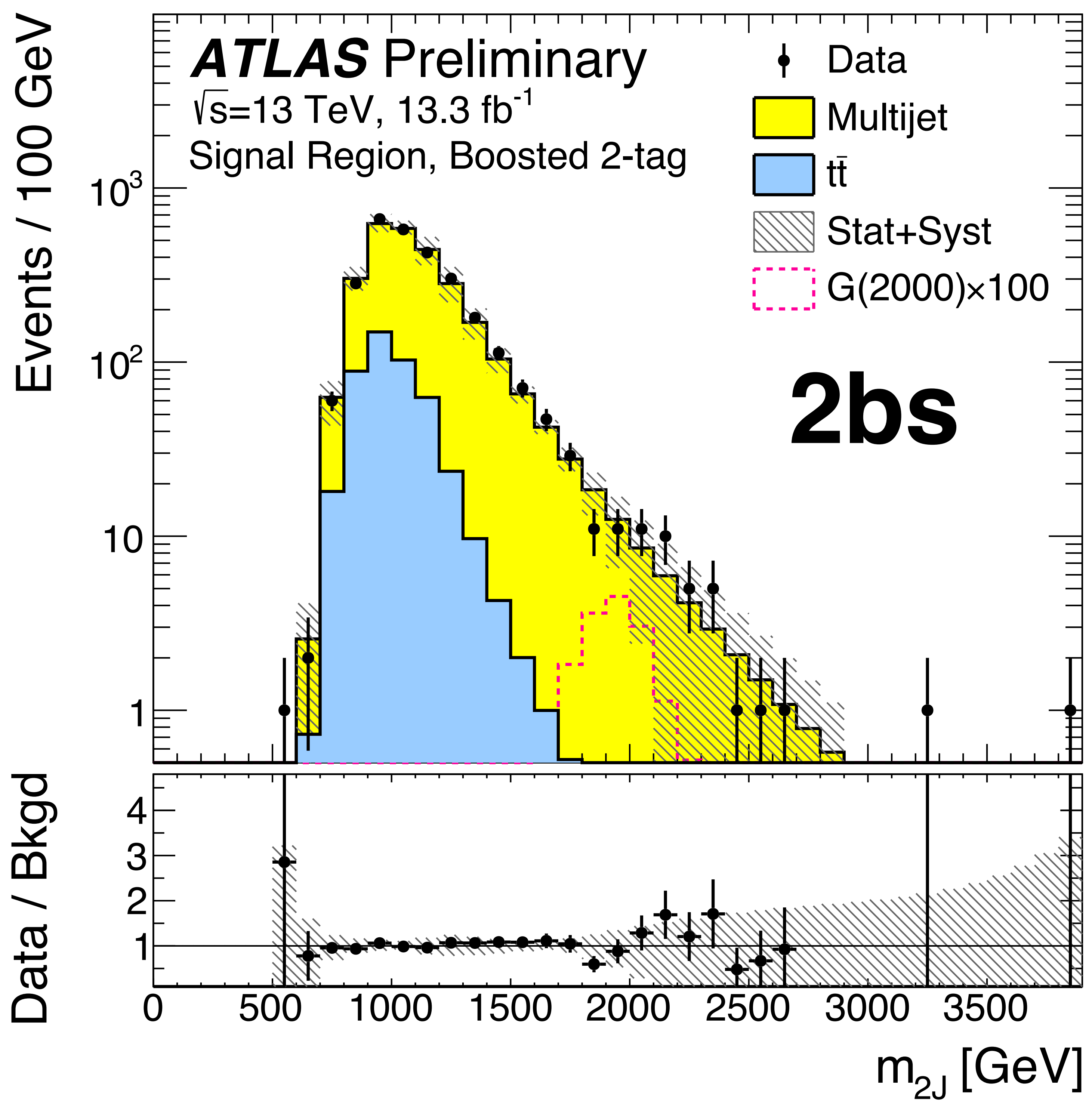


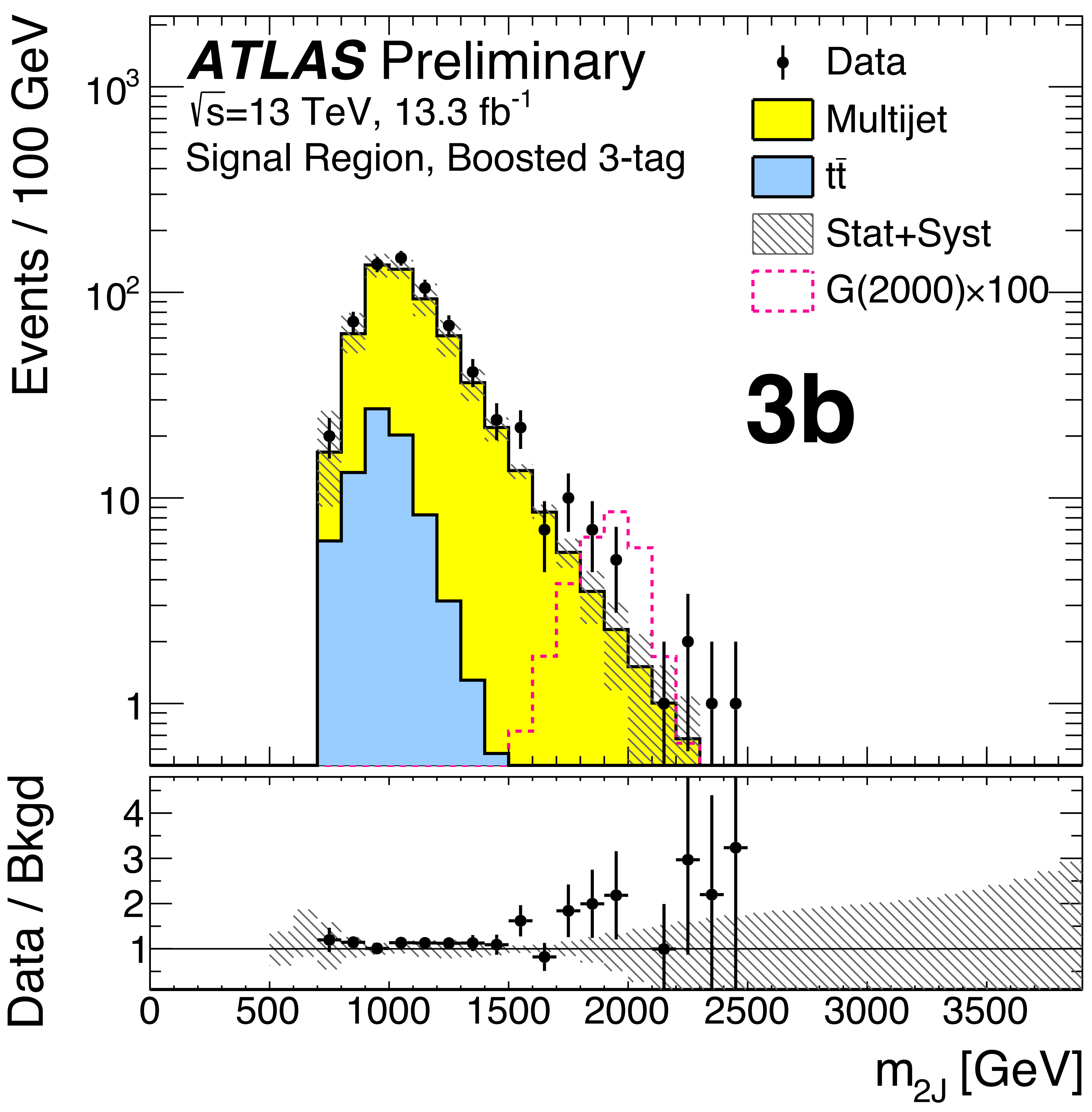
Signal Region: Boosted

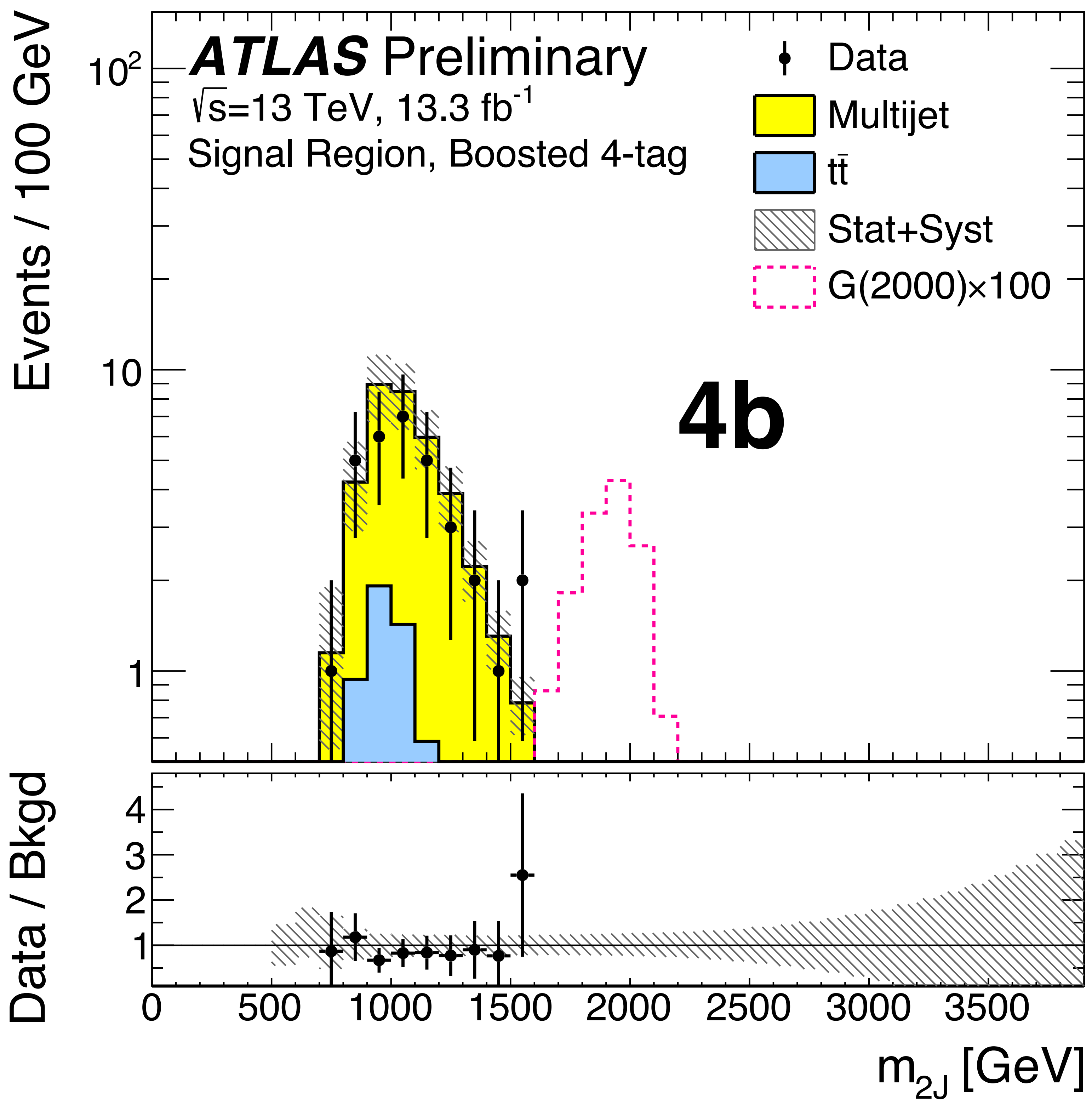
ATLAS-CONF-2016-049

- Final discriminant: **dijet invariant mass**; no significant excess observed

Channel	2bs	3b	4b
Obs	**2813**	**671**	**32**
Exp	2770 ± 130	596 ± 39	38 ± 9





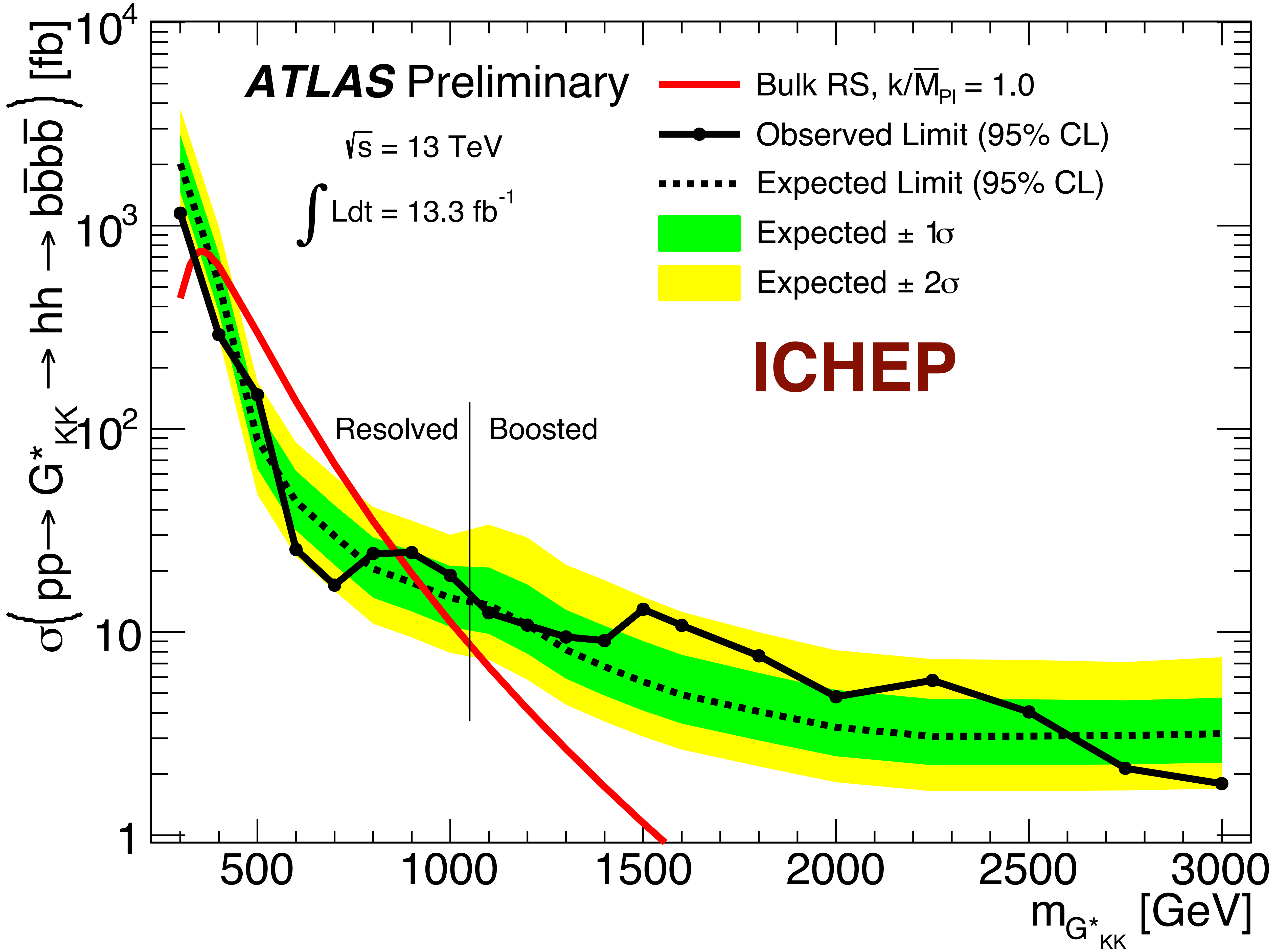


Combined Limits

ATLAS-CONF-2016-049

- Resolved + Boosted Combined Asymptotic Limits

- Non-Resonance limit:
  - bbbb: **1 pb** (1.3 pb expected)

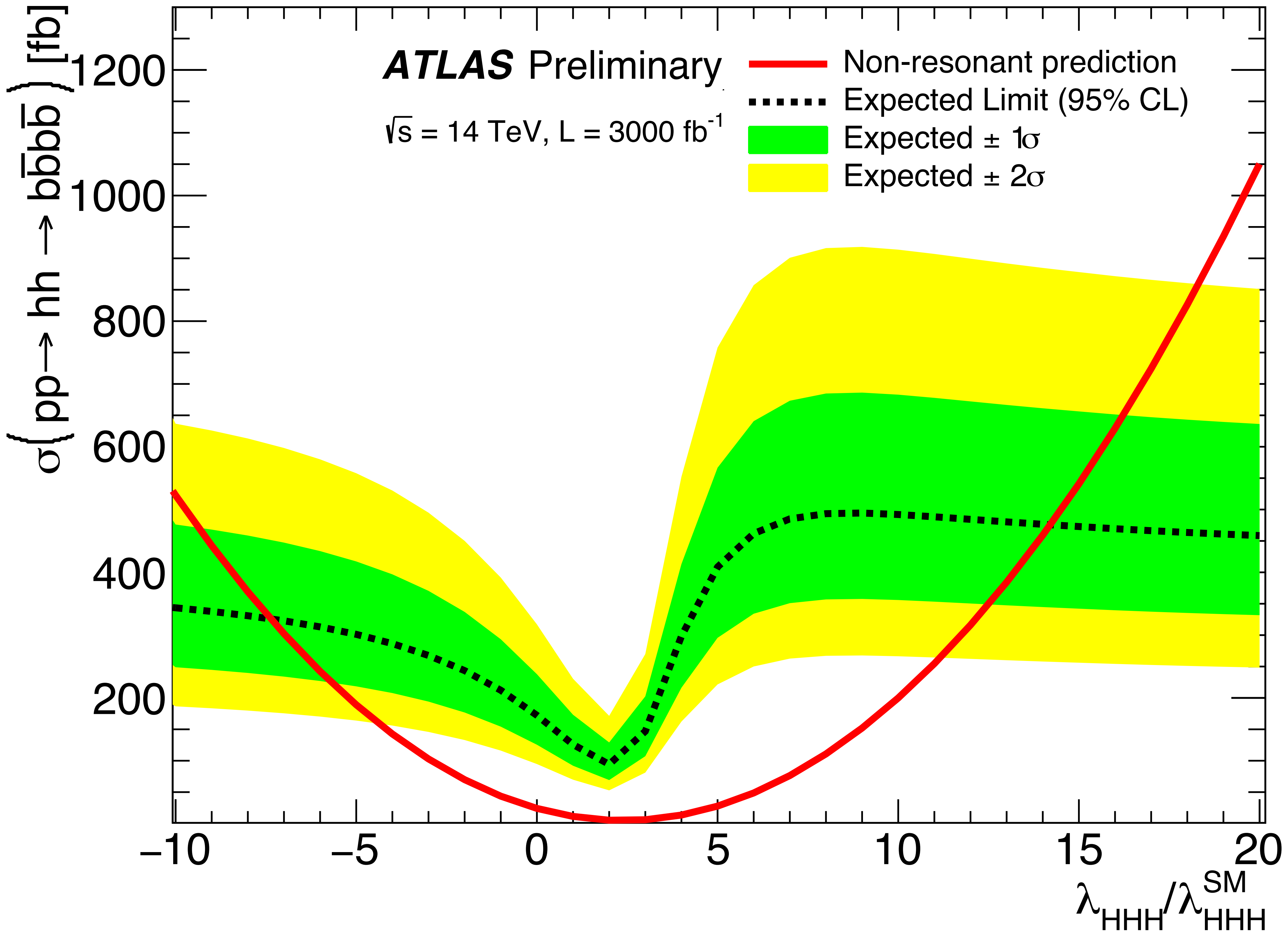


Conclusion

- Searches covered by ATLAS
  - bbbb (8 TeV, 13 TeV 3 fb^{-1}, 13 fb^{-1})
  - bbWW* (13 TeV in progress)
  - $bb\tau\tau$ (8 TeV, 13 TeV in progress)
  - bbγγ (8 TeV, 13 TeV 3 fb^{-1})
  - WW*γγ (8 TeV, 13 TeV 13 fb^{-1})
  - WW*WW* (13 TeV in progress)
- So far **no significant excess observed**, 13 TeV non-resonance limit at **1 pb**

Conclusion

ATLAS-CONF-2016-024



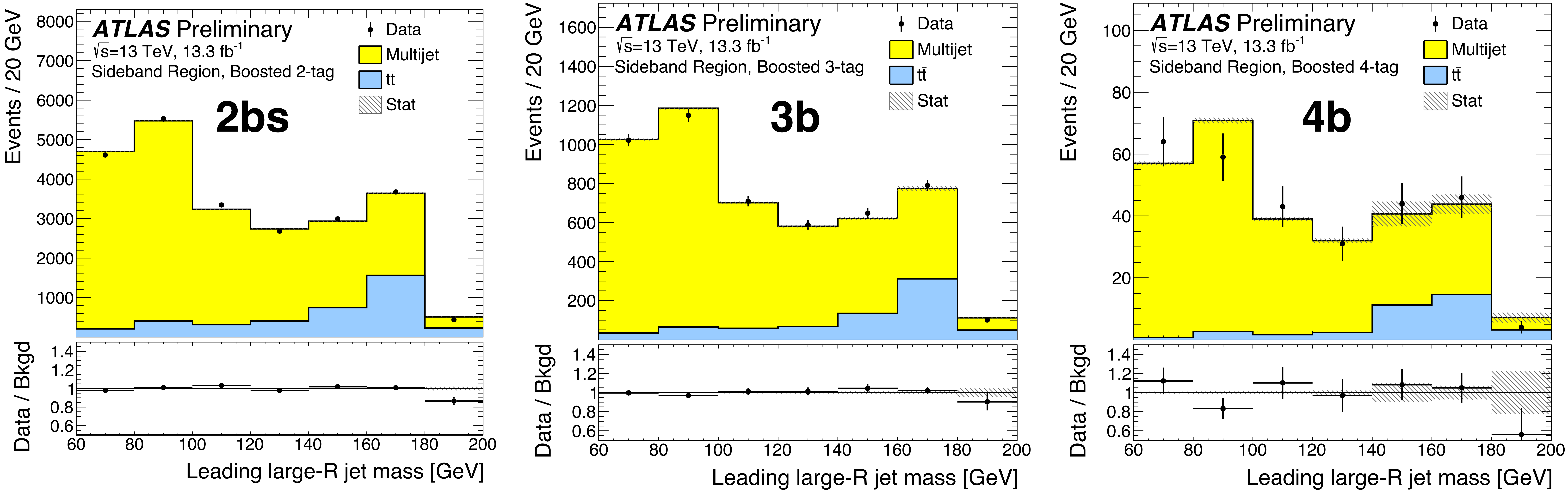
- Searches covered by ATLAS
  - **bbbb** (8 TeV, 13 TeV 3 fb^{-1}, 13 fb^{-1})
  - bbWW* (13 TeV in progress)
  - bb$\tau\tau$ (8 TeV, 13 TeV in progress)
  - bbγγ (8 TeV, 13 TeV 3 fb^{-1})
  - WW*γγ (8 TeV, 13 TeV 13 fb^{-1})
  - WW*WW* (13 TeV in progress)
- So far **no significant excess observed**, 13 TeV non-resonance limit at **1 pb**
- Also protect studies—see talks tomorrow!
- Search teams are actively working on development and 2016 data! Stay tuned!

Back up Slides

Fit on Leading Jet Mass Distribution

ATLAS-CONF-2016-049

- Given: $N^{\nu_b}_{data} = \mu^{\nu_b}_{qcd} N^{0b}_{qcd} + \alpha^{\nu_b}_{t\bar{t}} N^{\nu_b}_{t\bar{t}}$
- Simultaneous **fit** of μ_{qcd}, a_{tt} to extract the normalization factors
- All fits are independent



Reweighting Details

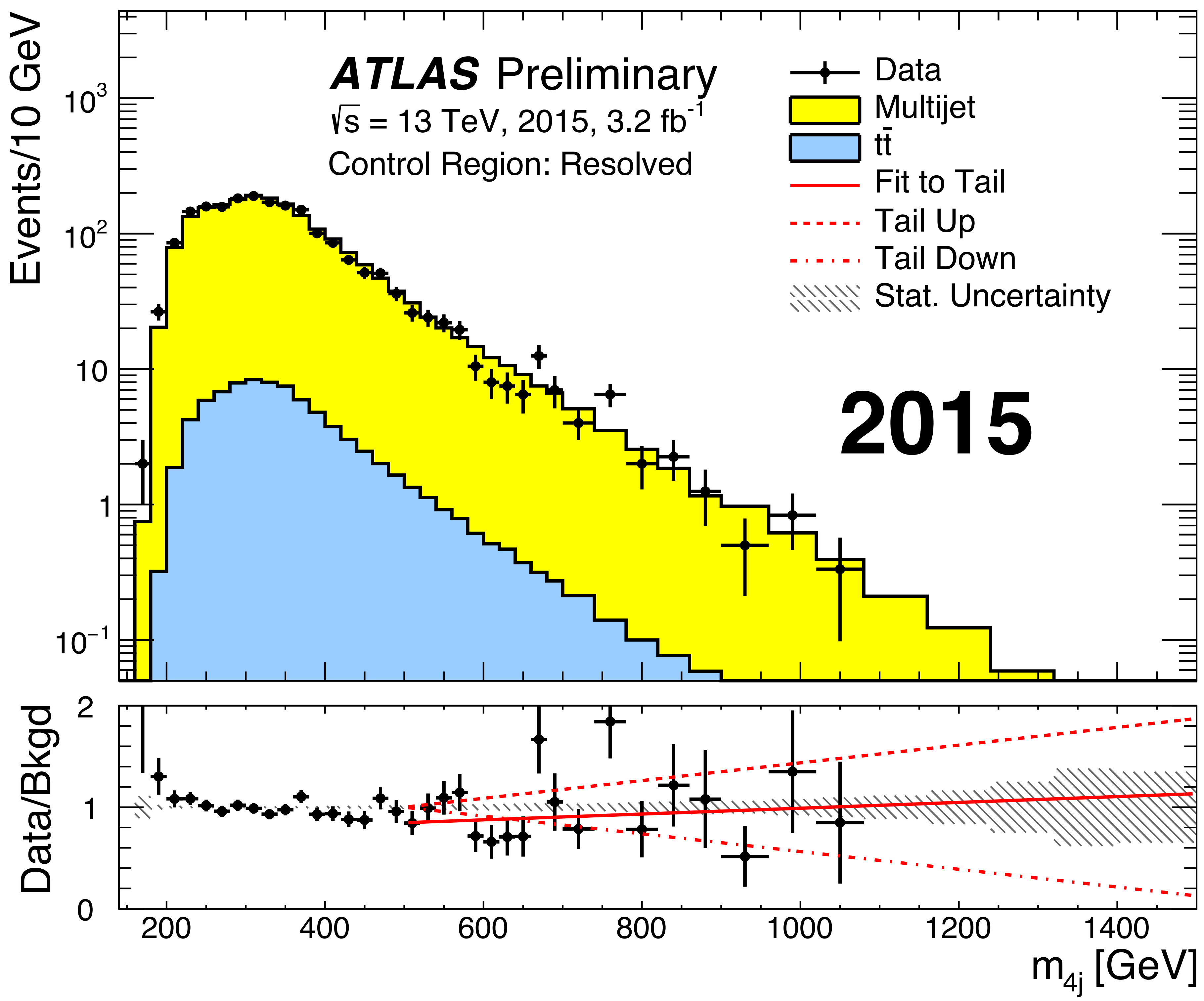
- Kinematics dependence of μ_{qcd} is corrected by reweighting
- Resolved: Njet distribution, leading Higgs candidate pT, subleading Higgs candidate E
- Boosted; leading Higgs candidate pT, leading track jet pT of the leading Higgs candidate, leading track jet pT of the subleading Higgs candidate
- Iterated reweighting is used such that the correlations are taken into account.

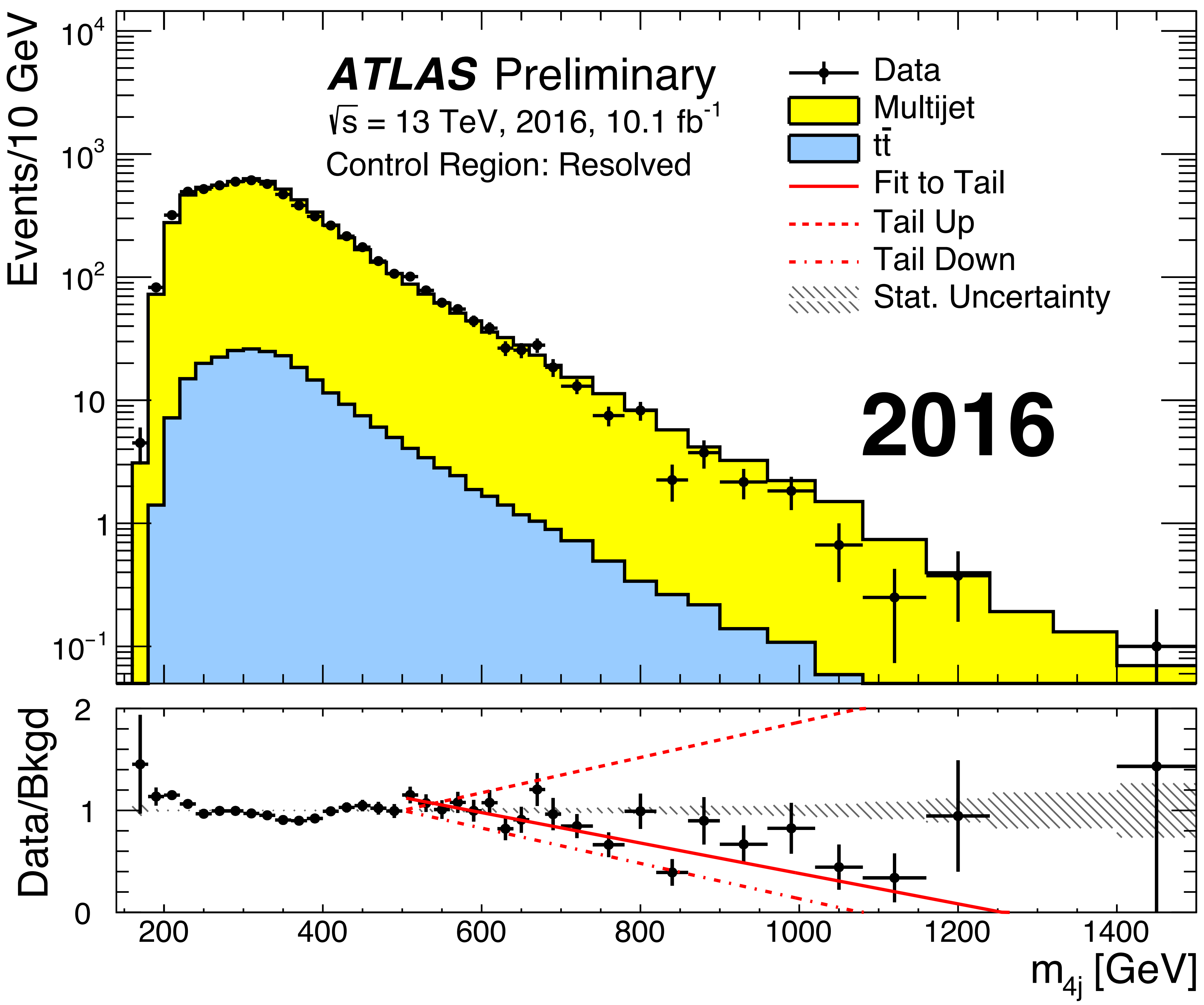
Control Region: Resolved

ATLAS-CONF-2016-049

- **Good** agreement in shape and normalization

Obs	3995	12752
Exp	4021 ± 88	12970 ± 110



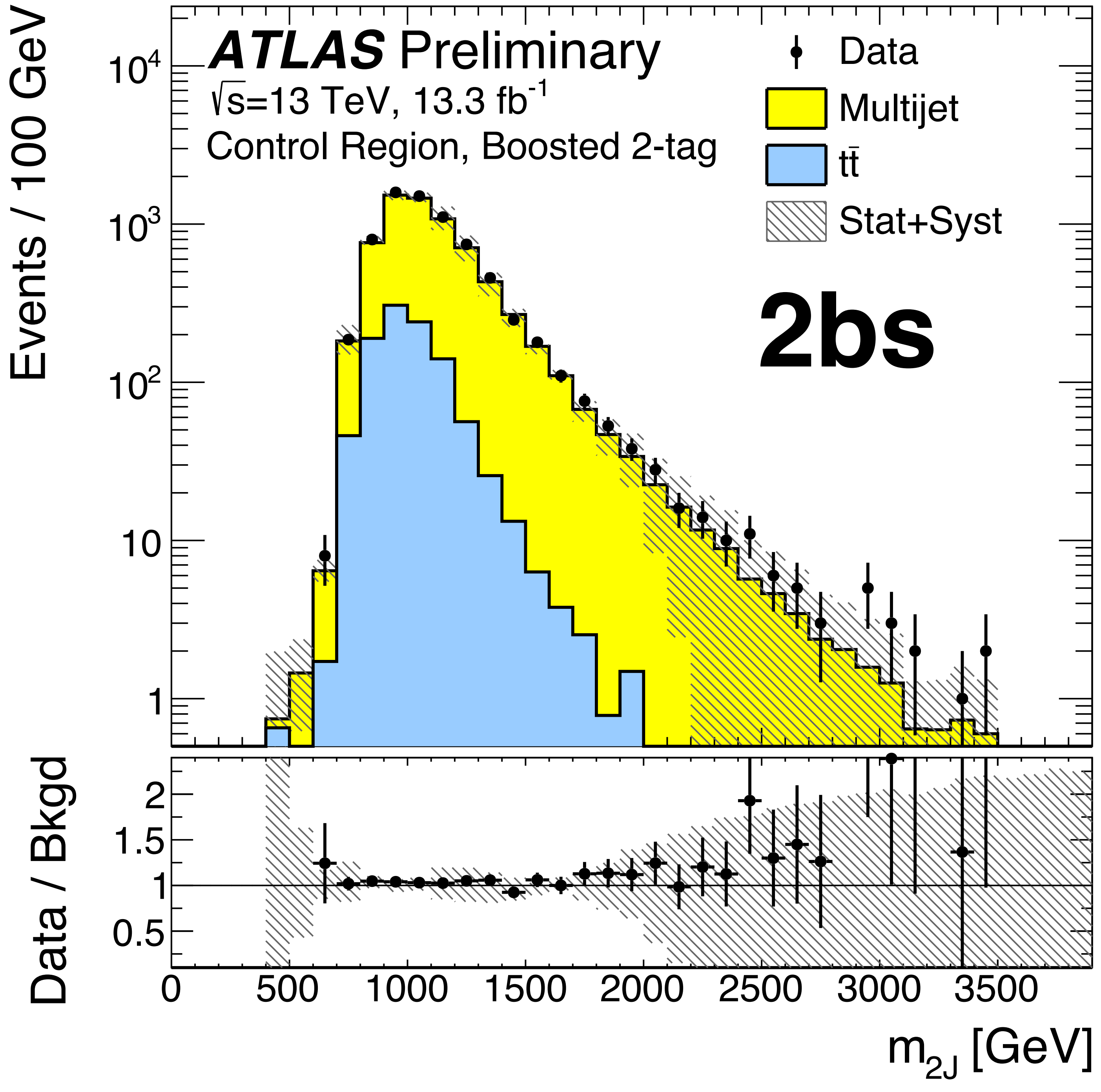


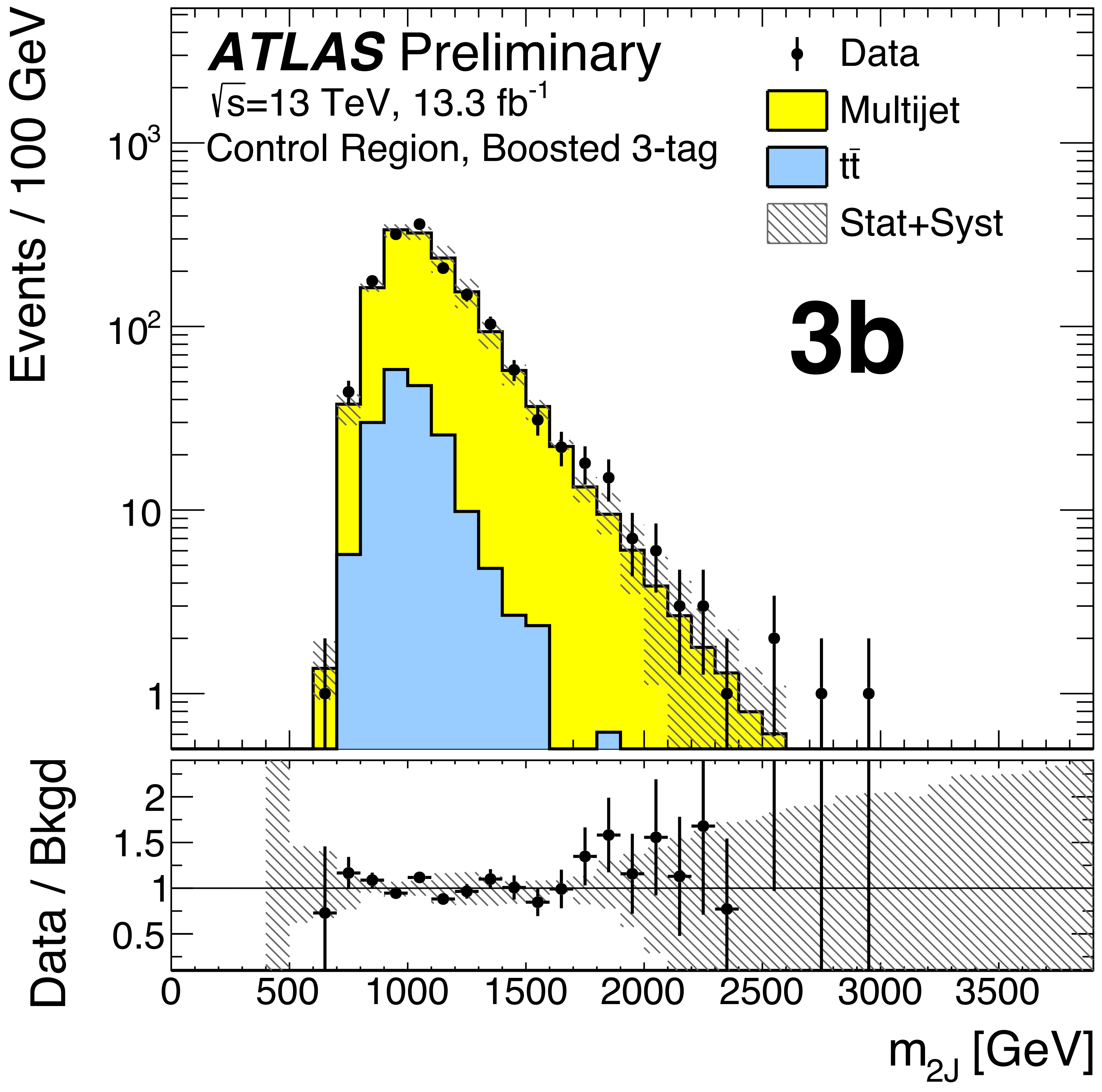
Control Region: Boosted

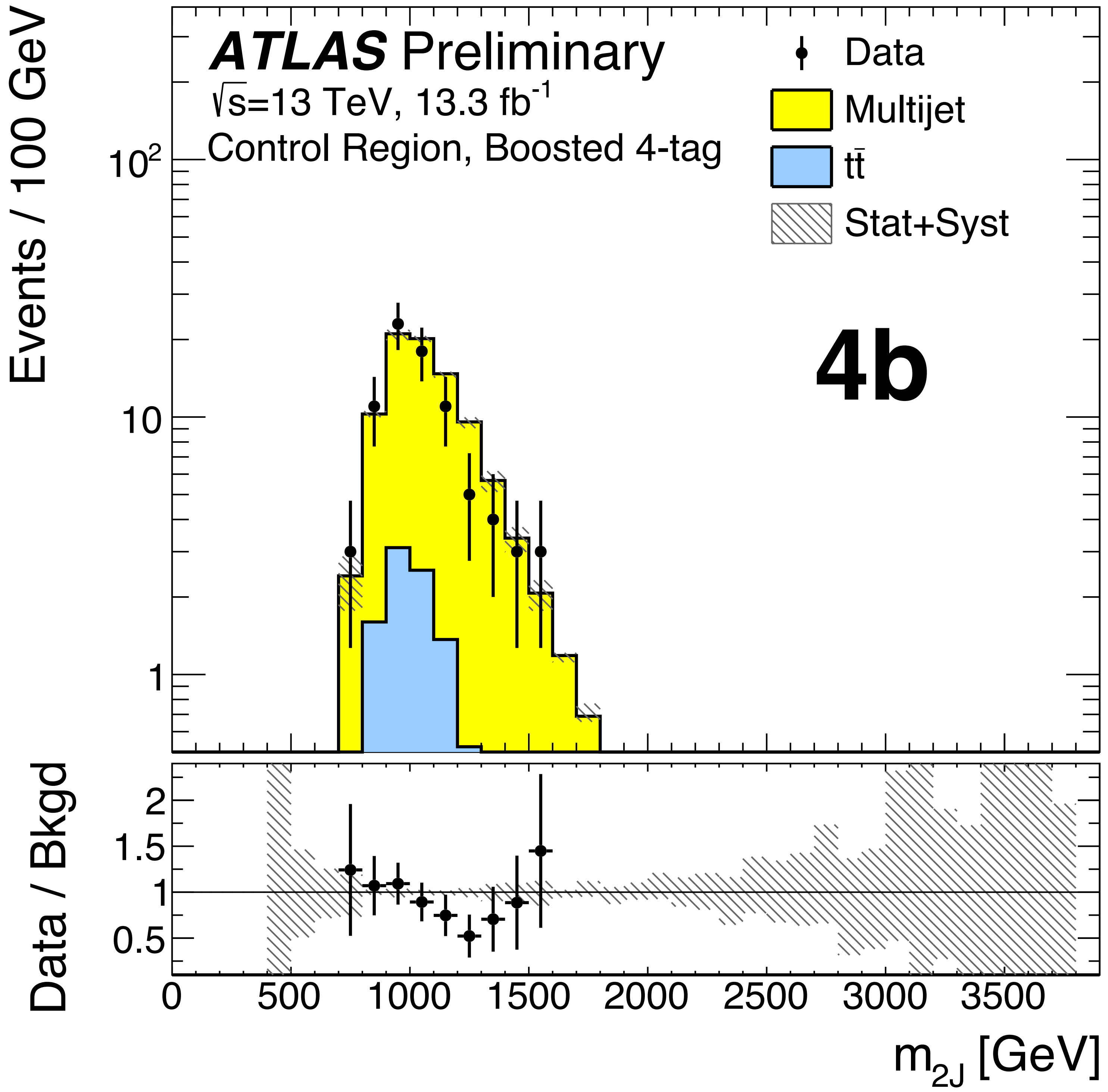
ATLAS-CONF-2016-049

- **Good** agreement in shape and normalization

Obs	**7200**	**1529**	**81**
Exp	6954 ± 52	1507 ± 24	94.4 ± 5.8







Uncertainties Countdown

ATLAS-CONF-2016-049

- Signal uncertainty mainly comes from **b-tagging**
- Bkg uncertainty is dominated by **data driven** control region estimates
- Background/QCD **shape uncertainty** is also applied

Resolved

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

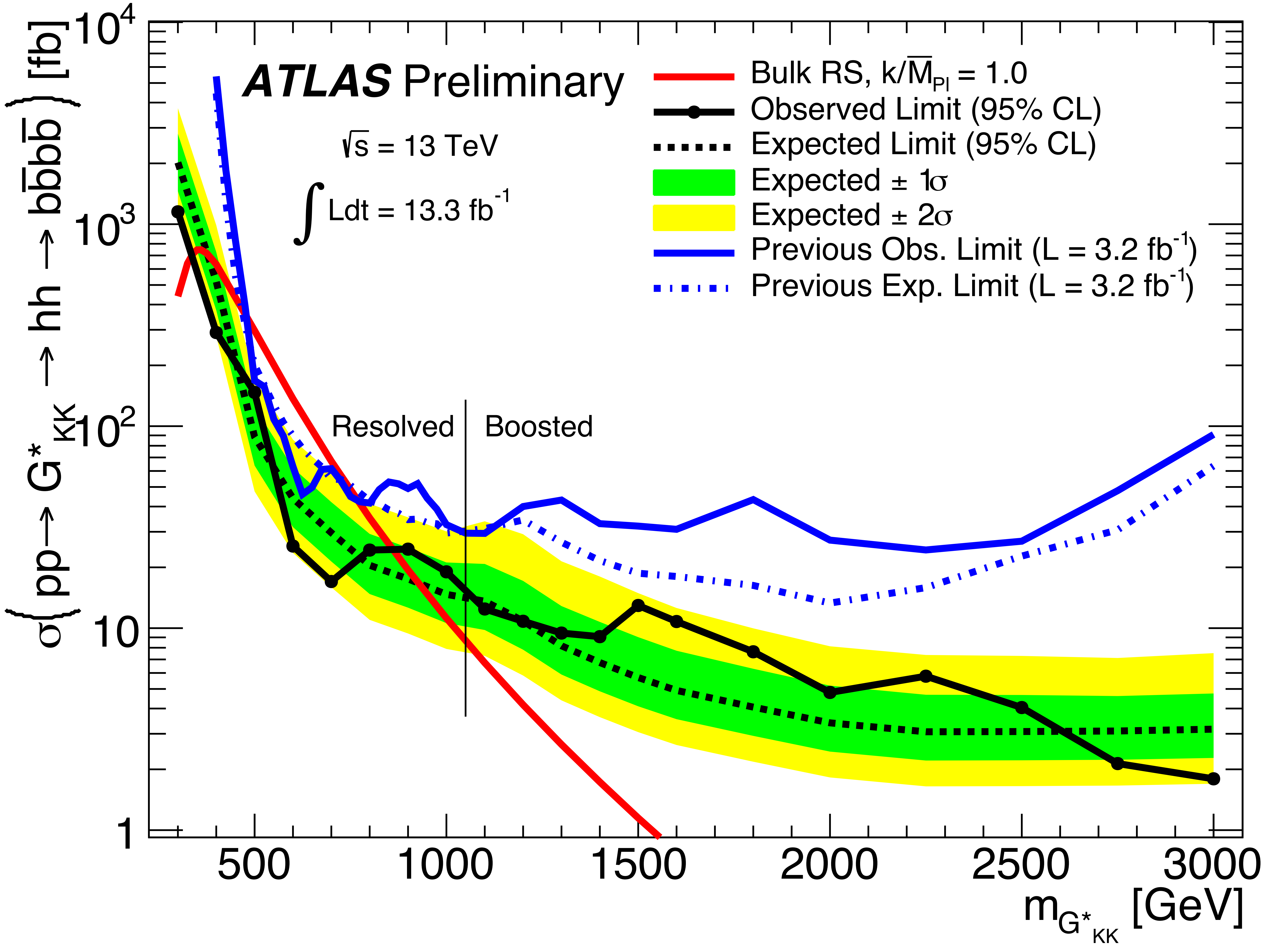
Boosted

Source	2-tag-split Background	2-tag-split G^*_{KK} (2 TeV)	3-tag Background	3-tag G^*_{KK} (2 TeV)	4-tag Background	4-tag 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

Limit Comparison

ATLAS-CONF-2016-049

- ICHEP-Moriond Limit Direct Comparison



Resolved and Boosted Results

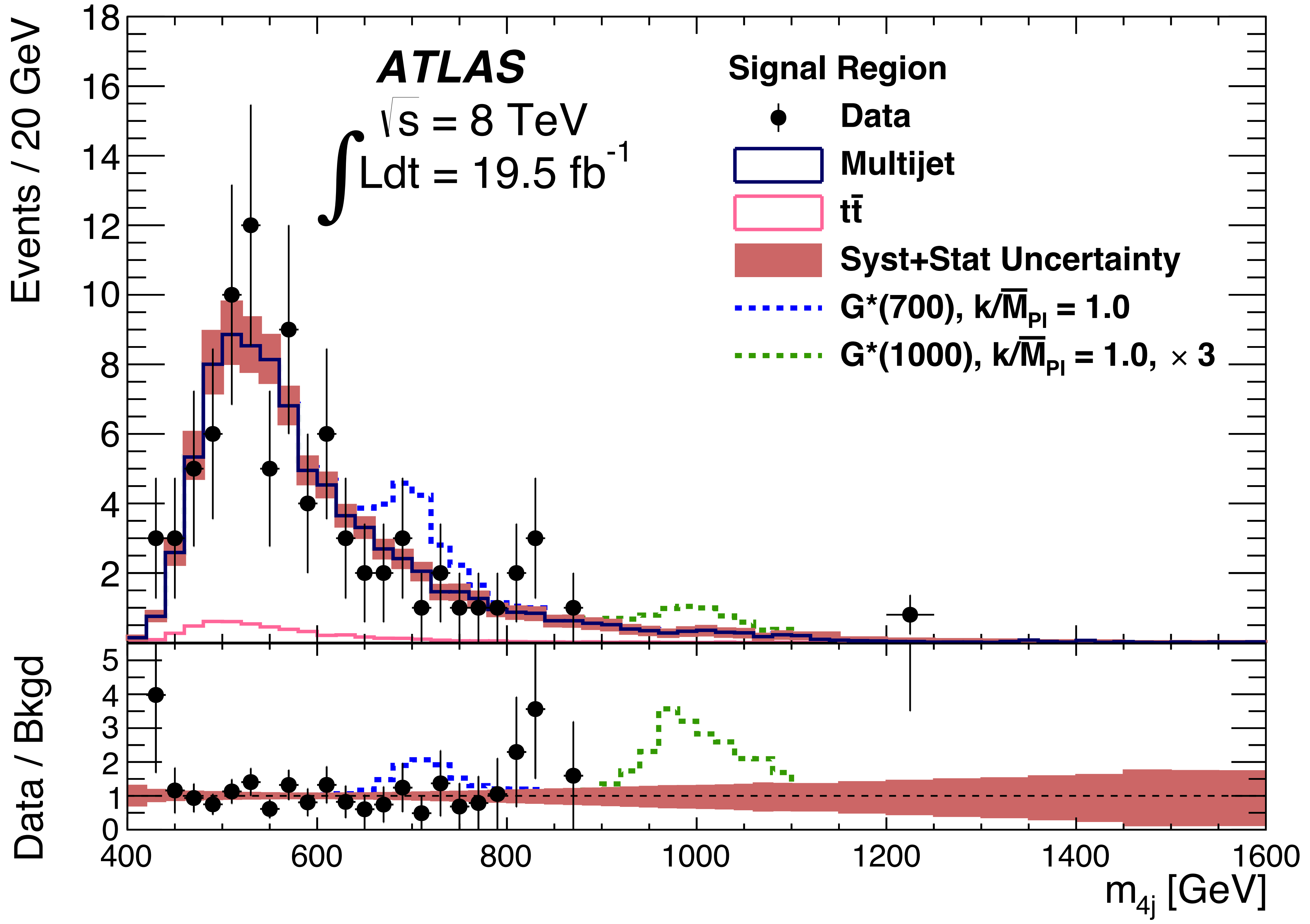
Eur. Phys. J. C (2015) 75:412

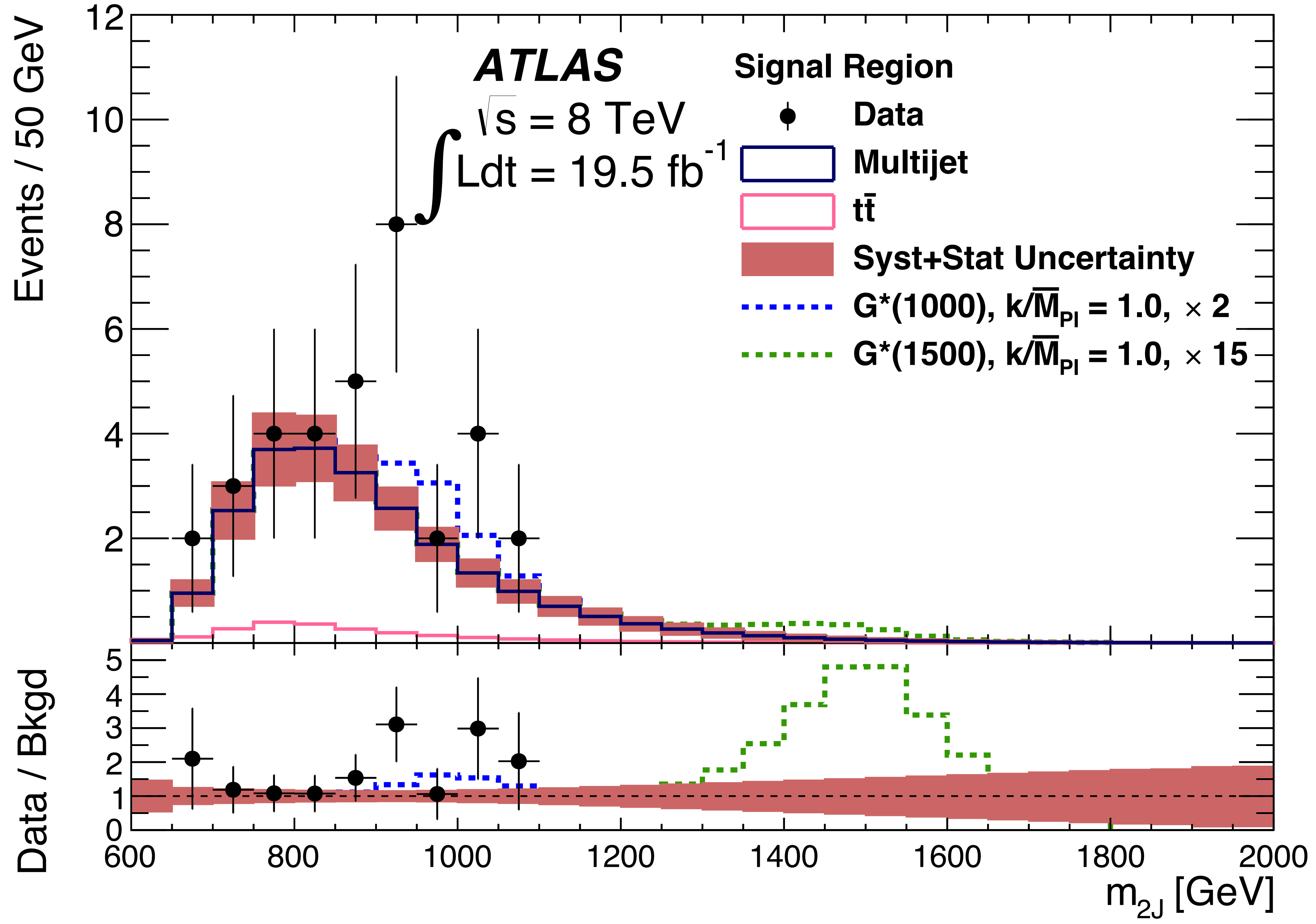
Resolved

Sample	Signal Region Yield
Multijet	81.4 ± 4.9
$t\bar{t}$	5.2 ± 2.6
Z+jets	0.4 ± 0.2
Total	87.0 ± 5.6
Data	87
SM hh	0.34 ± 0.05
$G^*_{\rm KK}$ $(500\,GeV)$, $k/\bar{M}_{\rm Pl} = 1$	27 ± 5.9

Boosted

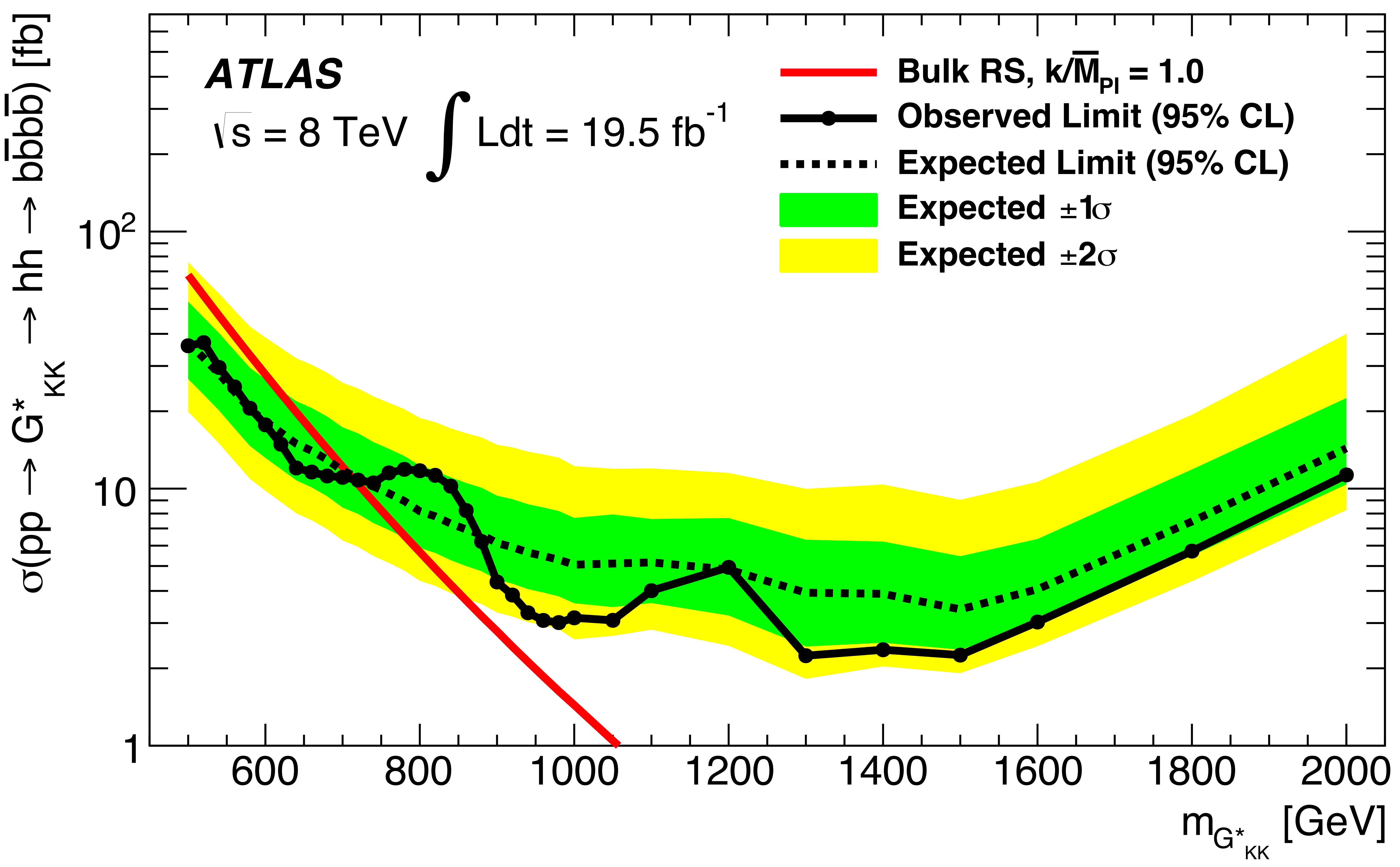
Sample	Signal Region Yield
Multijet	23.5 ± 4.1
$t\bar{t}$	2.2 ± 0.9
Z+jets	0.14 ± 0.06
Total	25.7 ± 4.2
Data	34
$G^*_{\rm KK}$ $(1000\,GeV)$, $k/\bar{M}_{\rm Pl} = 1$	2.1 ± 0.6





Combined Limit

Eur. Phys. J. C (2015) 75:412

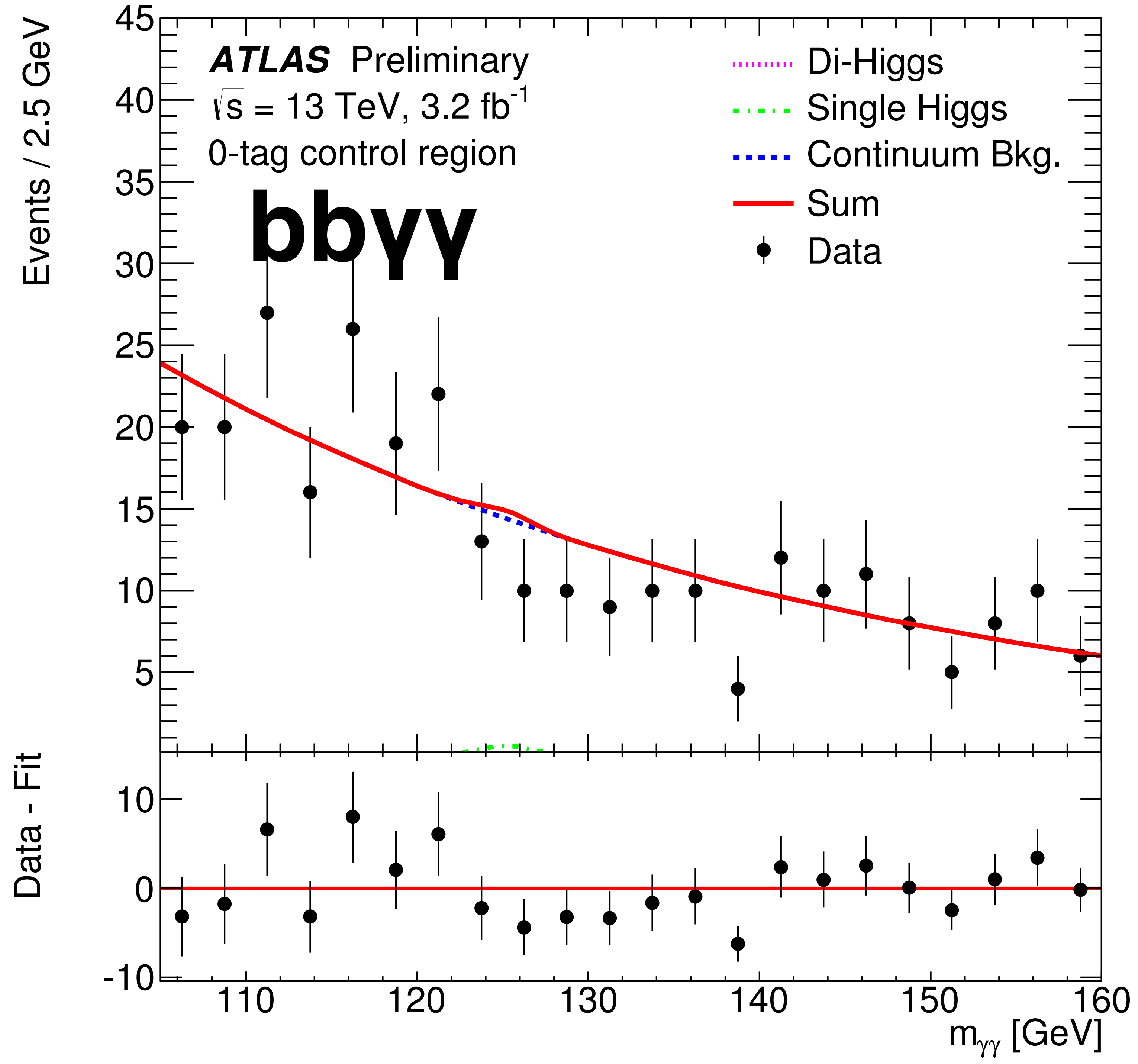


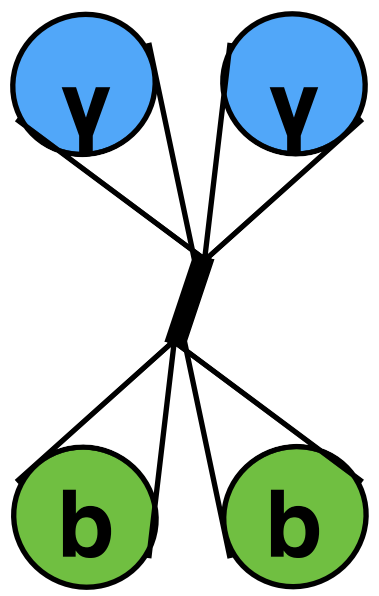
Control Regions

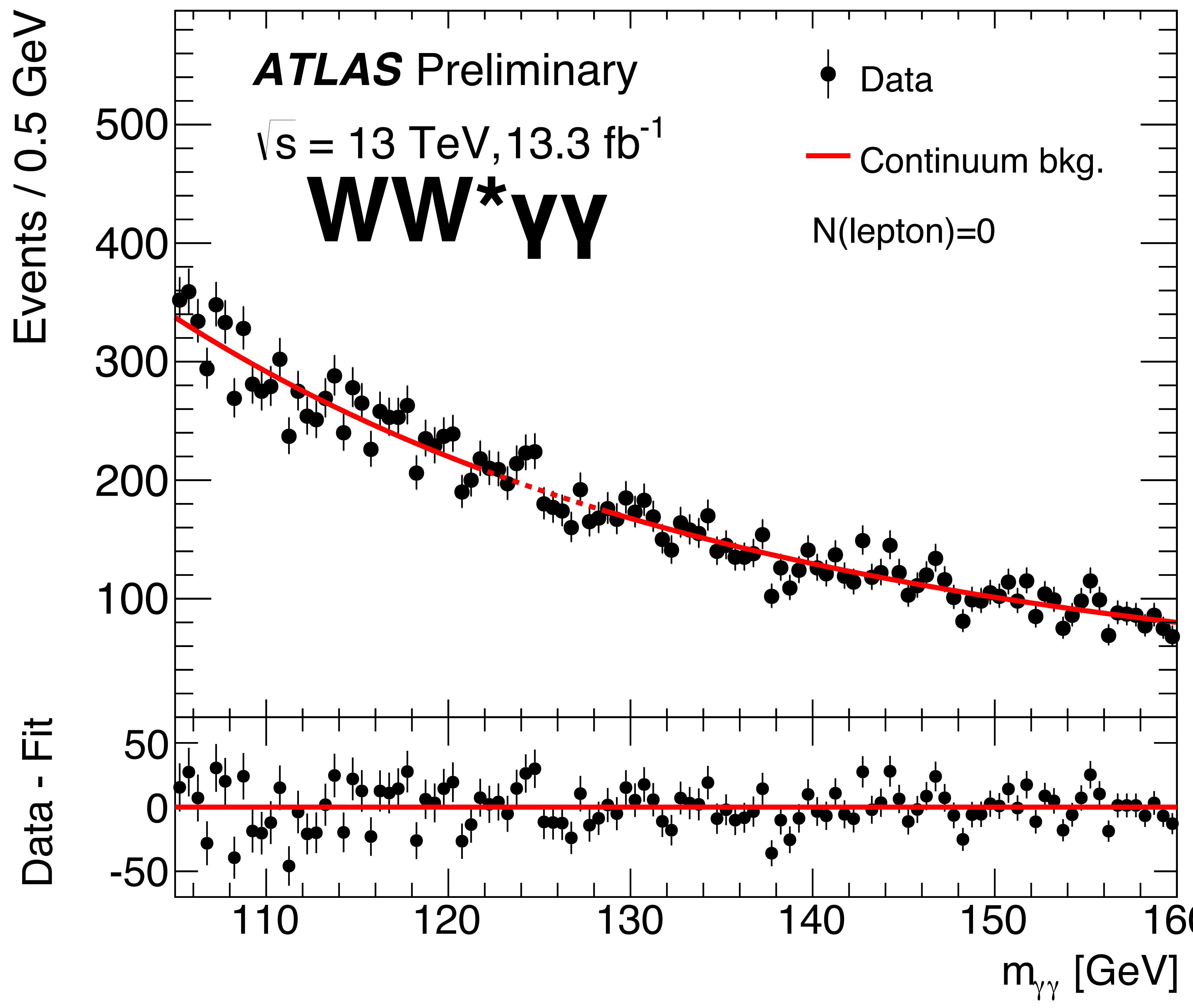
ATLAS-CONF-2016-004

ATLAS-CONF-2016-071

- Control region: bbγγ—0b-tags; WW*γγ—zero lepton + 2 jets







bbγγ Systematics

ATLAS-CONF-2016-004

ATLAS-CONF-2016-071

- Systematics dominated by photon energy resolution

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

WW*γγ Systematics

ATLAS-CONF-2016-004

ATLAS-CONF-2016-071

- Systematics dominated by statistics

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	-