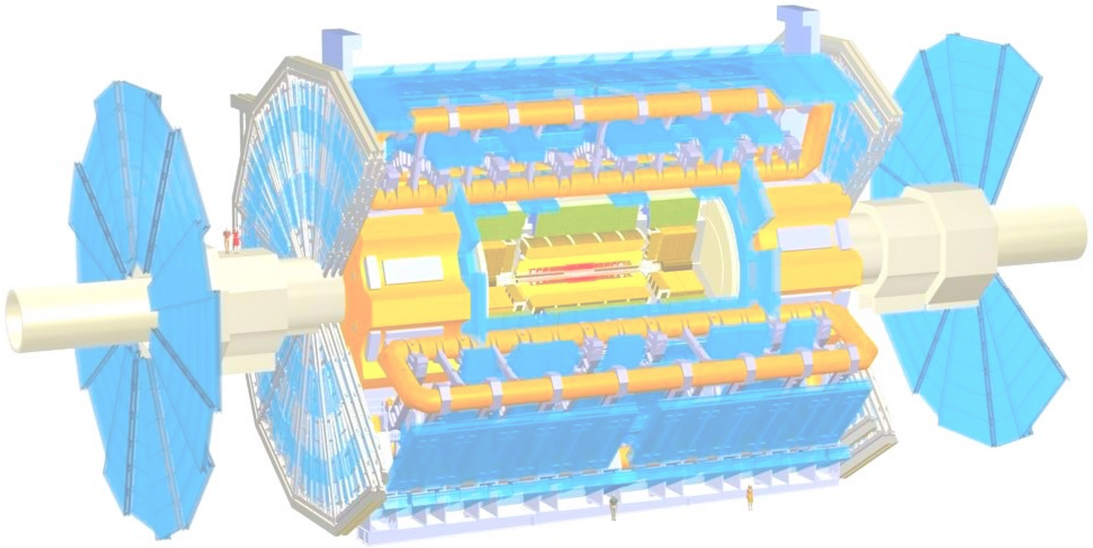
Search for di-Higgs to 4b with the ATLAS detector



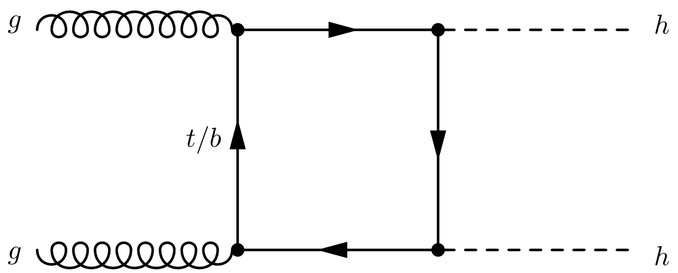
2016 Public (13 fb^{-1}) and **2017 Expected (24/36 fb^{-1})** Results

Tony(Baojia)Tong, Harvard University

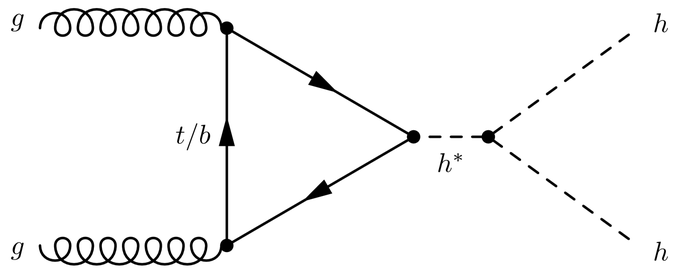
DPF, Aug.2, 2016

Di-Higgs production

- A “Beyond Standard Model” Standard Model process



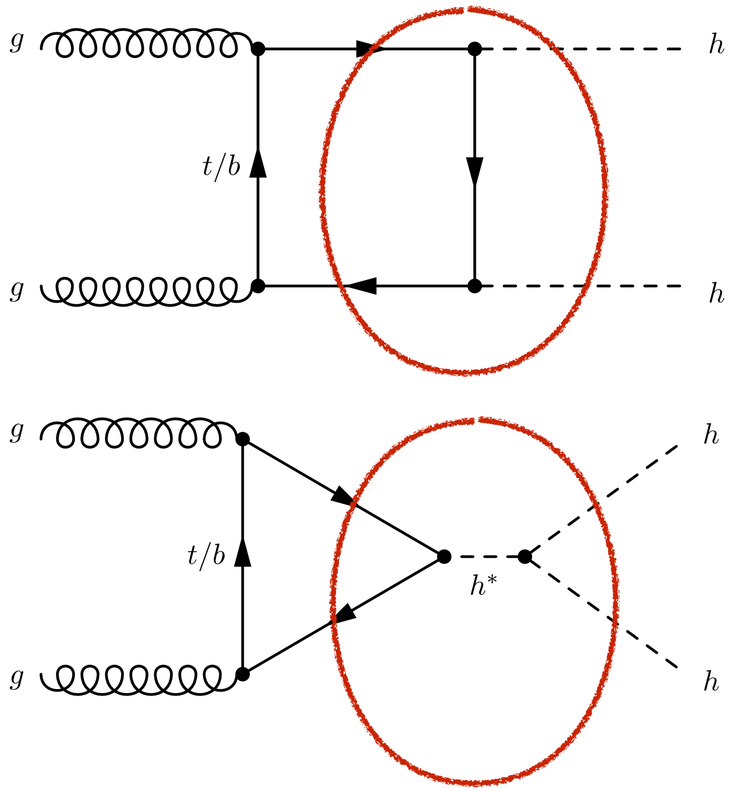
- Cross section small in SM:
  - 8 TeV ~ 10 fb (NNLO)
  - 13 TeV ~ 34 fb (NNLO + NNLL)



D.Florian,J.Mazzitelli, Arxiv1505.07122

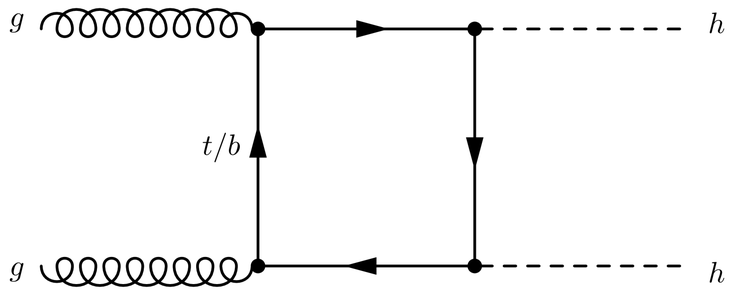
Di-Higgs production

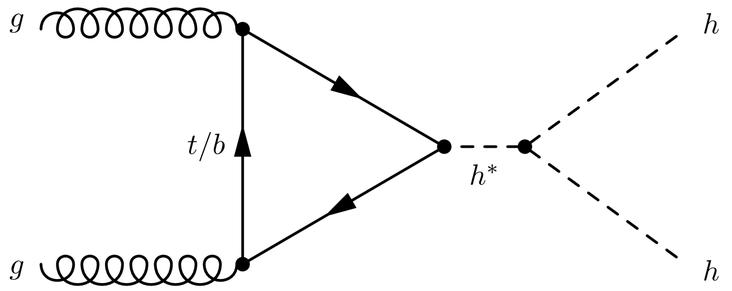
- Cross section small in SM:
  - 8 TeV ~ 10 fb
  - 13 TeV ~ 34 fb
- Larger if BSM physics exists
  - **Non-resonant Examples**
    - tth vertex modifications
    - λ_{hhh} triple-Higgs coupling

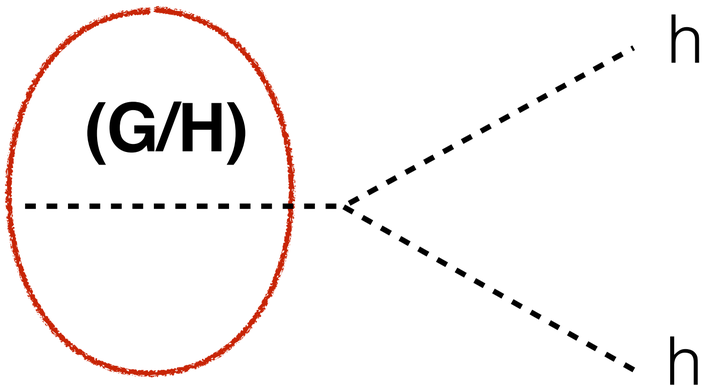


Di-Higgs production

- Cross section small in SM:
  - 8 TeV ~ 10 fb
  - 13 TeV ~ 34 fb
- Larger if BSM physics exists
  - Non-resonant Examples
    - tthh, tth vertex modifications
    - λ_{hhh} triple-Higgs coupling
  - **Resonant Examples**
    - KK Graviton, spin 2
    - Heavy Higgs: 2HDM, spin 0

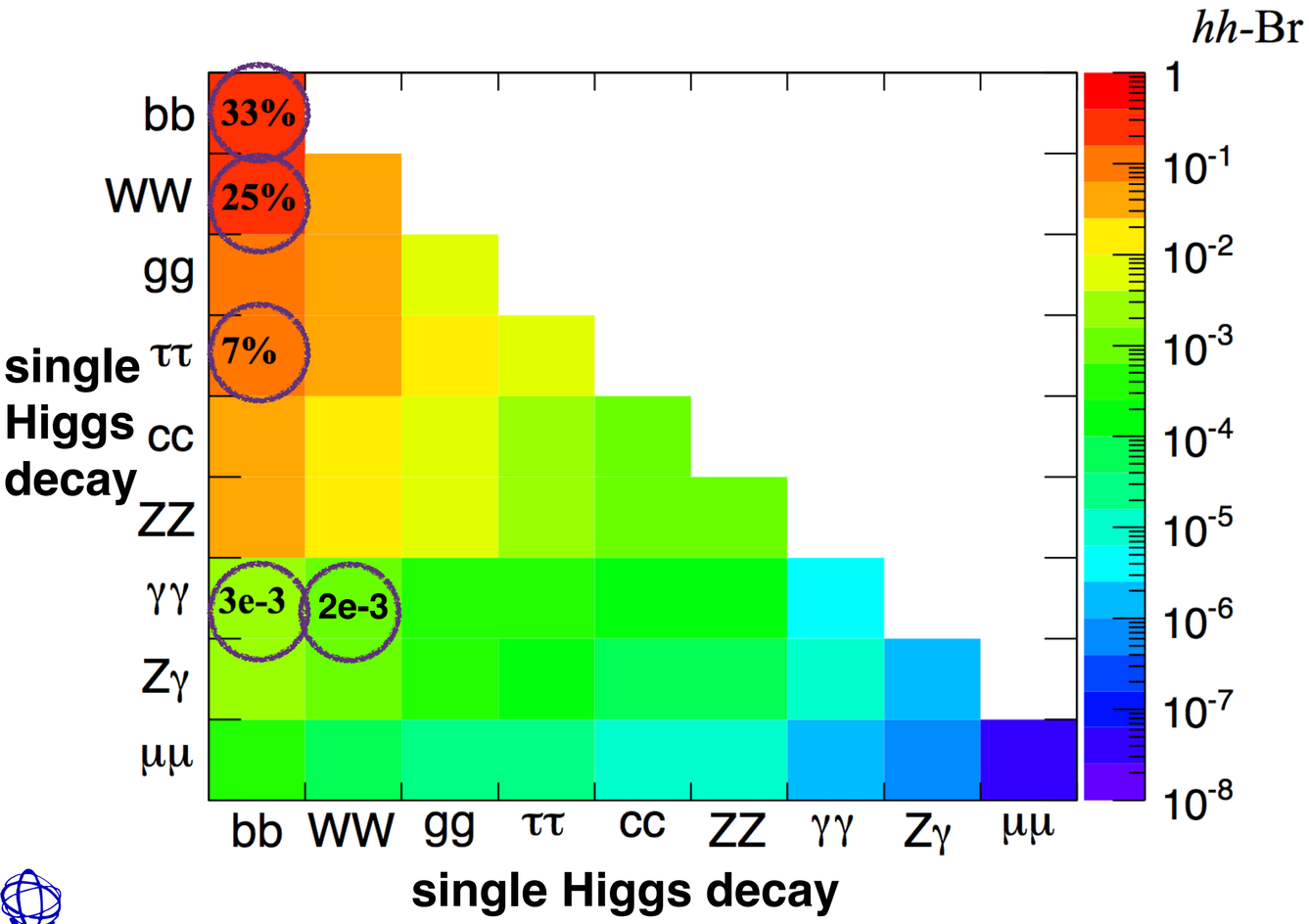


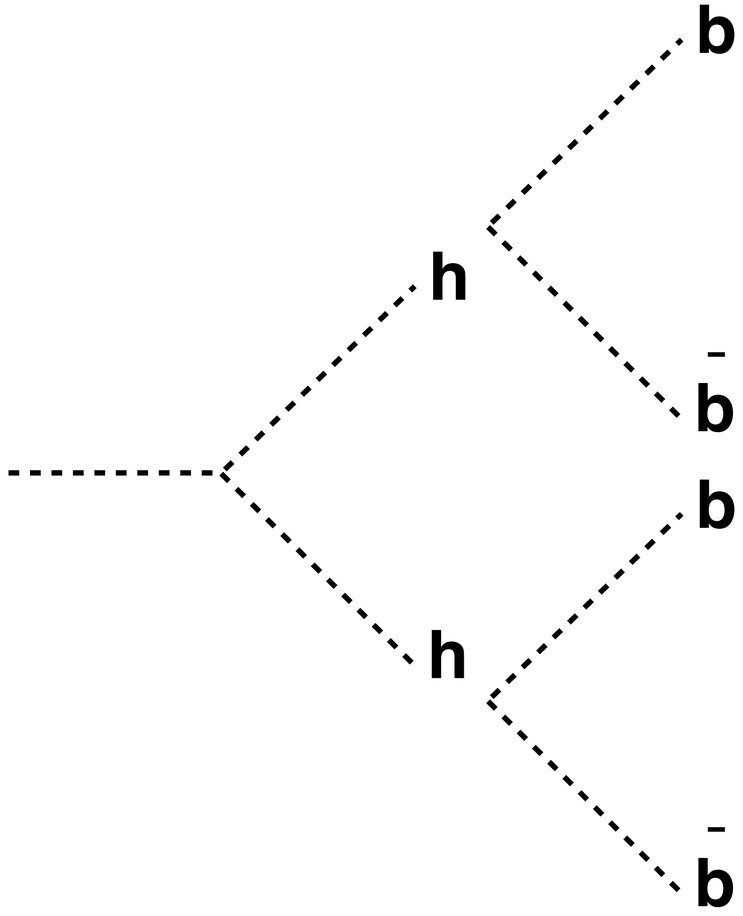




Di-Higgs decay

larger branching ratio—higher yield





Di-Higgs decay

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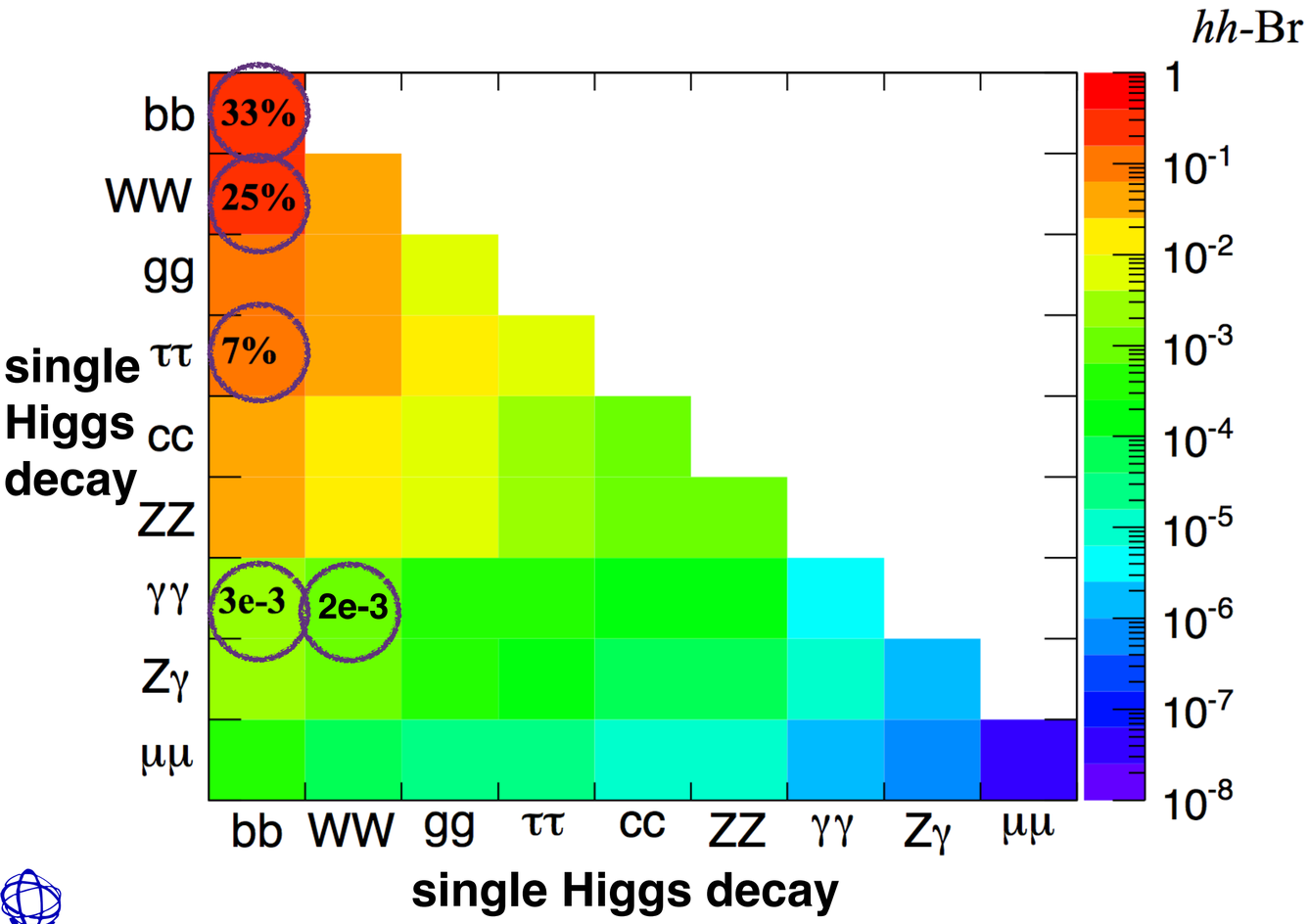
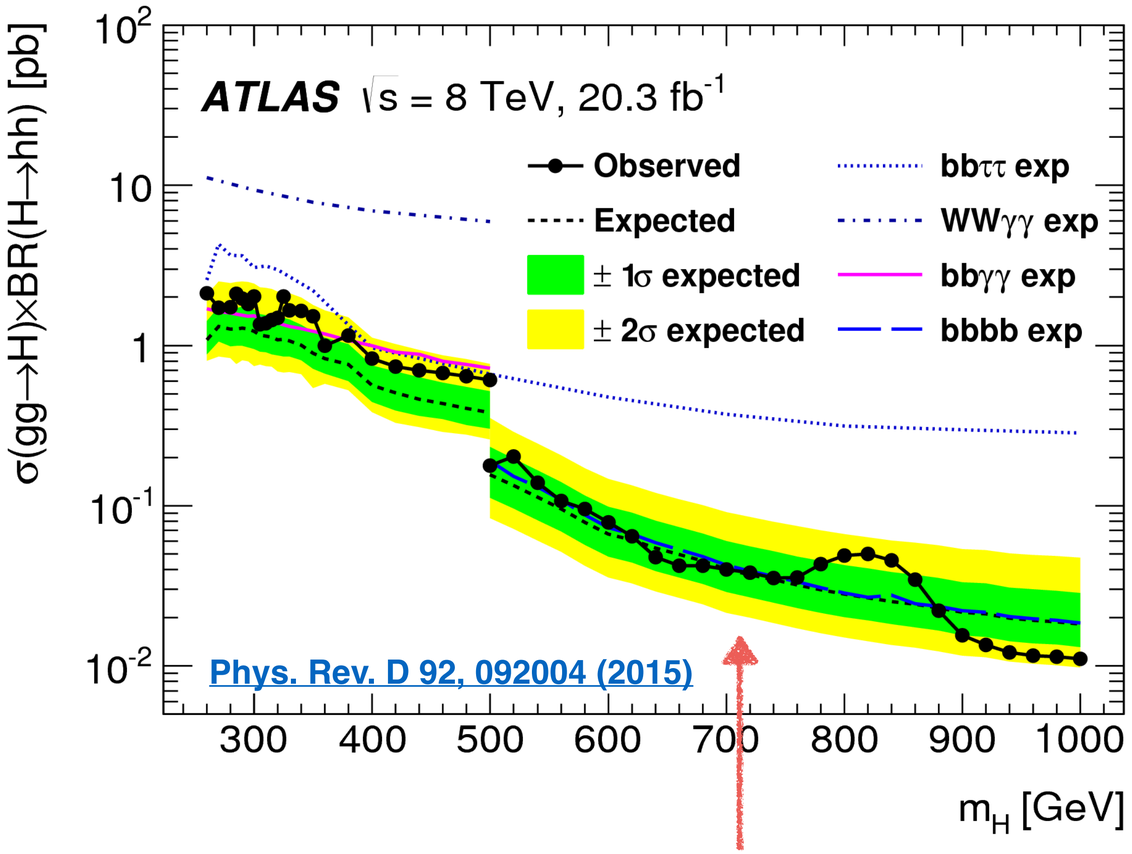


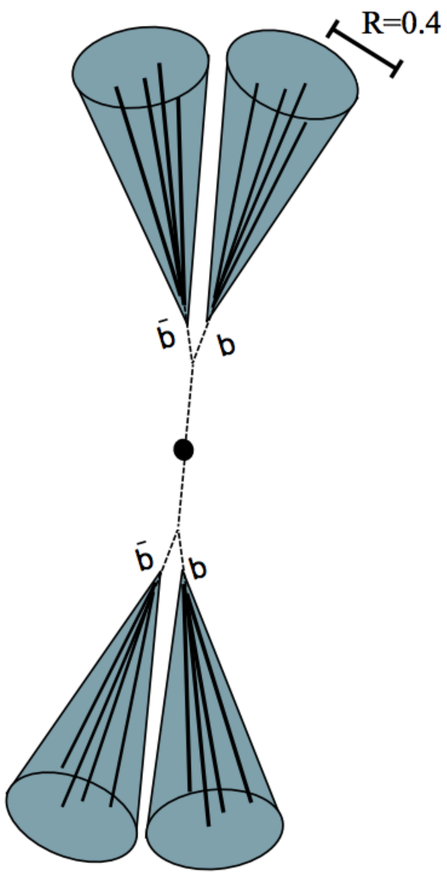


4b better limit for higher mass

Channels: Resolved

ATLAS-CONF-2016-049

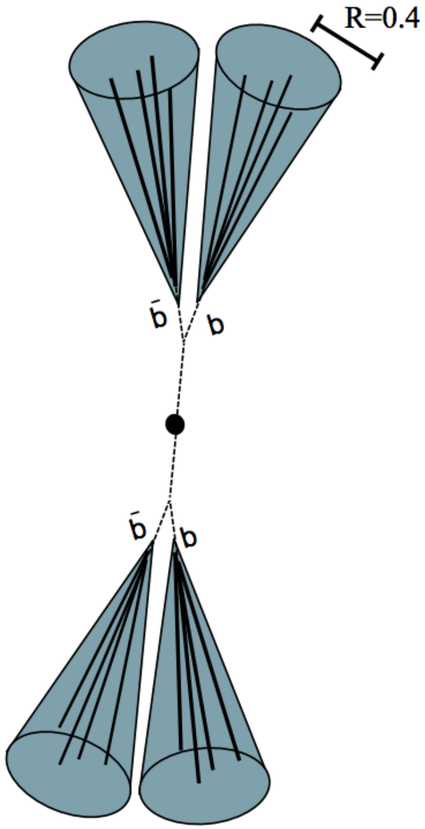
- Standard resolved 4b jets for the low mass range

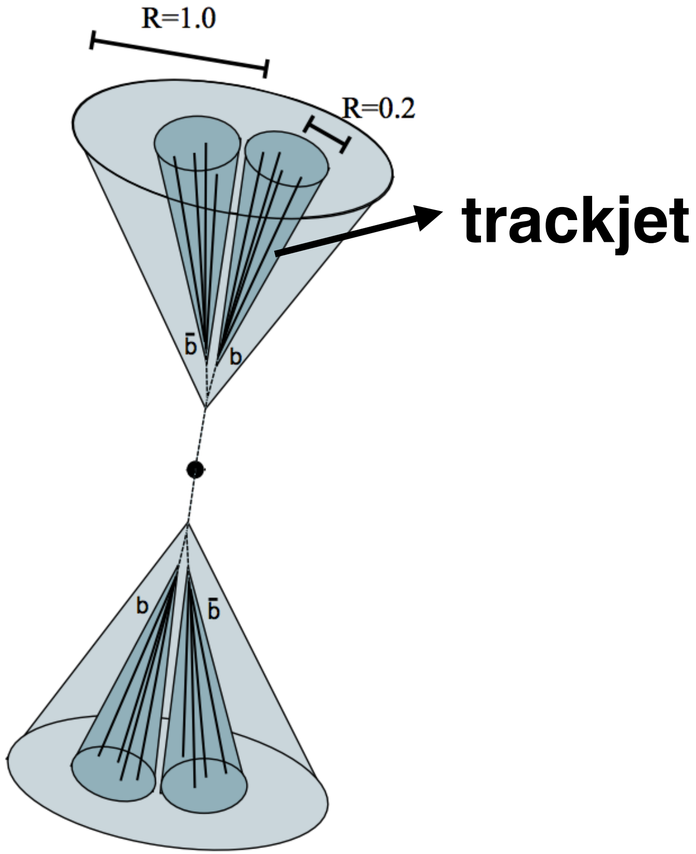


Channels: Resolved + Boosted

ATLAS-CONF-2016-049

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





Channels: Resolved + Boosted

ATLAS-CONF-2016-049

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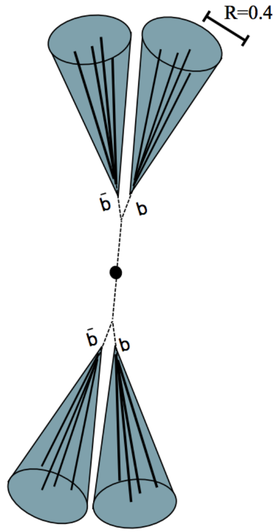
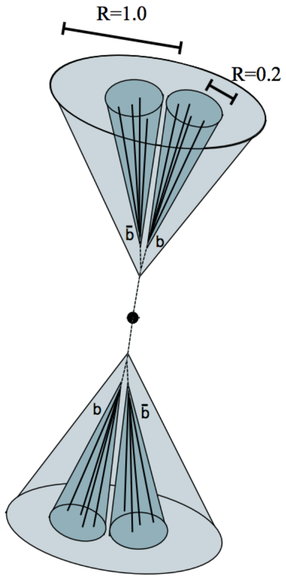
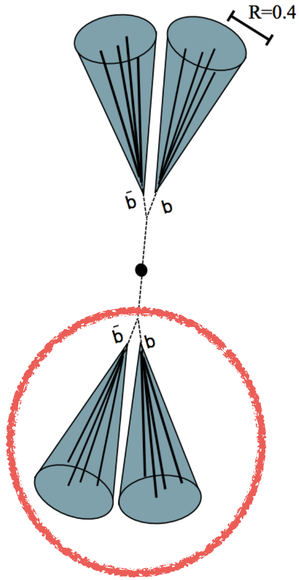


Objects/ Final State	Resolved (250–1100 GeV)	Boosted (1100-3000 GeV)
Trigger	Mixed b Trigger	Large R-jet Trigger
Jets	Four **0.4** Anti-kt Jets	Two **1.0** trimmed Anti-kt Jets
pT cuts	Jet pT > **40** GeV	Leading > **450** GeV Subleading > 250 GeV
B-tagging	70% on Jets	77% on R=**0.2** trk jets

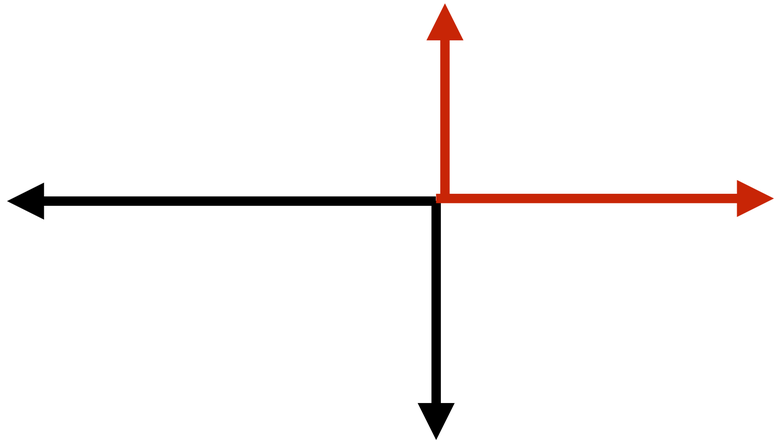


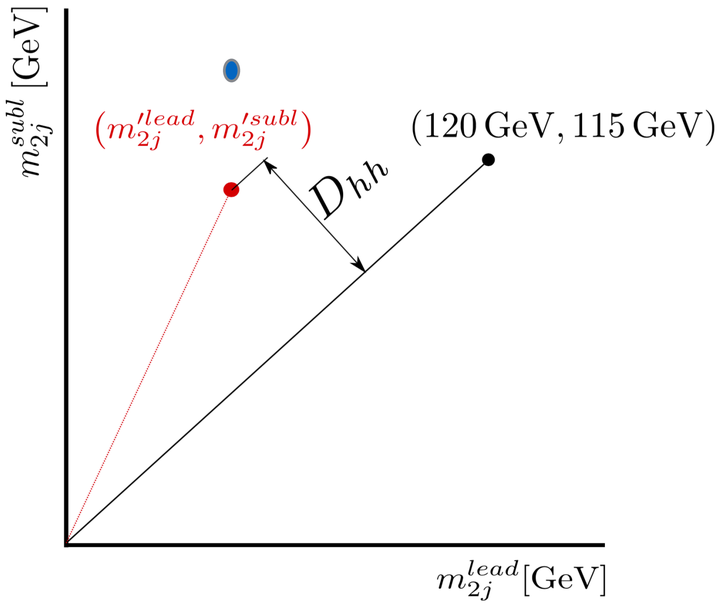
Resolved: Jets Pairing and Cuts

ATLAS-CONF-2016-049

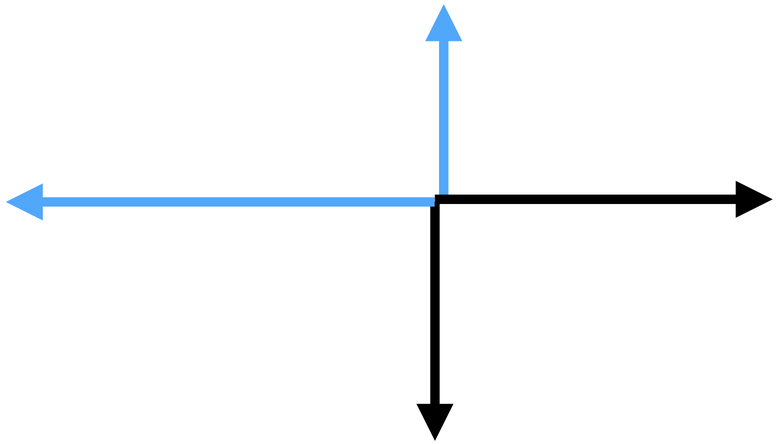


- Select hh pair that has the **minimal distance** to a diagonal line on the 2D mass plane
- **Minimize** the Higgs candidates **mass difference**



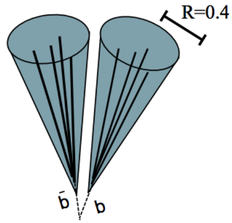


which pair?

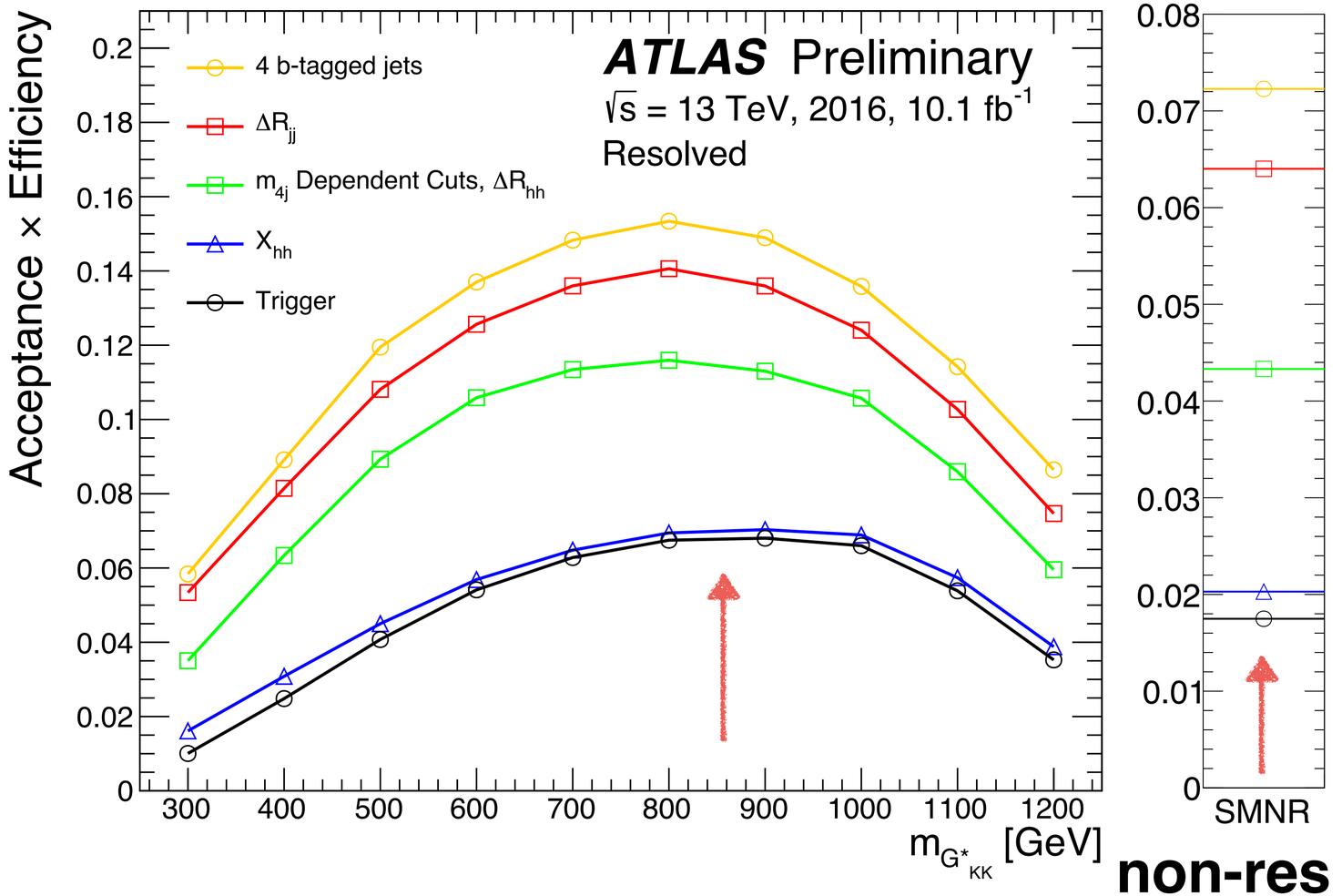


Resolved: Jets Pairing and Cuts

ATLAS-CONF-2016-049



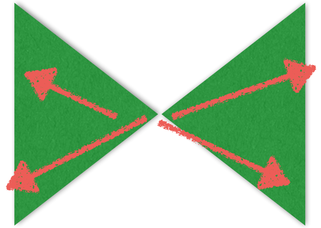
- Select hh pair that has the minimal distance to a diagonal line on the 2D mass plane
- m_{4j} dependent requirements on h **pT, eta, and dR_{jj}**
- **Fine** signal efficiency across **large** mass ranges



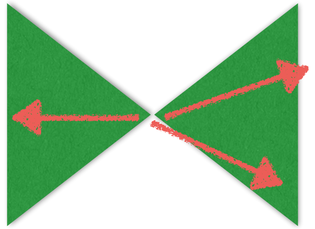
non-res

Boosted: Number of b-tagging

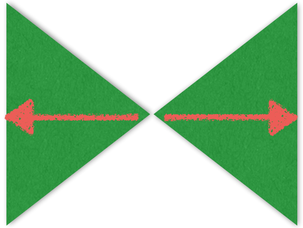
- Three Signal Regions:



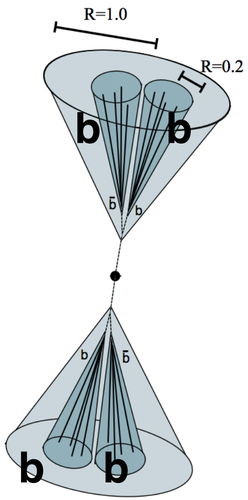
- 4b



- 3b: (recover efficiency)

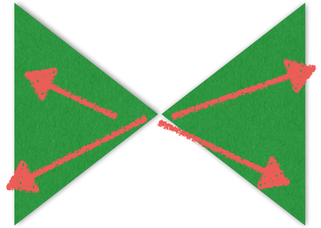


- 2b split (merging of trackjets)

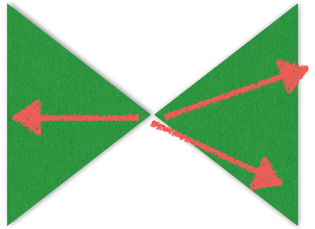


Boosted: Number of b-tagging

- Three Signal Regions:



- 4b



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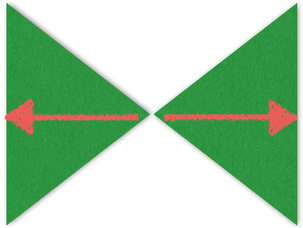

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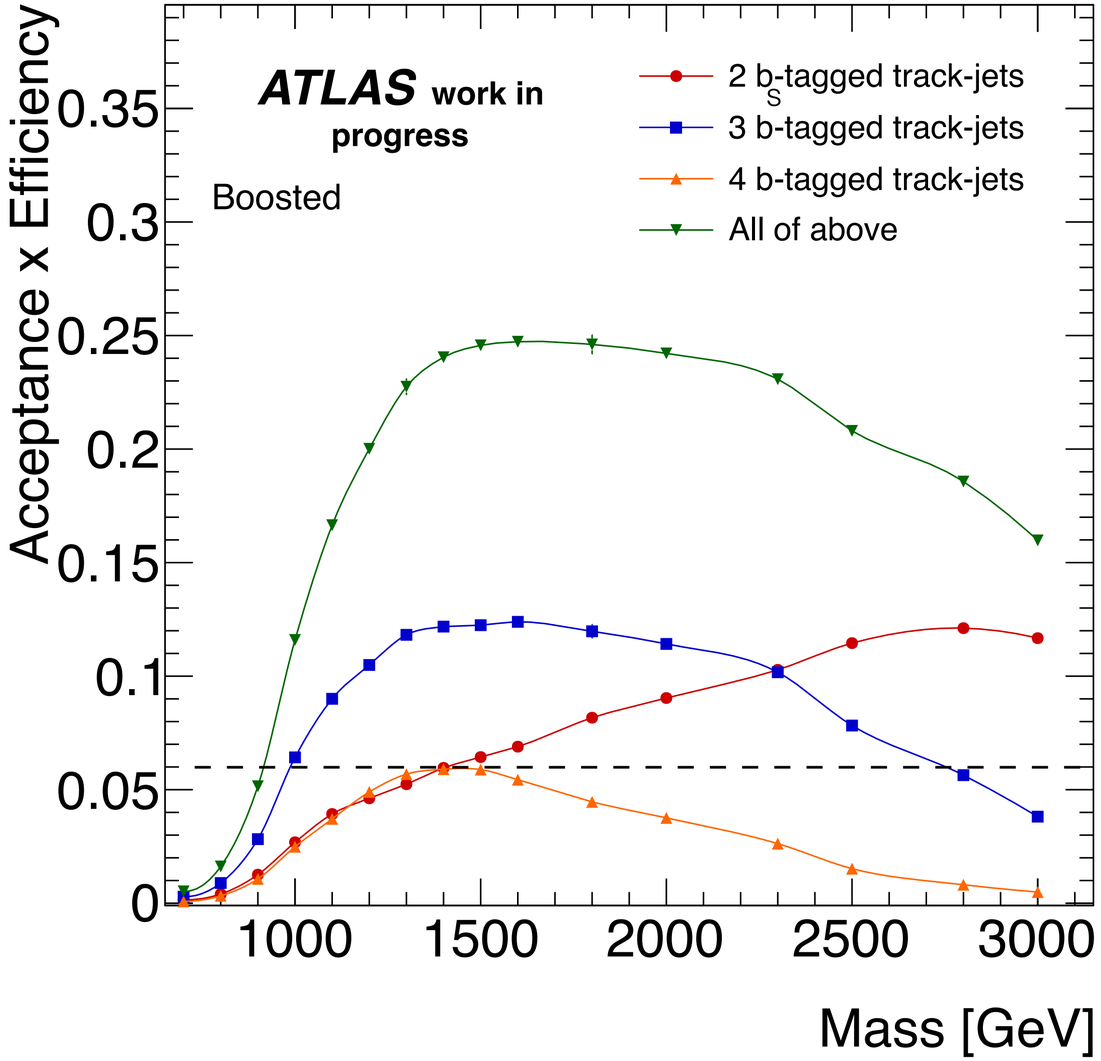
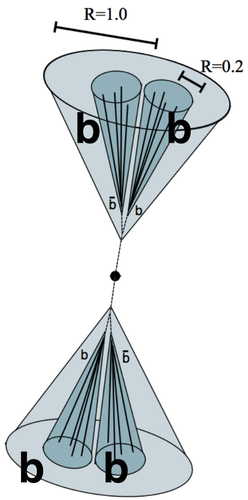
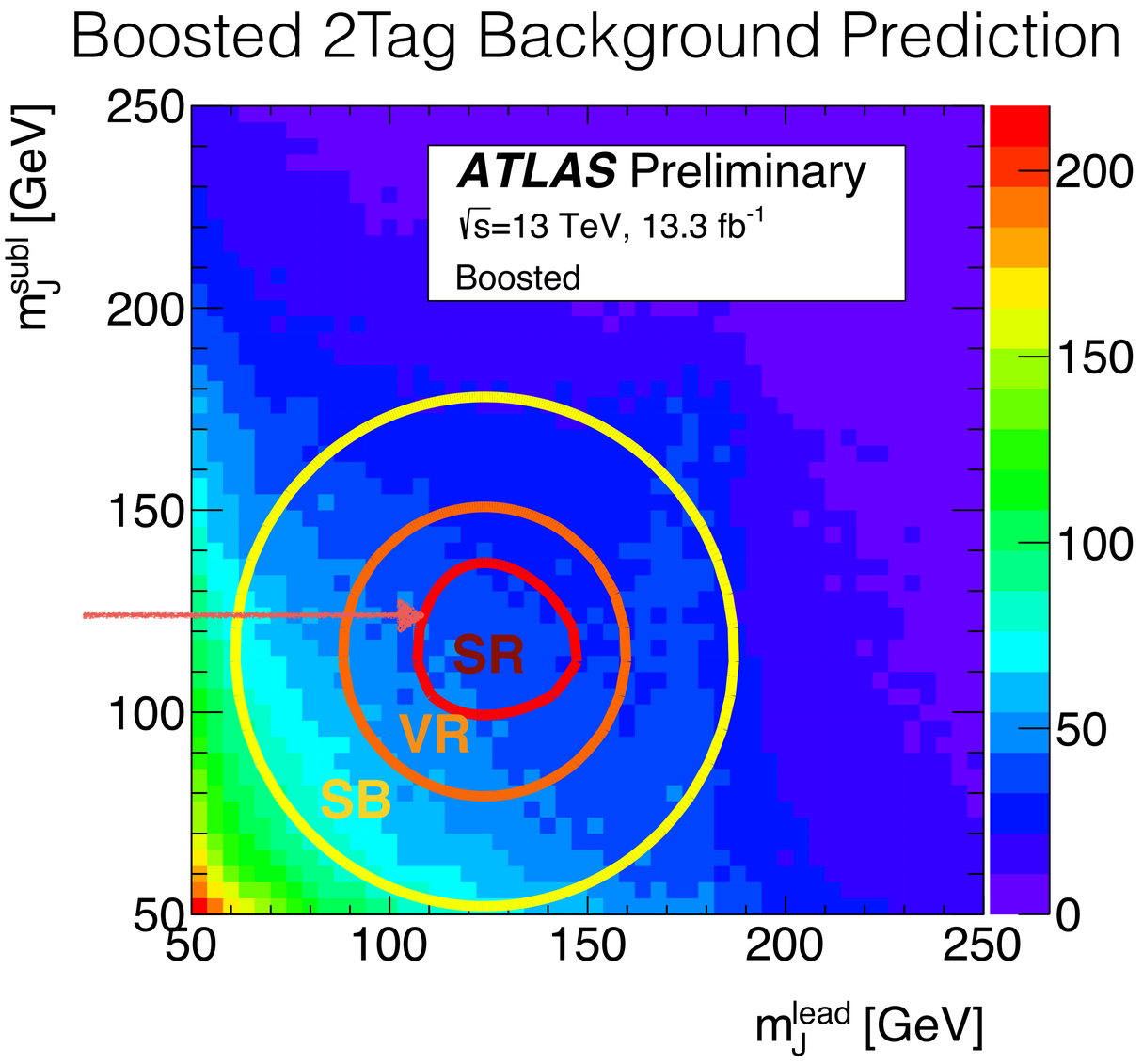




Regions: Two Higgs Mass Plane

ATLAS-CONF-2016-049

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

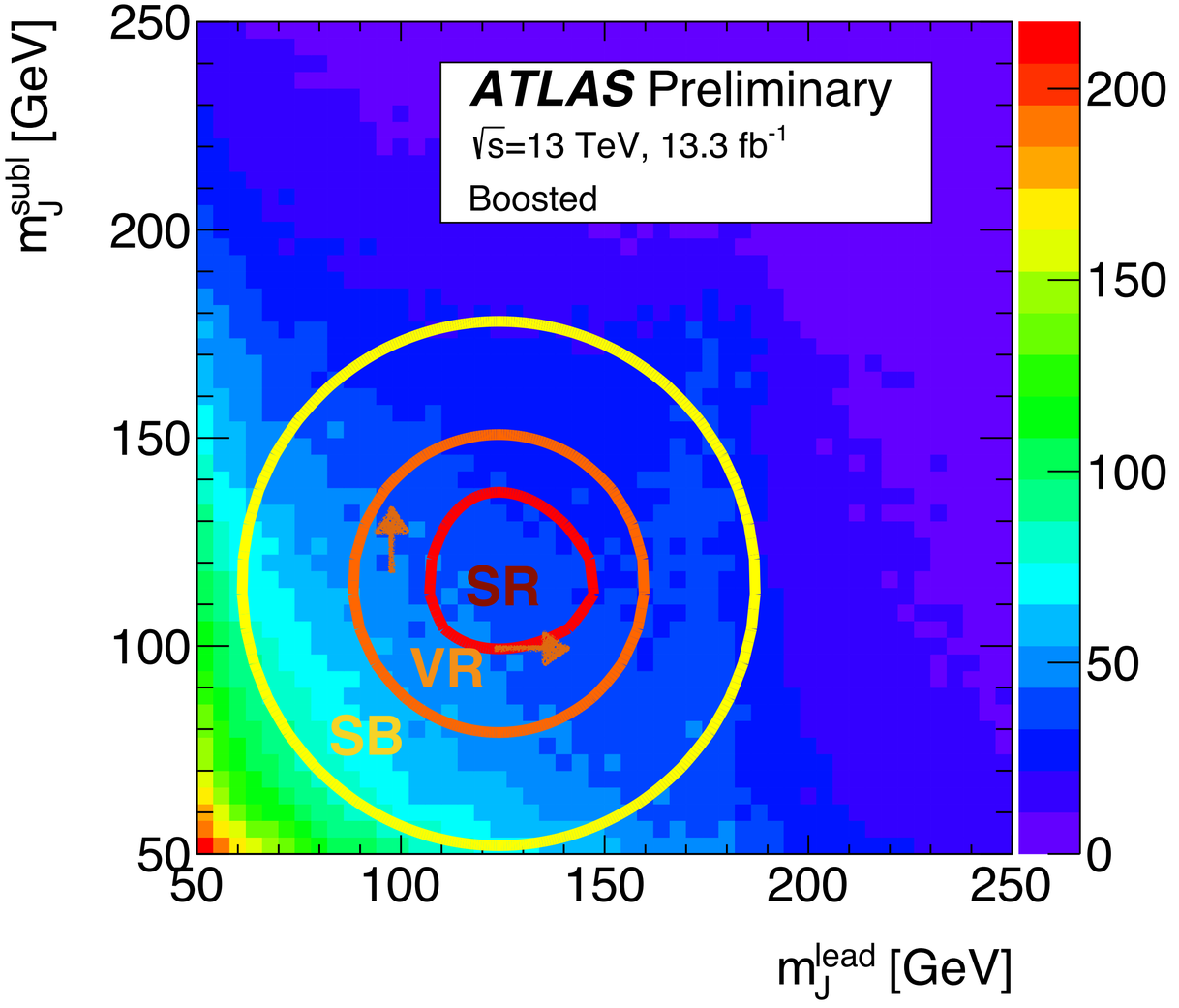


Regions: Two Higgs Mass Plane

ATLAS-CONF-2016-049

- **Signal Region** (SR):
  - "Circle" centered at h mass
- **Validation Region** (VR):
  - Ring outside SR (for validation)

Boosted 2Tag Background Prediction

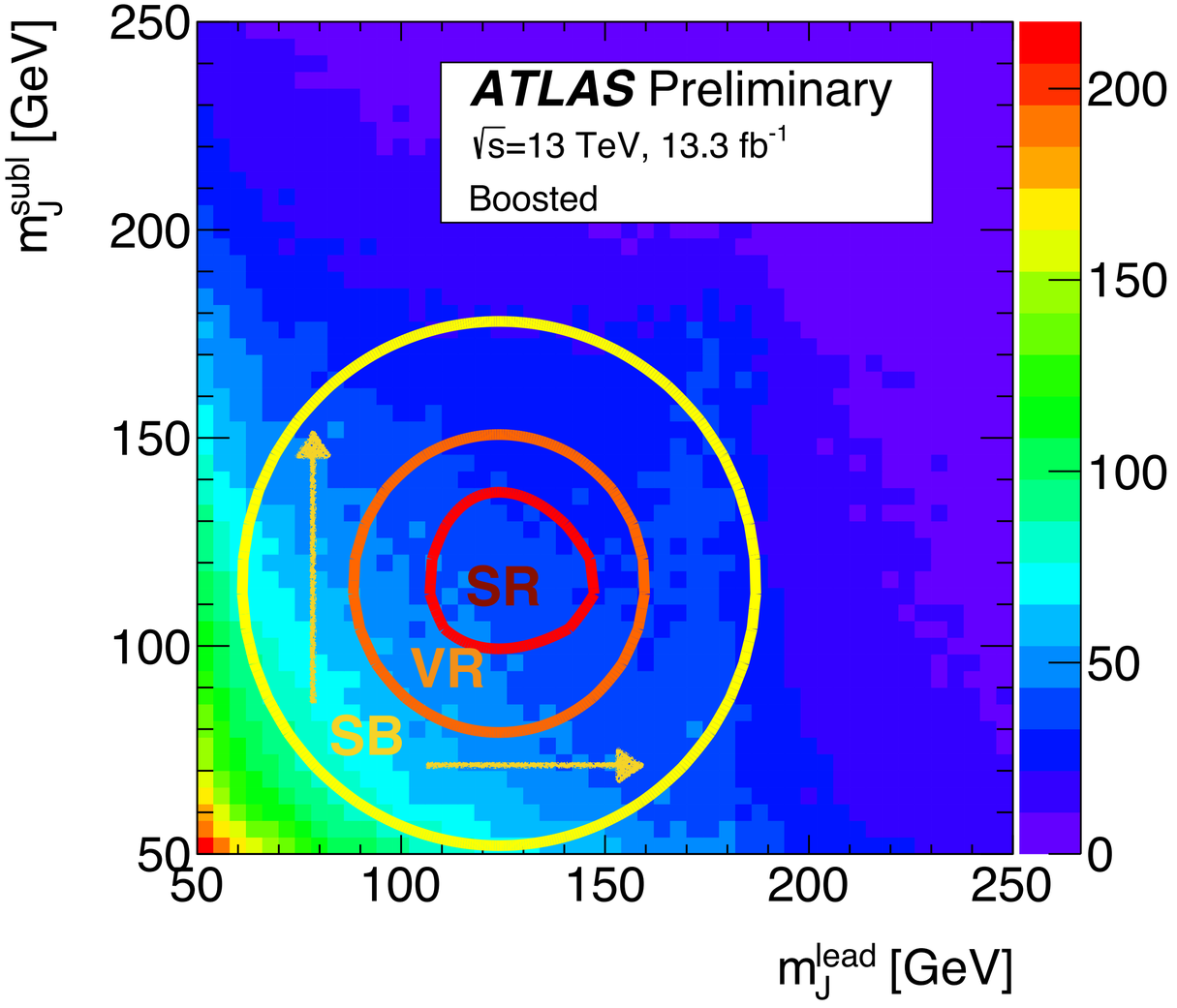


Regions: Two Higgs Mass Plane

ATLAS-CONF-2016-049

- **Signal Region** (SR):
  - "Circle" centered at h mass
- **Validation Region** (VR):
  - Ring outside SR (for validation)
- **Sideband Region** (SB):
  - Ring outside VR (for modeling)

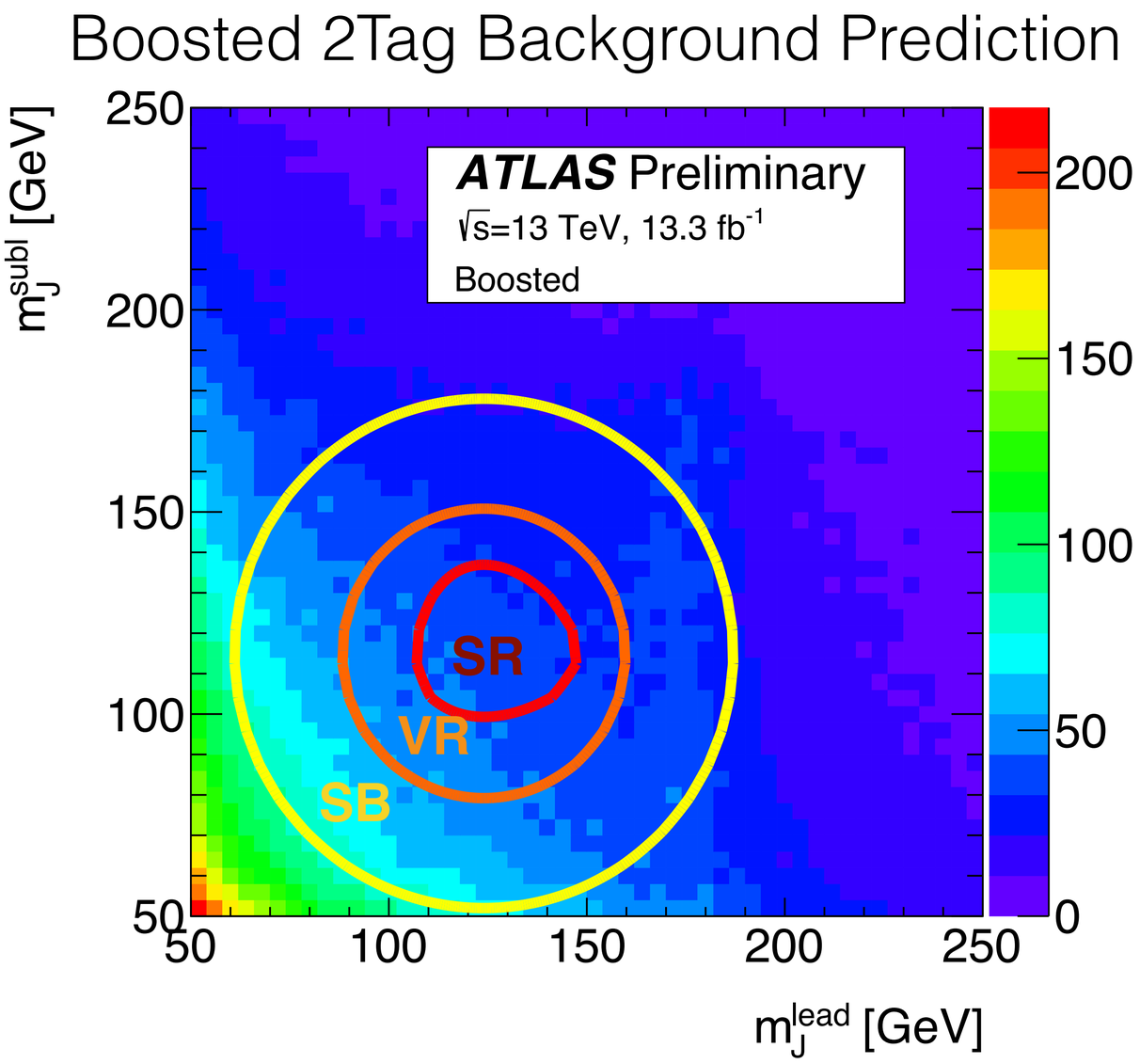
Boosted 2Tag Background Prediction



Background

ATLAS-CONF-2016-049

- Background:
  - 90-85% qcd—data driven
  - 10-15% ttbar—MC



Background

ATLAS-CONF-2016-049

- Background:
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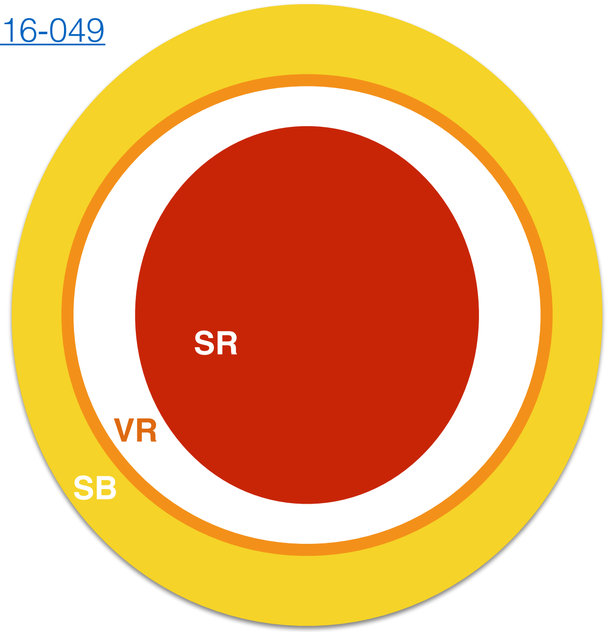
  - 10-15% ttbar—MC

- Need shape and normalization estimates for qcd events

4b



N 4b SR/VR
???

Background

ATLAS-CONF-2016-049

- Background:
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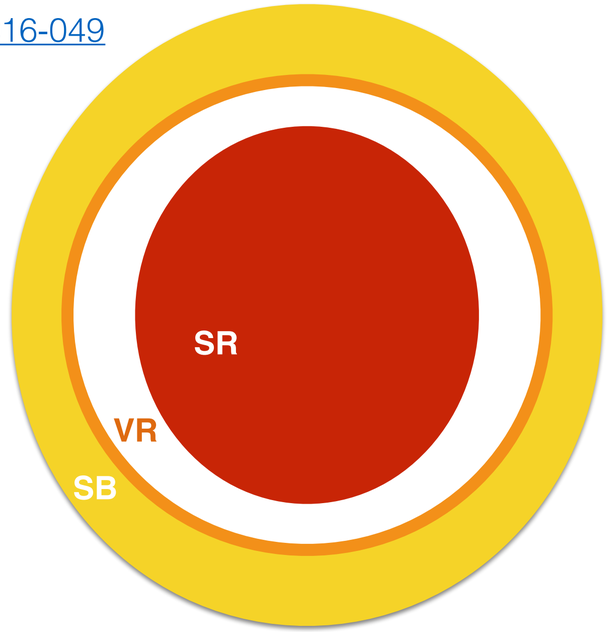
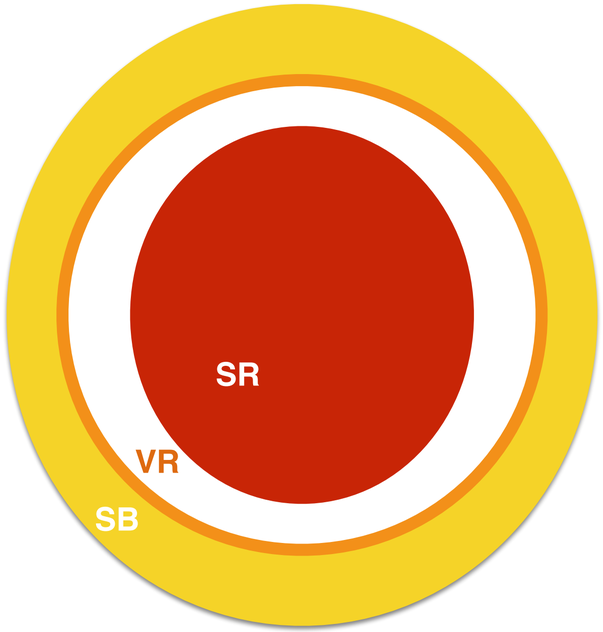
4b



$N_{4b\ SR/VR} \sim N_{0b\ SR/VR}$

- use lower-b-tag low-signal yield region to **model** higher-b-tag regions

0b



Background

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  - 90-85% qcd—data driven
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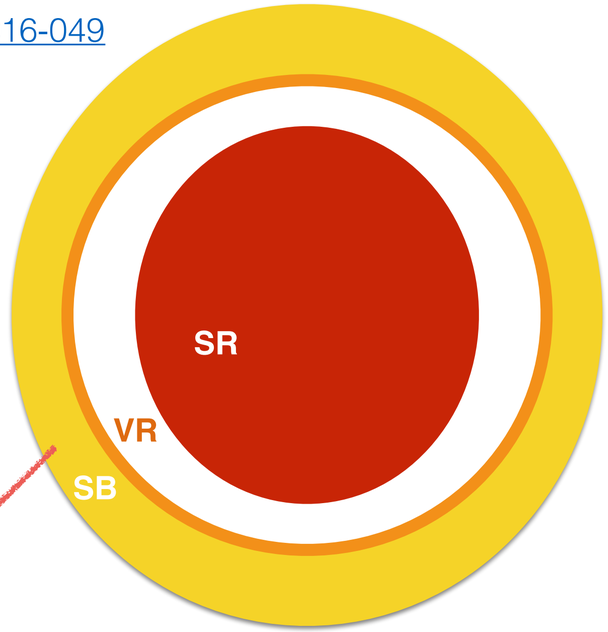
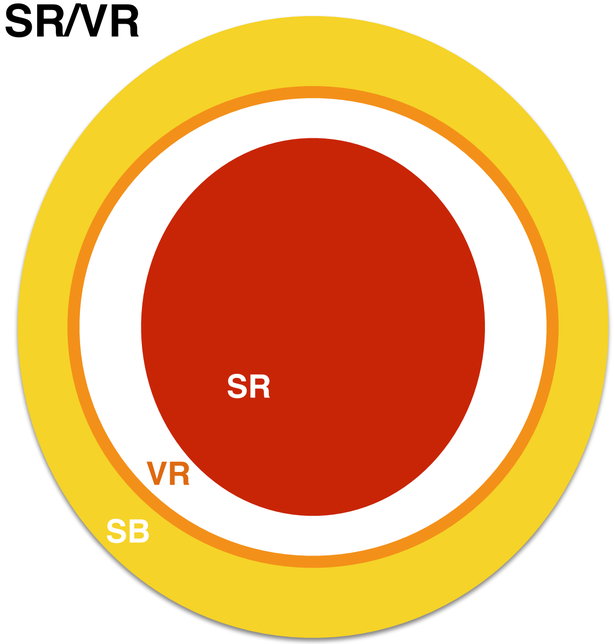
4b



$$N_{4b\ SR/VR} = N_{4b\ SB} / N_{0b\ SB} * N_{0b\ SR/VR}$$

0b



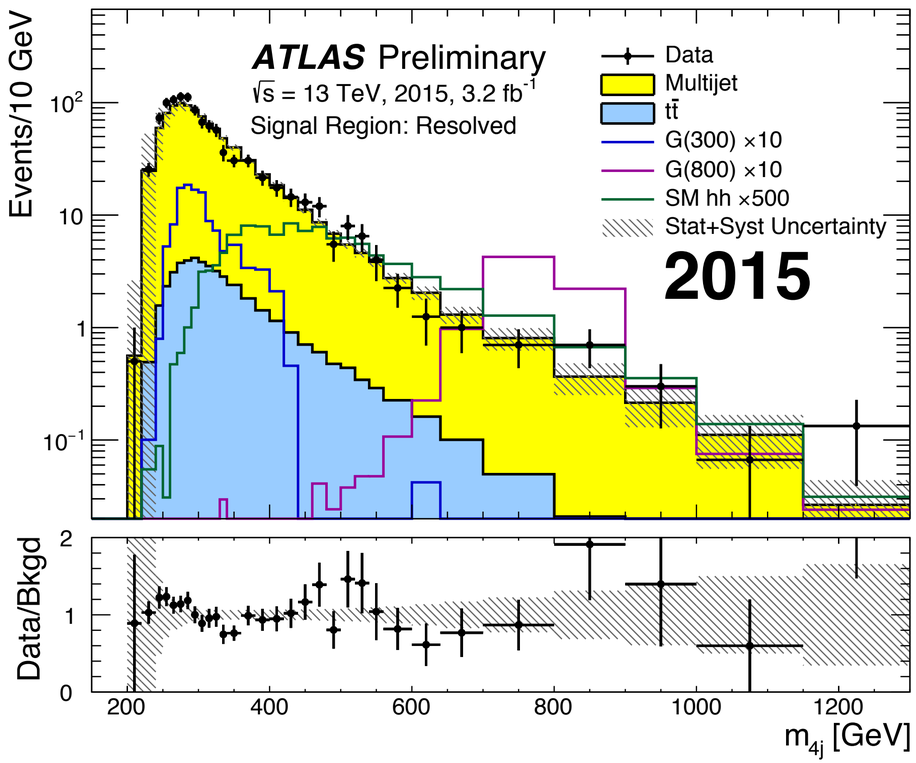
- use lower-b-tag low-signal yield region to model higher-b-tag regions
- derive the **normalization** factor from the Sideband, check in Validation

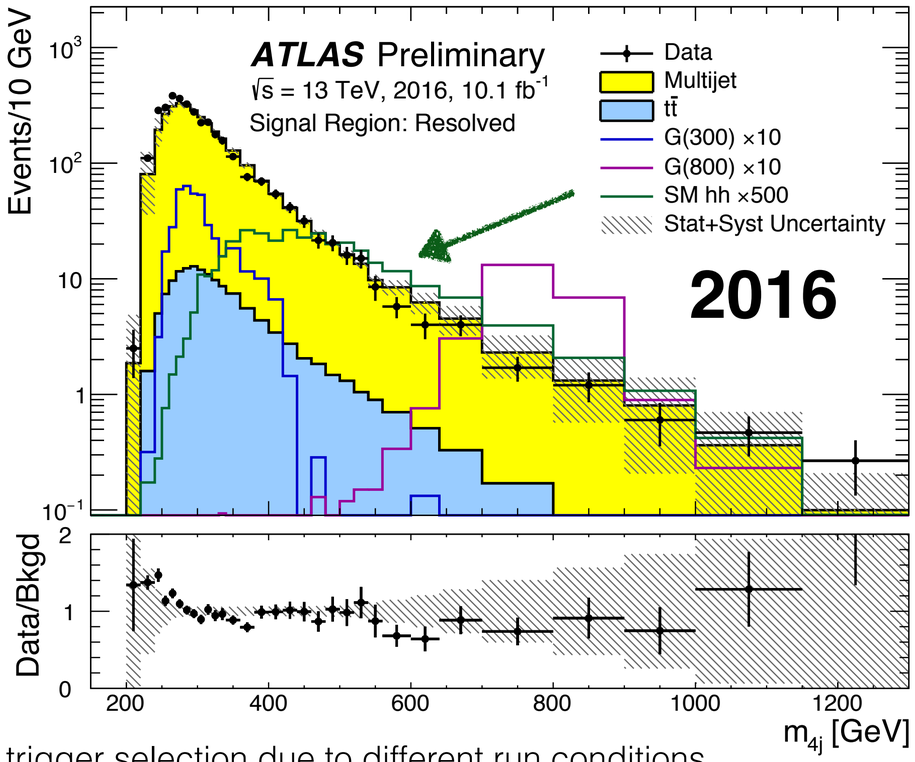
Signal Region: Resolved

ATLAS-CONF-2016-049

- Final discriminant: **m4j**, **four jets's invariant mass**; no significant excess observed

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





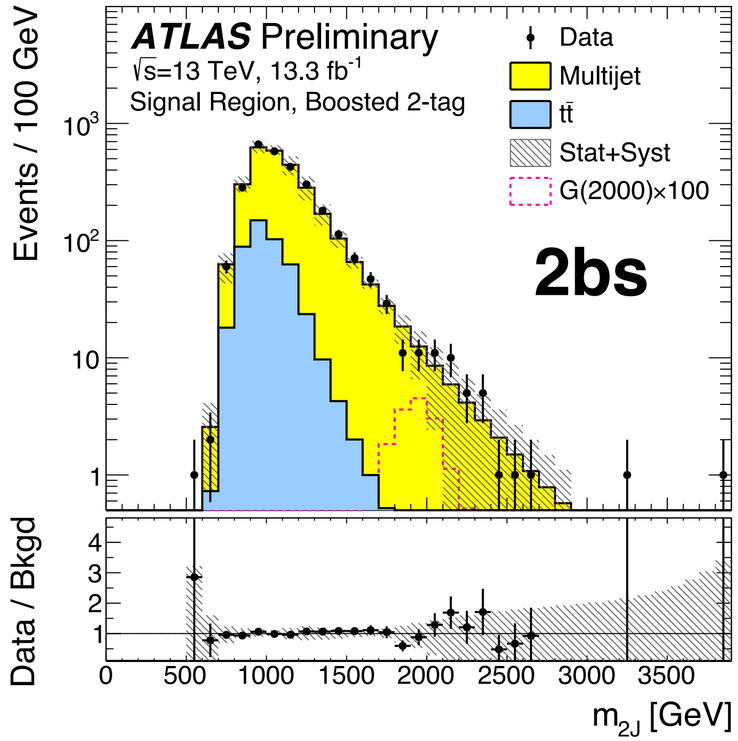
*2015 and 2016 have different trigger selection due to different run conditions

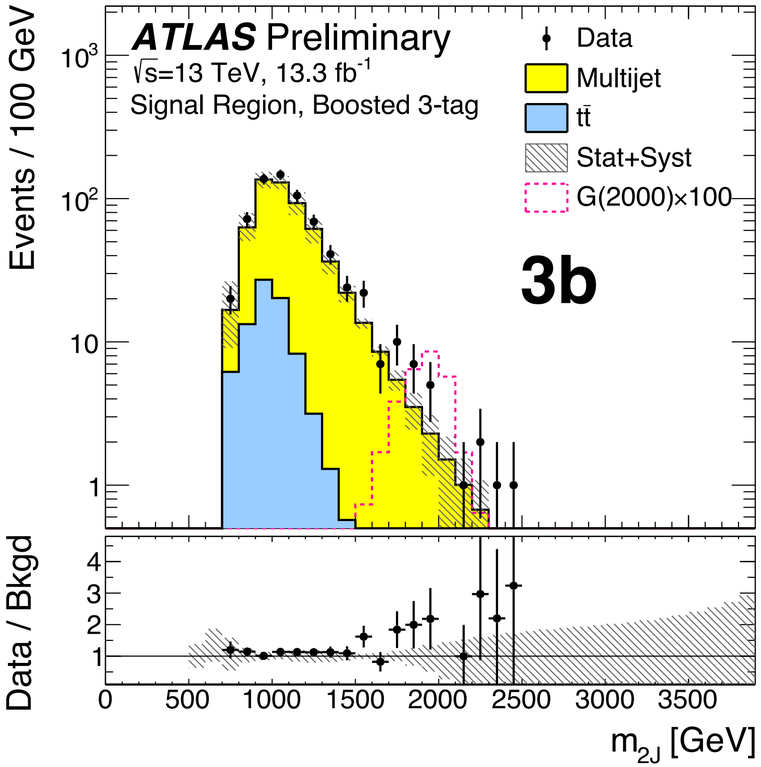
Signal Region: Boosted

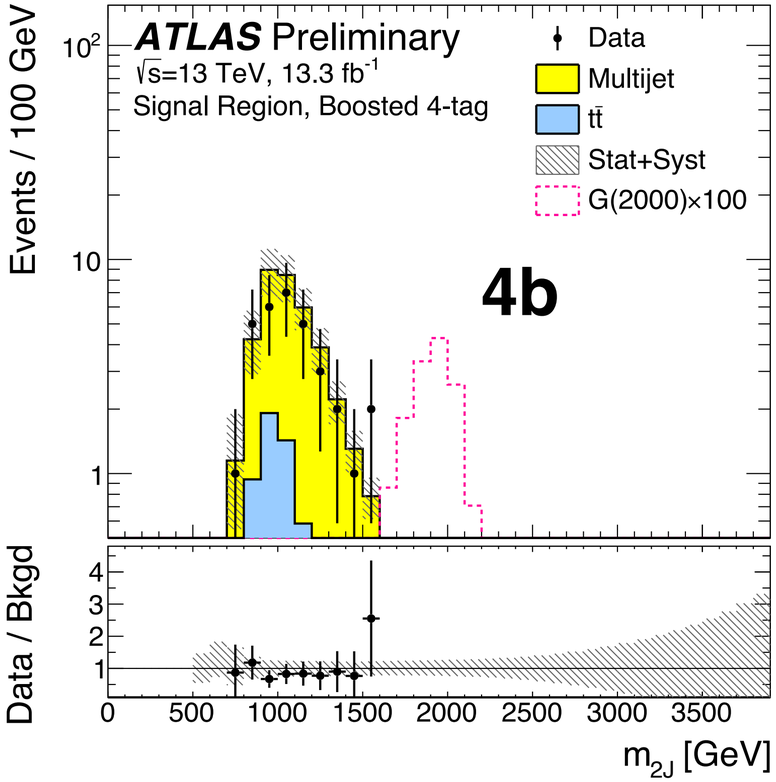
ATLAS-CONF-2016-049

- Final discriminant: **m2j**, **dijet invariant mass**; no significant excess observed

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





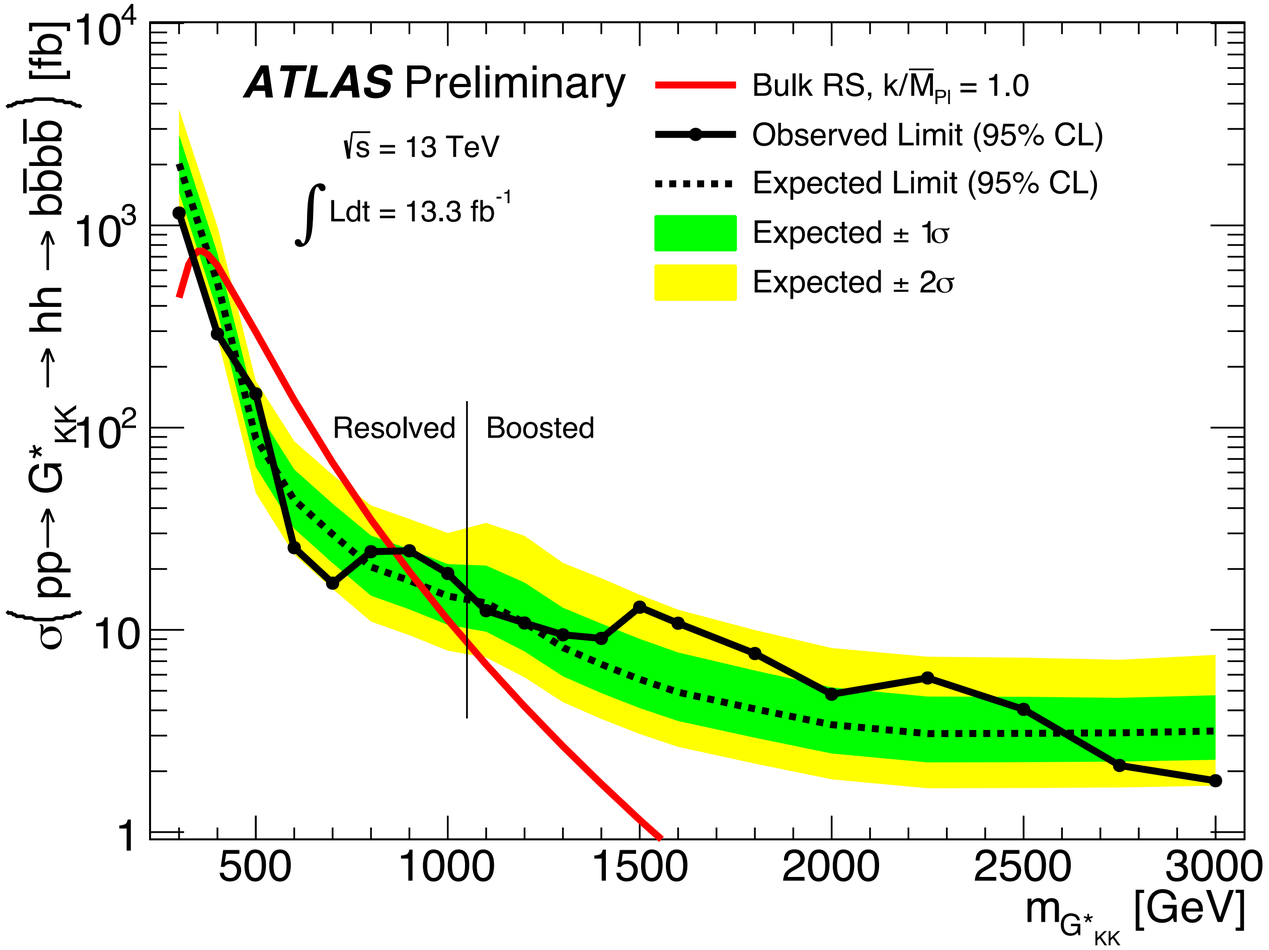


Combined Limits

ATLAS-CONF-2016-049

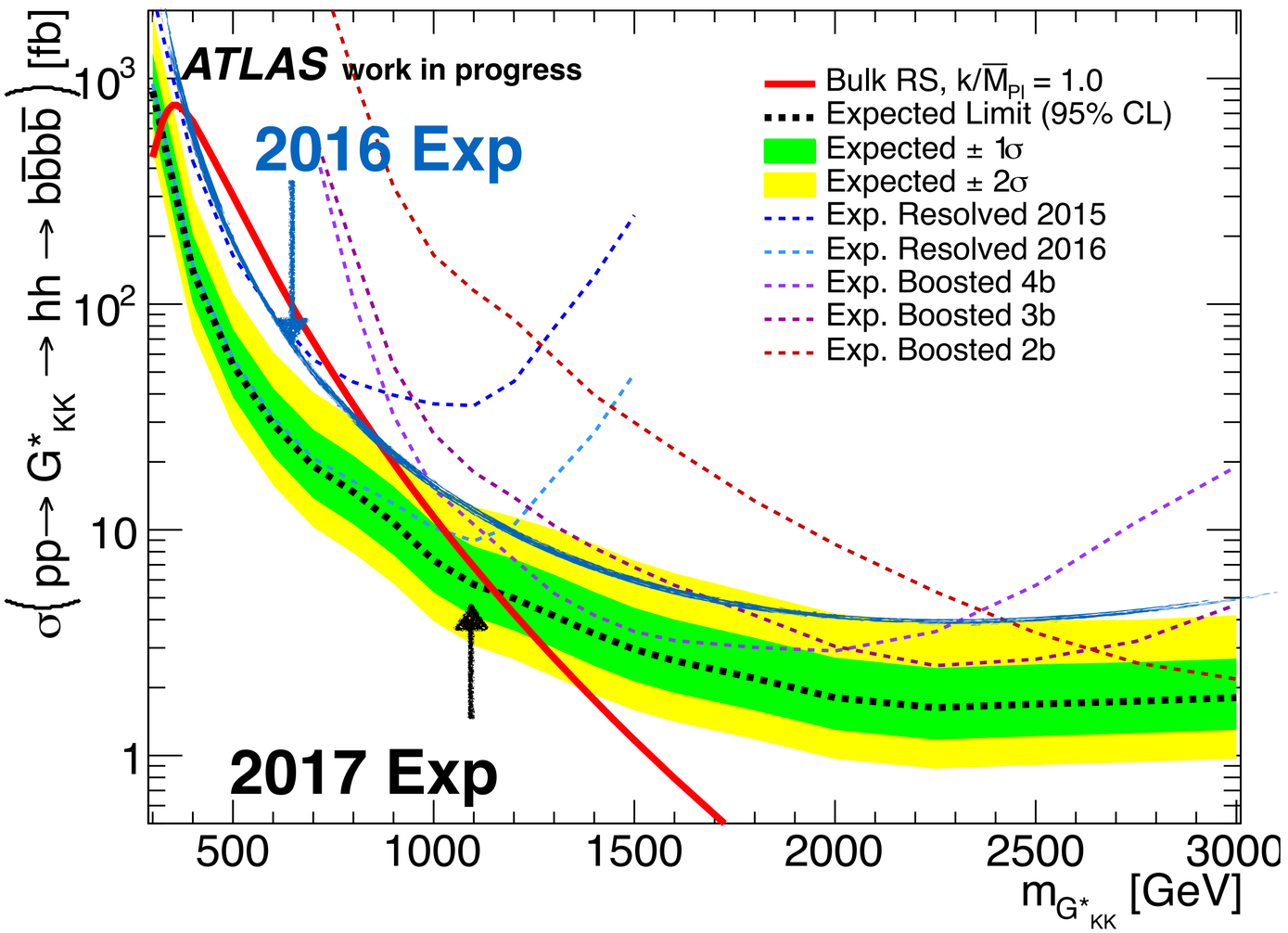
- Resolved (< 1 TeV) + Boosted (> 1 TeV) Limits

- Non-Resonance limit:
  - **1 pb** (1.3 pb expected)
  - **μ ~ 29** (39 expected)



New: Combined Expected Limits

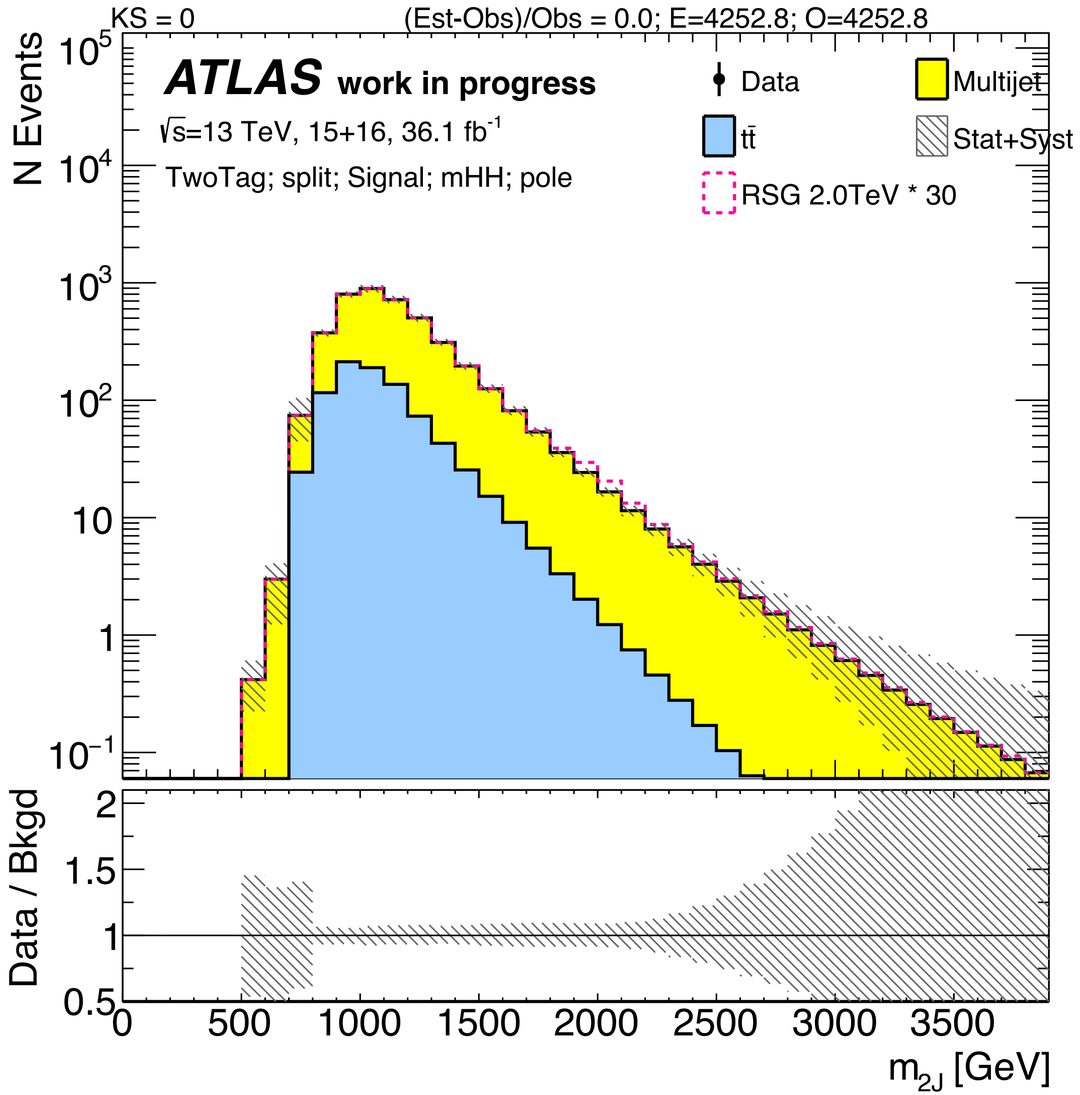
- 2017 current analysis is almost done!
- Resolved/Boosted 24/36 fb^{-1} **Statistically Combined** Limits
- Non-Resonance limit:
  - 200 fb expected
  - **μ ~ 19** expected



Conclusion

- ATLAS **hh → bbbb** current search results have been presented
- So far **no significant excess observed**, 13 TeV non-resonance limit at **1 pb**
- **A new 2017 result is coming soon**! Stay tuned!

2017 Boosted Expected 2Tag-split Signal Region



Back up Slides

APS | DIVISION OF PARTICLES & FIELDS

DPF 2017

MEETING OF THE AMERICAN PHYSICAL SOCIETY DIVISION OF PARTICLES AND FIELDS

Run I non-res limit comparison

Phys. Rev. D 92, 092004 (2015)

RunI non-res limits rel to SM	Obs**(Exp)**
bb$\tau\tau$	160 (**130**)
WW*γγ	1150 (**680**)
bbγγ	220 (**100**)
bbbb	63 (**63**)
Combination	70 (**48**)

Summary of HH ATLAS Results

ATLAS Search Results	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		

Fit on Leading Jet Mass Distribution

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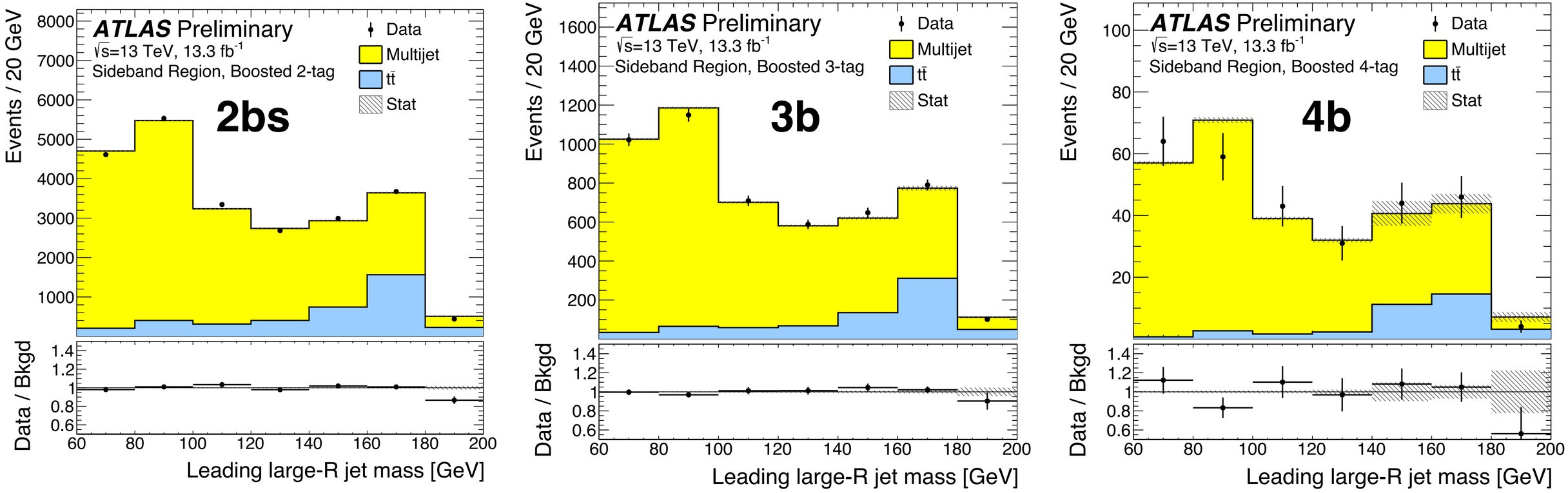
- Given: $N^{\nu_b}_{data} = \mu^{\nu_b}_{qcd} N^{0b}_{qcd} + \alpha^{\nu_b}_{t\bar{t}} N^{\nu_b}_{t\bar{t}}$
- Simultaneous **fit** of μ_{qcd}, a_{tt} to extract the normalization factors
- All fits are independent



Reweighting Details

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

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

- 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

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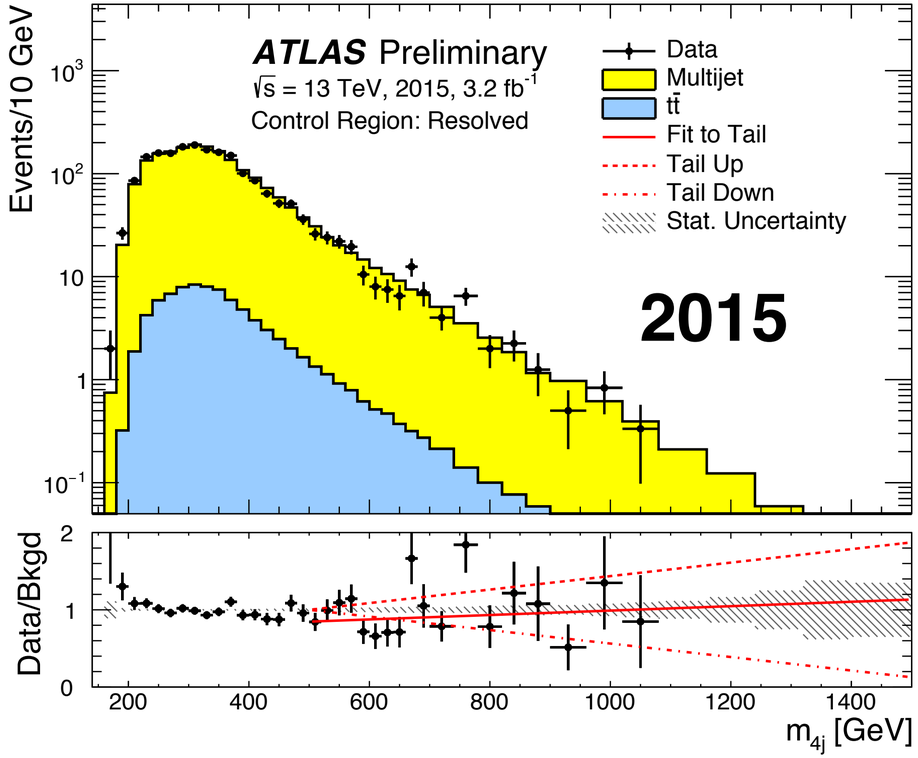
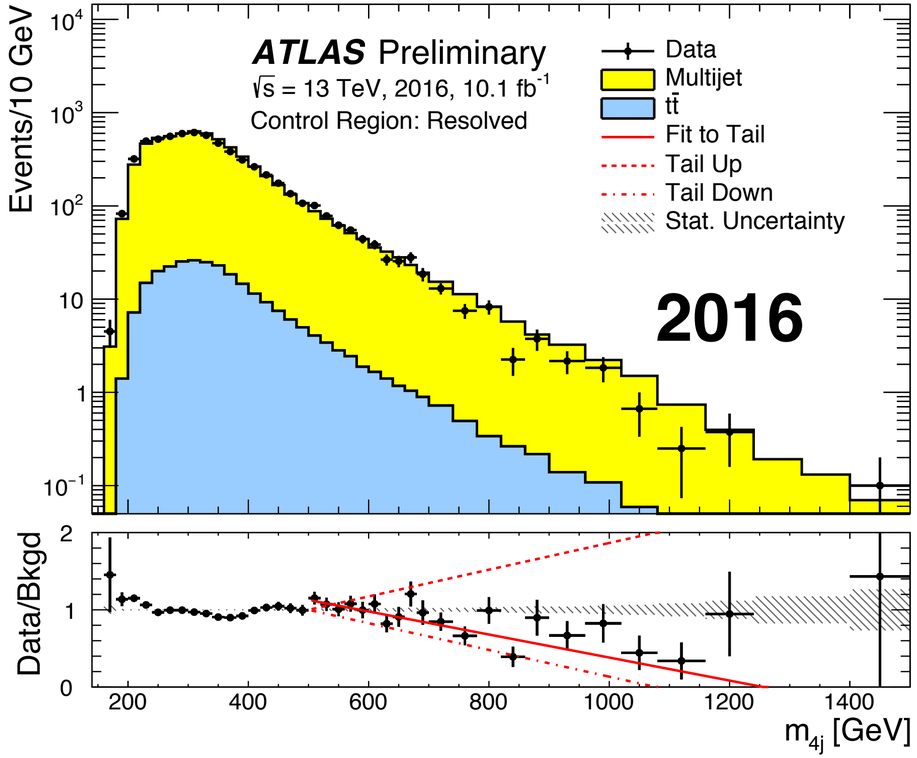
- **Good** agreement in shape and normalization

Obs	**3995**	**12752**
Exp	4021 ± 88	12970 ± 110



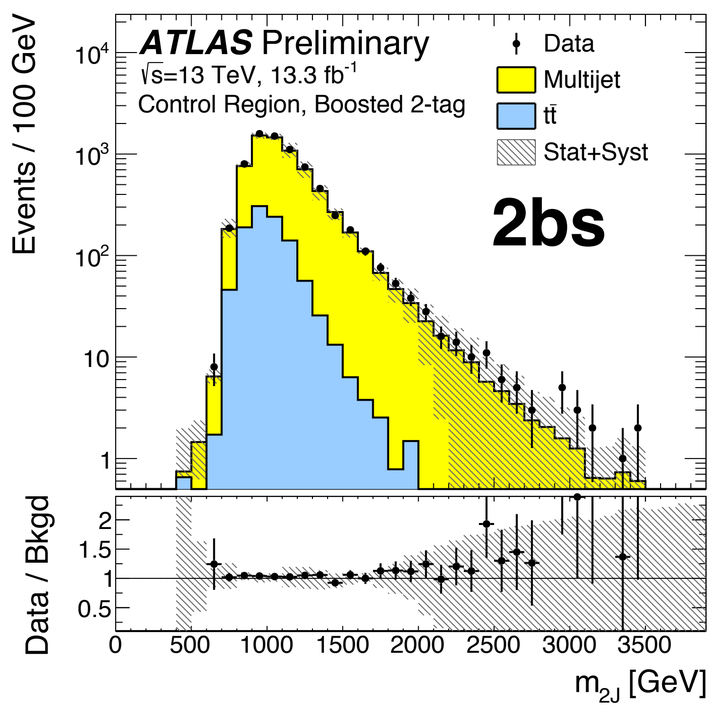


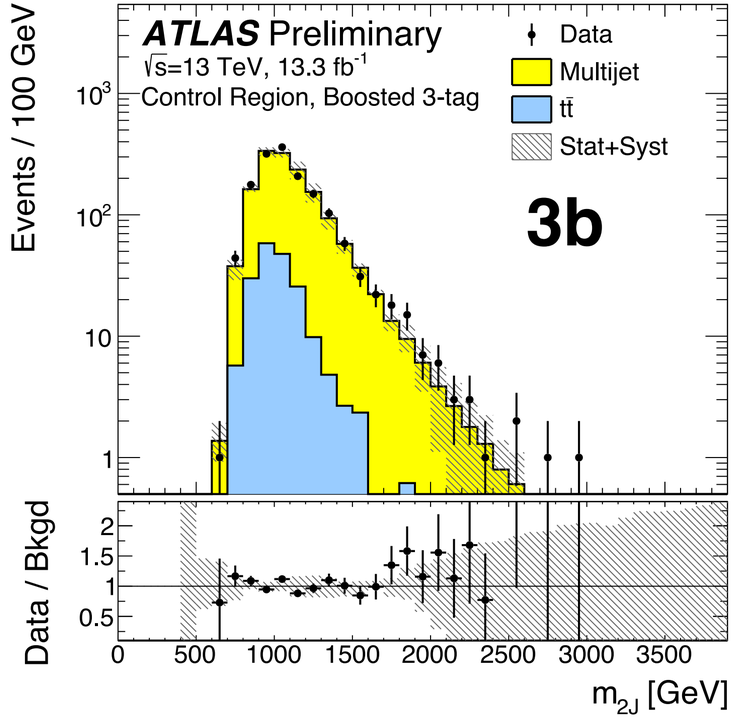
Control Region: Boosted

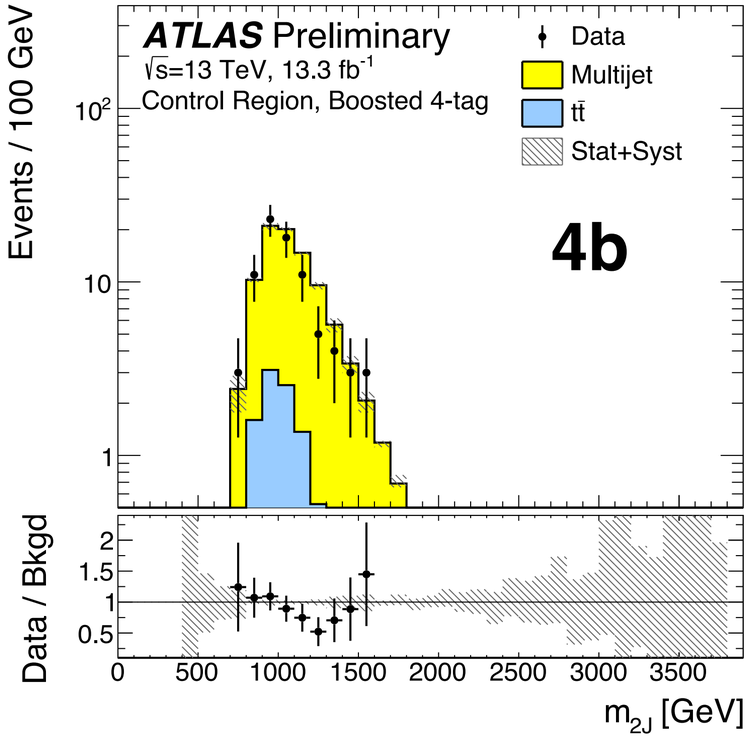
ATLAS-CONF-2016-049

- **Good** agreement in shape and normalization

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







Uncertainties Countdown

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- Signal uncertainty mainly comes from **b-tagging**
- Bkg uncertainty is dominated by **data driven** validation 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

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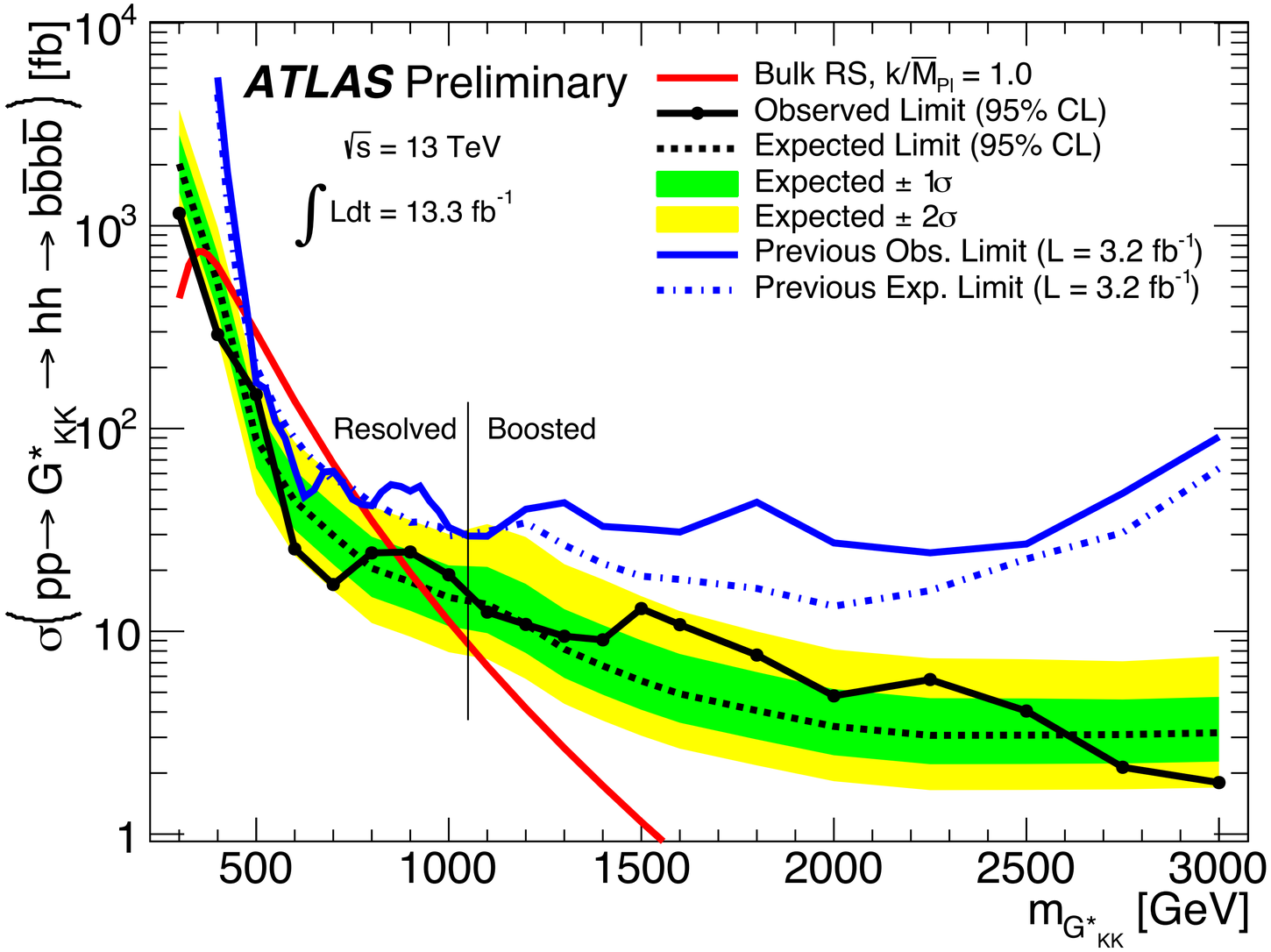
- ICHEP-Moriond Limit Direct Comparison

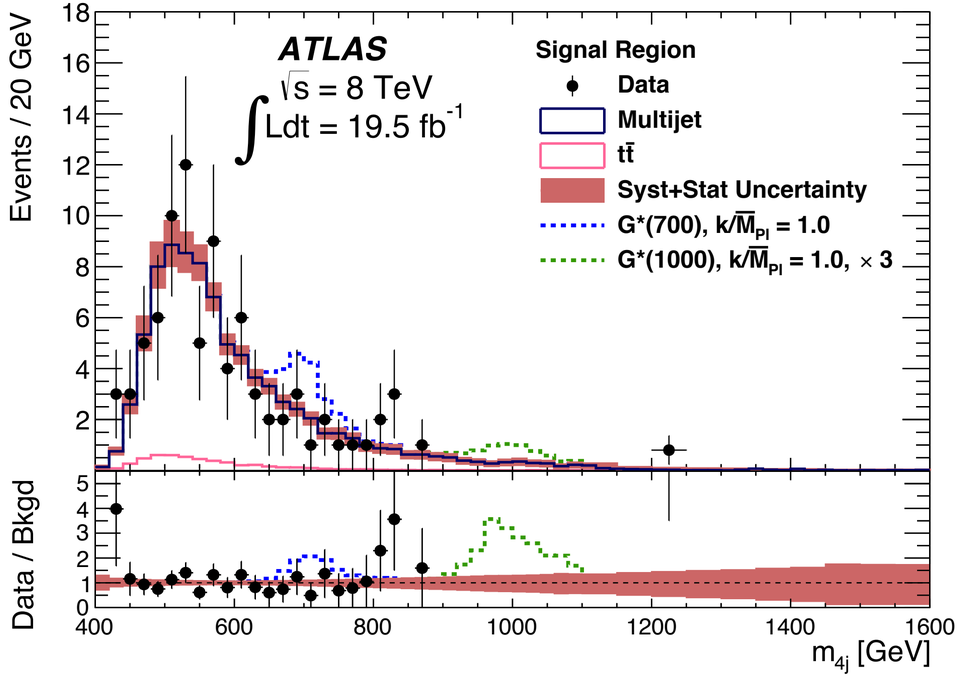


Resolved and Boosted Results

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

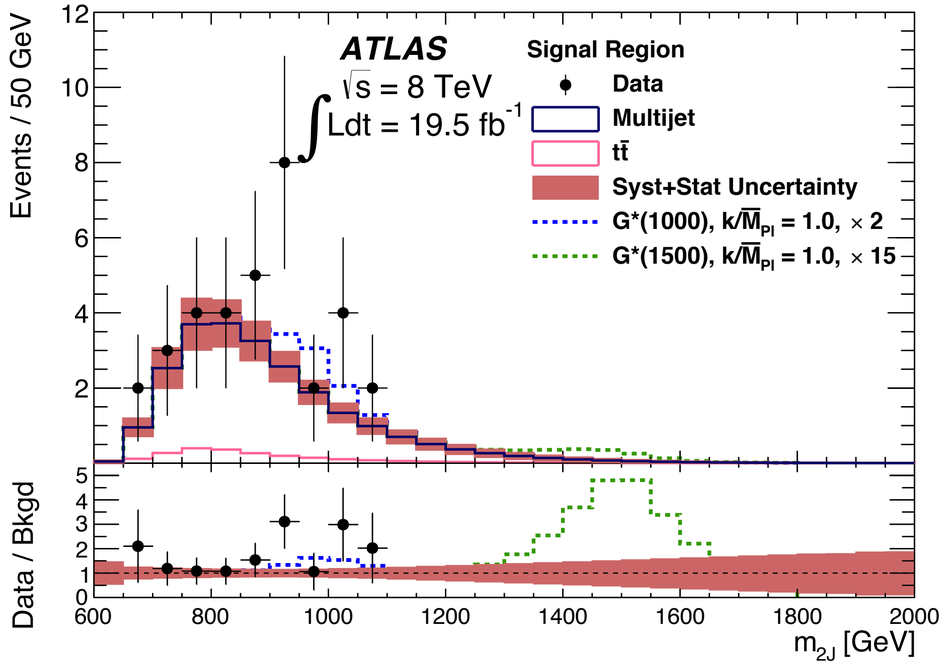
Resolved

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^*_{KK} $(500\,GeV)$, $k/\bar{M}_{\mathrm{Pl}} = 1$	27 ± 5.9



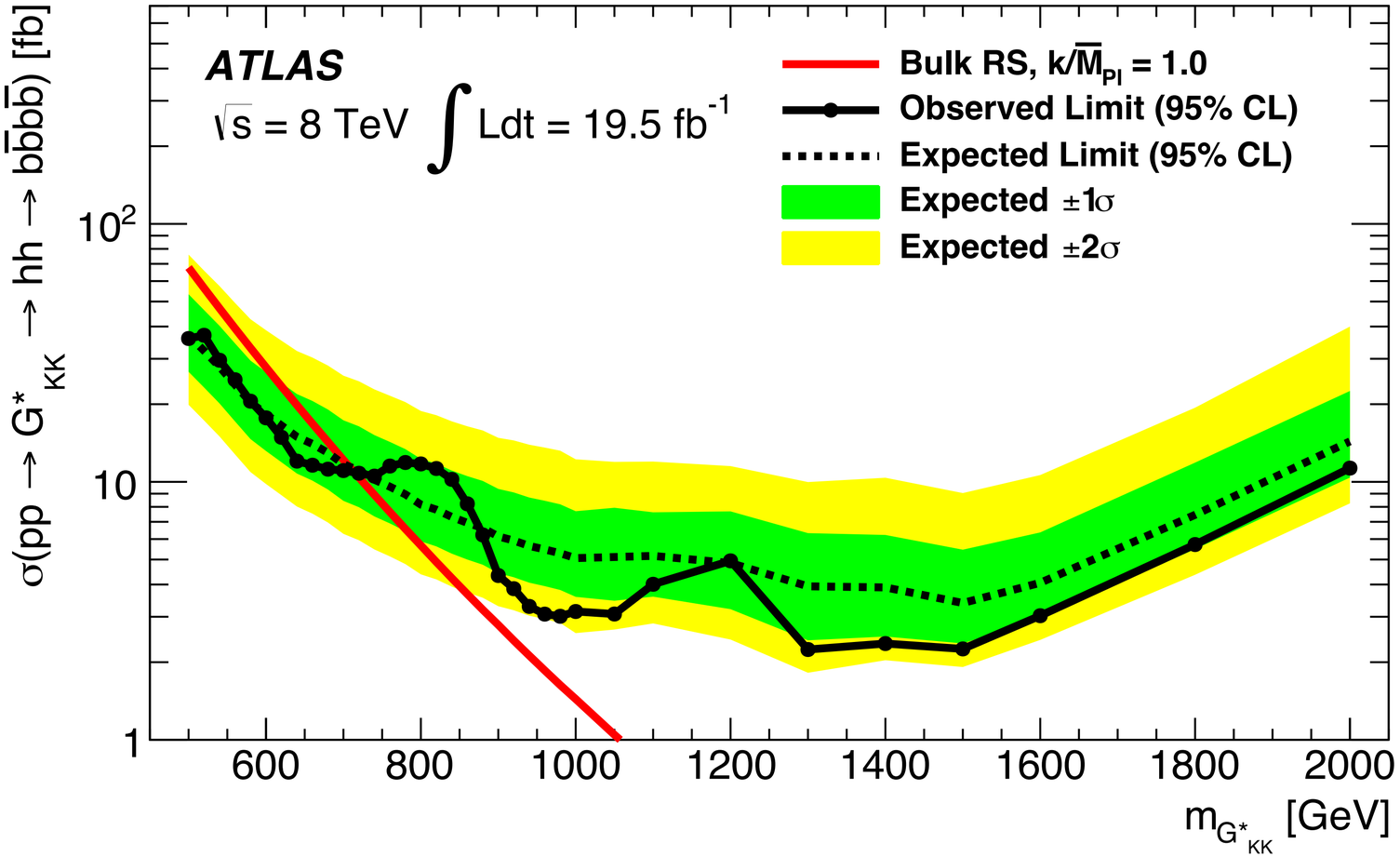
Boosted

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^*_{KK} $(1000\,GeV)$, $k/\bar{M}_{\mathrm{Pl}} = 1$	2.1 ± 0.6

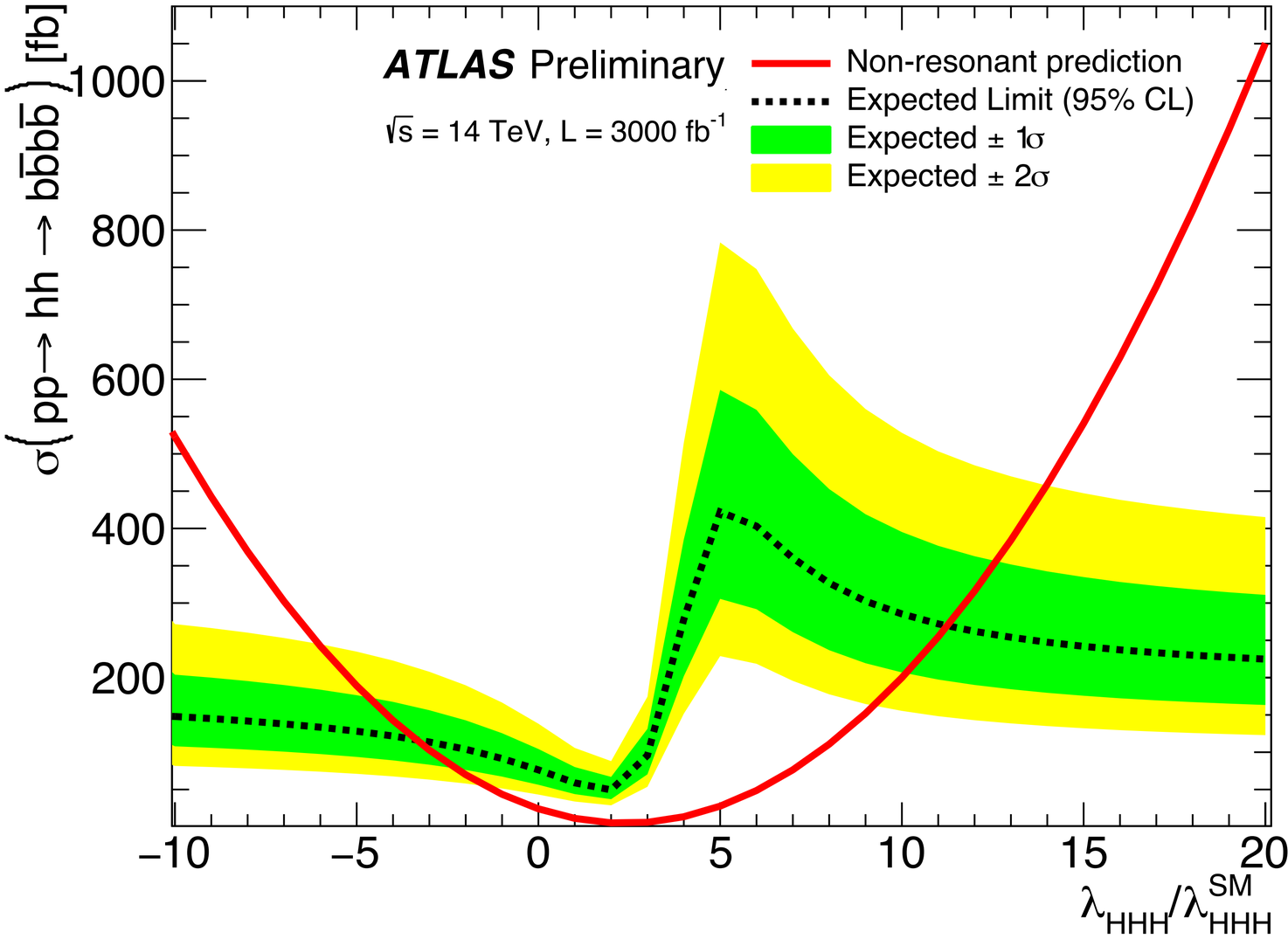


Combined Limit

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



Future Perspectives

ATLAS-CONF-2016-024

- Extrapolation of current 2016 results
- Limit: $-3.5 < \lambda_{hhh} < 11$