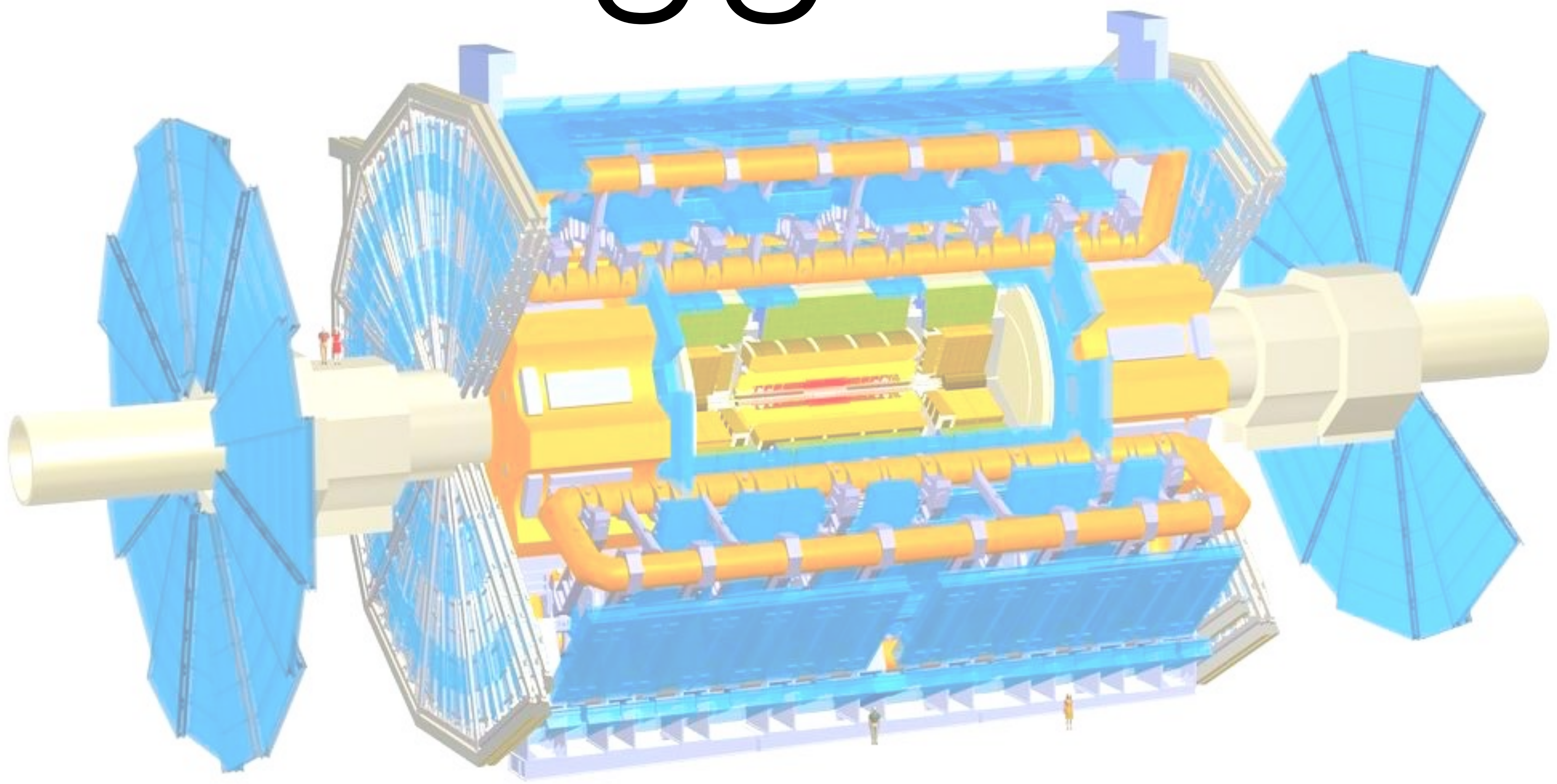
A Tale of Two Higgs — Search for di-Higgs to 4b in ATLAS



Tony(Baojia)Tong, Harvard University

Thesis defense, 2018.04.27

Search for di-Higgs to 4b in ATLAS

- **Chapter 1: Why search for it**
  - **Motivation, Theory, History**

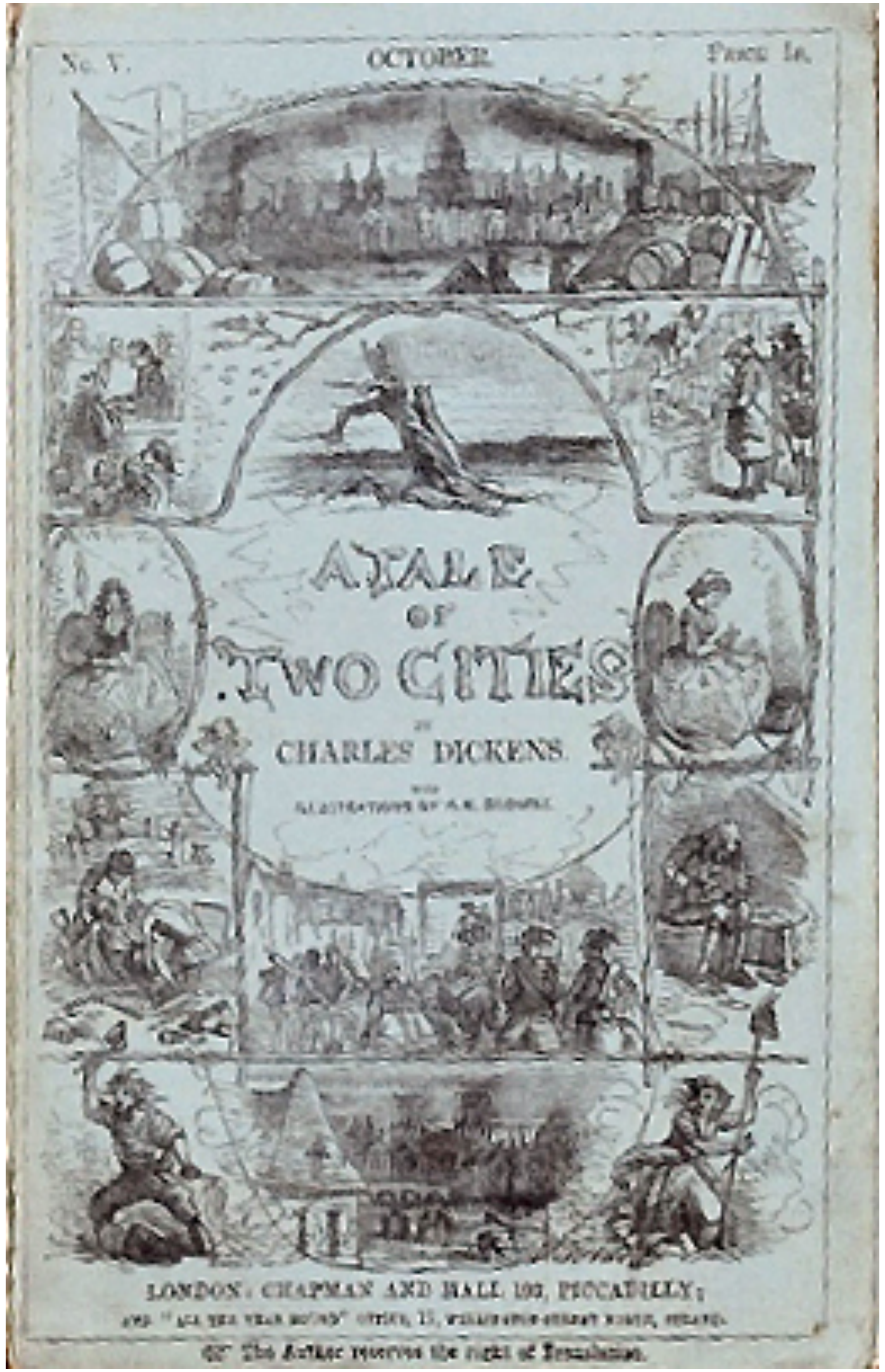
- Chapter 2: How to search
  - Selection, Optimization, Background estimation

- Chapter 3: Where we are
  - Results, Discussions, Future perspectives

After 2012…

- “It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness… it was the spring of hope, it was the winter of despair…”

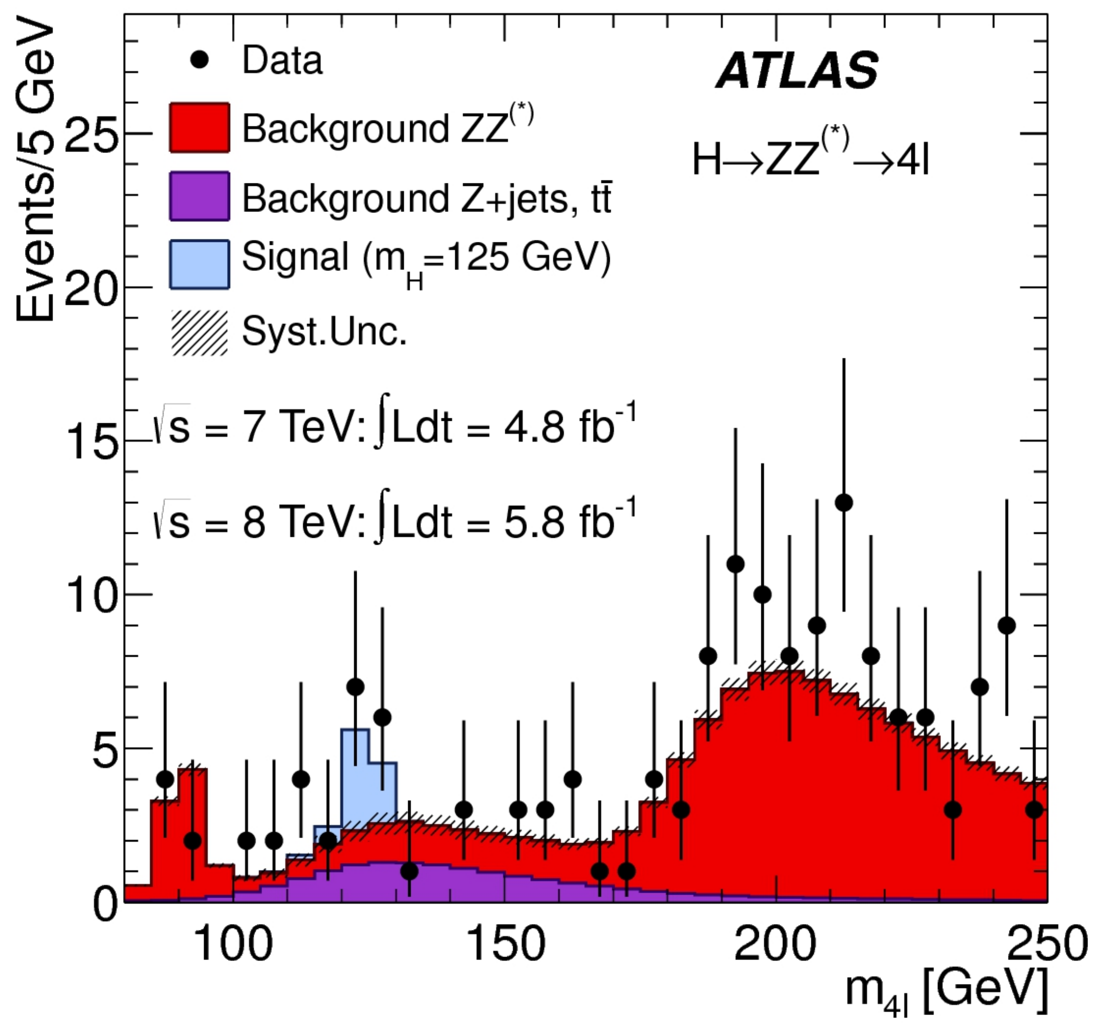
- — Charles Dickens, *A Tale of Two Cities*

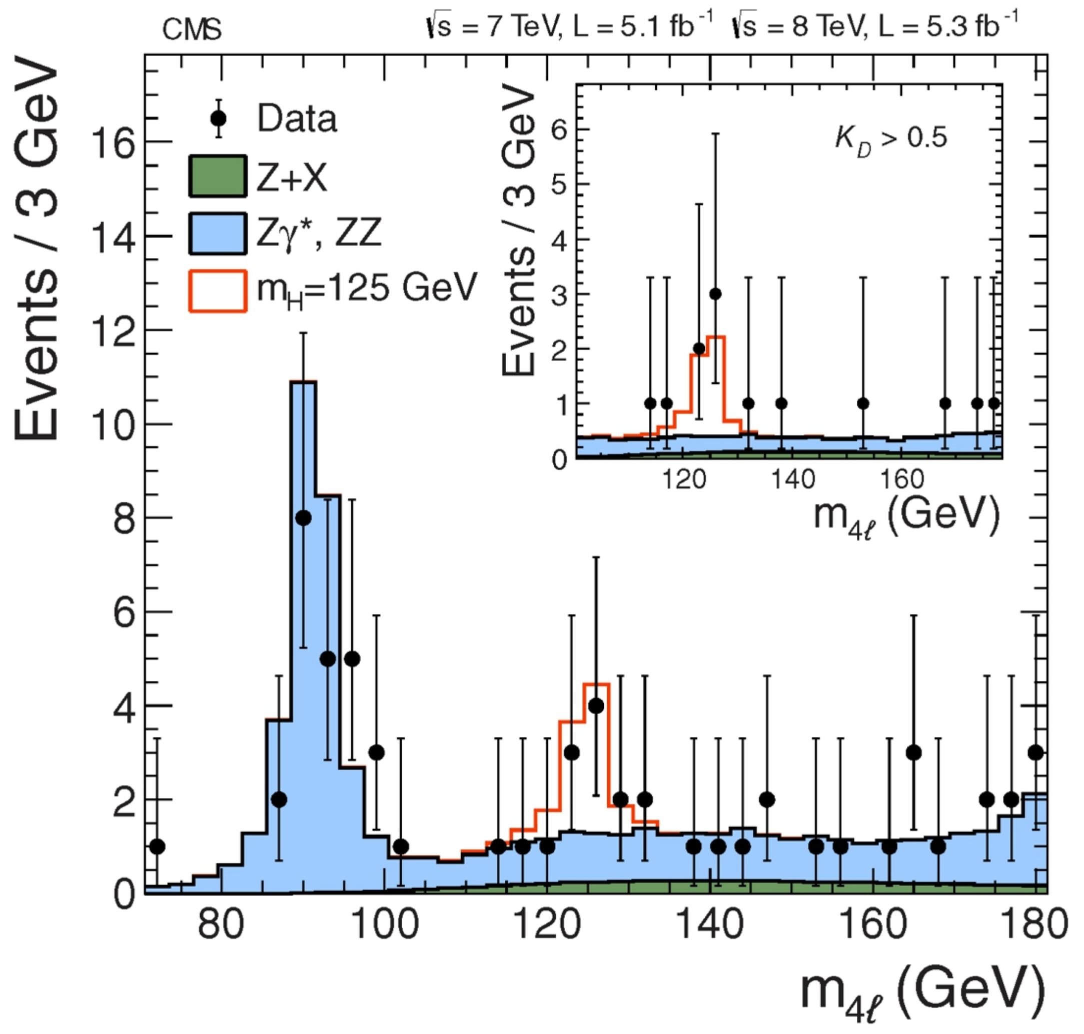


After 2012…

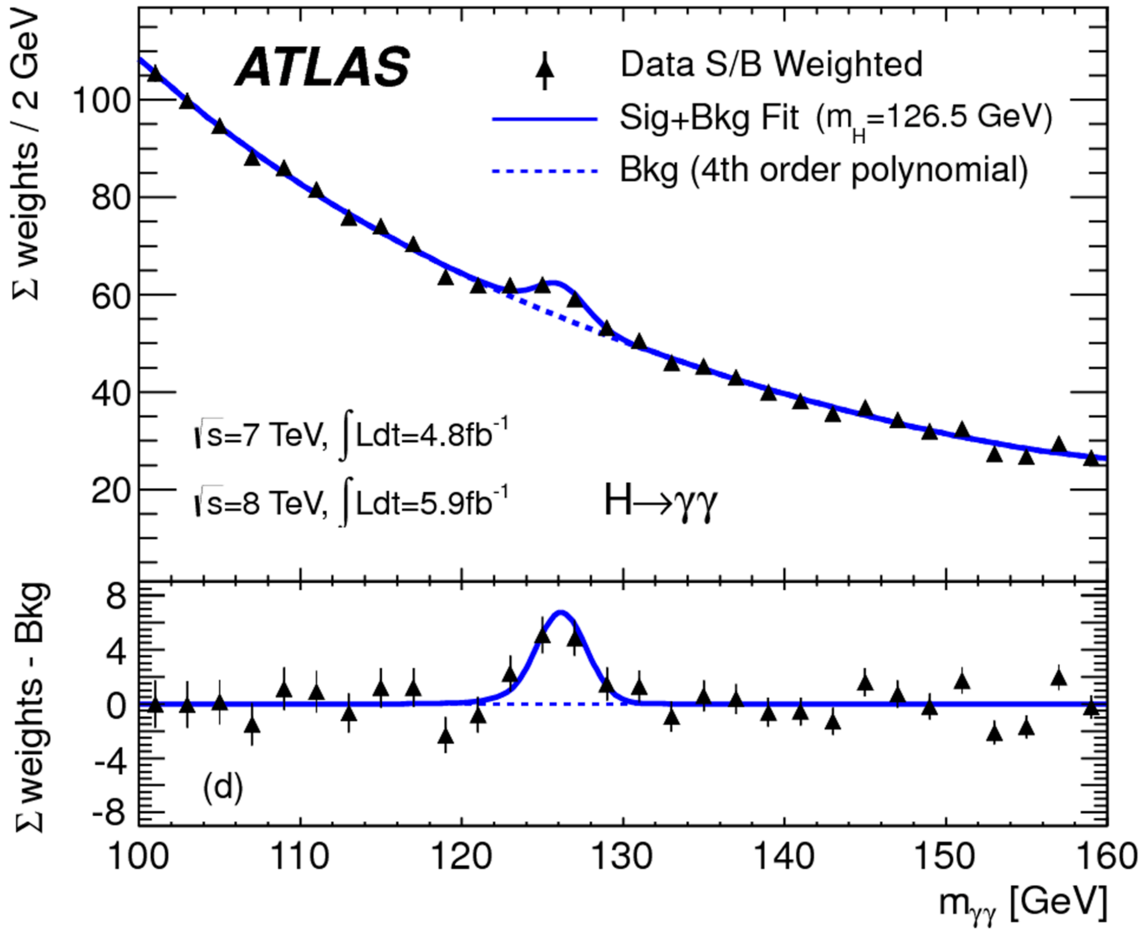
- "It was the **best of times**, it was the worst of times, it was the **age of wisdom**, it was the age of foolishness… it was **the spring of hope**, it was the winter of despair…"

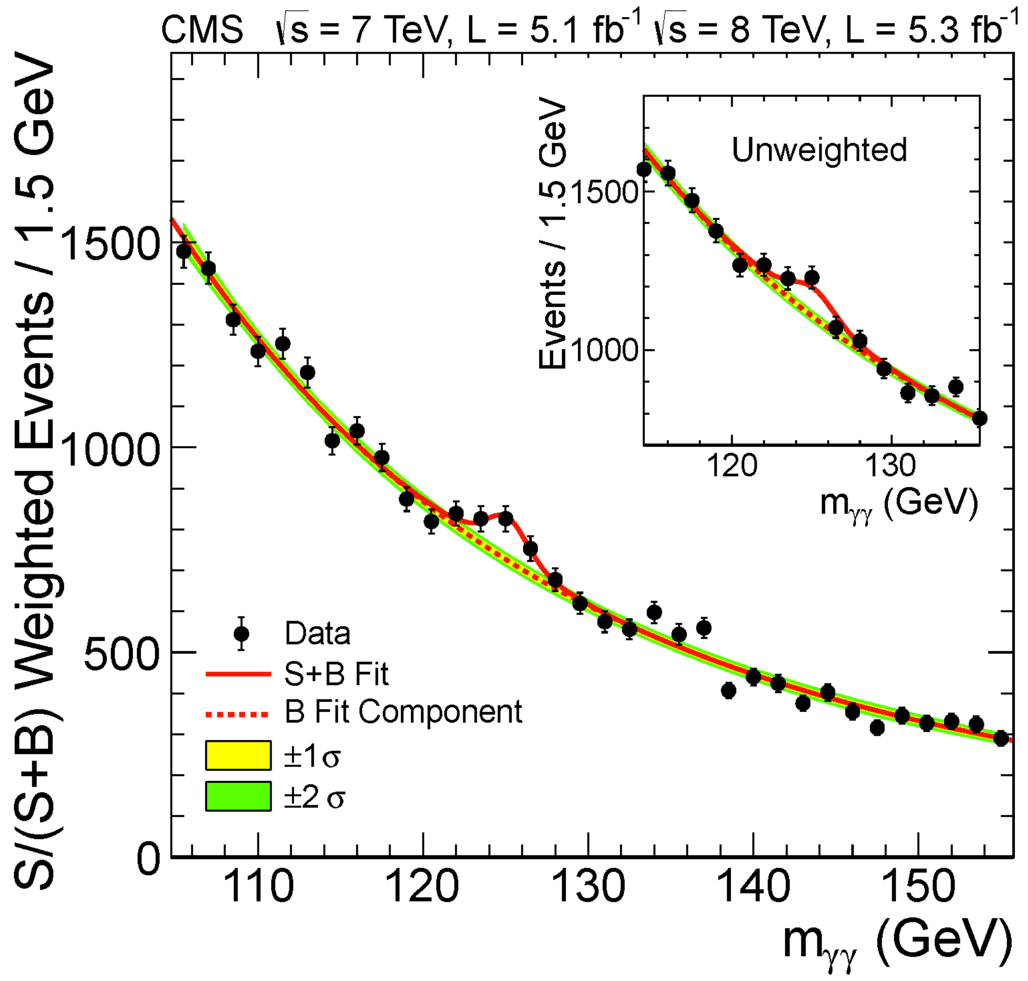
- It is also the time after the Higgs discovery!





[ATLAS](#), [CMS](#)





Higgs in SM

- Interaction with the Higgs field gives **mass** to fermions and vector bosons

- The Higgs scalar potential:

Mass λ_{hhh} λ_{4h}

$$-\frac{m_h^2 v^2}{8} + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

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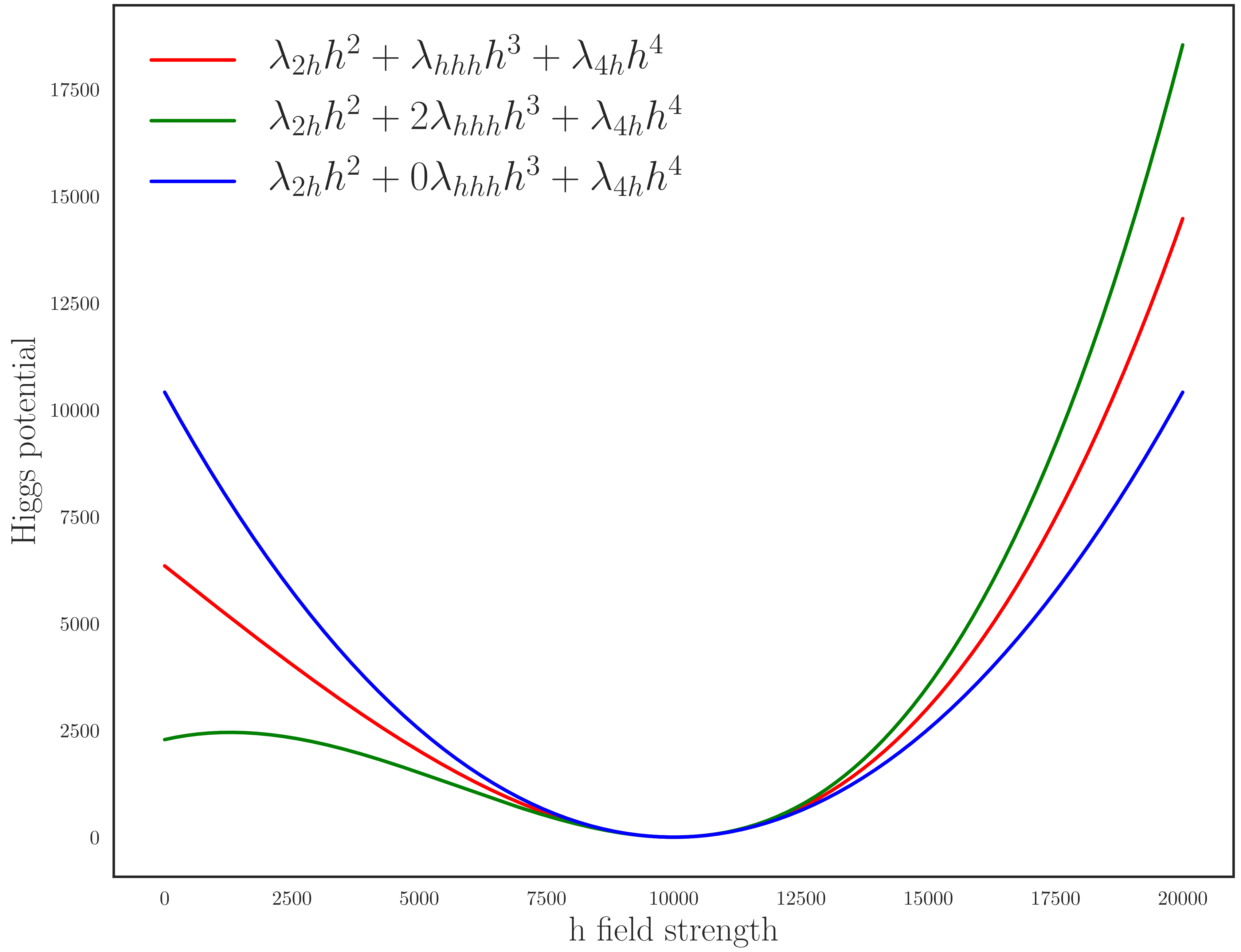
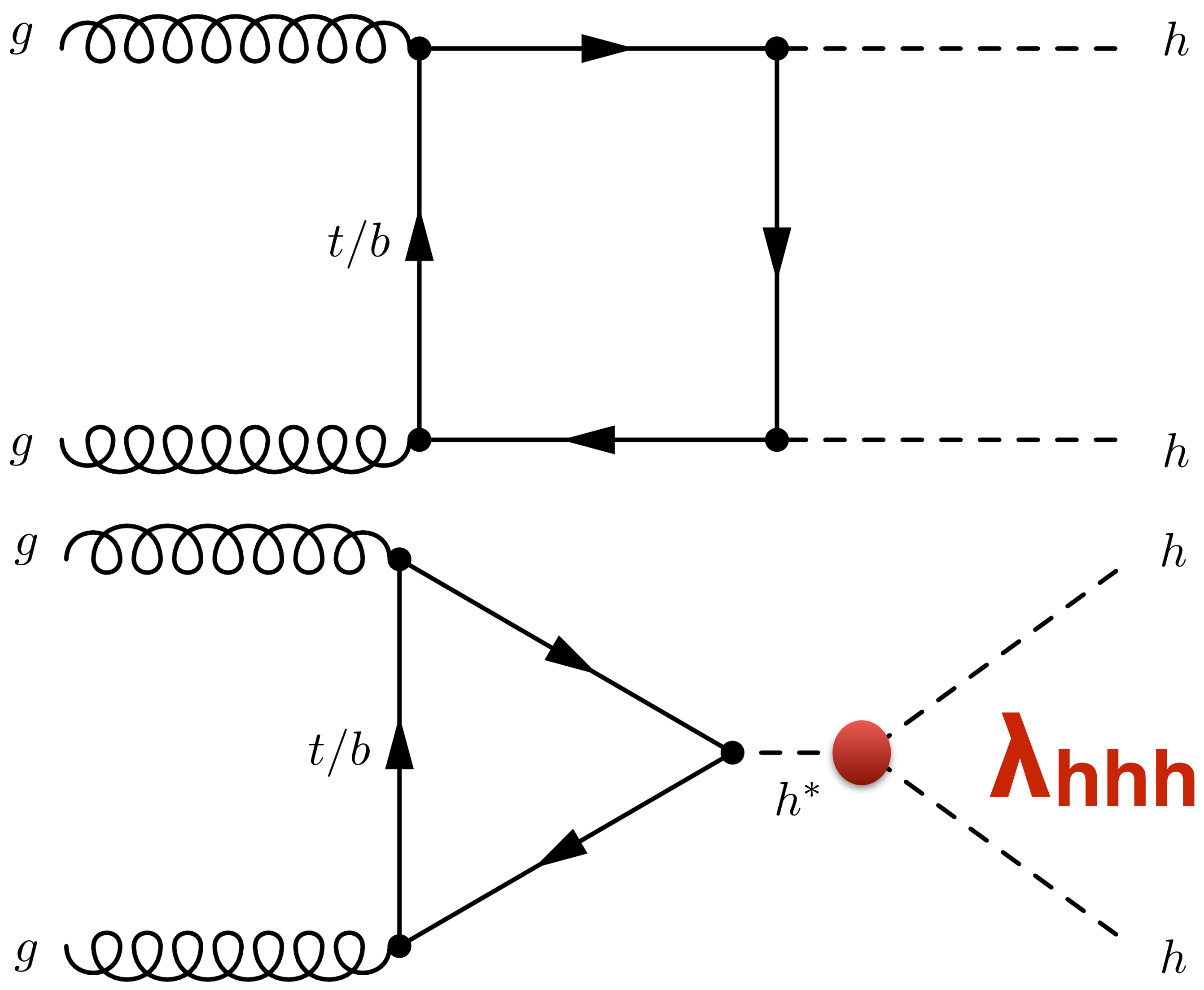
- The Higgs scalar potential:
- The $\boldsymbol{\lambda_{hhh}}$, or "Higgs self-coupling", reflects the **shape** of the Higgs potential
- $\boldsymbol{\lambda_{hhh}}$ term also contributes to di-Higgs production



Di-Higgs Cross Section

- Two diagrams:
  destructive interference



- Small cross section ~ at 13 TeV:
  34 fb (NNLO + NNLL) arxiv 1604.06447

Di-Higgs Cross Section

- Two diagrams:
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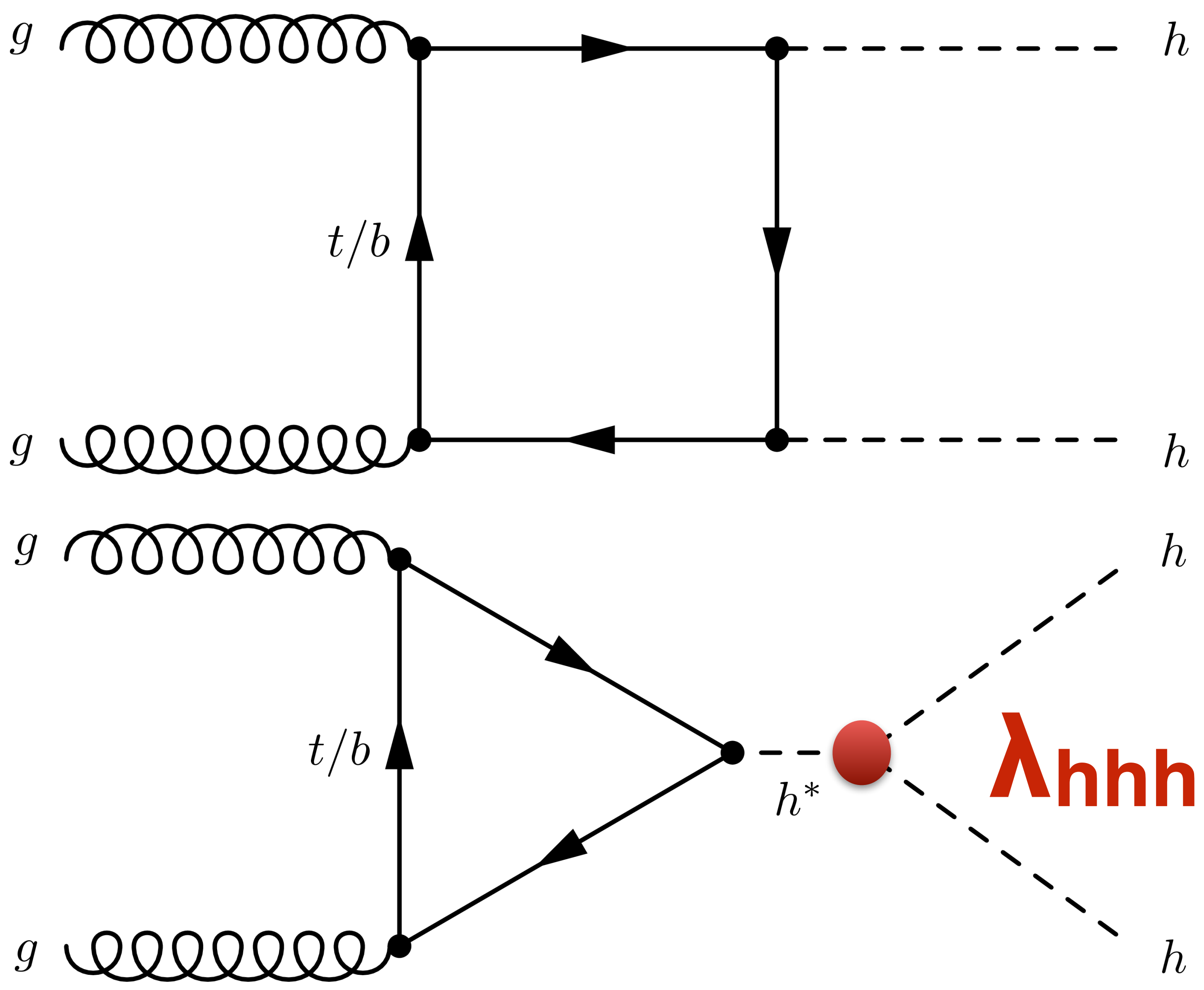

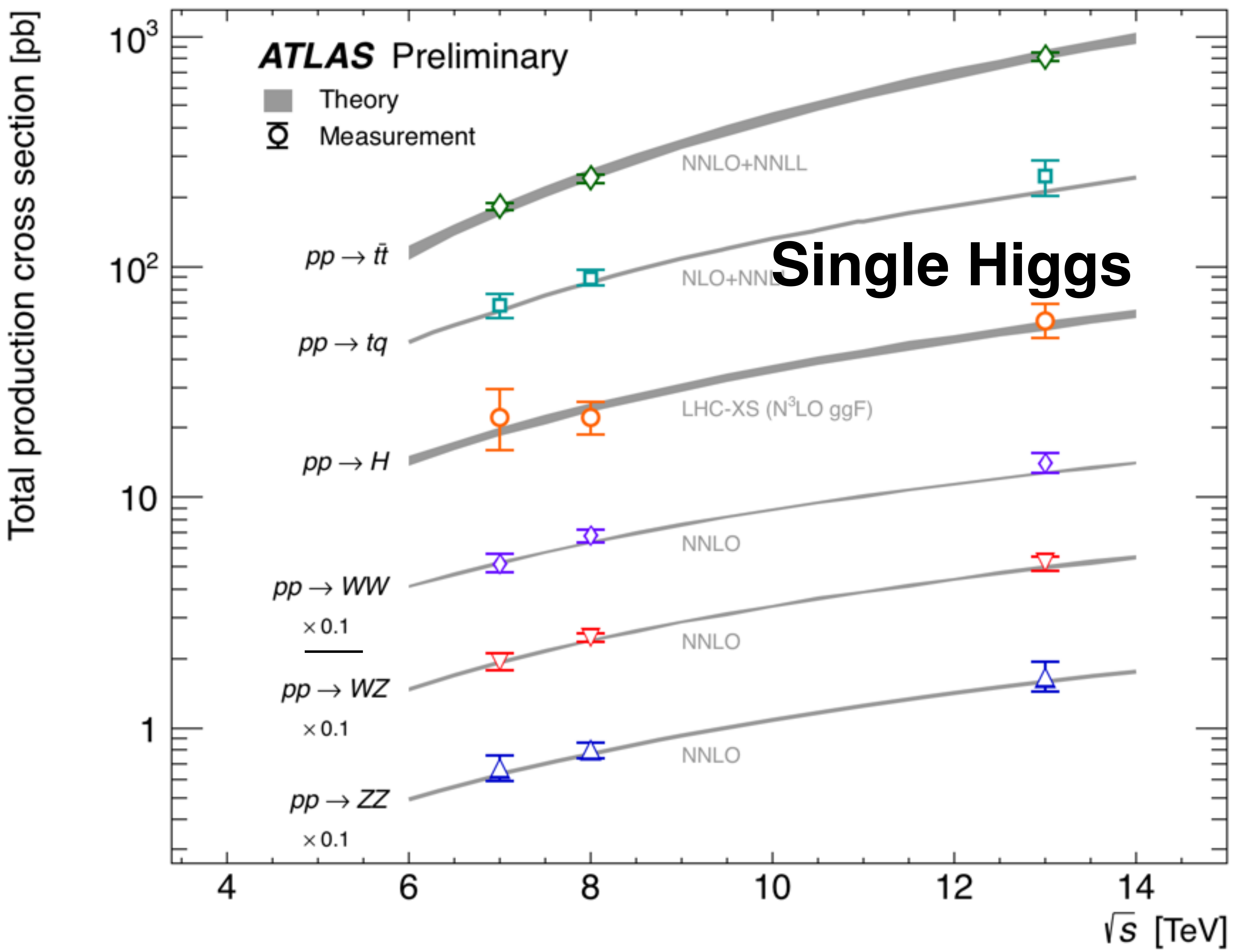

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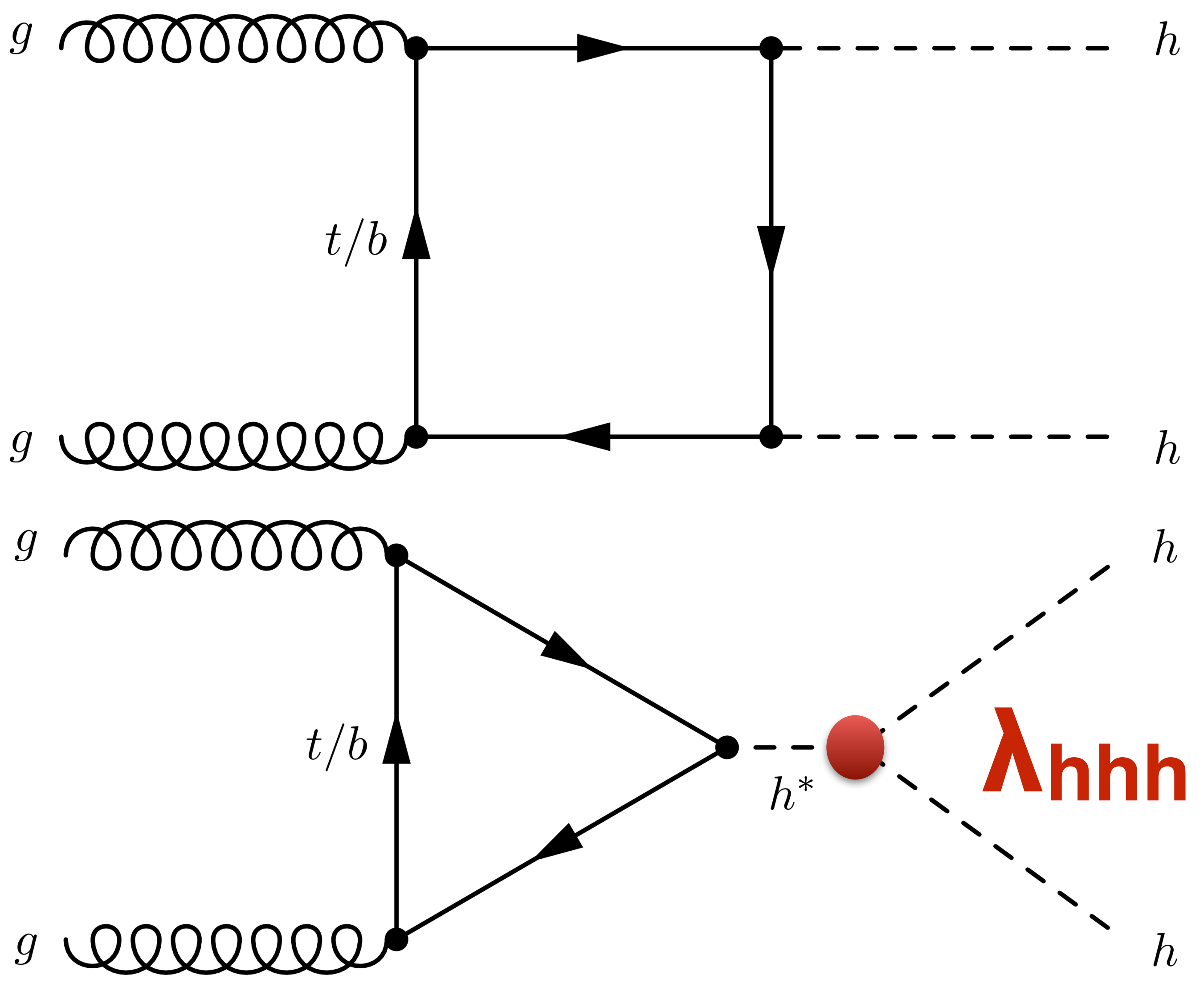
SM cross section as a function of energy

Di-Higgs Cross Section

- Two diagrams: destructive interference



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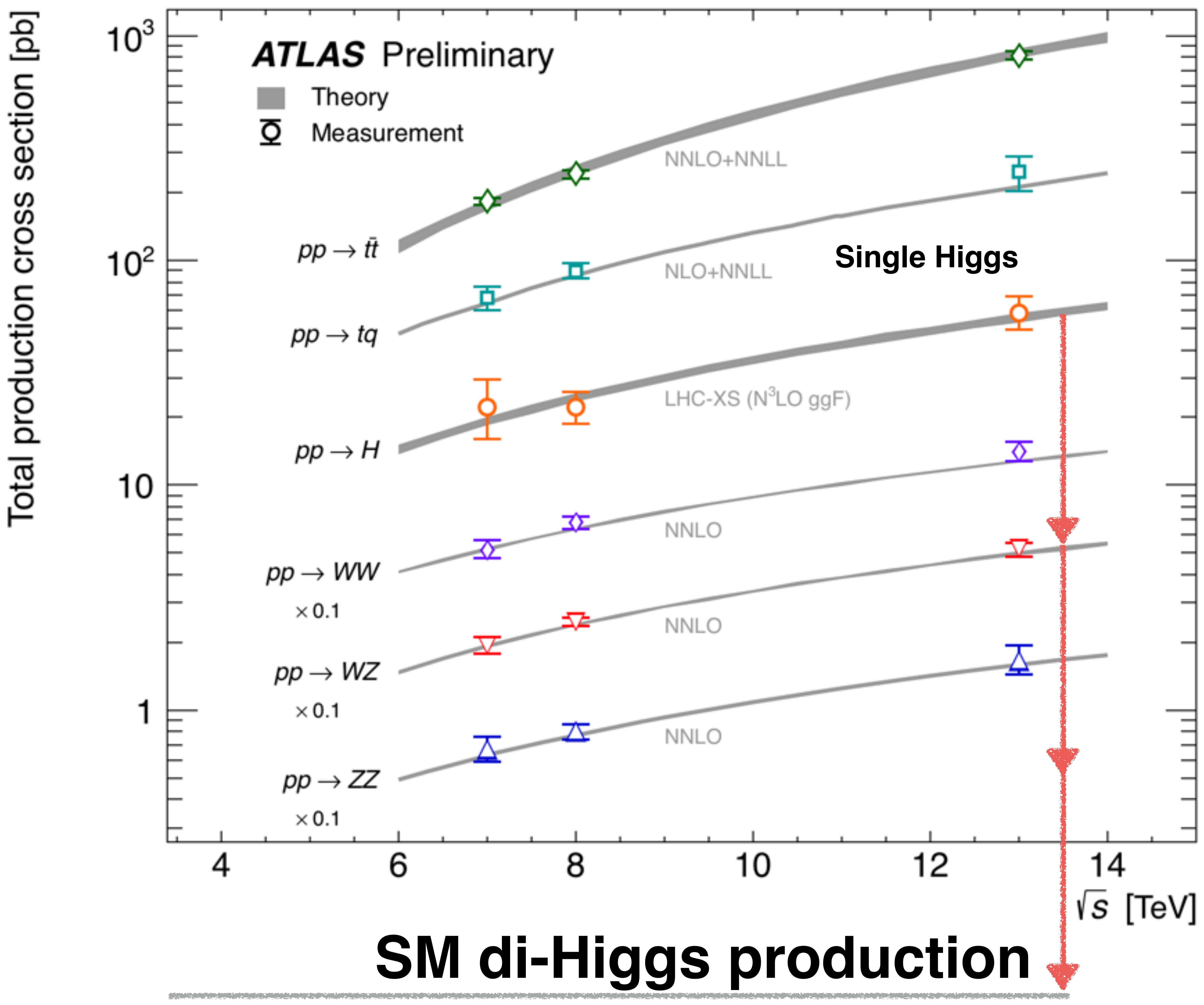
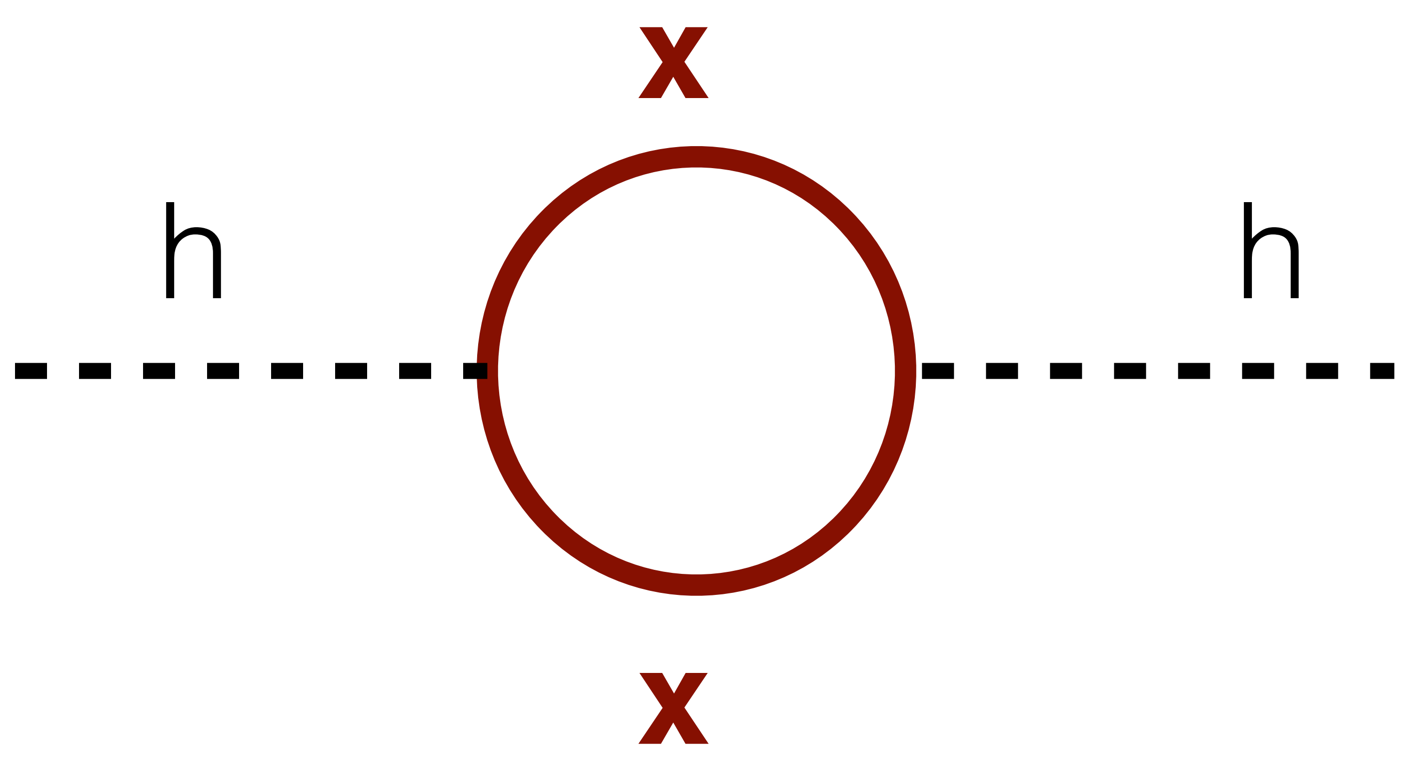


Reachable at HL-LHC, but why now?

Di-Higgs in BSM

- We think Beyond Standard Model Physics exists: gravity, dark matter…
- If BSM physics interacts with the standard model particles, then they are very likely to have direct/indirect coupling to the Higgs



Di-Higgs in BSM

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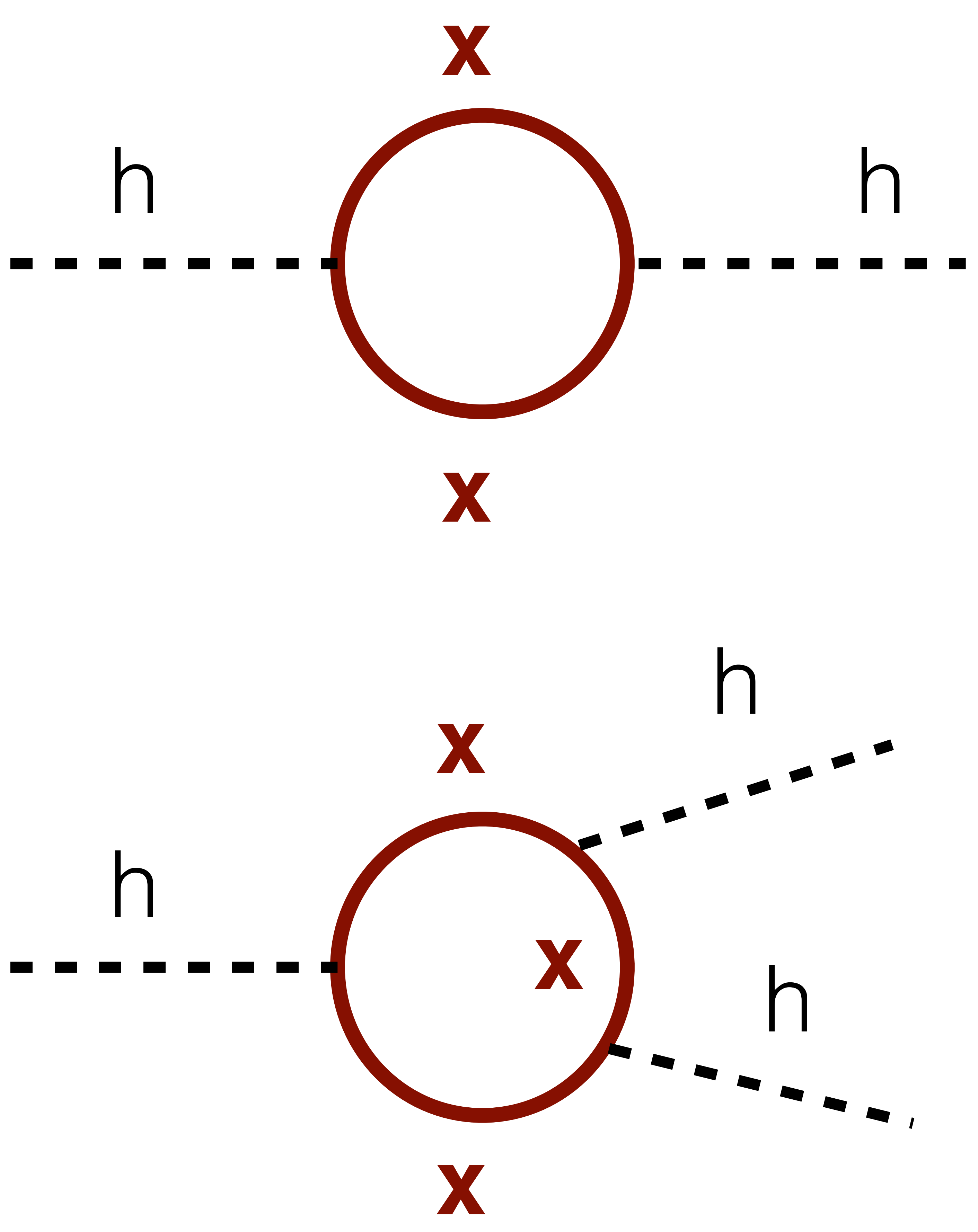
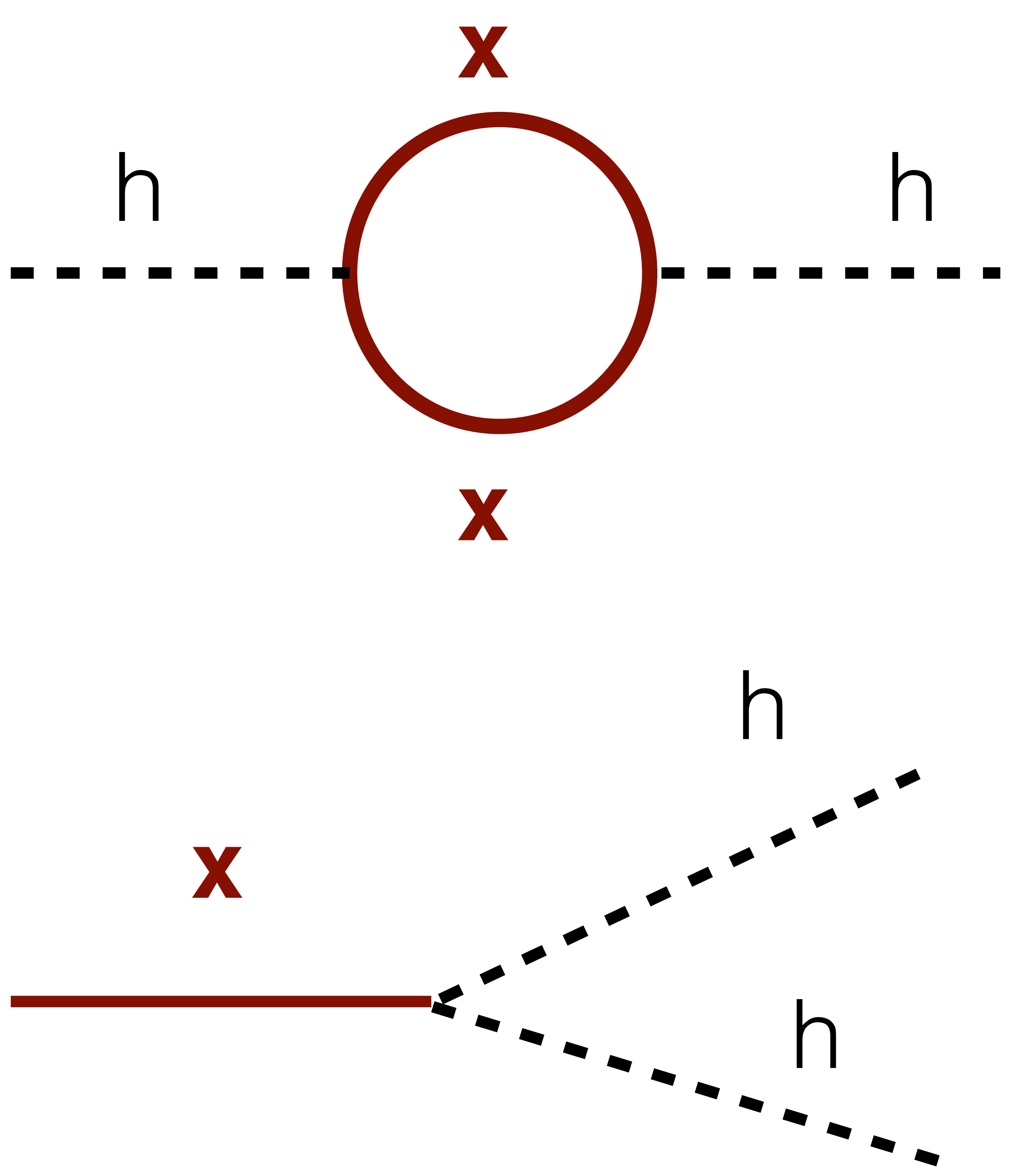
- If BSM physics interacts with the standard model particles, then they are very likely to have direct/indirect coupling to the Higgs
- Moreover, if BSM physics affects the Higgs mass through loops, they are also very likely to **modify λ_{hhh}**



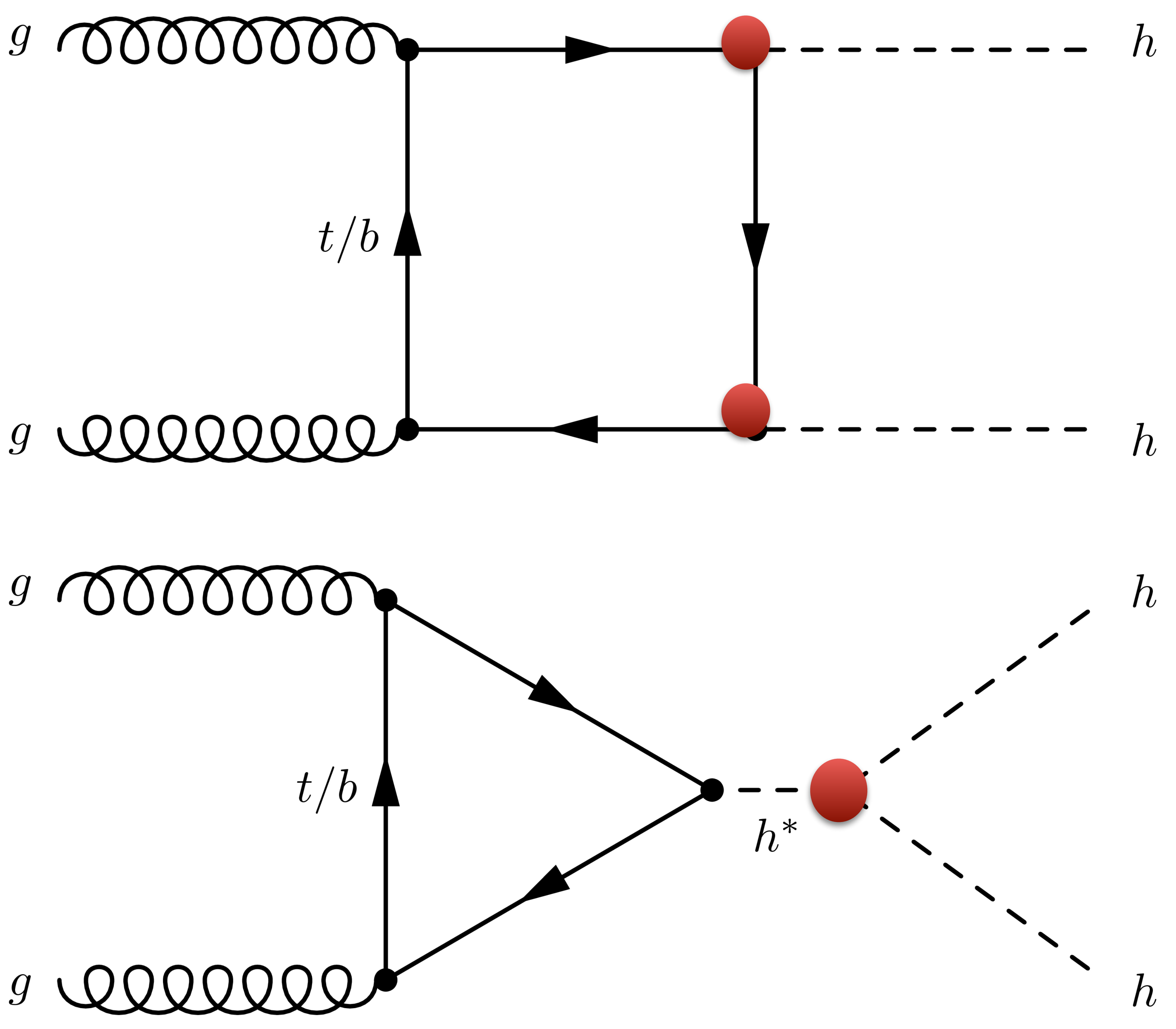
Di-Higgs in BSM

- We think Beyond Standard Model Physics exists: gravity, dark matter…
- If BSM physics interacts with the standard model particles, then they are very likely to have direct/indirect coupling to the Higgs
- Also, if BSM physics particles are heavy, they can **directly decay to di-Higgs**



Di-Higgs in BSM

- BSM could significantly enhance di-Higgs
  - **Non-resonant** signals
    - tthh, tth vertex modifications
    - Modified λ_{hhh}



Di-Higgs in BSM

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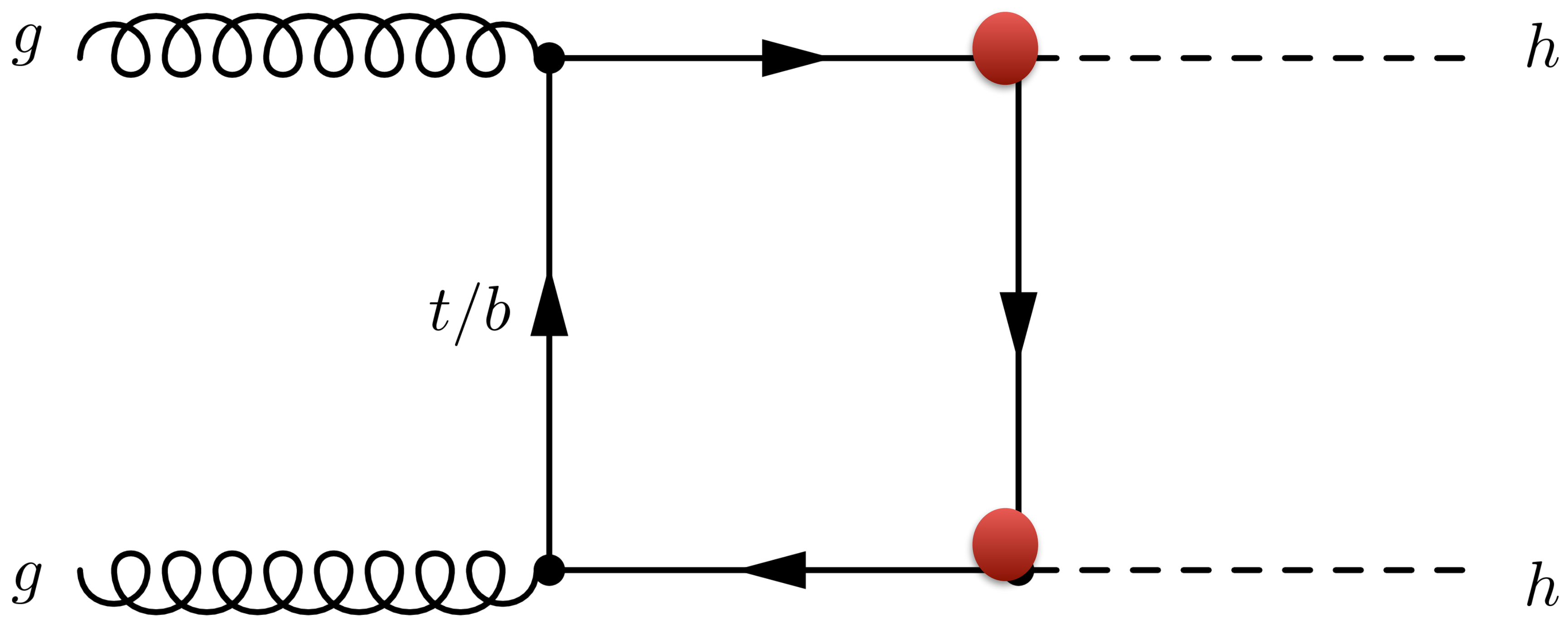
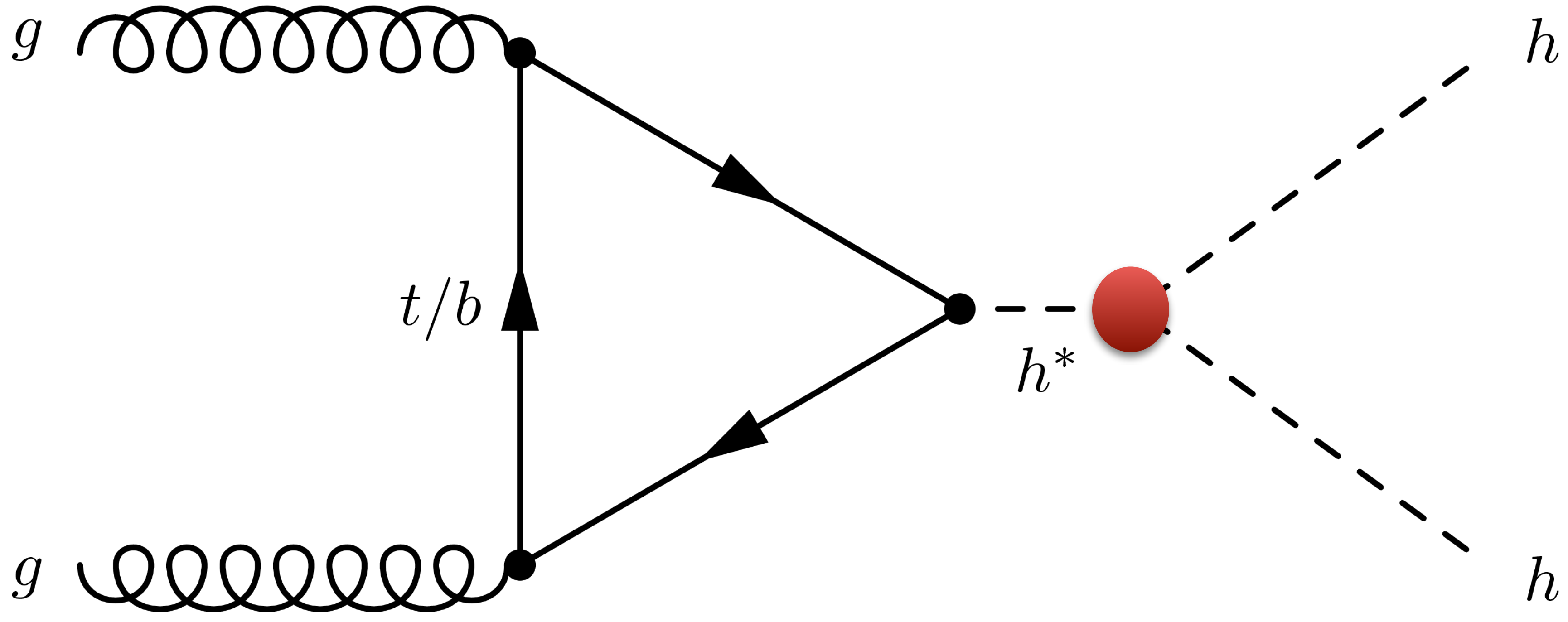
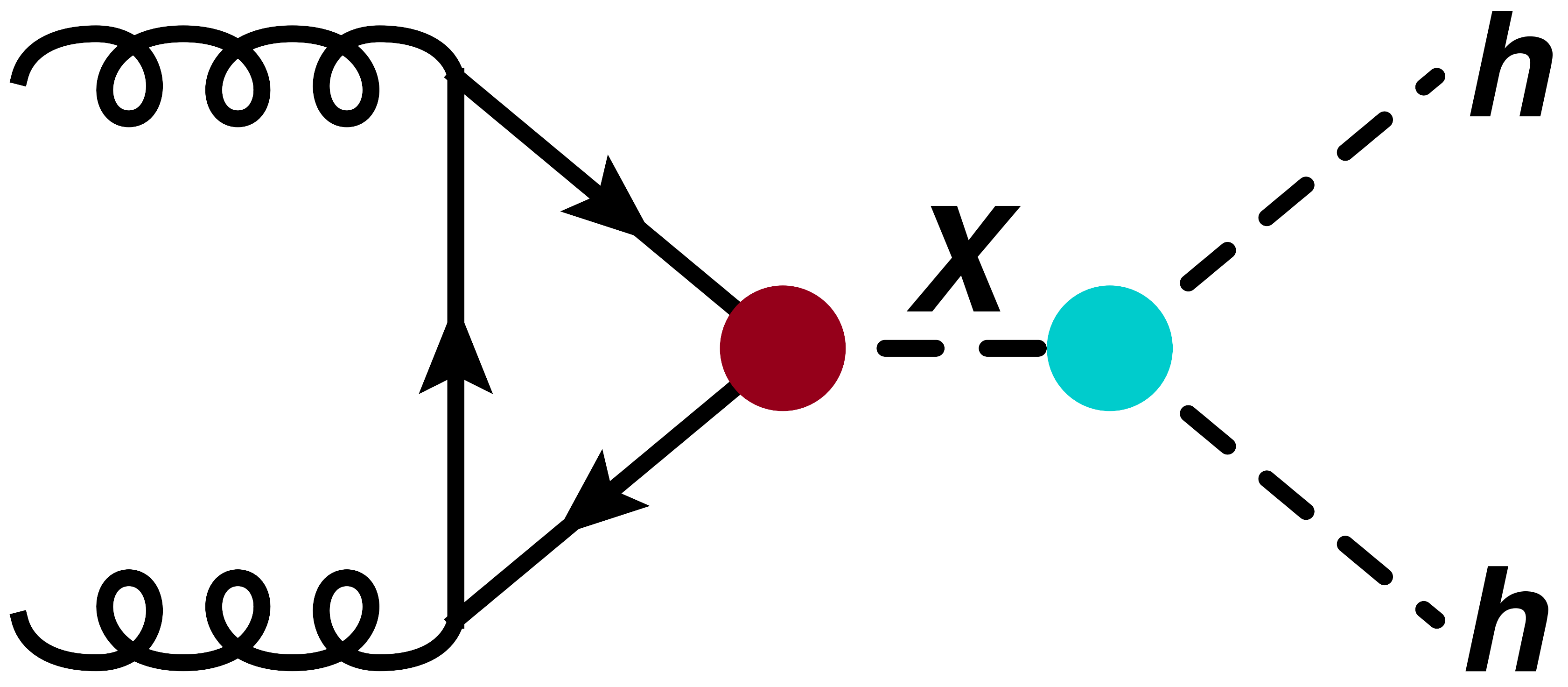
  - **Resonant** signals
    - KK Graviton (spin 2)
    - Heavy Higgs: 2HDM (spin 0)







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    - Modified λ_{hhh}
  - **Resonant** signals
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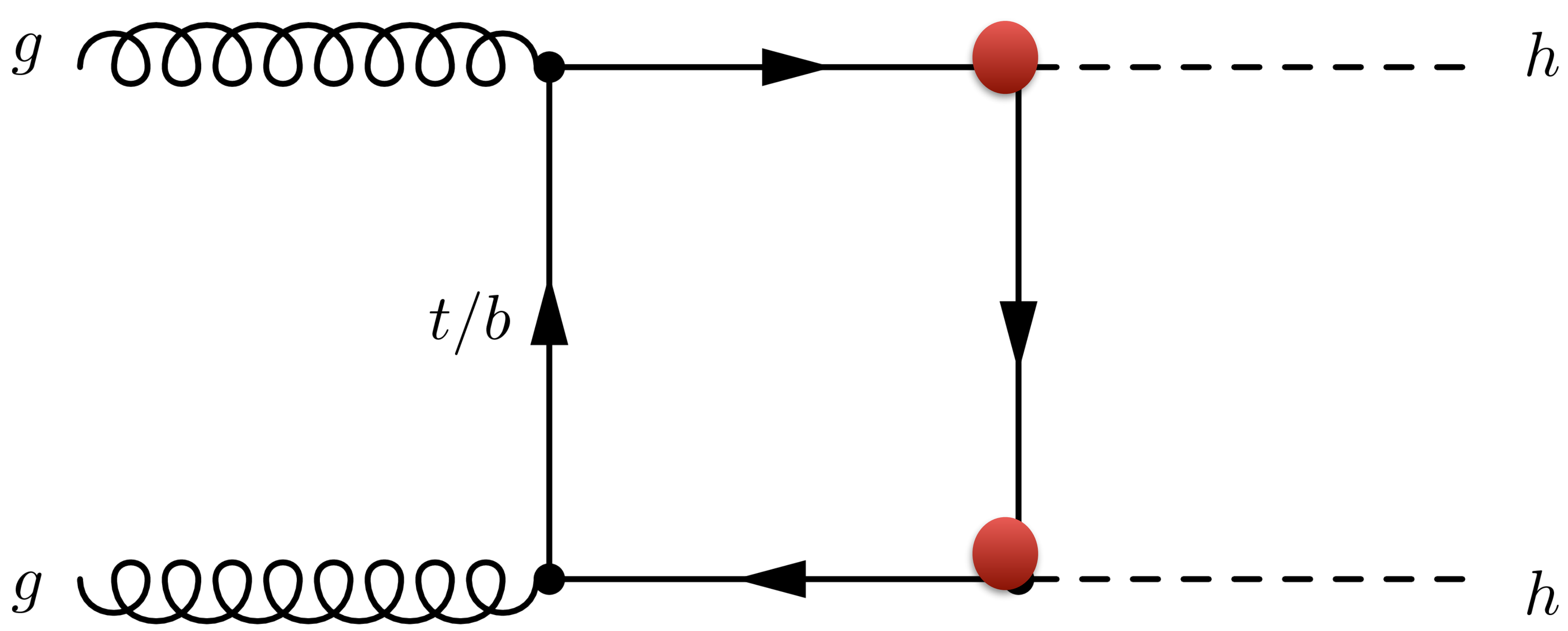
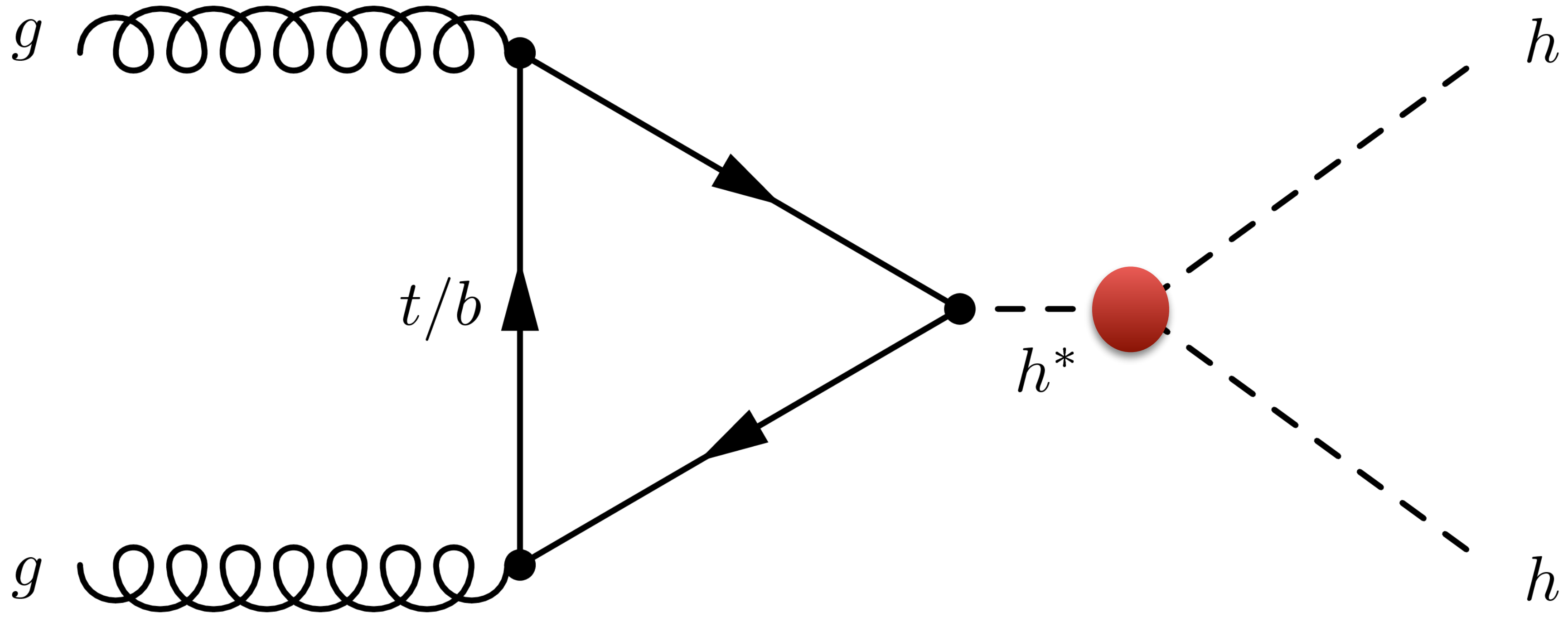
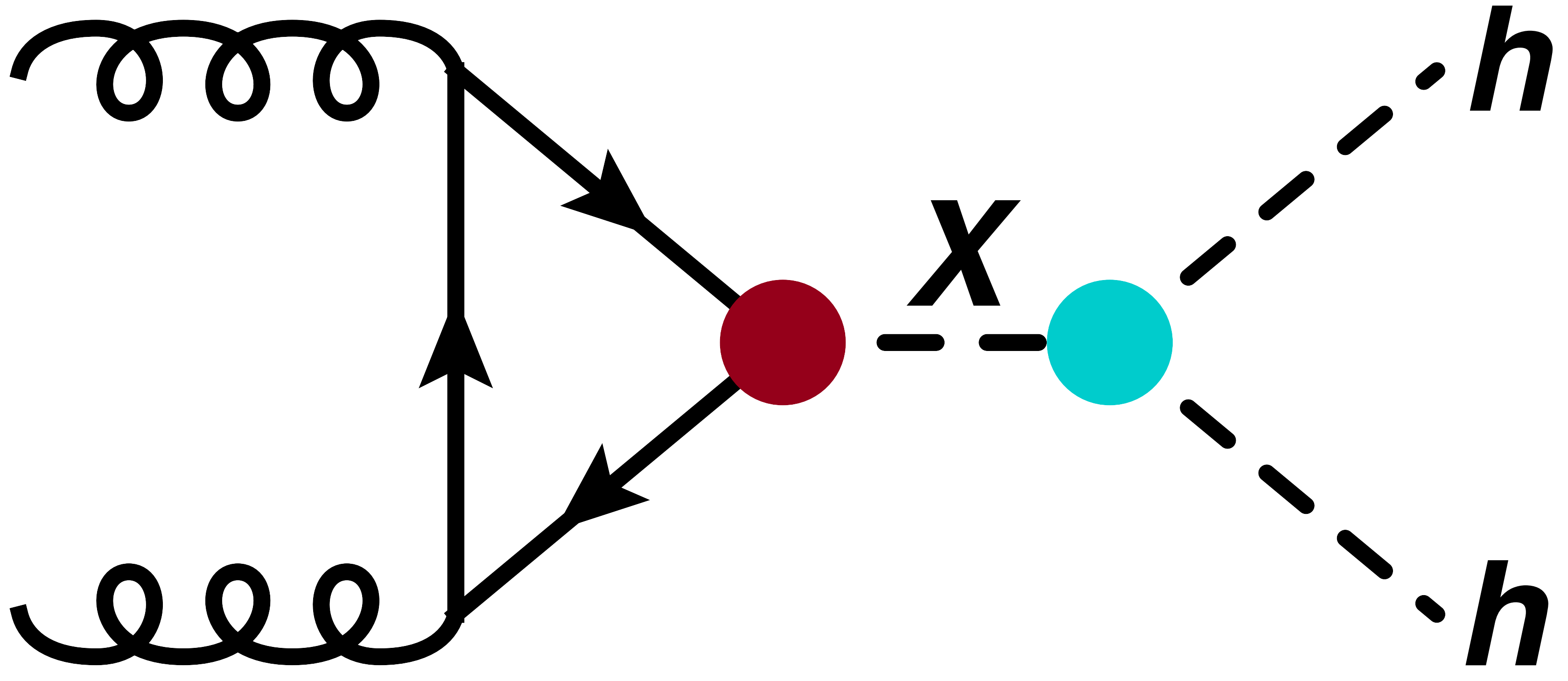
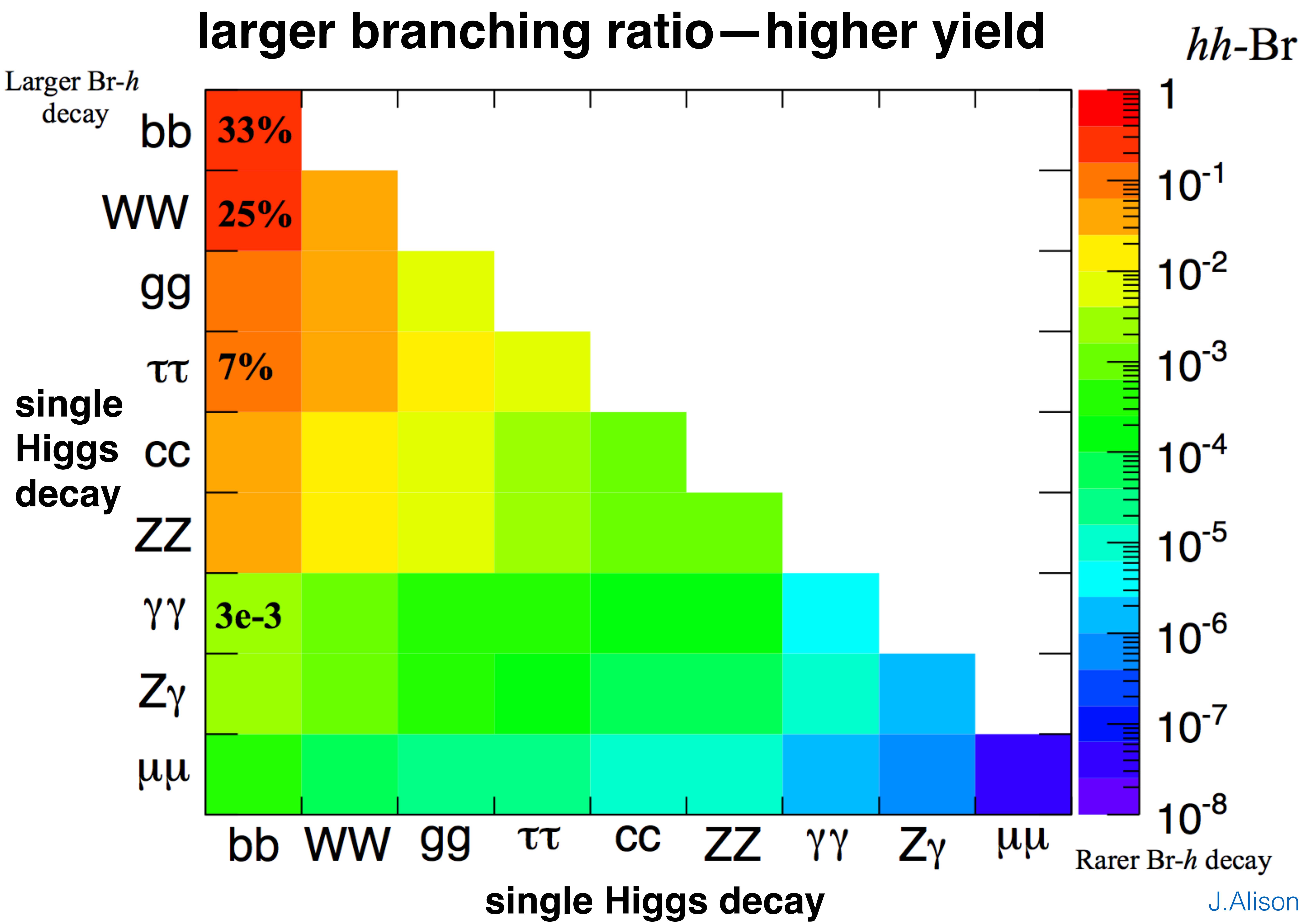
    - Heavy Higgs: 2HDM (spin 0)
- Can be **sensitive** at 13 TeV!
  - 2 TeV signal cross section increases by a factor of **10** from 8 to 13 TeV







Di-Higgs decay



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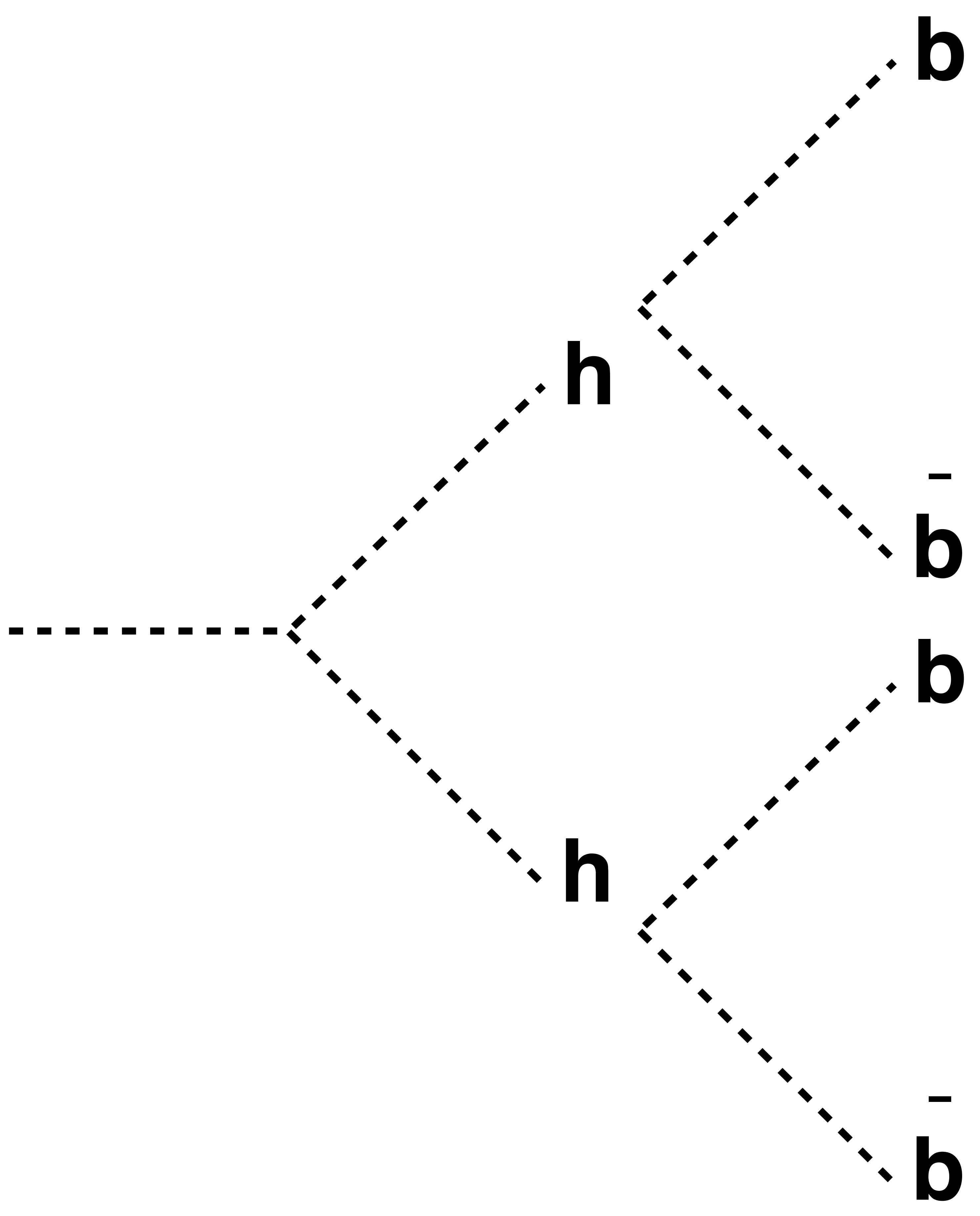
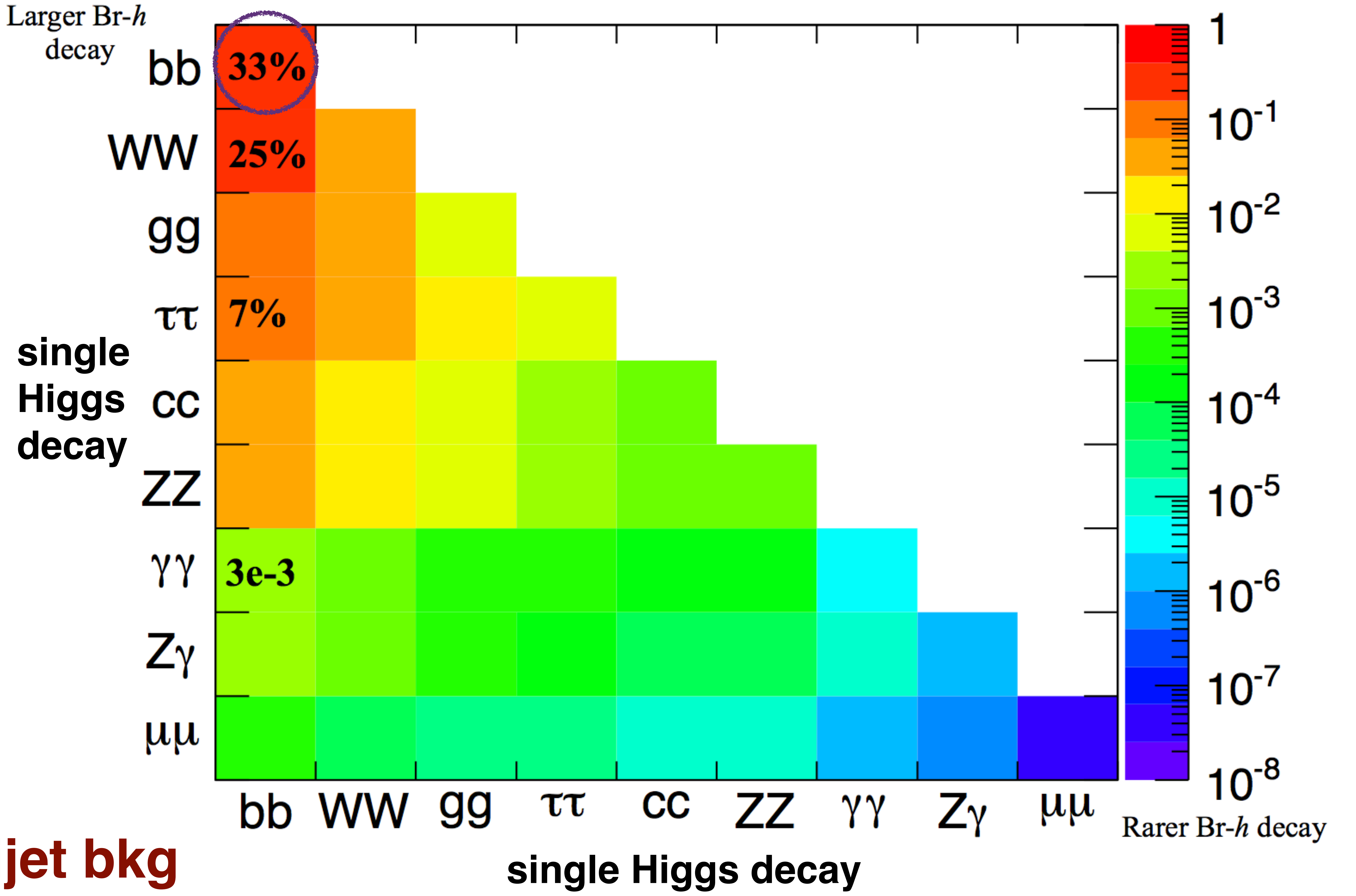
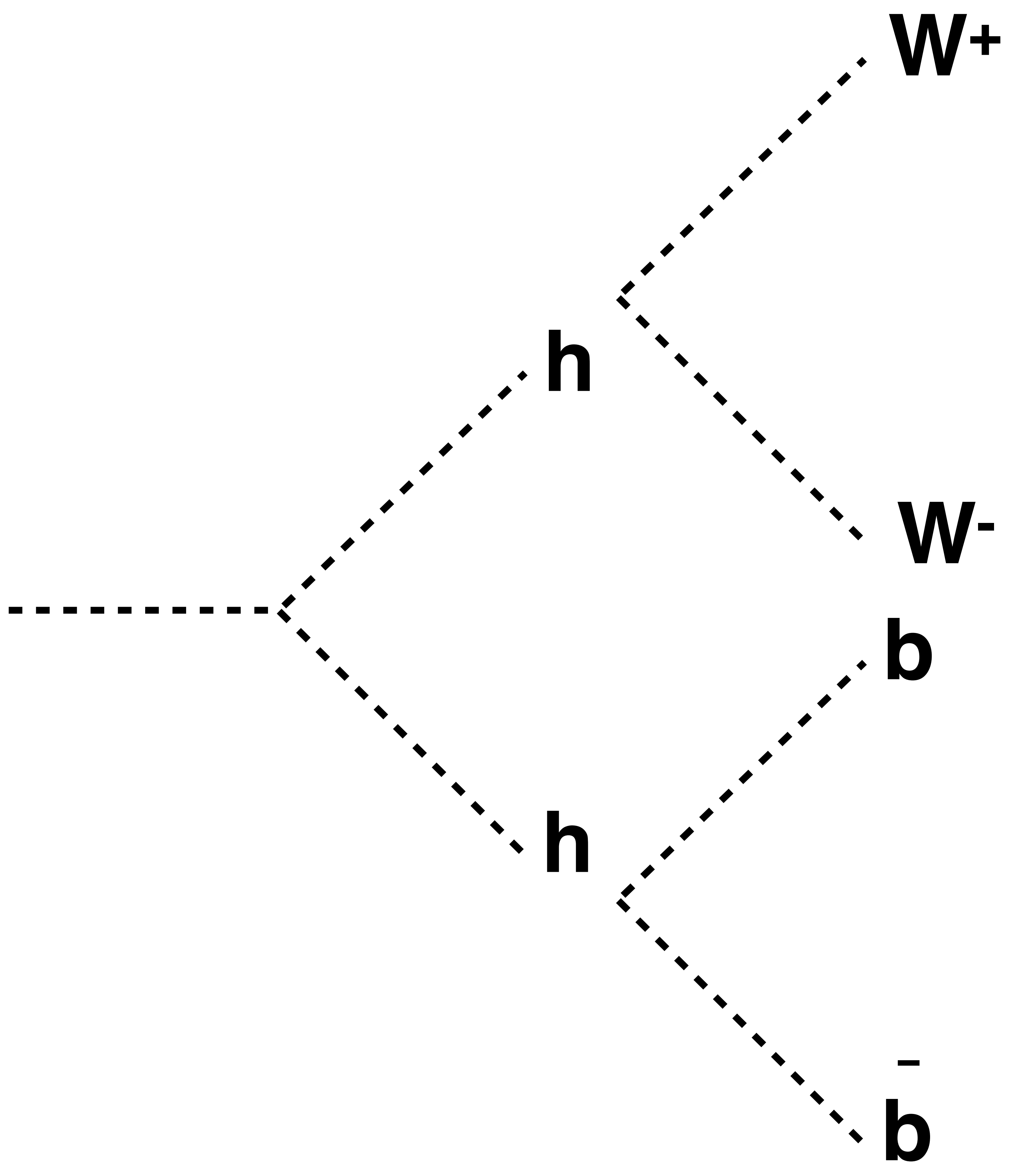


larger branching ratio—higher yield



Largest yield, large multijet bkg

Di-Higgs decay



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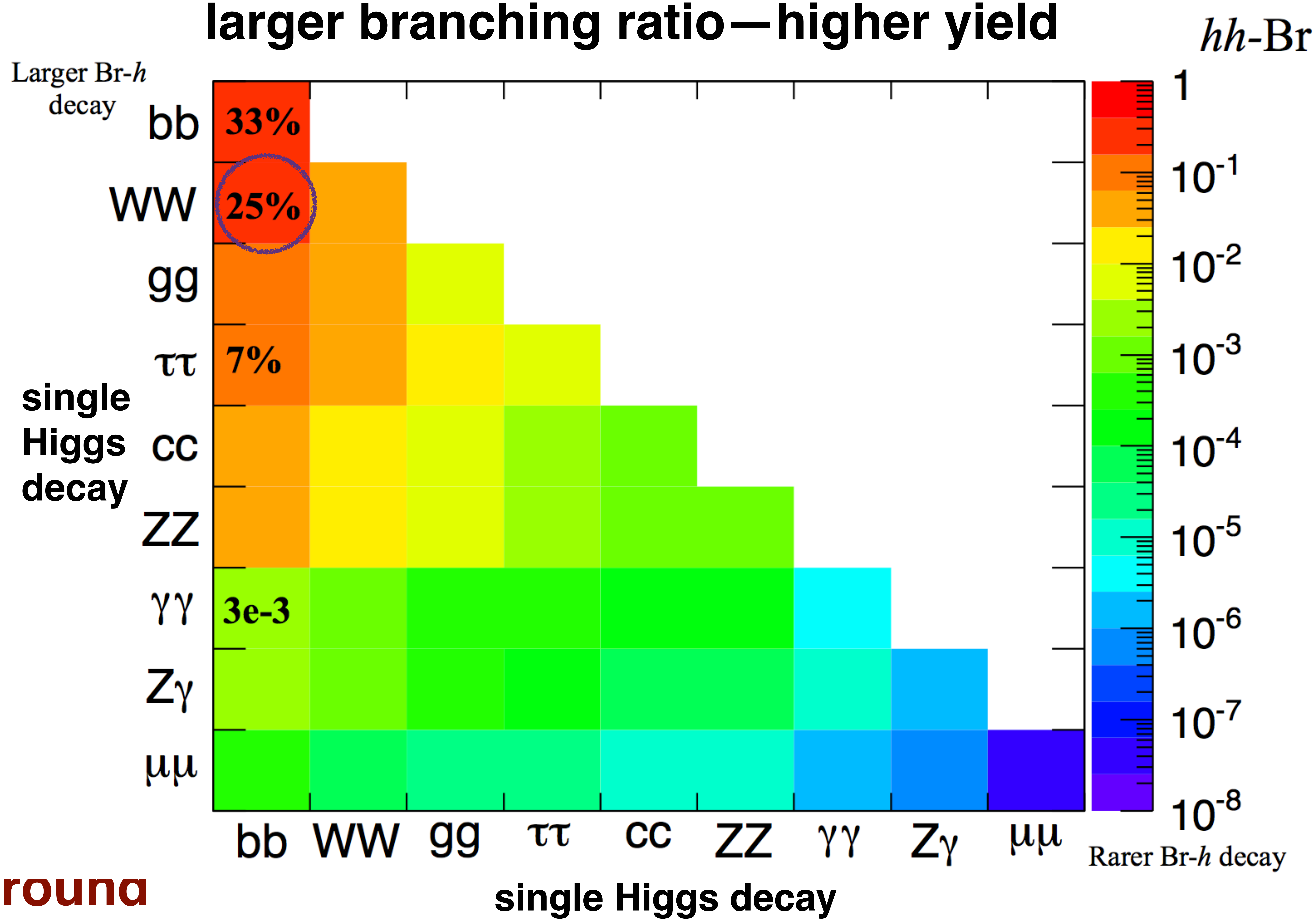
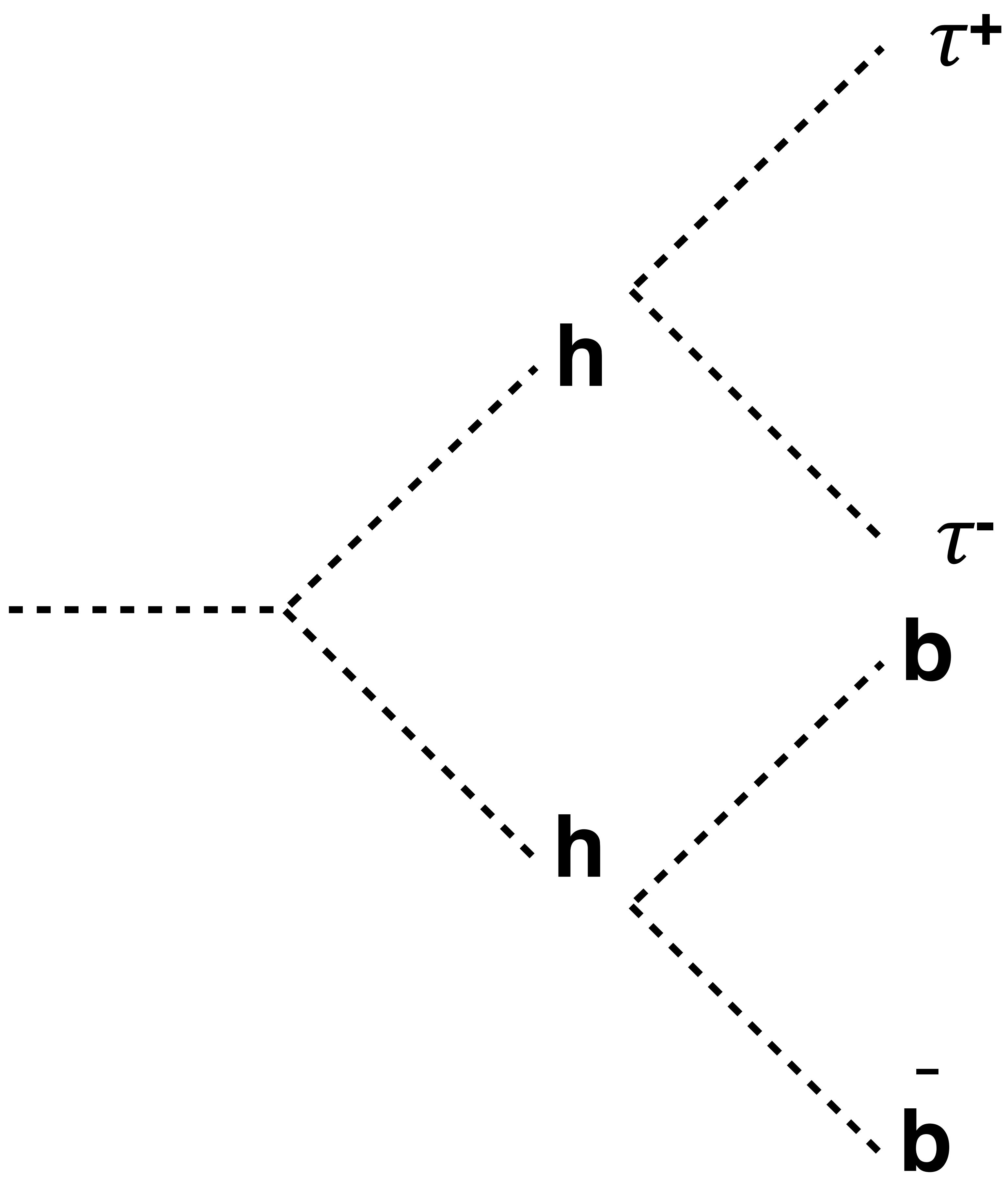


Large yield, ttbar background

Di-Higgs decay



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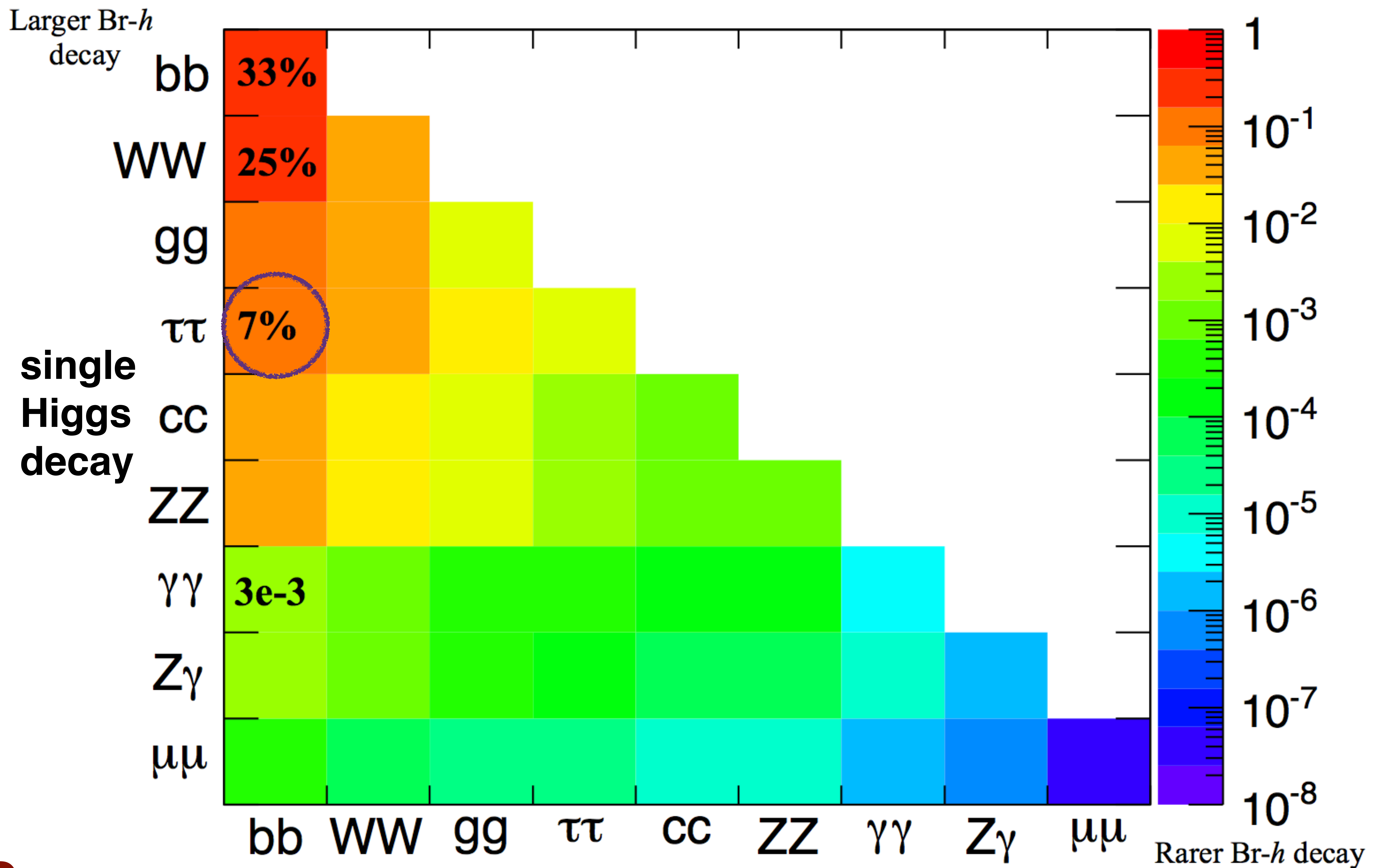
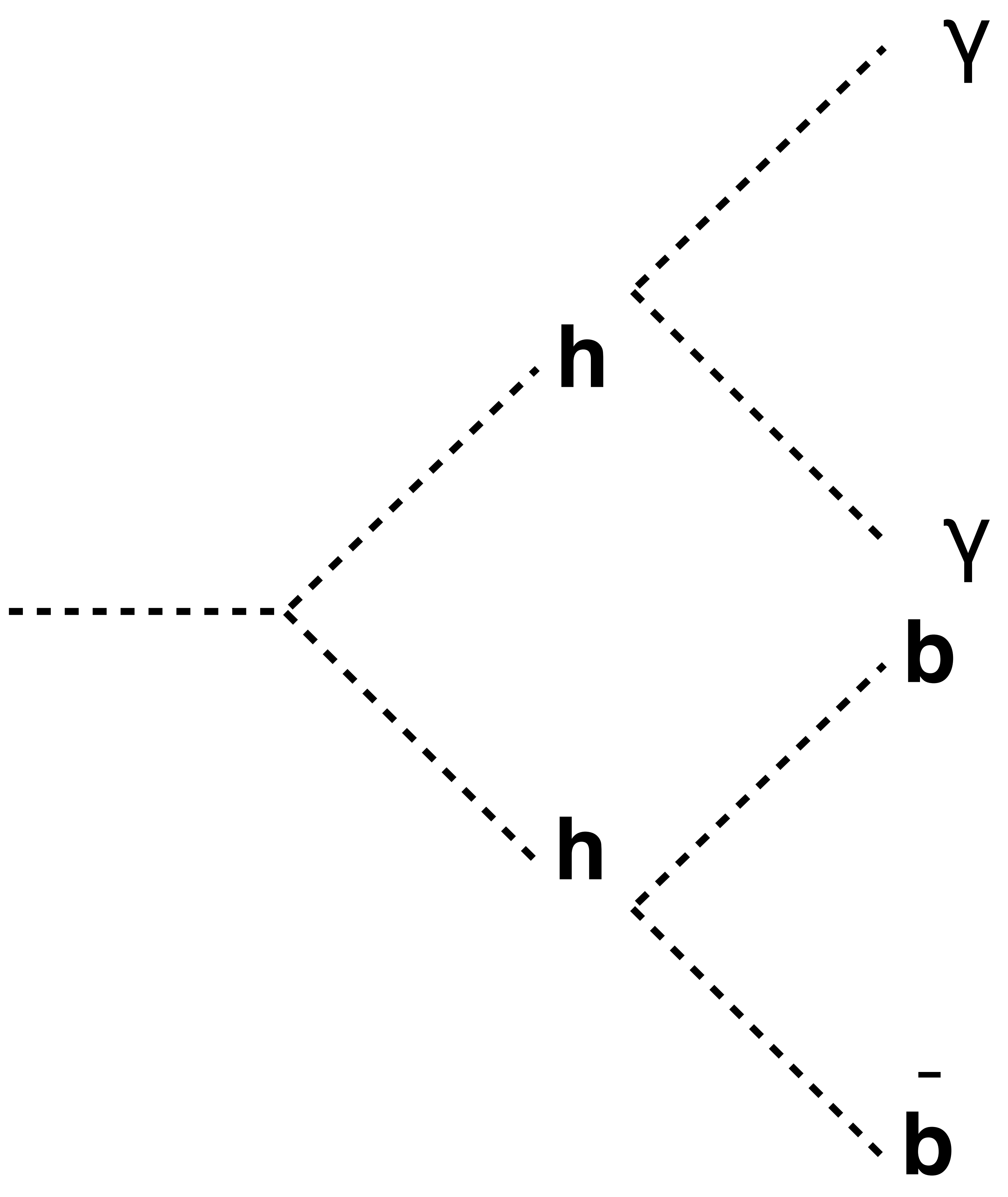


Good yield, hard τ ID

Di-Higgs decay



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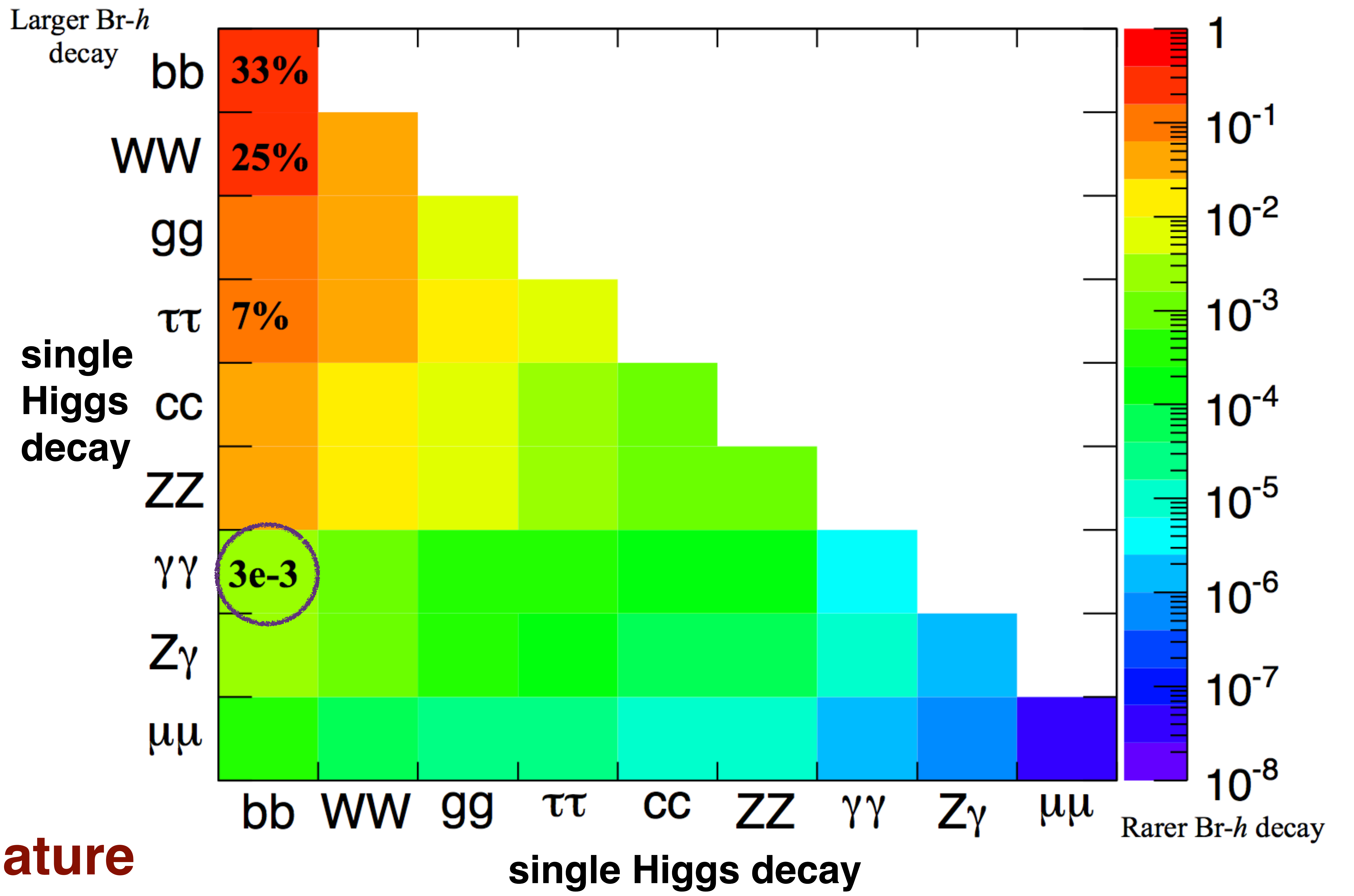
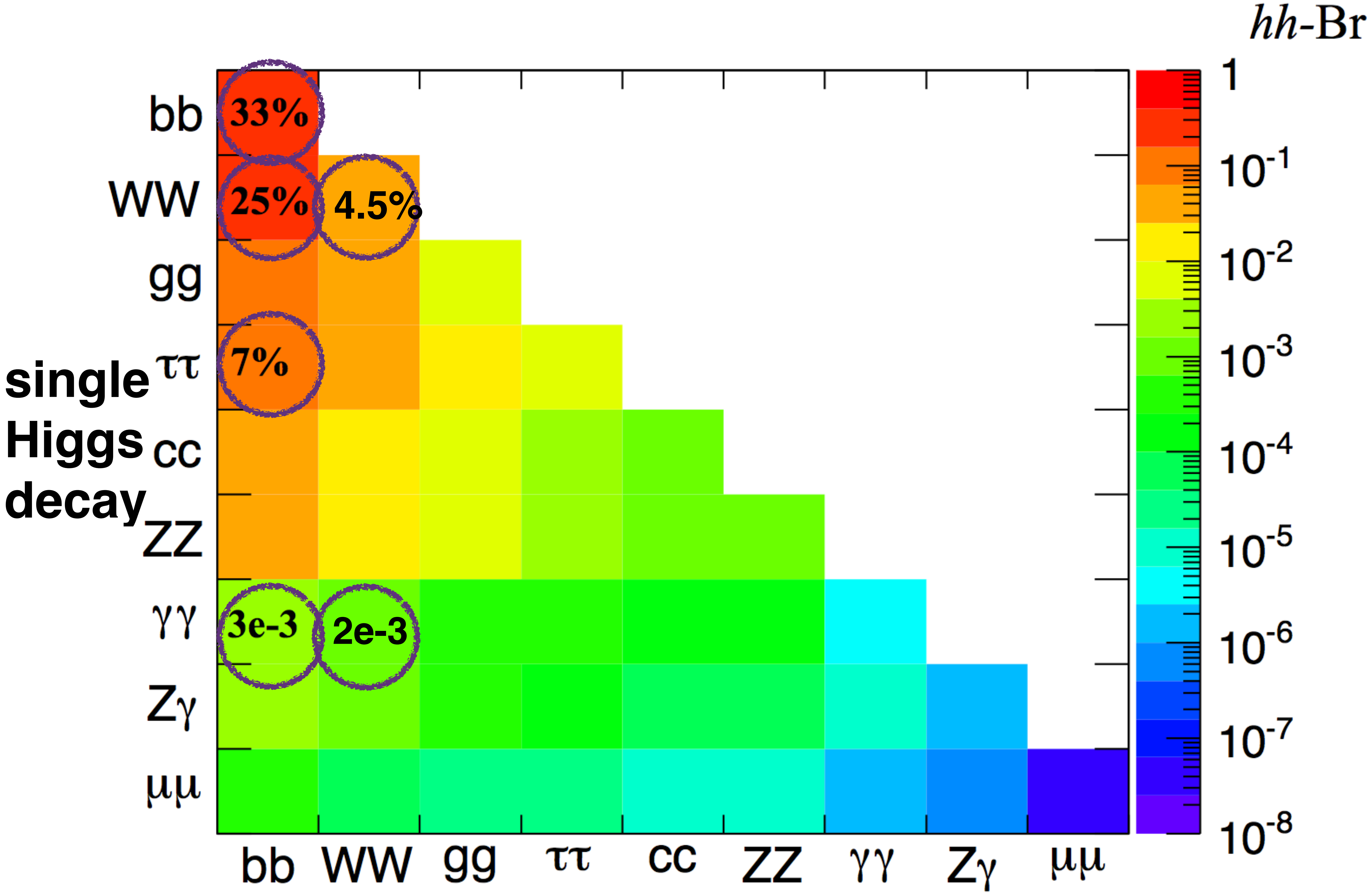


Low yield, yet clean signature

Di-Higgs decay

larger branching ratio—higher yield



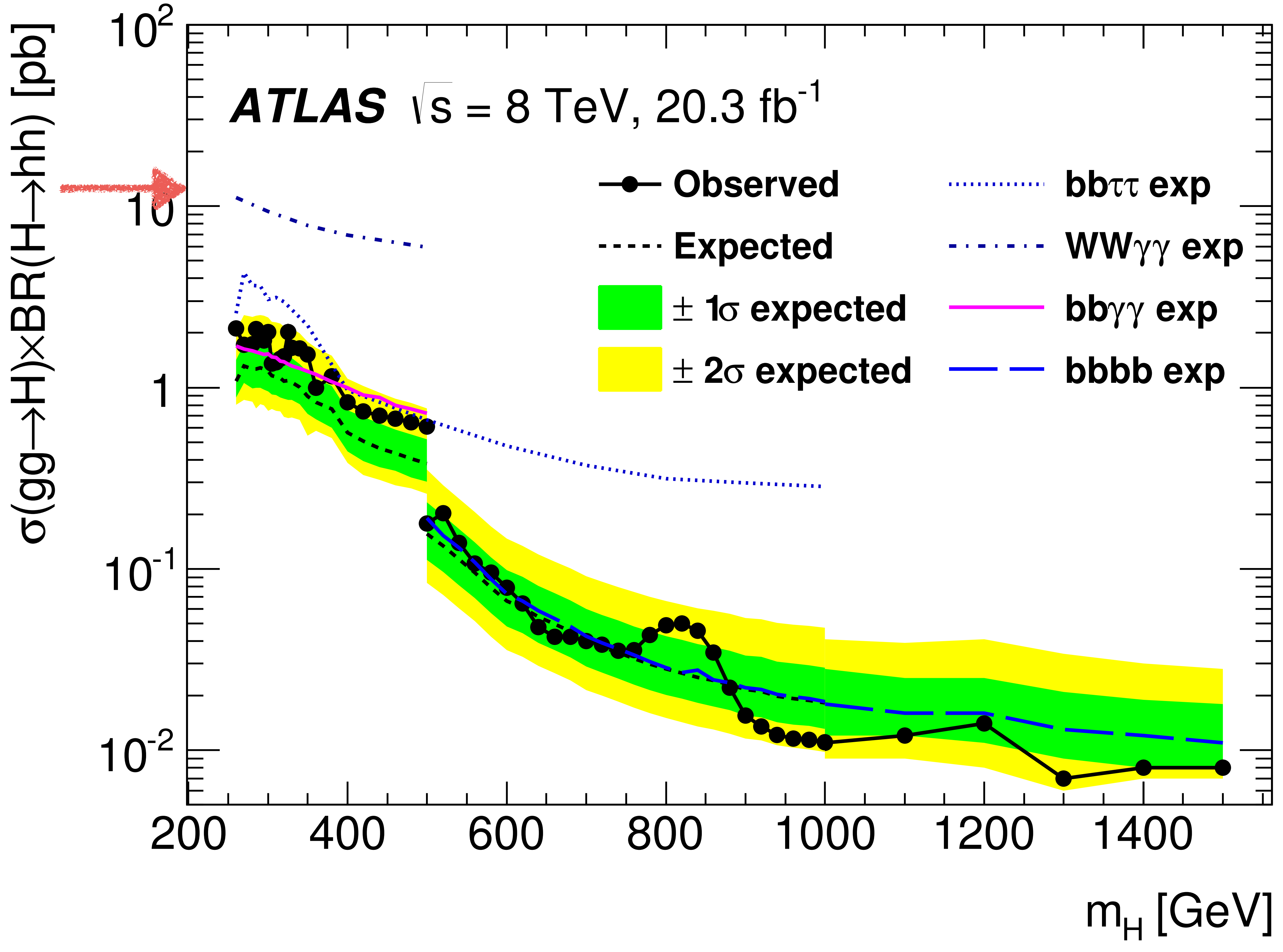
ATLAS Search Results (links)	8TeV, fb^{-1}	13TeV, fb^{-1}	HL-LHC
bbbb	20	3 / 13 / 36	prospect
bb$\tau\tau$	20		prospect
bbγγ	20	3	prospect
WW*γγ	20	13	
Combination	20		

Di-Higgs searches comparison

Phys. Rev. D 92, 092004 (2015)

- Model: resonant, non-resonant
  - Low Mass channels:
    - **WW*γγ** (250 ~ 500 GeV)

Run I Combined Limit



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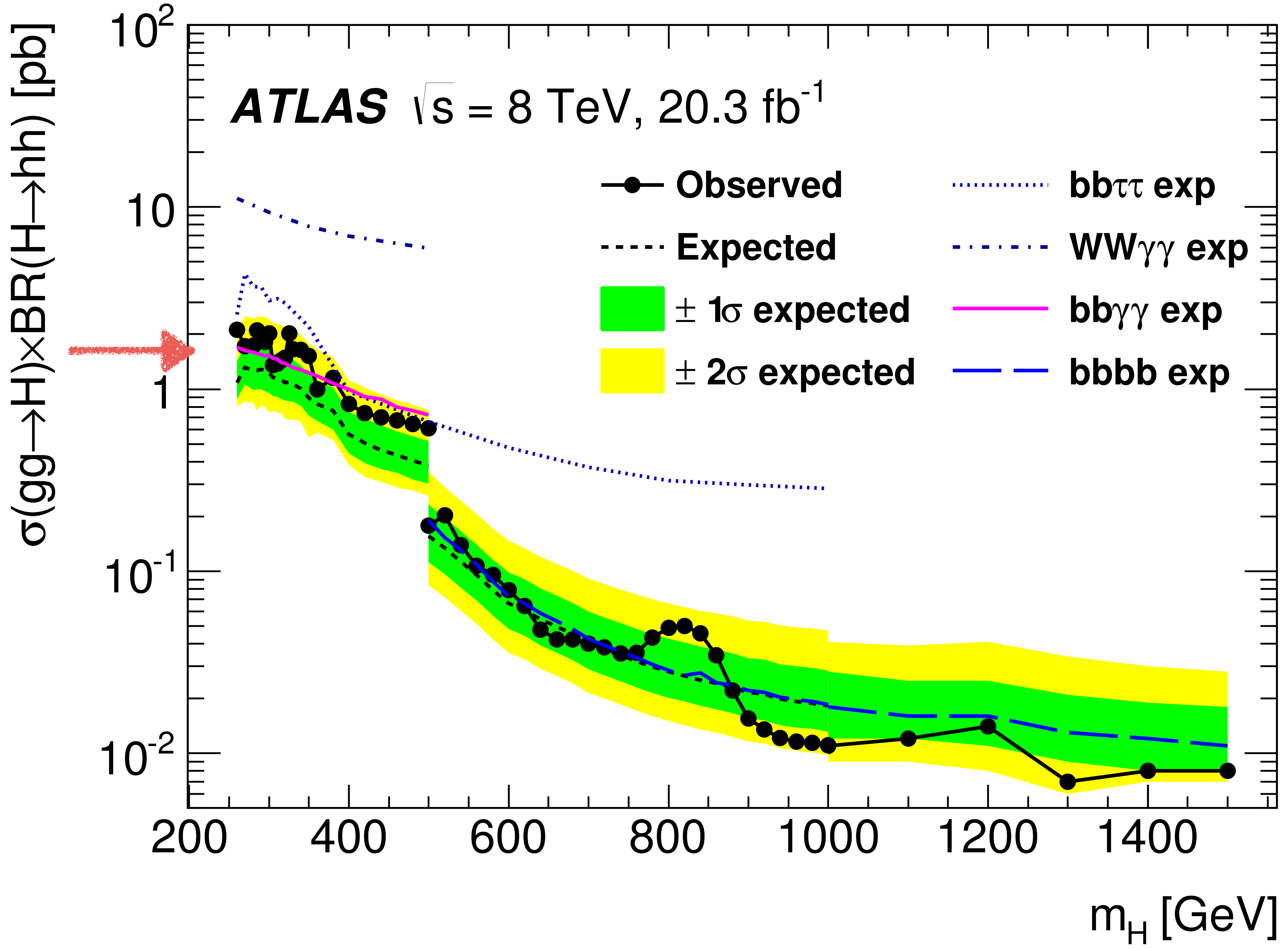

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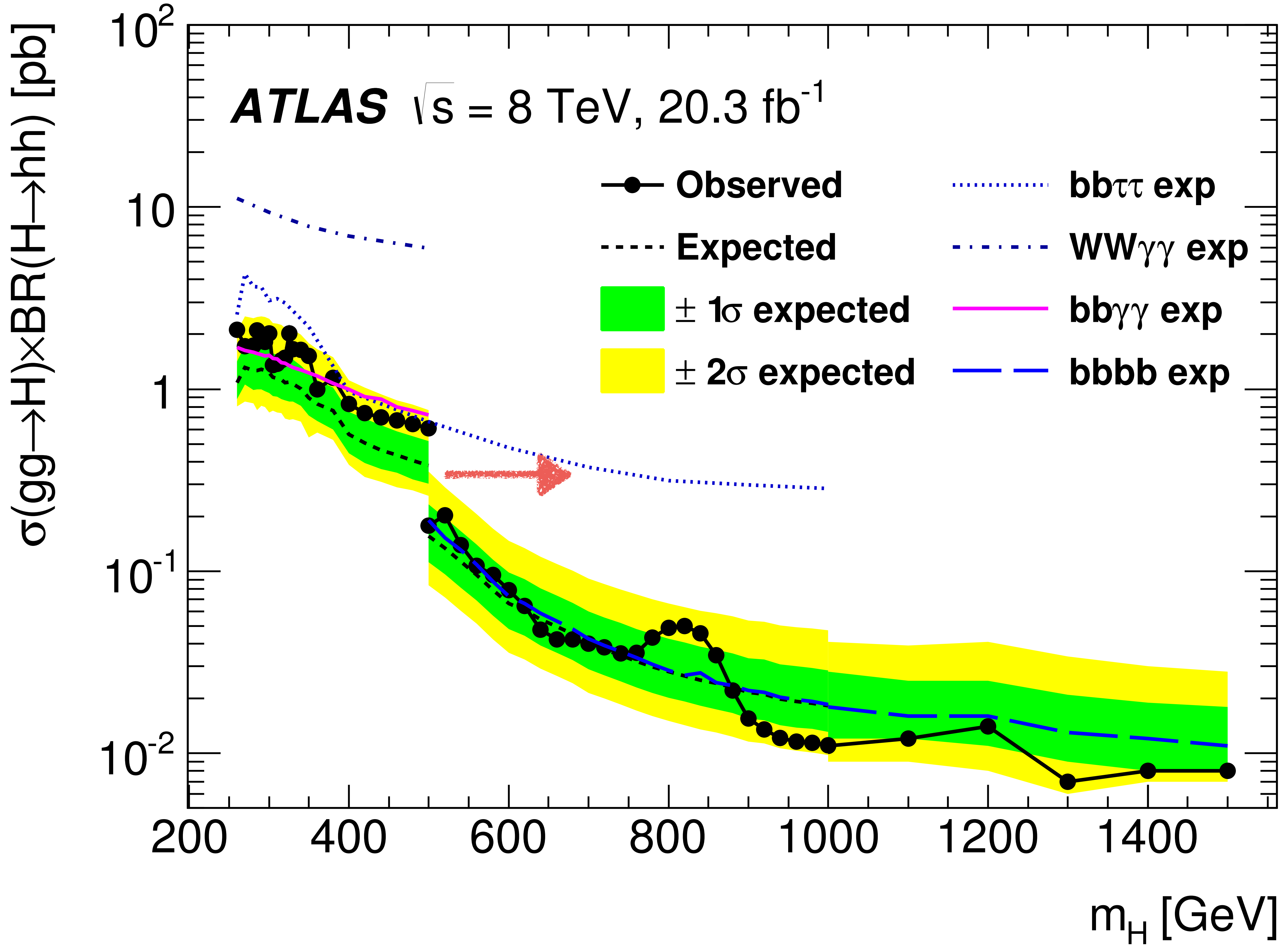
  - Higher Mass channels
    - **bb**$\tau\tau$ (250 ~ 1000 GeV)

Run I Combined Limit



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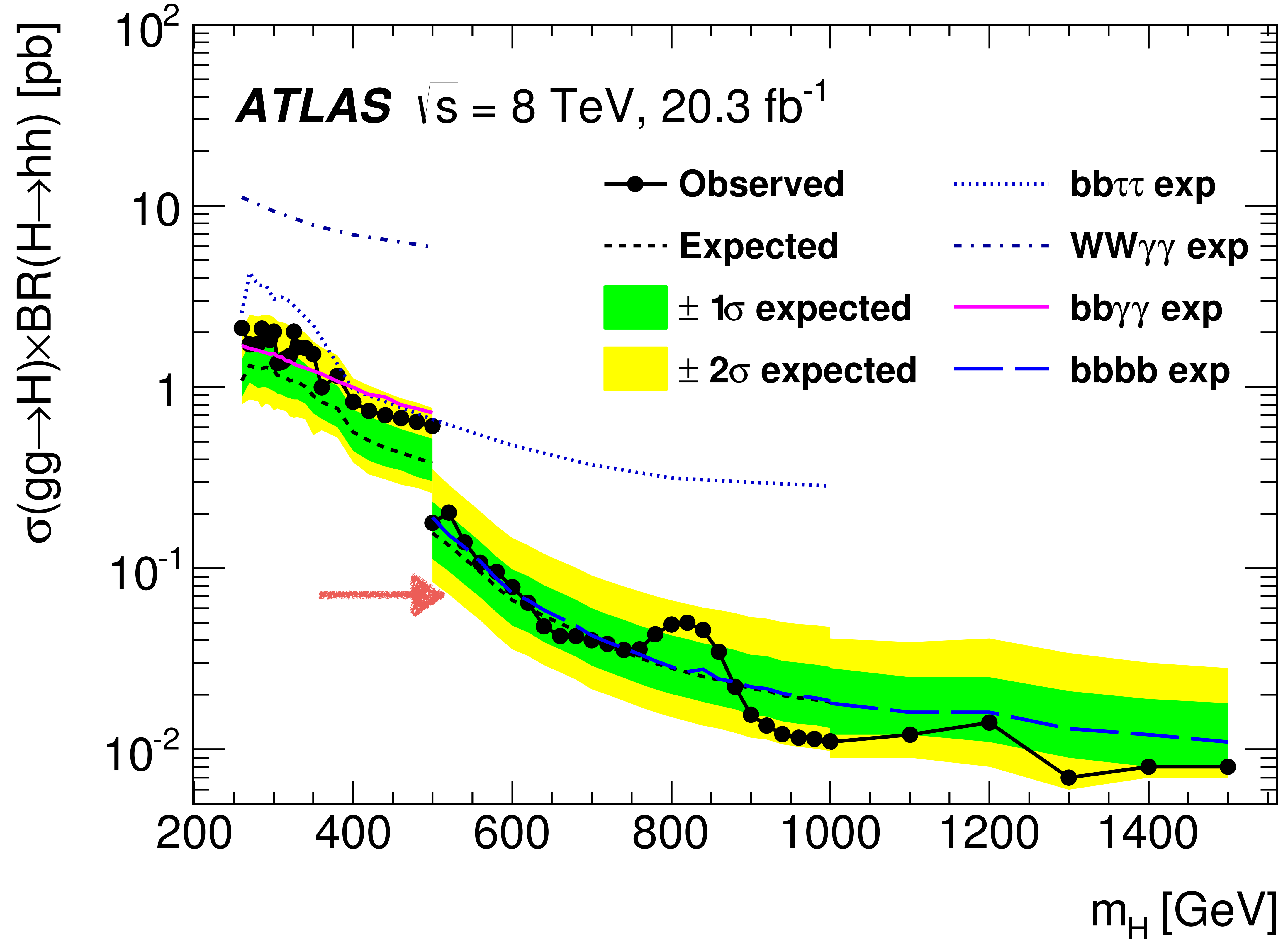
  - Higher Mass channels
    - bbττ (250 ~ 1000 GeV)
    - **bbbb** (500 ~ 1600 GeV)

Run I Combined Limit



4b high mass search: large range, great sensitivity, focus of this talk

Search for di-Higgs to 4b in ATLAS

- Chapter 1: Why search for it
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- **Chapter 2: How to search**
  - **Selection, Optimization, Background estimation**

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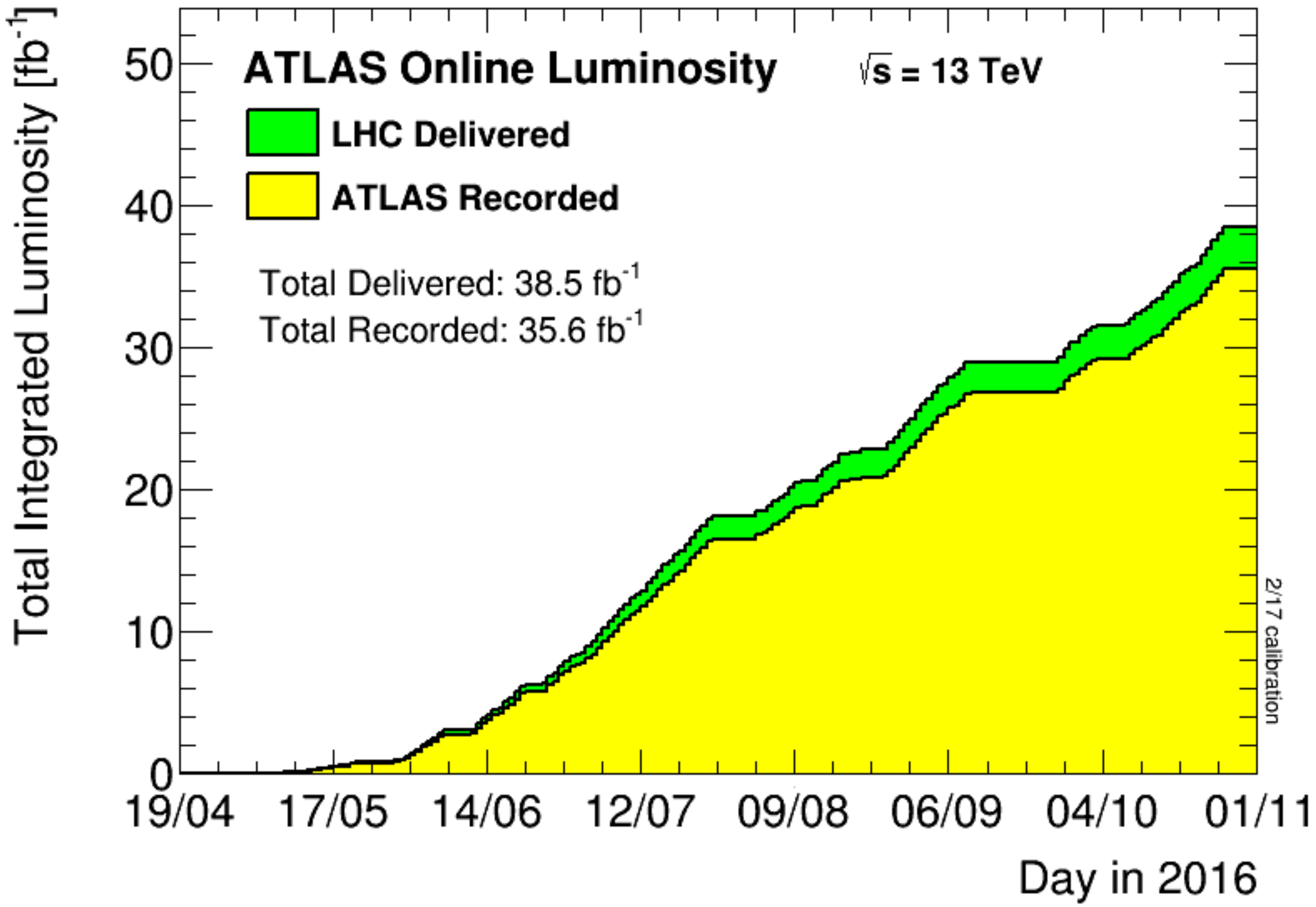
  - Results, Discussions, Future perspectives

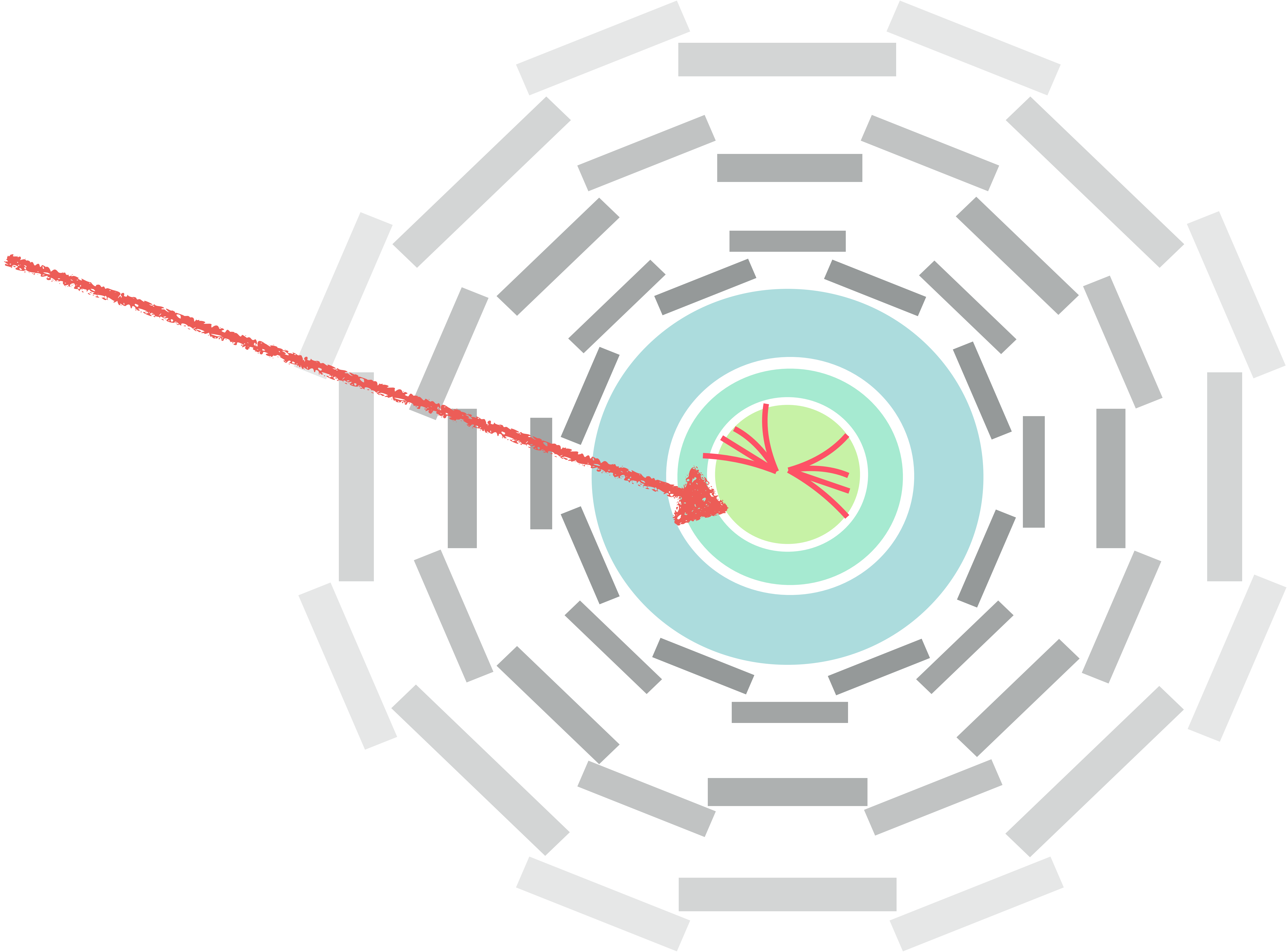
Thanks to the LHC

- We have data! — 2015 + 2016 ~ 36 fb^{-1}



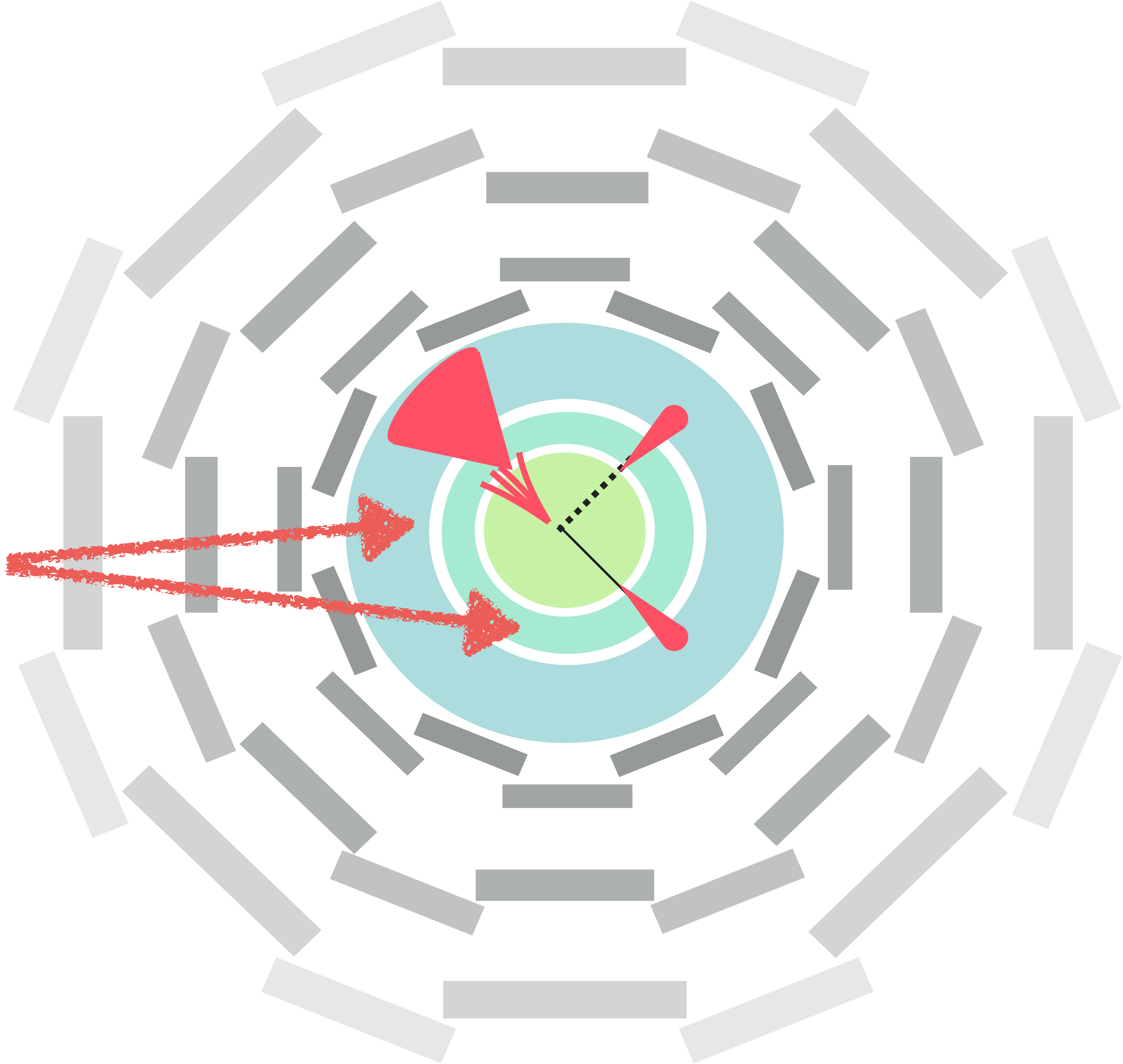
ATLAS Detector

- Inner detector for charged tracks reconstruction



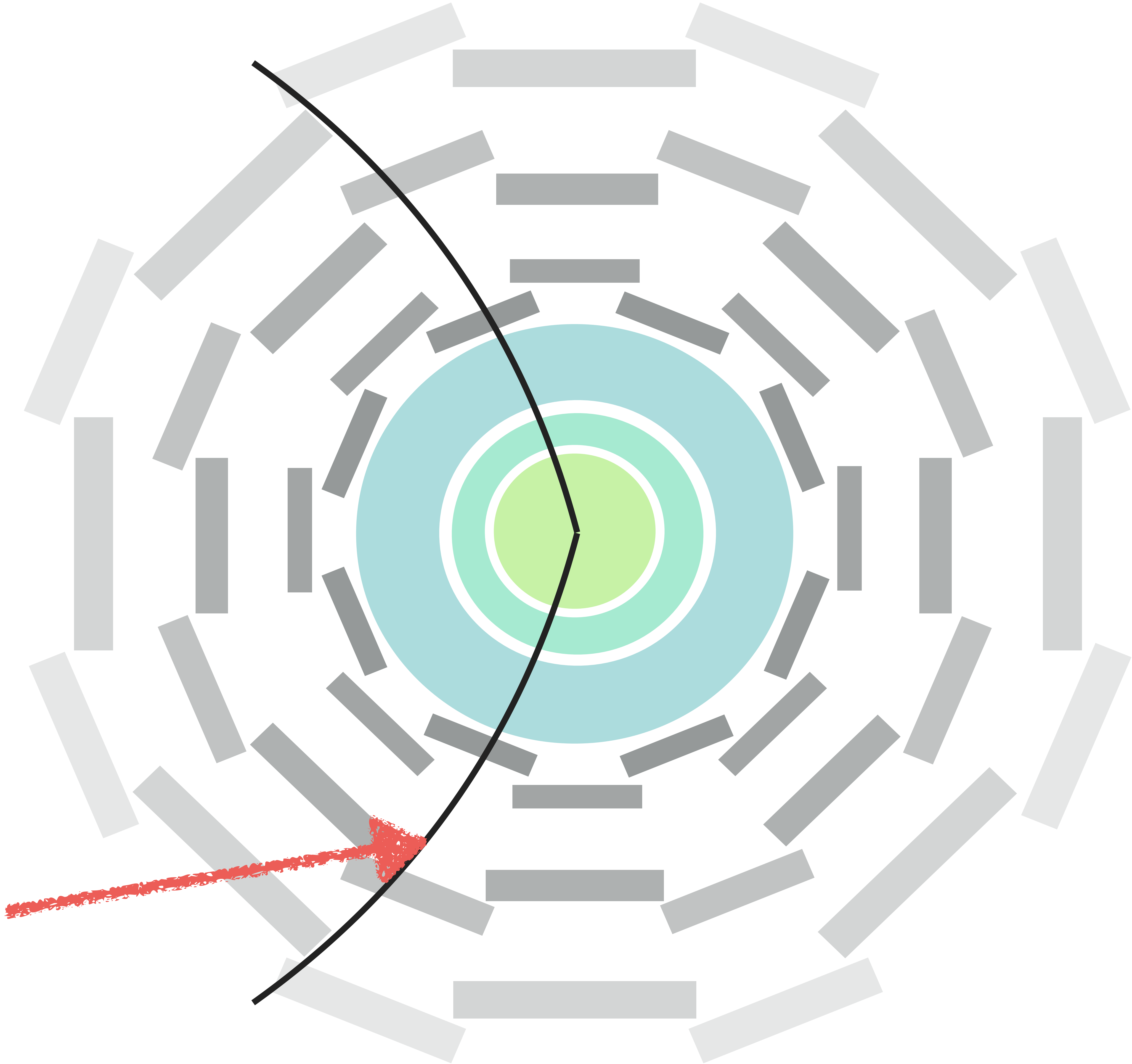
ATLAS Detector

- Inner detector for charged tracks reconstruction
- Calorimeters for hadronic energy measurements and triggering

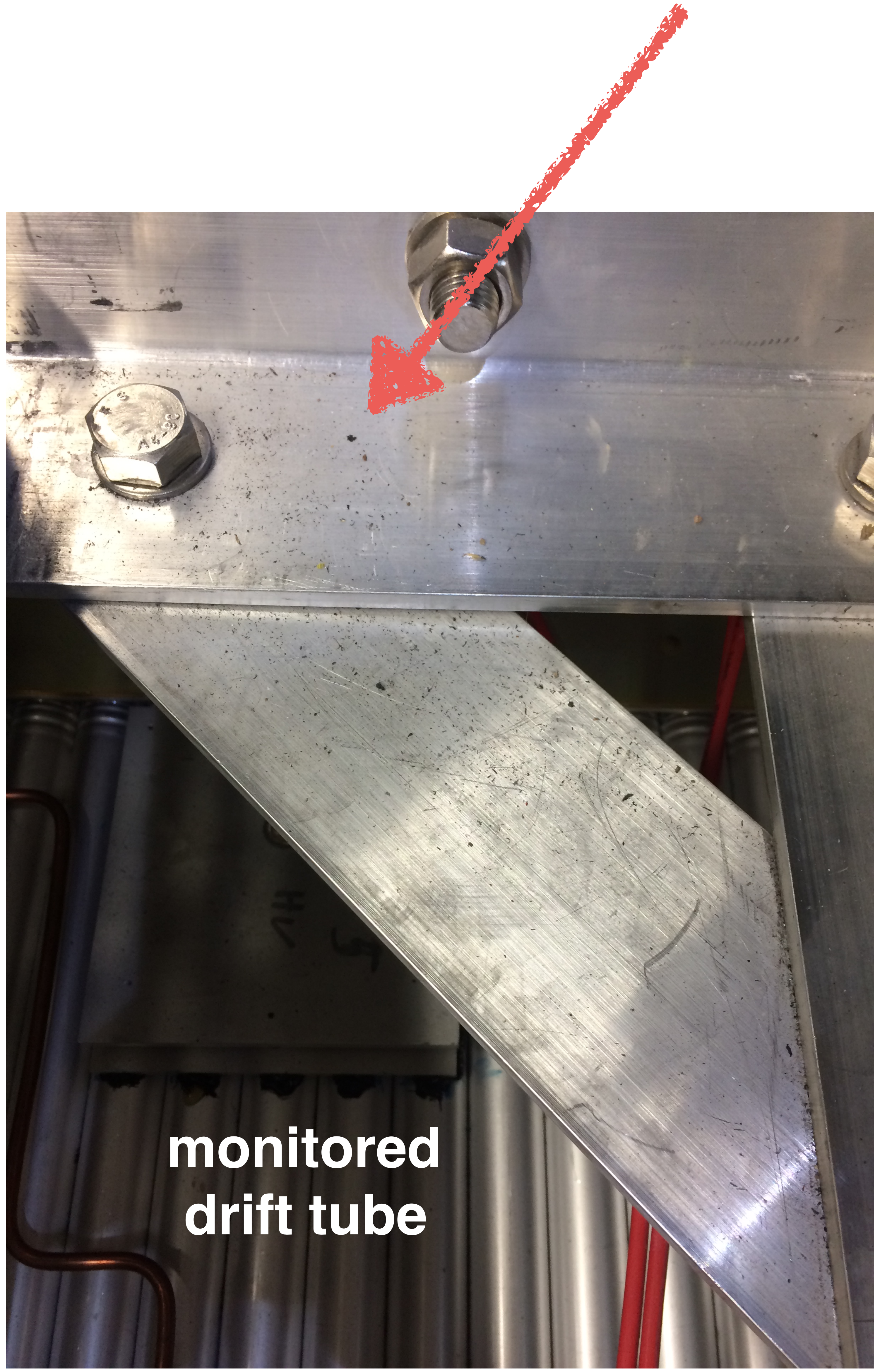


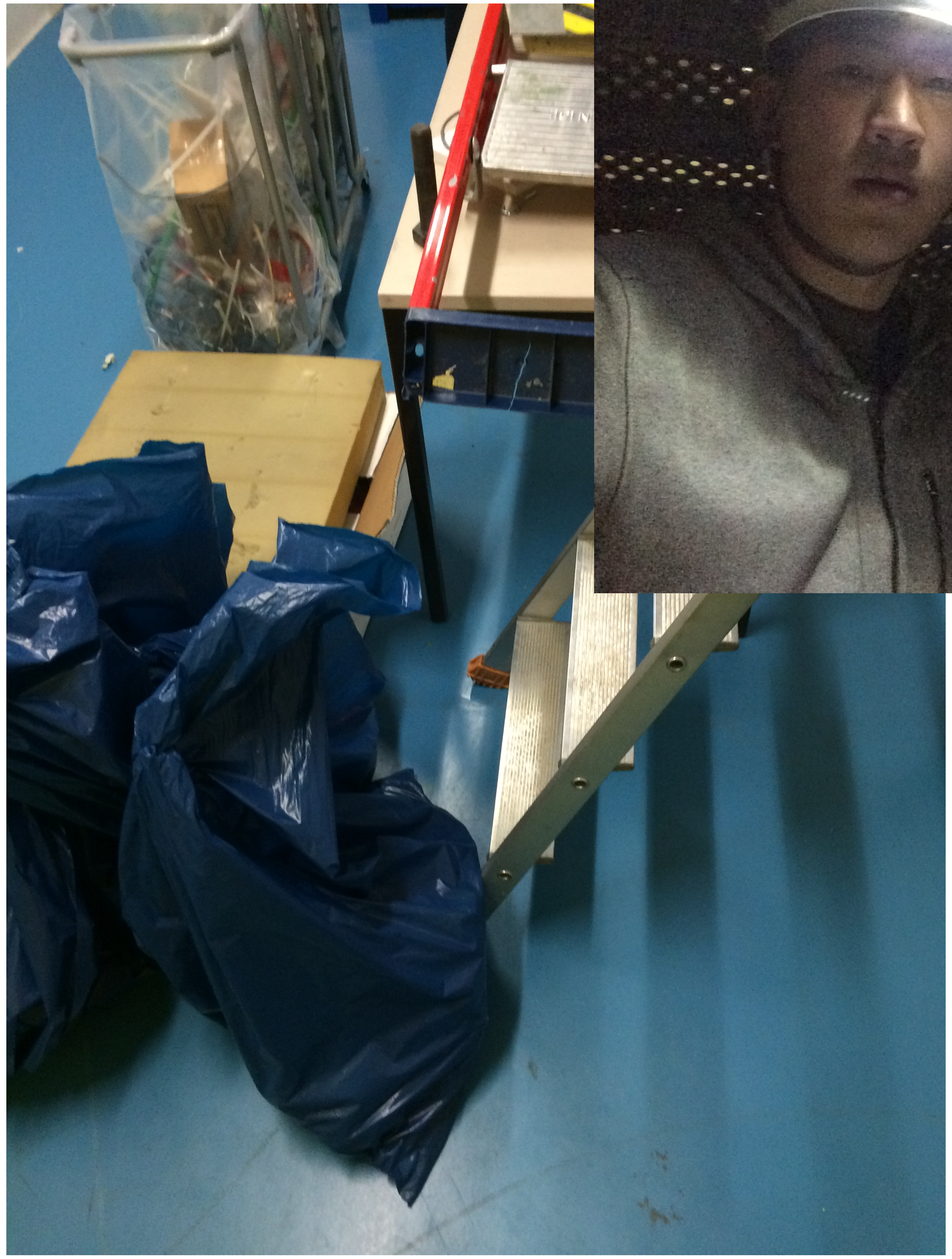
ATLAS Detector

- Inner detector for charged tracks reconstruction
- Calorimeters for hadronic energy measurements and triggering
- Muon Spectrometer for muon measurement and triggering



Picking up dust in the Muon Spectrometer

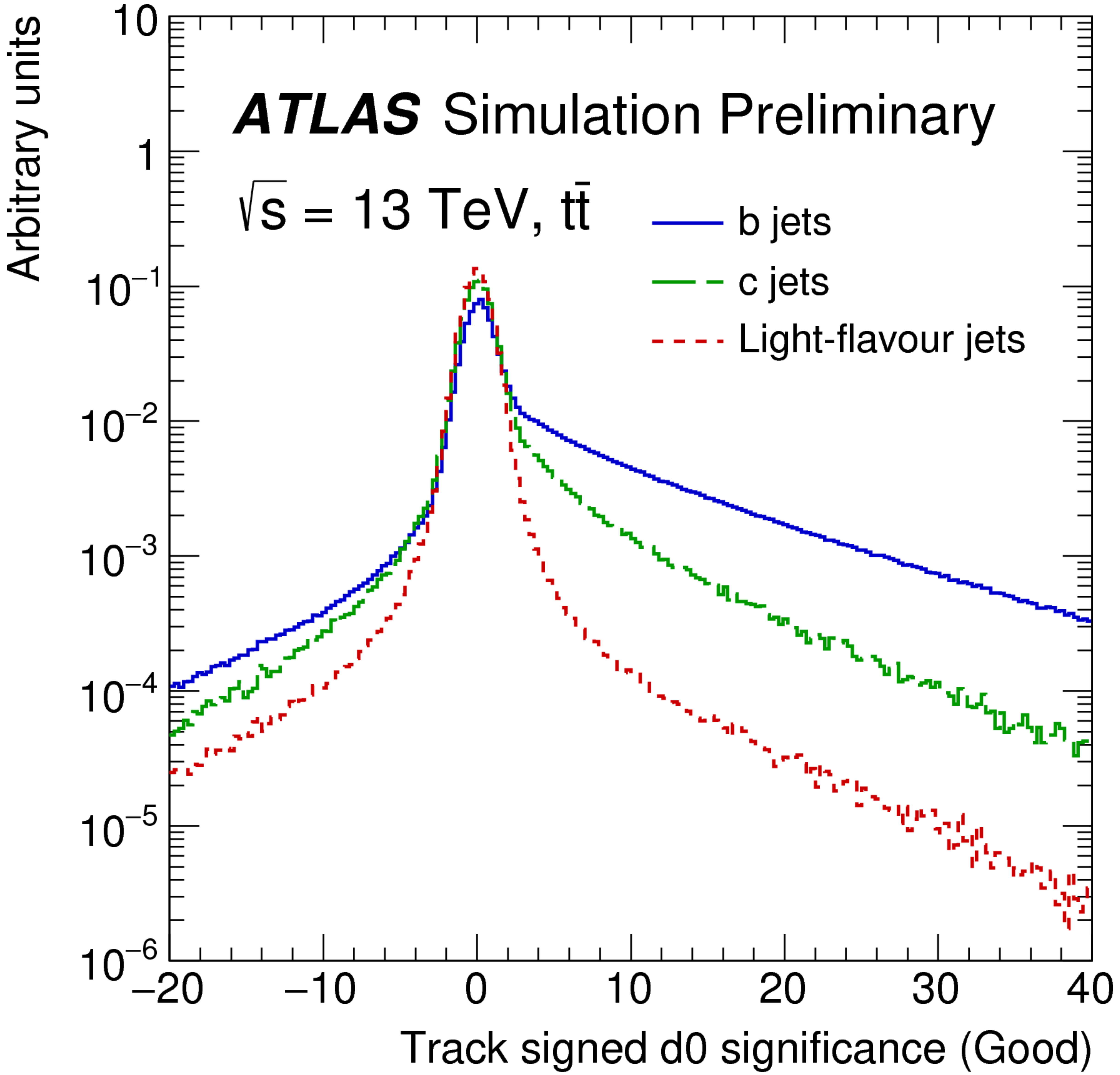




b-tagging in ATLAS

ATLAS-PHYS-PUB-2016-012

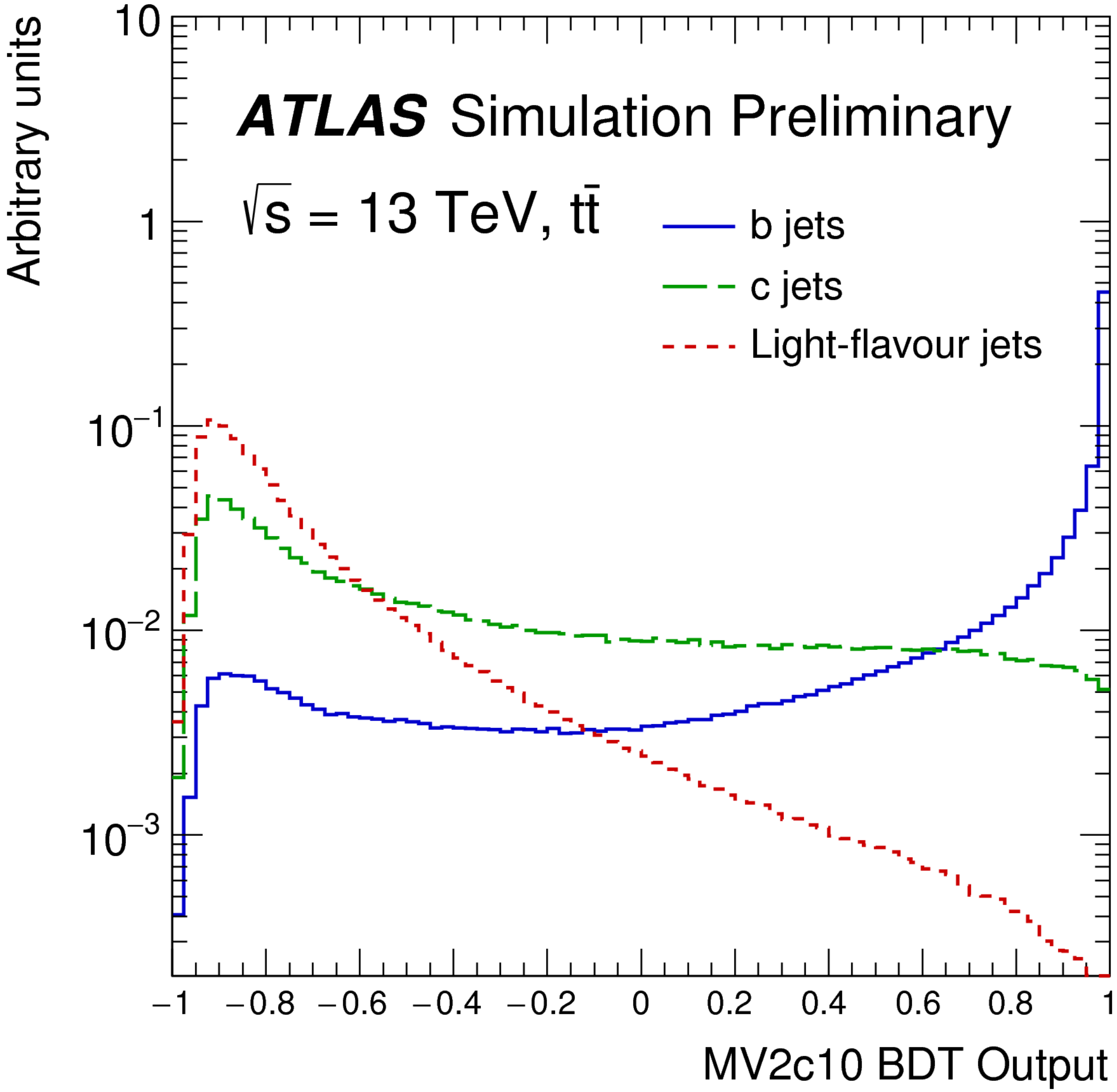
- Long lifetime of b-hadron
- b-decay "far" from the interaction point



b-tagging in ATLAS

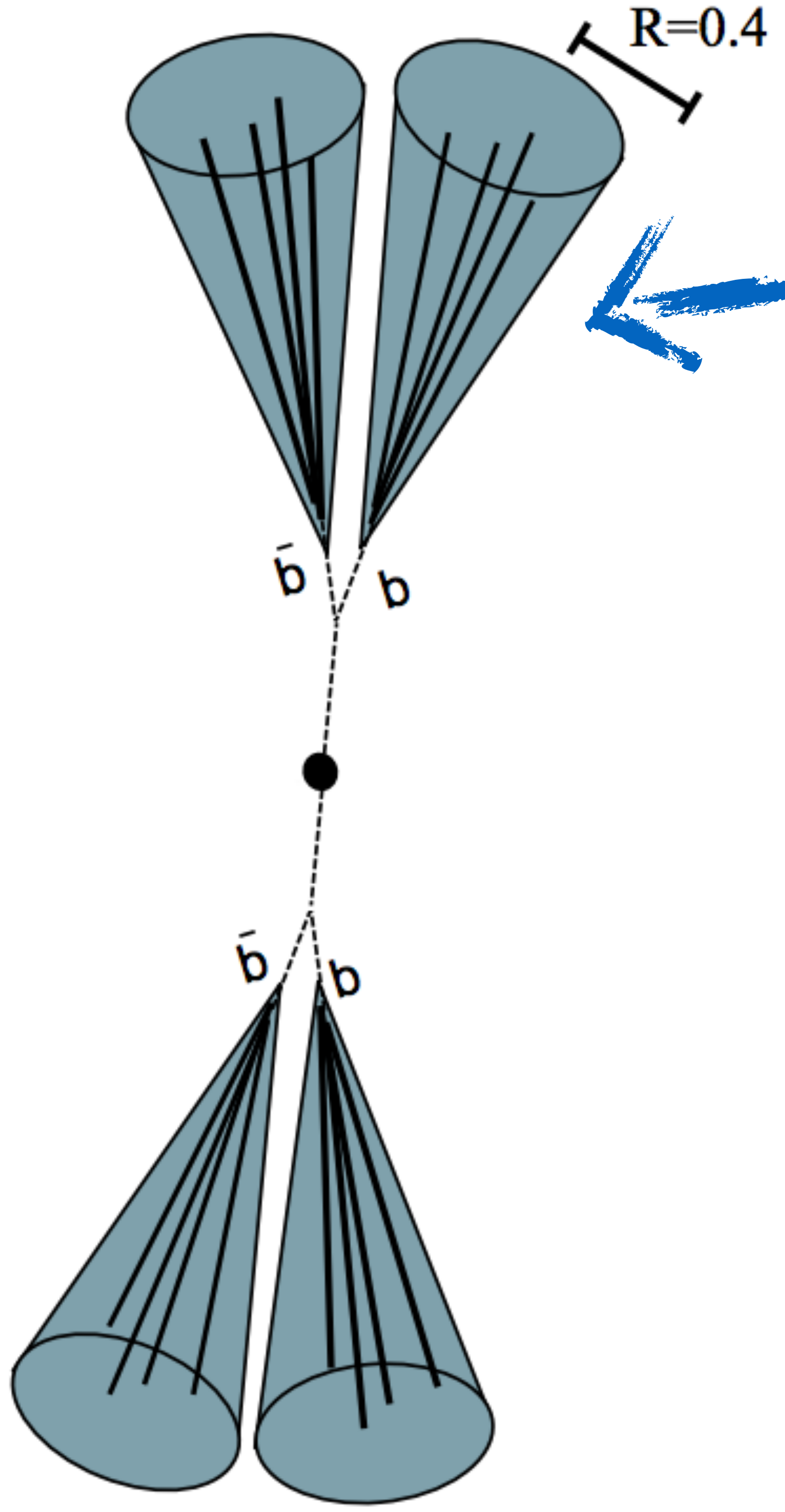
ATLAS-PHYS-PUB-2016-012

- Long lifetime of b-hadron
- b-decay "far" from the interaction point
- Combine impact parameter, secondary vertex and topology information into a MVA tagger
- Can also tag clustered track — "trackjet"

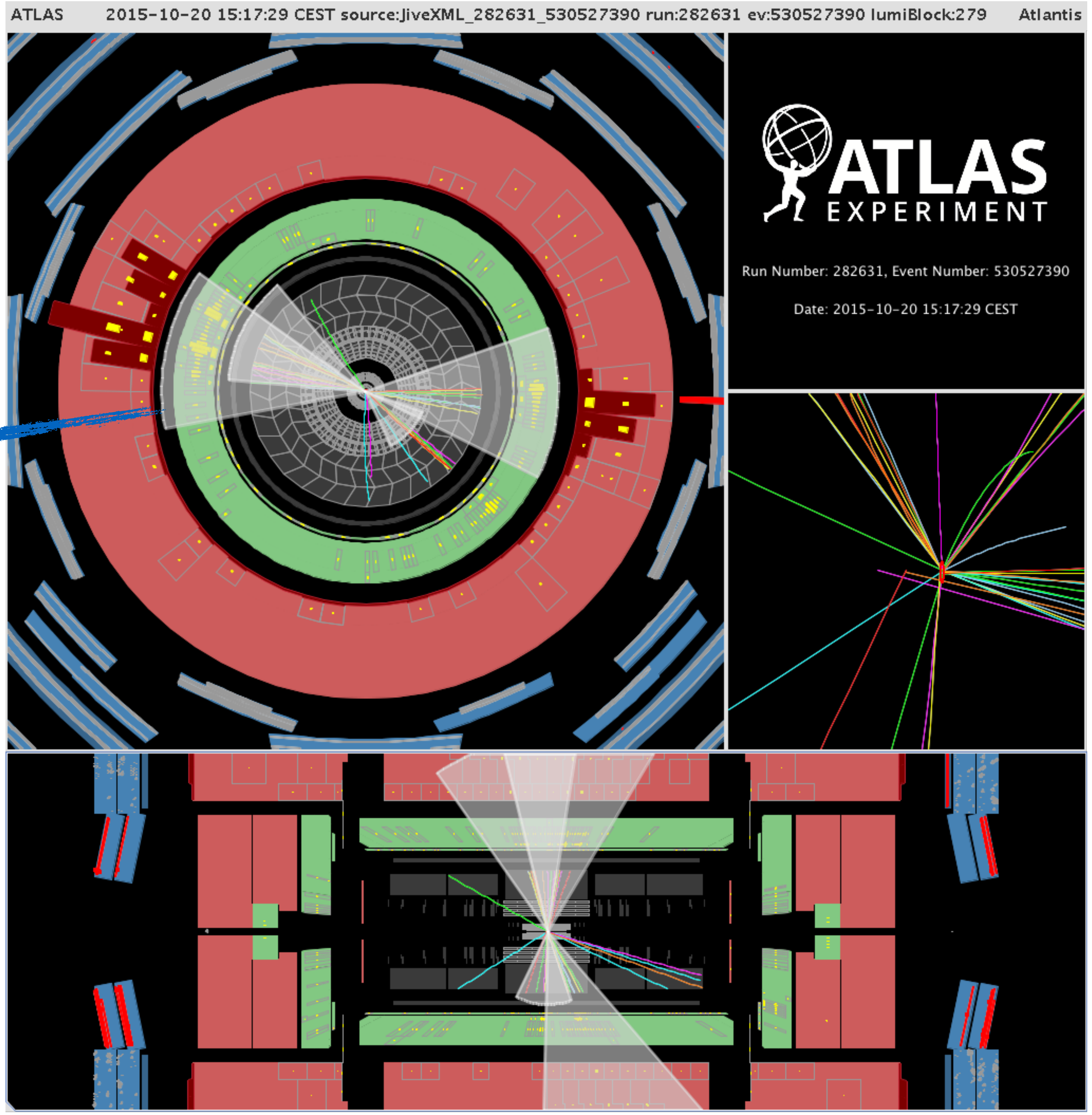


Back to di-Higgs

- bbbb final state is all hadronic
- 4b-tagged jets
- Run II di-Higgs candidate

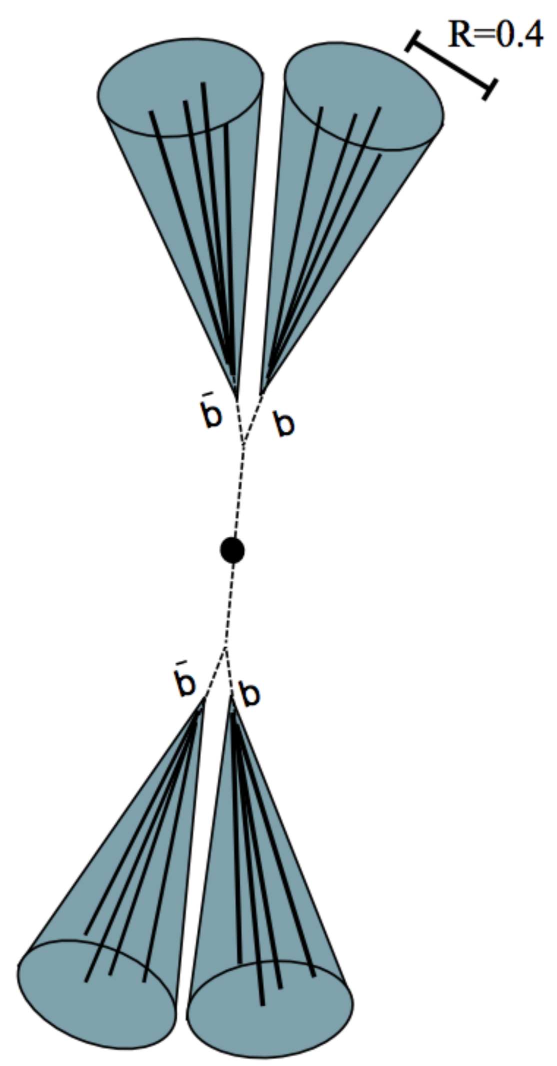


RunII data hh4b resolved candidate



Back to di-Higgs

- Standard resolved 4b jets for the low mass range



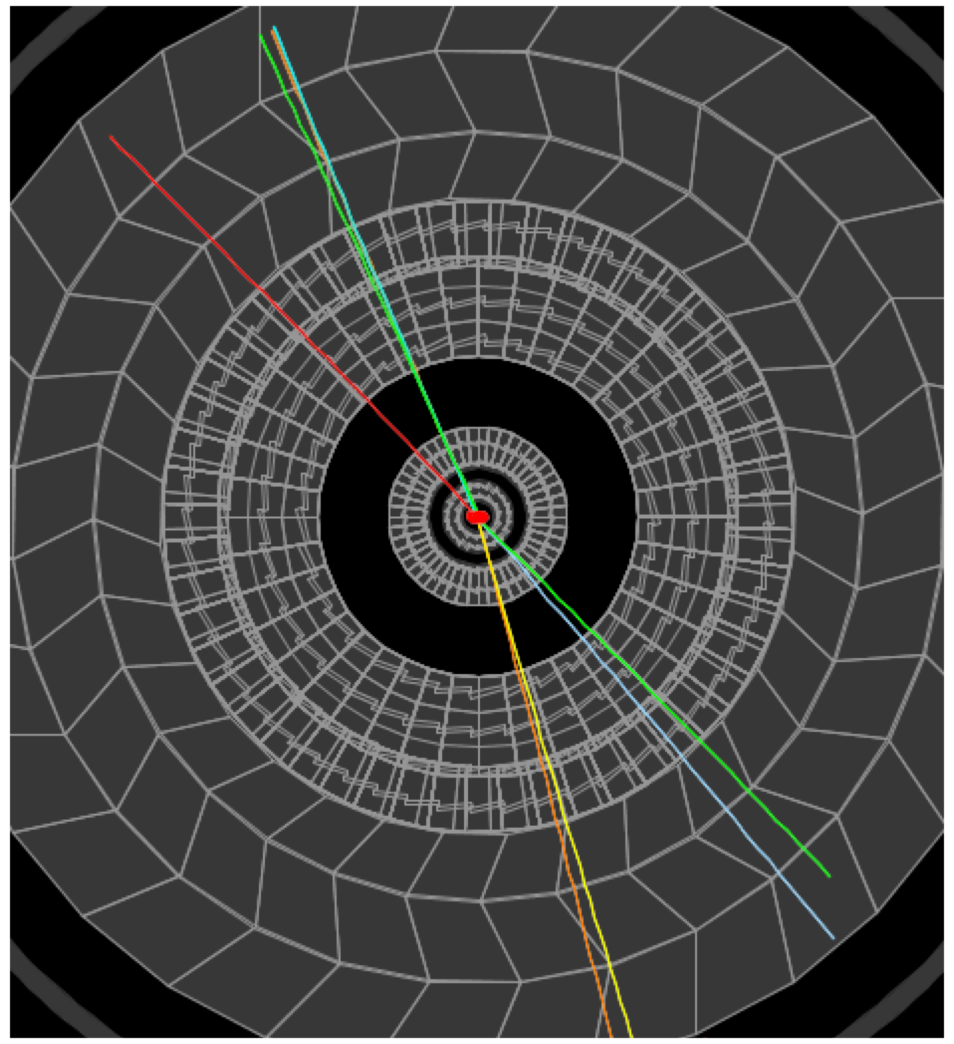
Objects/ Final State	Resolved (250–1400 GeV)	
Trigger	Mixed b Trigger	
Jets	Four R=**0.4** Jets	
pT cuts	Jet pT > **40** GeV	
B-tagging	70% WP*	

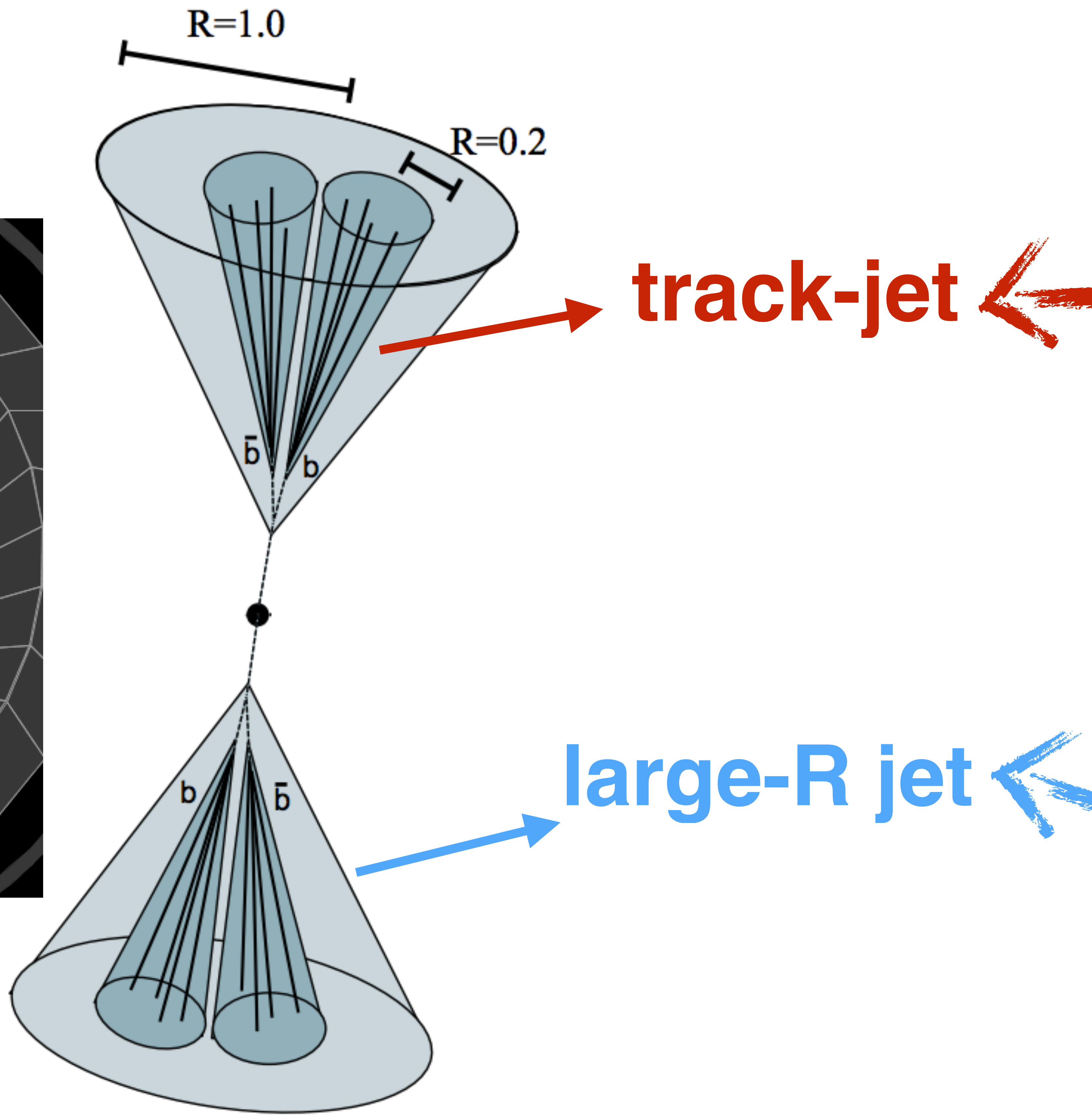
*At b-tagging 70%, c jet rejection is 12 and light rejection is 380

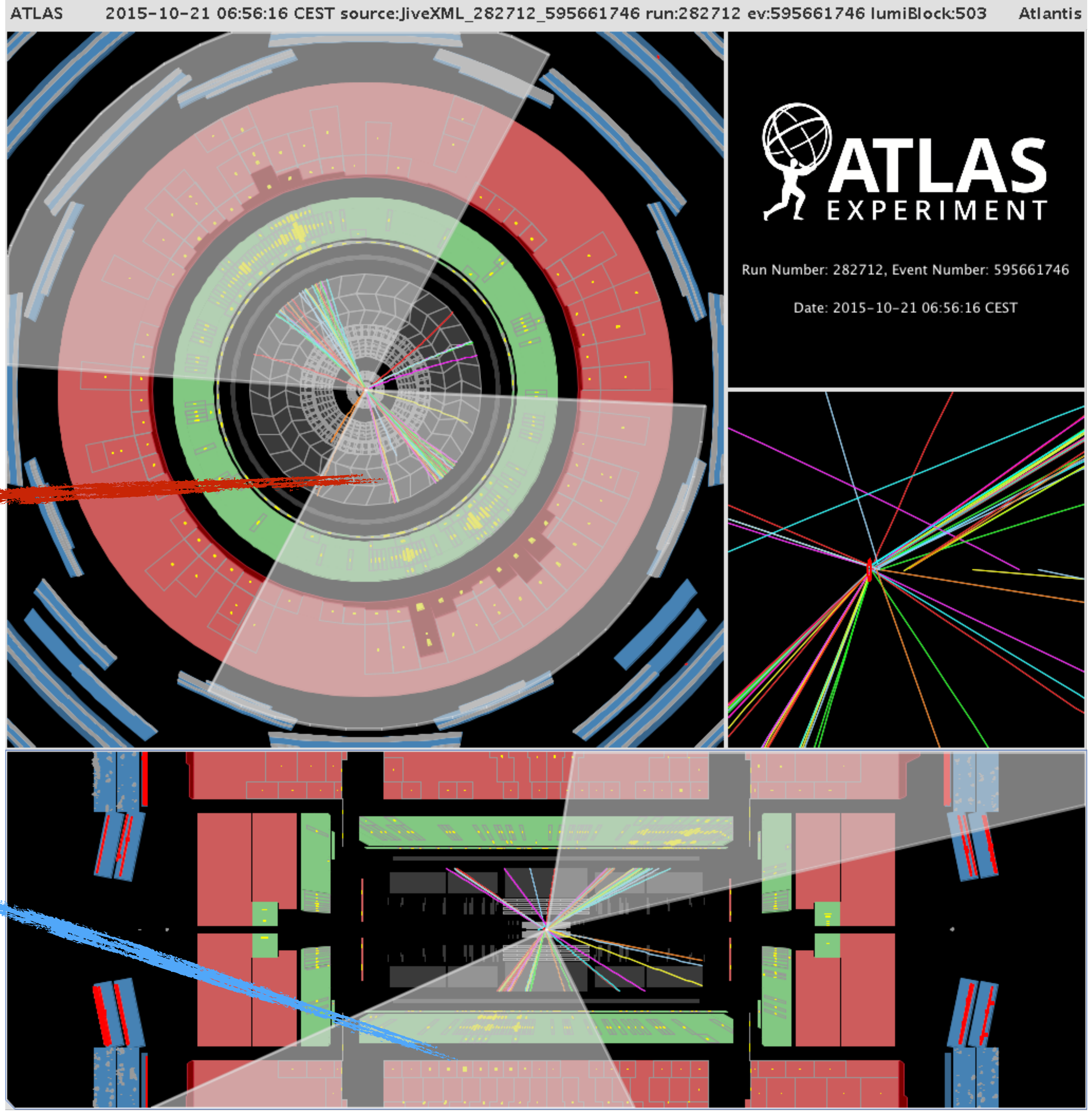
Boosted Jets

- **1.5 TeV** resonance → ~ 600 GeV p Higgs → ΔR_{bb} ~$2m_h/p$ ~ **0.4**

RunII data boosted 4b candidate







Boosted Jets and the Two Channels

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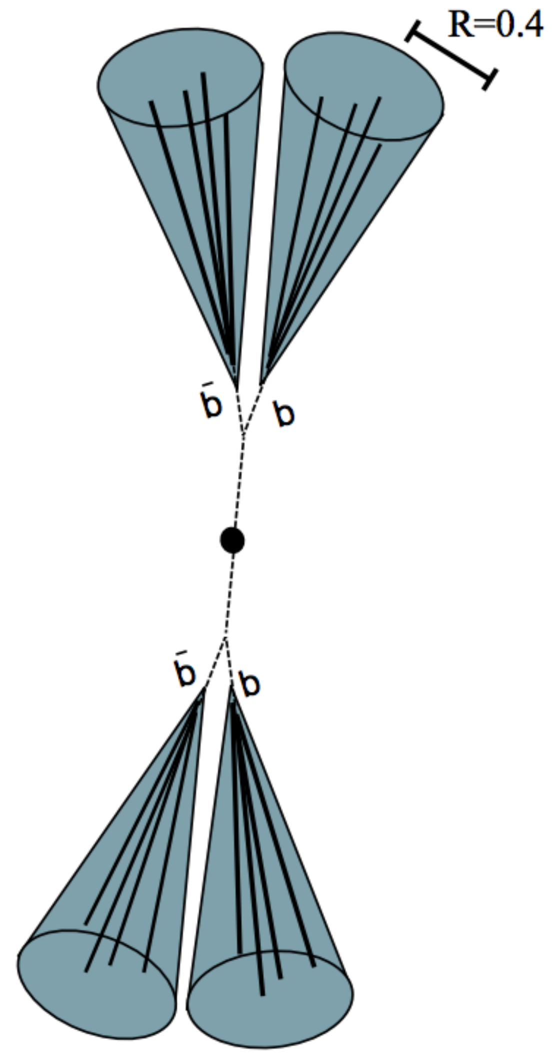
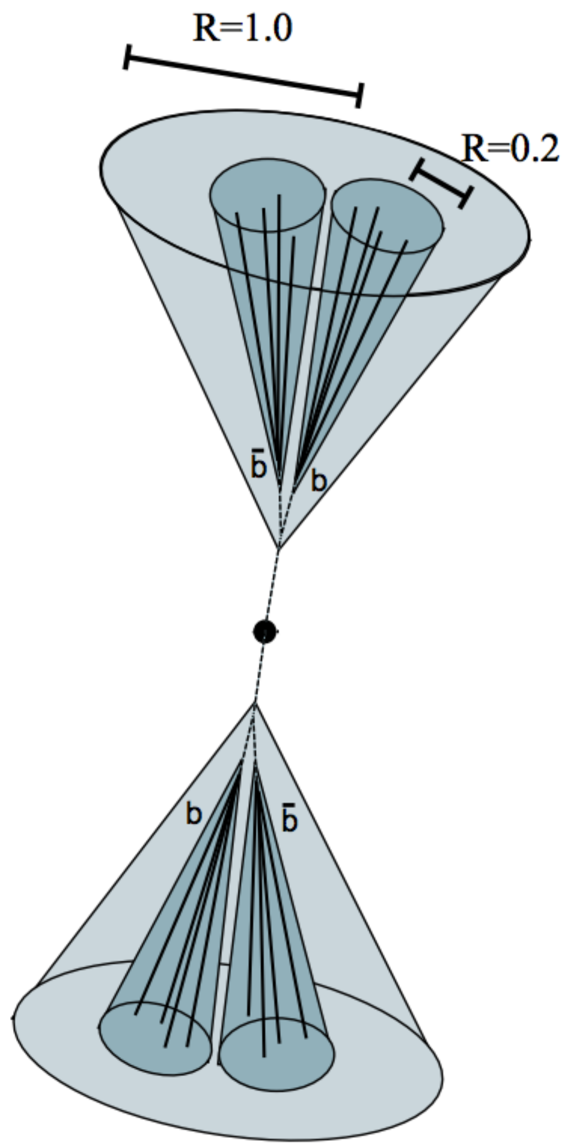


Objects/ Final State	Resolved (250–1400 GeV)	Boosted (1000-3000 GeV)
Trigger	Mixed b Trigger	Large R-jet Trigger
Jets	Four R=**0.4** Jets	Two R=**1.0** trimmed Jets
pT cuts	Jet pT > **40** GeV	Leading > **450** GeV Subleading > **250** GeV
B-tagging	70% WP	70% WP on R=**0.2** track-jets



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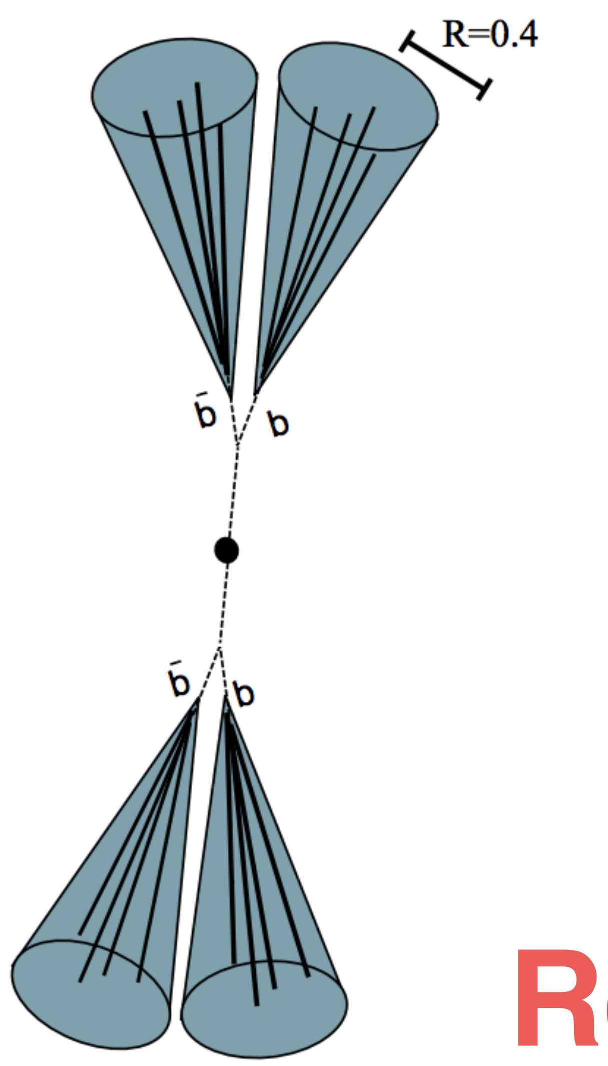
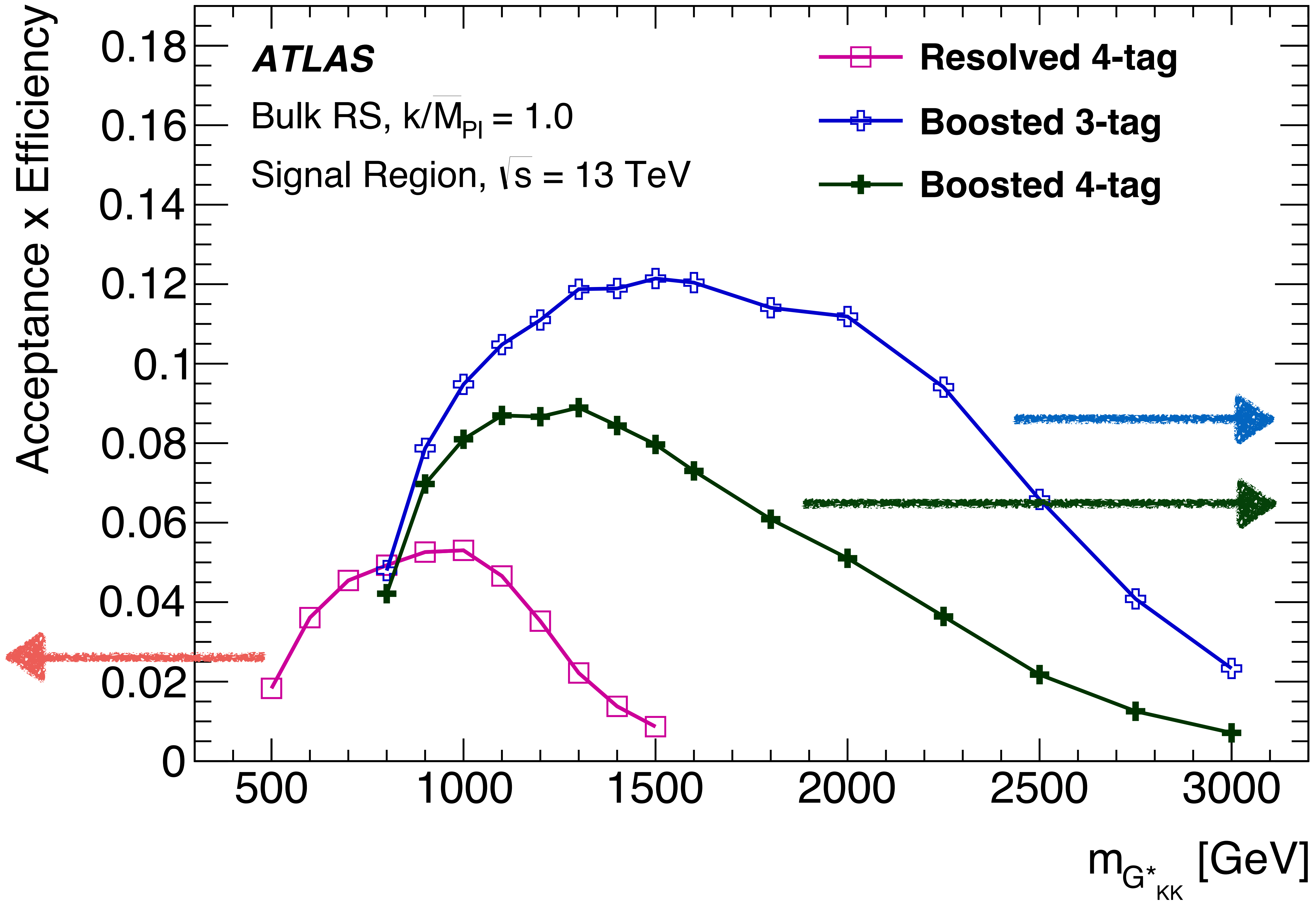
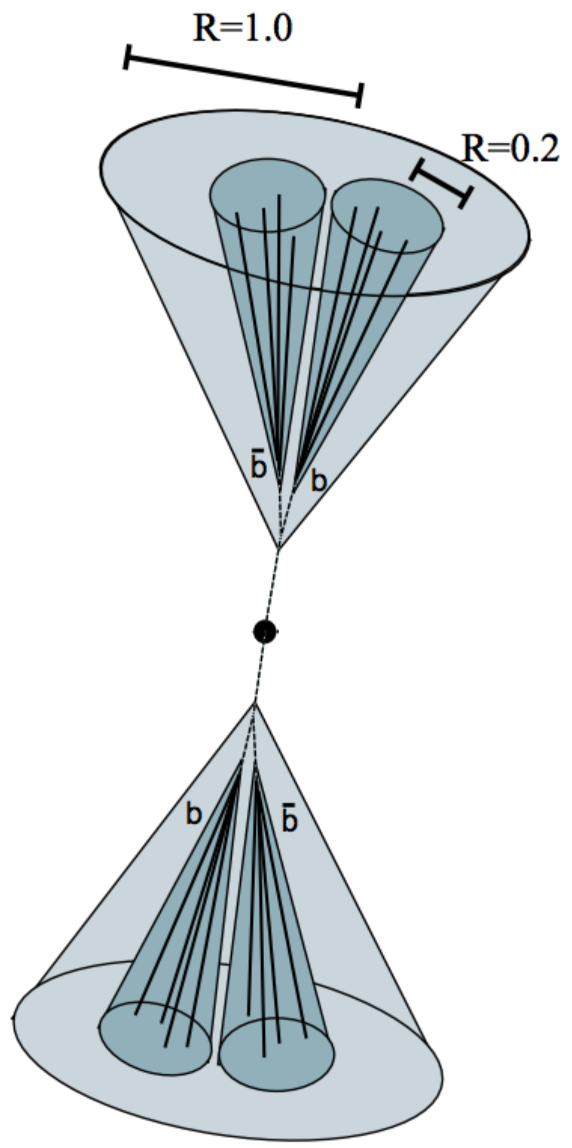


Resolved

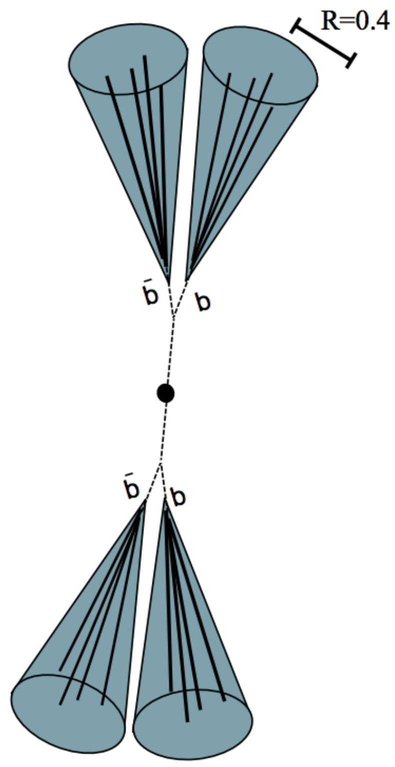


Boosted

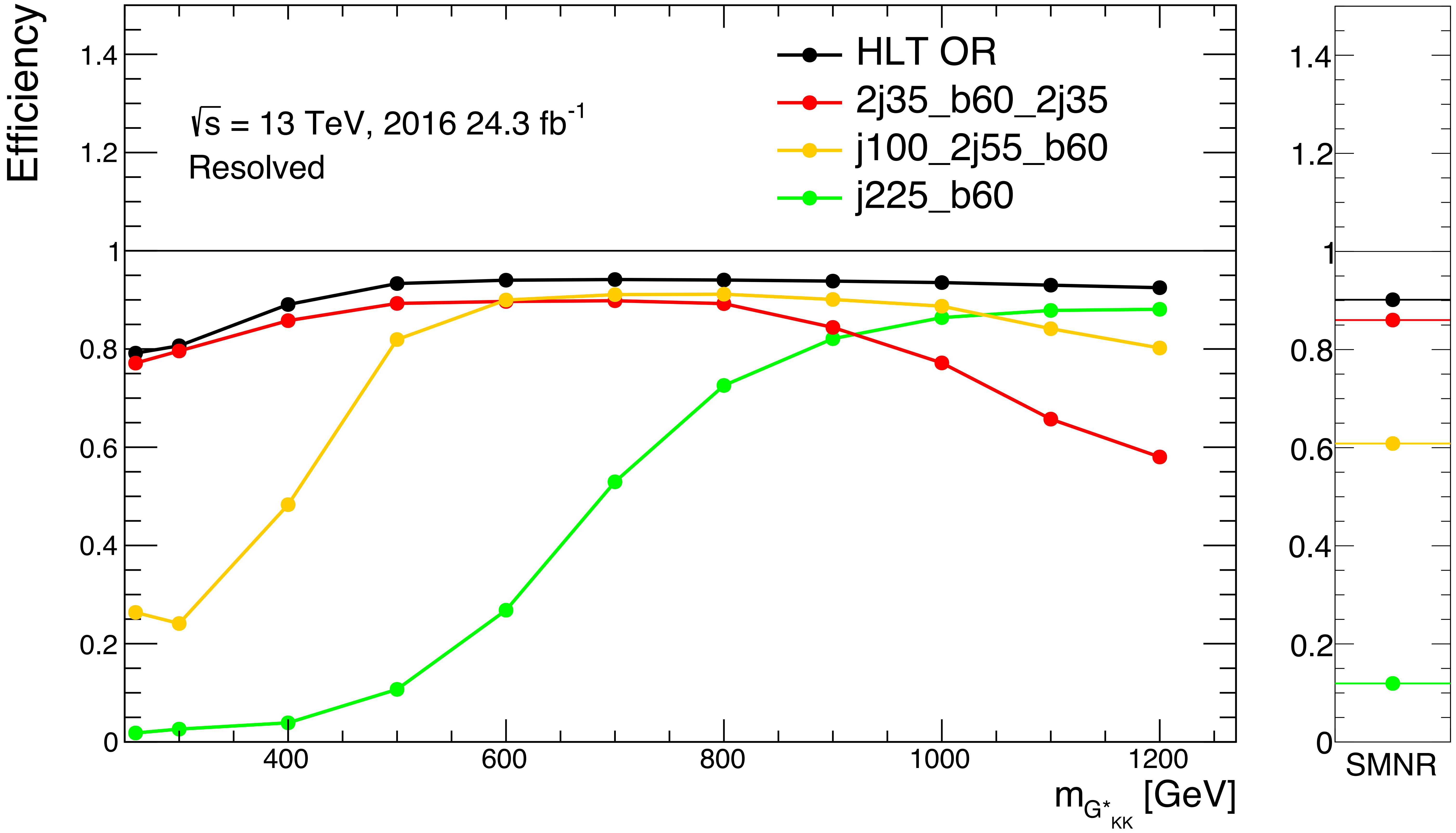


Resolved: Selection

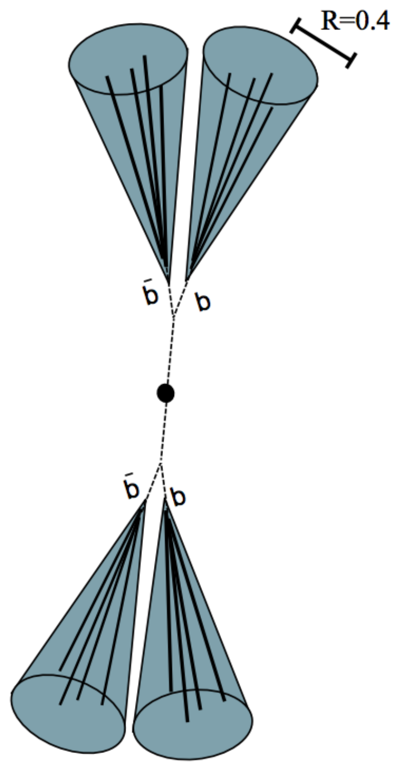
- Good trigger efficiency overall ~ 95%



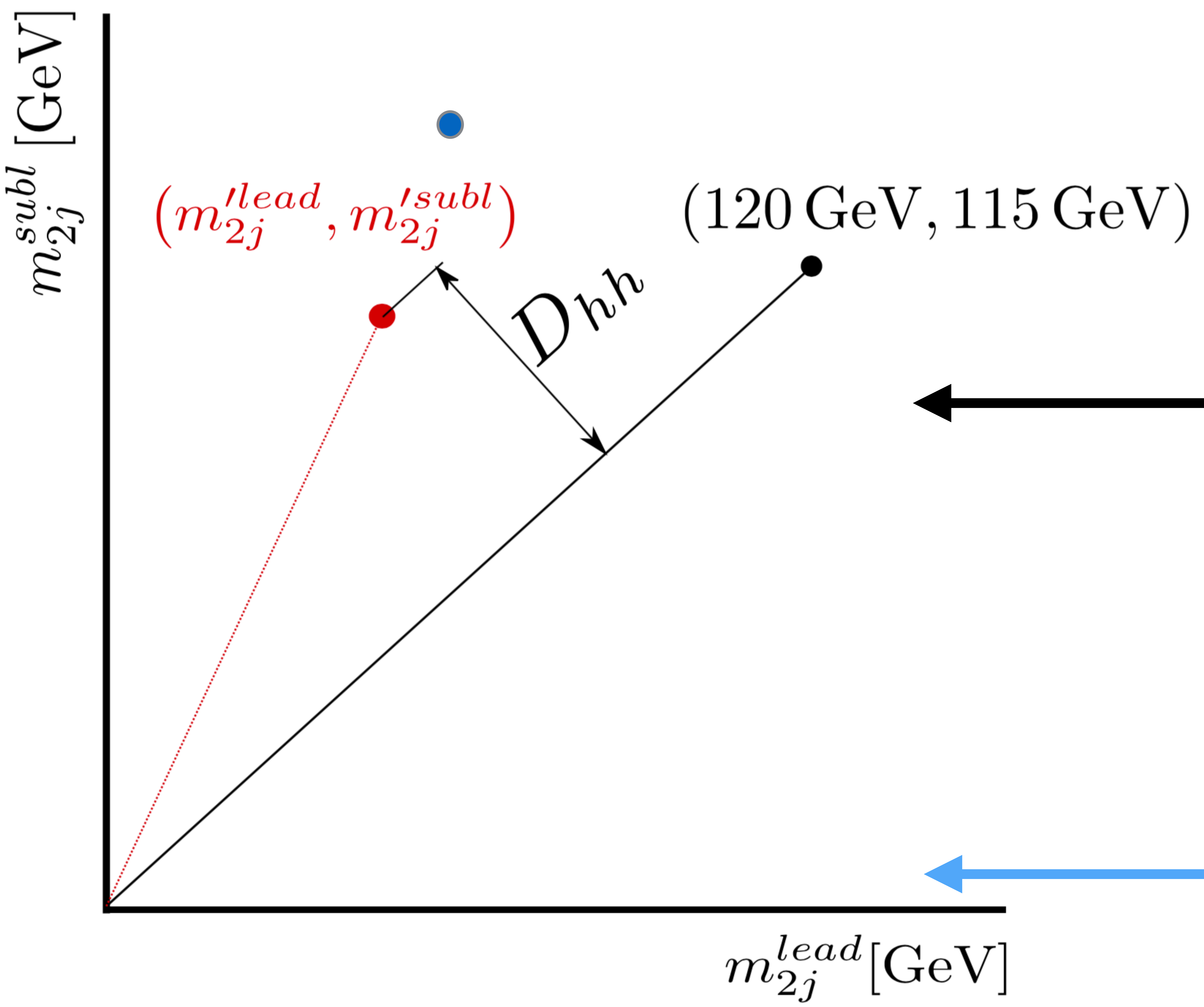
2016 Trigger Efficiency

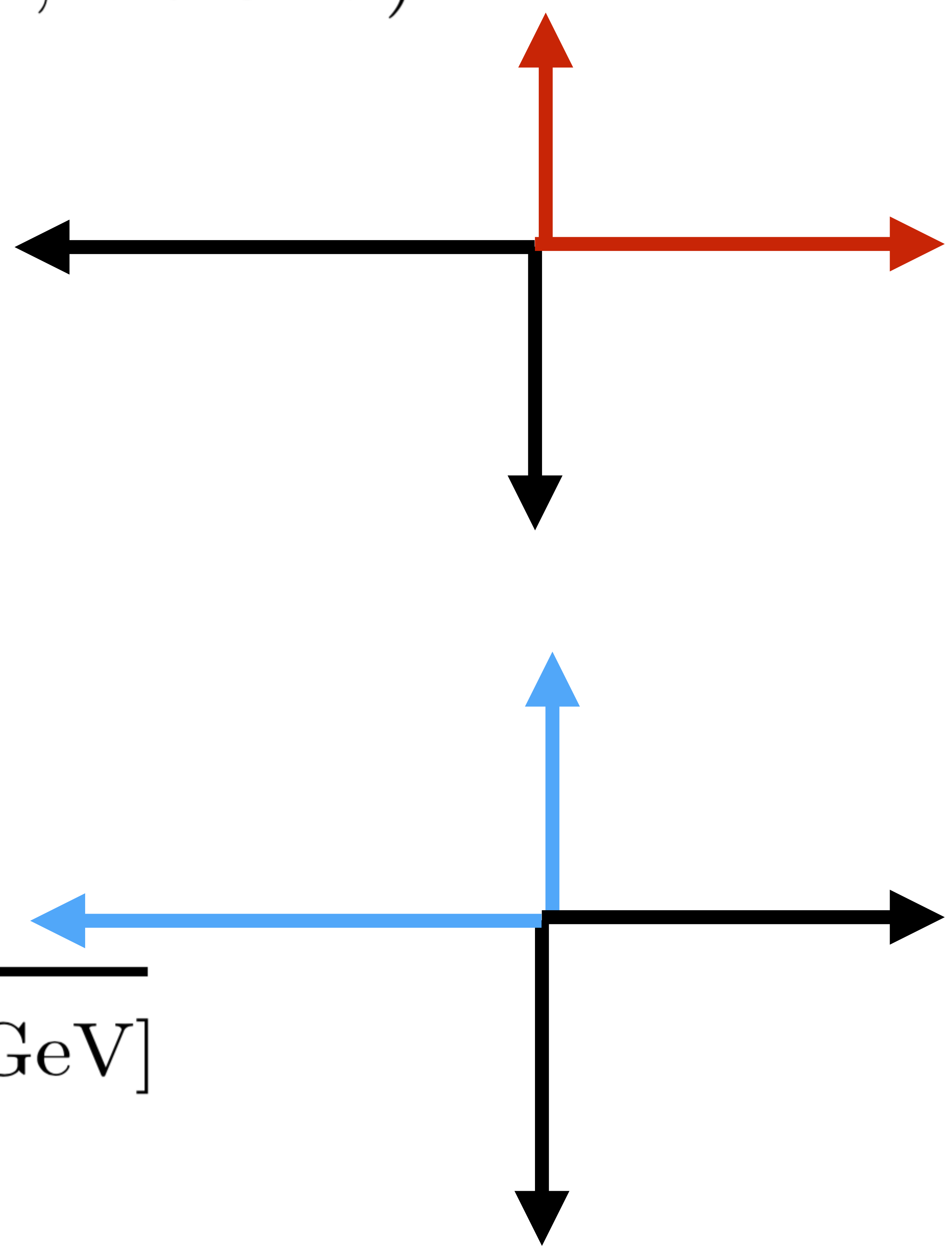


Resolved: Selection



- Good trigger efficiency overall ~ 95%
- Select jets pair that has the minimal distance to the diagonal line on the 2D mass plane
- **Minimize** the Higgs candidates **mass difference**



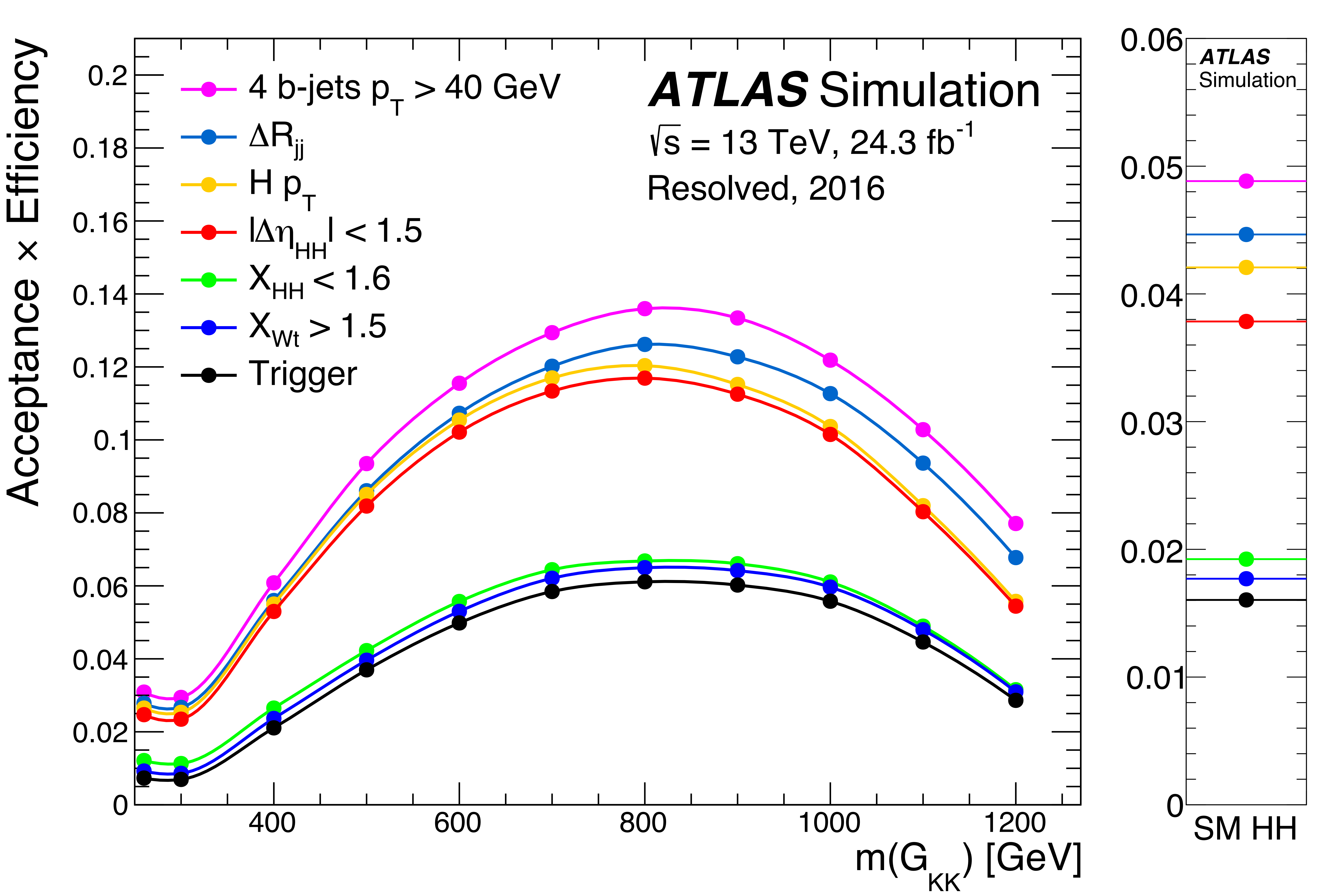


which pair?

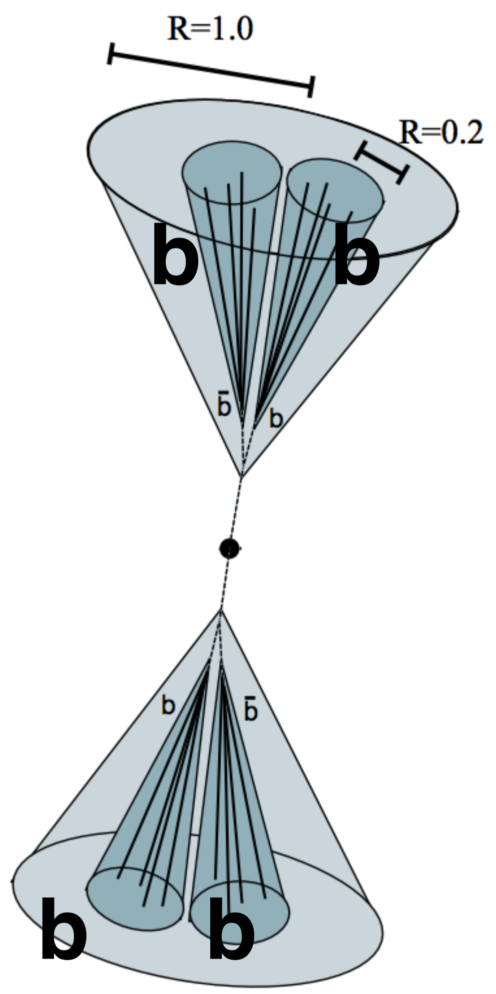
Resolved: Selection

- Good trigger efficiency overall ~ 95%
- Select jets pair that has the minimal distance to the diagonal line on the 2D mass plane
- **Fine** signal efficiency across **large** mass ranges

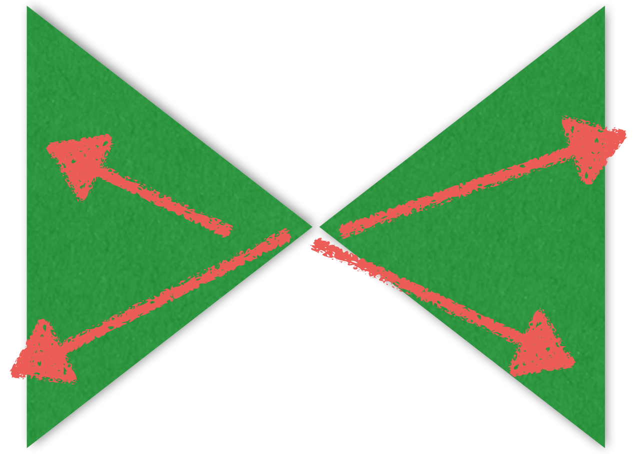
Total Acc x Efficiency



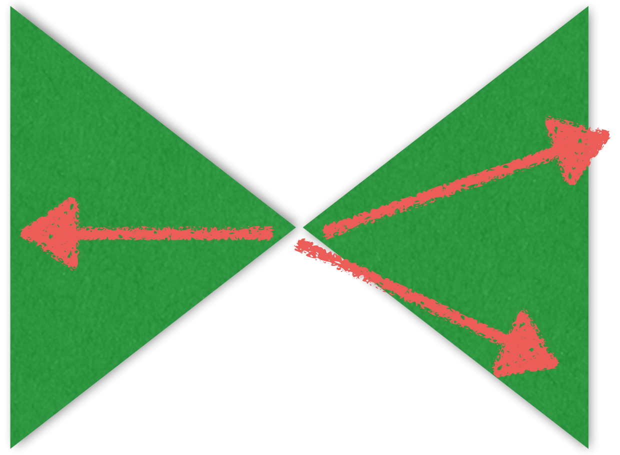
Boosted: Number of b-tagging



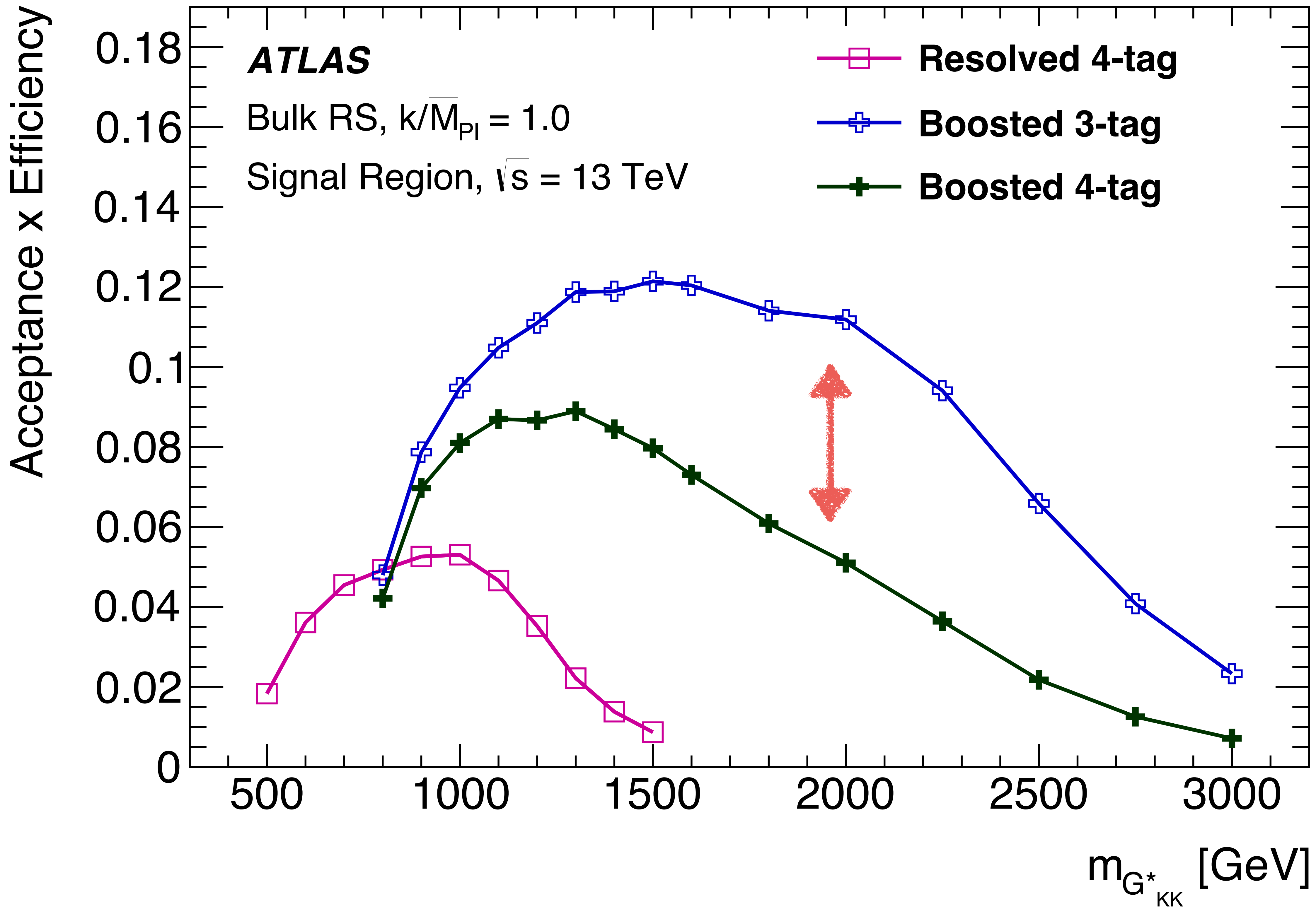
- Three Signal Regions:



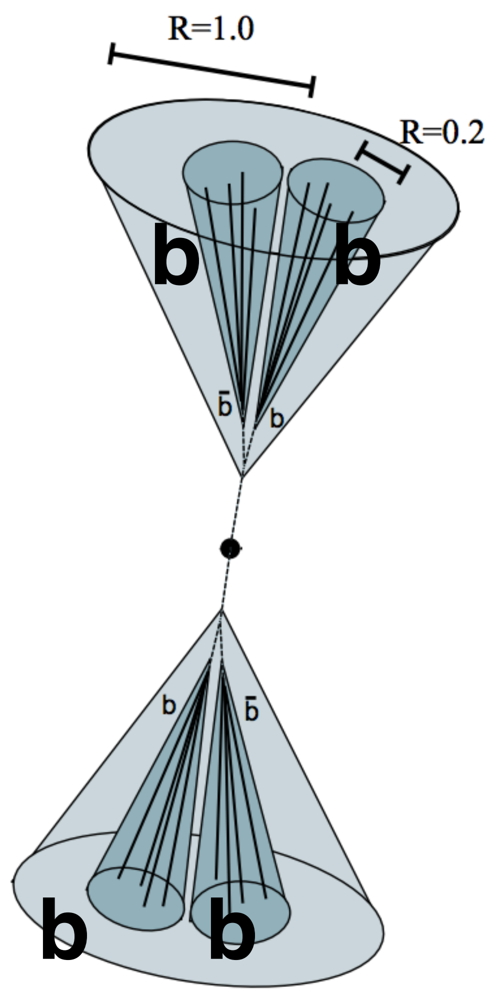
  - 4b



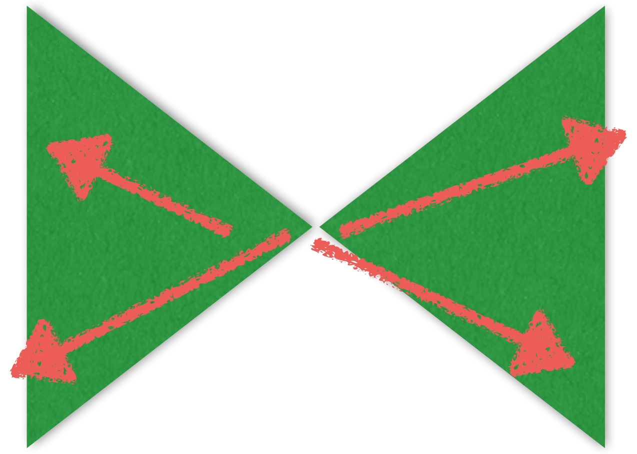
  - 3b: (recover efficiency)



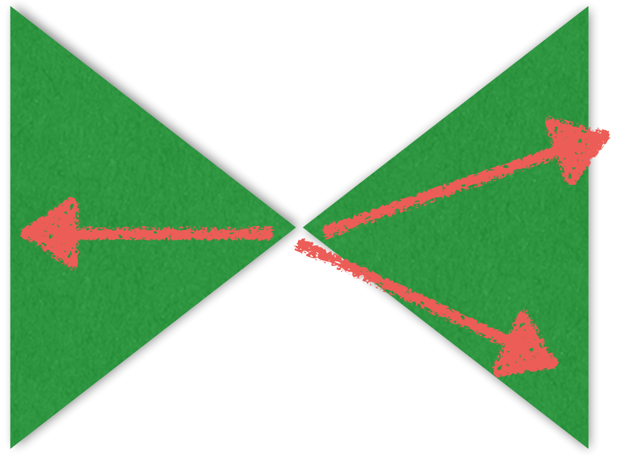
Boosted: Number of b-tagging



- Three Signal Regions:

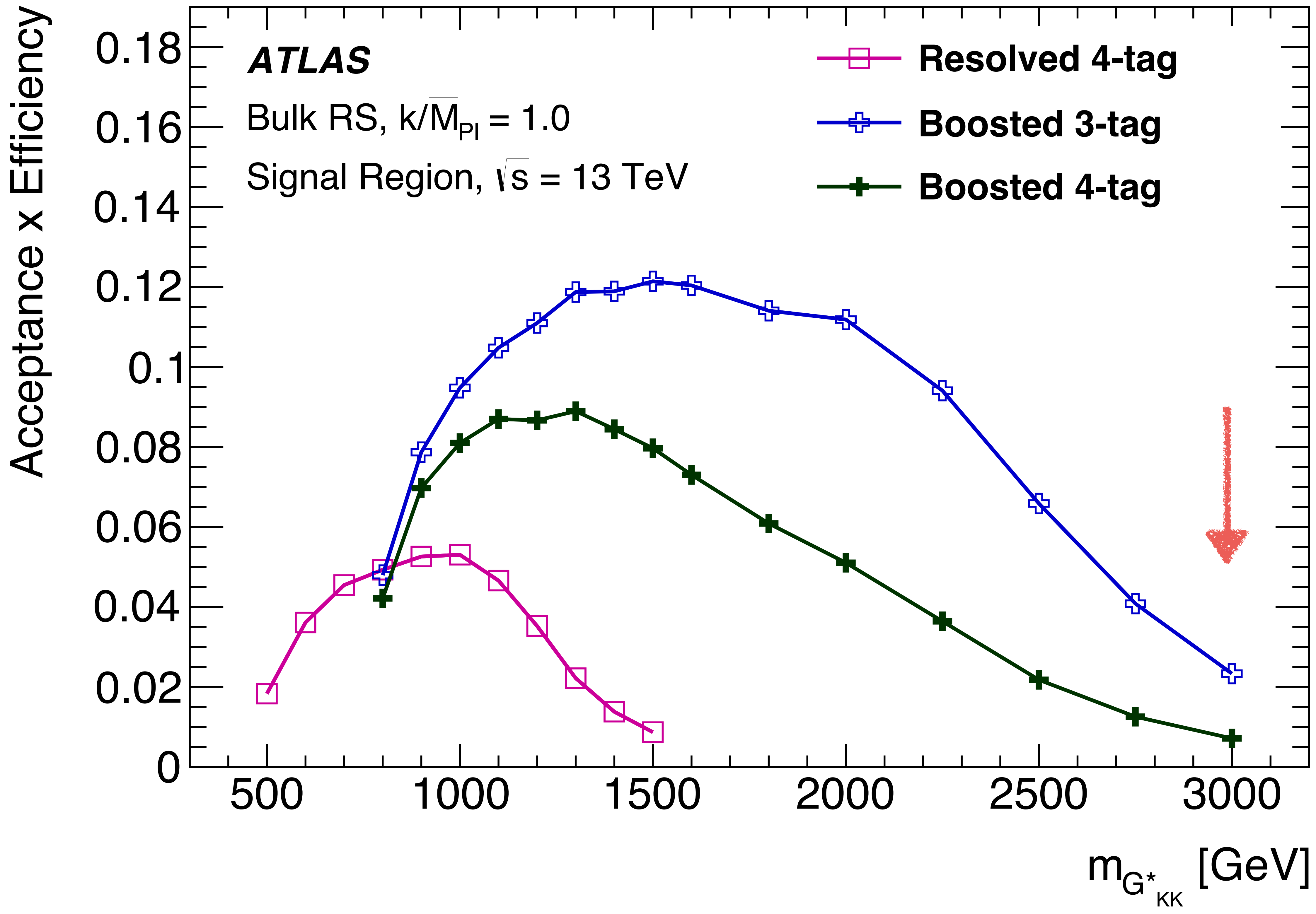


  - 4b

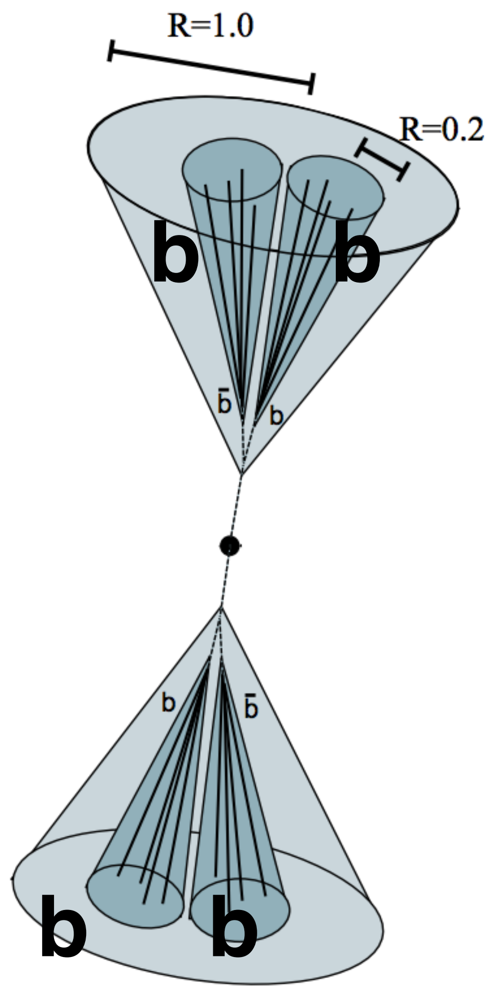


  - 3b: (recover efficiency)

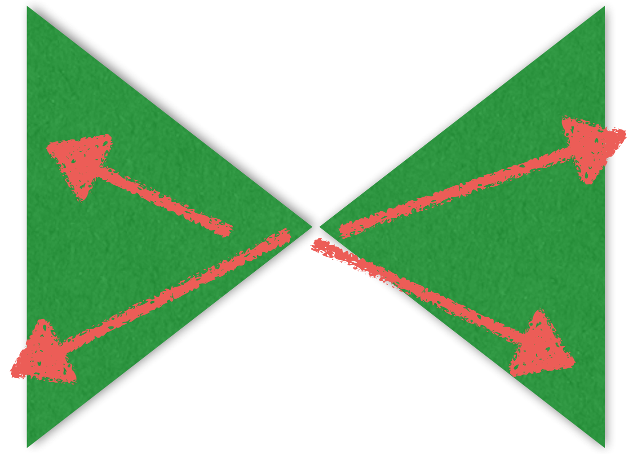
- **2.5 TeV** resonance → ~ 1200 GeV p Higgs → ΔR_{bb} ~ **0.2**
- Trackjets merge



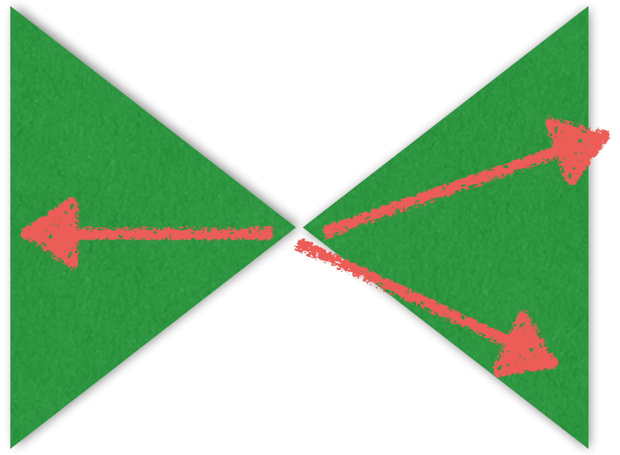
Boosted: Number of b-tagging



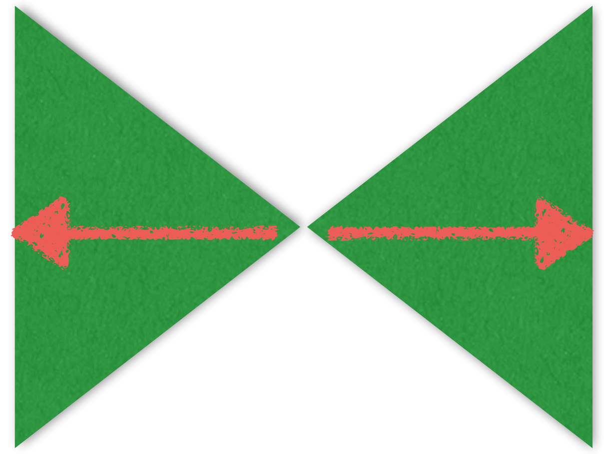
- Three Signal Regions:



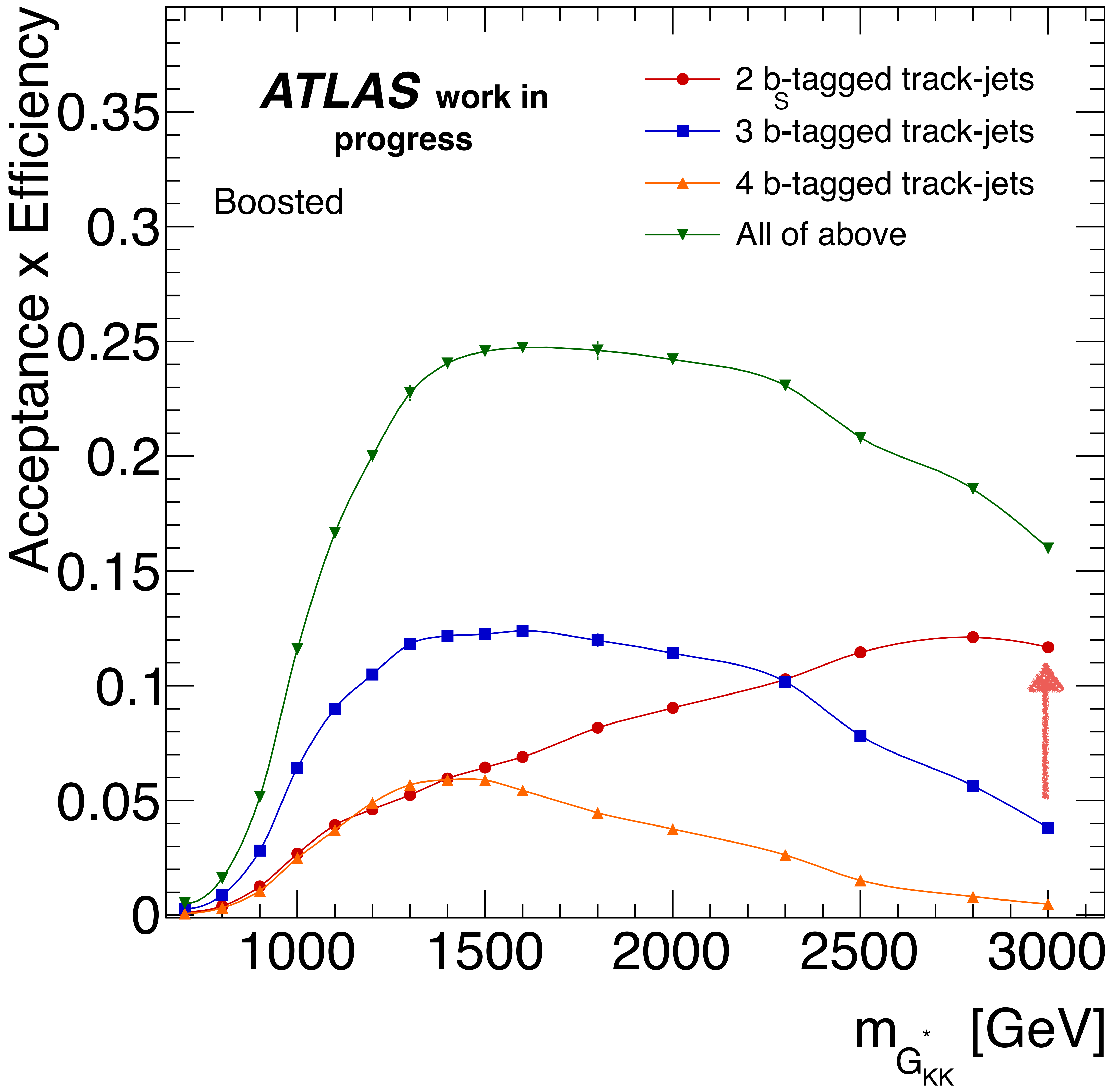
  - 4b



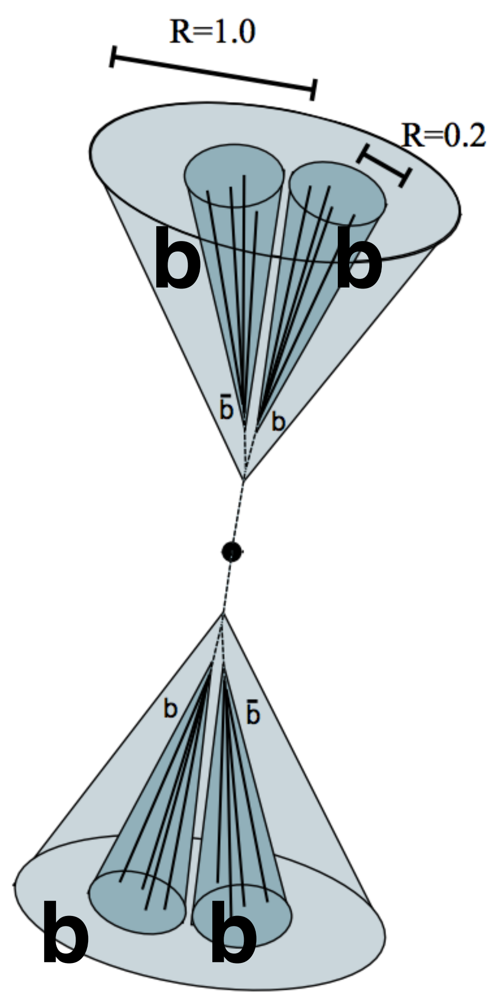
  - 3b: (recover efficiency)



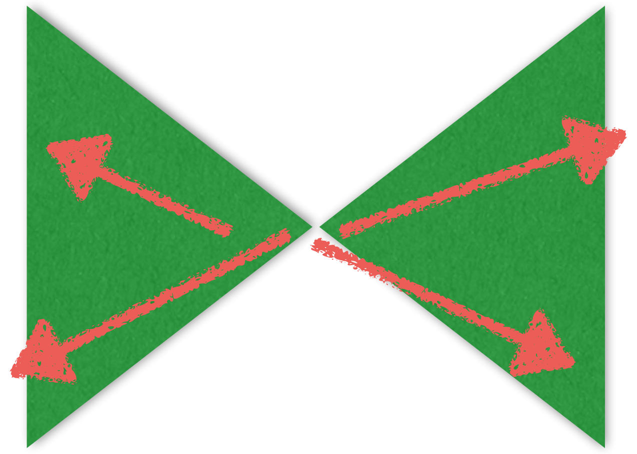
  - 2b split (merging of trackjets)



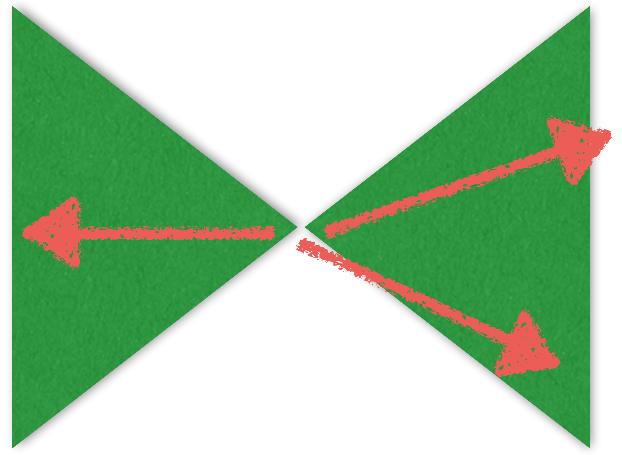
Boosted: Number of b-tagging



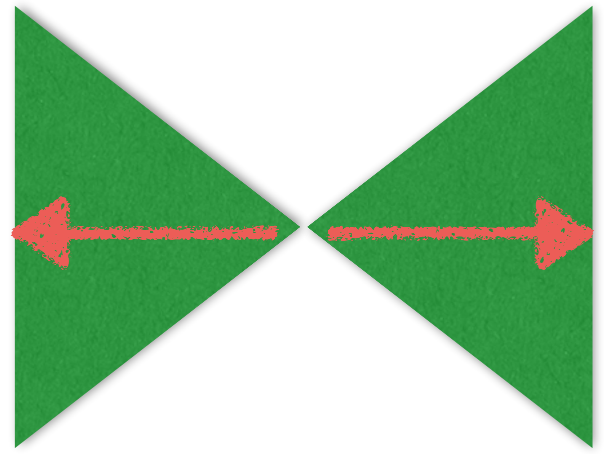
- Three Signal Regions:



  - 4b



  - 3b: (recover efficiency)



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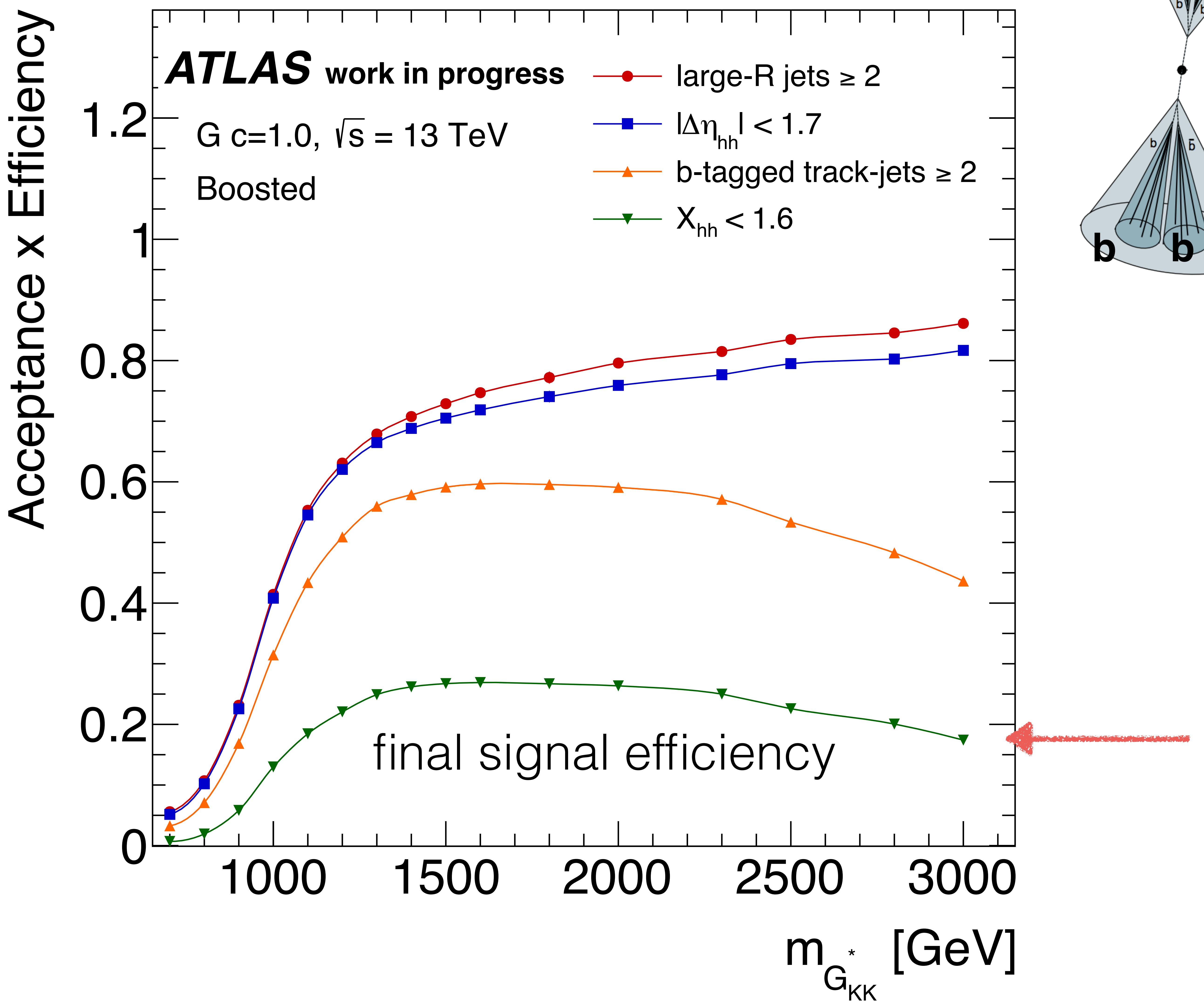
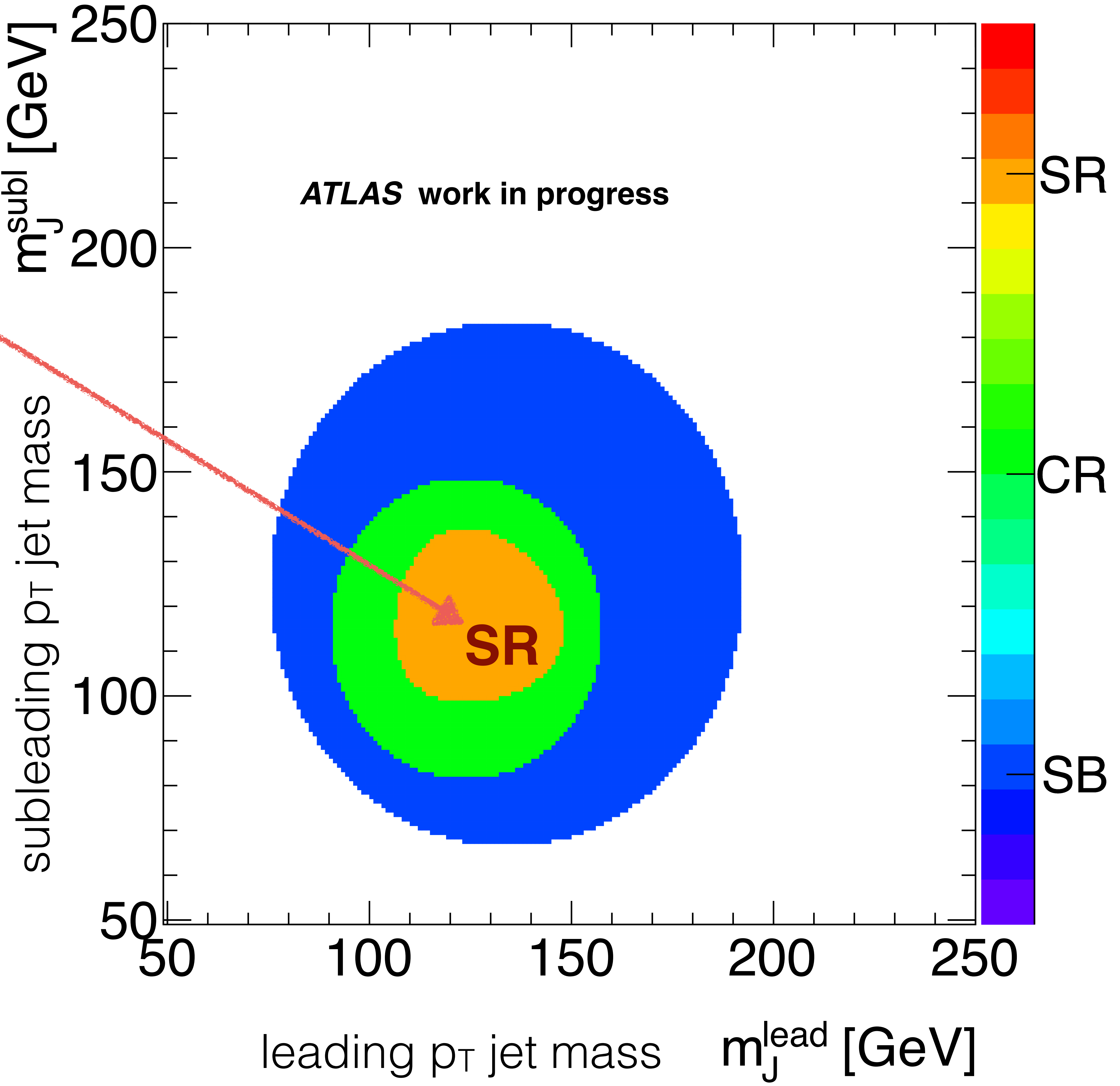


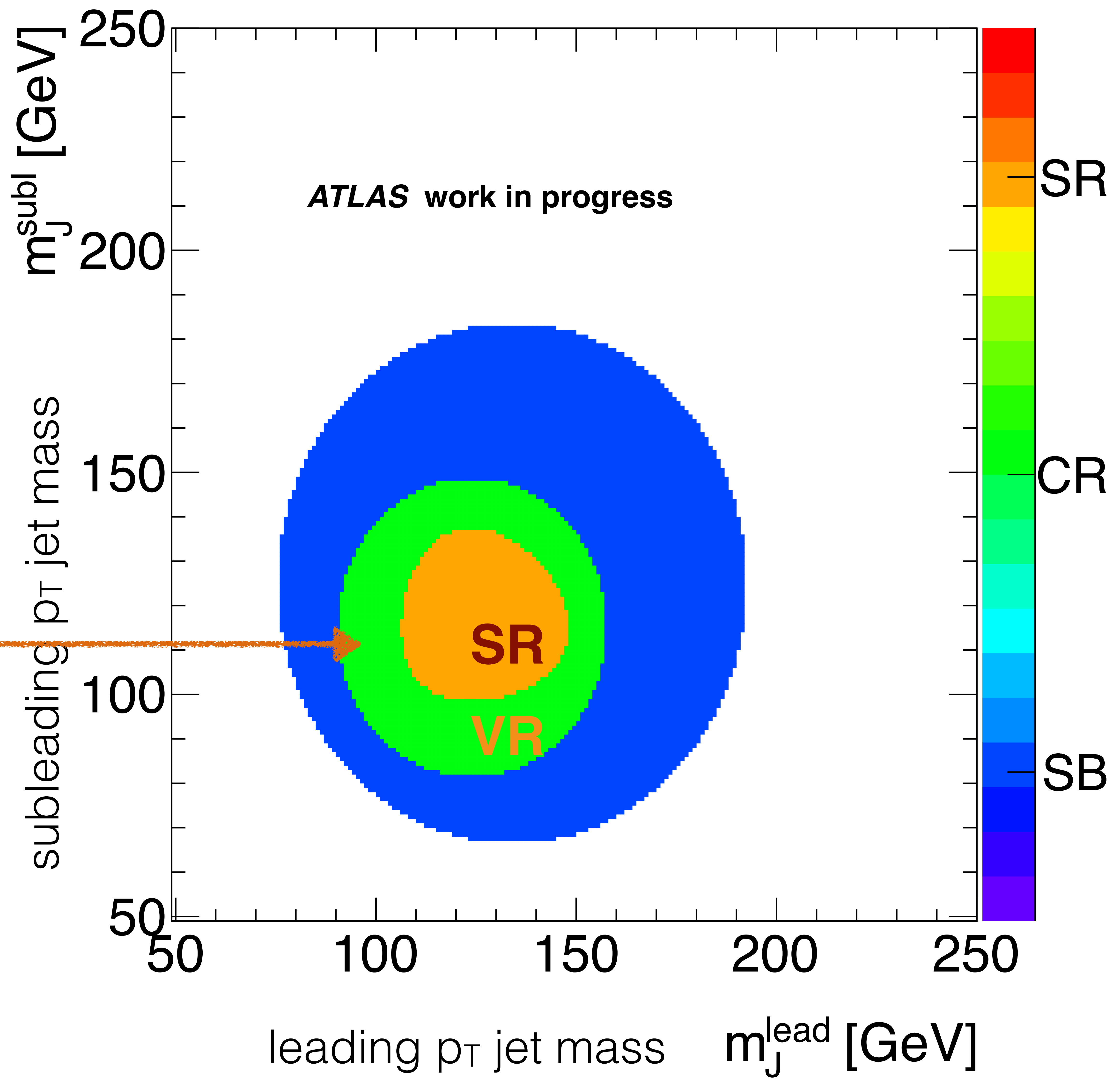
Regions: Two Higgs Mass Plane

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



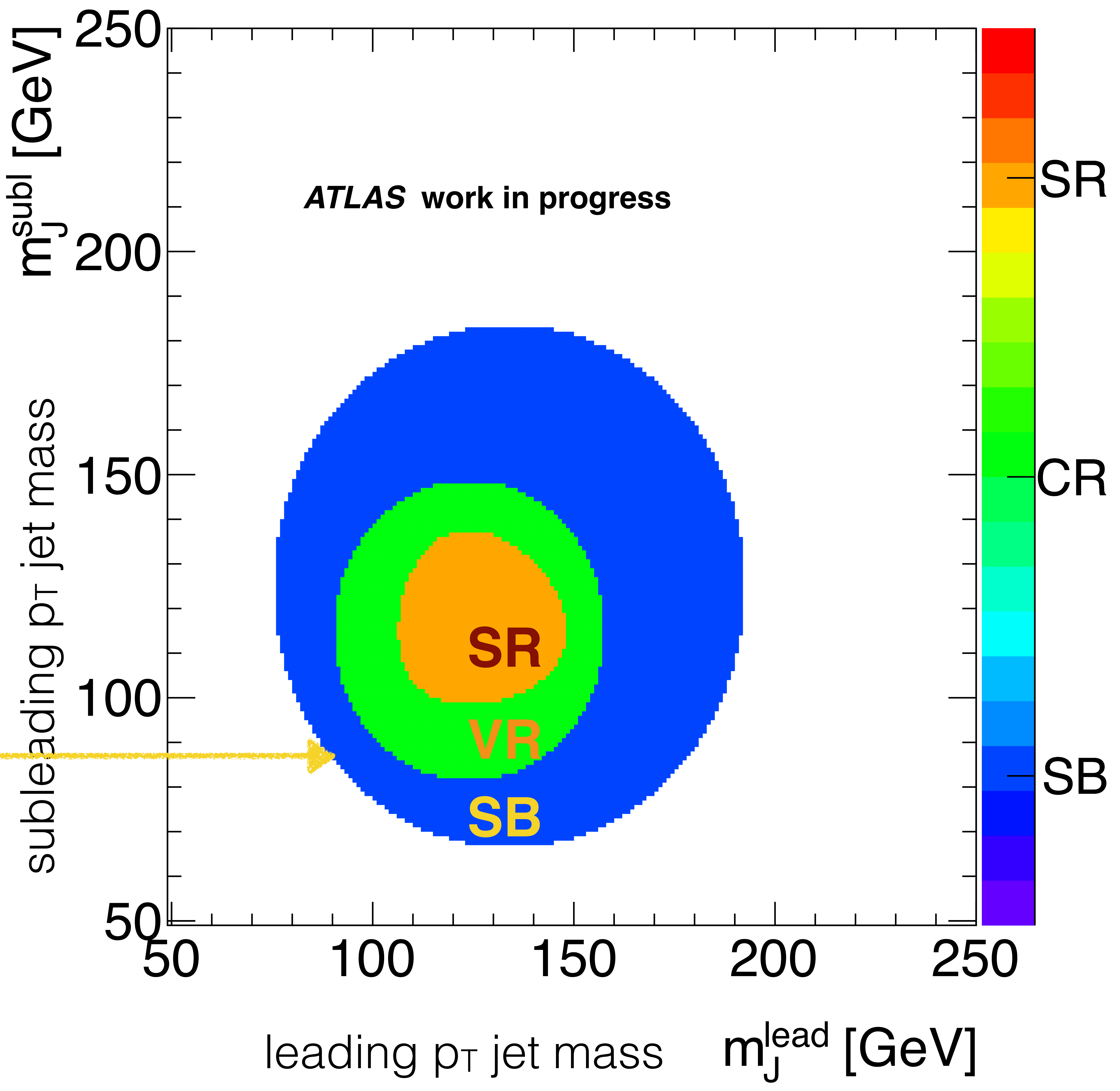
Regions: Two Higgs Mass Plane

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



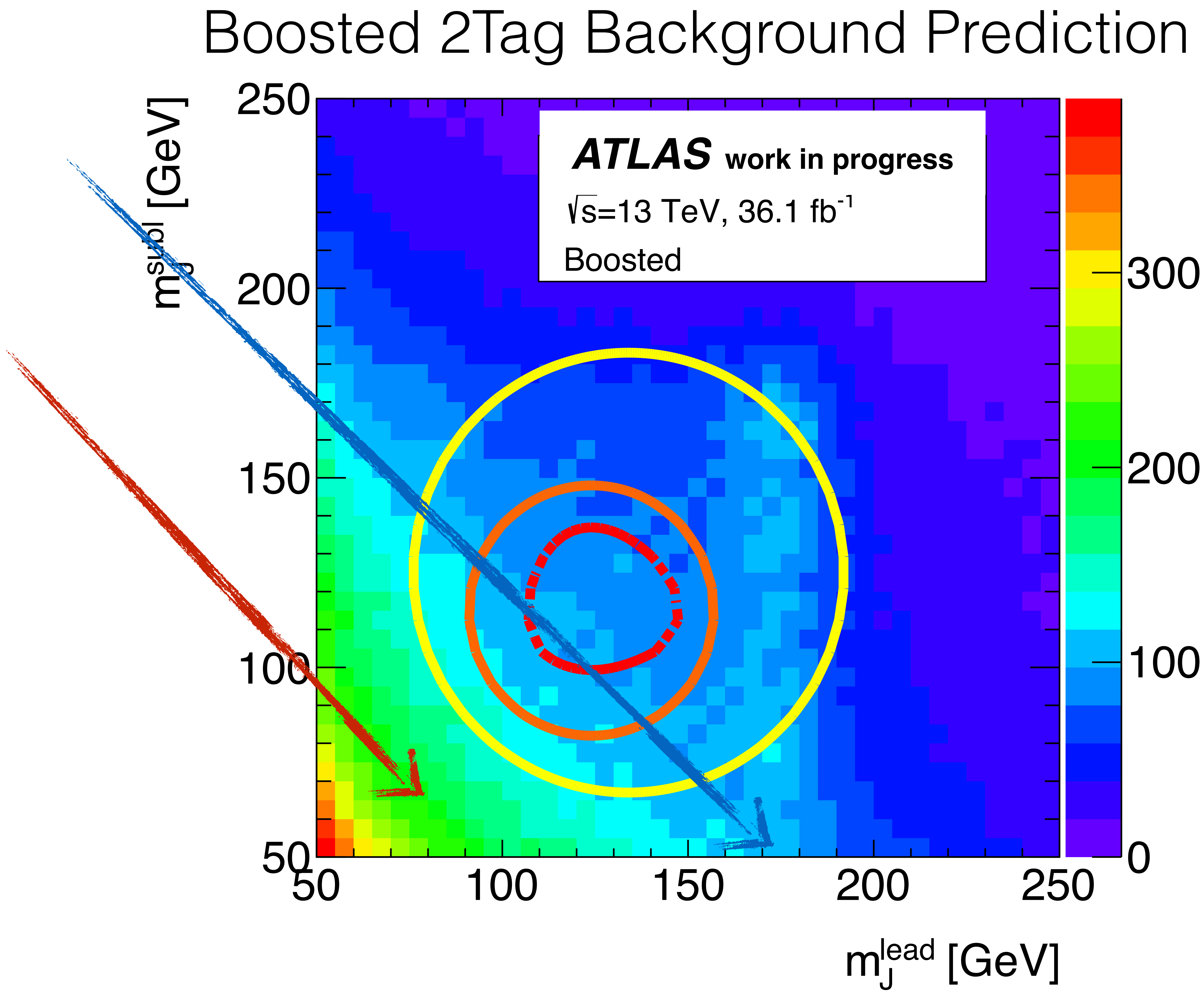
Regions: Two Higgs Mass Plane

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



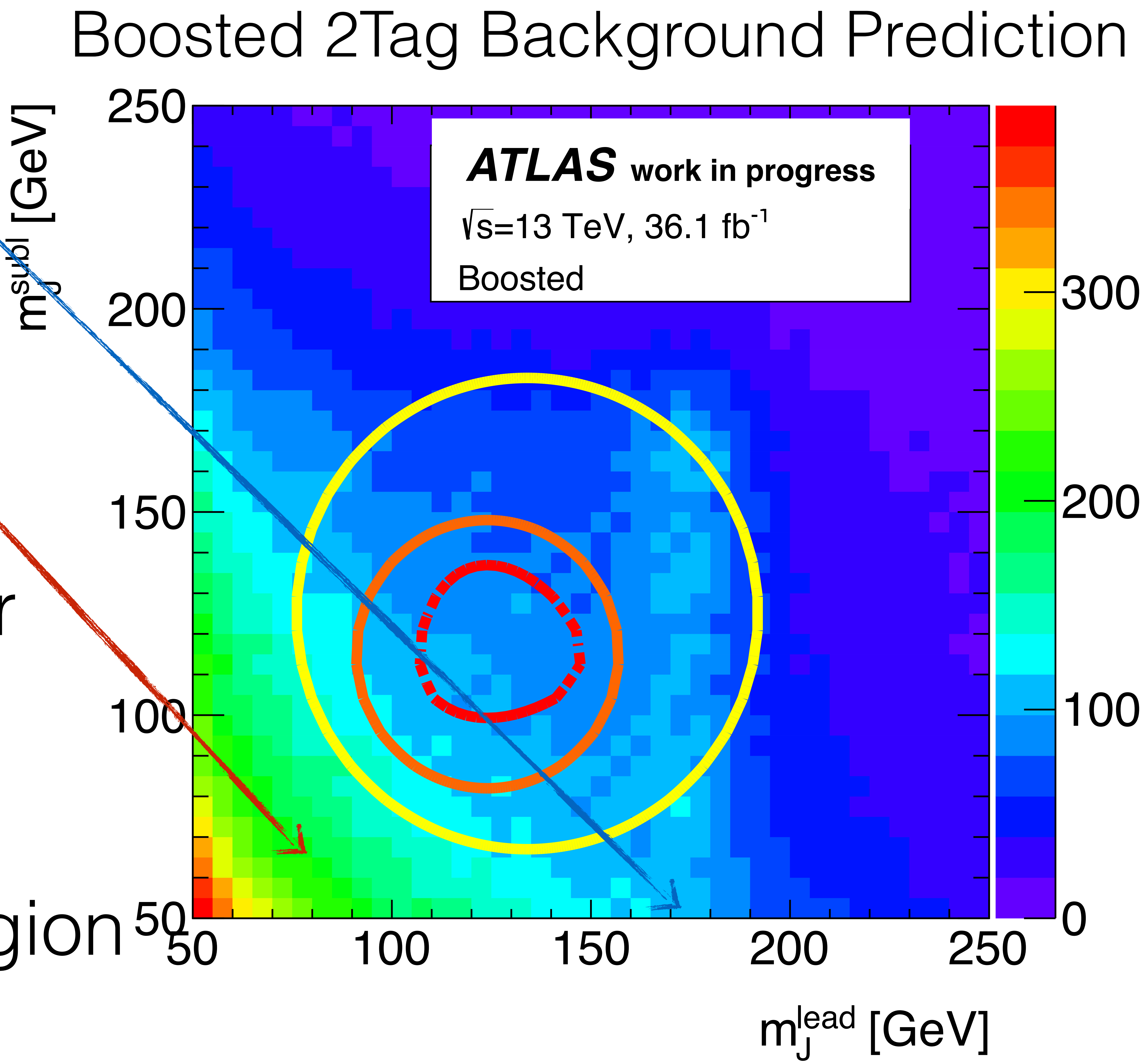
Background

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



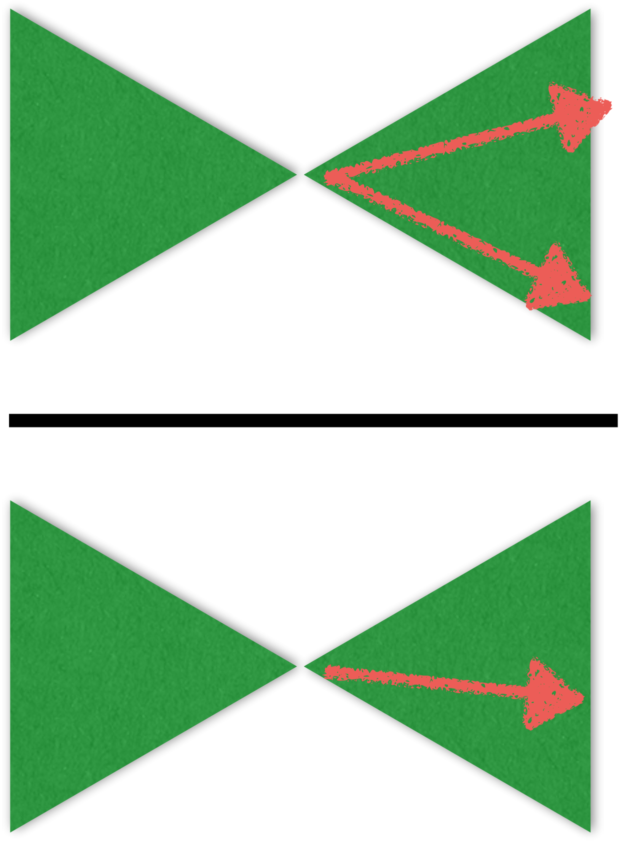
Background

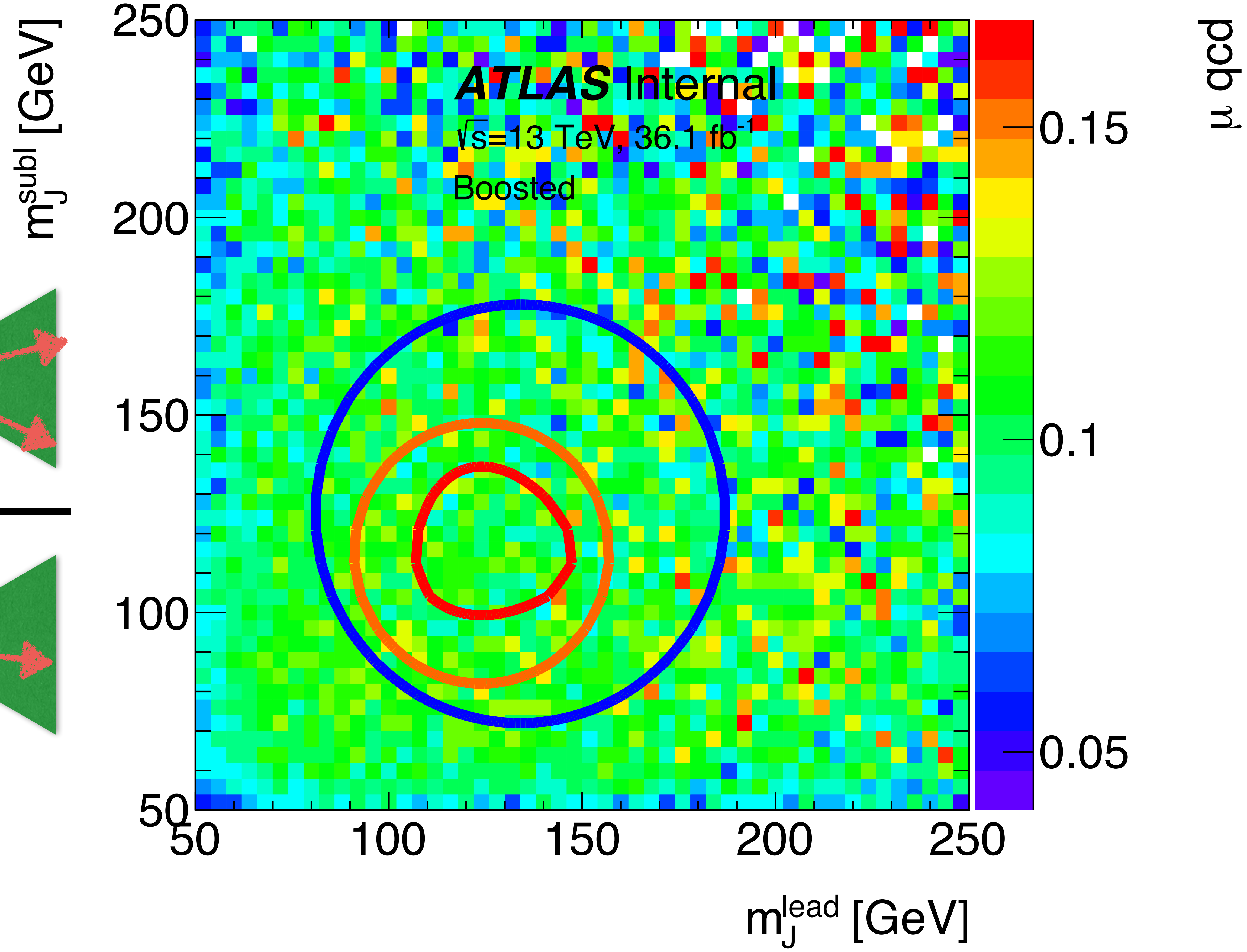
- Background:
  - 10-15% **ttbar**—MC
  - 90-85% **qcd**—data driven
- Data driven because heavy flavor MC is hard to simulate
- Generalized ABCD method: Use lower-b-tag, lower-signal yield region to model higher-b-tag regions



Hard work: Constant muqcd validation

- TwoTag/OneTag data ratio on 2D mass plane
- SB/VR/SR ratio is the same; outside SB is different





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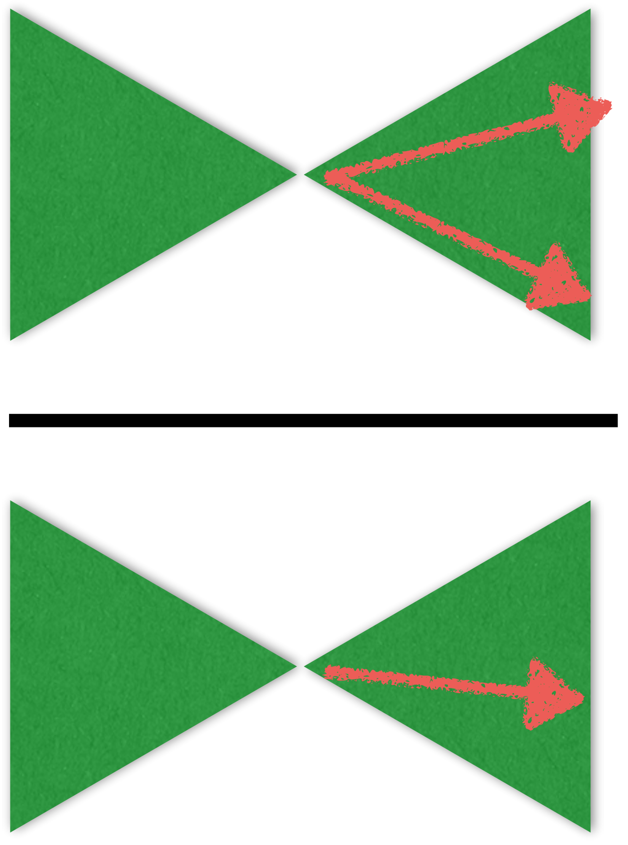
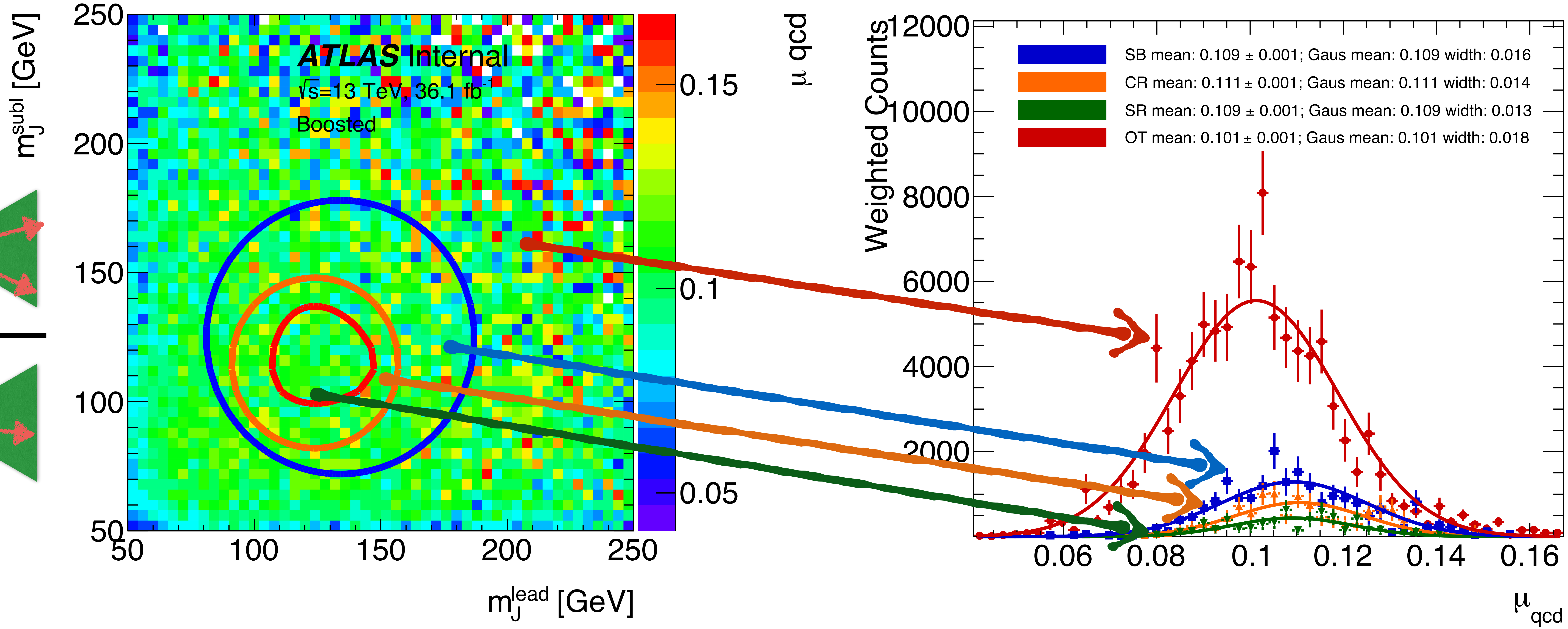
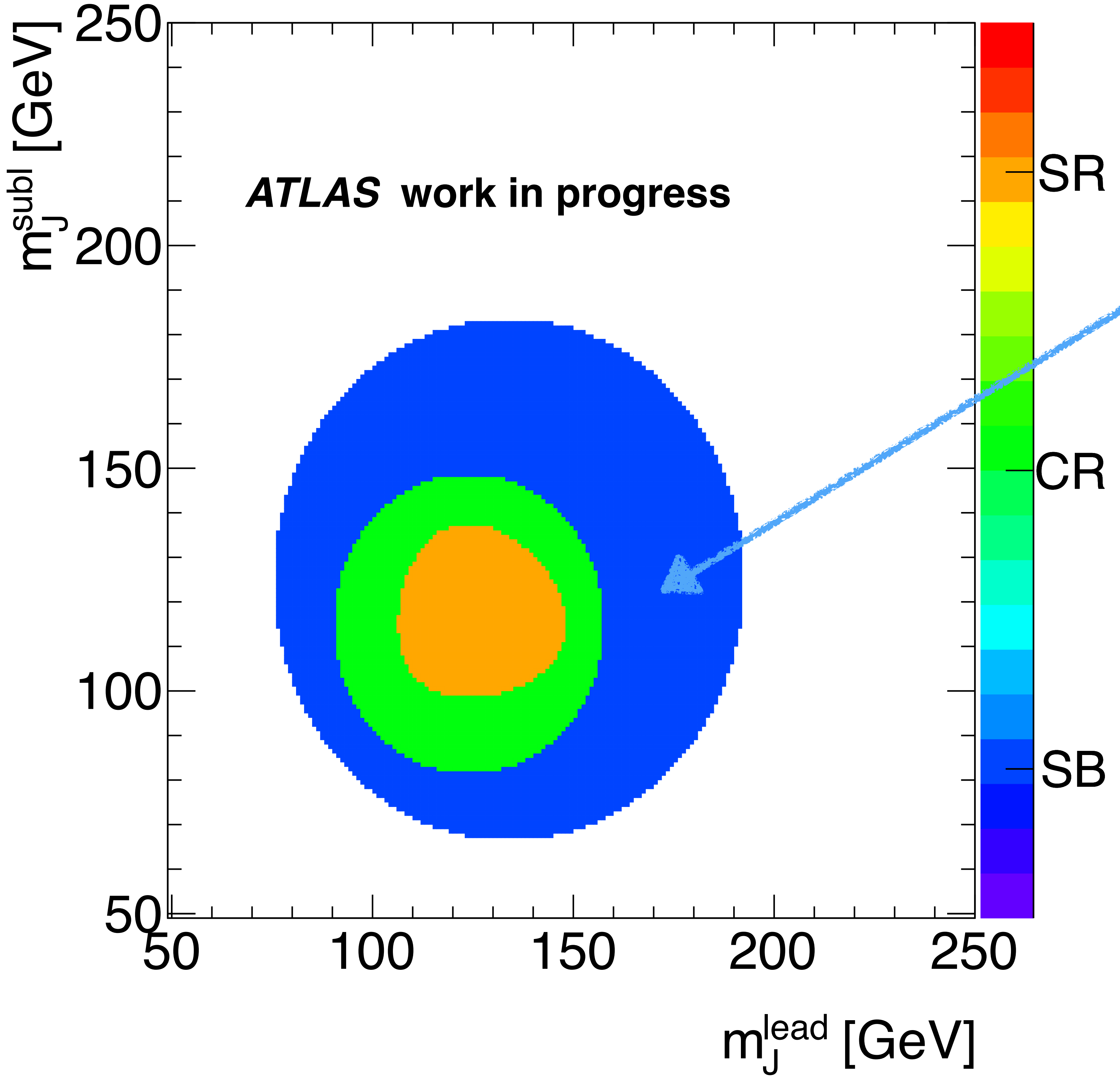
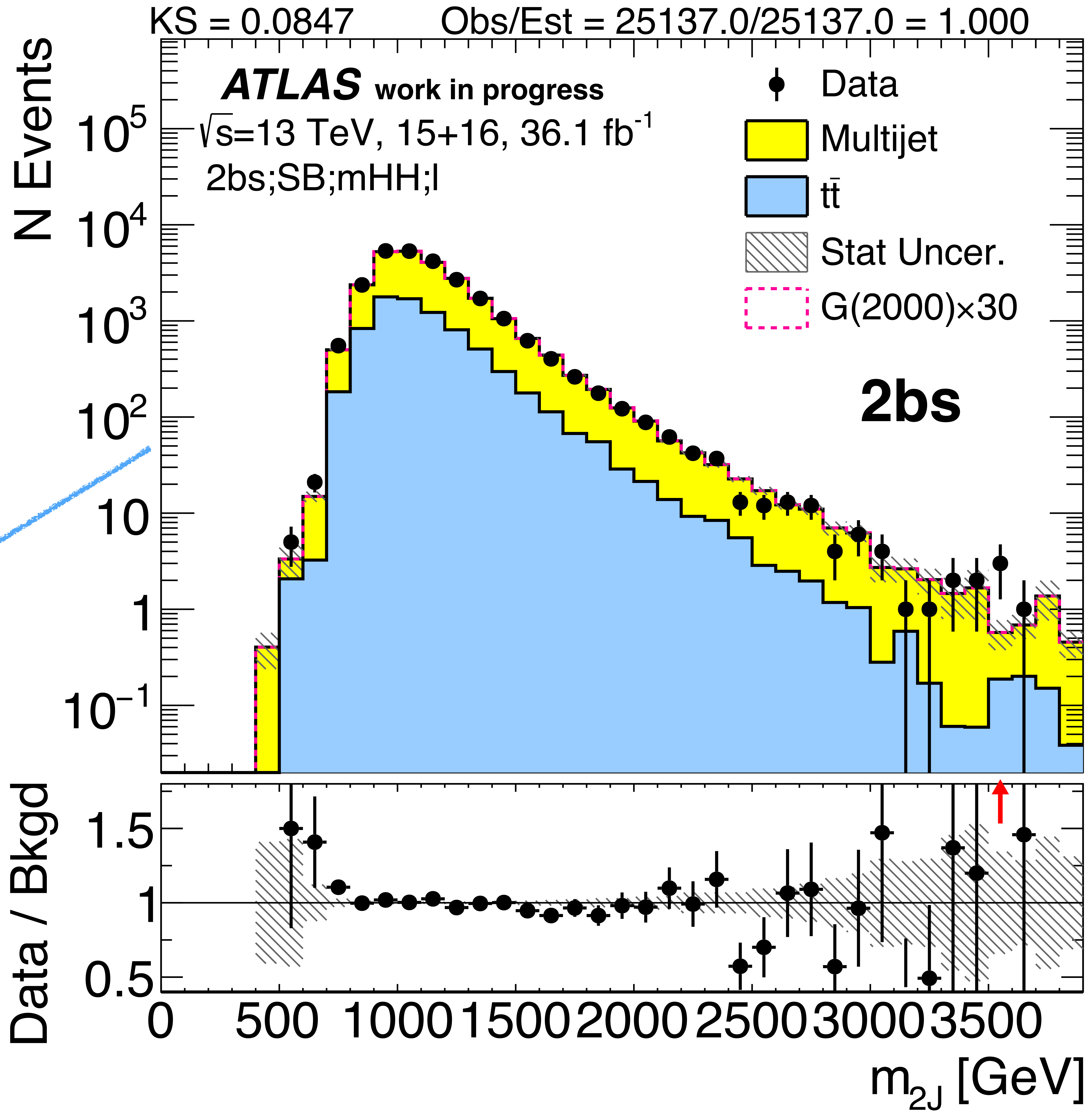




Sideband Region MJJ

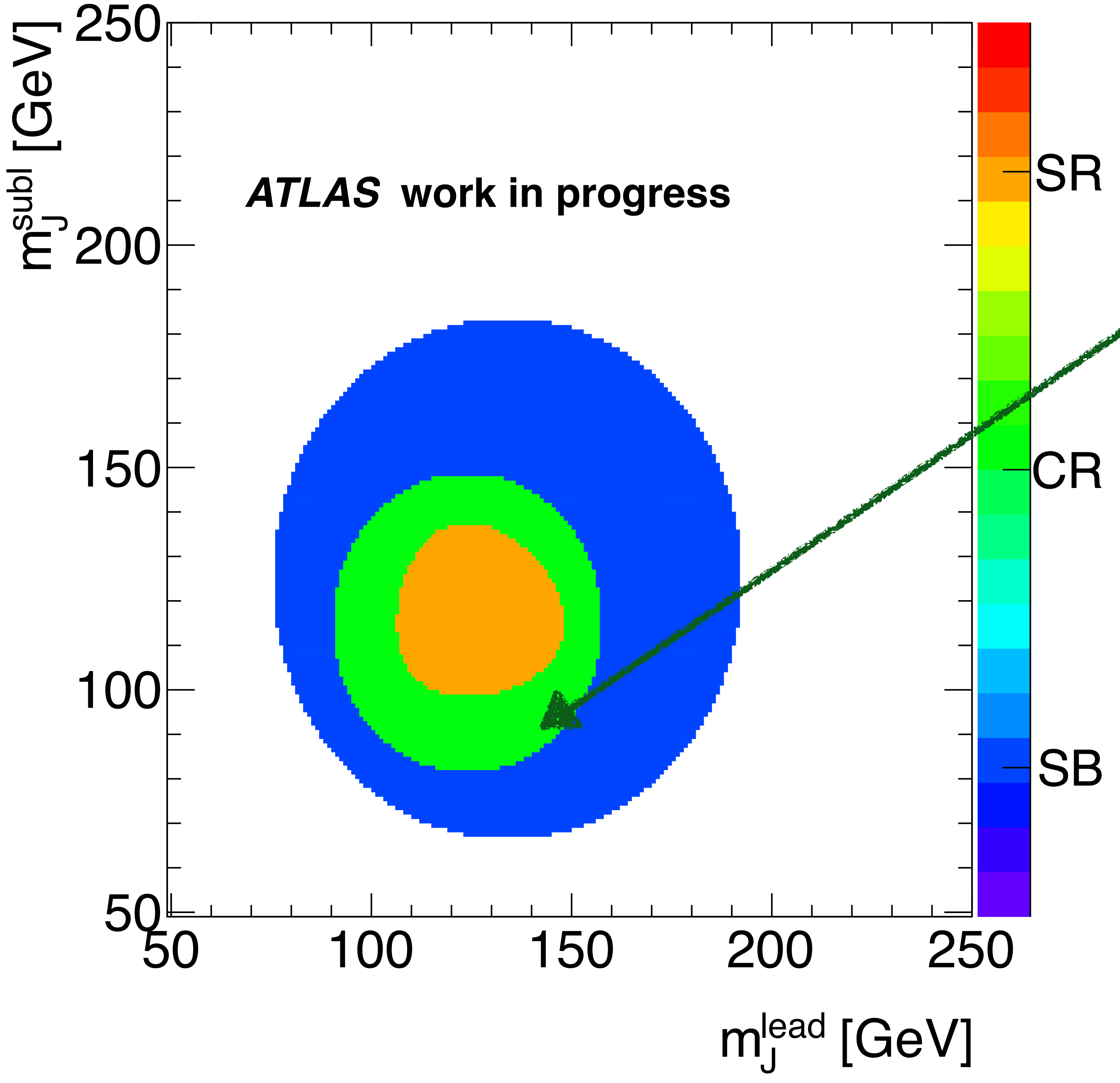
- **Good** agreement in shape; normalization agree by construction

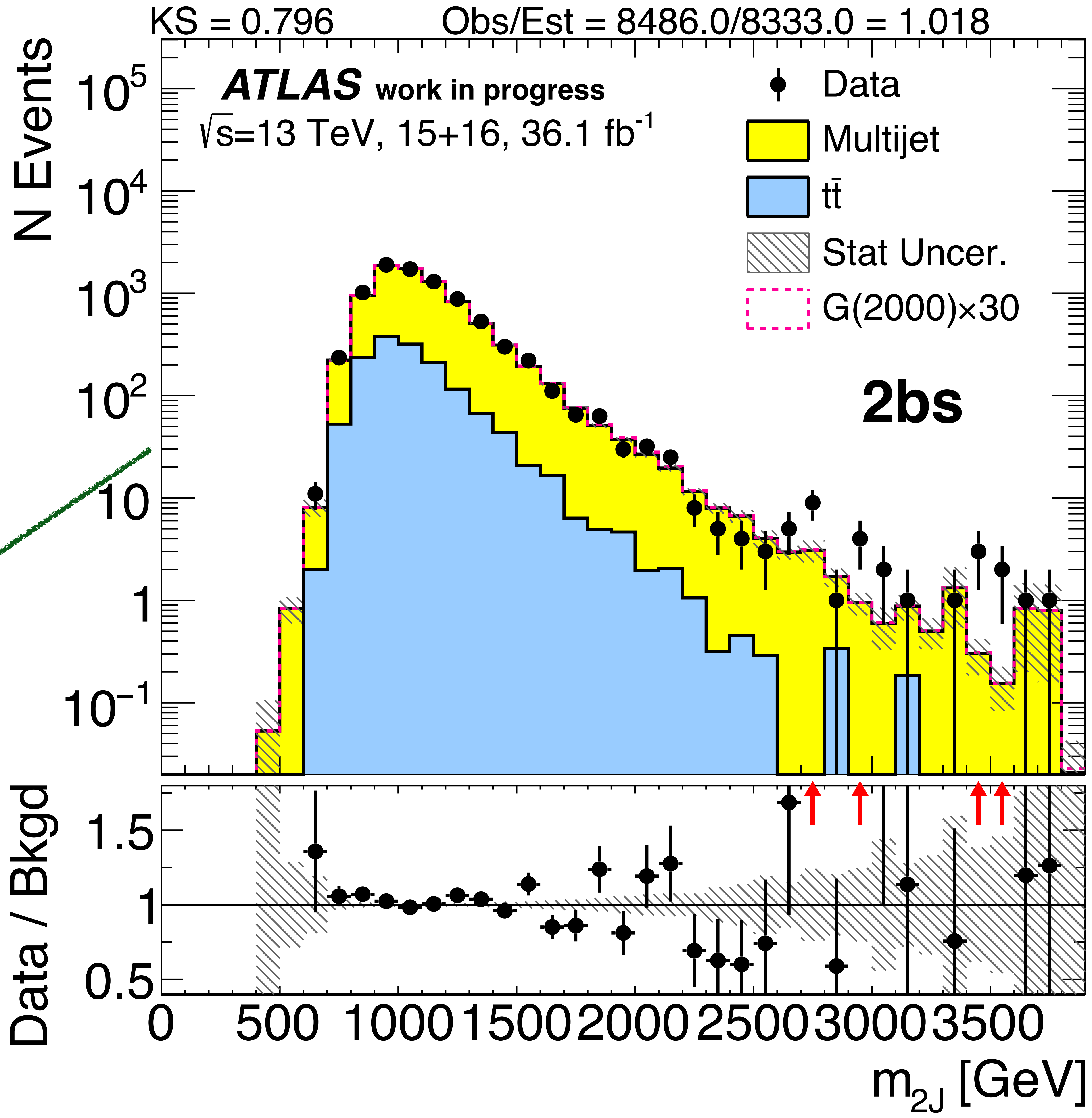




Validation Region MJJ

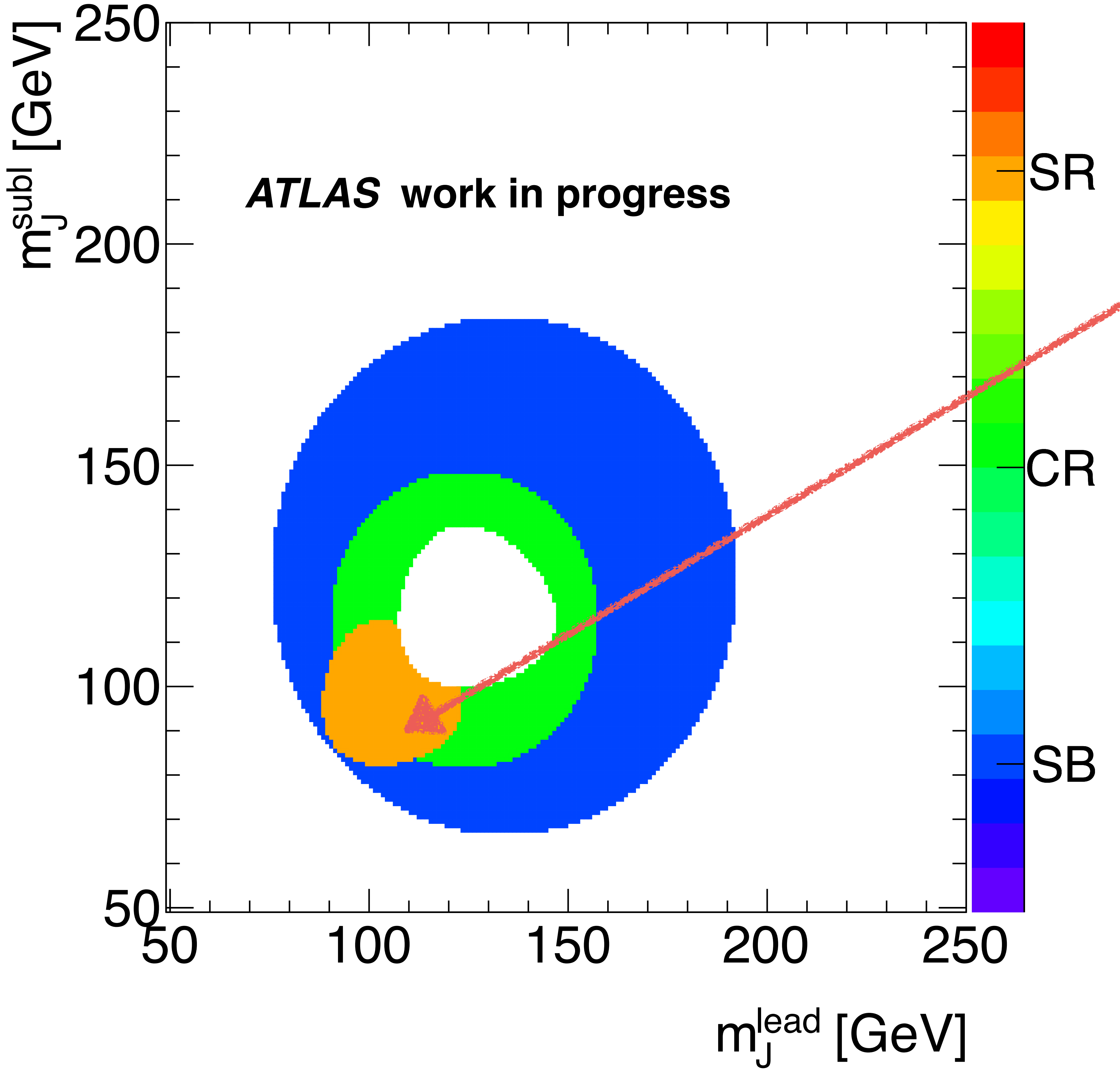
- **Good** agreement; from this closure test, **derive systematics**

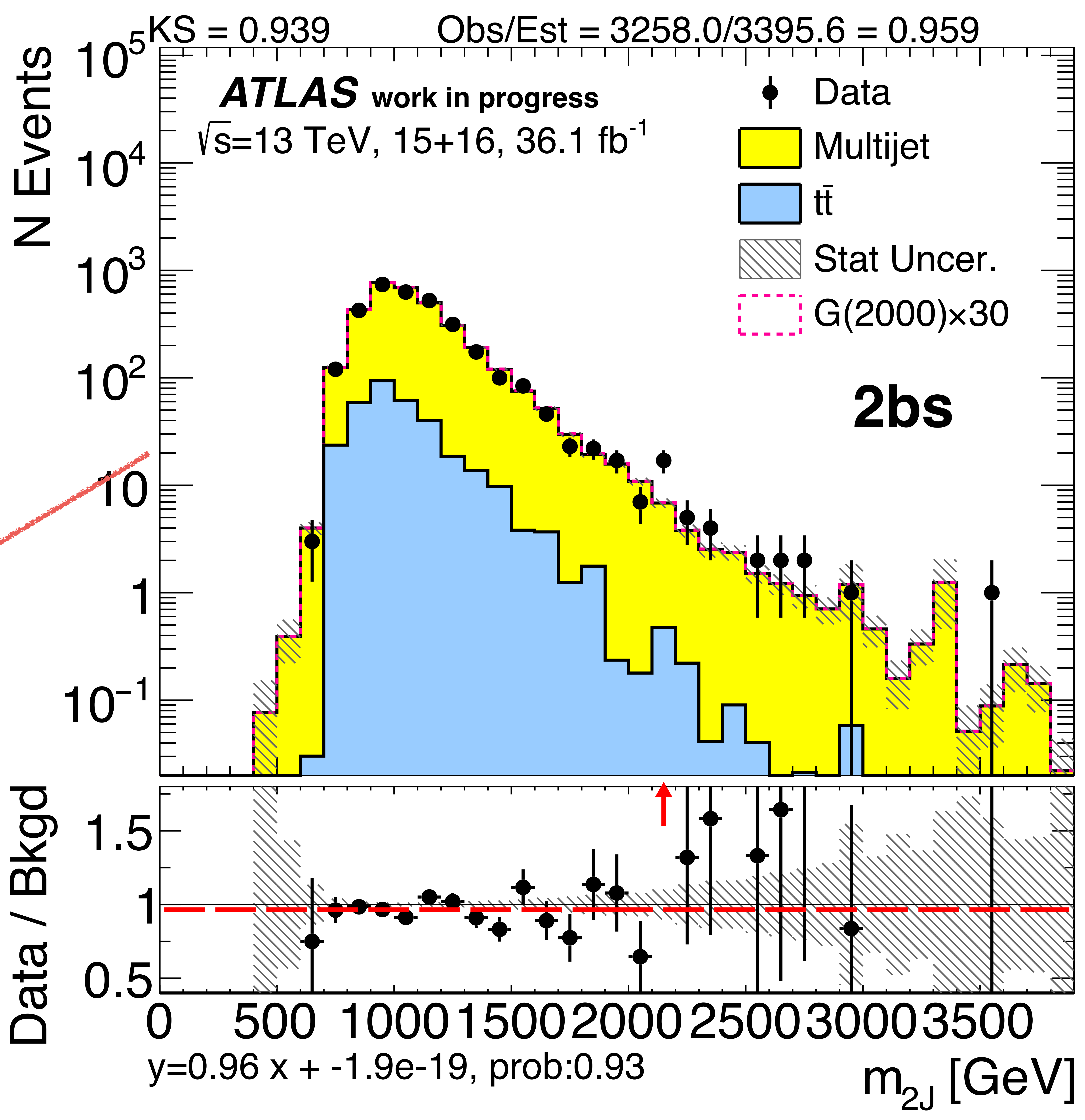




Low Mass Validation

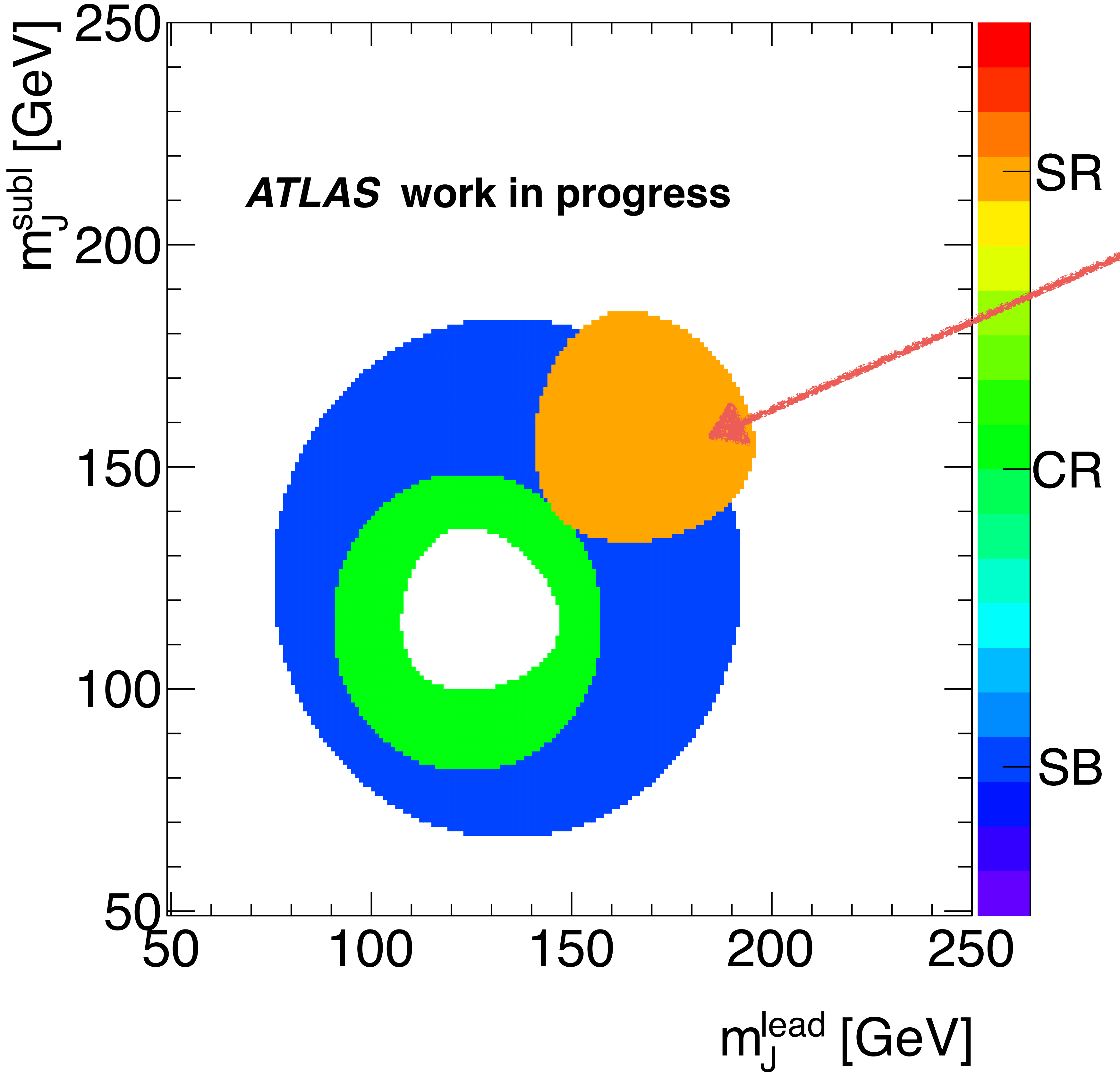
- Extra low mass QCD enriched region is used for unblinding tests—looks fine!

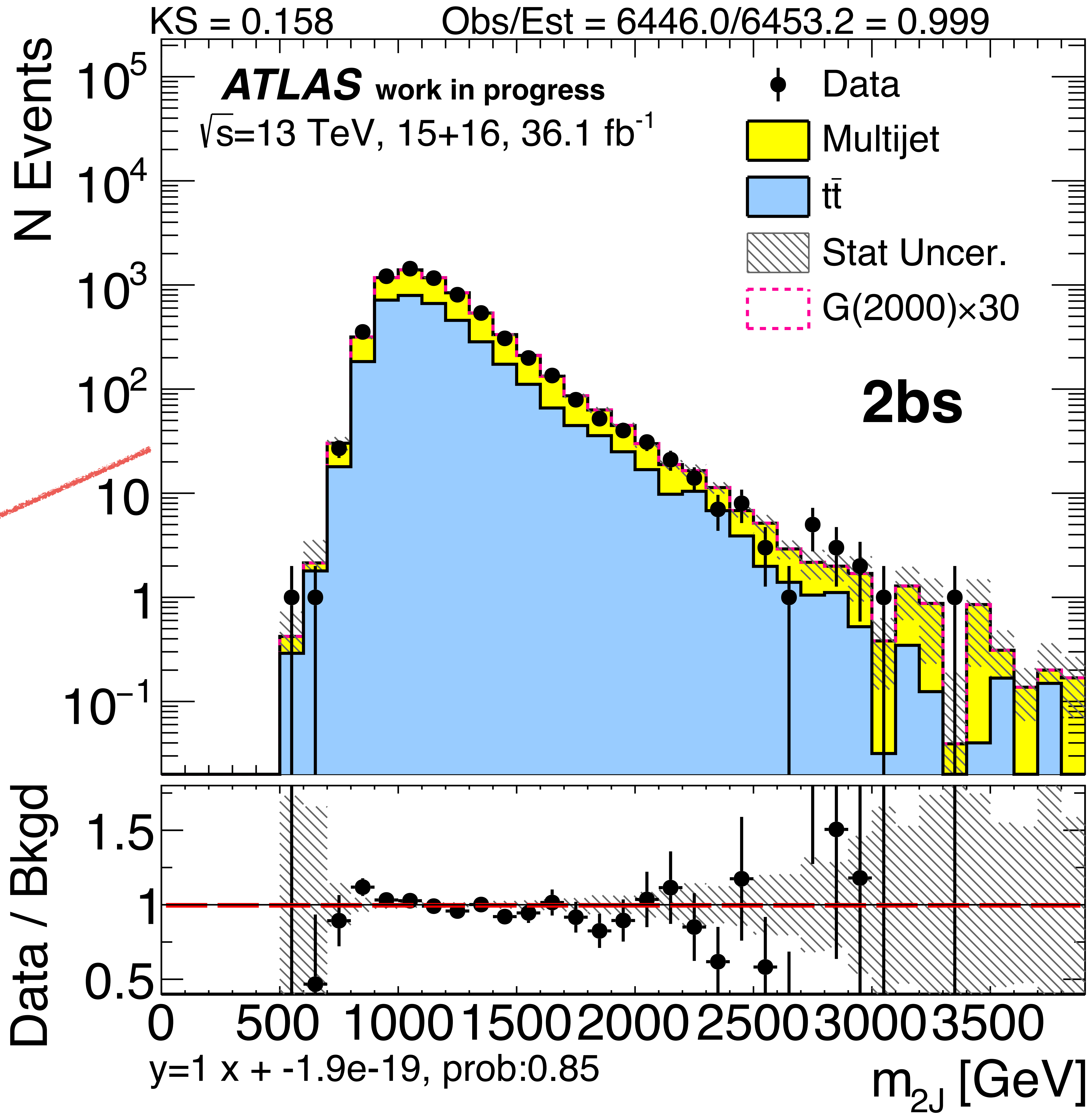




High Mass Validation

- Extra high mass ttbar enriched region is also used for unblinding tests—looks fine!





Overview of Systematics

- Signal **MC uncertainty** mainly comes from **b-tagging**

	Two-tag			Three-tag			Four-tag		
Source	Background	G_{KK}	Scalar	Background	G_{KK}	Scalar	Background	G_{KK}	Scalar
Luminosity	-	2.1	2.1	-	2.1	2.1	-	2.1	2.1
JER	0.25	0.74	1	1.4	0.93	0.93	0.45	1.1	1.5
JMR	0.52	12	12	1.4	12	13	7.9	13	14
JES/JMS	0.43	1.7	2.1	2.0	1.9	2.2	1.3	3.7	5.7
b-tagging	0.83	27	29	0.48	2	2.9	1.1	28	28
Bkgd estimate	2.8	-	-	5.8	-	-	16	-	-
Statistical	0.6	1.2	1.3	1.3	1.0	1.1	3.1	1.6	1.9
Total Syst	3.1	30	32	6.6	13	14	18	31	32

Overview of Systematics

- Signal **MC uncertainty** mainly comes from **b-tagging**
- Background modeling **normalization uncertainty** is dominated by validation region non-closure tests
- **Shape uncertainty** is also applied, derived from control region

	Two-tag			Three-tag			Four-tag		
Source	Background	G_{KK}	Scalar	Background	G_{KK}	Scalar	Background	G_{KK}	Scalar
Luminosity	-	2.1	2.1	-	2.1	2.1	-	2.1	2.1
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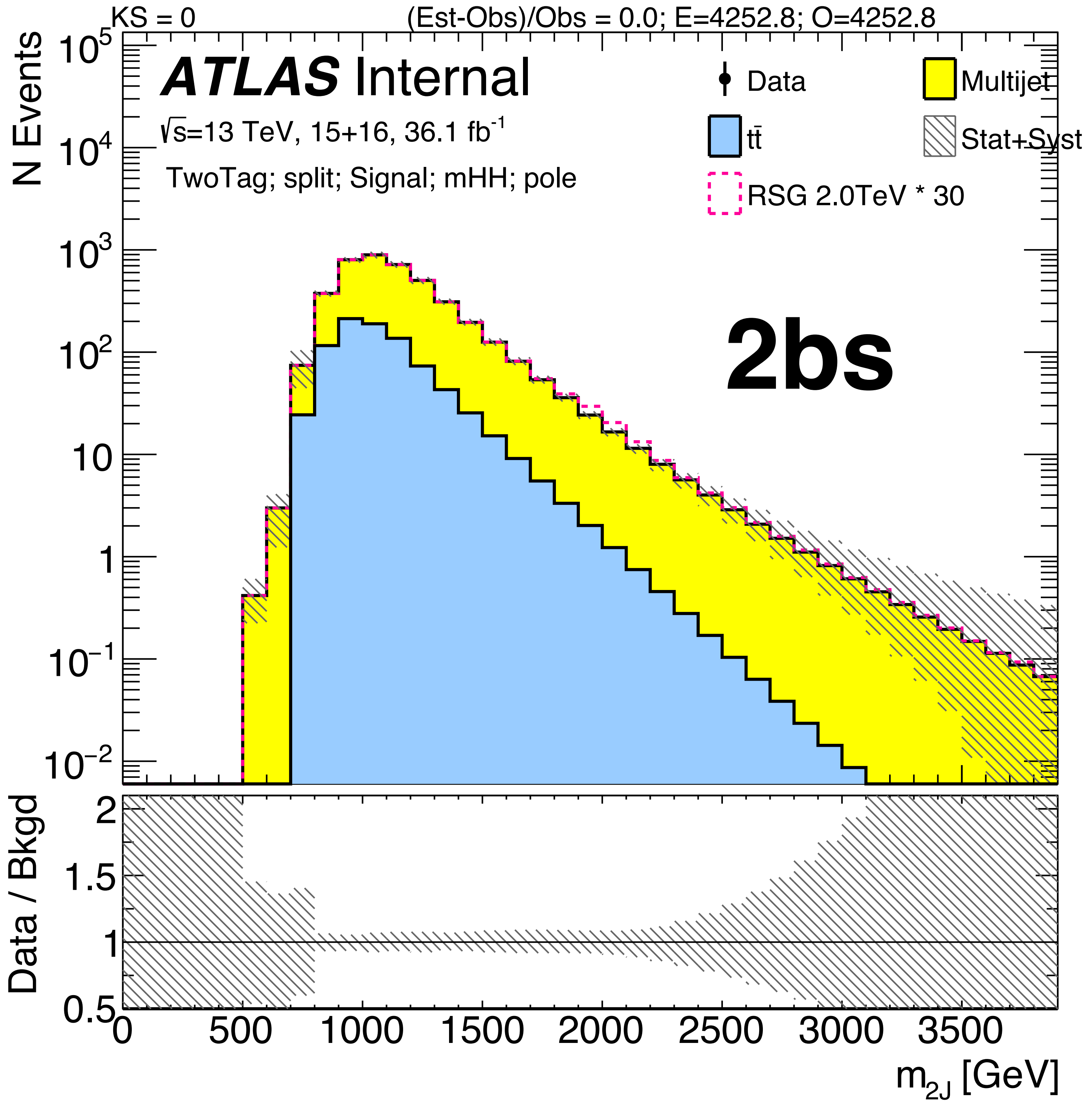
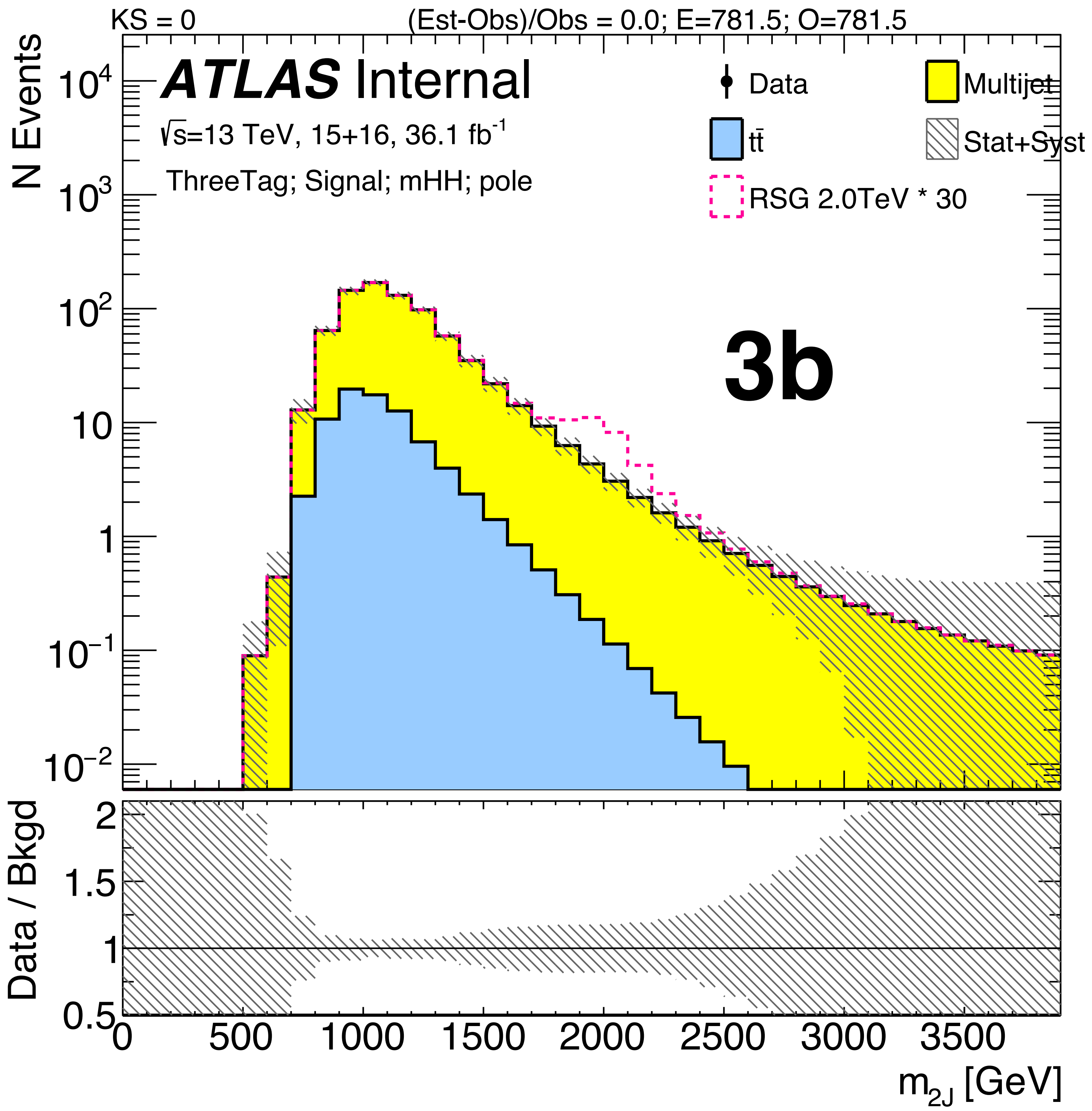
Search for di-Higgs to 4b in ATLAS

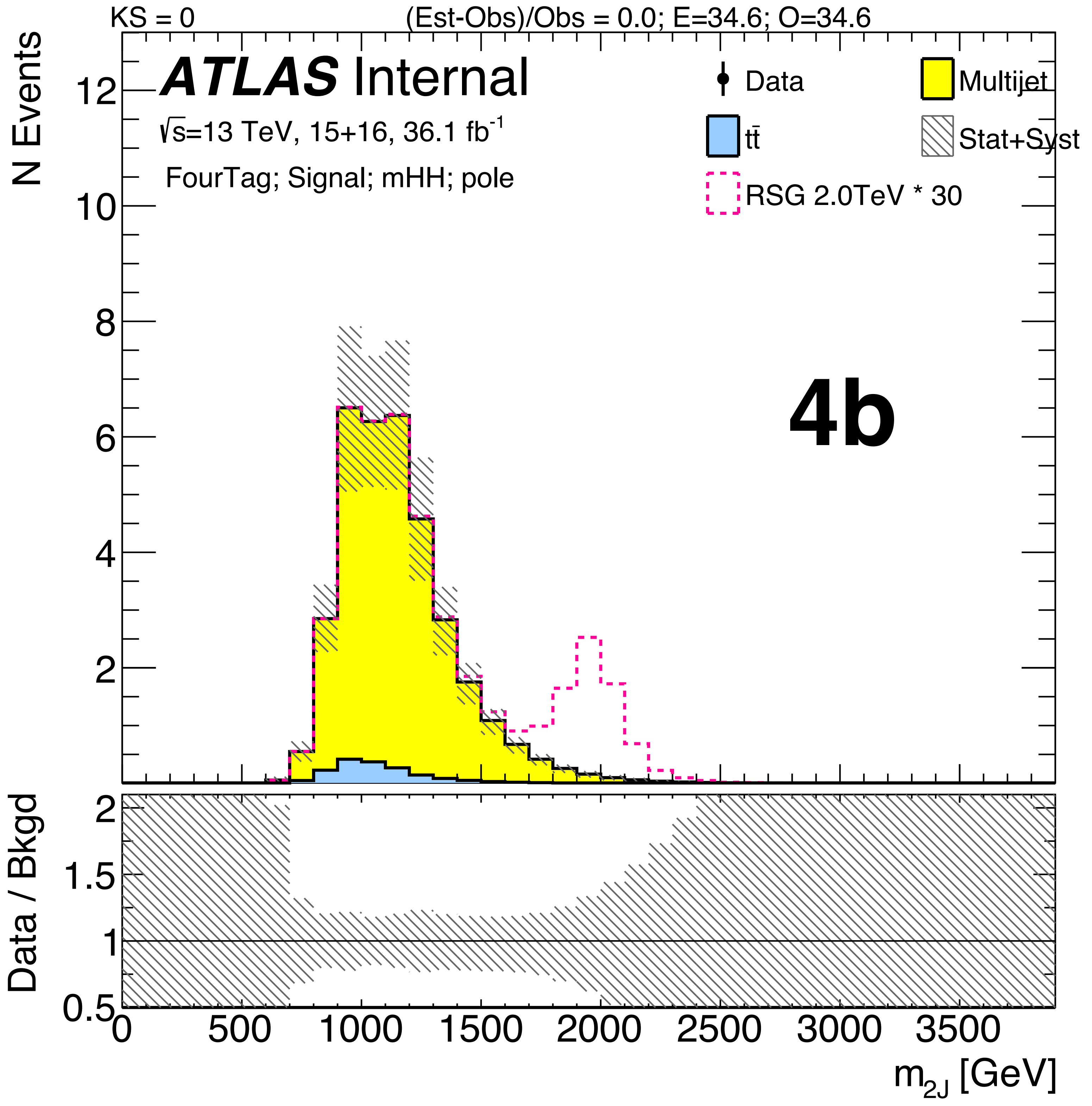
- Chapter 1: Why search for it
  - Motivation, Theory, History
- Chapter 2: How to search
  - Selection, Optimization, Background estimation
- **Chapter 3: Where we are**
  - **Results, Discussions, Future perspectives**

Signal Region Predictions: mHH

- With full systematics, final discriminate, blinded

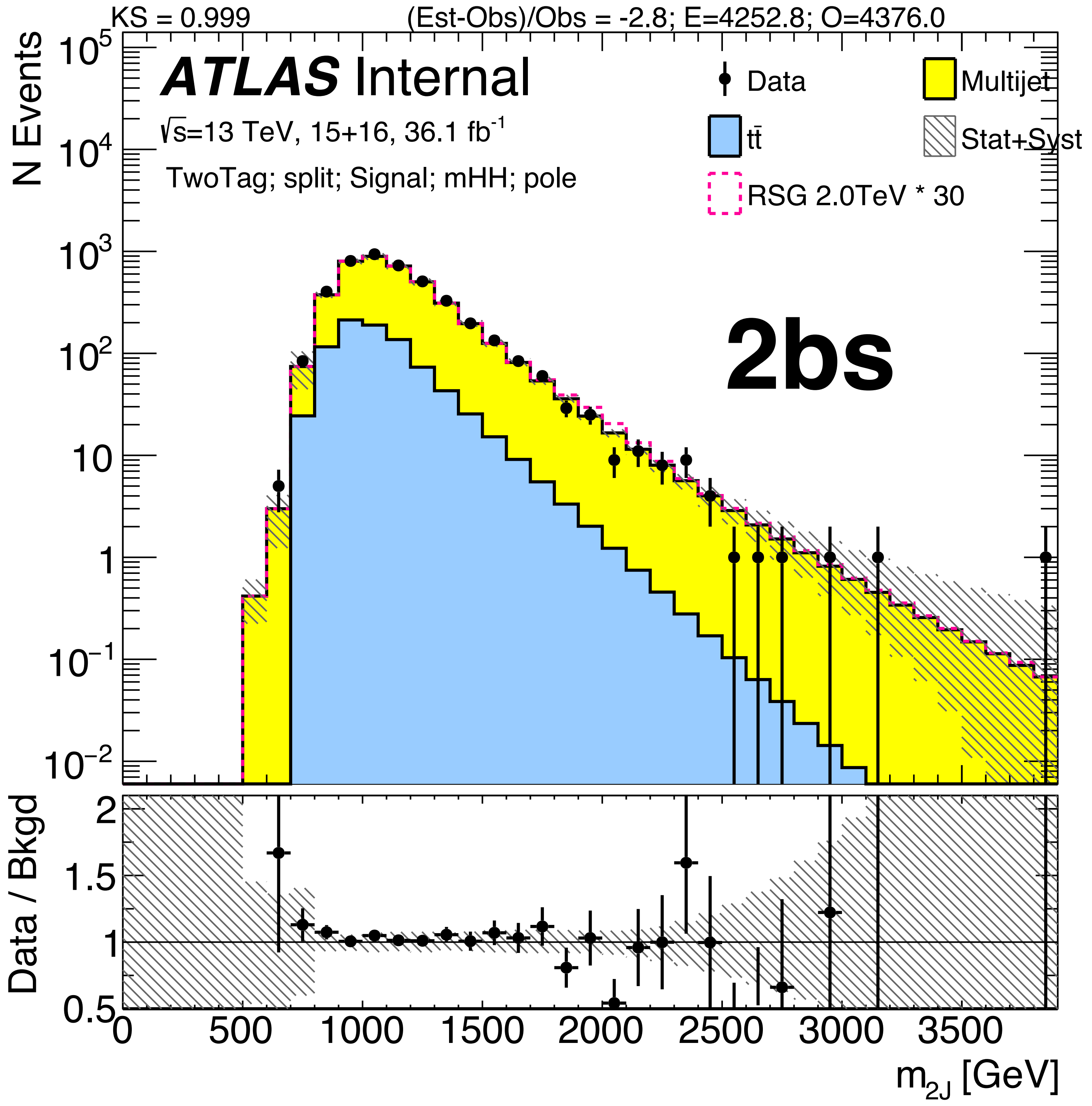


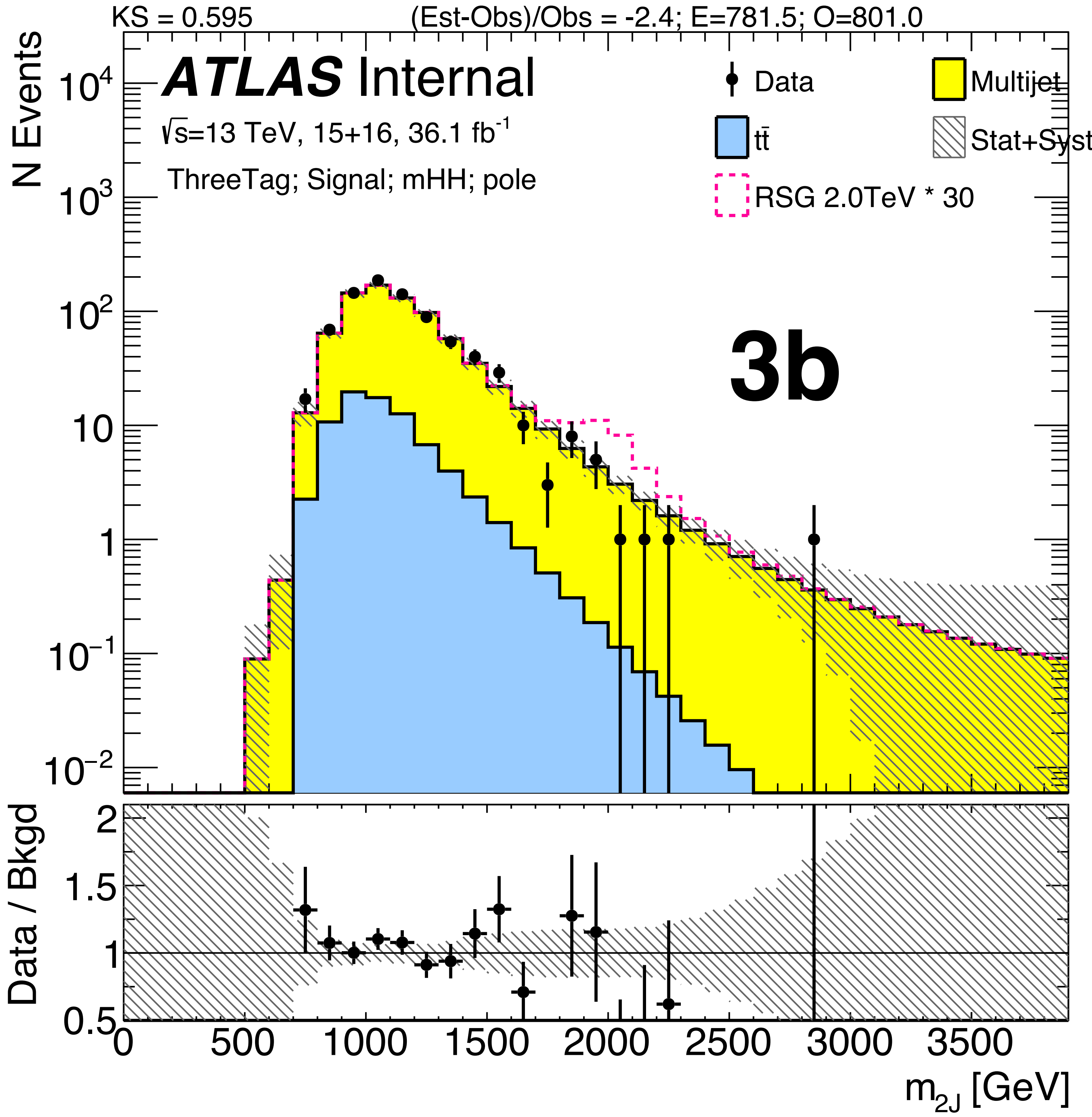


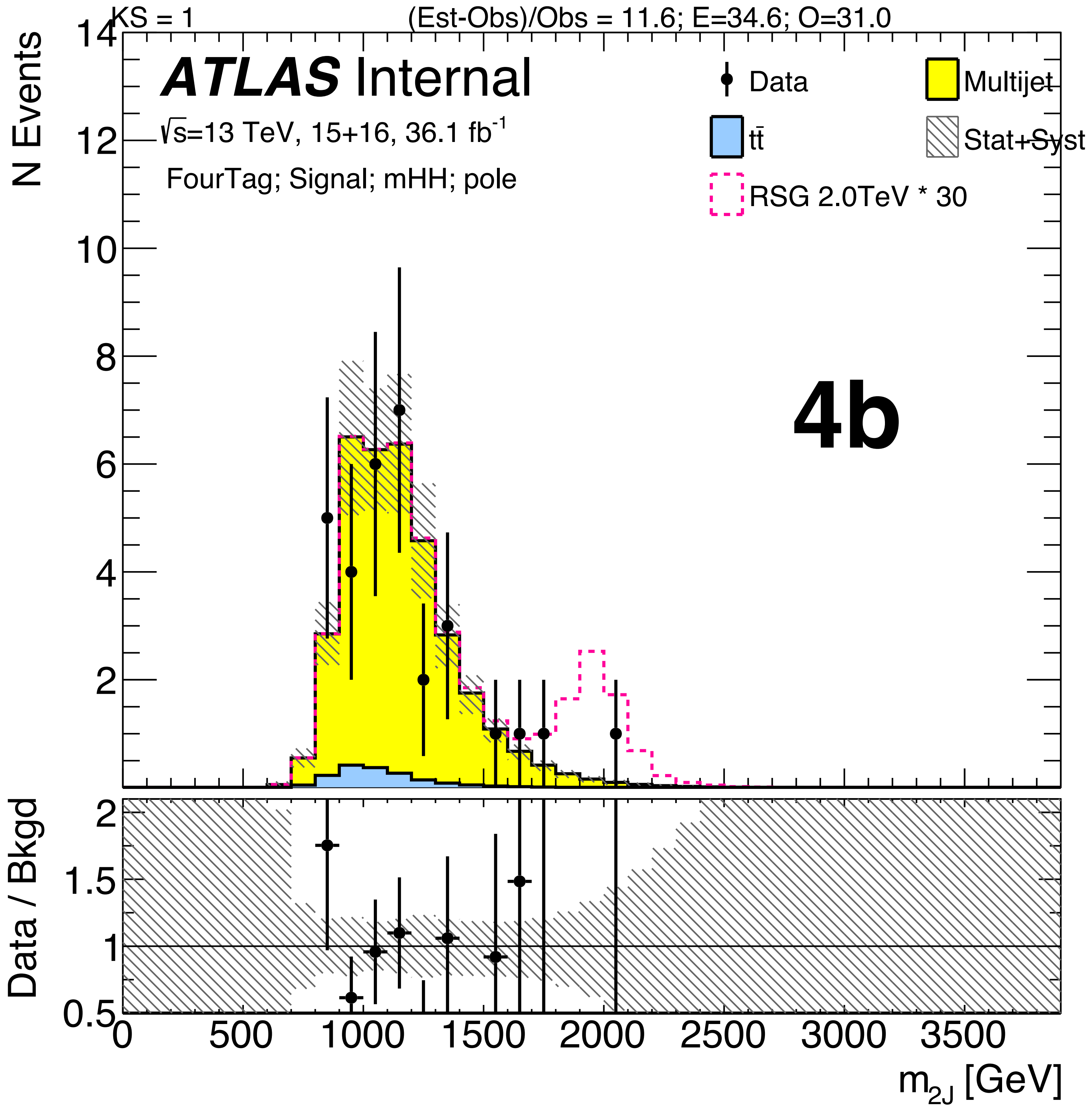


Signal Region Predictions: mHH

- With full systematics, final discriminate, **unblinded**







Signal Region: Boosted

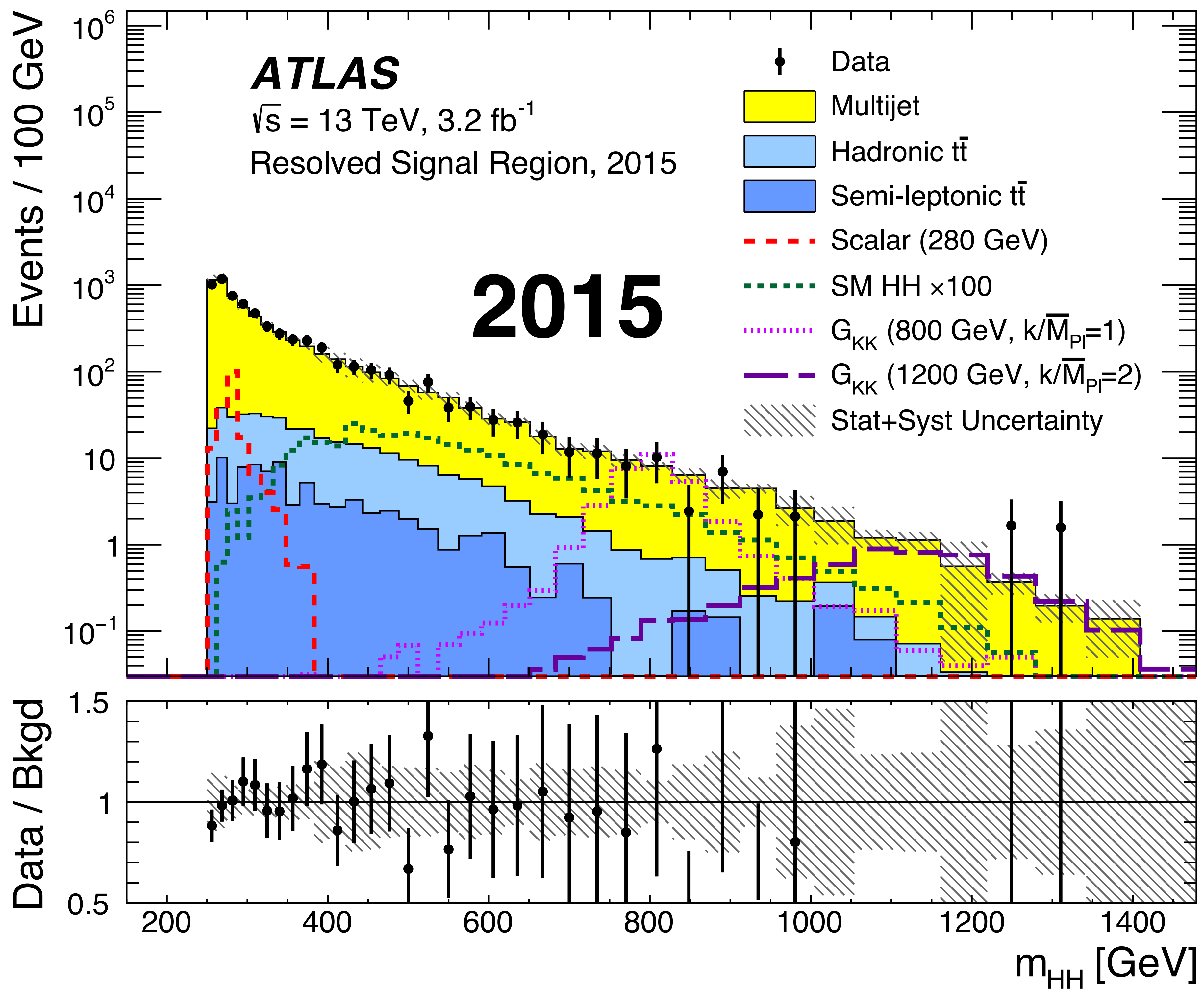
- Final discriminant: **m2j, dijet invariant mass**; no significant excess observed

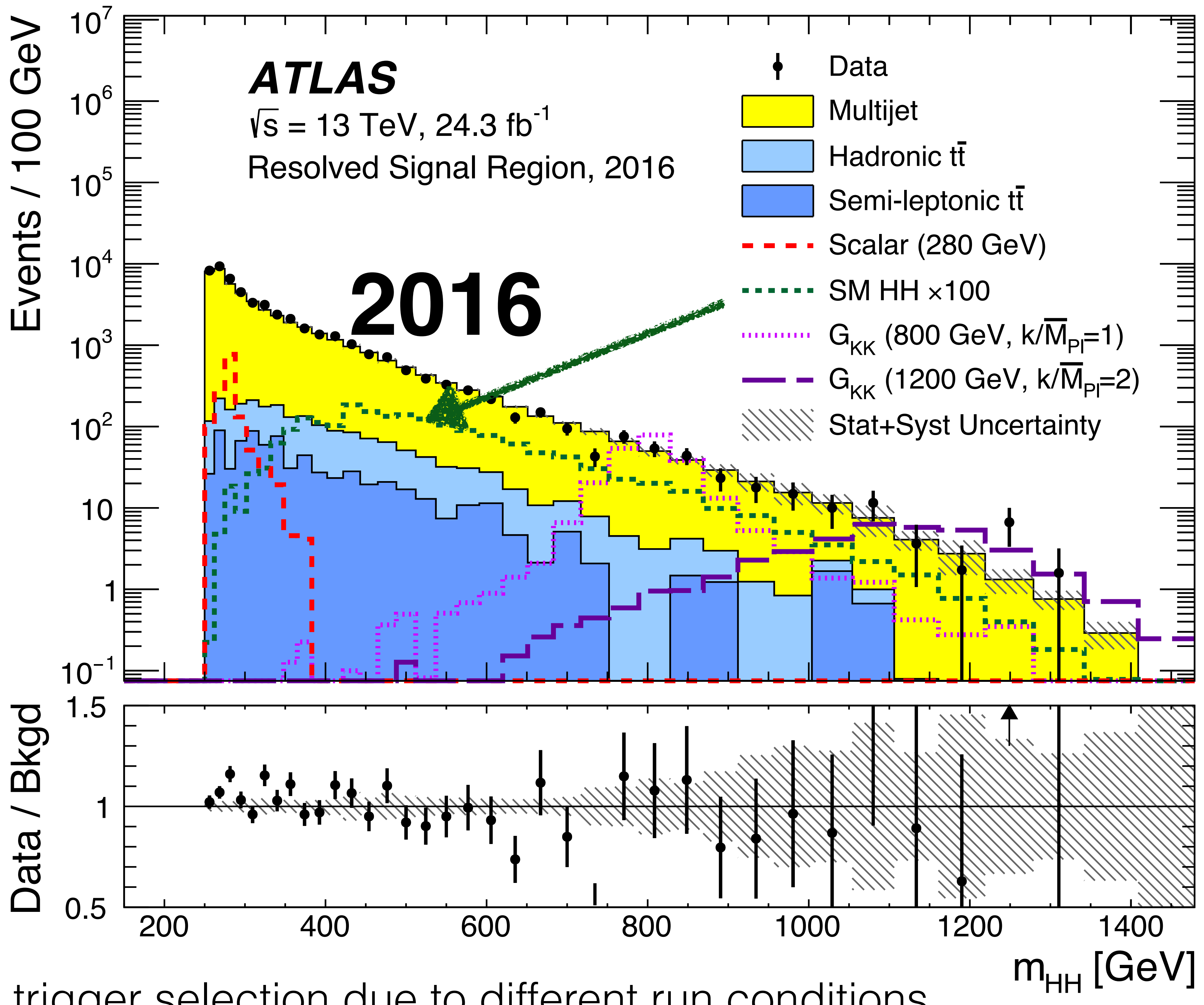
Channel	**2bs**	**3b**	**4b**
Obs	**4376**	**801**	**31**
Exp	4250 ± 130	782 ± 51	35 ± 6

Signal Region: Resolved

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

Data	2015	2016
Obs	**928**	**7430**
Exp	930 ± 70	7130 ± 130



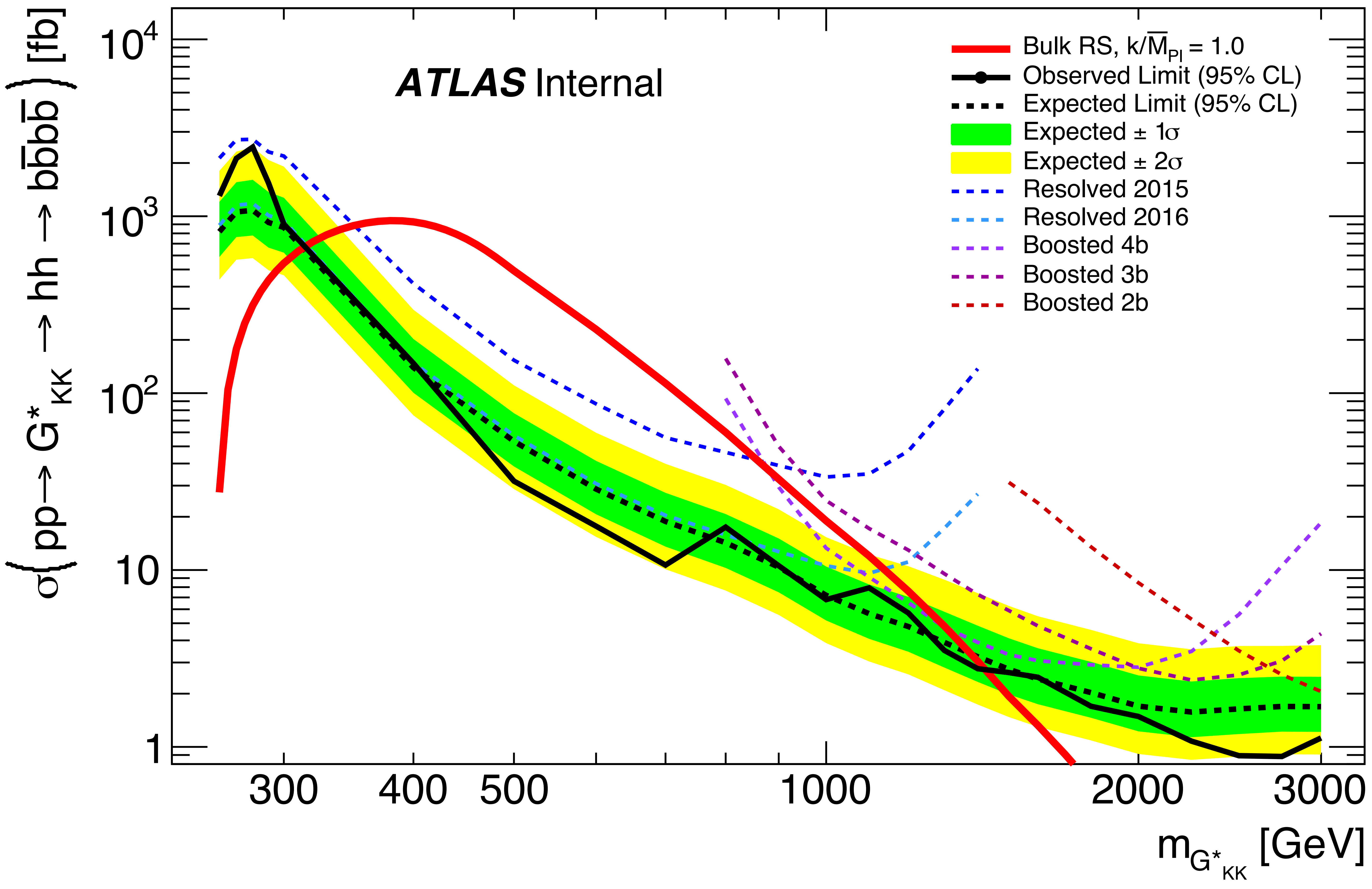


*2015 and 2016 have different trigger selection due to different run conditions

Current Combined Limits

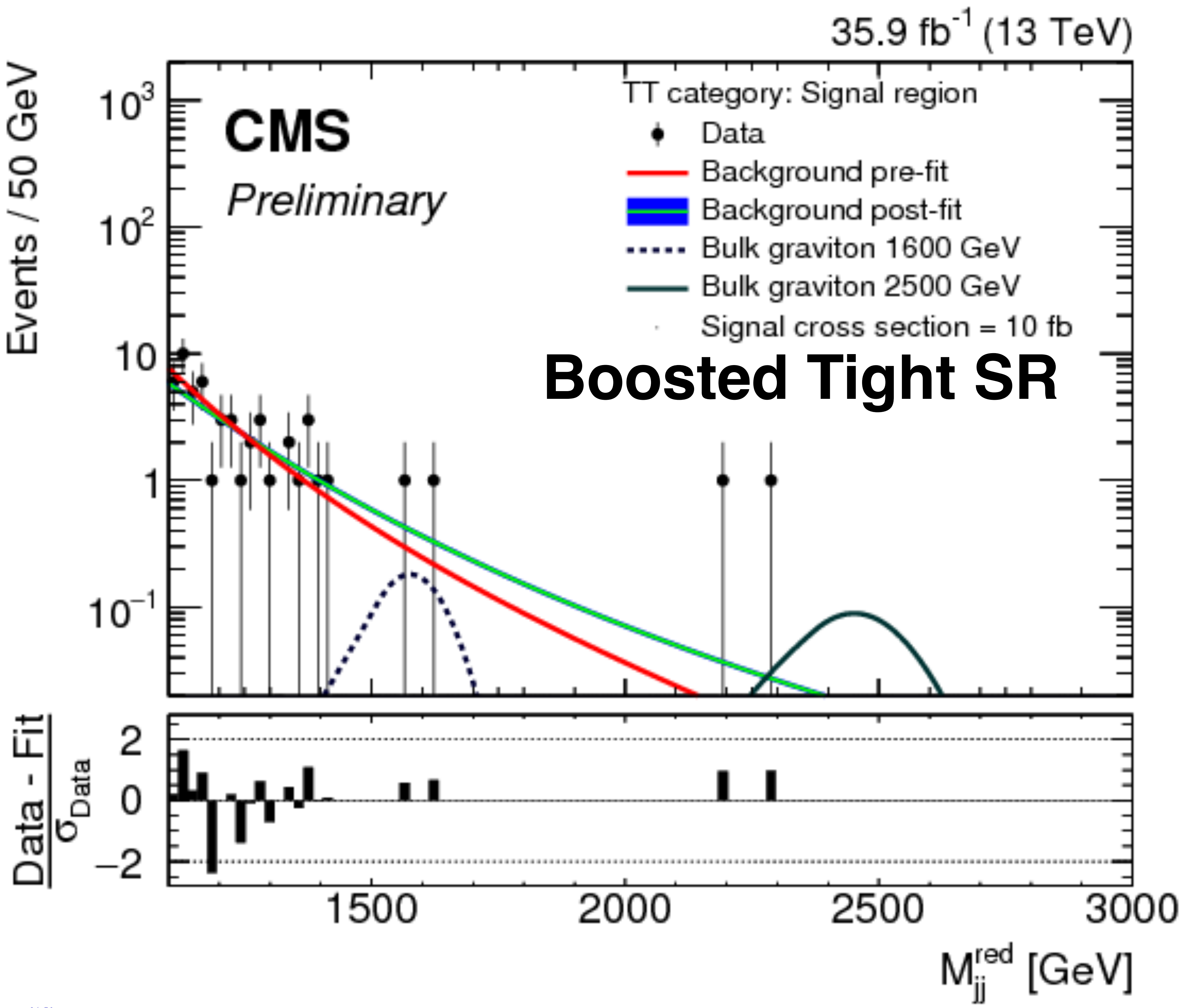
- **2017** current analysis is done!
- Resolved/Boosted 27/36 fb^{-1} **Statistically Combined** Limits
- Non-Resonance limit on HH to 4b:
  - 147 fb observed
  - **μ ~ 13** (20.7 expected)

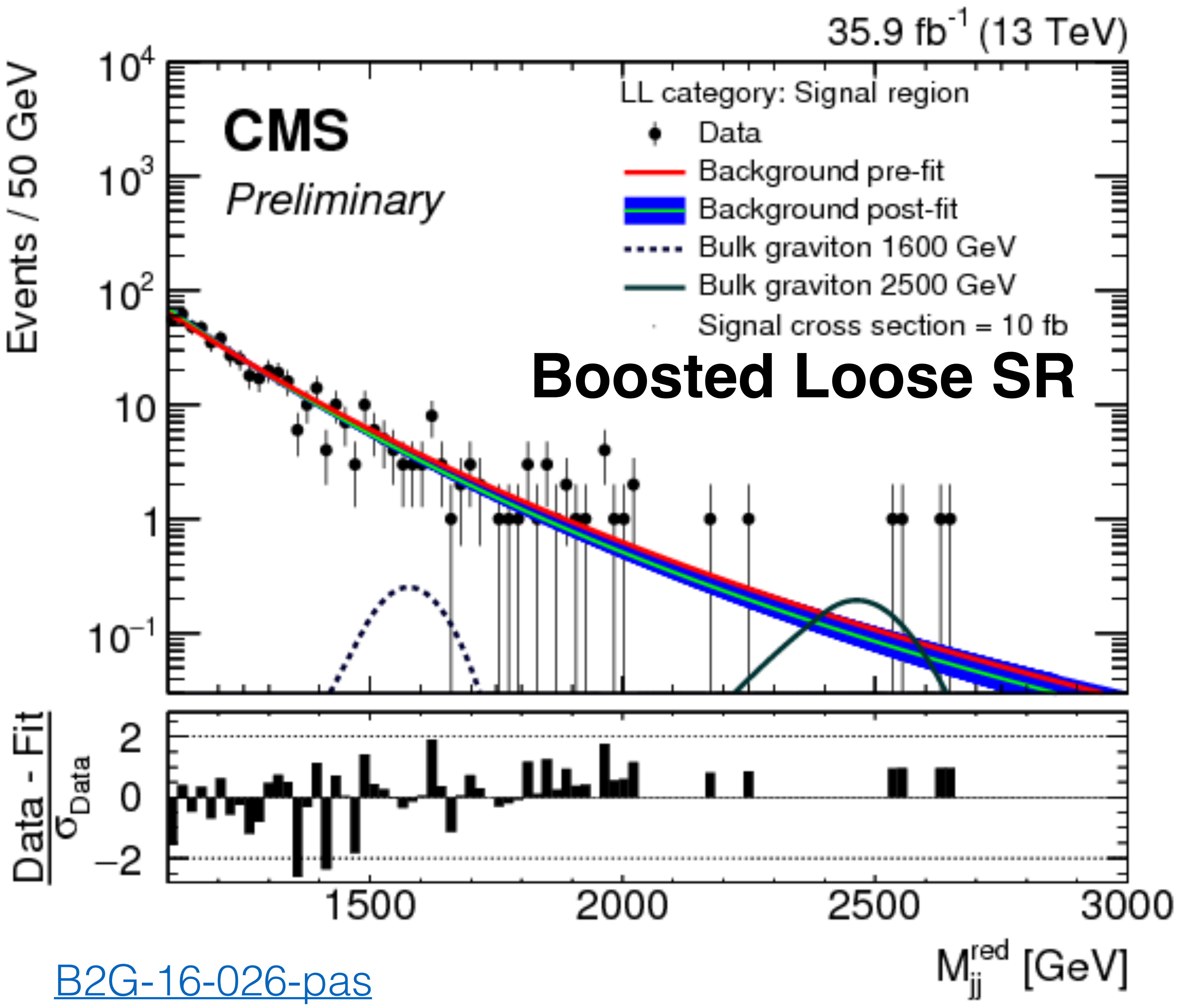
Spin 2, narrower width



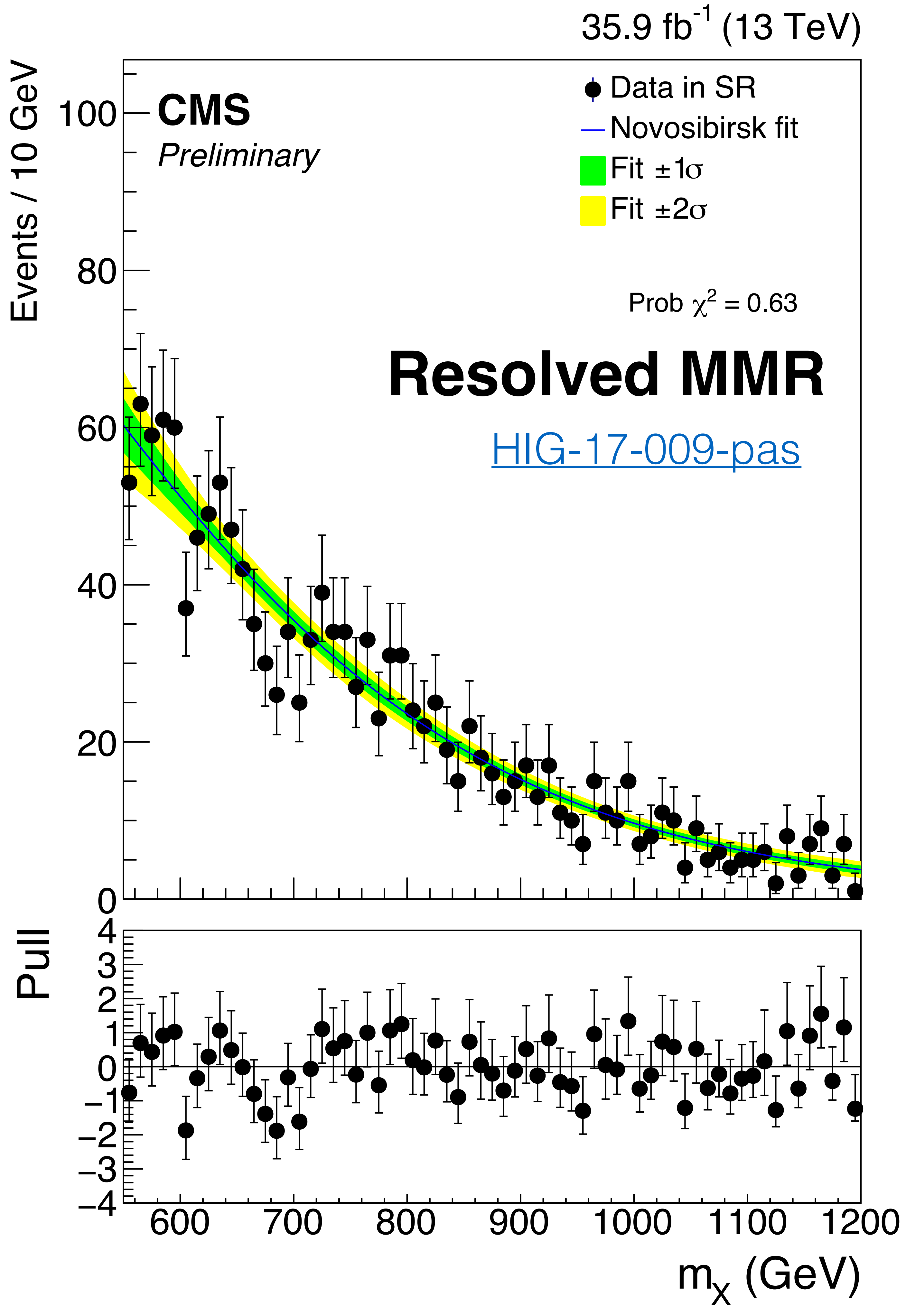
CMS Signal Regions

- CMS published resonant 4b results with 36 fb^{-1}
- No significant excess found in 260 - 3000 GeV





B2G-16-026-pas

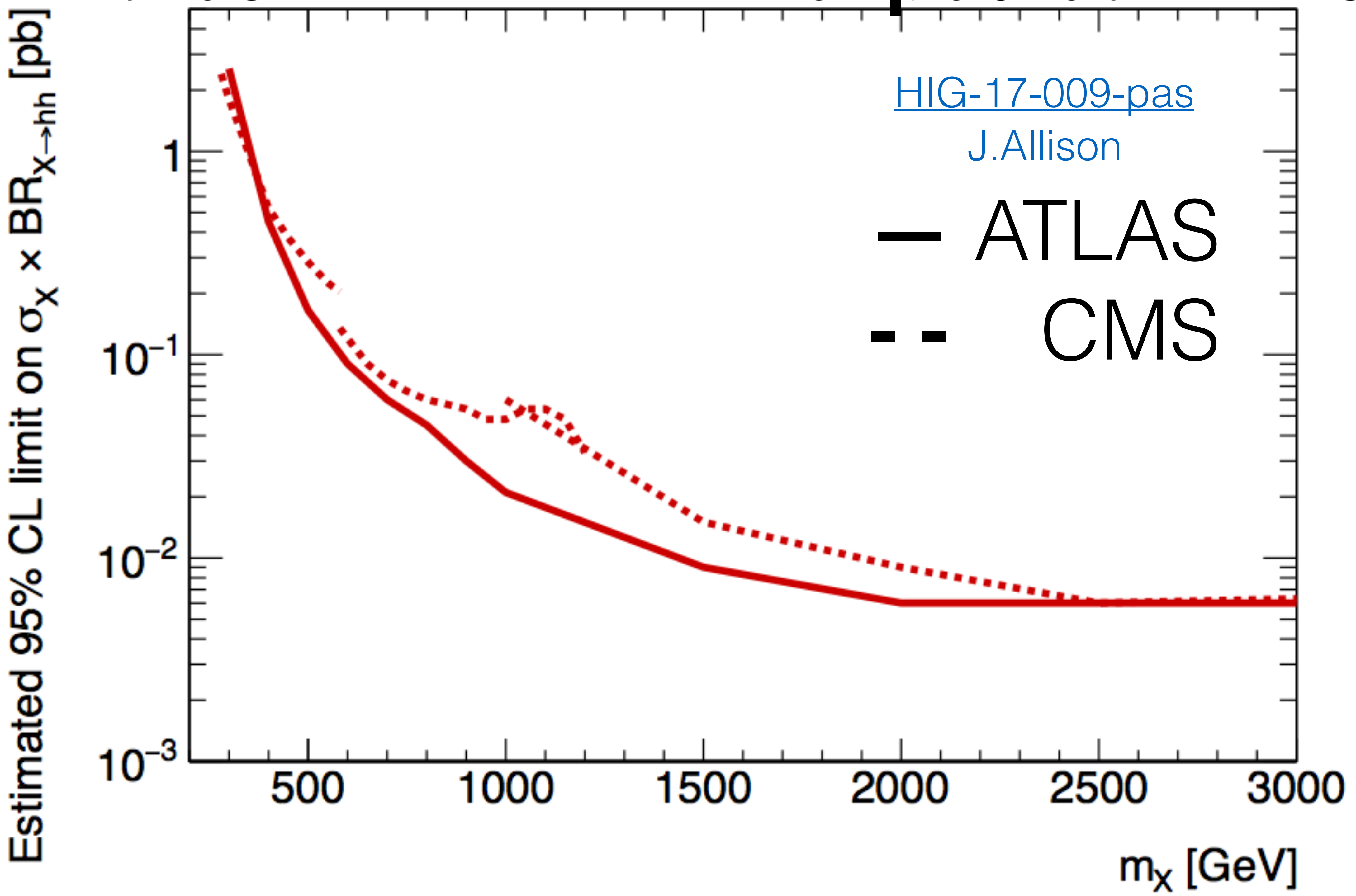


HIG-17-009-pas

Current di-Higgs status

- Limits on resonant models (spin 0) as a function of resonance mass
- Expected boosted 4b limit between **ATLAS** and **CMS** are very similar, despite the different methods

Latest Run II HH4b expected limits

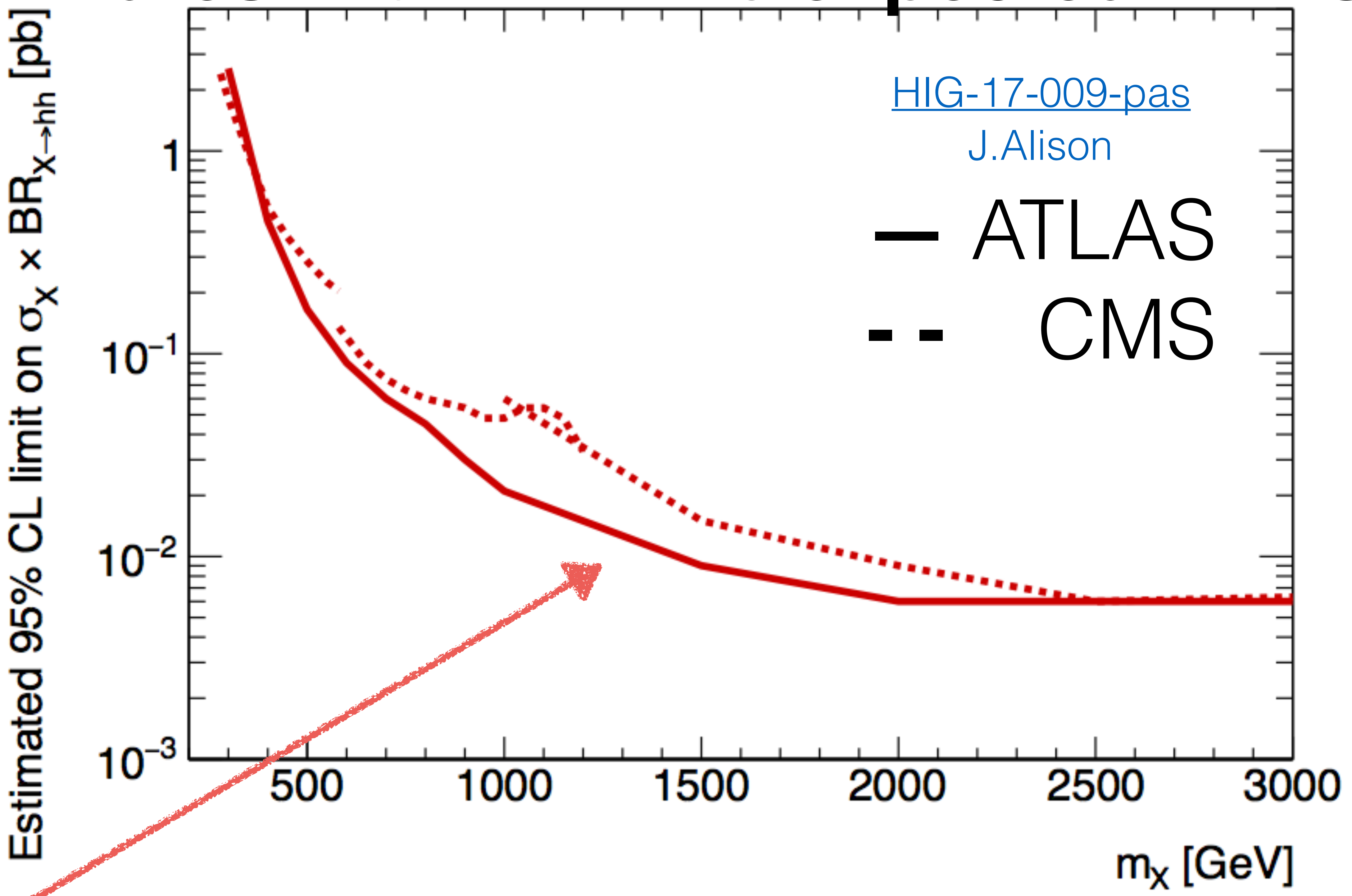


HH boosted 4b	ATLAS	CMS
b-tagging	**fixed-radius**	**double-b tagger**
bkg estimation	**ABCD method**	**mainly direct fit**
signal region	**circle**	**square**

Current di-Higgs status

- Limits on resonant models (spin 0) as a function of resonance mass
- Expected boosted 4b limit between **ATLAS** and **CMS** are very similar, despite the different methods
- Resolved + Boosted combination pays off for signals between 1- 1.5 TeV

Latest Run II HH4b expected limits



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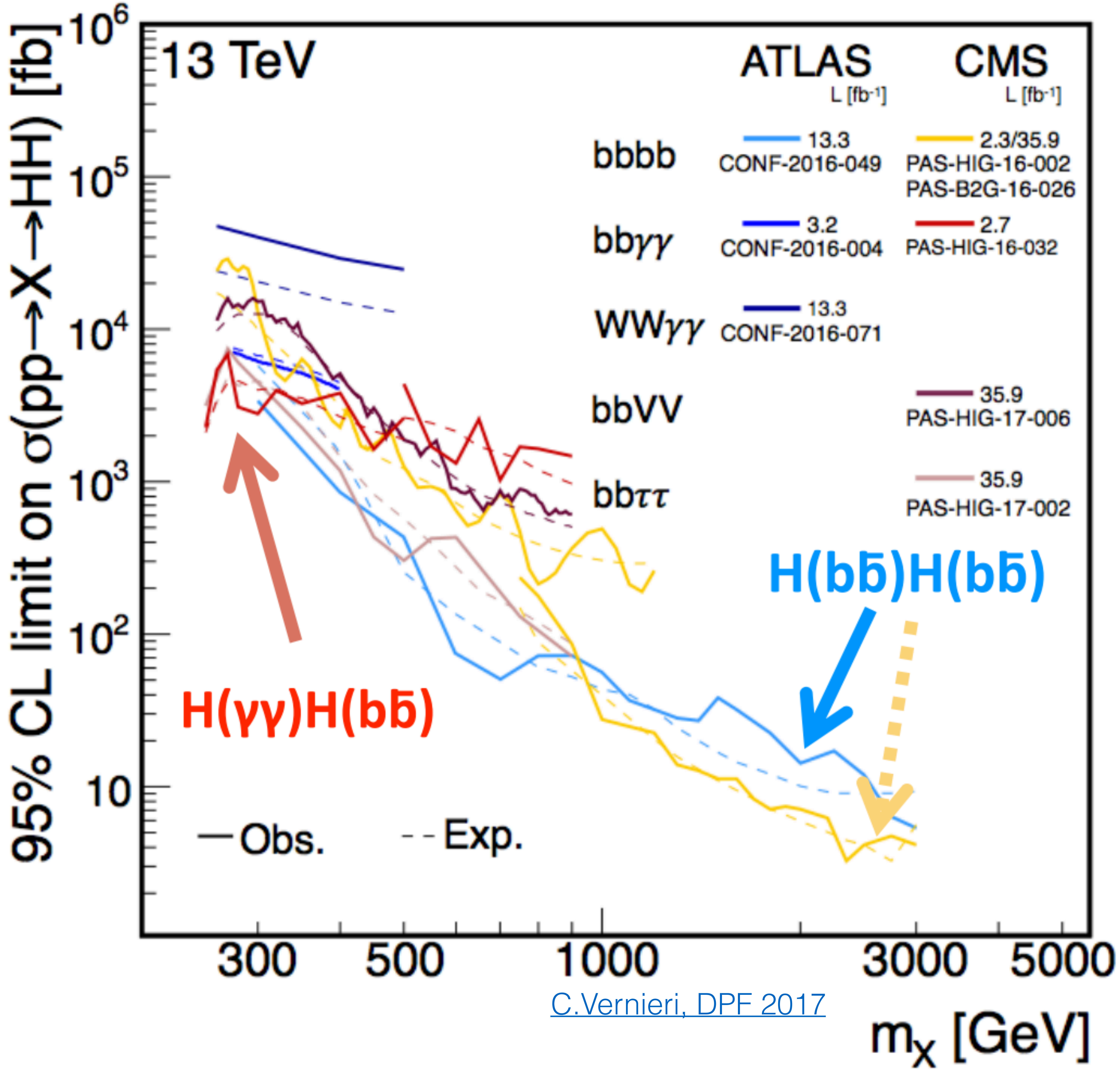
Current di-Higgs status

- Limits on resonant models (spin 0) as a function of resonance mass
- Expected boosted 4b limit between **ATLAS** and **CMS** are very similar, despite the different methods
- Compared with other channels, 4b is still the most sensitive at high mass

Latest Run II HH search limits



C.Vernieri, DPF 2017

Current di-Higgs non-resonant limits

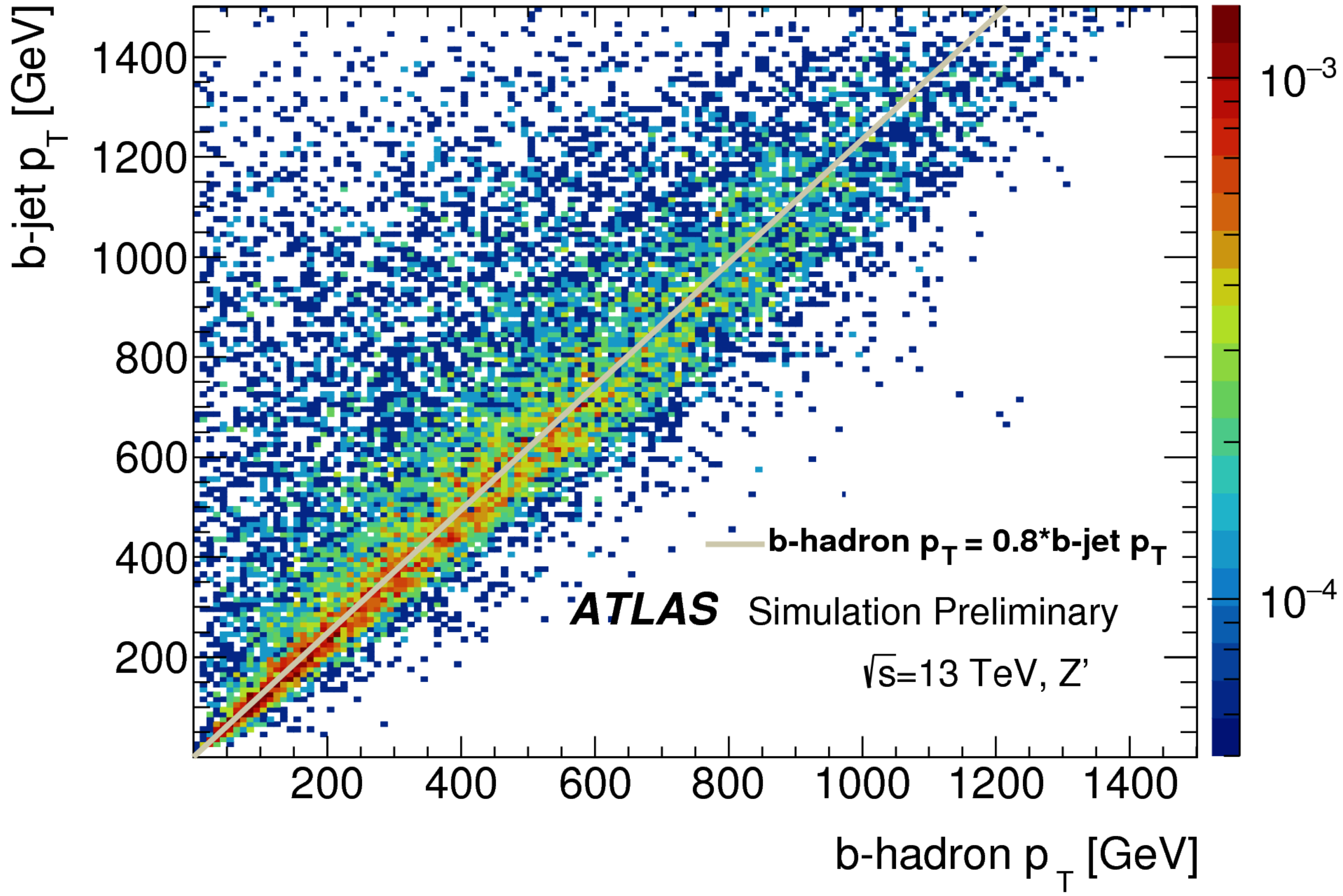
- Summary of 13 TeV Limits of non-resonant di-Higgs cross section / the standard model cross section

Channel 3fb^{-1}, 13fb^{-1}, 36fb^{-1}	μ — σ/σ_{SM} — Obs (Exp)	
	ATLAS	**CMS**
bbbb	**29 (38)**	342 (308)
bbWW	-	**79 (89)**
bb$\tau\tau$	-	**30 (25)**
bbγγ	117 (161)	**19 (16)**
WW*γγ	747 (386)	-

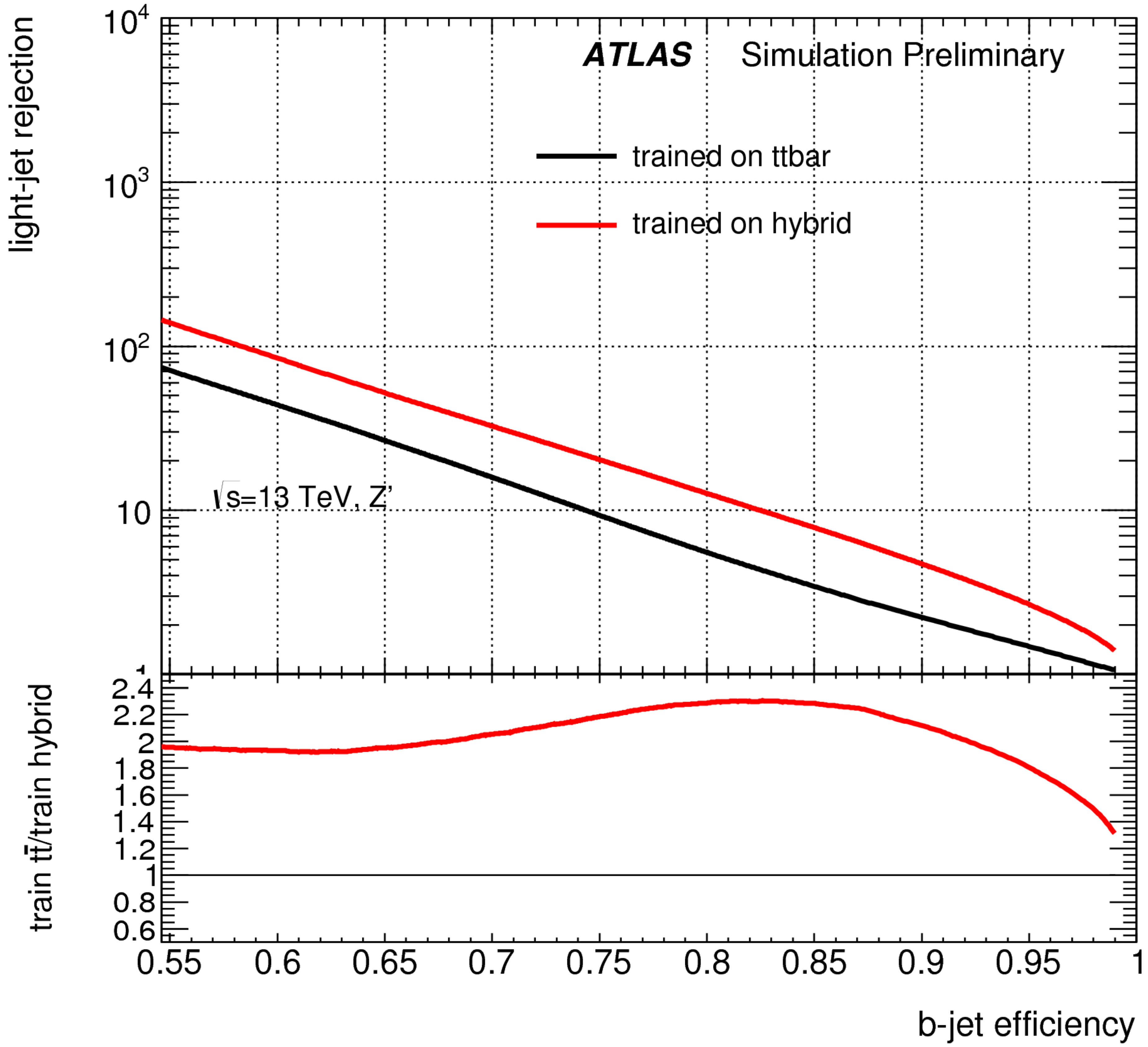
ATL-PHYS-PUB-2017-013

Boosted HH4b future improvements

- Limiting factor is signal acceptance: **b-tagging**; substructure
- Expect better results at 120 fb^{-1} !



high pT MVA training sample, "hybrid"

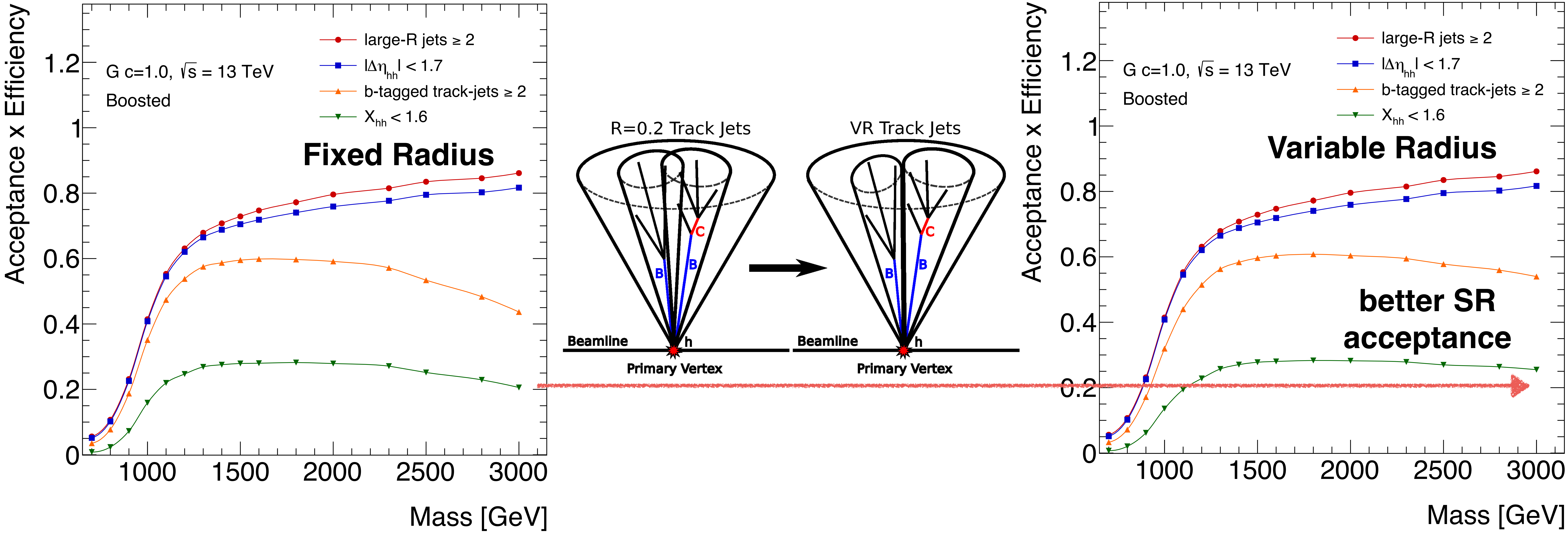


higher light jet rejection at high pT

ATL-PHYS-PUB-2017-010

Boosted HH4b future improvements

- Limiting factor is signal acceptance: b-tagging; **substructure**
- Expect better results at 120 fb^{-1} !



Future Perspectives

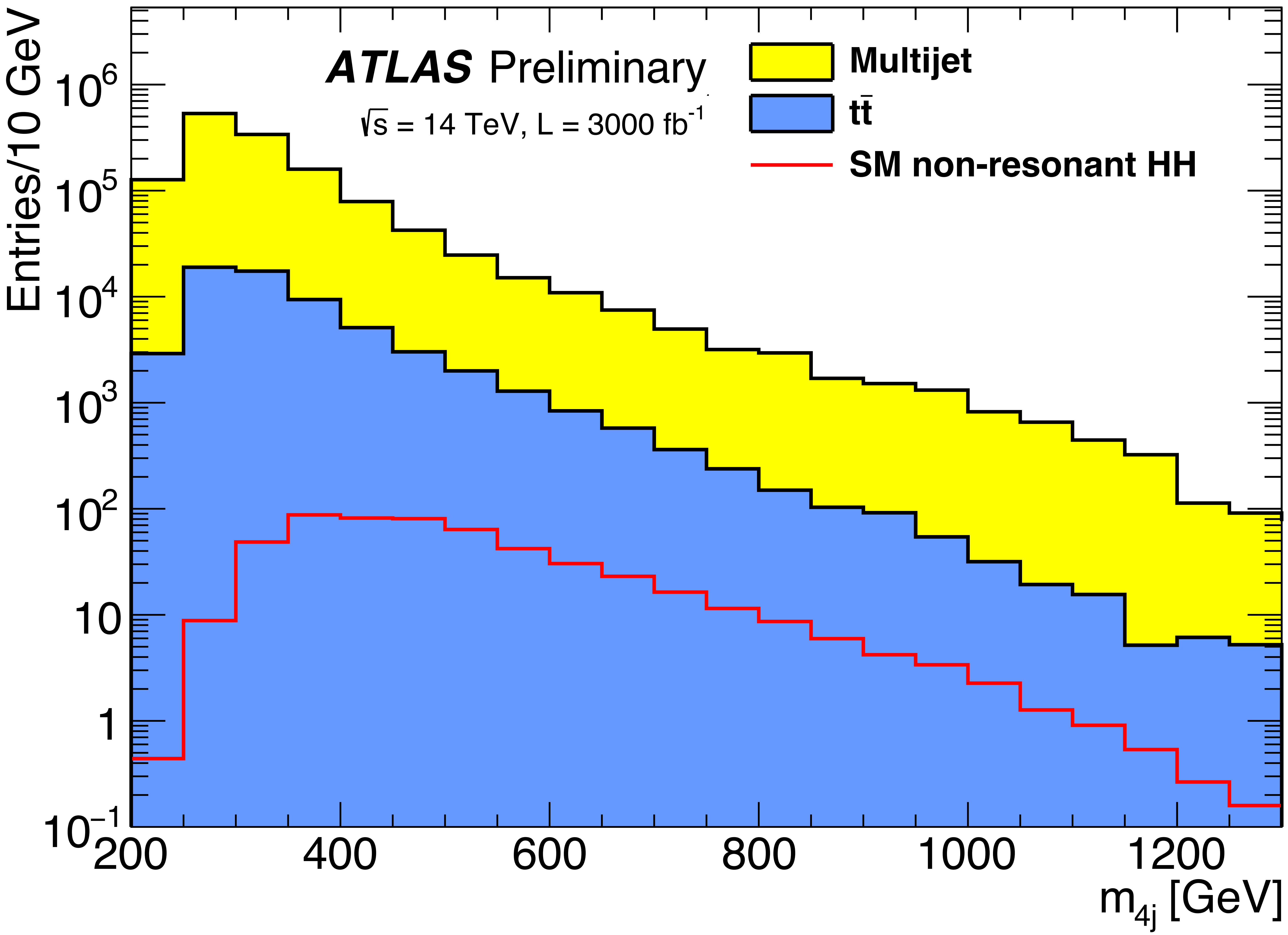
ATLAS-CONF-2016-024

- Full High-Luminosity LHC will have 3000 fb^{-1} data
- One of the ultimate goals is to constrain λ_{hhh}

Future Perspectives

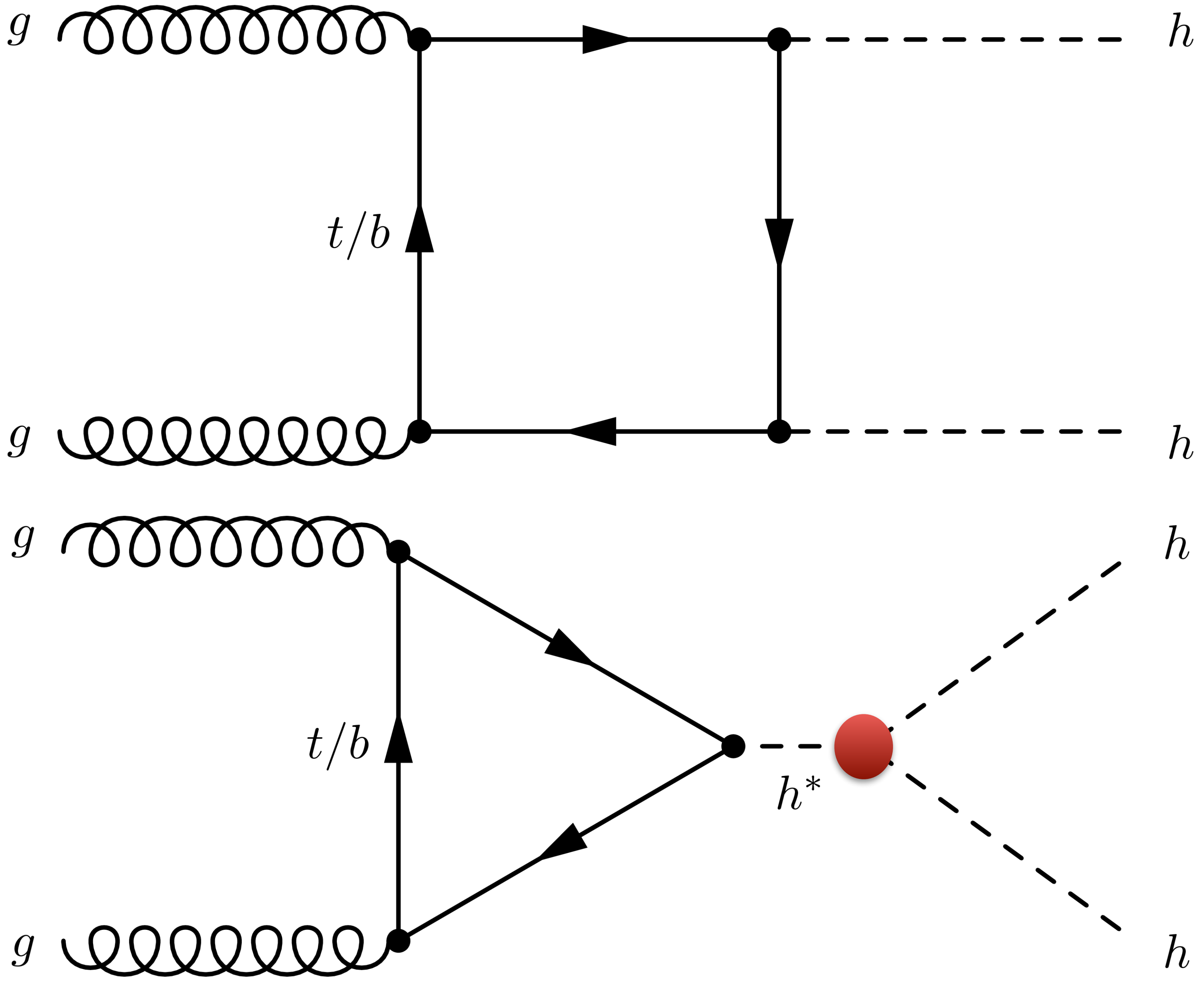
ATLAS-CONF-2016-024

- Extrapolation of current di-Higgs to 4b 2016 ICHEP results

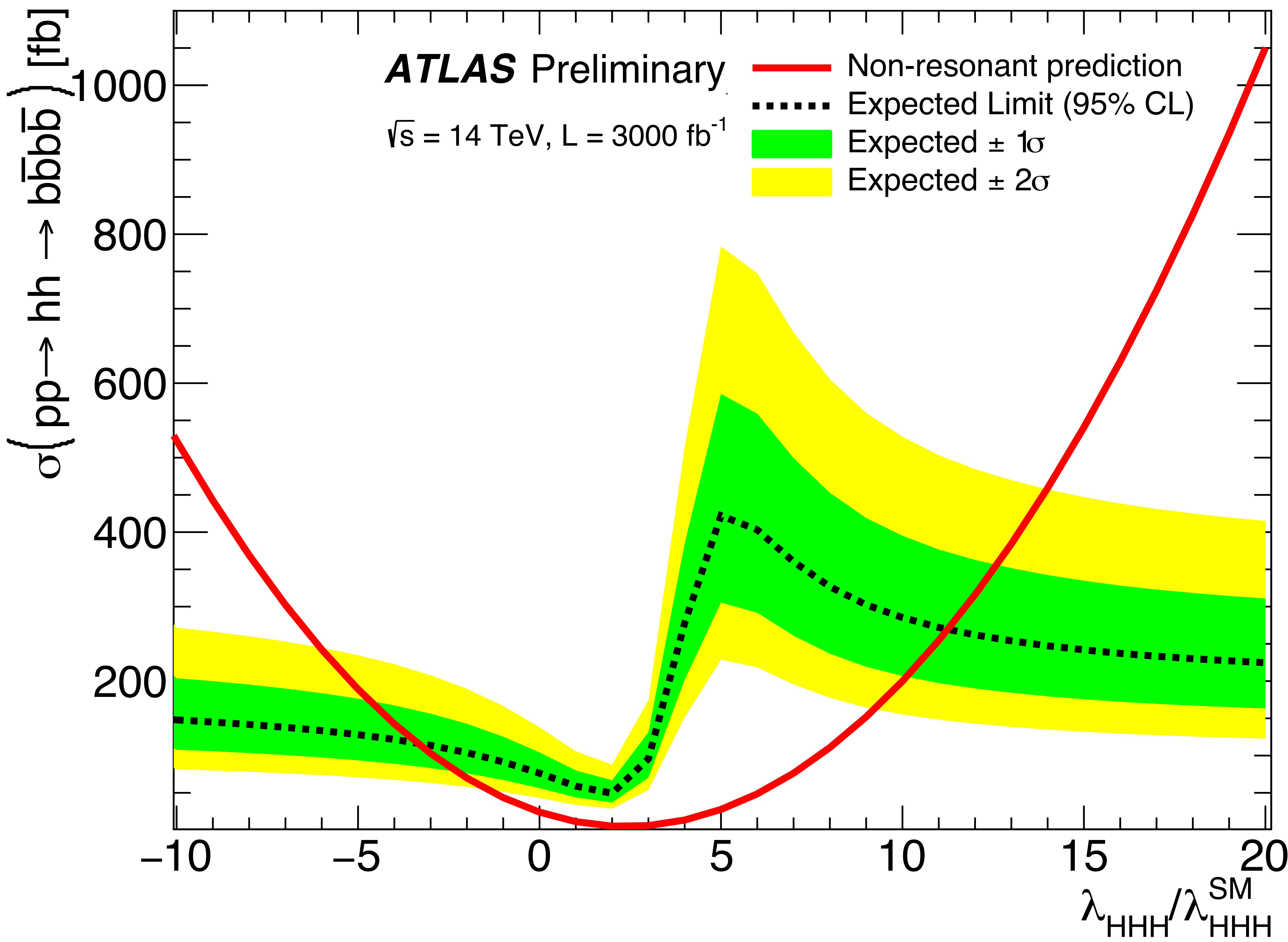


Future Perspectives

ATLAS-CONF-2016-024



- Limit: -3.5 < λ_{hhh} < 11



Future di-Higgs Status

- Summary of HL-LHC di-Higgs Limits on σ/σ_{SM}

Channel 3000 fb^{-1}	σ/σ_{SM} Stat (Stat + Syst)	
	ATLAS	CMS
bbbb	1.5 (5.2)	2.9 (7.0)
bbWW	-	4.6 (4.8)
$bb\tau\tau$	- (4.3)	3.9 (5.2)
bbγγ	-(1.05)	1.3 (1.3)
WW*γγ	-	-

Future di-Higgs Status

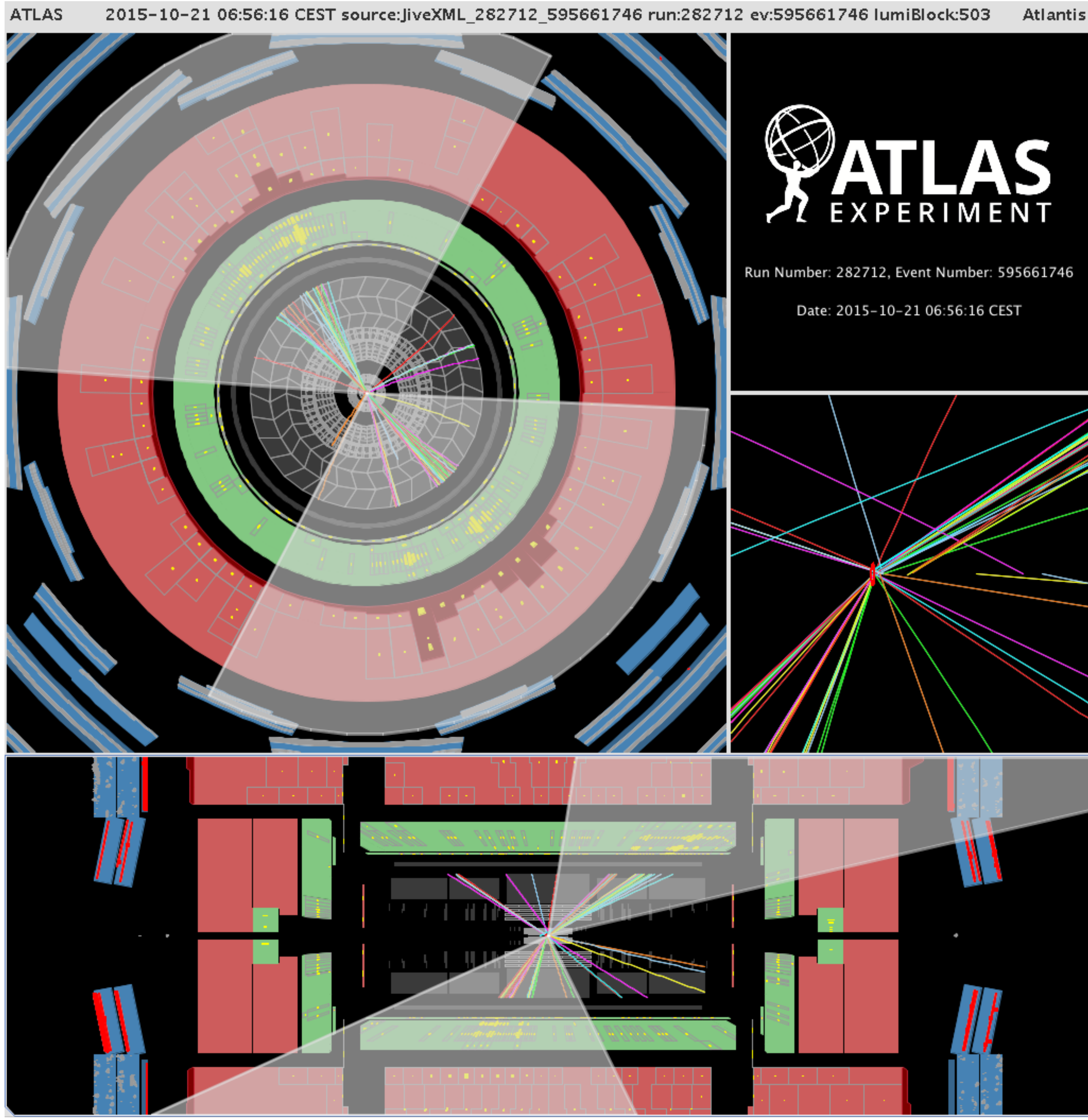
- Summary of HL-LHC di-Higgs Limits on σ/σ_{SM}
- Will need ALAS and CMS **combination** to pin it down
- + a lot of hard work :)

Channel **3000 fb^{-1}**	**σ/σ_{SM} Stat (Stat + Syst)**	
	ATLAS	**CMS**
bbbb	**1.5 (5.2)**	**2.9 (7.0)**
bbWW	-	4.6 (4.8)
bb$\tau\tau$	- (4.3)	3.9 (5.2)
bbγγ	**-(1.05)**	**1.3 (1.3)**
WW*γγ	-	-

Conclusion

- Study of di-Higgs production has a short history but will have a much **longer** future, will be fun to work on!
- Searches for BSM signals are already interesting:
  - Limits from 260 GeV to 3 TeV
  - So far **no significant excess observed**, 13 TeV 4b non-resonance limit at **147 fb**

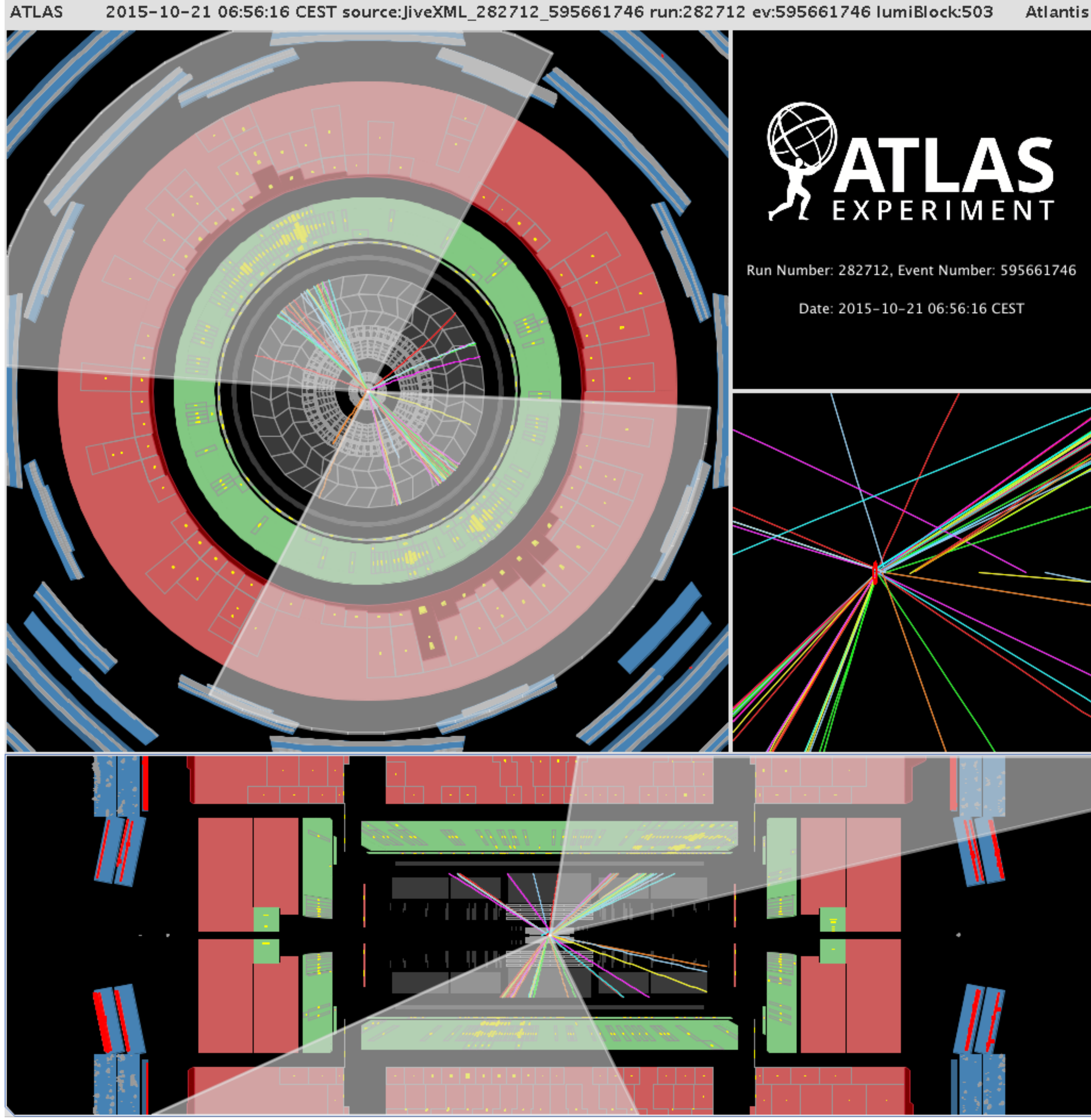
Run II Boosted Event



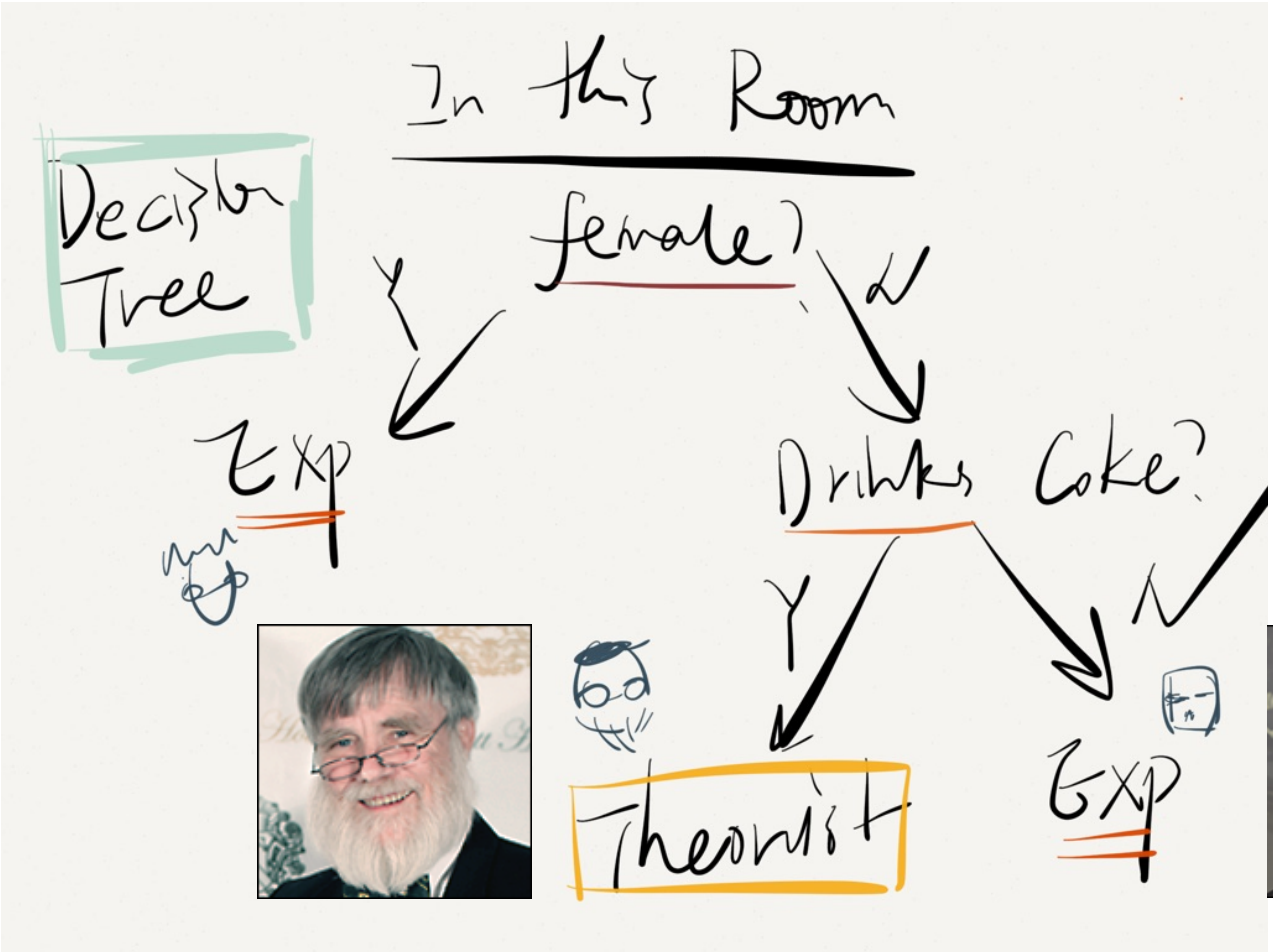
Conclusion

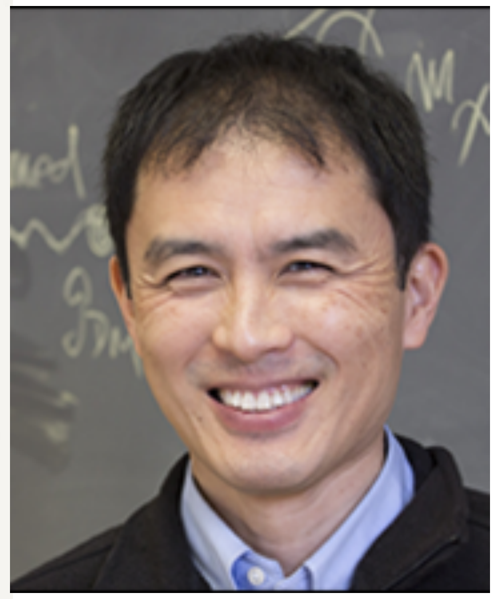
- “It is a far, far better thing that I do, than I have ever done; it is a far, far better result that I got to than I have ever known.”

Run II Boosted Event



My committee!





Harvard ATLAS

Back up Slides

Back up Slides

- Theory
- b-tagging
- Run I & II ATLAS Results Reviews
- Current Resolved
- Current Boosted: Background; RW; Syst; Optimization

Theory Back-ups

Higgs in SM

- Interaction with the Higgs field gives **mass** to fermions and vector bosons

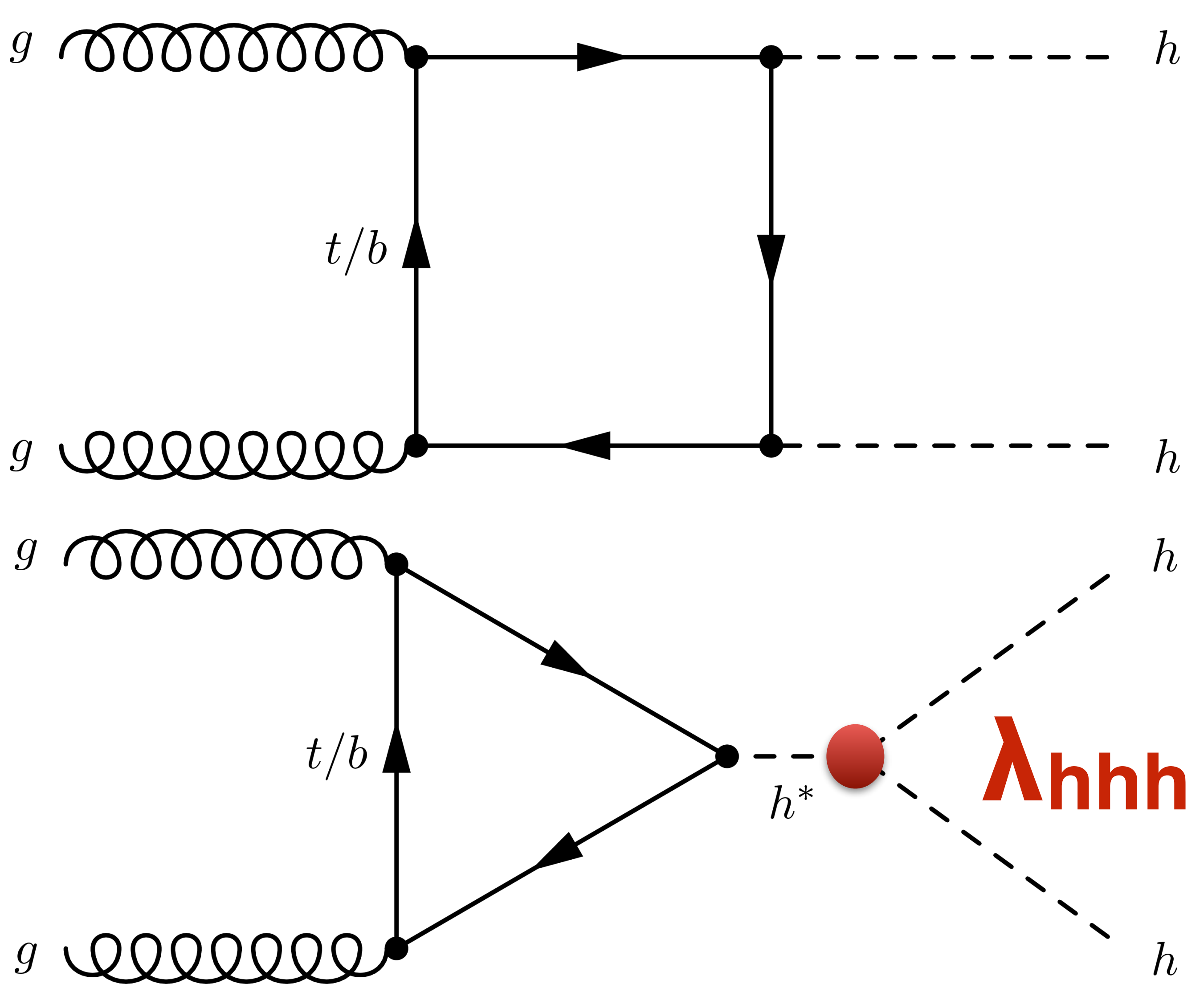
- And we found the Higgs boson!

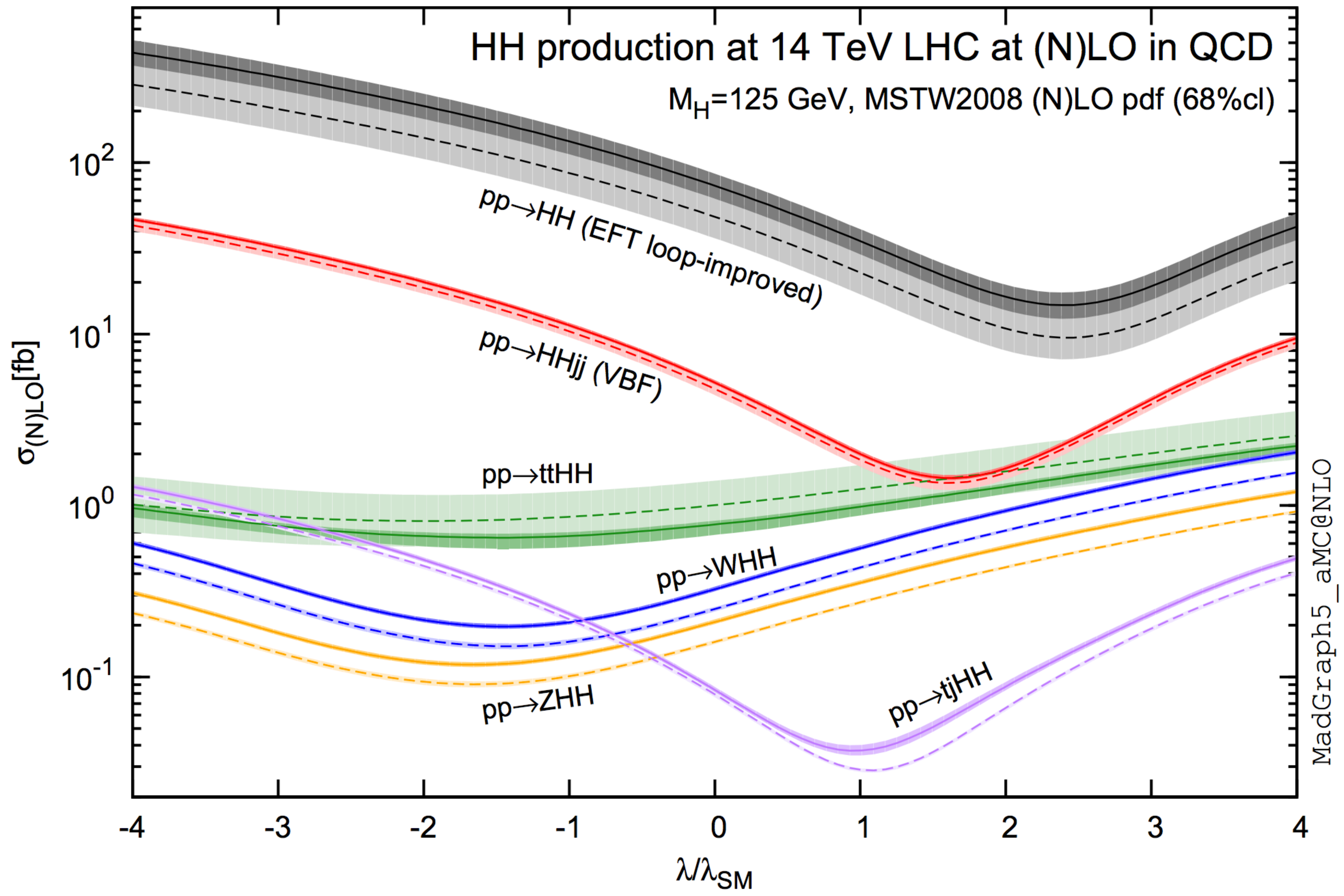
$$V(\phi) = -\mu\phi^2 + \lambda\phi^4$$

Di-Higgs Cross Section

arxiv 1401.7340

- Two diagrams:
  destructive interference



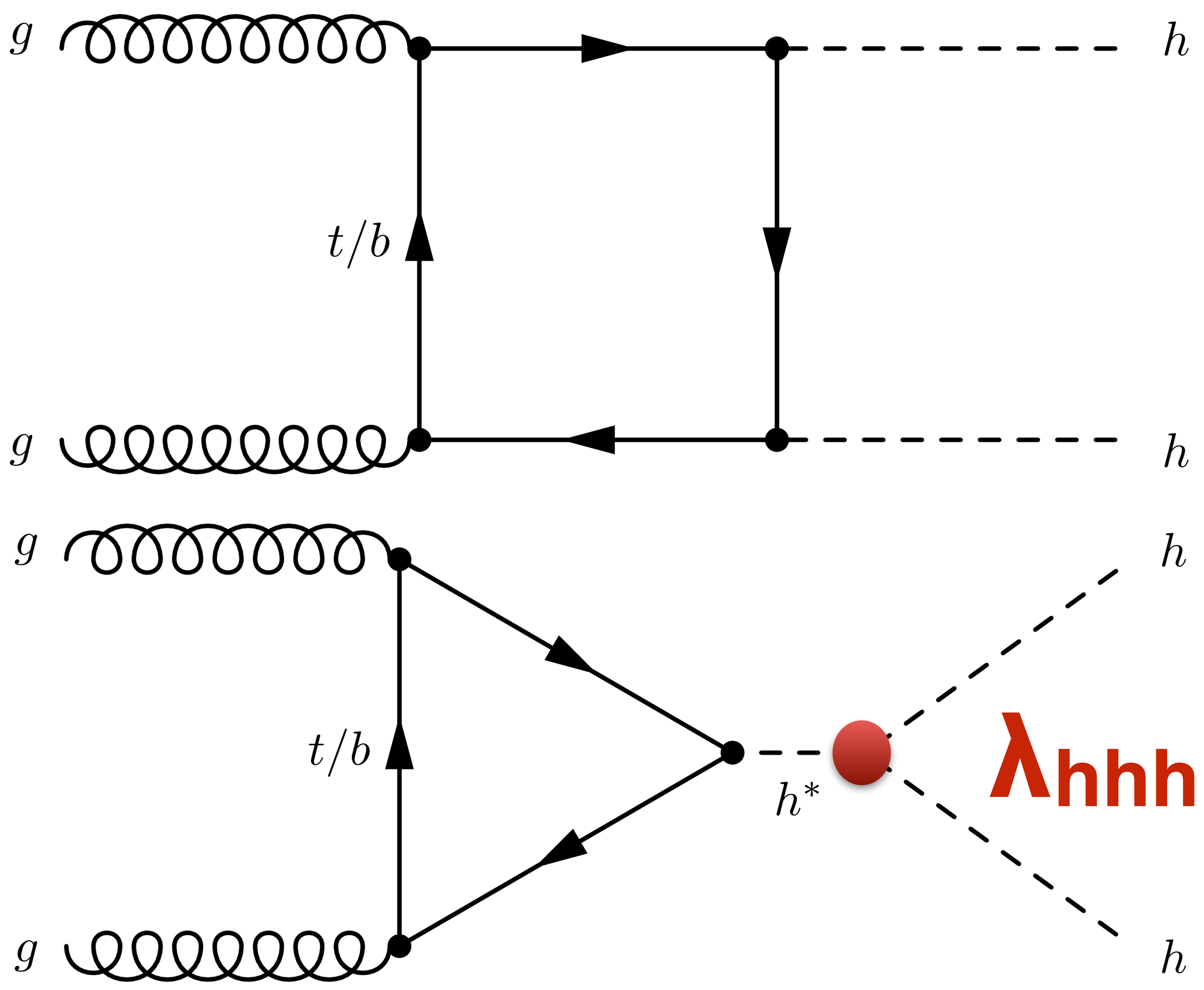


HH cross section as a function of λ/λ_{hhh}

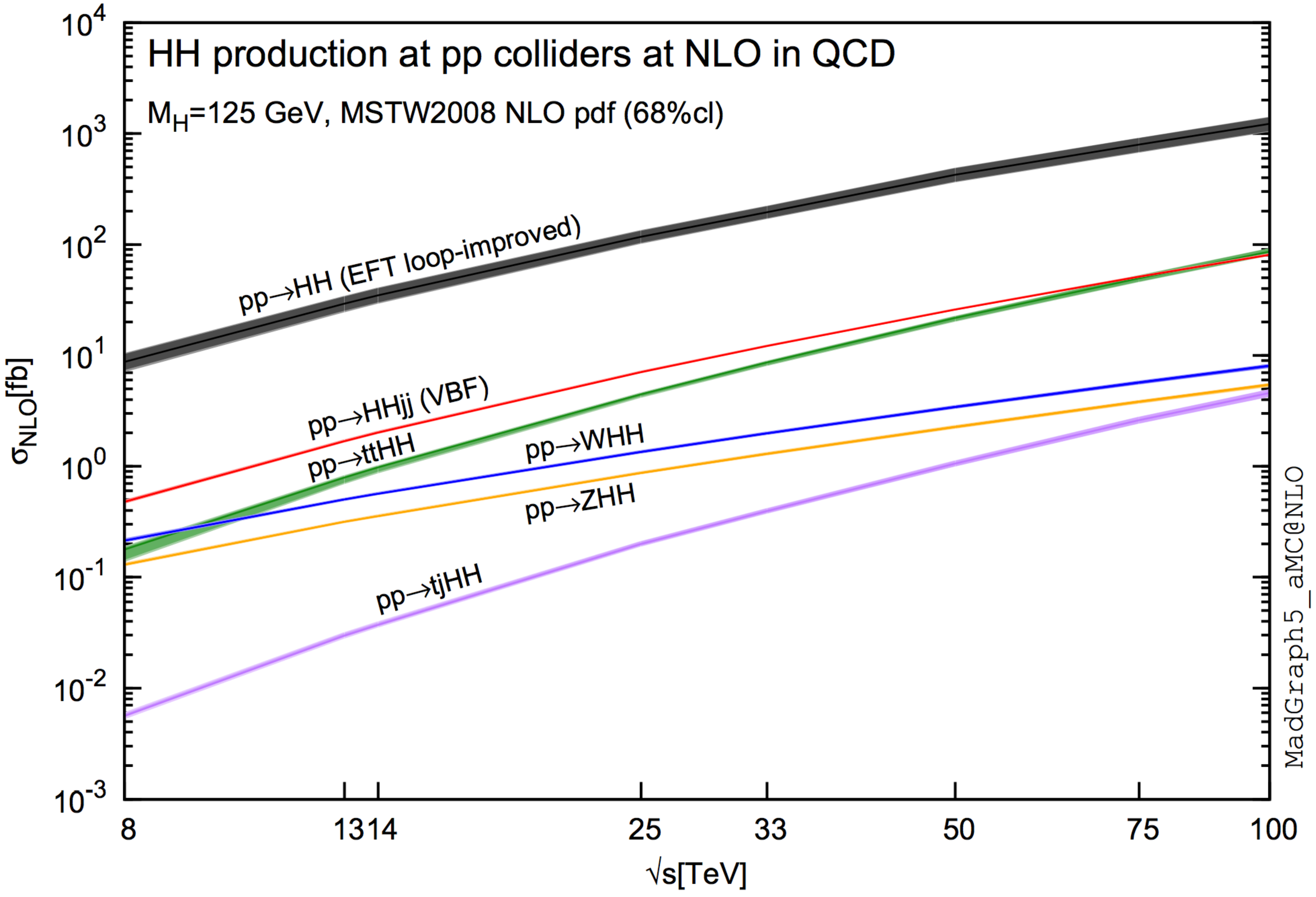
Di-Higgs Cross Section

arxiv 1401.7340

- Two diagrams:
  destructive interference



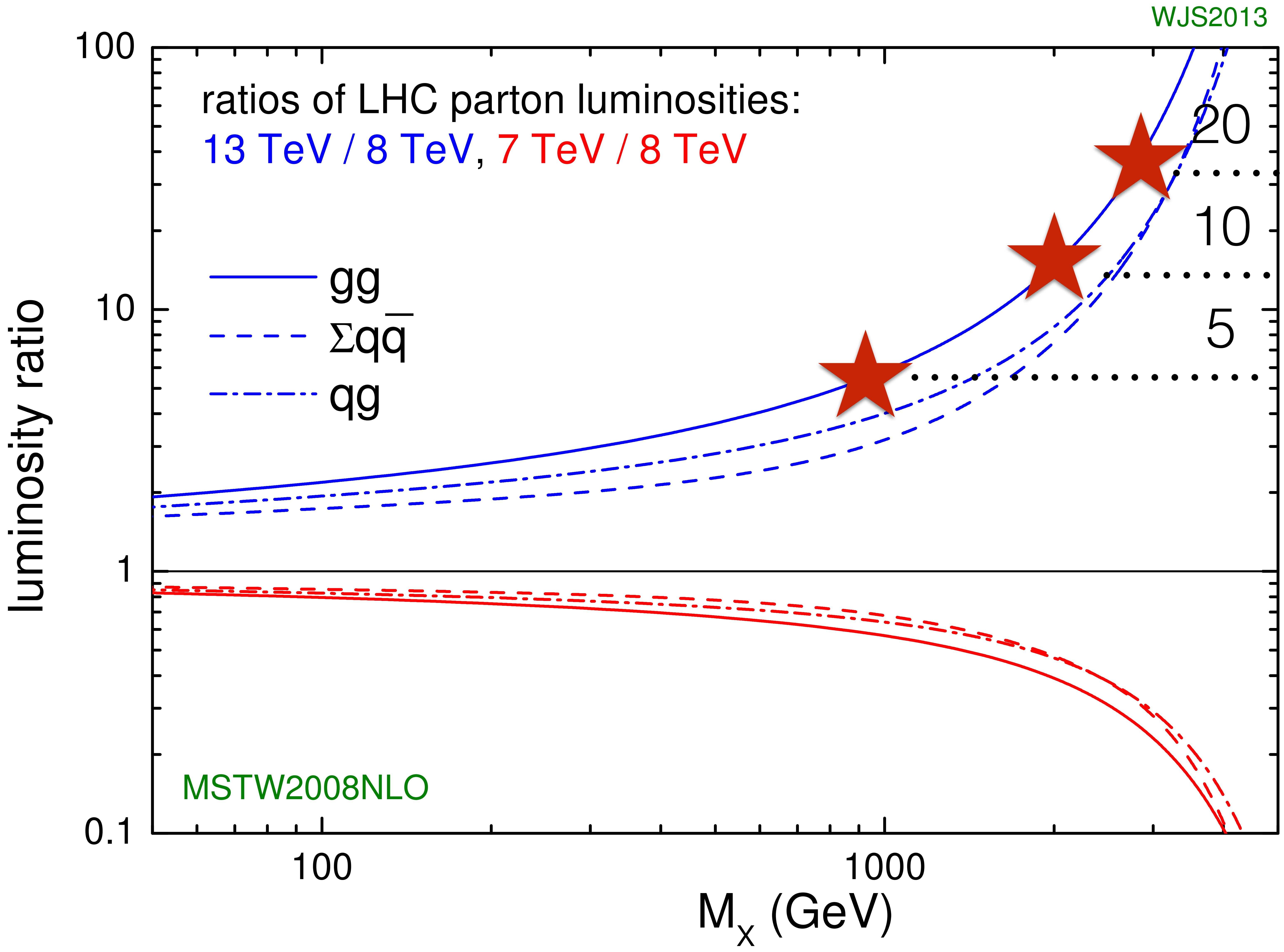
- Small Cross Section ~ at 13 TeV: **34 fb** (NNLO + NNLL)



HH cross section as a function of energy

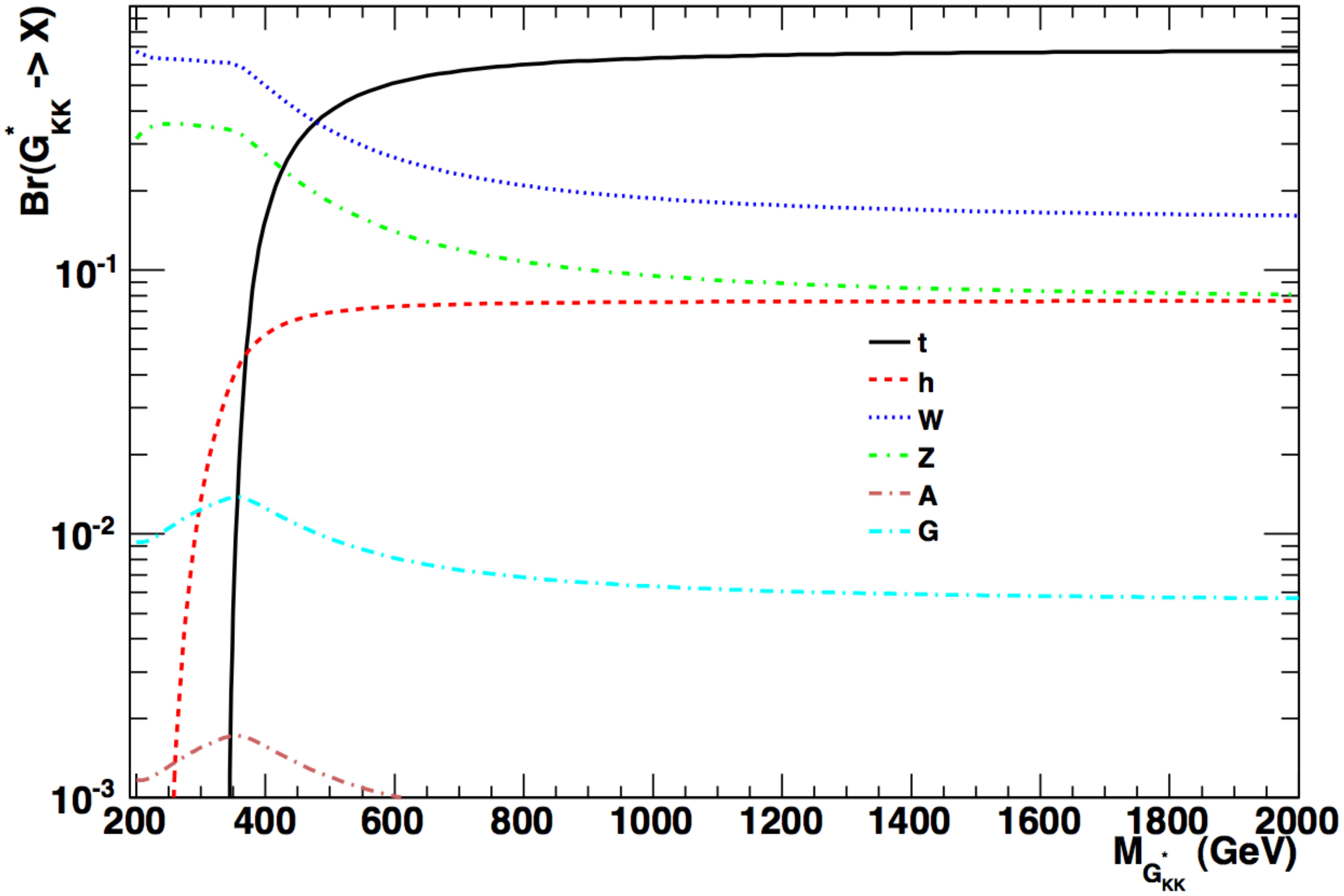
Patron Luminosity Ratios

- Given the increased mass reach of the LHC in Run 2, it is particularly important to focus on resonant searches at **high mass**



RSG branching ratio

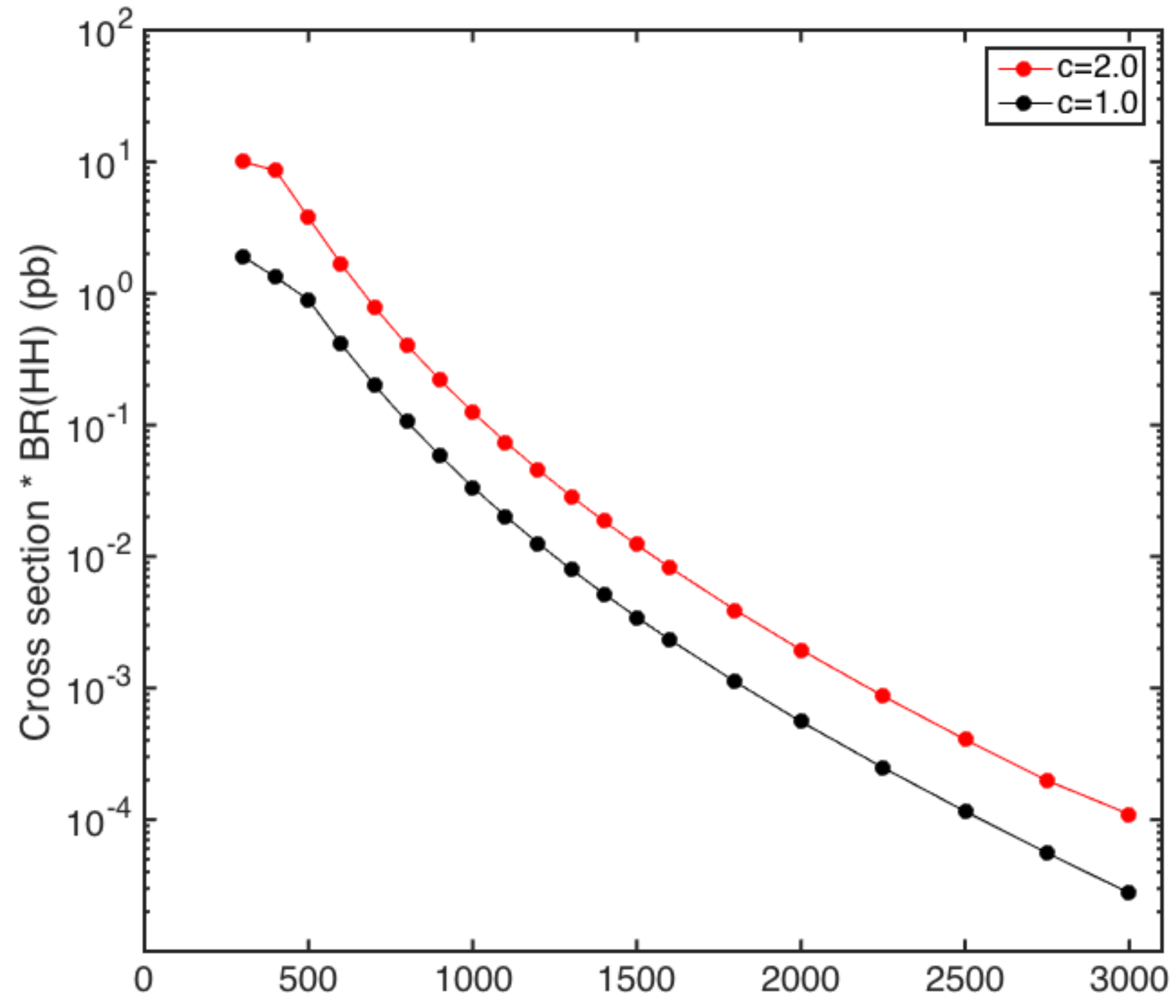
- RSG branching ratio as a function of mass computed in MadGraph with the CP3-Origins implementation

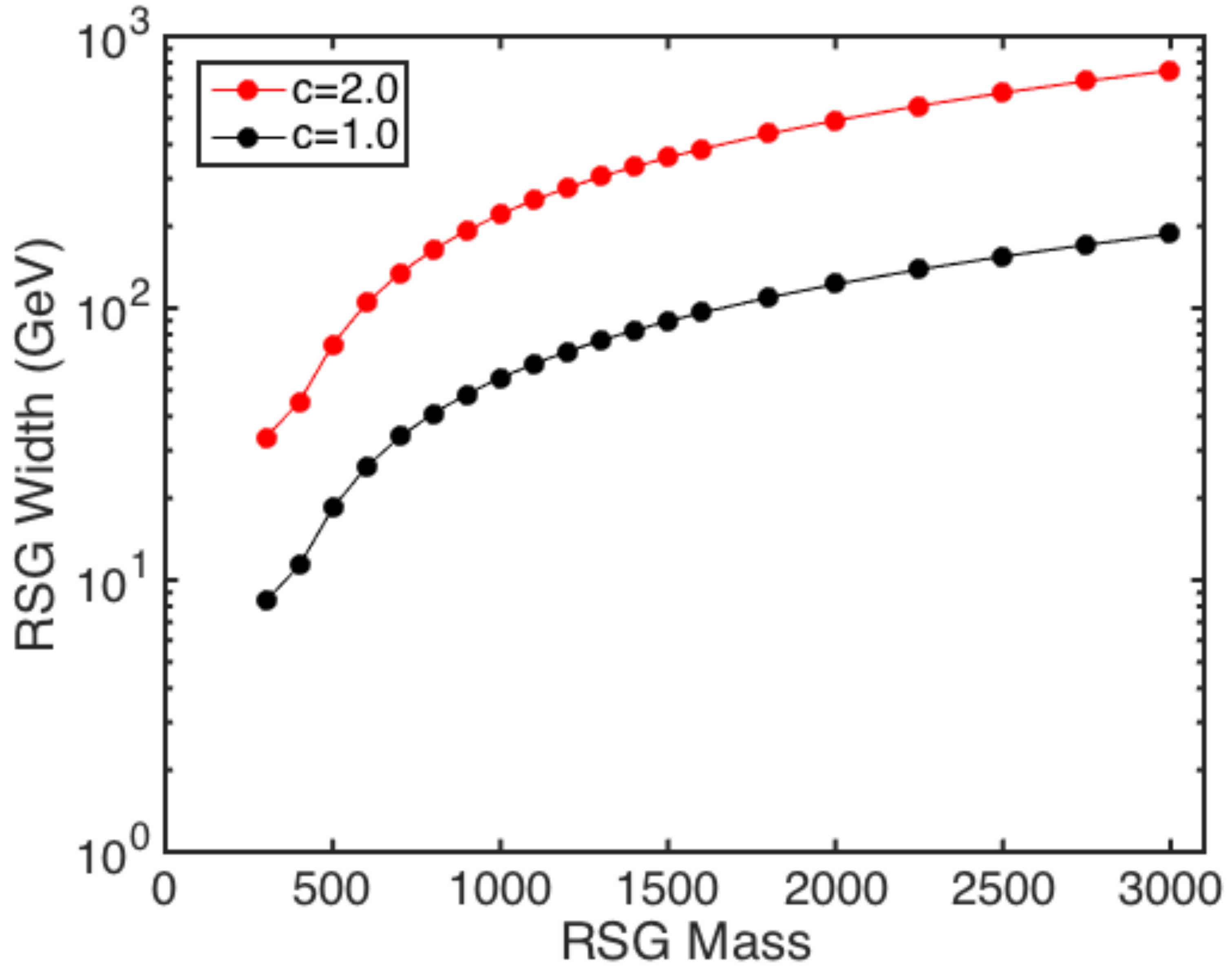


RSG cross section and width

- c is the ratio of curvature parameter k and the M_{pl}, reduced plank mass

- The width of the graviton increases with both c and mG

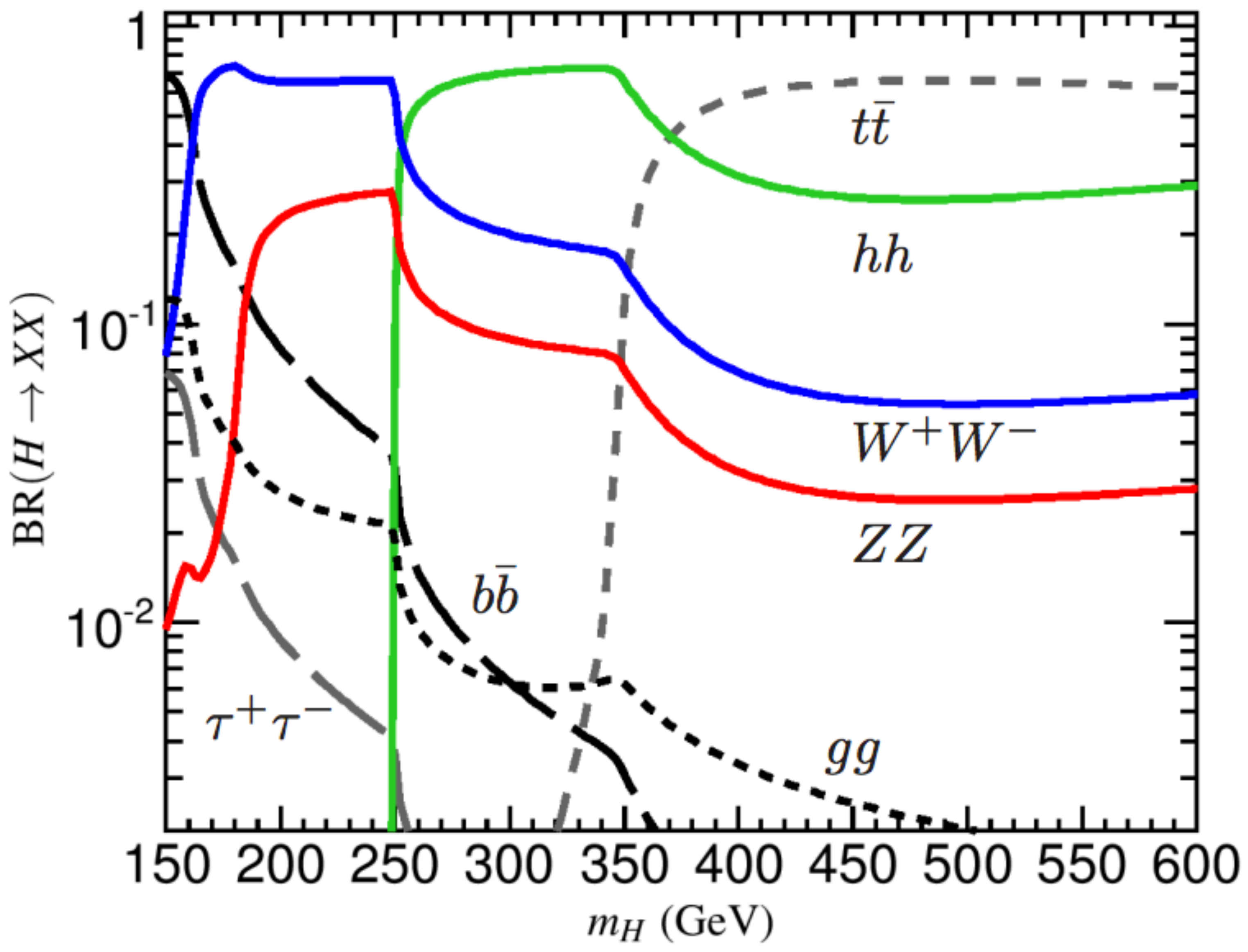




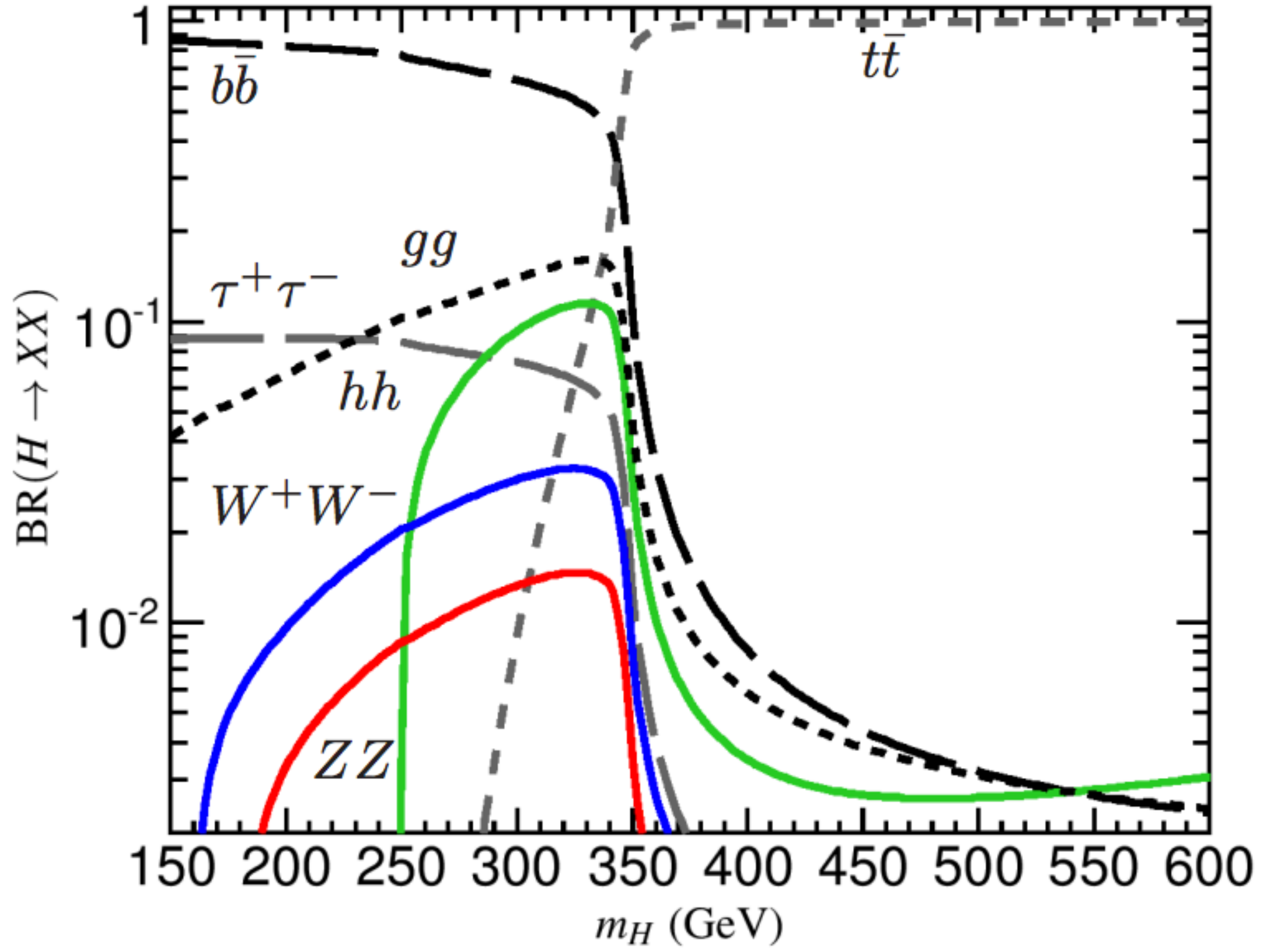
2HDM branching ratio

- In Type 1 models, the charged fermions only couple to the second Higgs doublet, leading to a fermiophobic light Higgs. In Type 2 models, up-type quarks couple to the first doublet while down-type quarks couple to the second doublet.
- Used Type-2 2HDM with cos(b-a) = 0.2 and tan(b) = 1

Type I



Type II



b-tagging

b-tagging Details

- MV2c10: trained with 7% c-fraction
- Rejection and purity information

- **IP[2/3]D** *Uses transverse/longitudinal impact parameters significances*
  - Likelihood ratios between b-, c- and light-jet hypothesis.
- **SV1** *Reconstructs secondary vertex and uses information on:*
  - Invariant mass of tracks pointing to same vertex.
  - Number of two-track vertices.
  - Angular separation between jet and PV → SV direction.
- **JetFitter** *Exploits the topology of the weak b/c-hadron decay chain*
  - A Kalman filter is used to find common line for the b and c vertices

} Inputs to **MV2** tagger (BDT)

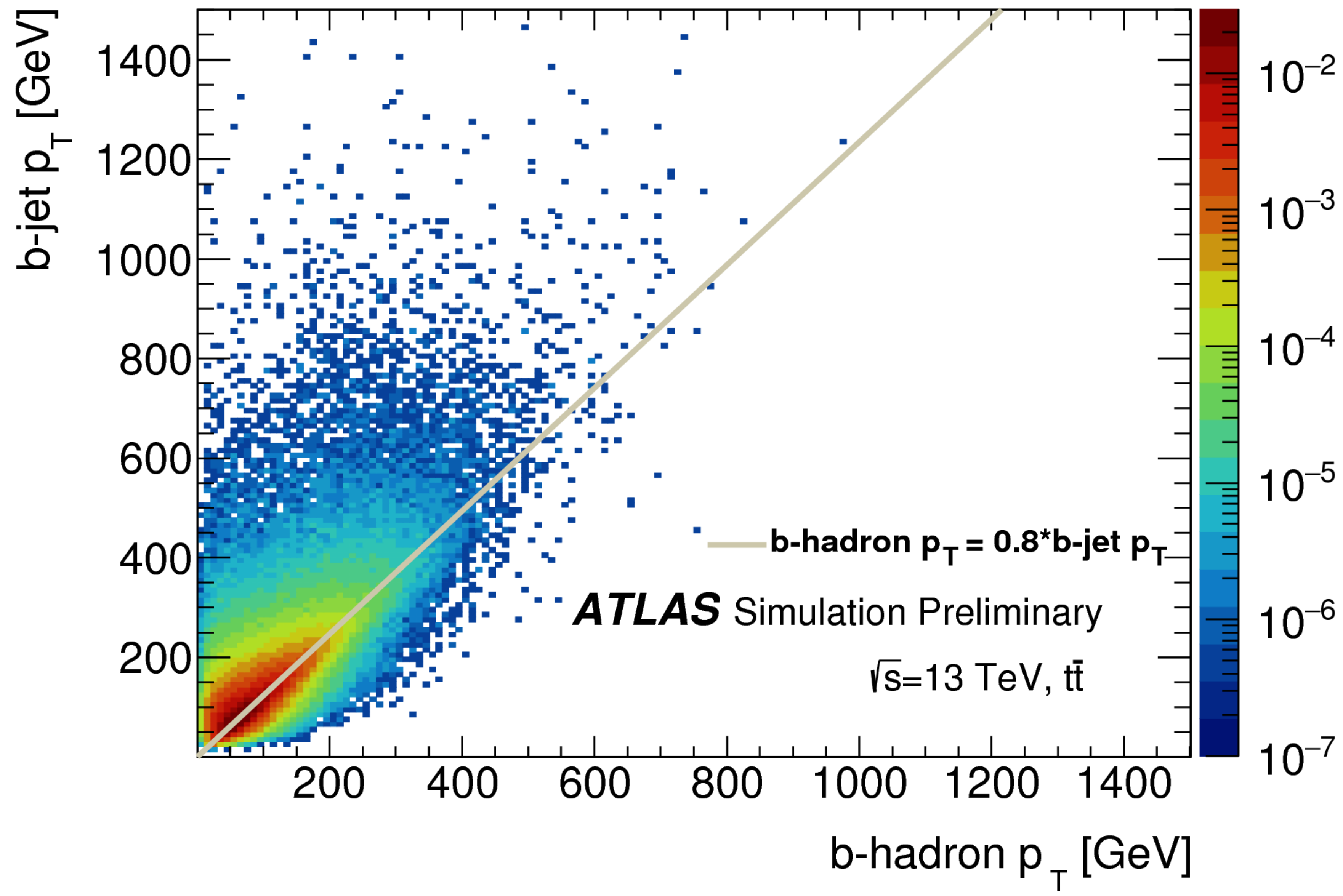
	Purity	C RR	Tau RR	light RR
EM-70wp	97	12	54	380
Trk-70wp	93	7	17	120

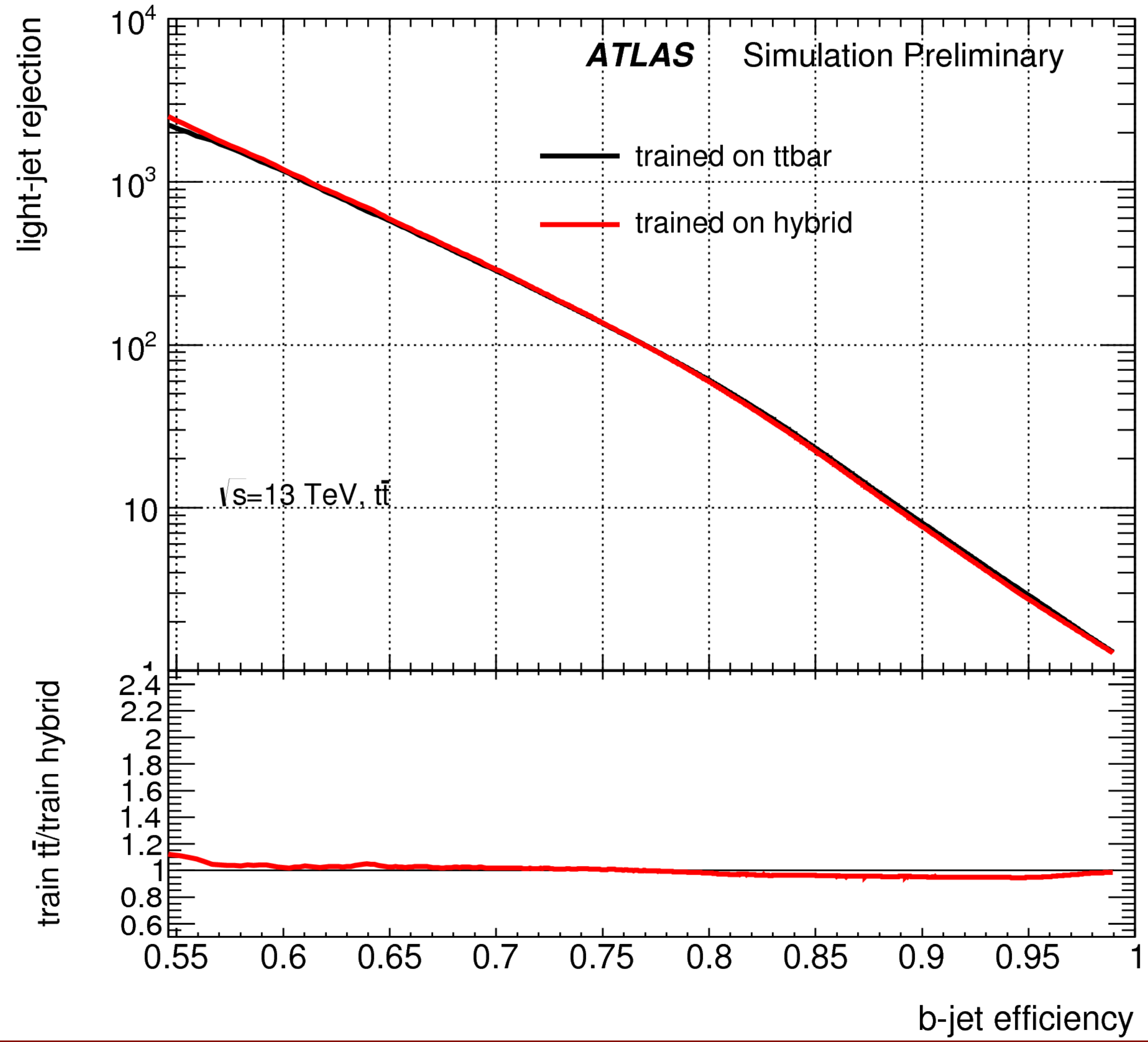
twiki

HH4b future improvements

- Limiting factor is signal acceptance:
  - b-tagging
  - trackjet size

- Expect better results at 120 fb^{-1} !

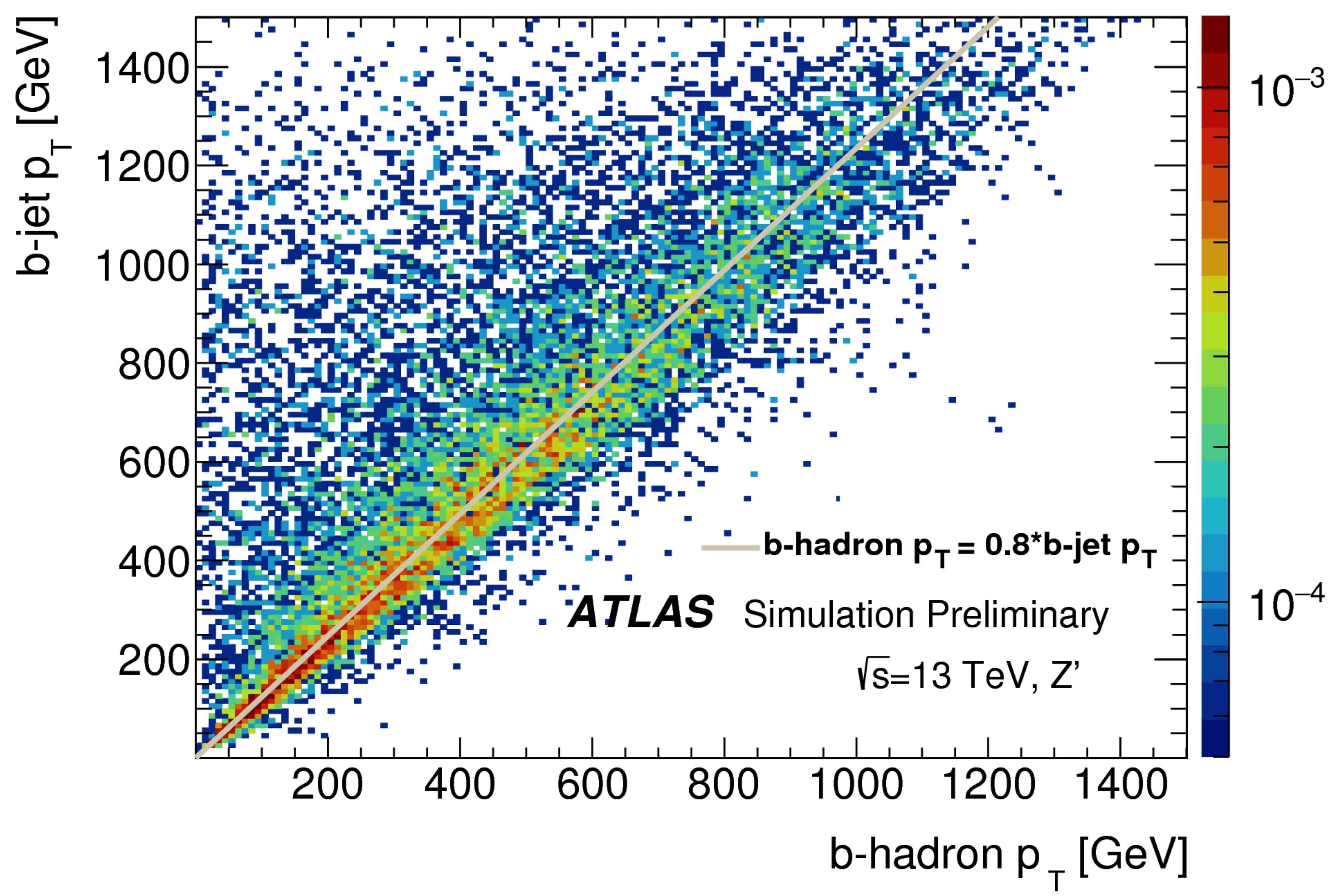


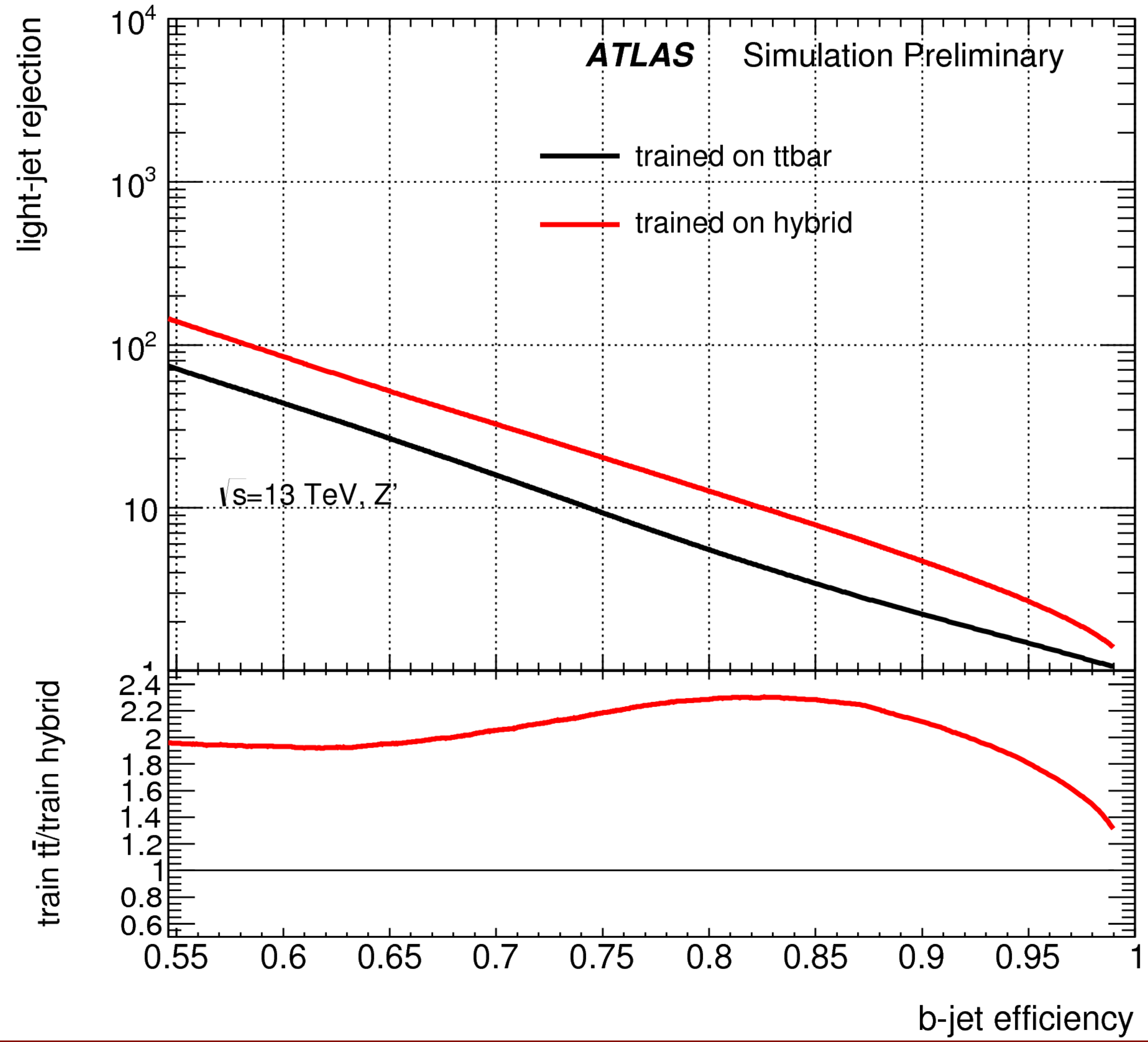


HH4b future improvements

- Limiting factor is signal acceptance:
  - b-tagging
  - trackjet size
- Expect better results at 120 fb^{-1} !

ATL-PHYS-PUB-2017-013





Run I & II ATLAS Results Reviews

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**)

Resolved and Boosted Results

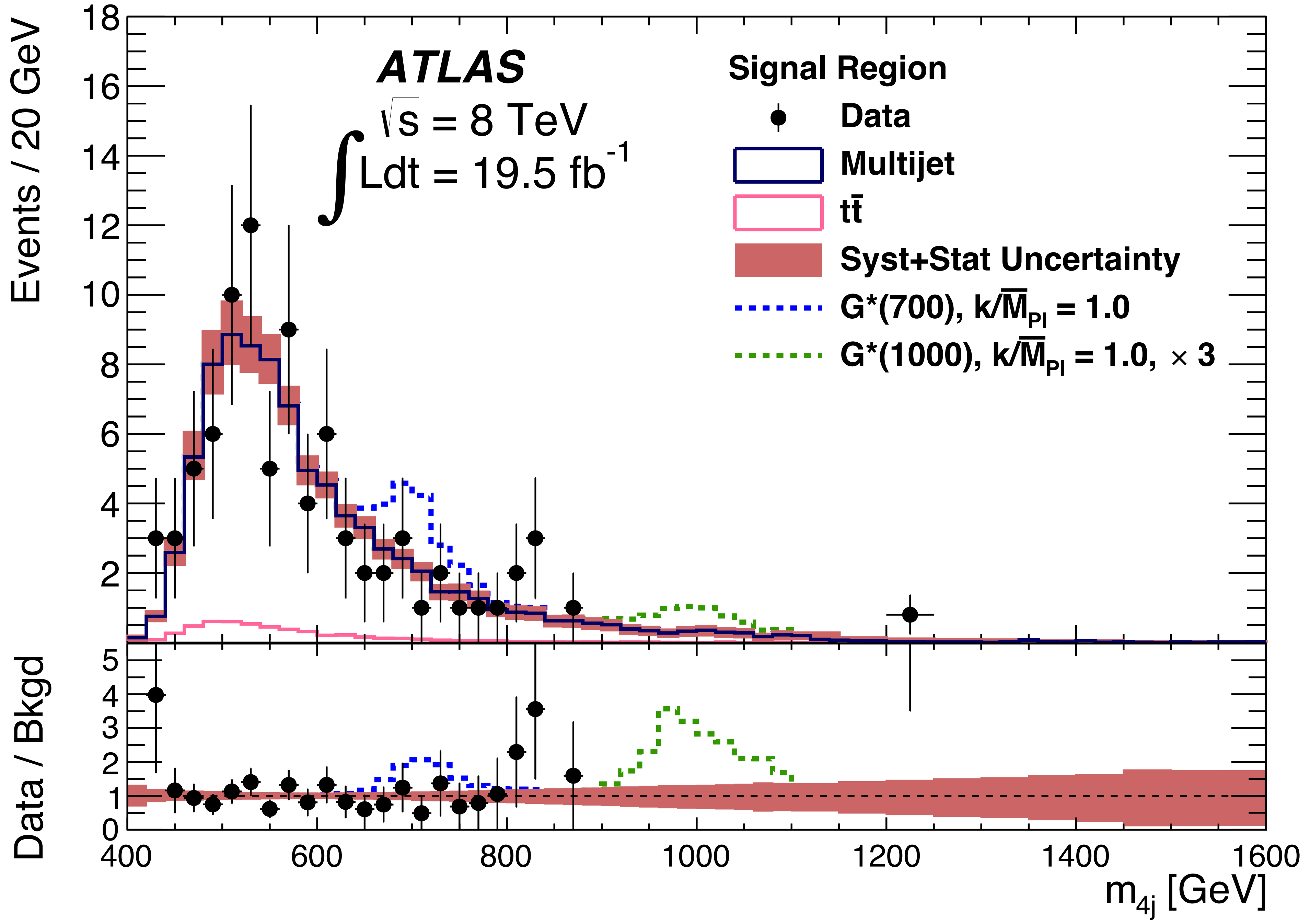
Eur. Phys. J. C (2015) 75:412

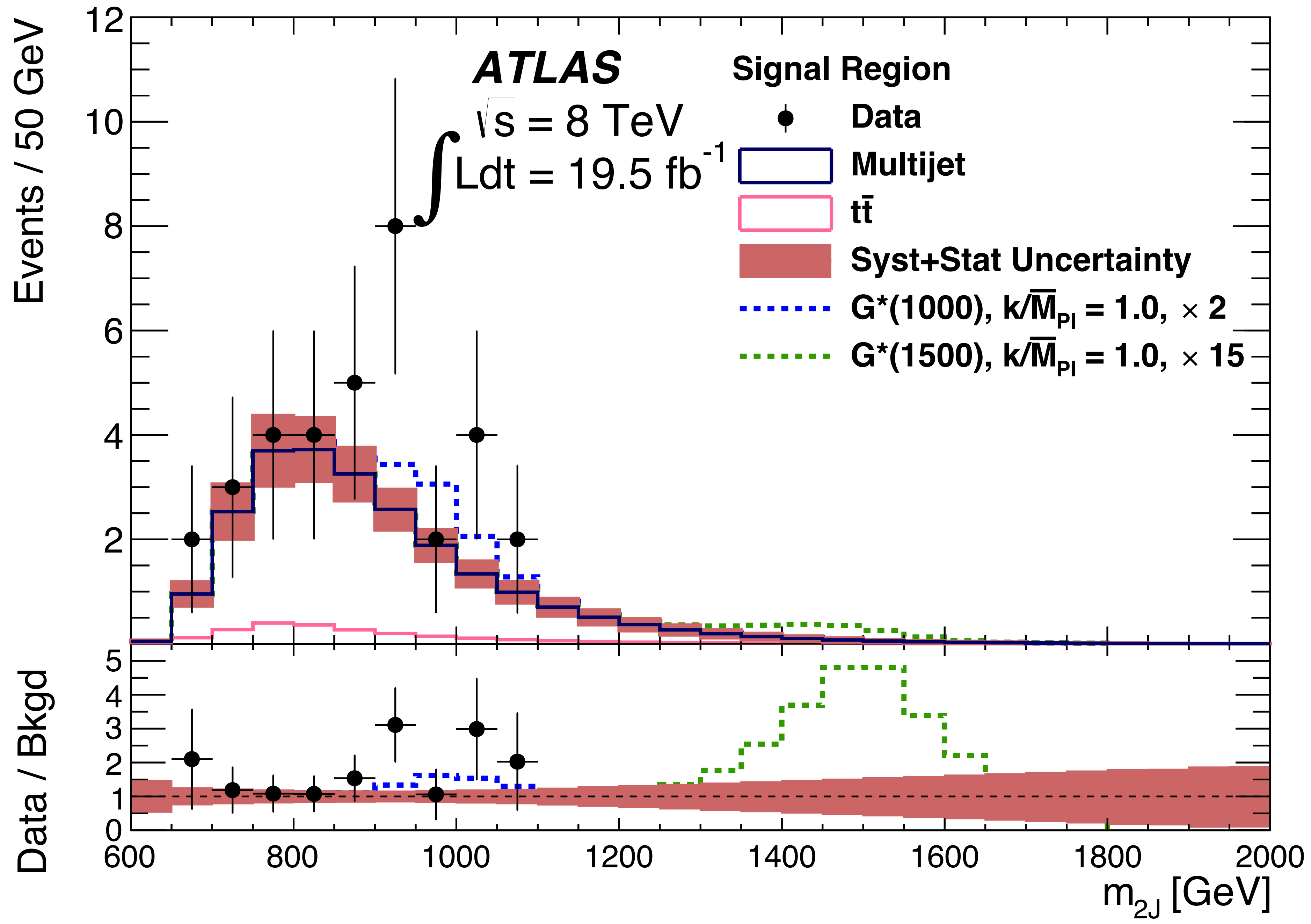
Resolved

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

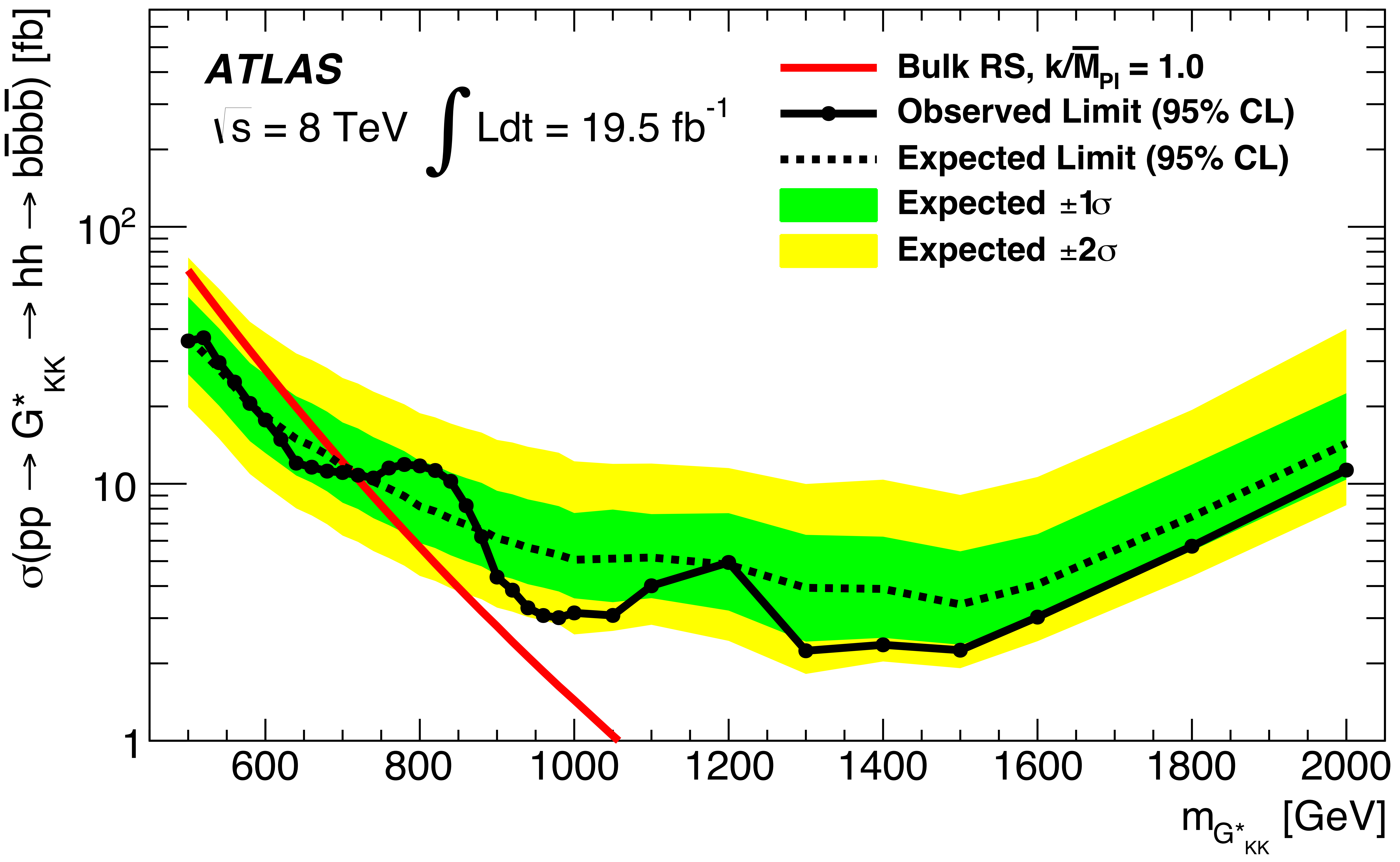
Sample	Signal Region Yield
Multijet	23.5 ± 4.1
$t\bar{t}$	2.2 ± 0.9
Z+jets	0.14 ± 0.06
Total	25.7 ± 4.2
Data	34
G^*_{KK} (1000 GeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	2.1 ± 0.6





Combined Limit

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

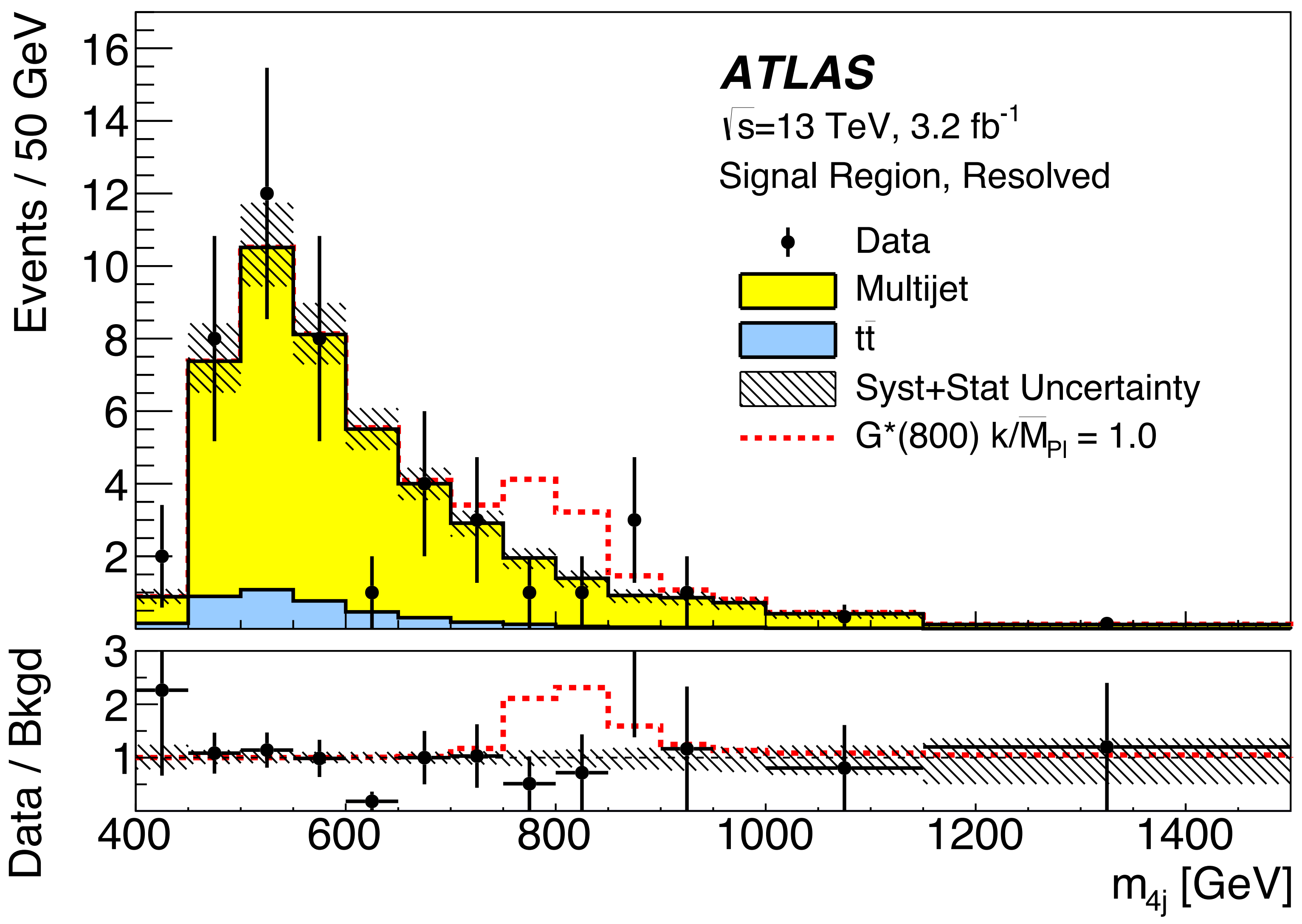


2015 Results

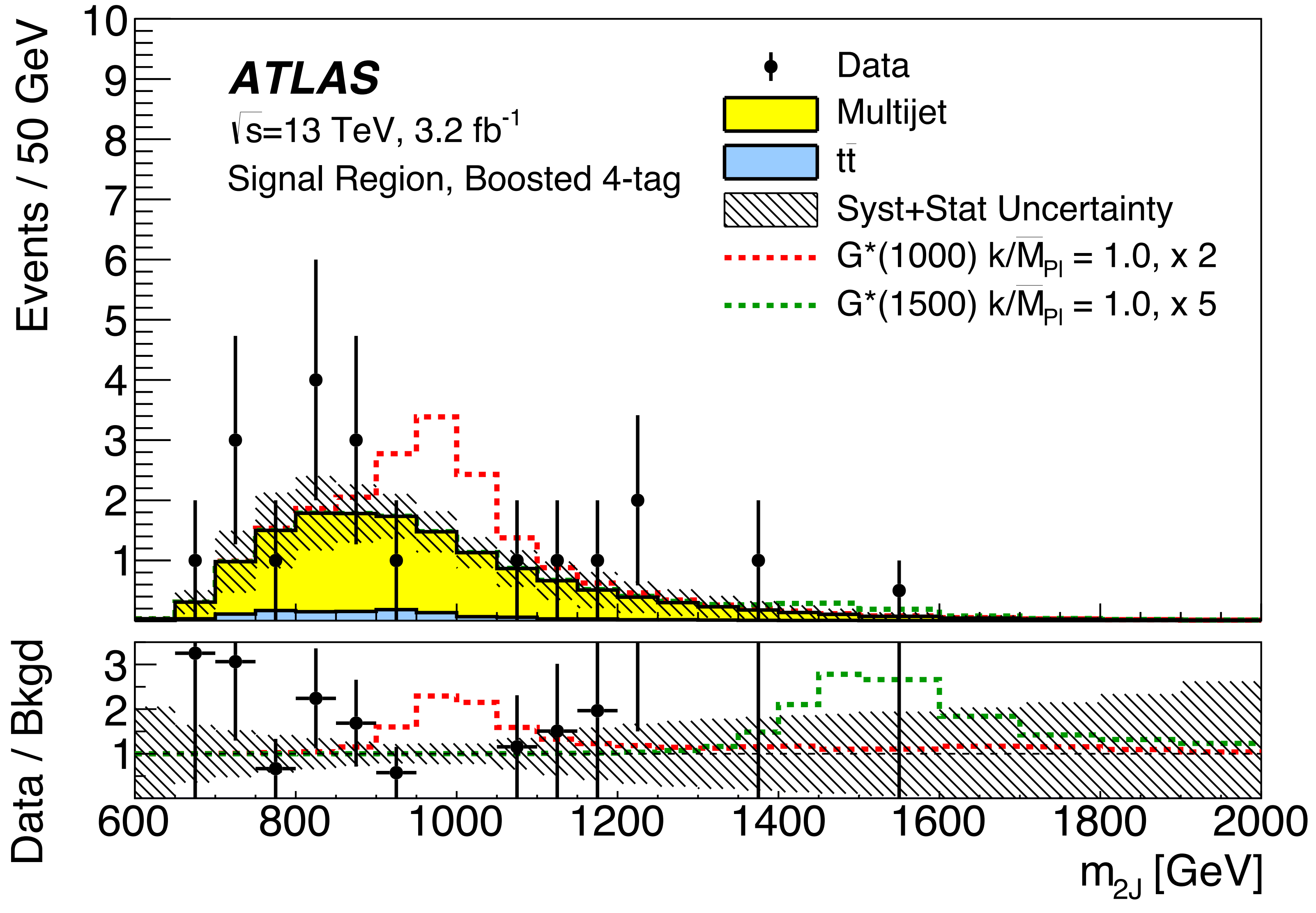
Phys. Rev. D 94.052002 (2016)

Signal	Resolved	Boosted 4b	Boosted 3b
Exp	47.6 ± 3.8	14.6 ± 2.4	284.8 ± 19.4
Obs	46	20	316

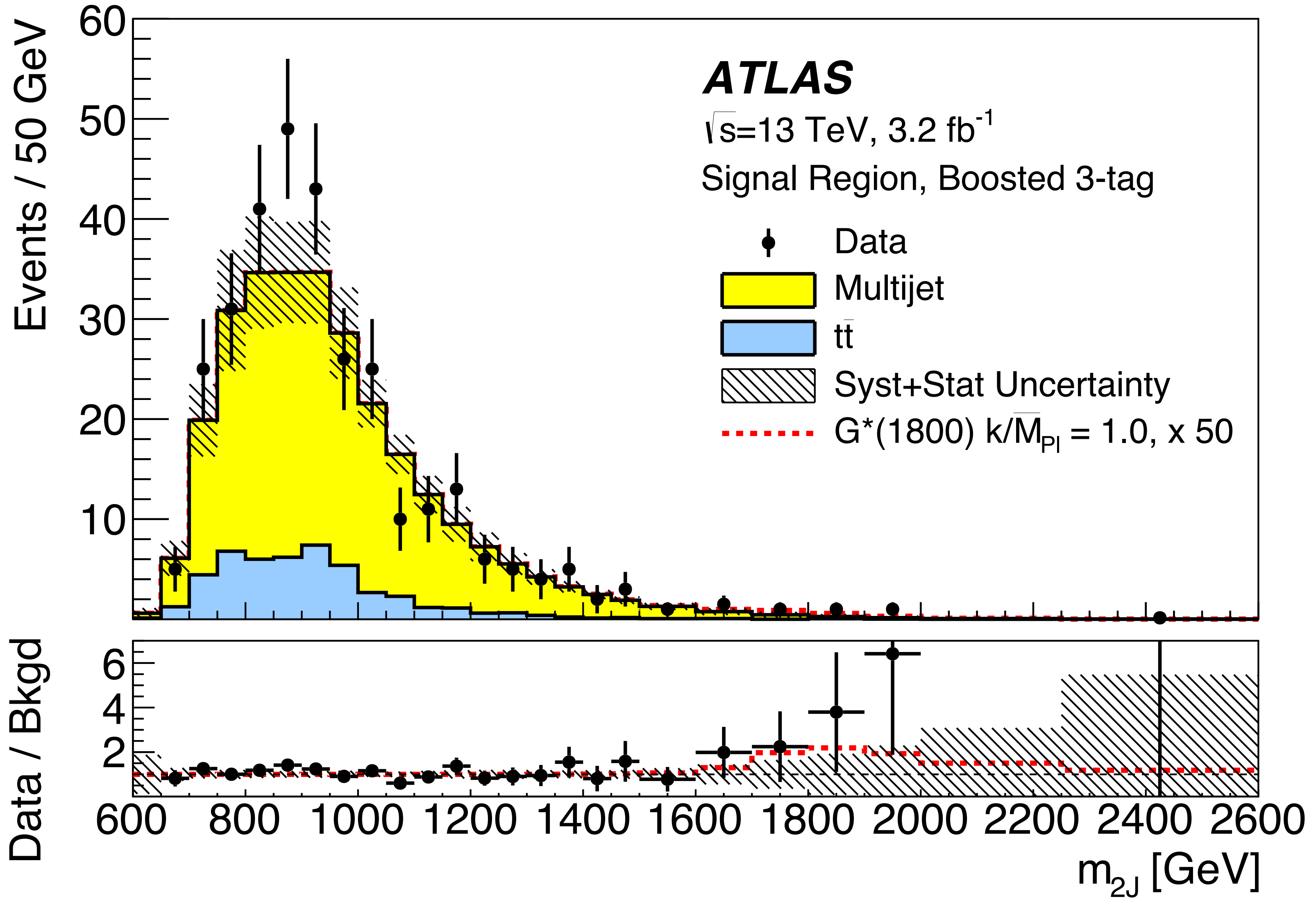
Resolved: 4 Jet Invariant Mass



Boosted 4b: 2 Jet Invariant Mass



Boosted 3b: 2 Jet Invariant Mass

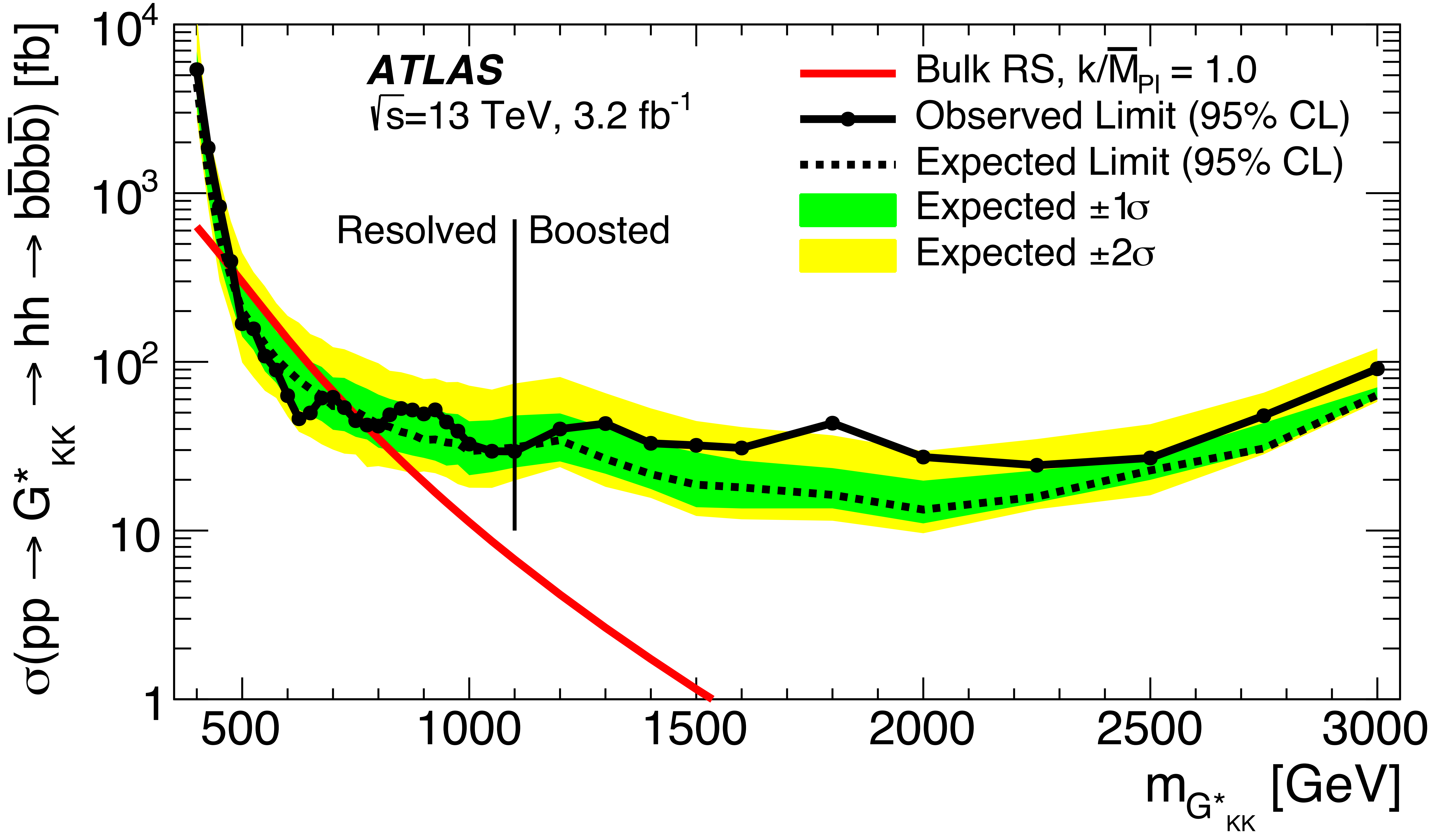


Limits with 3.2 fb^{-1}

Phys. Rev. D 94.052002 (2016)

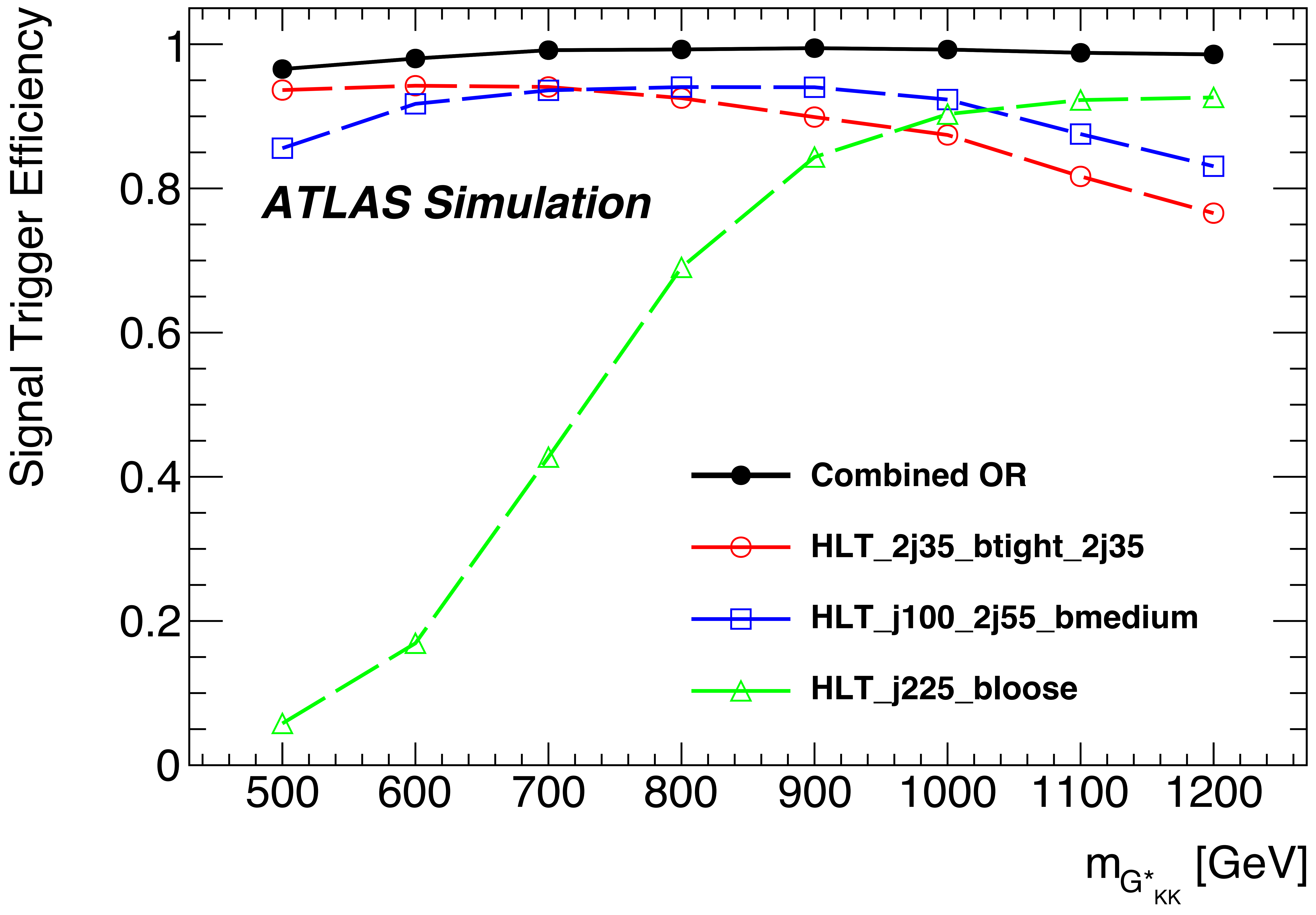
- Resolved + Boosted Combined Asymptotic Limits
- Statistical uncertainty limited
- Non-Resonance limit:
  - bbbb: **1.22 pb** (1.3 pb expected)

Spin 2, narrower width



Resolved Trigger Efficiency

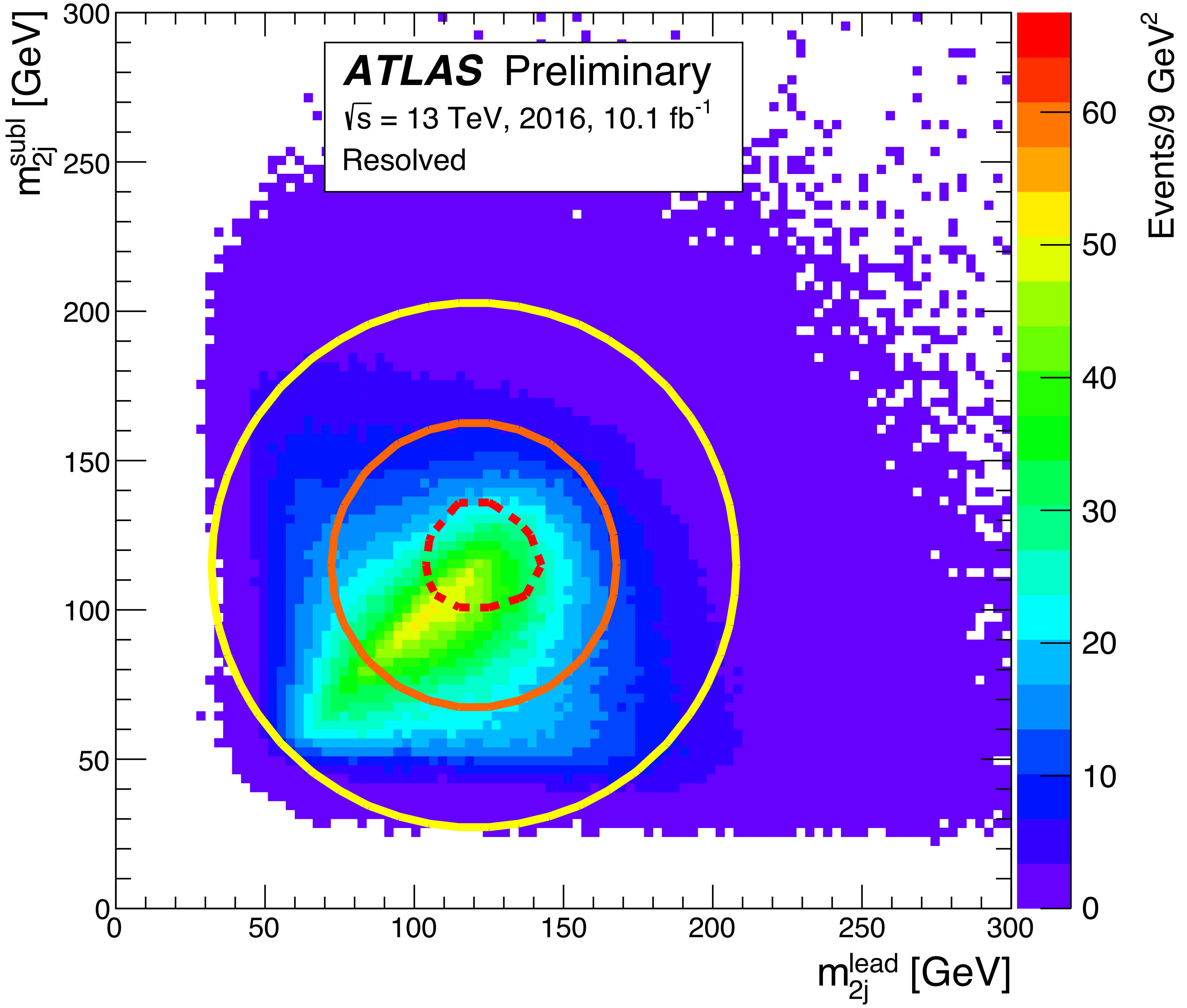
- Or of three triggers

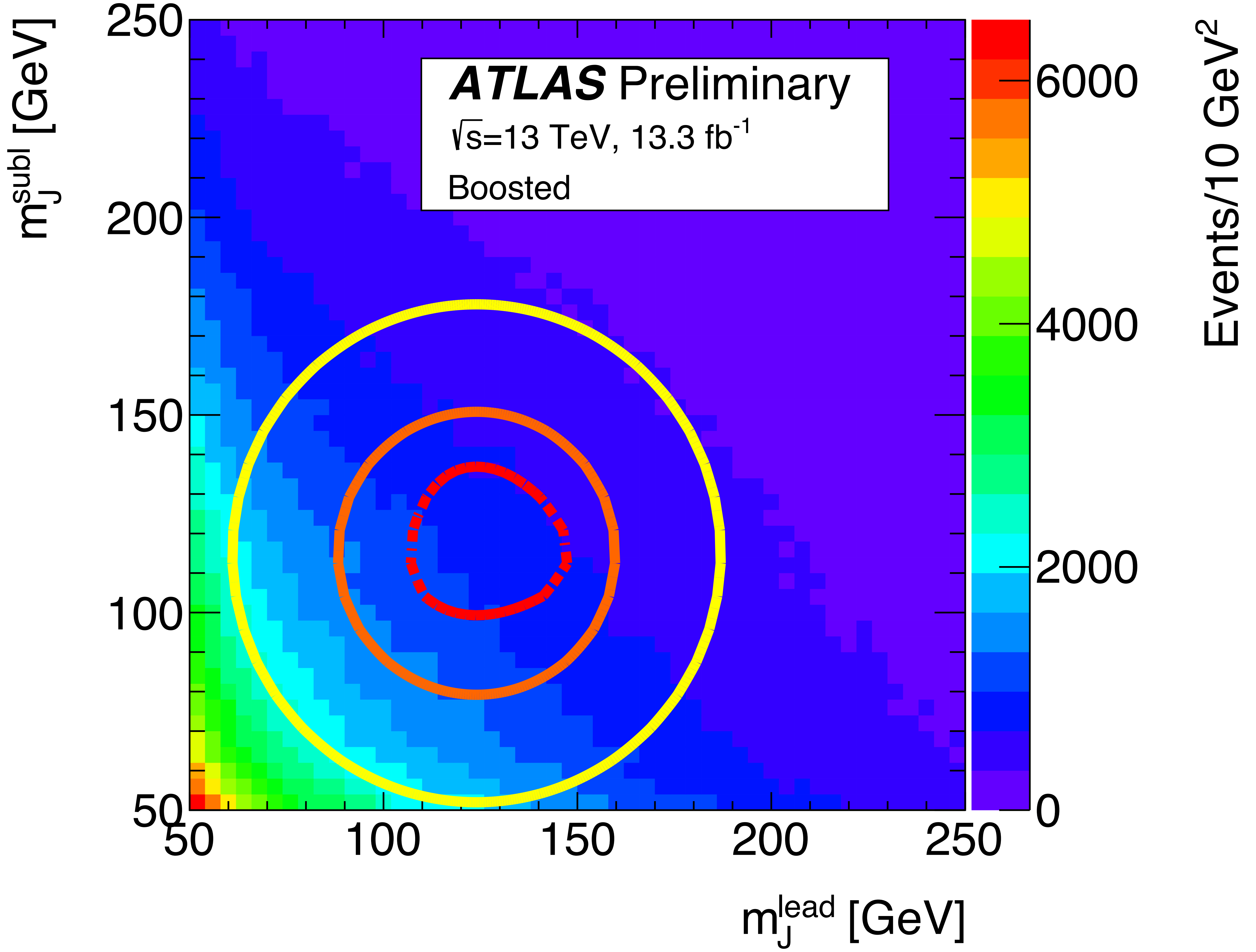


Two Jet Mass Plane

ATLAS-CONF-2016-049

- Updated Sideband, Control and Signal Regions

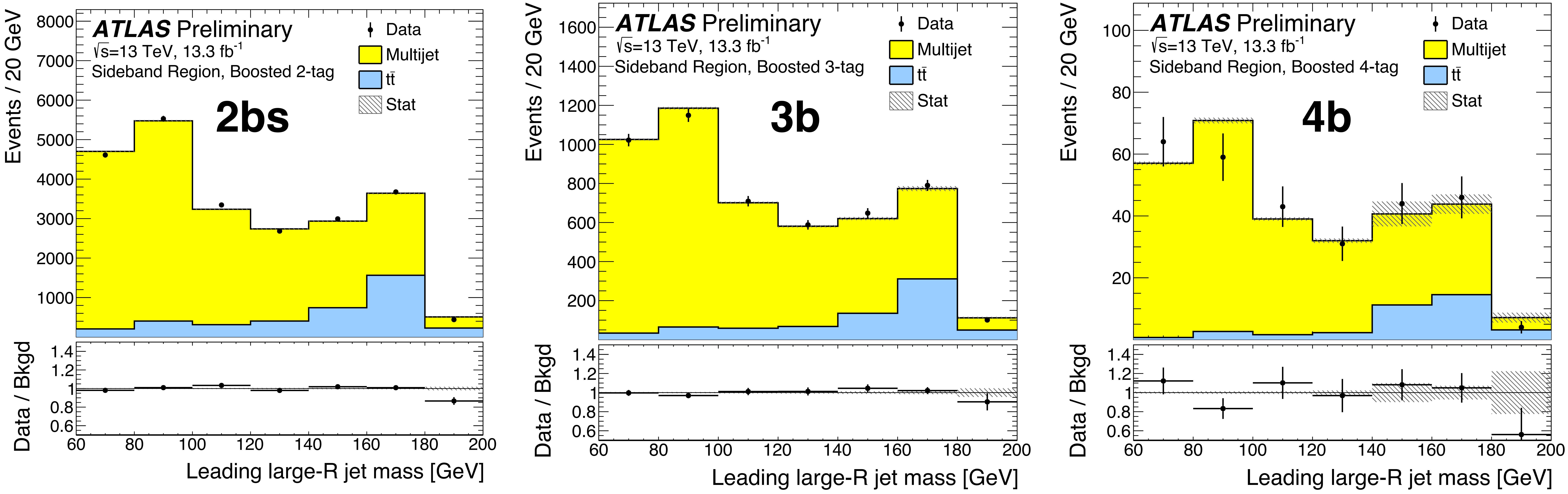




Fit on Leading Jet Mass Distribution

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

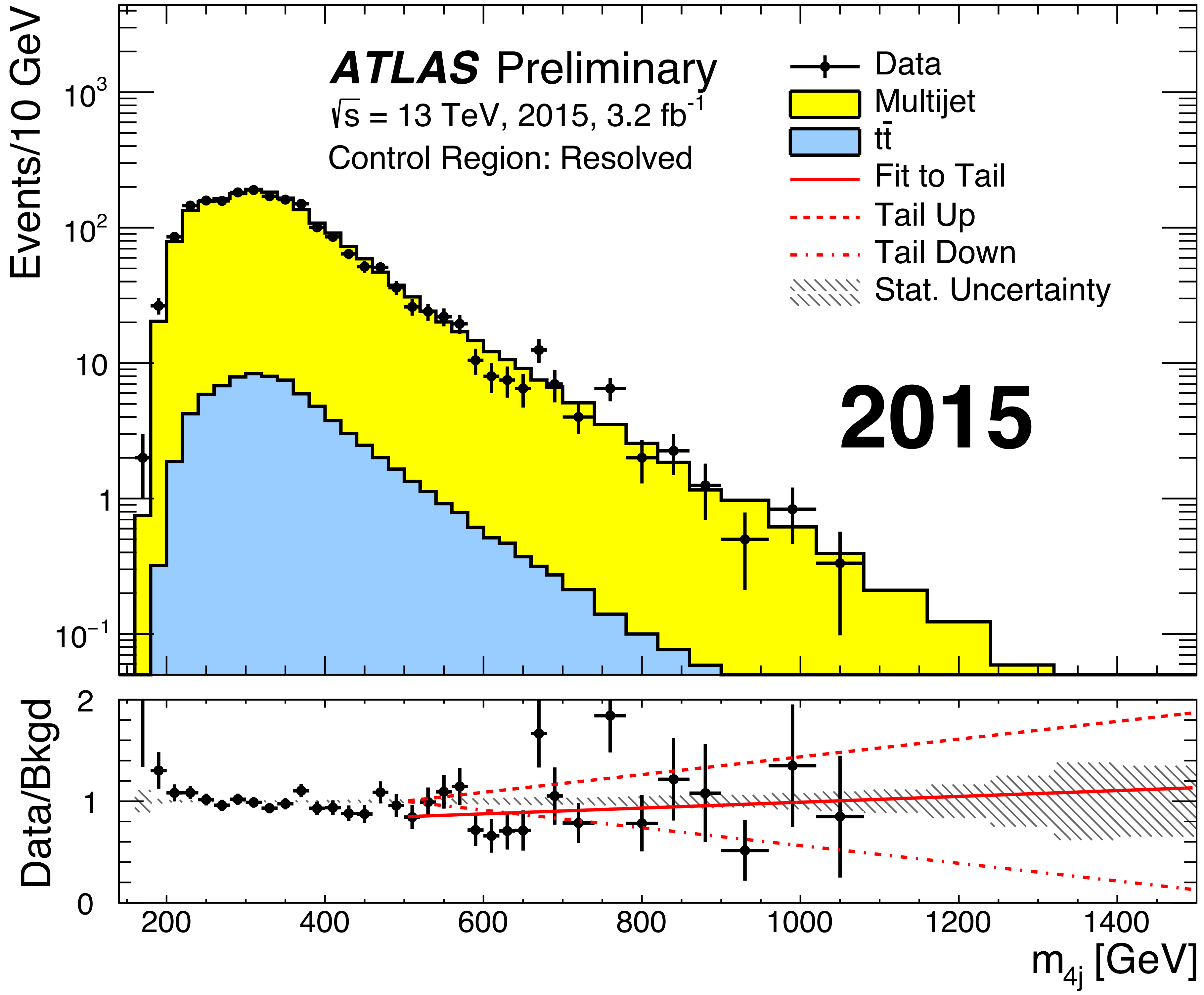
- Kinematics dependence of μ_{qcd} is corrected by reweighting
- Resolved:
  - Njet distribution, leading Higgs candidate pT, subleading Higgs candidate E
- Boosted:
  - leading Higgs candidate pT, leading track jet pT of the leading Higgs candidate, leading track jet pT of the subleading Higgs candidate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

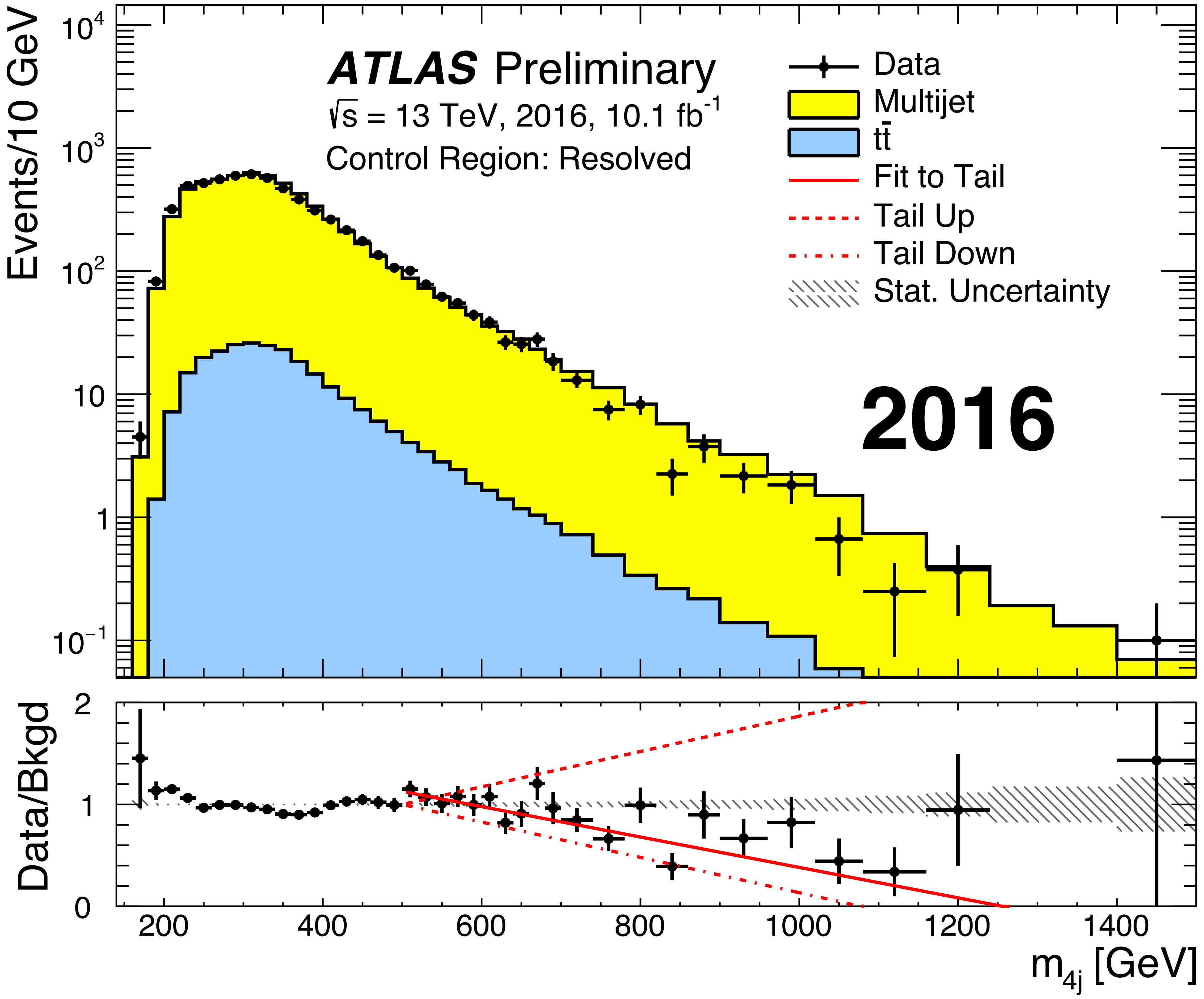
Control Region: Resolved

ATLAS-CONF-2016-049

- **Good** agreement in shape and normalization

Obs	3995	12752
Exp	4021 ± 88	12970 ± 110



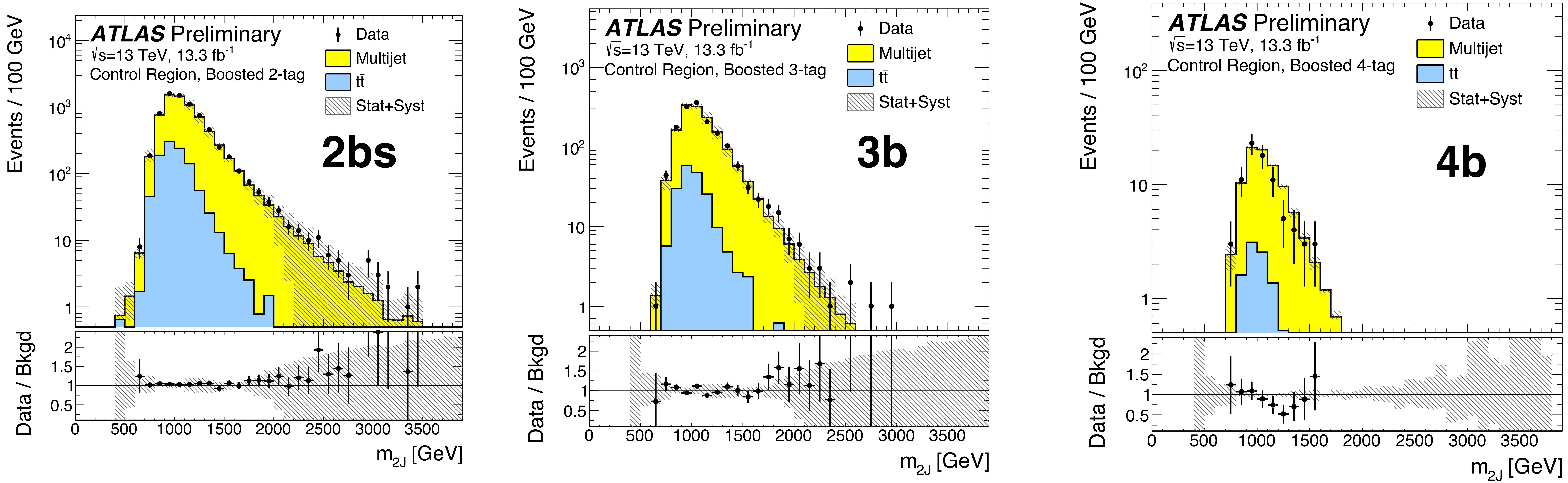


Control Region: Boosted

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

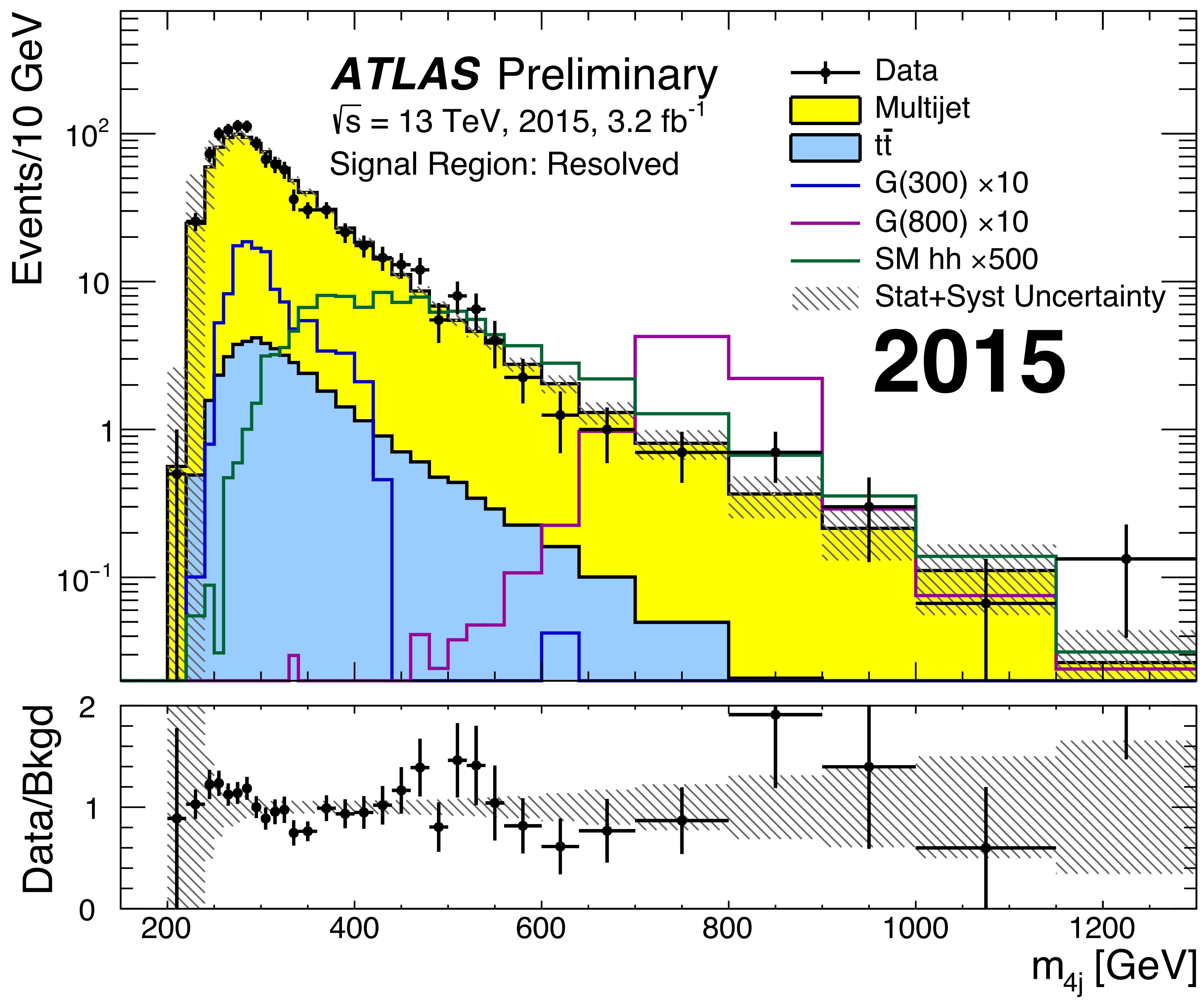
Source	2-tag-split Background	2-tag-split G^*_{KK} (2 TeV)	3-tag Background	3-tag G^*_{KK} (2 TeV)	4-tag Background	4-tag G^*_{KK} (2 TeV)
Luminosity	-	2.9	-	2.9	-	2.9
JER	-	0.1	-	0.1	-	0.3
JMR	-	12	-	12	-	12
JES/JMS	-	4.5	-	4.2	-	3.3
b-tagging	-	58	-	15	-	38
Theoretical	-	2.7	-	2.3	-	2.4
Bkg Estimate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

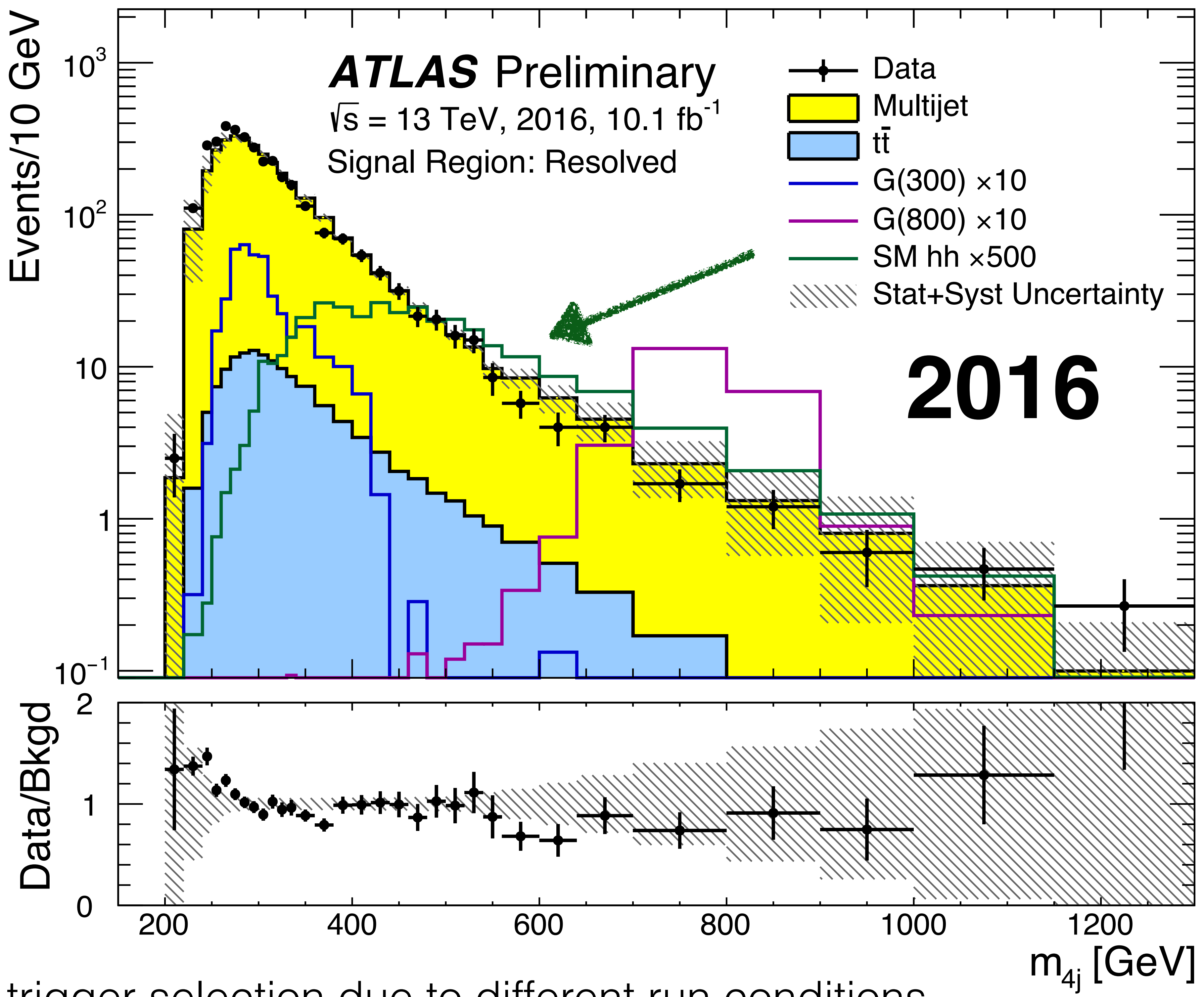
2016: Resolved

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





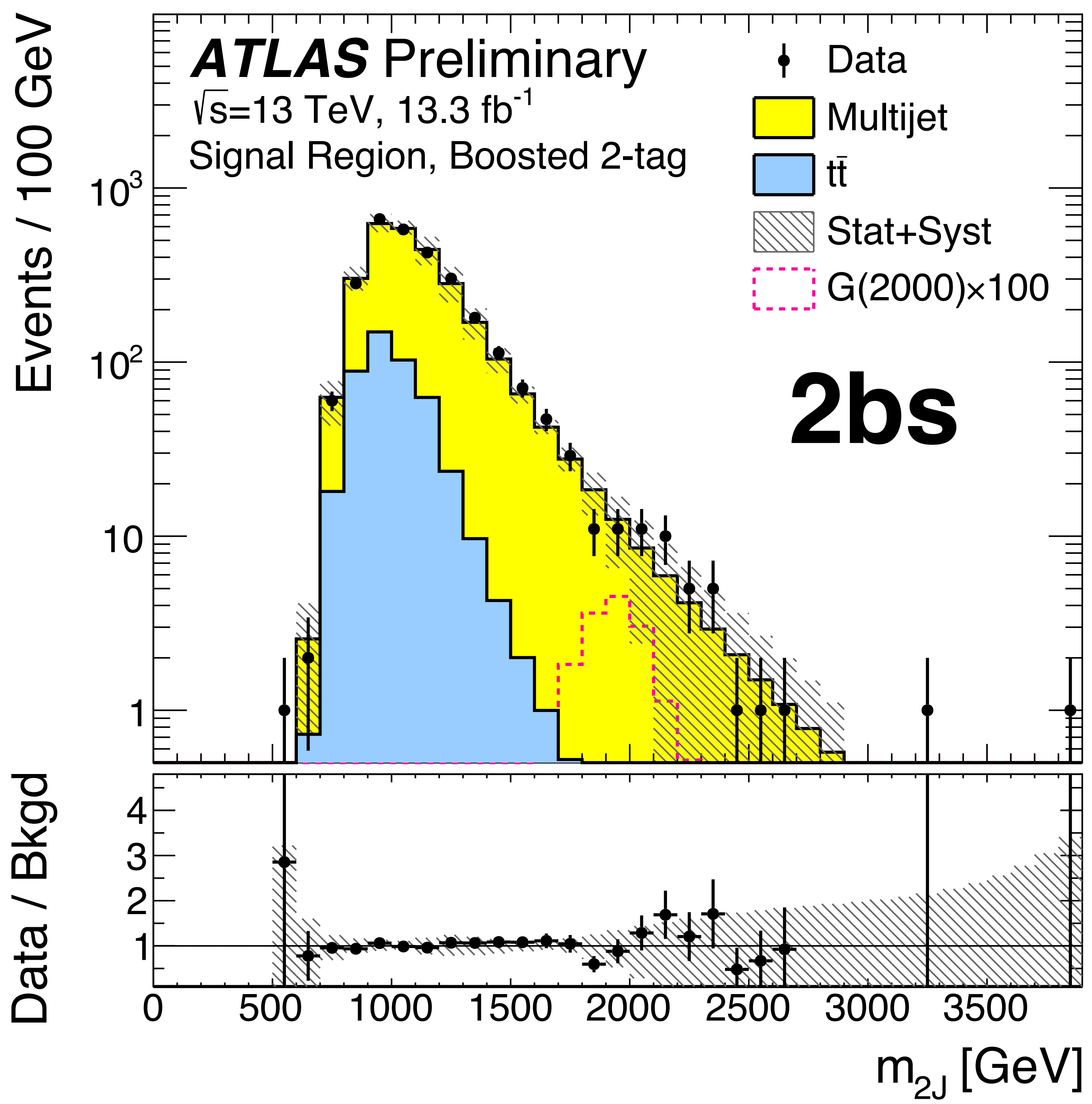
*2015 and 2016 have different trigger selection due to different run conditions

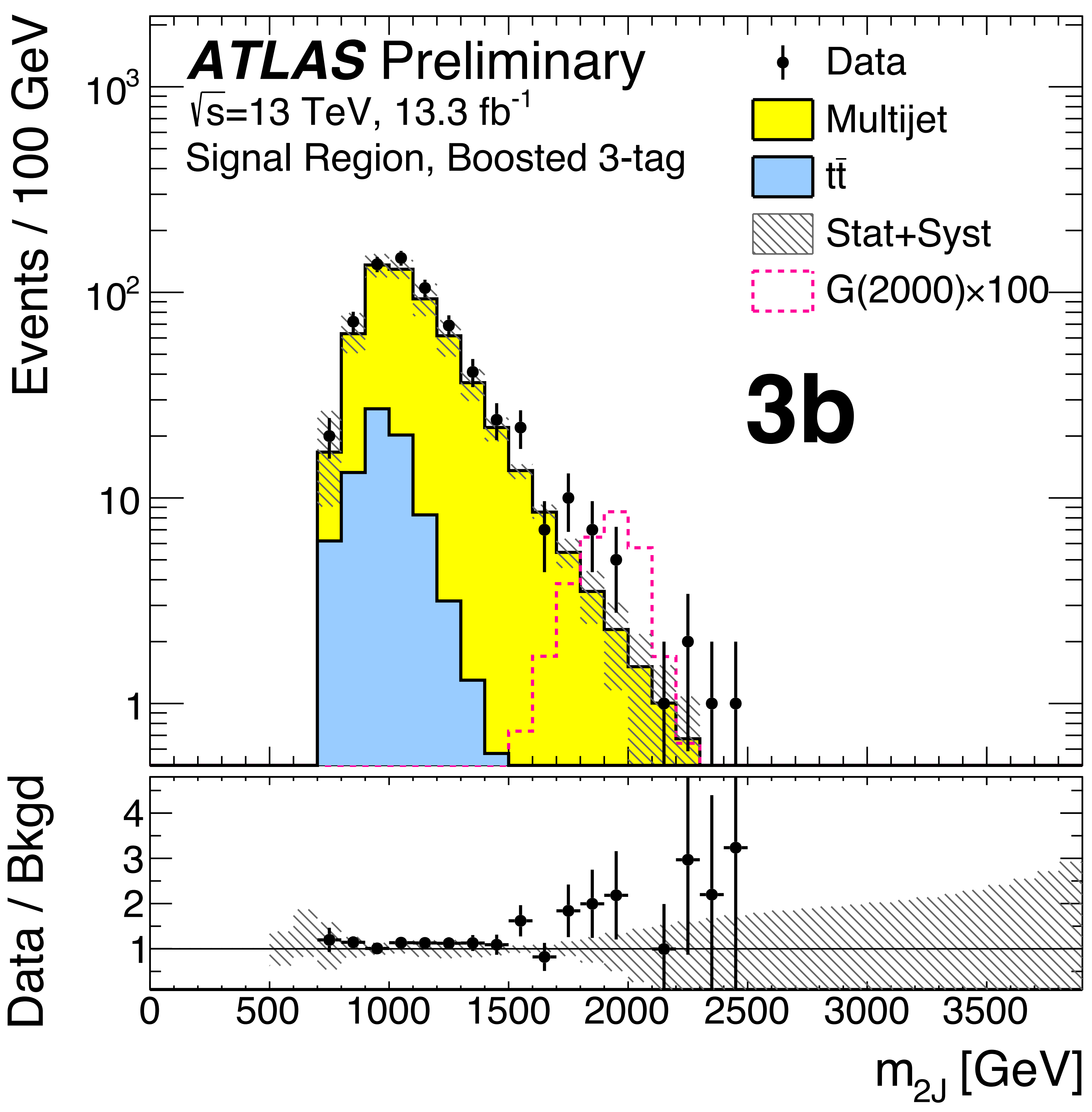
2016: Boosted

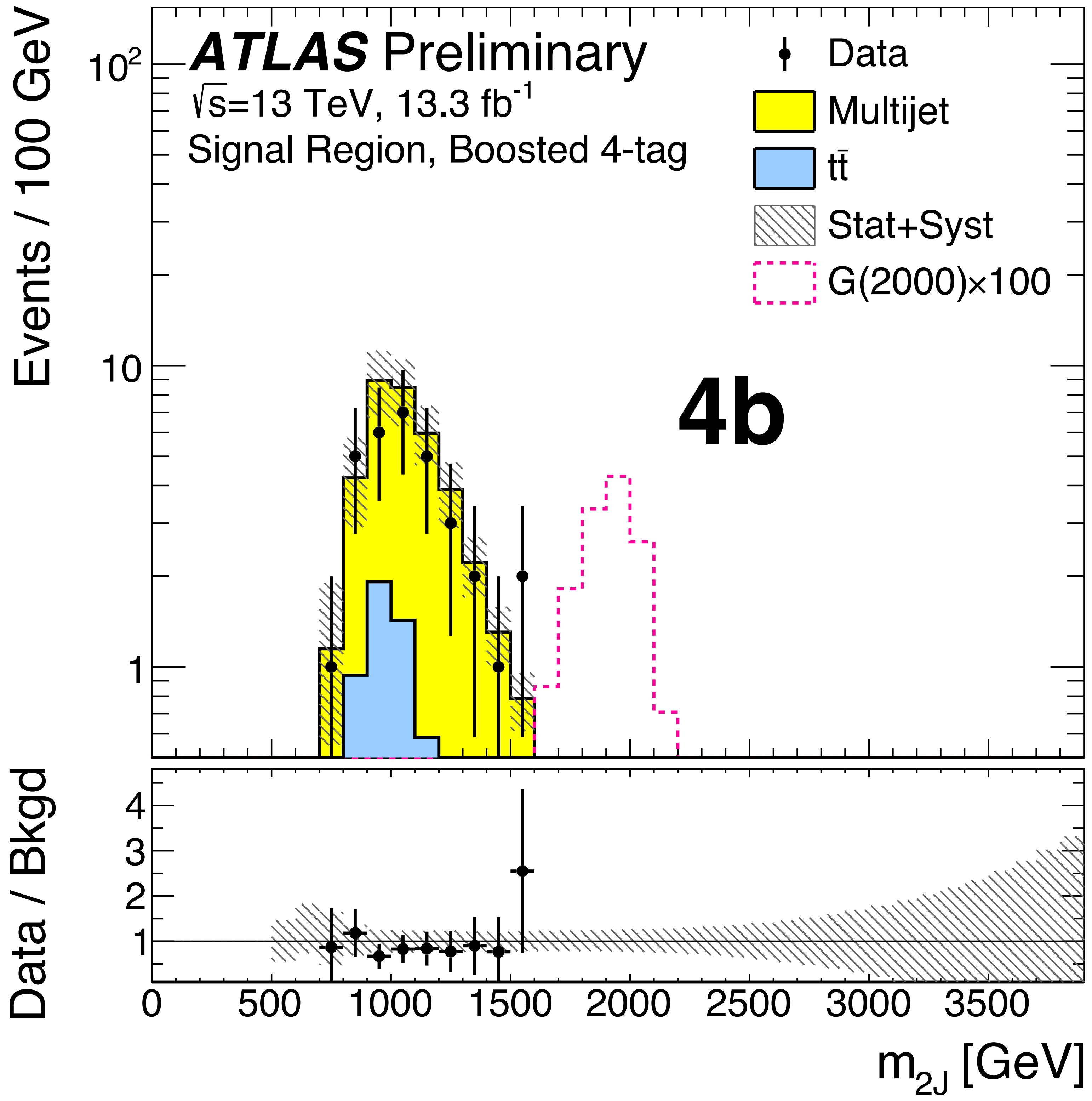
ATLAS-CONF-2016-049

- 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

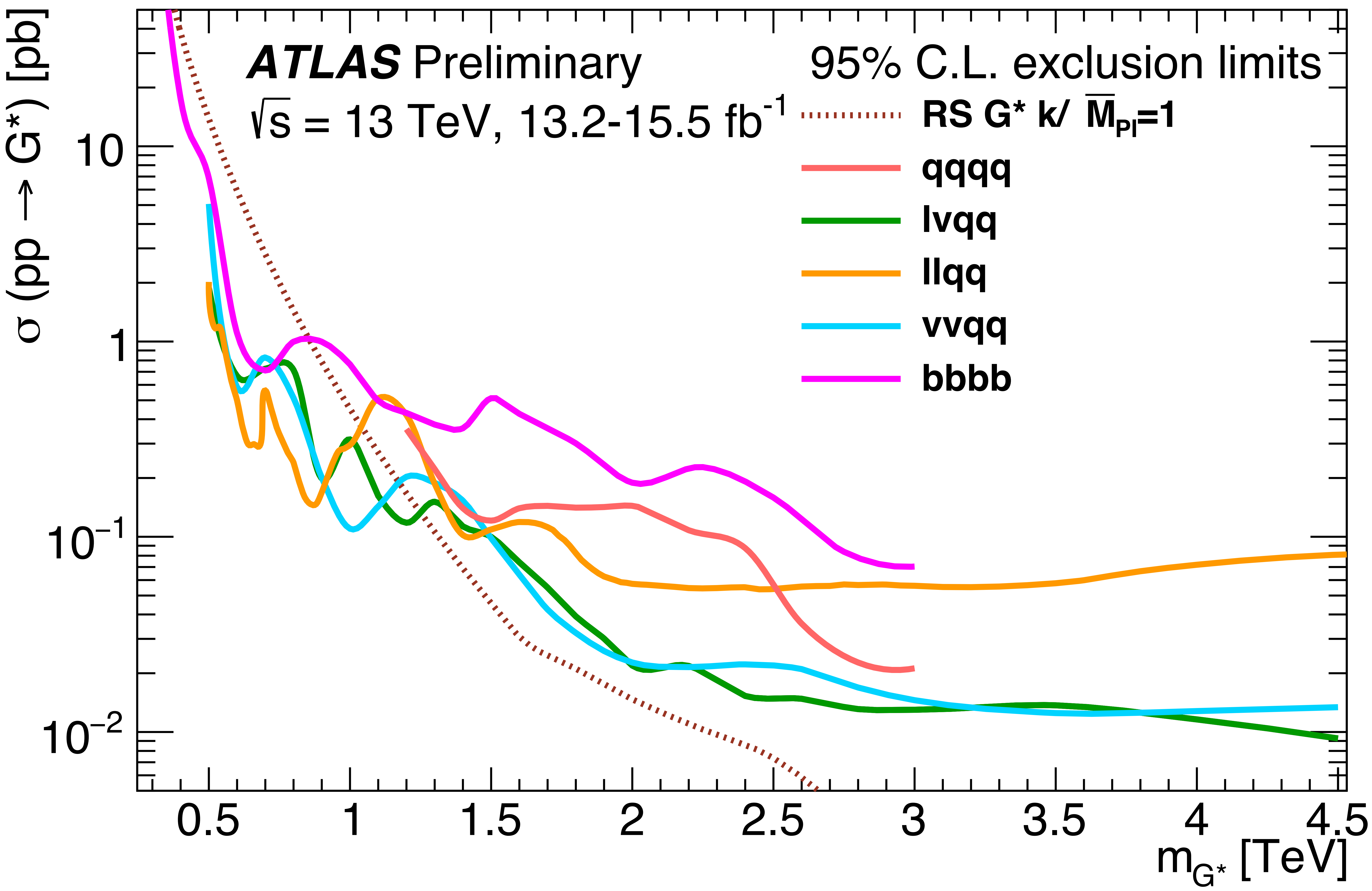




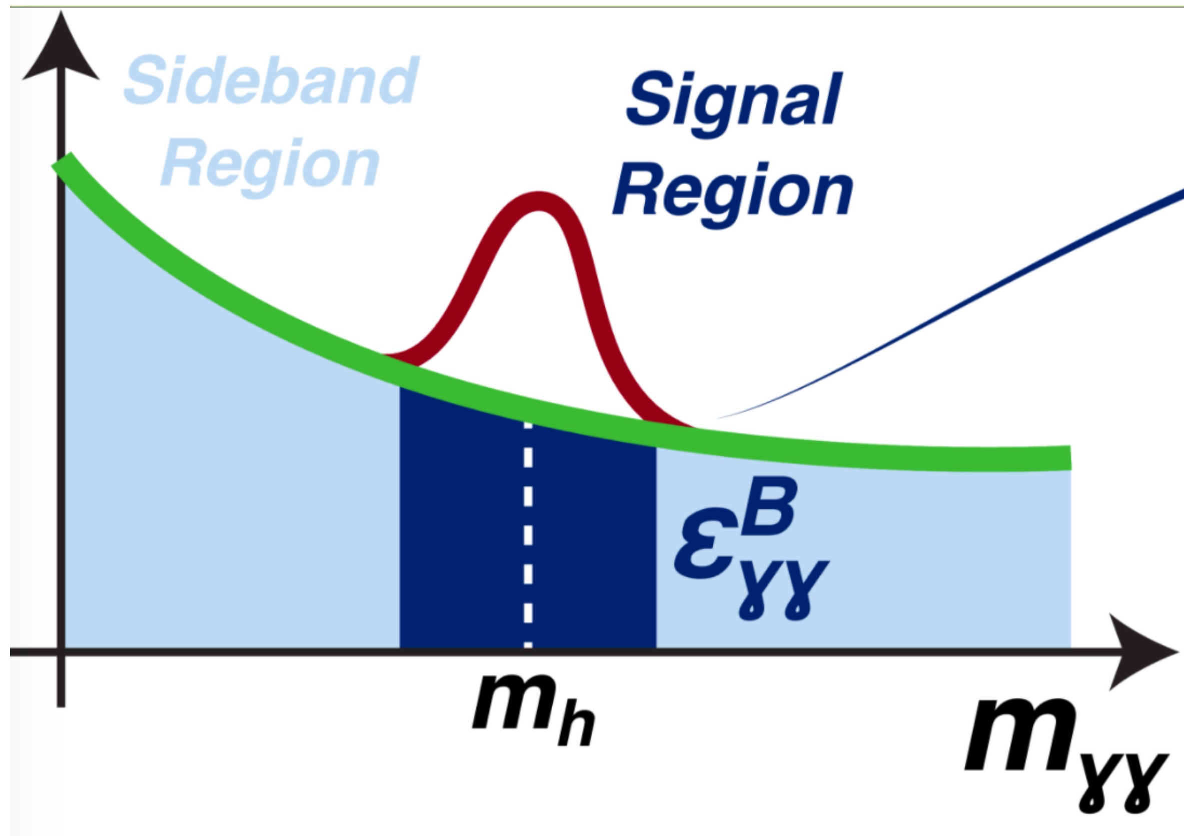


RSG Limit Comparison

Link



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

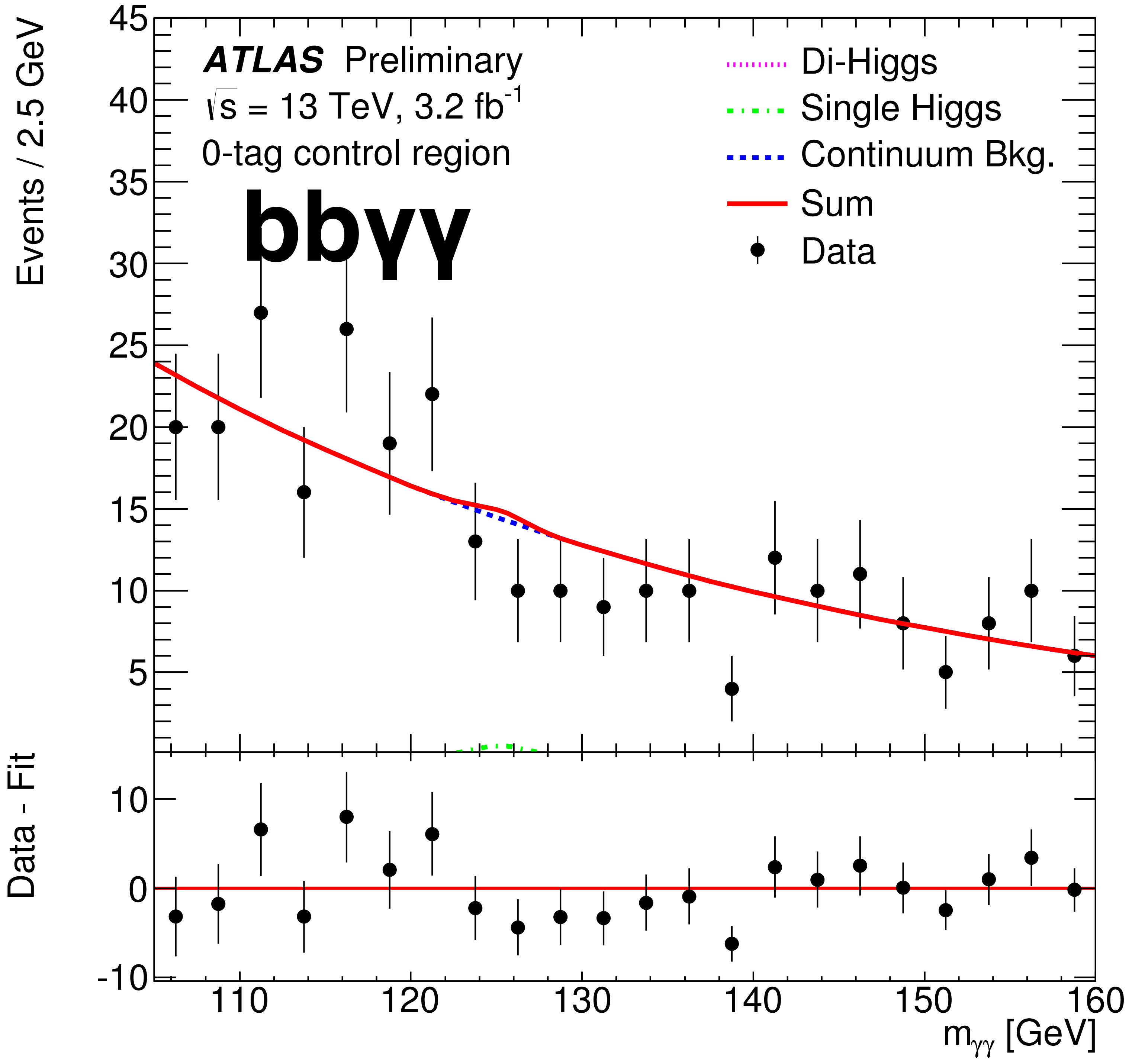
di-Higgs Decay/ Signal Regions	**bbγγ**		**WW*γγ** (semi-leptonic only)
Resonance	tighter mass window: 122 GeV < $m_{\gamma\gamma}$ < 128 GeV		
	2 b-jets 95 GeV < m_{bb} < 135 GeV	mass window cuts on $m_{bb\gamma\gamma}$	2 jets, **1 lepton**
Non-resonance		fit the full $m_{\gamma\gamma}$ without tighter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

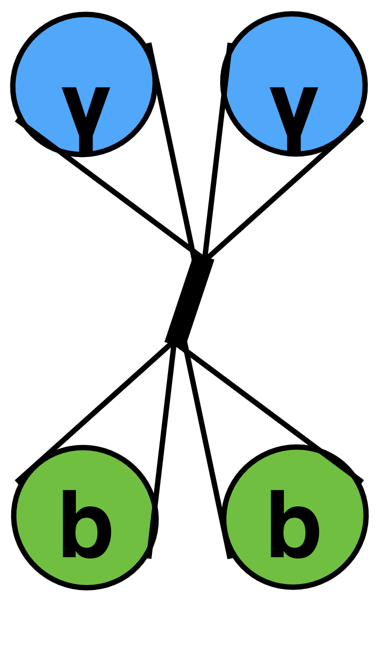
Control Regions

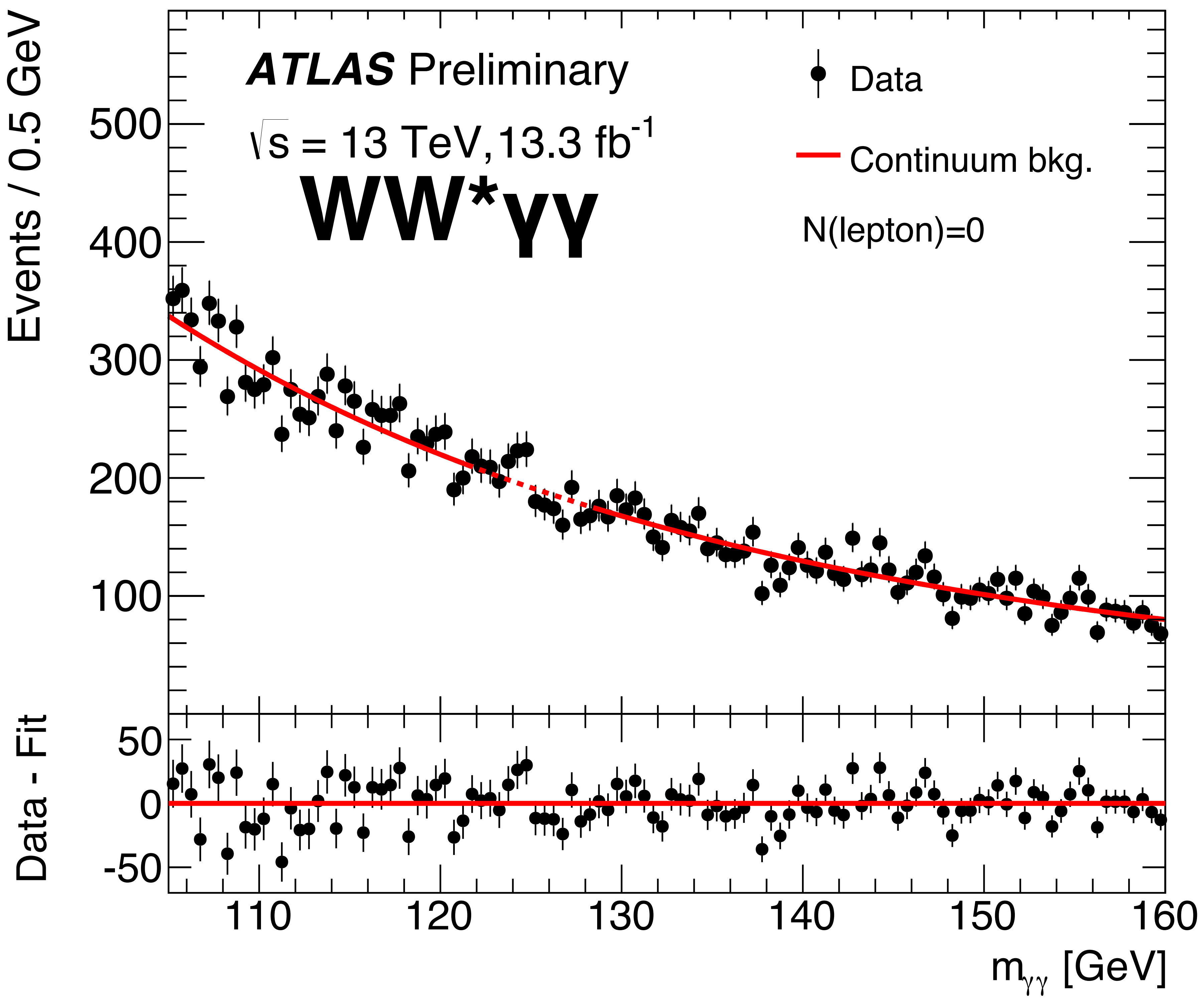
ATLAS-CONF-2016-004

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	-

bbγγ and WW*γγ Signal Regions

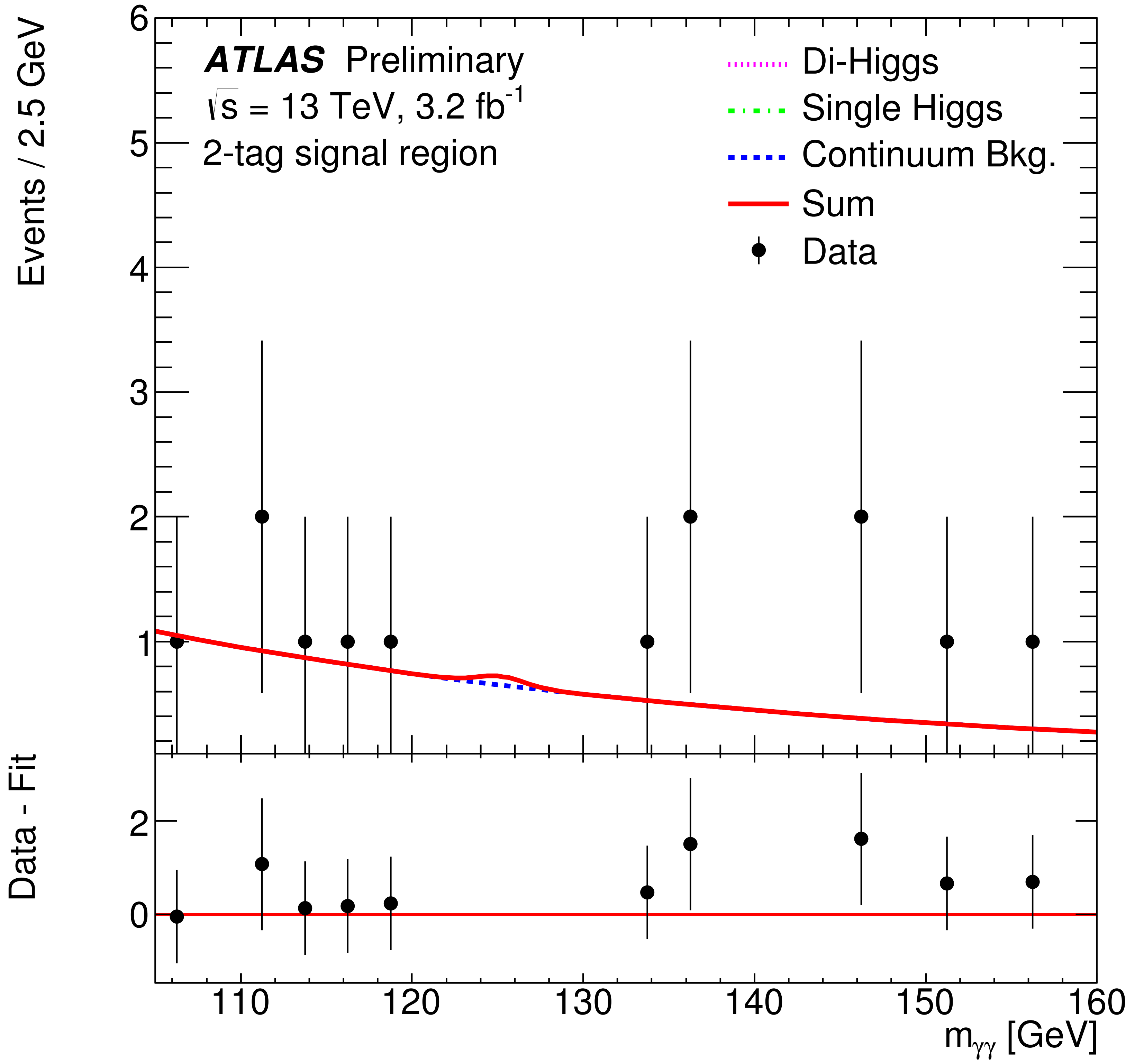
ATLAS-CONF-2016-004

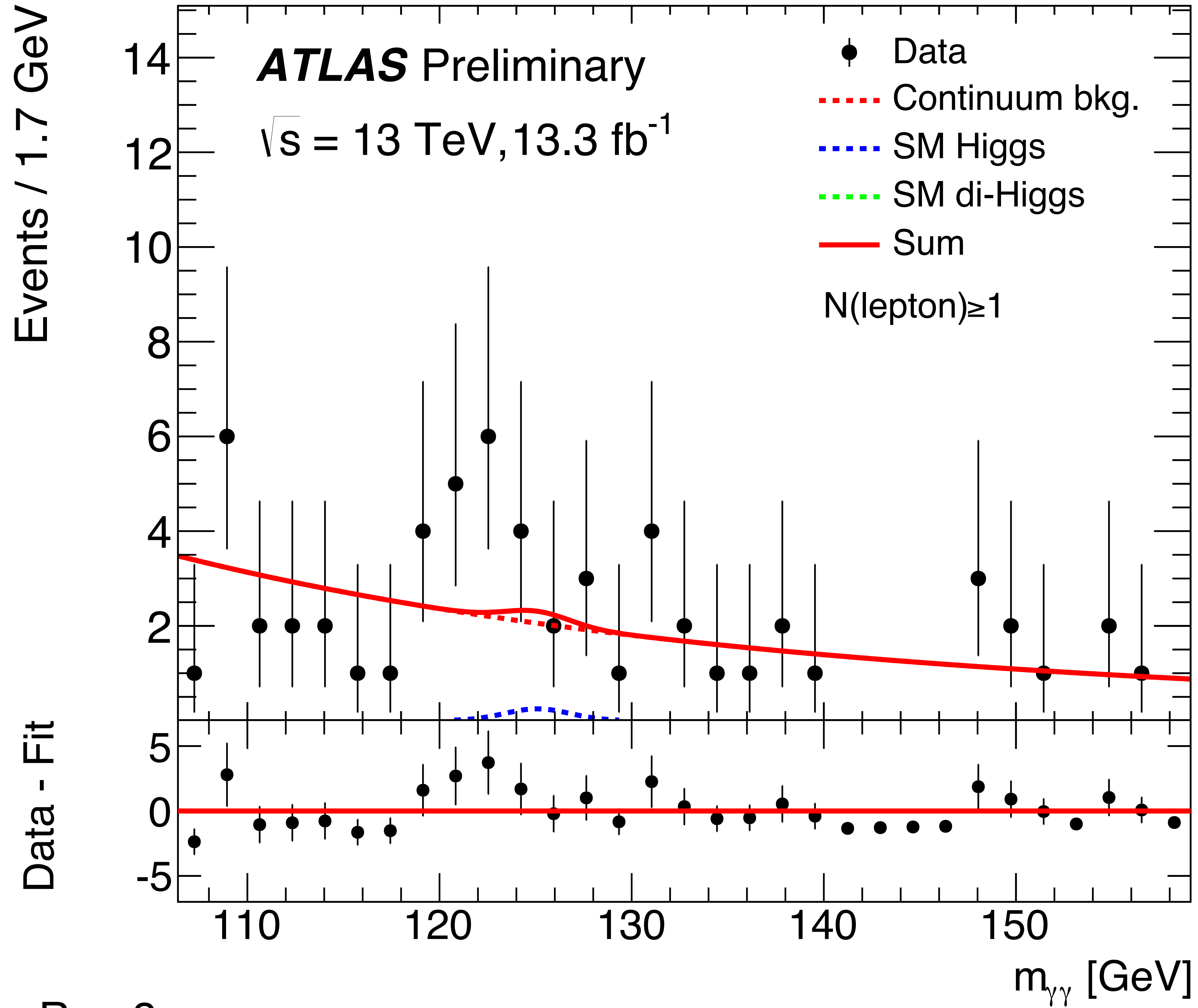
ATLAS-CONF-2016-071

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





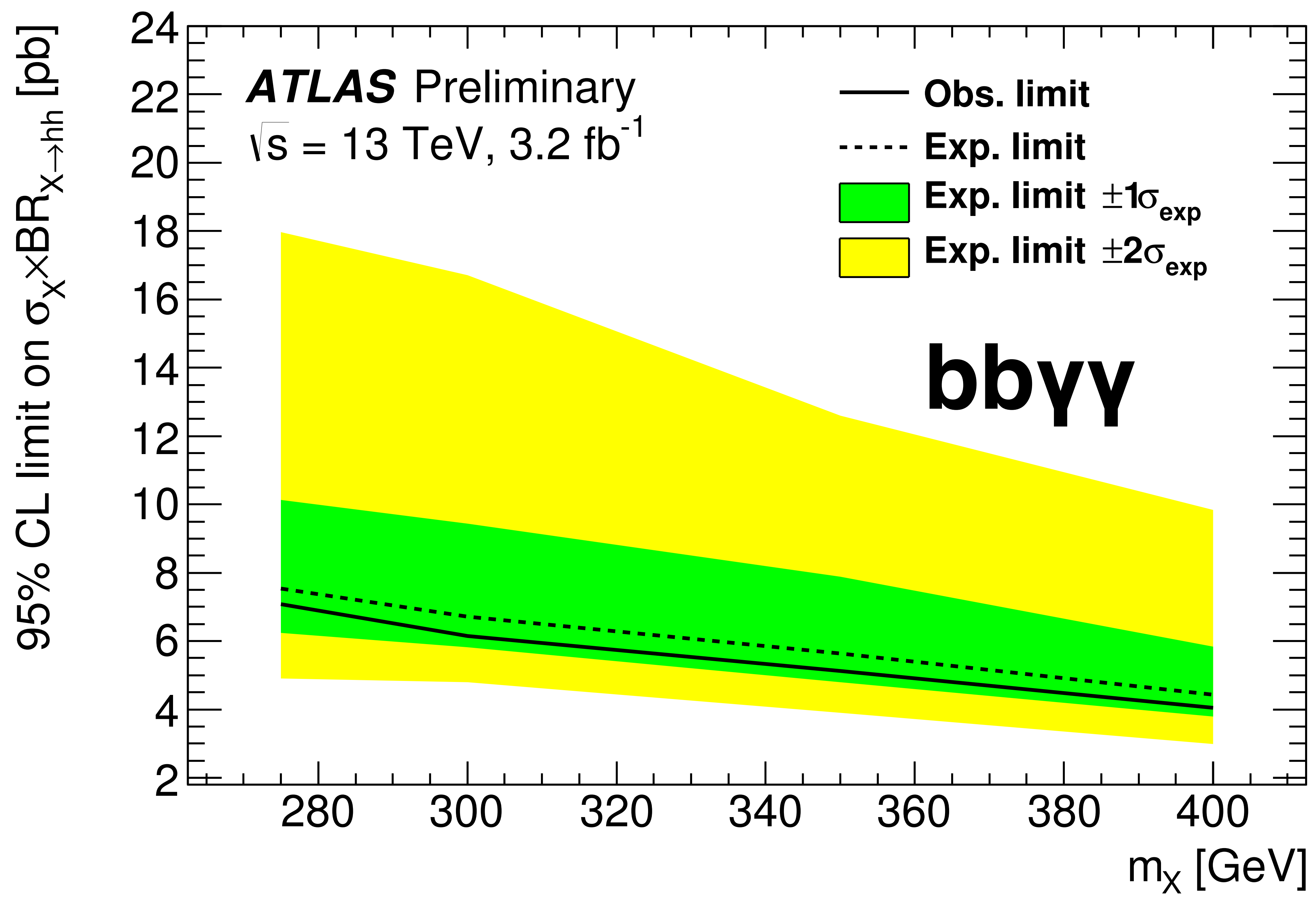
bbγγ observed an excess in Run-1, not confirmed by Run-2

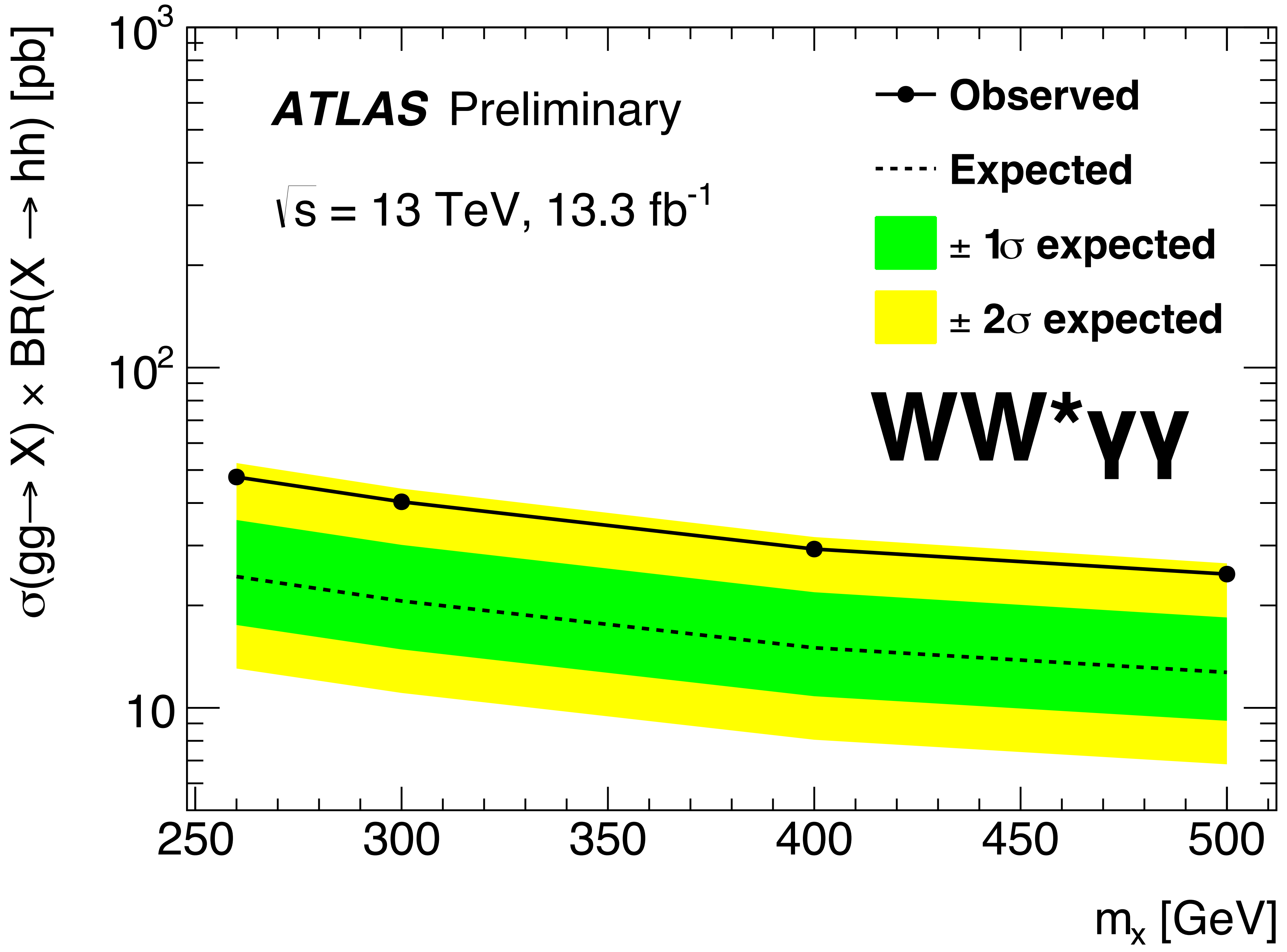
bbγγ and WW*γγ Limits

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)



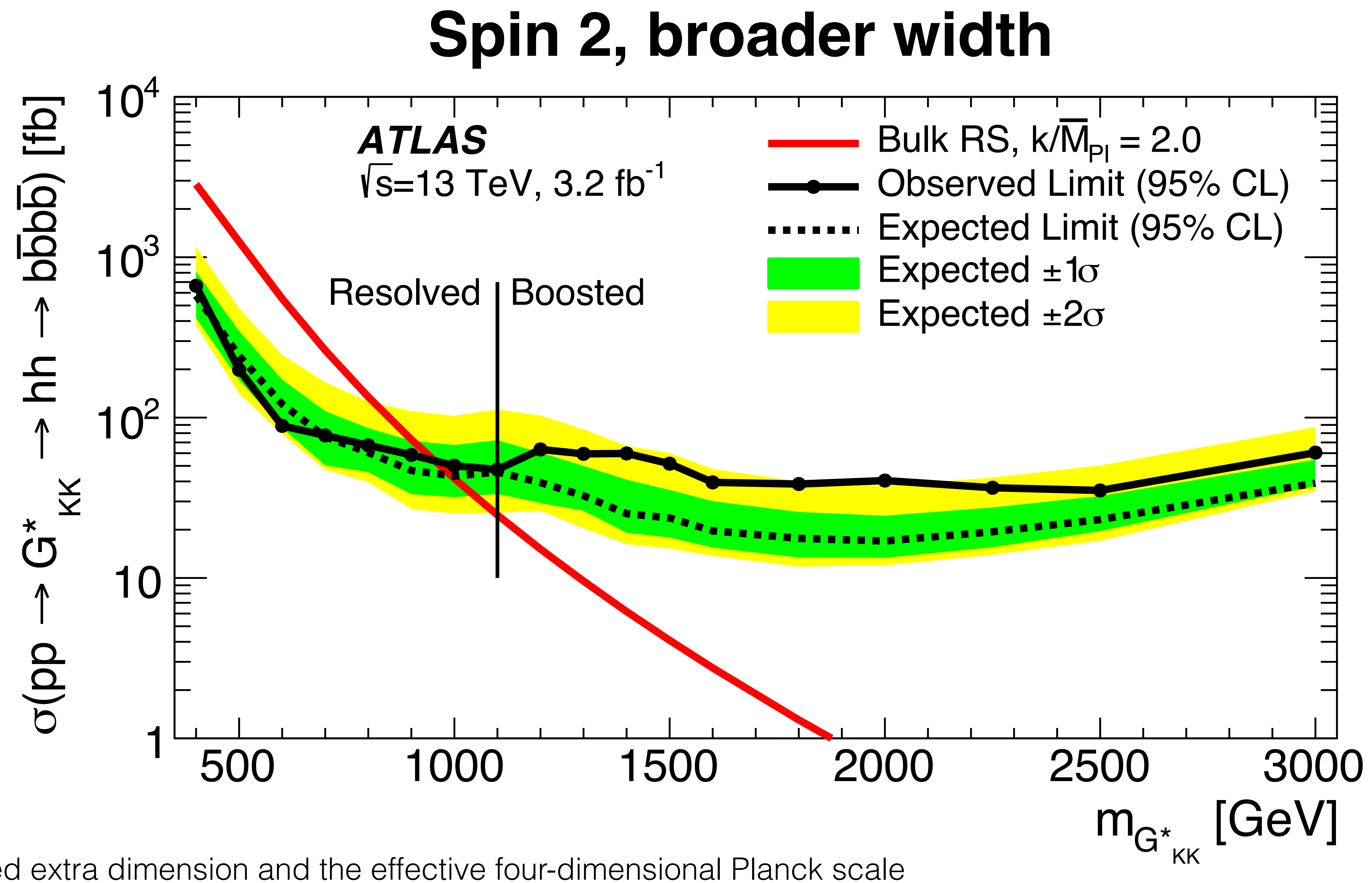


Limits with 3.2 fb^{-1}

Phys. Rev. D 94.052002 (2016)

- Resolved + Boosted Combined Asymptotic Limits

- Non-Resonance limit:
    - bbbb: **1.22 pb** (1.3 pb expected)

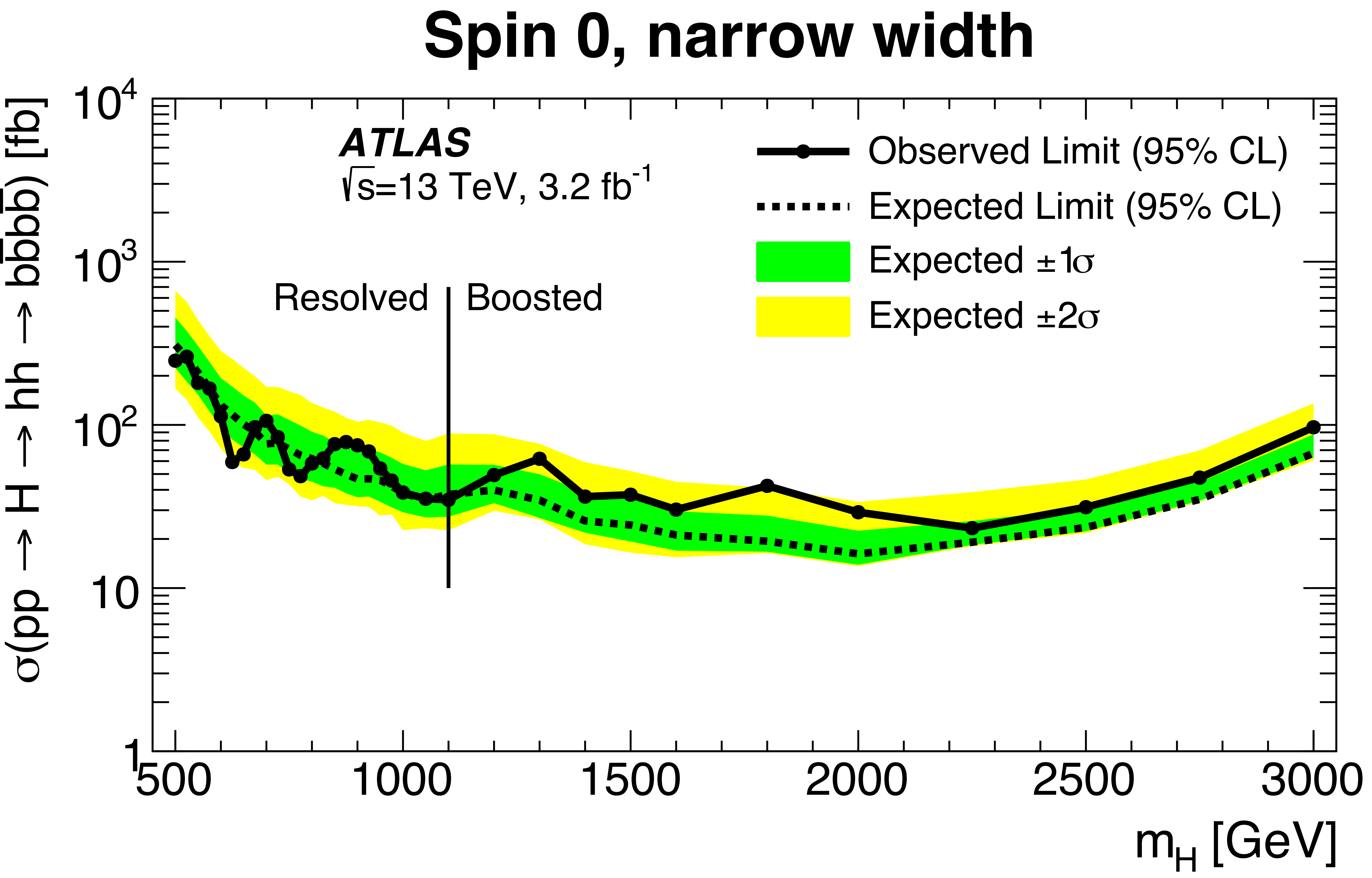


*The parameter k corresponds to the curvature of the warped extra dimension and the effective four-dimensional Planck scale

Limits with 3.2 fb^{-1}

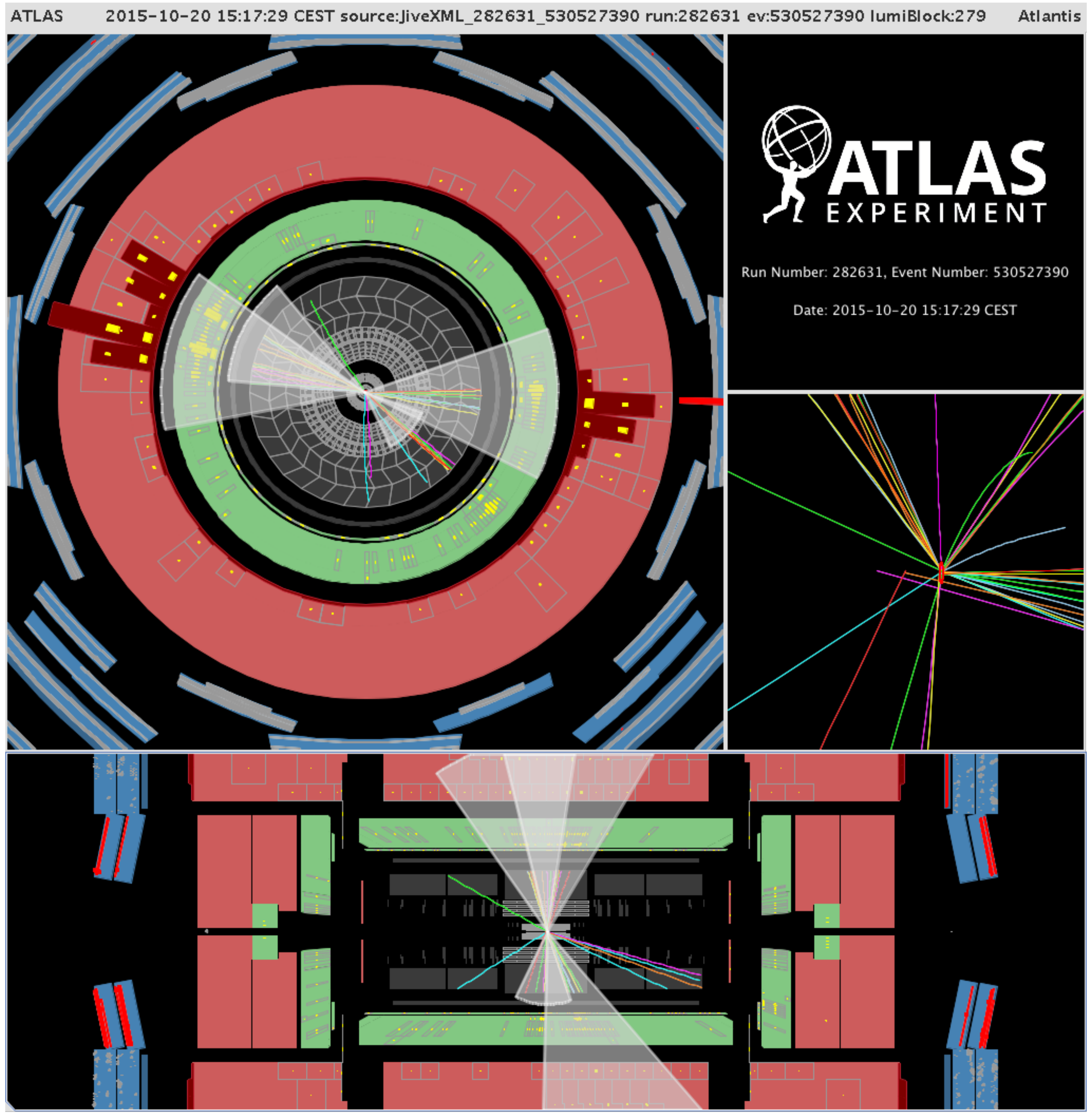
Phys. Rev. D 94.052002 (2016)

- Resolved + Boosted Combined Asymptotic Limits
- Non-Resonance limit:
  - bbbb: **1.22 pb** (1.3 pb expected)

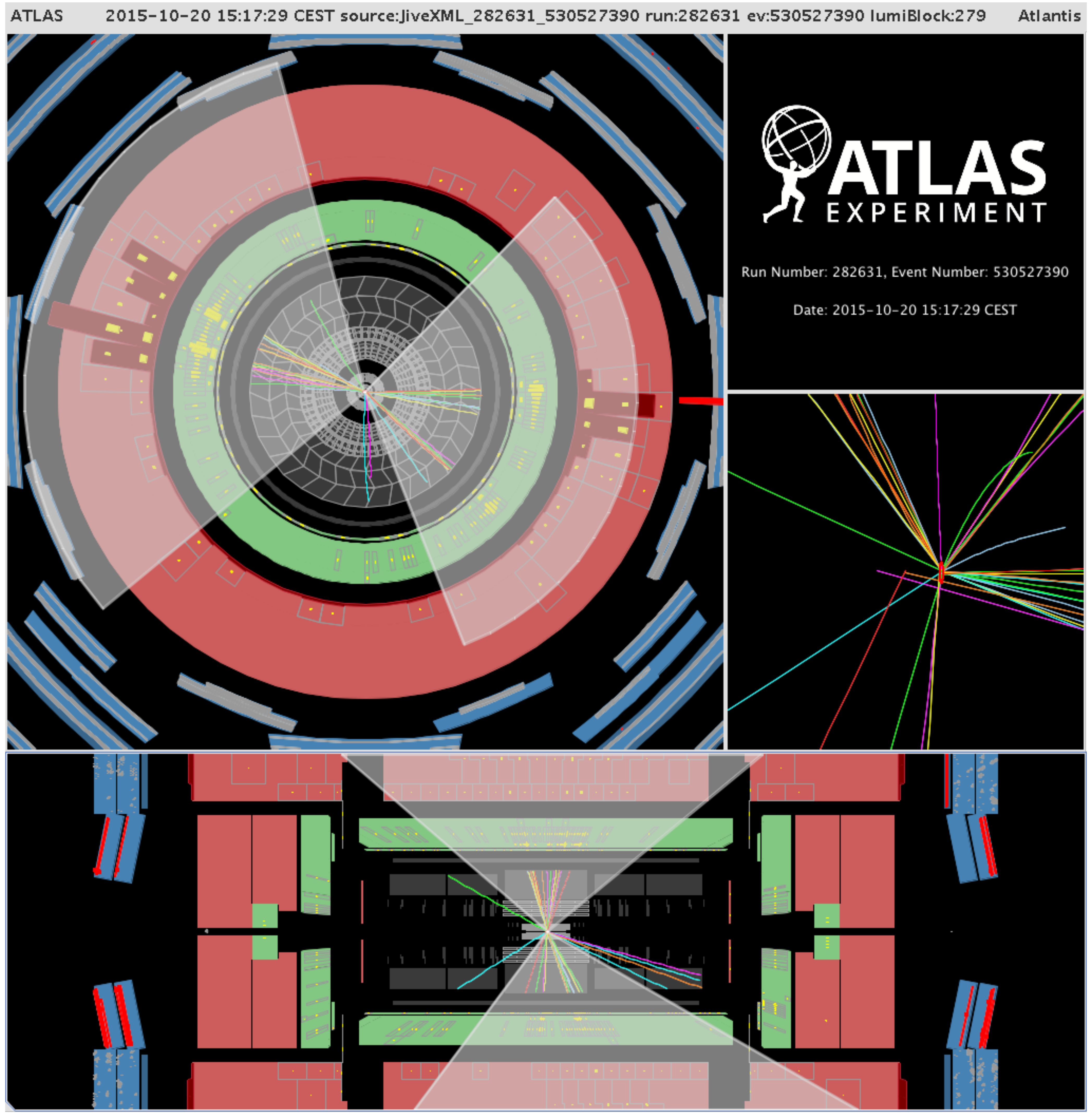


Same event: two views!

Resolved View



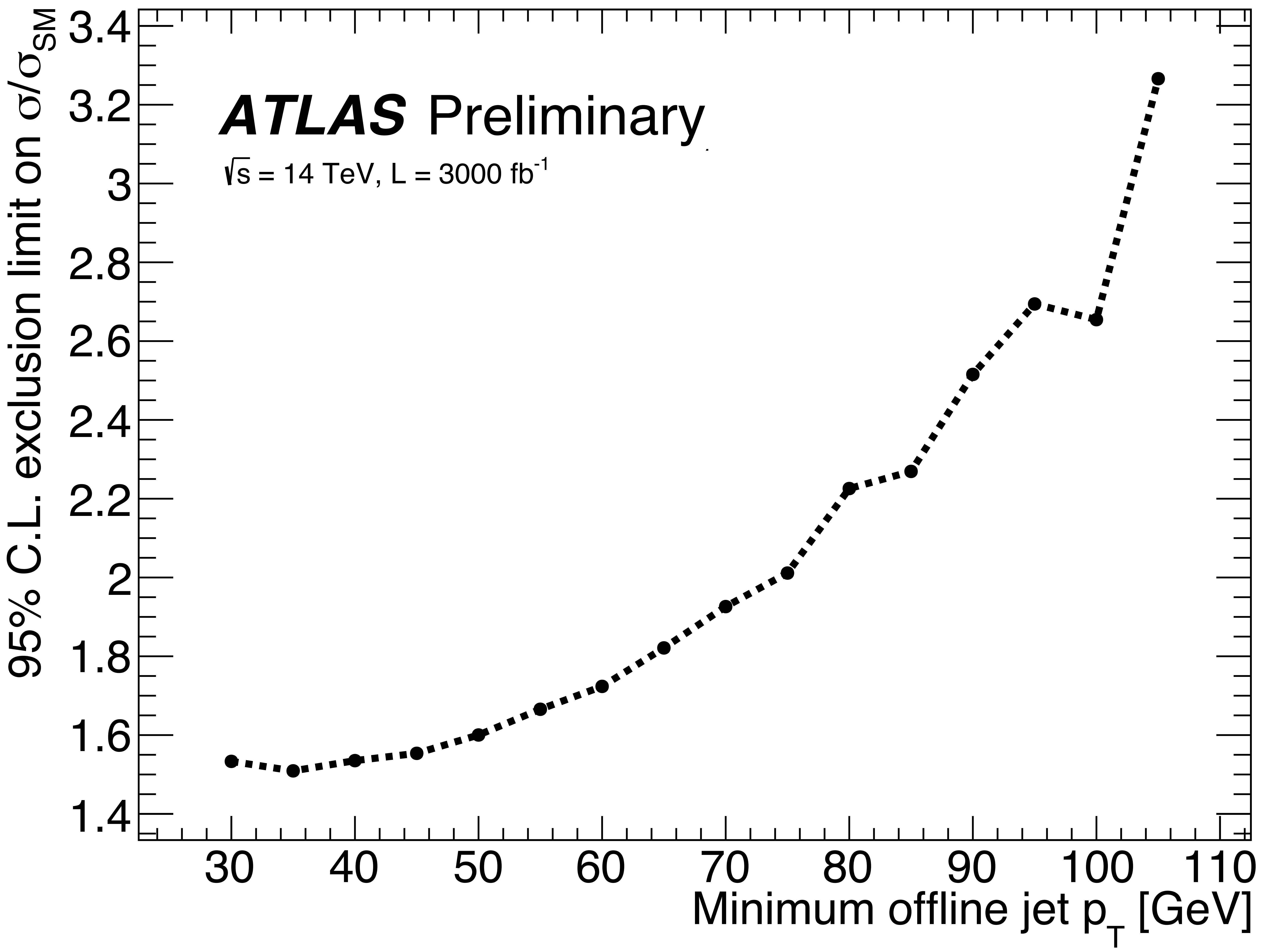
Boosted View



HL-LHC Limit vs Jet pT

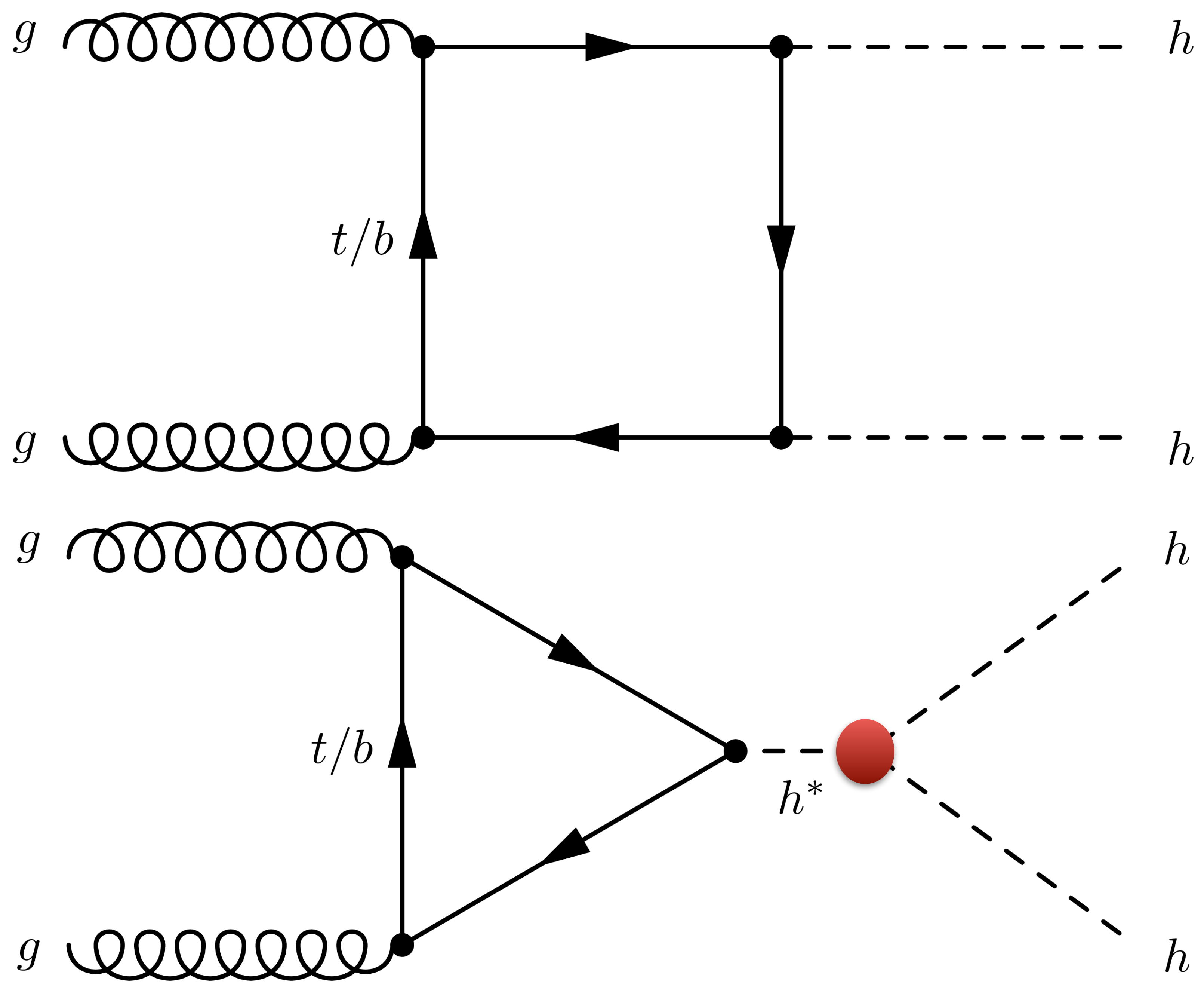
ATLAS-CONF-2016-024

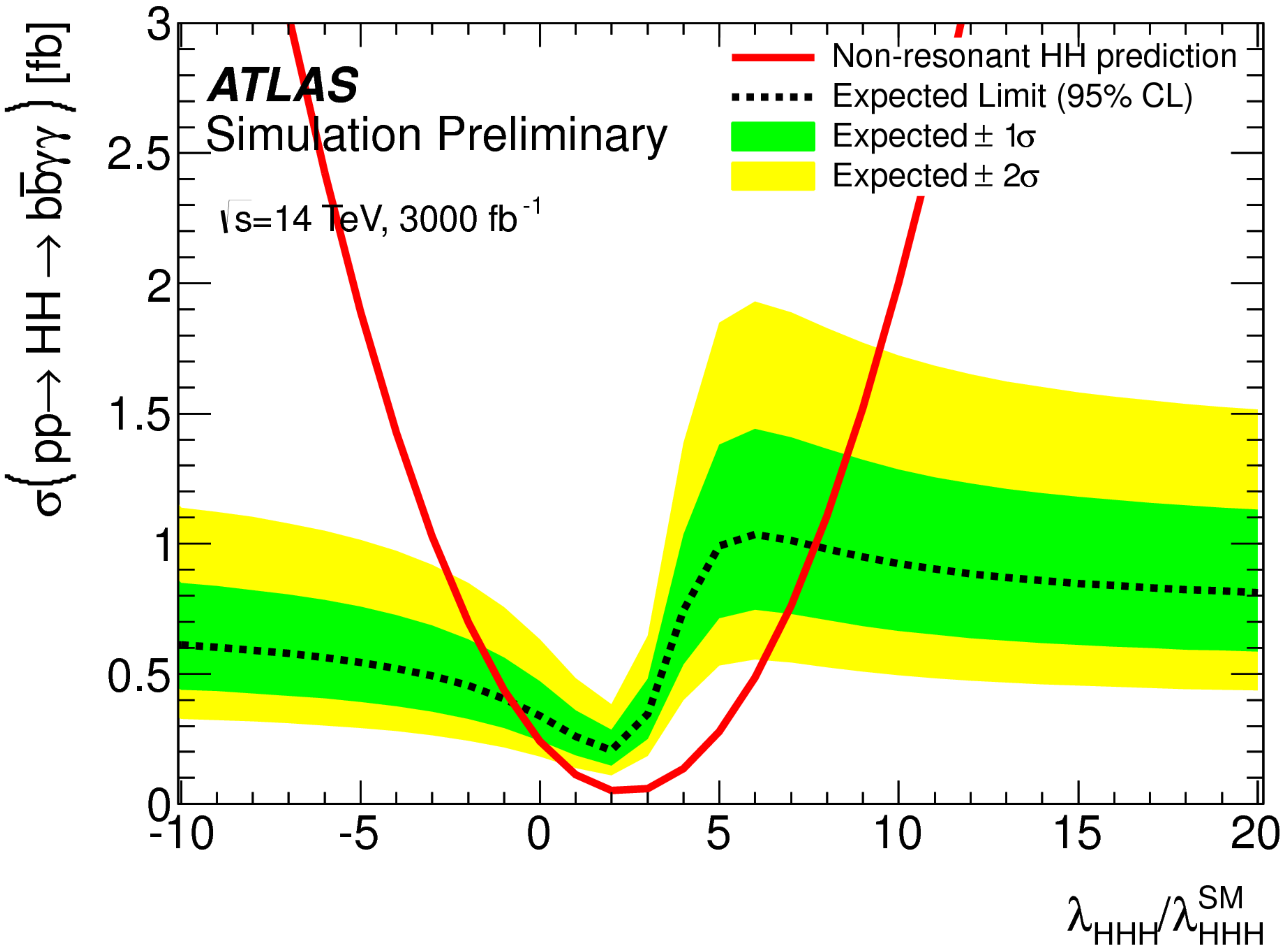
- Expected Limit on cross section ratio, as a function of minimum jet pT required for the four b-tagged jets candidates



Future Perspectives

ATLAS-CONF-2017-001



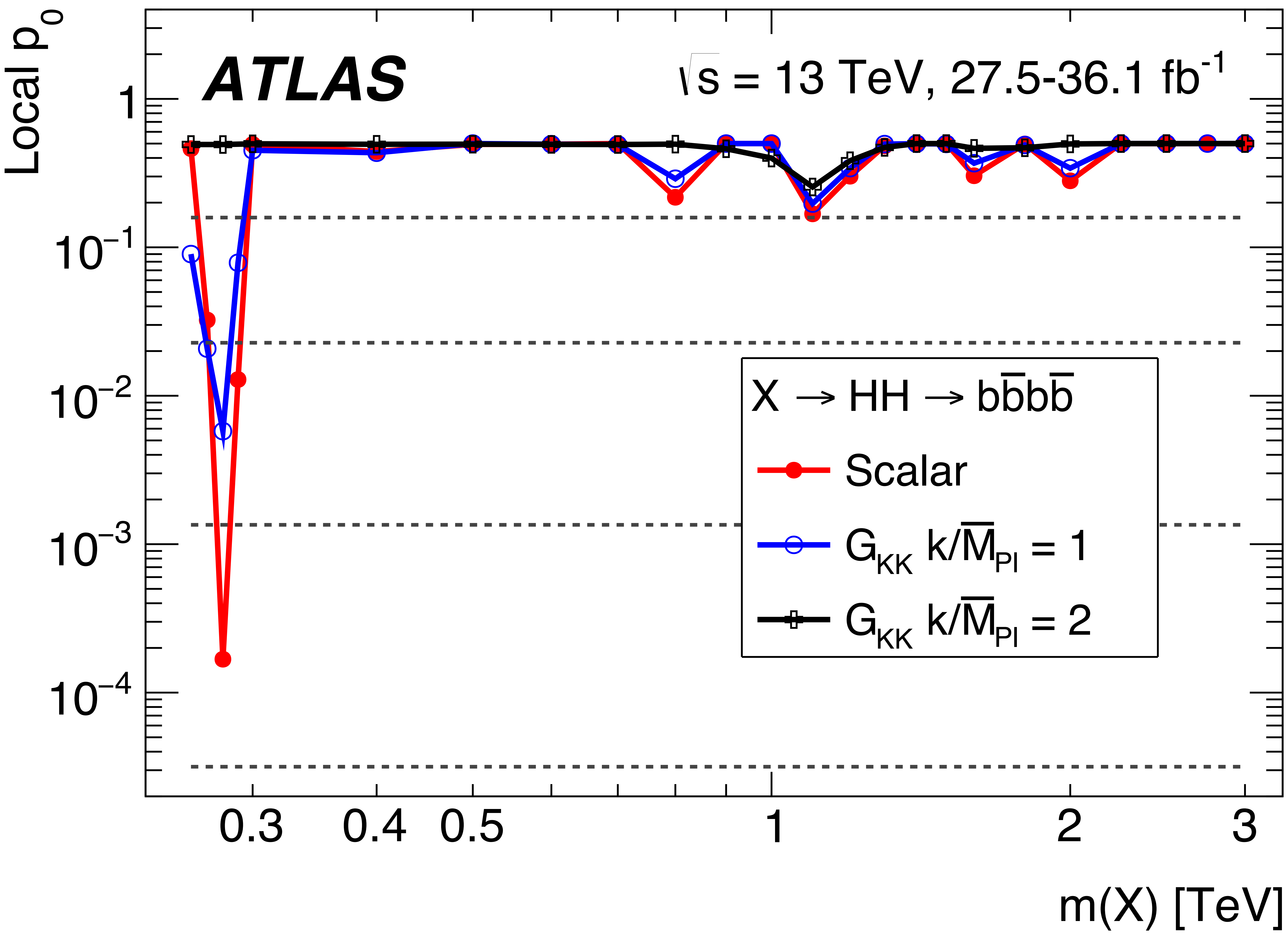


- Limit: $-0.8 < \lambda_{hhh} < 7.7$

di-Higgs p-values

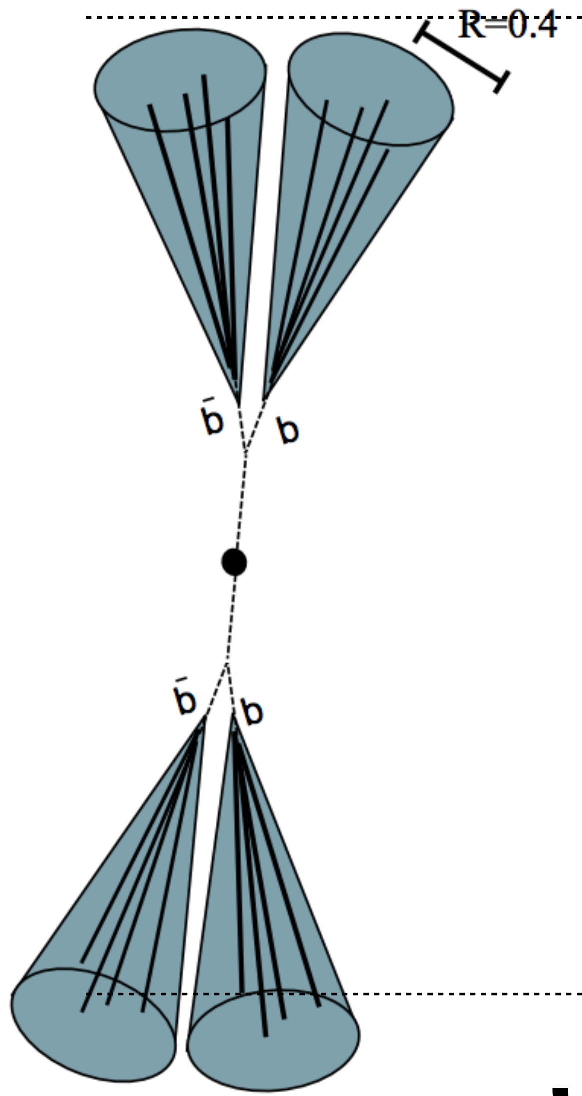
- The smallest p_0 is found for the narrow-width scalar at 280 GeV and corresponds to 3.6 (2.3 global) standard deviations from the background-only hypothesis.
- The p_0 value for the G_{KK} model with $k/\bar{M}_{Pl}$=1 at the same mass is 2.5 standard deviations, the G_{KK} model with $k/\bar{M}_{Pl}$=2 is too wide to fit the excess.

local p_0 values



Current Resolved

Event Selection and Method

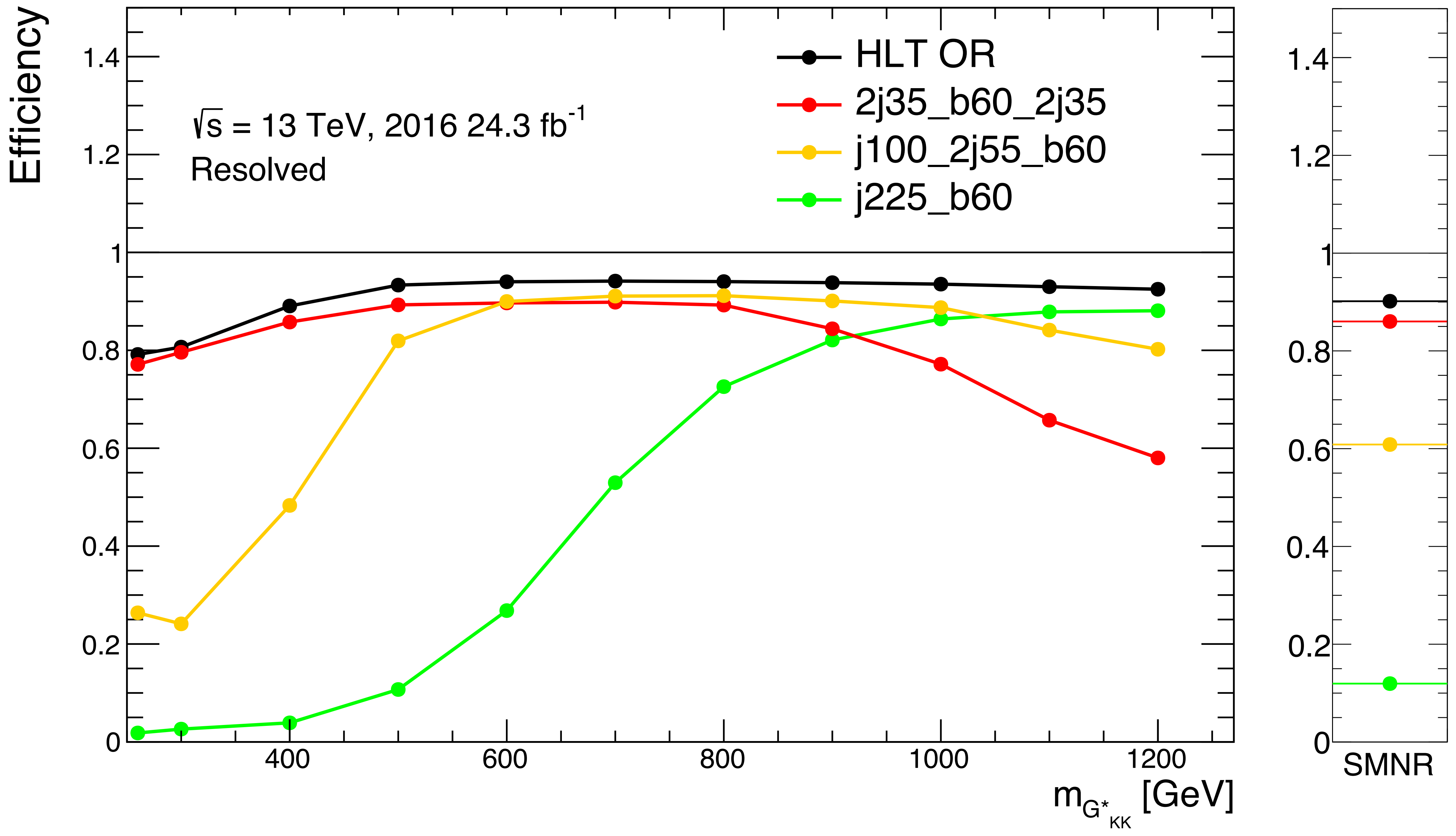


Cut	Explanation
GRL	Ensure data quality
Trigger	HLT_2j35_btight_2j35_L14J15.0ETA25 or HLT_j100_2j55_bmedium or HLT_j225_bloose (**2015**) HLT_2j35_bmv2c2060_split_2j35_L14J15.0ETA25 or HLT_j100_2j55_bmv2c2060_split or HLT_J225_bmv2c2060_split (**2016**)
Jet Cleaning	Do Jet Cleaning on the Resolved Jets with Loose cuts
4 Small R Jets	must have at least 4 small R jets (R=0.4 EMTopo)
Jet Selections	$pT > 40$ GeV; $\|\eta\| < 2.5$;
dη cut	$\|d\eta(h,h)\| < 1.5$; to reduce QCD background
b-tagging	*Mv2C10, 70% wp;* take 4 highest Mv2 jets, in case of more

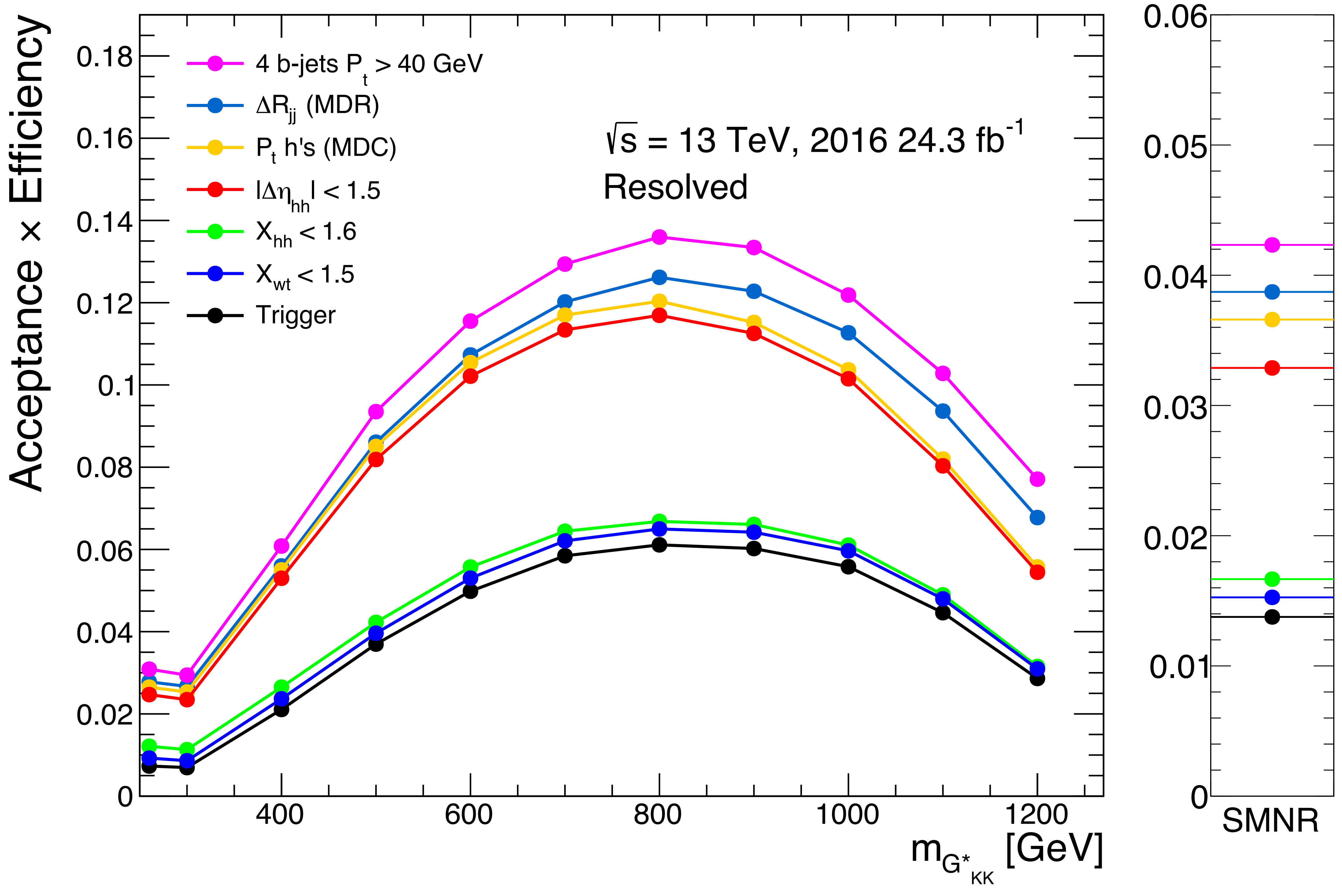
Resolved Selection Efficiency

- Good trigger efficiency overall ~ 95%
- Looser HC Pt and Δη cuts make up for 10 GeV rise in jet Pt cut
  - SM acceptance is about the same as 2016 ICHEP result

2016 Trigger Efficiency



Total Acc x Efficiency

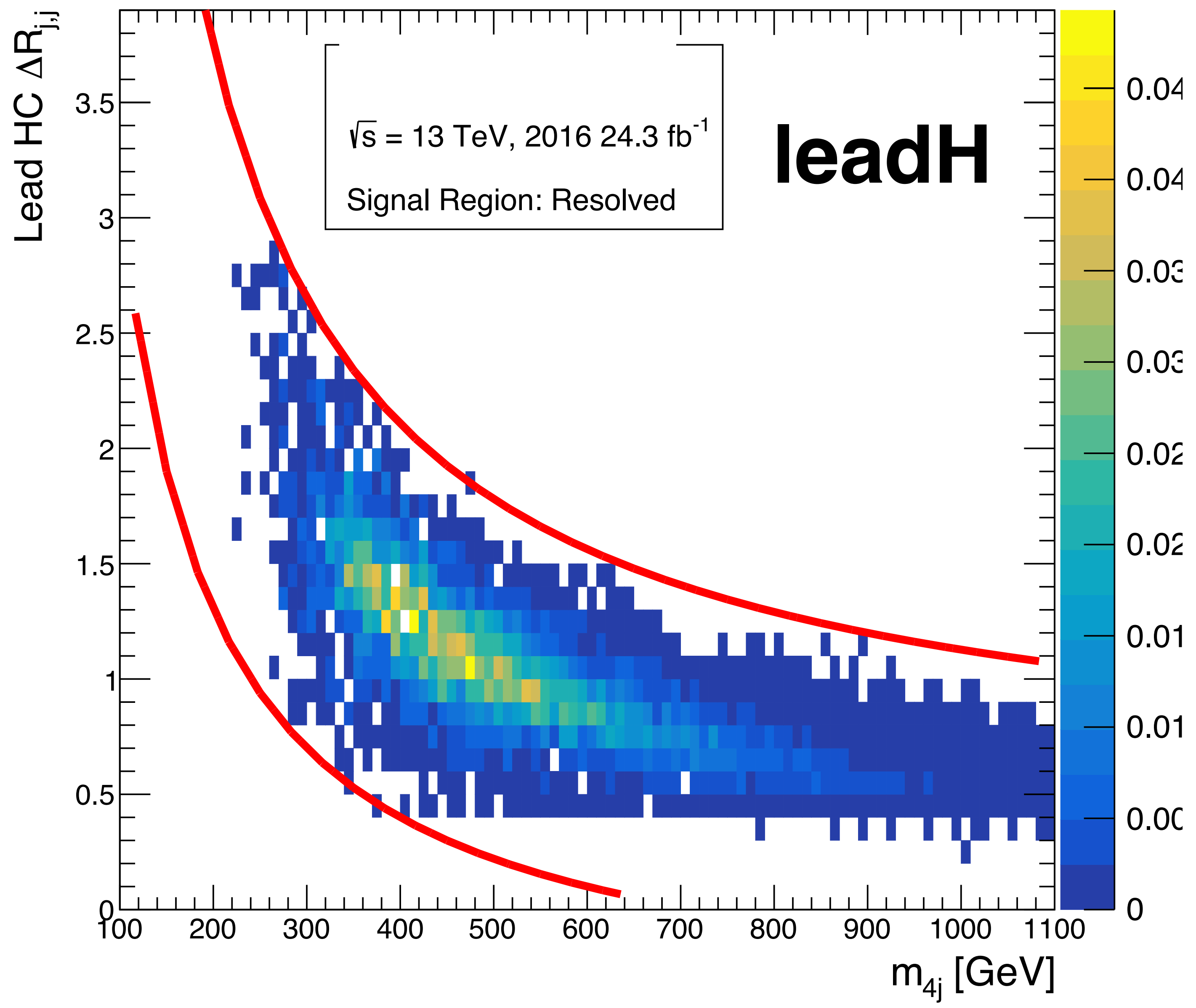


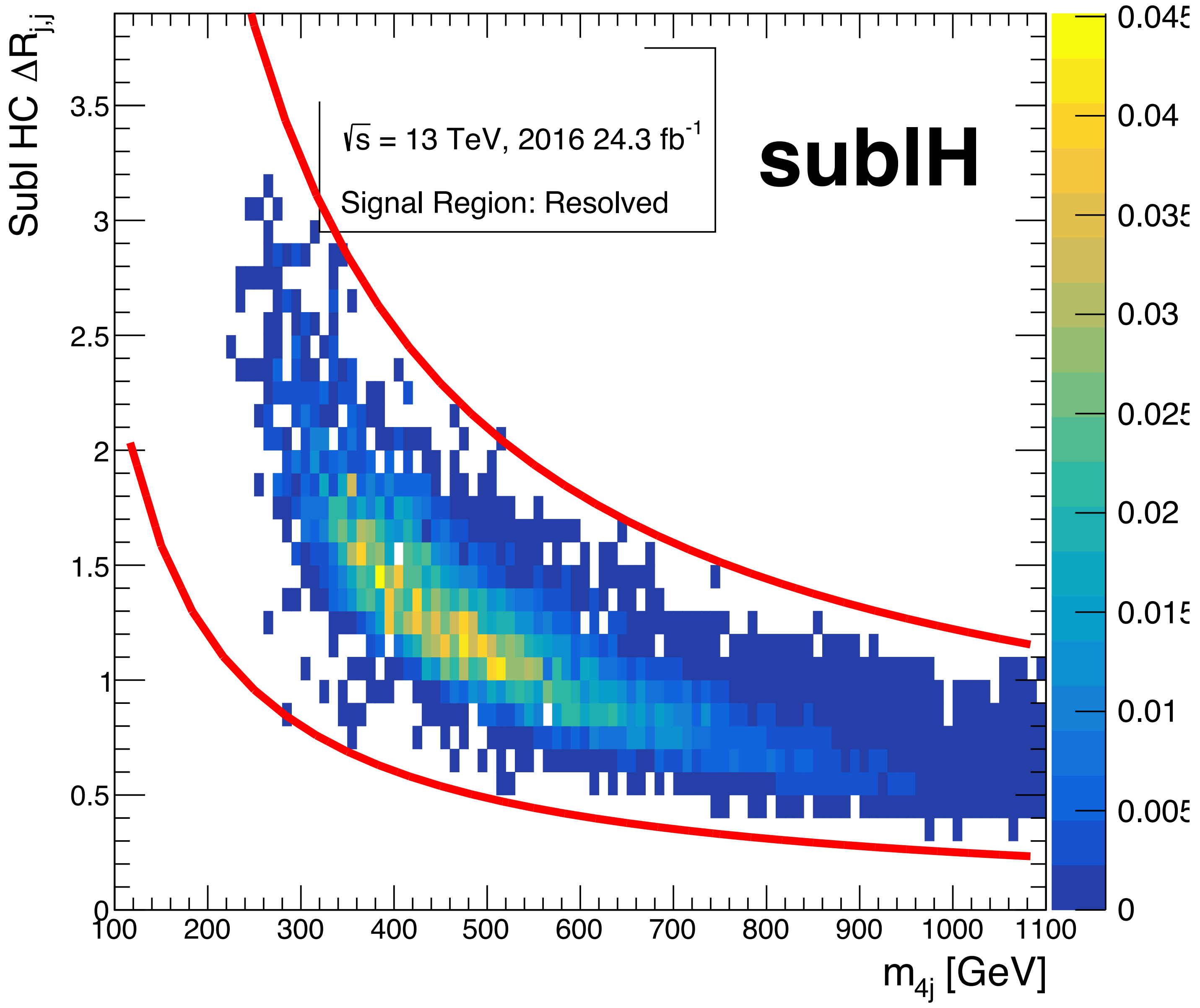
Jets Pair Combinatorics

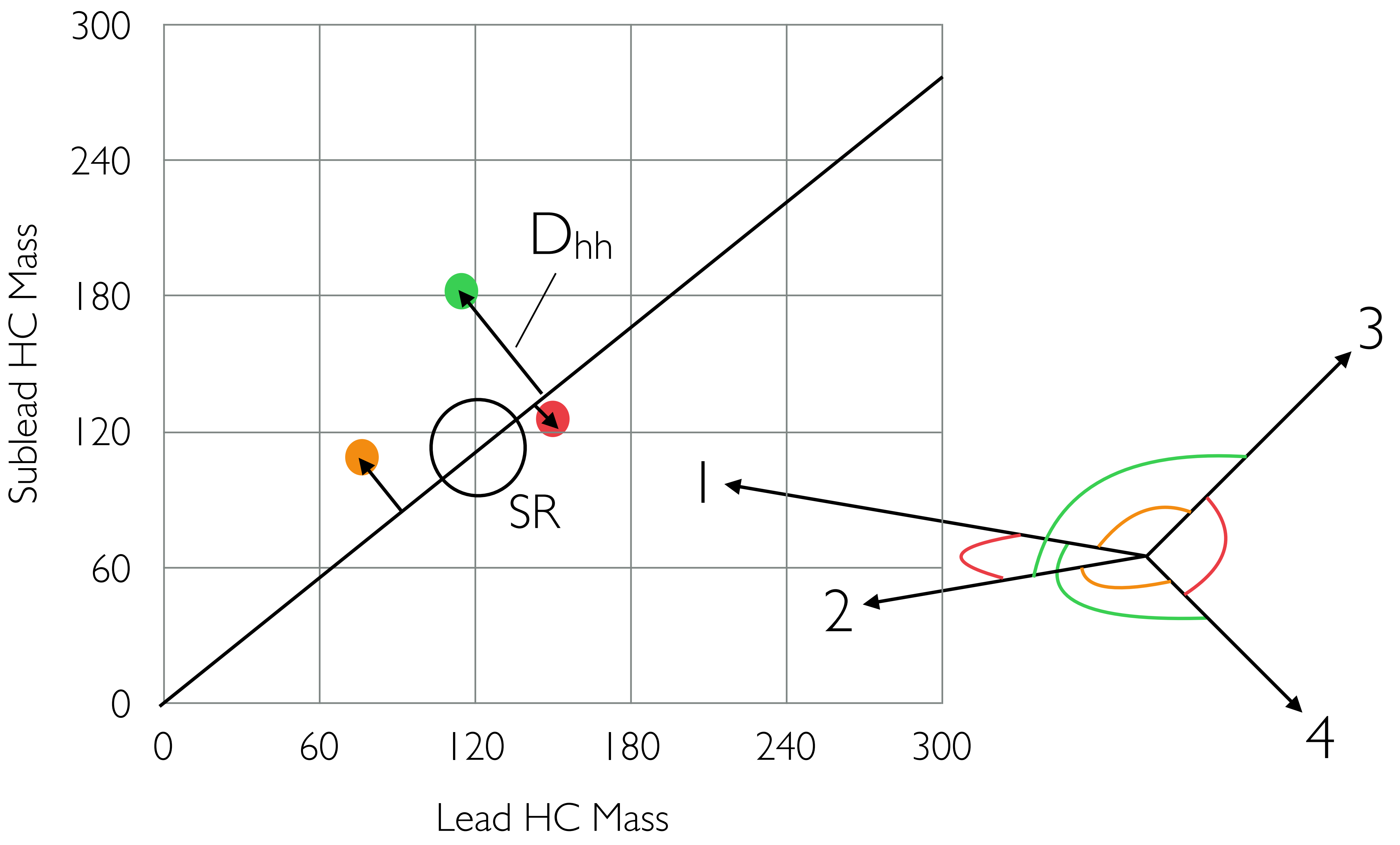
$$\left.\begin{aligned} \frac{360}{m_{4j}} - 0.5 < \Delta R_{jj,\text{lead}} < \frac{655}{m_{4j}} + 0.475 \\ \frac{235}{m_{4j}} < \Delta R_{jj,\text{subl}} < \frac{875}{m_{4j}} + 0.35 \end{aligned}\right\} \text{if } m_{4j} < 1250 \text{ GeV}$$

$$\left.\begin{aligned} 0 < \Delta R_{jj,\text{lead}} < 1 \\ 0 < \Delta R_{jj,\text{subl}} < 1 \end{aligned}\right\} \text{if } m_{4j} > 1250 \text{ GeV}$$

- Add m_{4j} dependent requirements on **dR_{jj}**
- Then, select hh pair that has the **minimal distance** to the diagonal line on the 2D mass plane



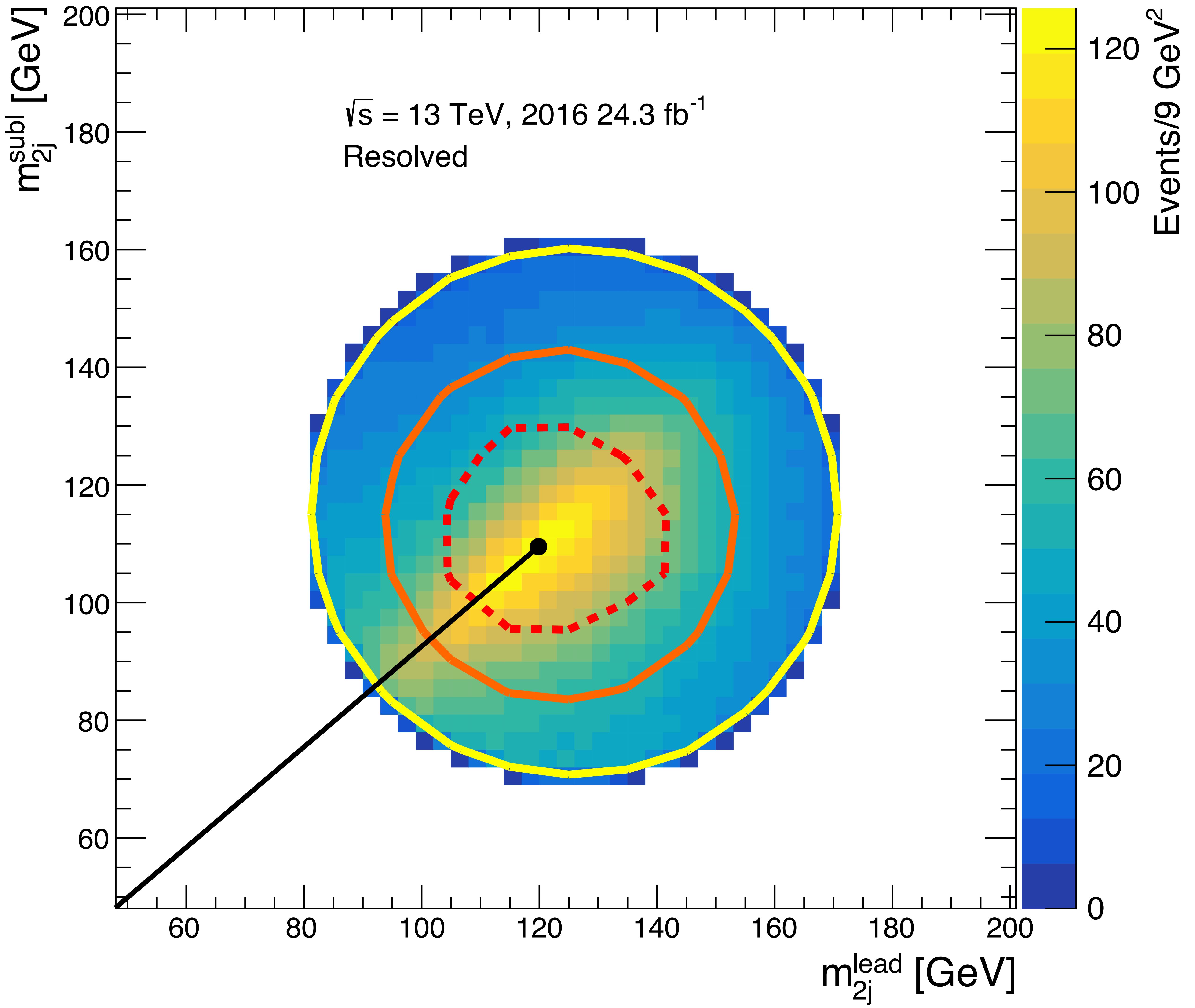




Two Higgs Mass Plane

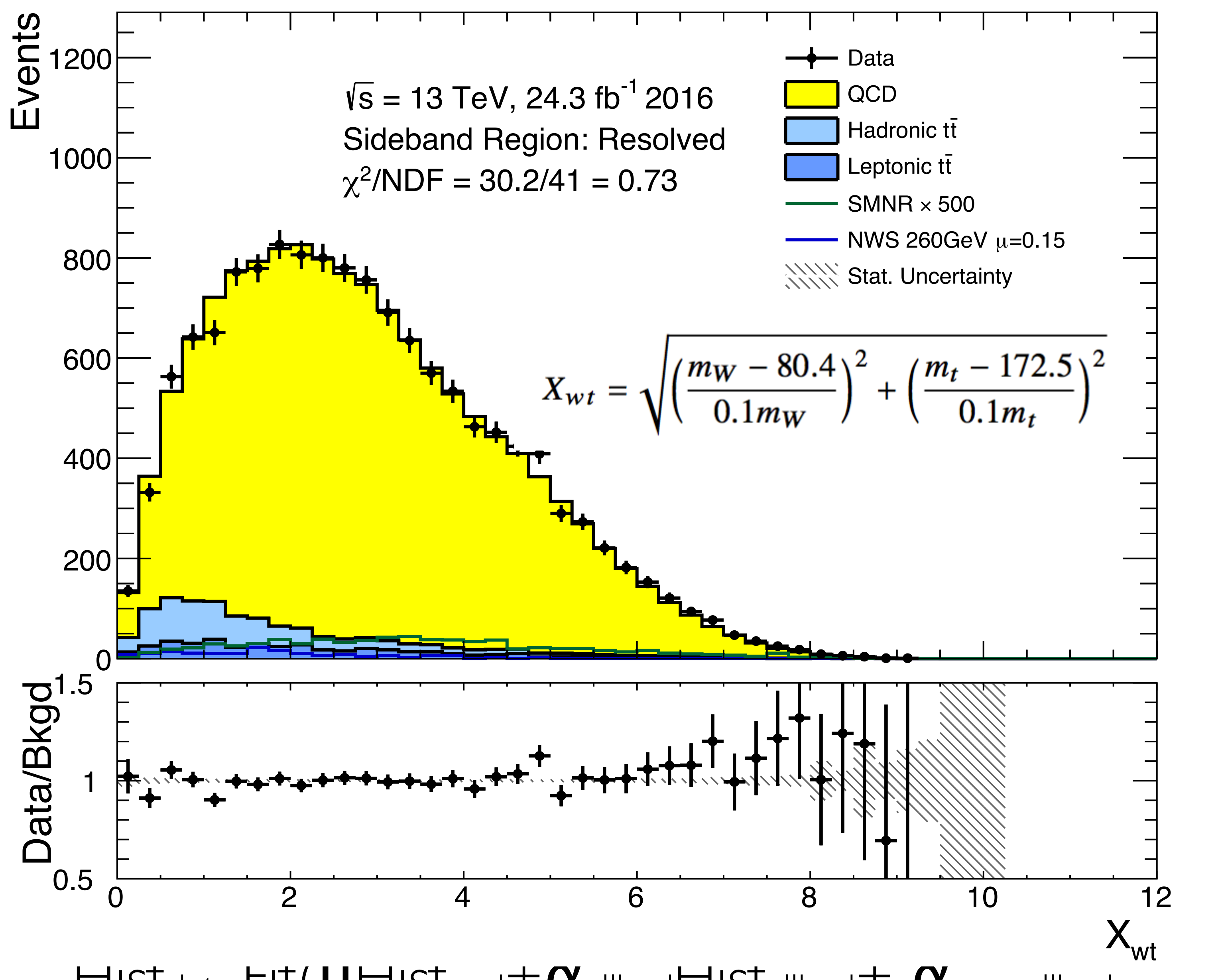
$$X_{hh} = \sqrt{\left(\frac{m_{2j}^{lead} - 120}{0.1 \times m_{2j}^{lead}}\right)^2 + \left(\frac{m_{2j}^{subl} - 110}{0.1 \times m_{2j}^{subl}}\right)^2}$$

- **Signal Region** (SR): $X_{hh} < 1.6$
- **Control Region** (CR) :
  - Ring outside SR (for validation)
  - Balanced between low/high masses Higgs candidates
- **Sideband** (SB):
  - Derive background normalization and kinematic reweighting functions



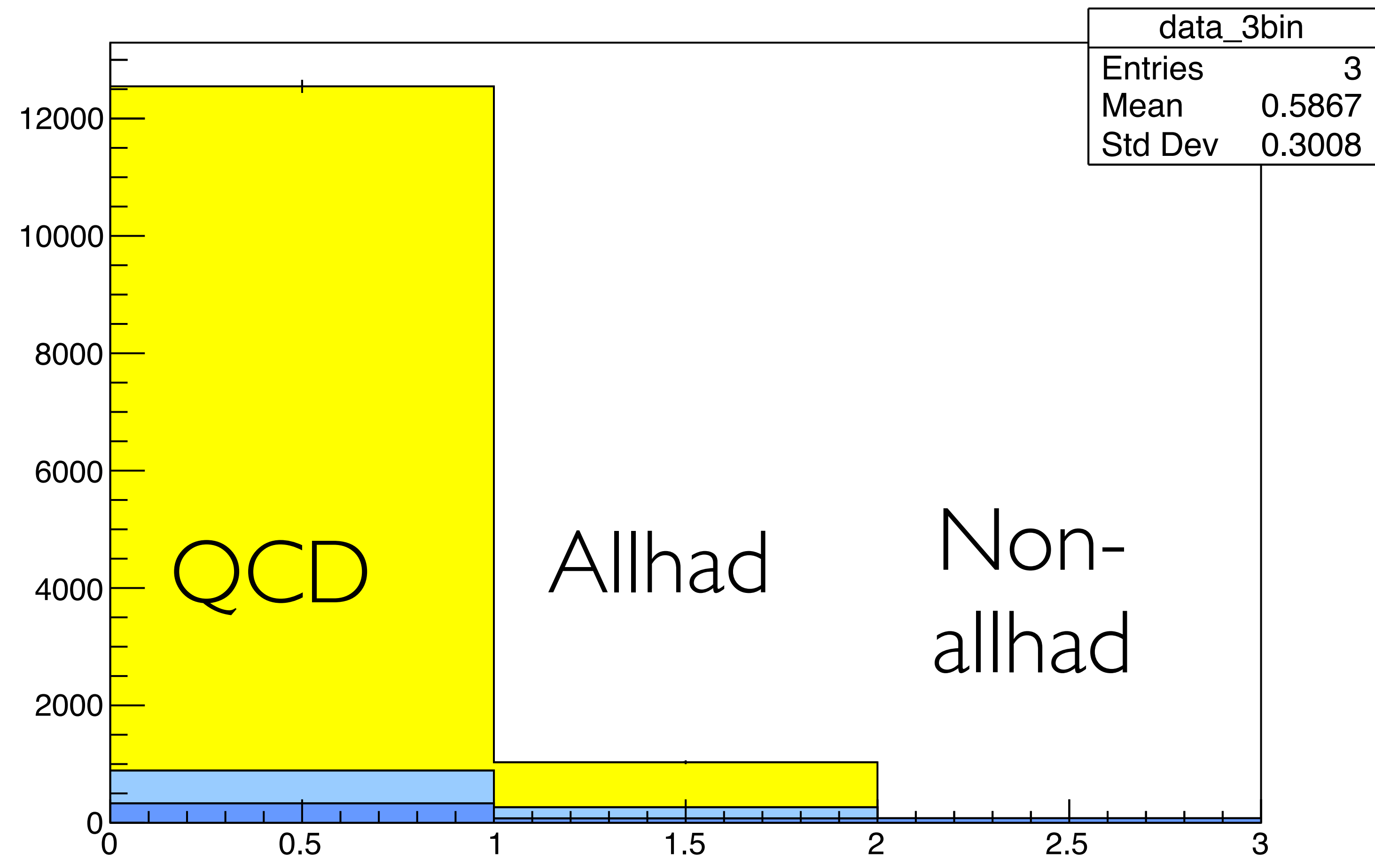
Top background modeling

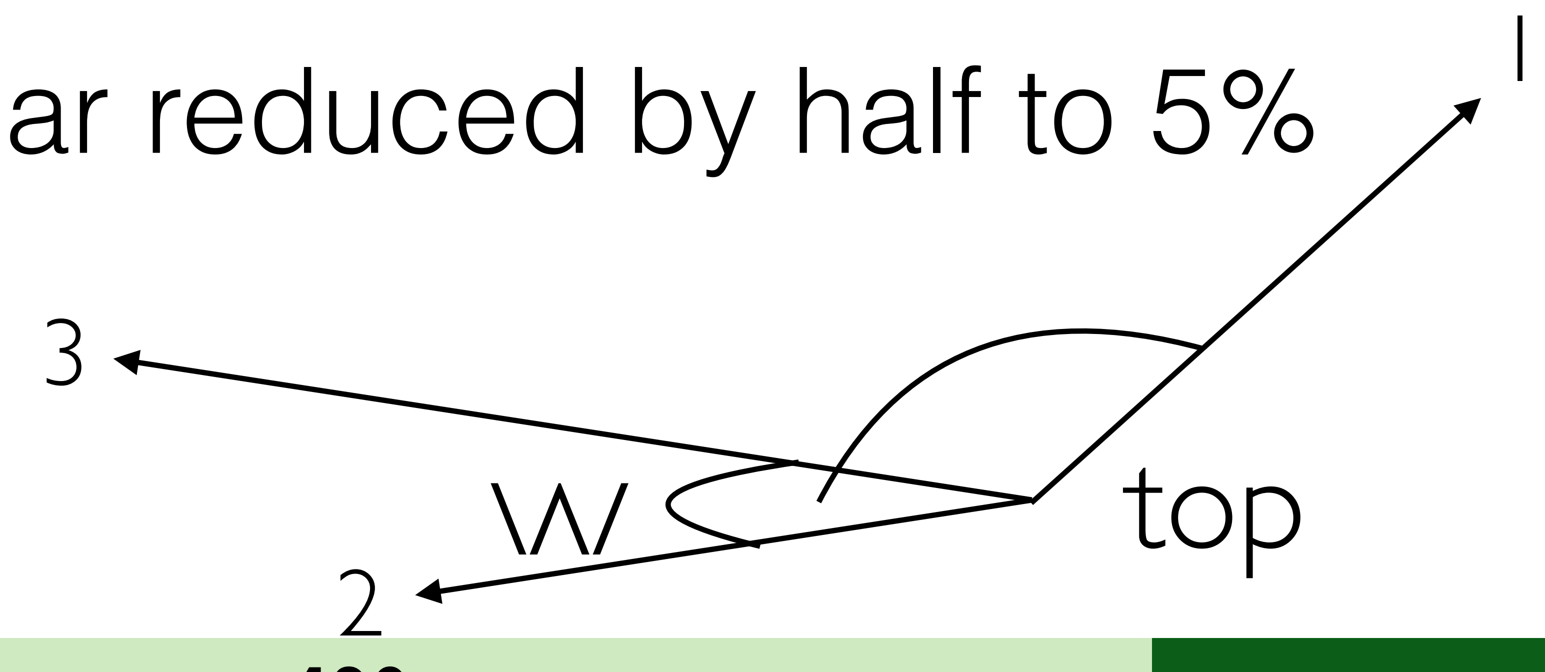
- Baseline normalization and shape **from MC**
- Build top discriminant X_{wt}: take three jets, sort them in MV2; lower 2 makes W candidate; all three makes top candidate
- **3-bin Fit to extract correct factor for ttbar:**
  - Non-allhad: enriched in ≥ 1 muon region
  - All-had: enriched in $X_{wt} < 0.75$ region
  - QCD: enriched in $X_{wt} > 0.75$ region
- Constrains top yield in data and reduces impact of 4b MC mis-modeling
- After $X_{wt} < 1.5$ cut in selection, ttbar reduced by half to 5% of total bkg



$Hist_{data}.Fit(\mu Hist_{qcd} + \alpha_{allhad} Hist_{allhad} + \alpha_{non\text{-}allhad}$

	μ	α_{allhad}	$\alpha_{non\text{-}allhad}$
Prefit	0.227	1.0	1.0
Postfit	0.225±0.002	1.1±0.3	1.7±0.2

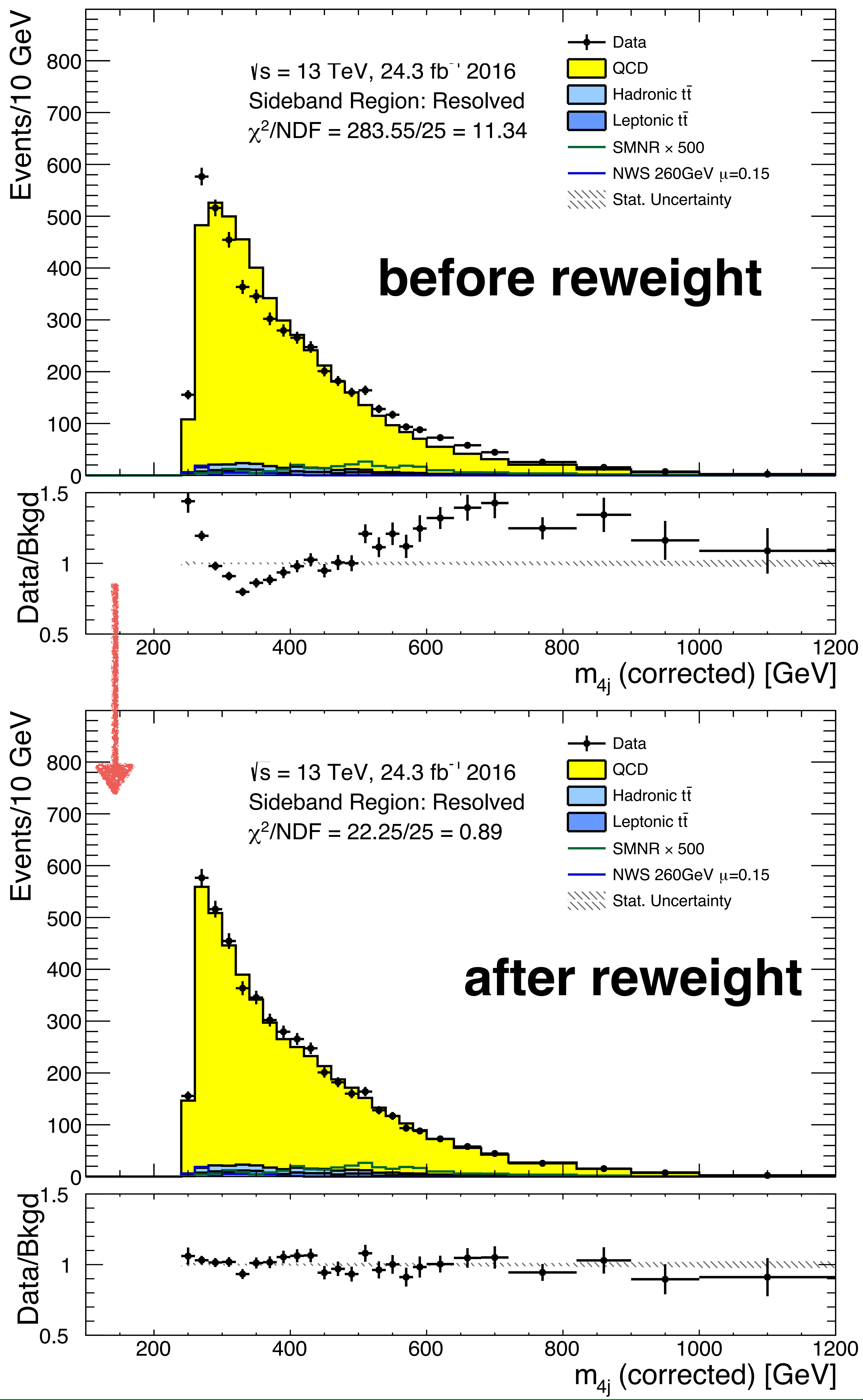




Multijet background modeling

- Baseline normalization and shape **from 2b Data**
- Combinatoric treatment of jet multiplicity: Details
  - Apply weight to 2b events: $w_n = P_{>=4b}(n)/P_{2b}(n)$ after picking two light jets at random as b-jets
- Also apply kinematic reweighting:
  - pT of softest jet: turn-on
  - pT of second-hardest jet
  - Average |η| of jets:
    - 4b events tend to be more central
  - dR_{jj} of two closest HCand jets, the other dR_{jj}:
    - Correct for correlations in HCand dR_{jj}

M4j in Sideband



Multijet background modeling

- Baseline normalization and shape **from 2b Data**
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- Also apply kinematic reweighting:
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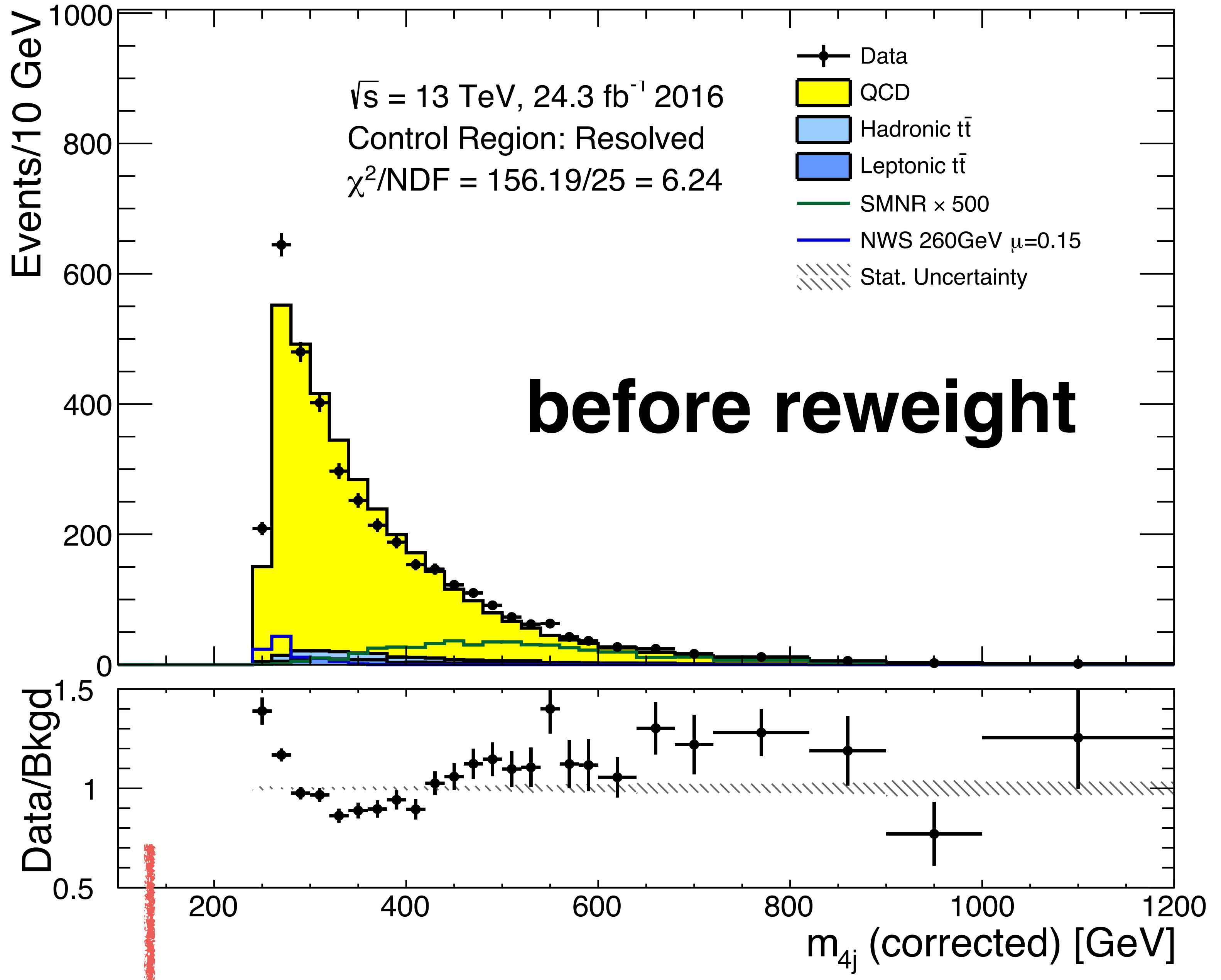
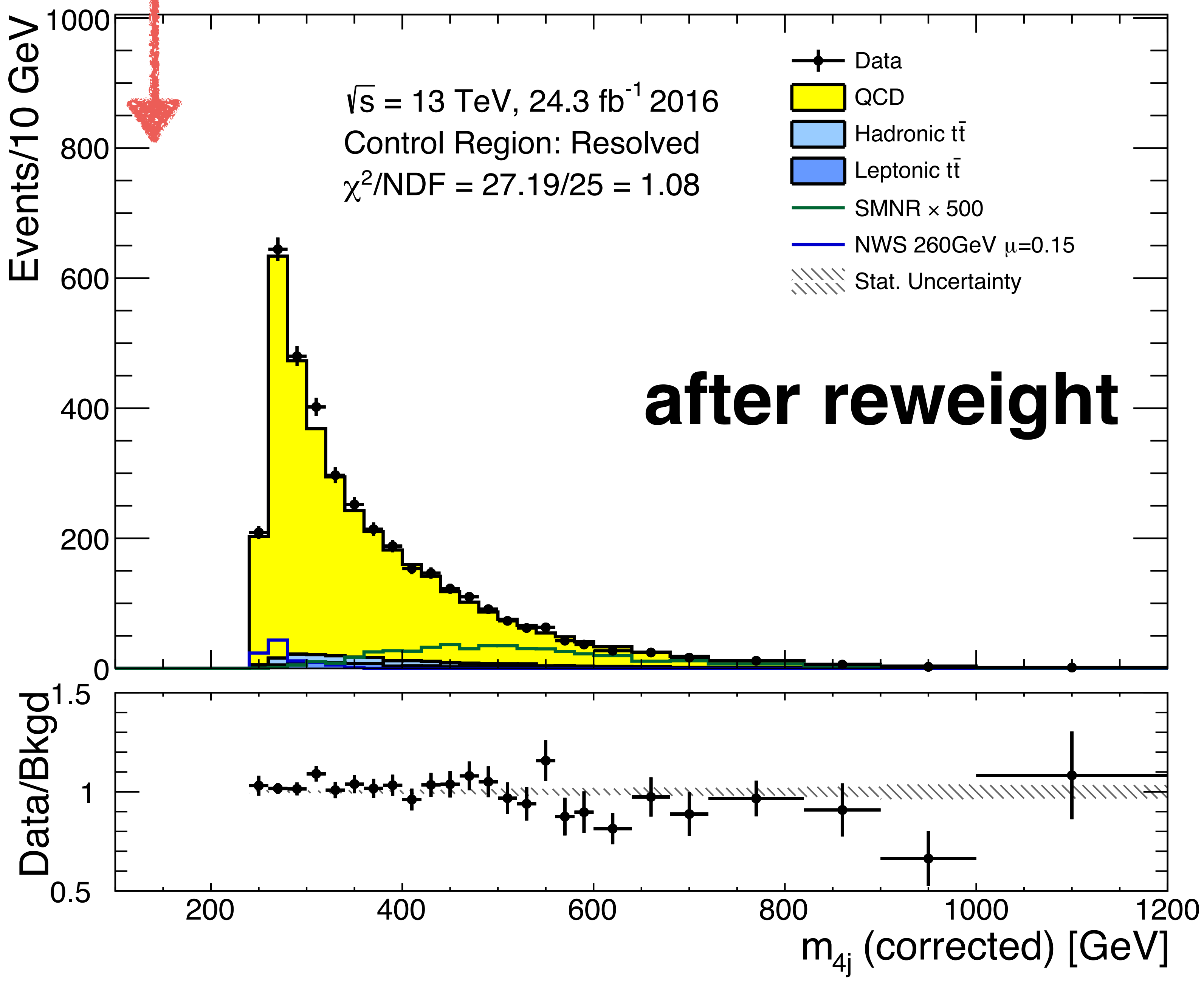
  - pT of second-hardest jet:
  - Average |η| of jets:
    - 4b events tend to be more central
  - dR_{jj} of two closest HCand jets, the other dR_{jj}:
    - Correct for correlations in HCand dR_{jj}

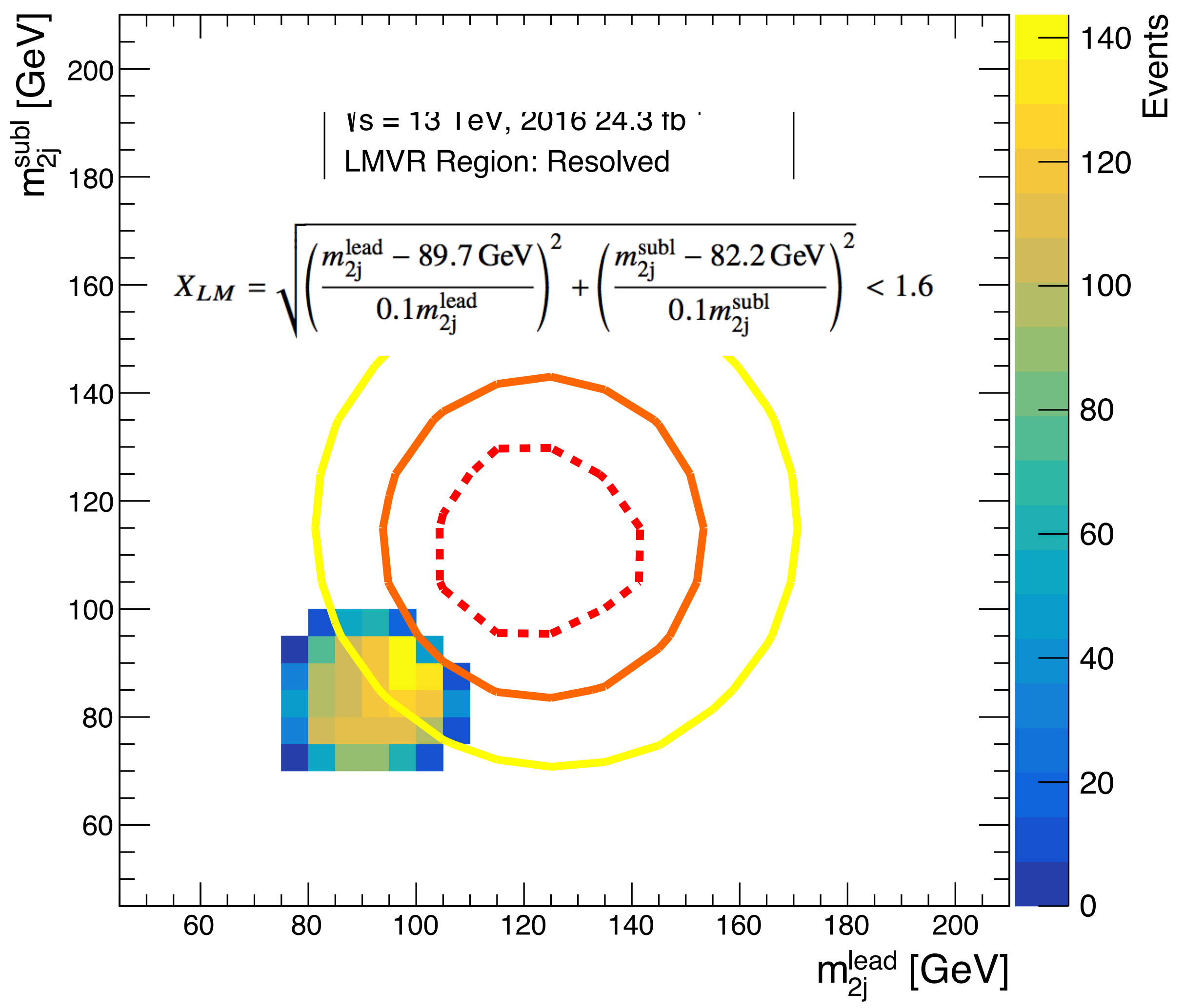
M4j in Control

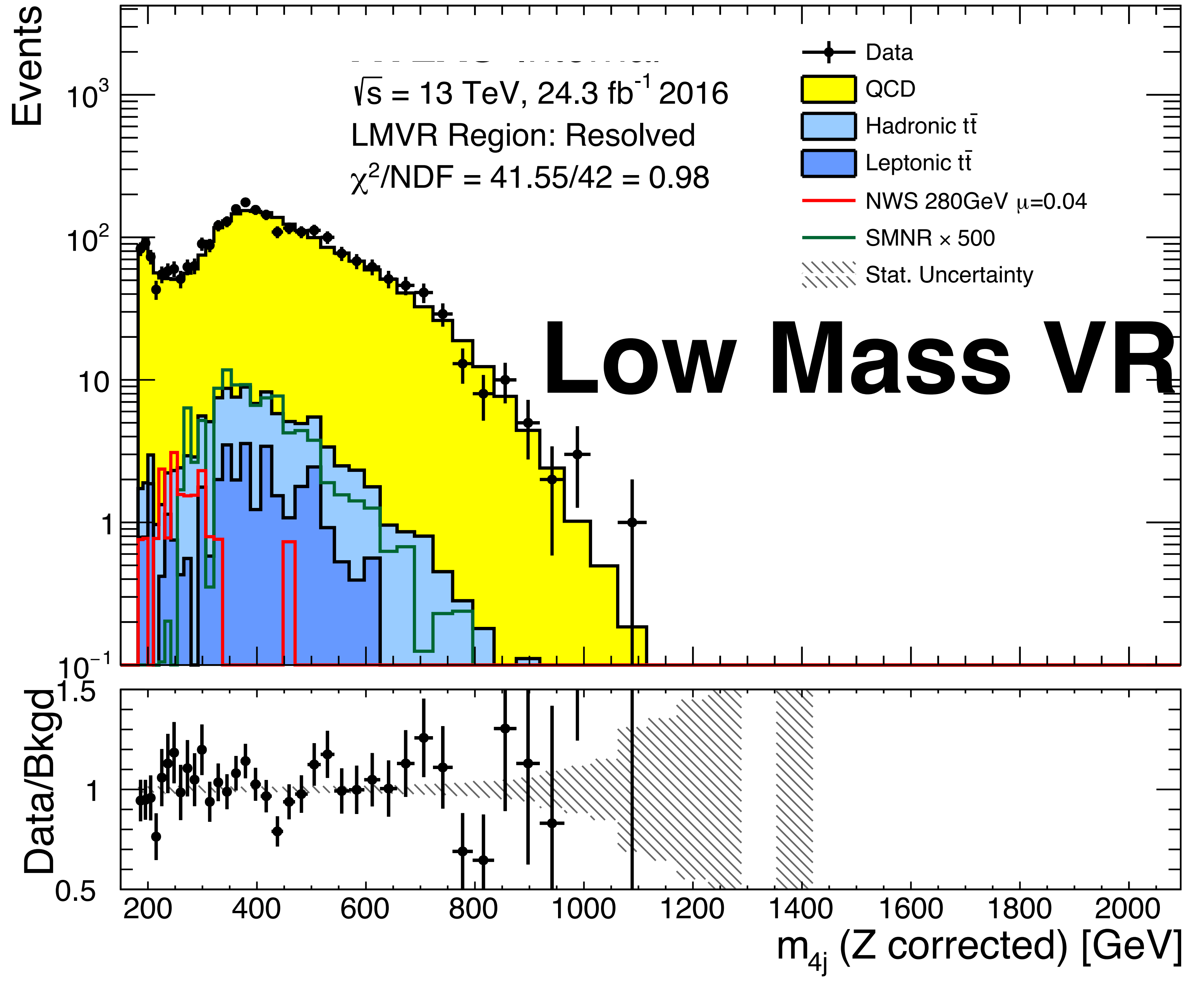


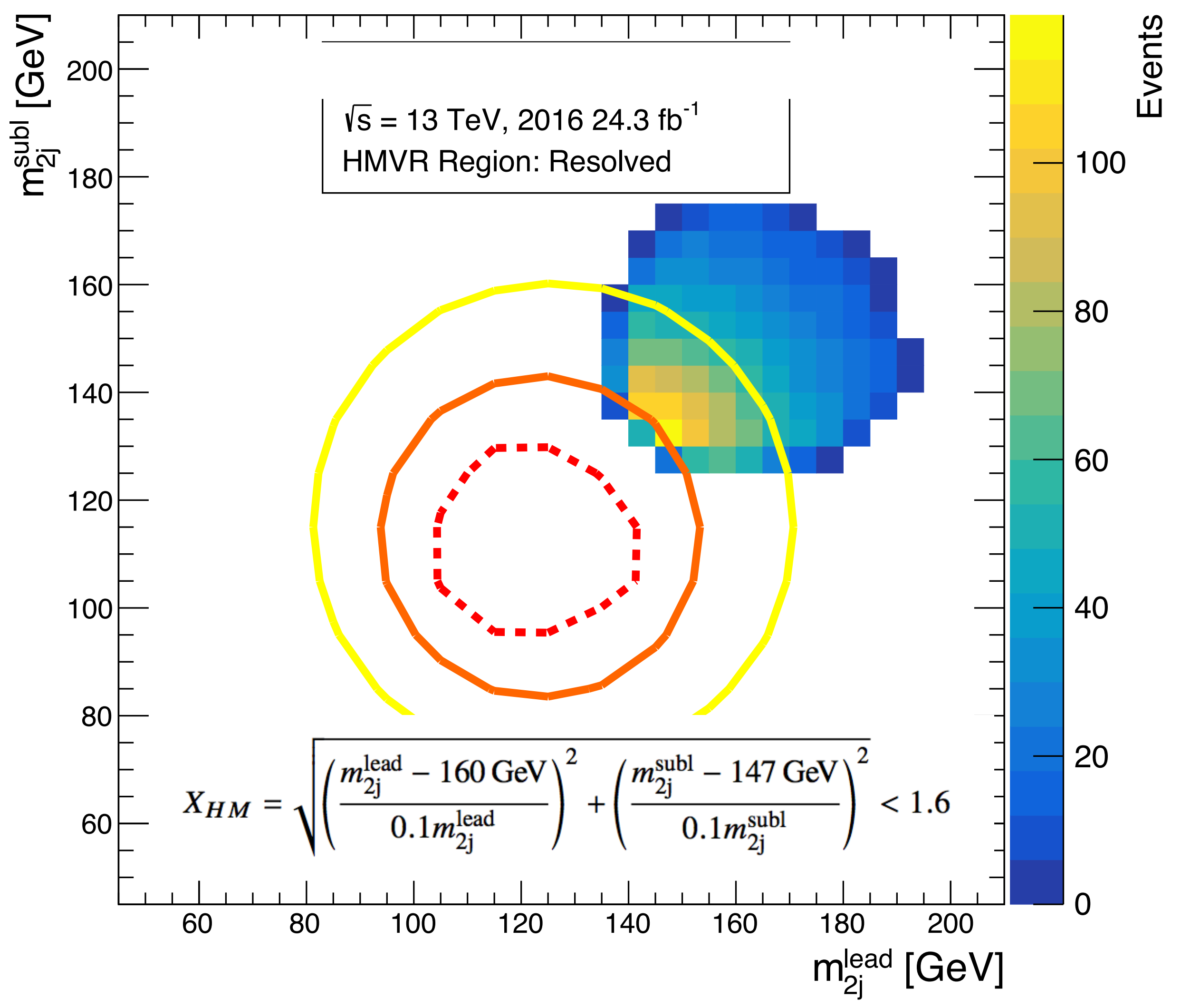


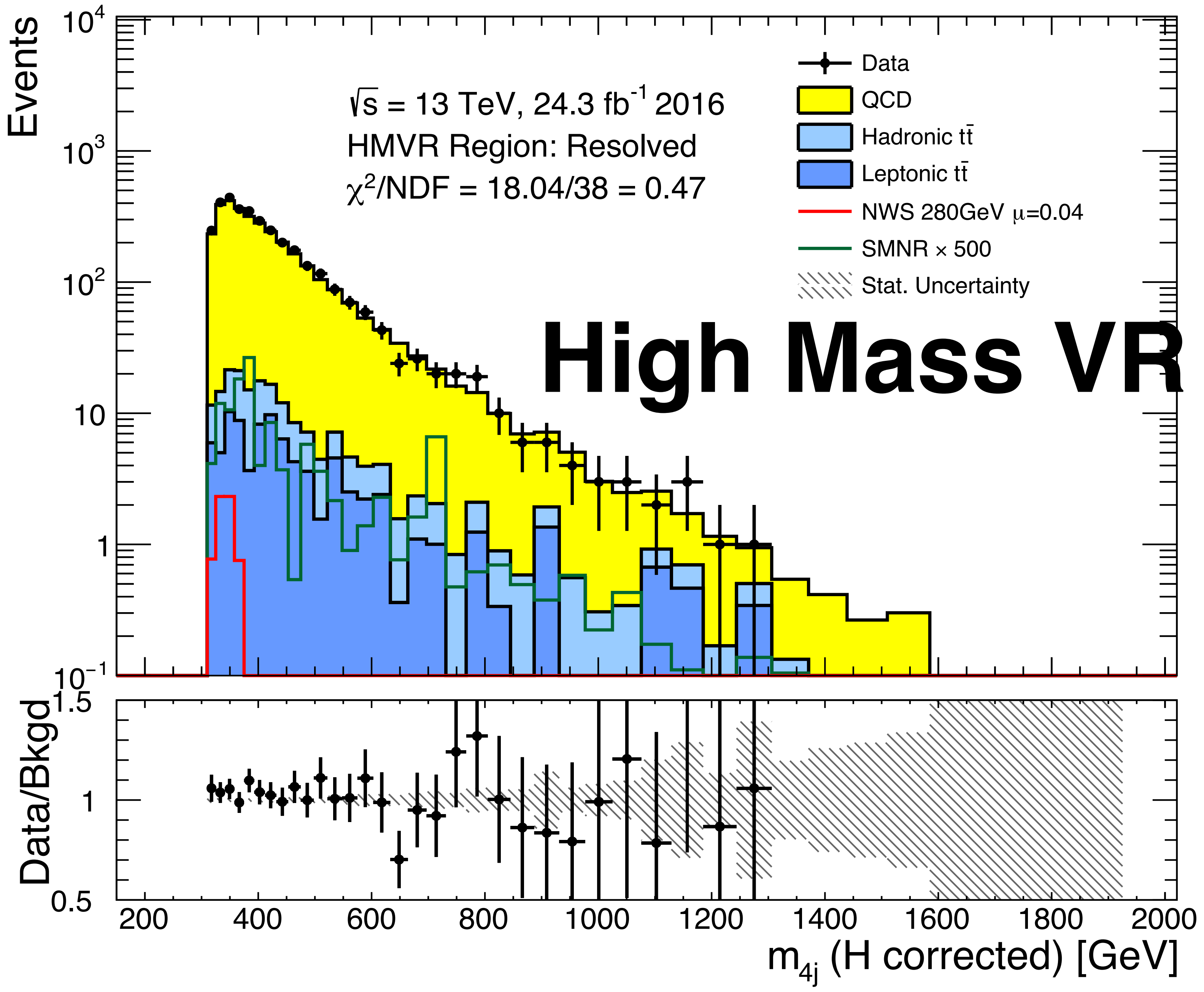
Low/High Mass Validation Region

- Further cross check other two regions centered above the HH mass and below the HH mass







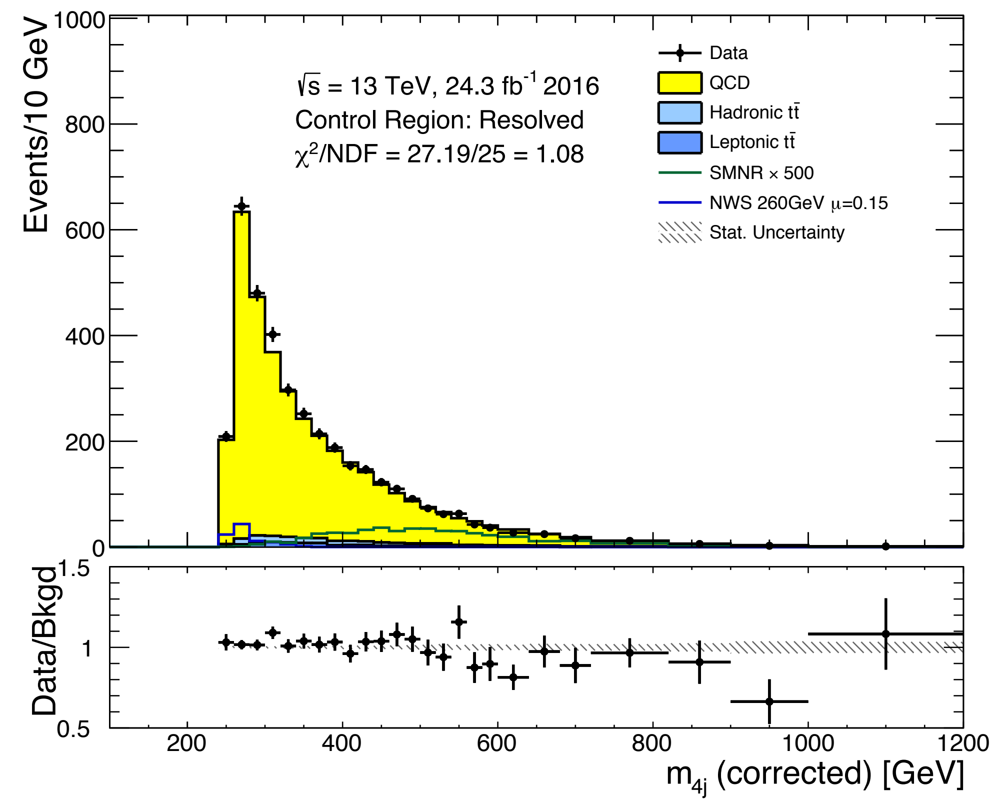


- Good data/prediction agreement in M_{4j} as well!

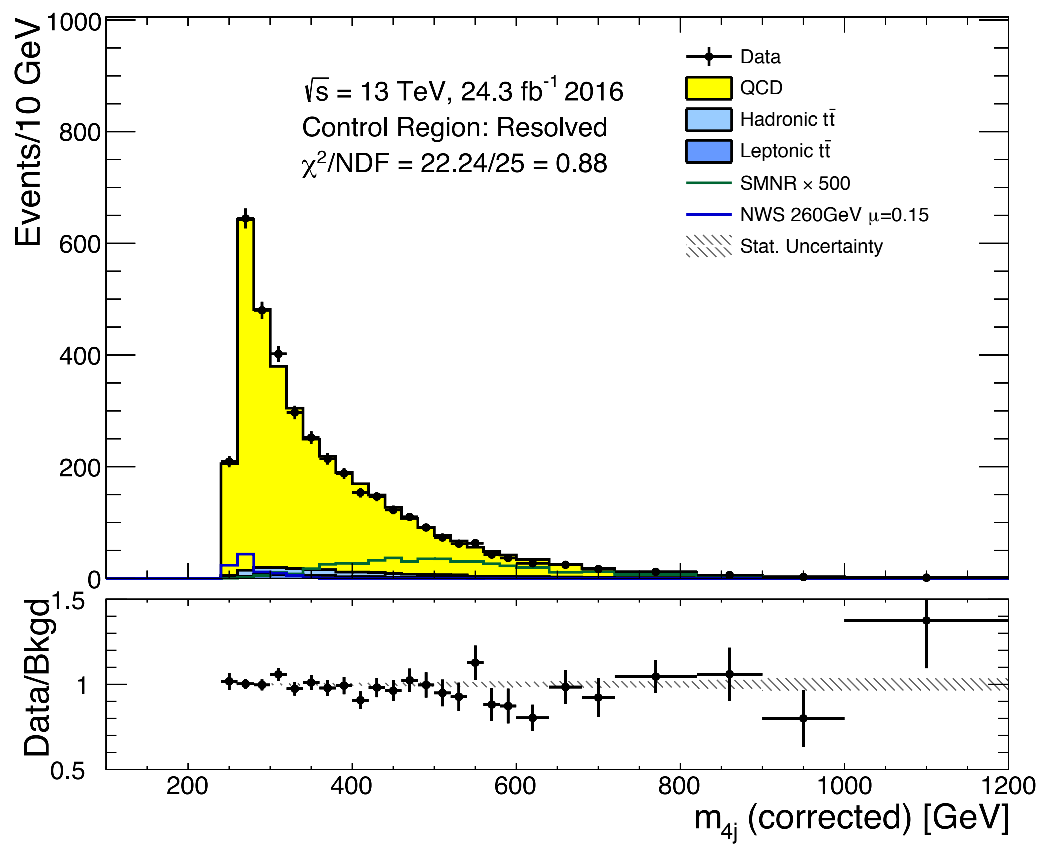
Overview of Systematics

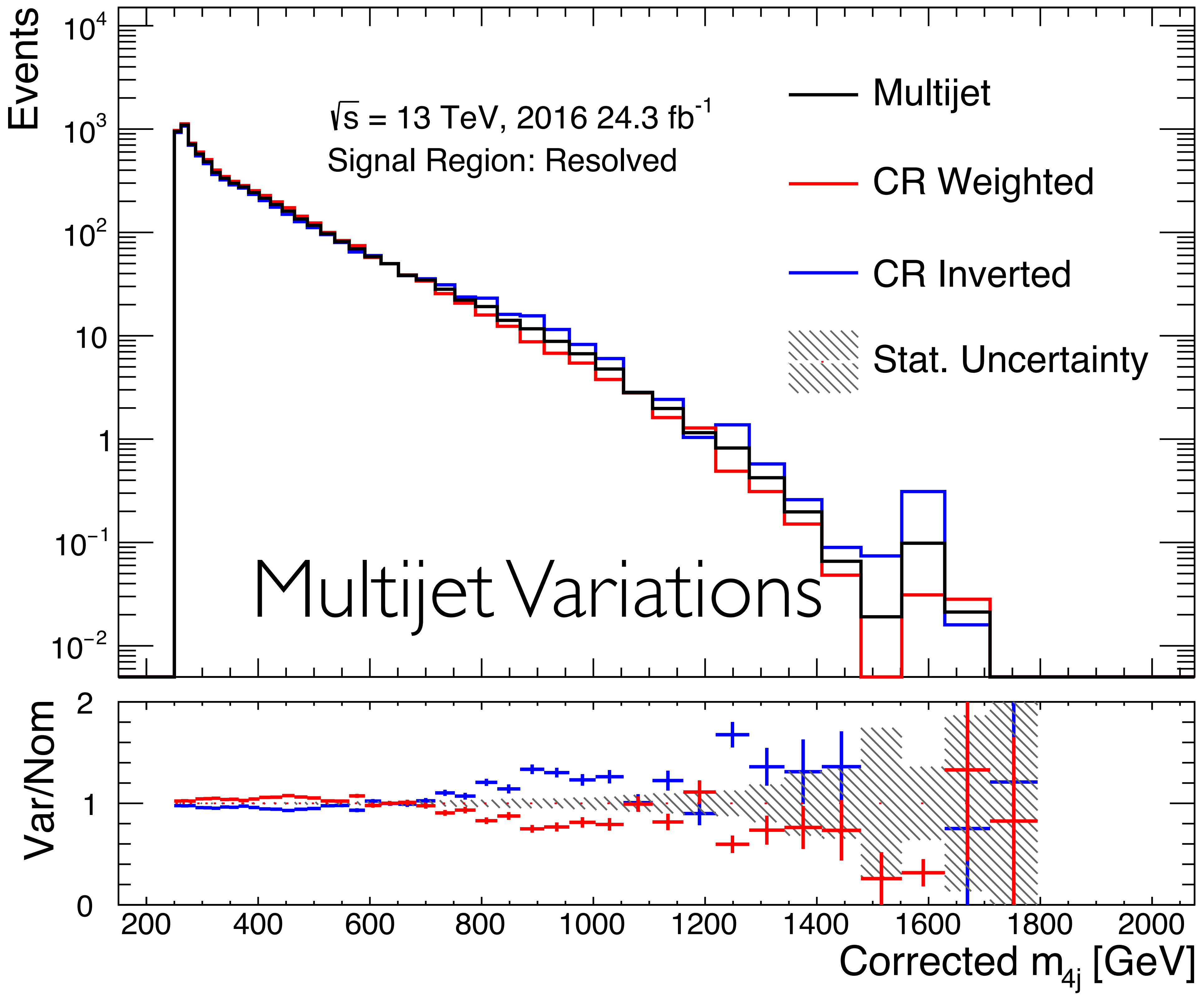
- Signal **MC uncertainty** mainly comes from **b-tagging**
- Background modeling **normalization uncertainty and shape uncertainty** is defined by the difference between control region derived signal region model and sideband region derived signal region model
  - The shape uncertainty is split into two separate components (by HT) to avoid being too restrictive

Model derived in Sideband



Model derived in Control

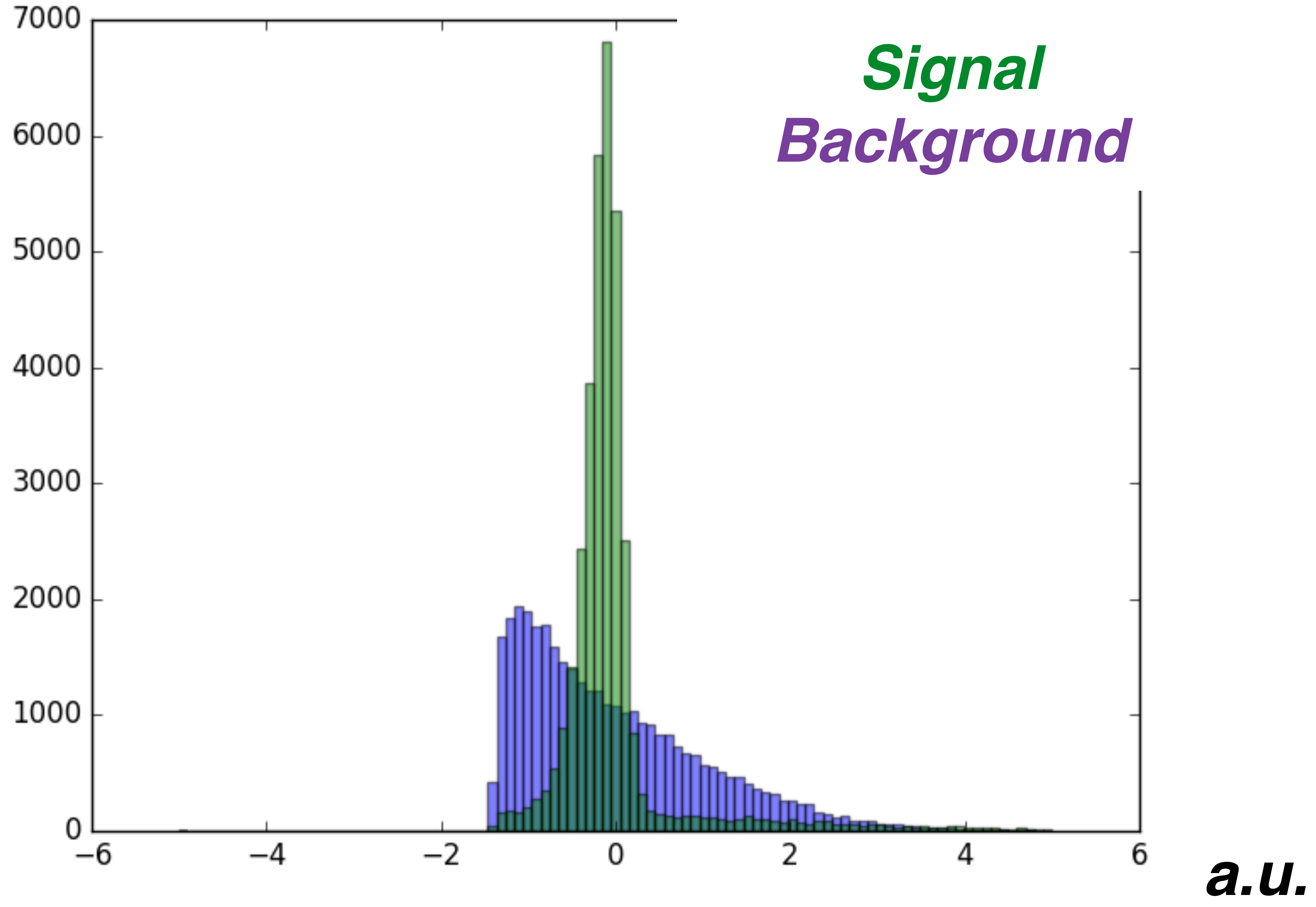




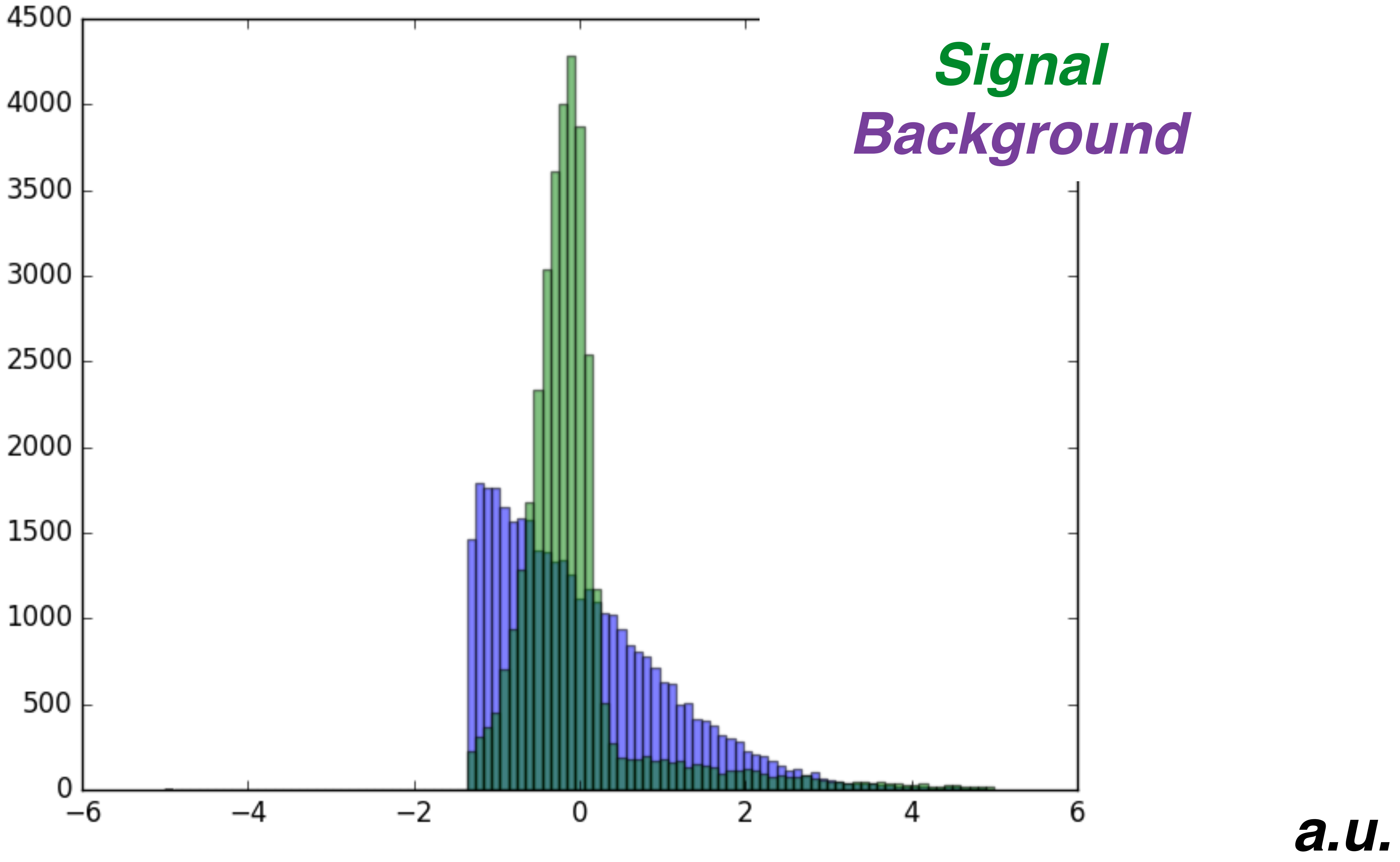
Machine Checked Signal Region

- Large-R jet mass is a good indicator for signal region
- Fixed cut on two of them or a more complicated selection?

leading p_T Jet mass, transformed



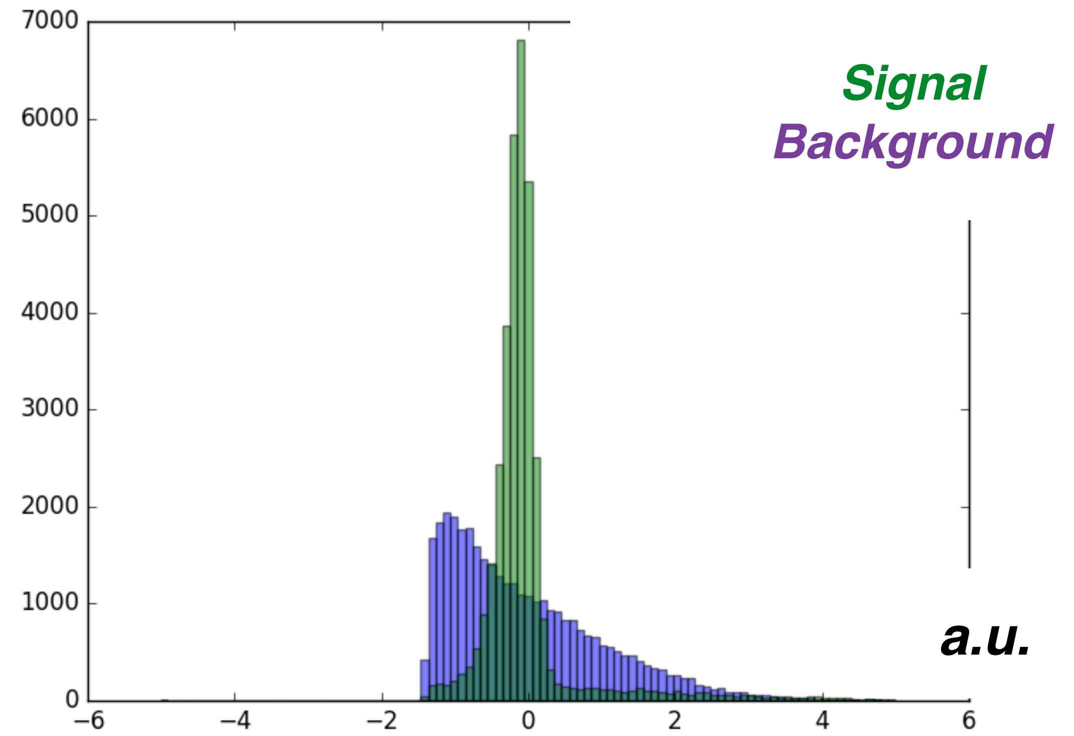
subleading p_T Jet mass, transformed



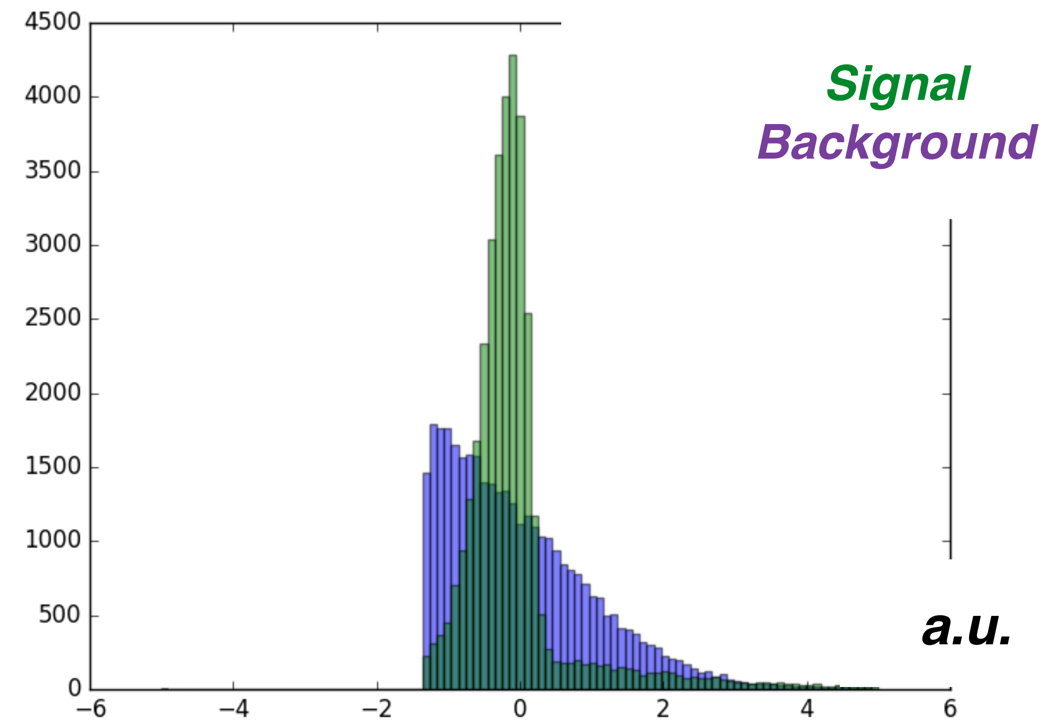
Machine Checked Signal Region

- Neural Net is great for non-linear models, exploiting correlation
- Simple three layer NN gives a circular output

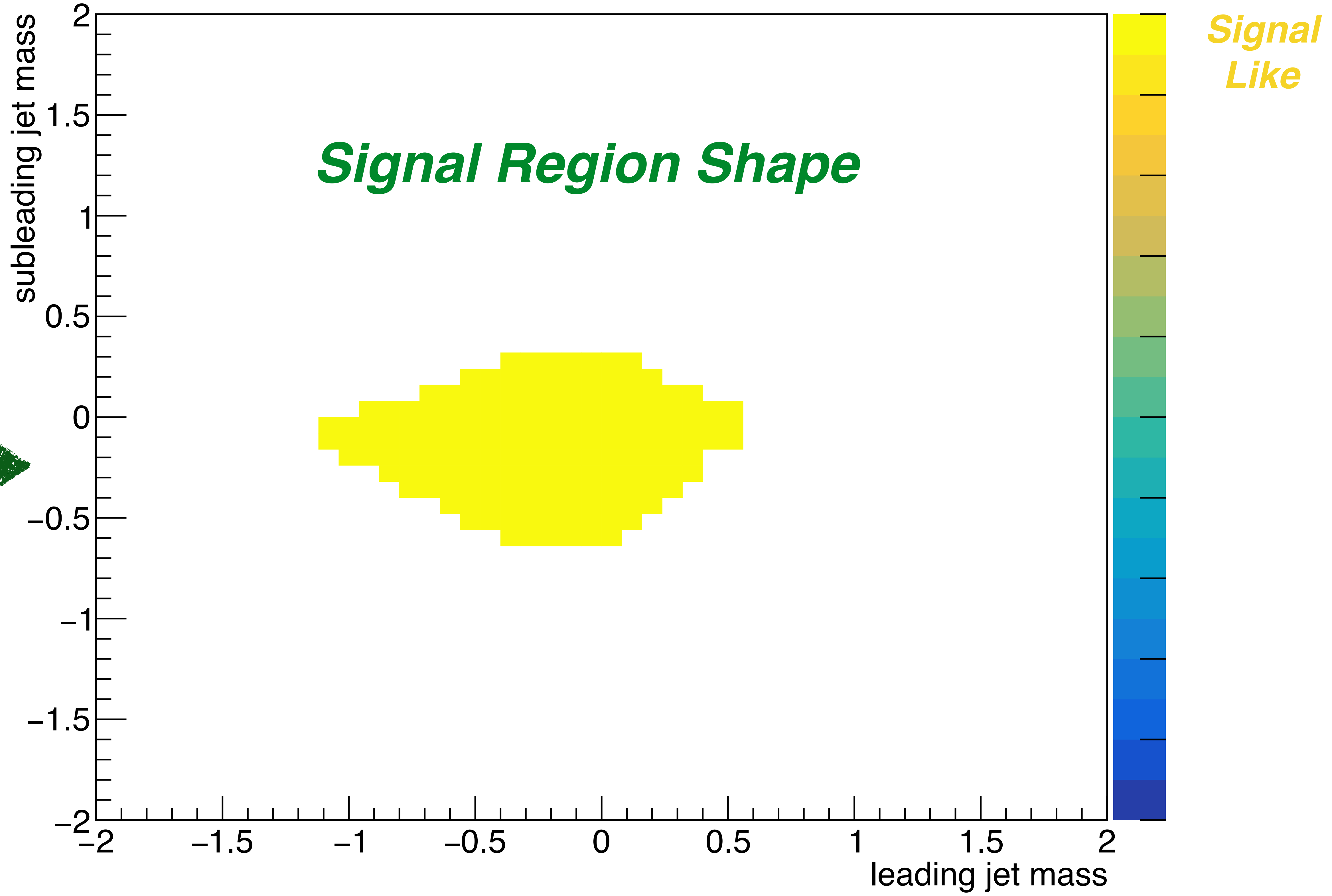
leading p_T Jet mass, transformed



subleading p_T Jet mass, transformed

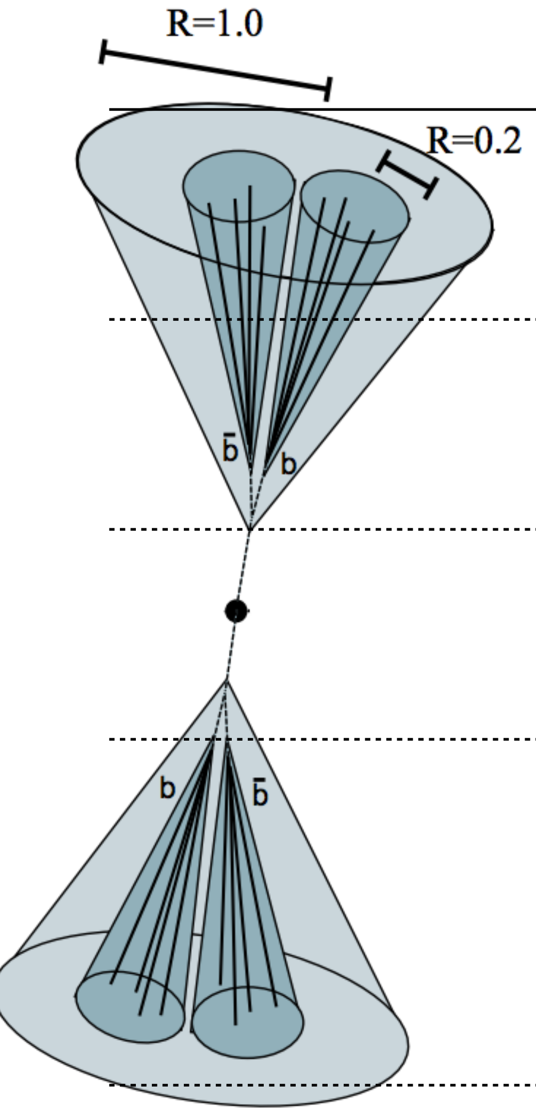


NN



Current Boosted Backgrounds

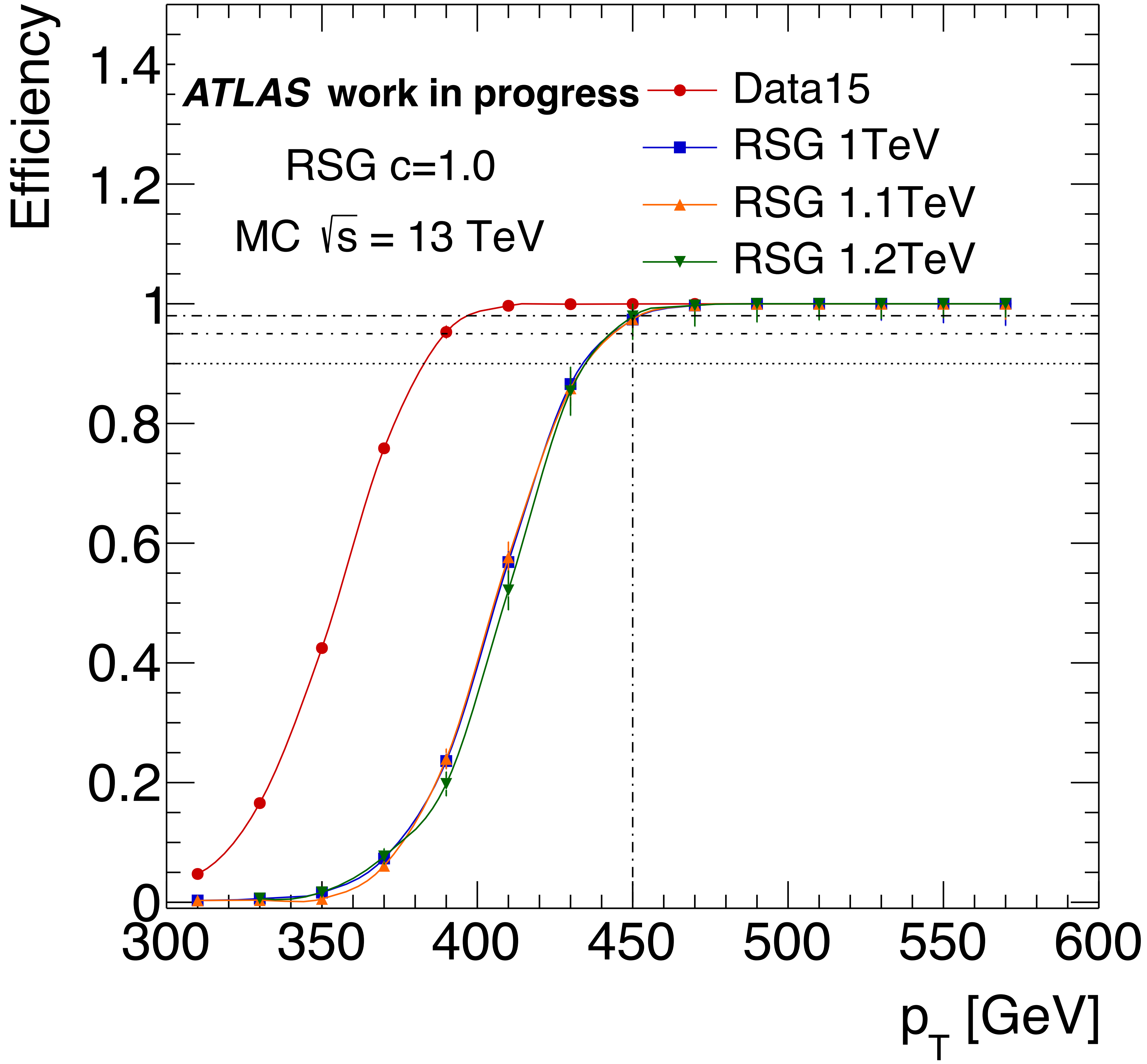
Event Selection and Method

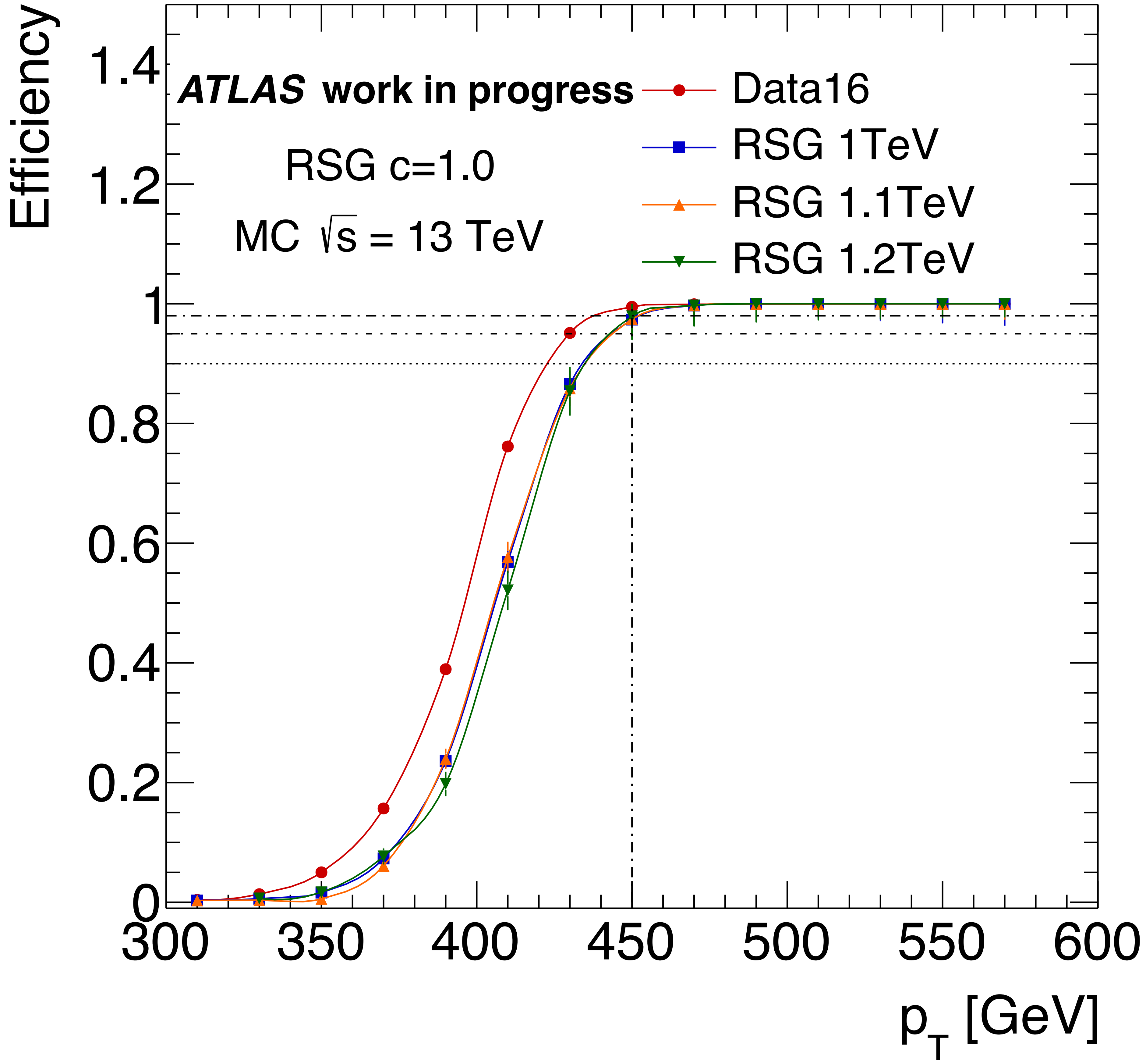


Cut	Explanation
GRL	Ensure data quality
Trigger	HLT_j360_a10_lcw(2015); HLT_j420_a10_lcw (2016)
Jet Cleaning	Do Jet Cleaning on the Resolved Jets with Loose cuts
2 Large-R Jet	must have at least 2 large R jets (Anti-kt R =1.0 LCTopo, trimmed)
Large-R Jet Selections	Leading jet pT > 450 GeV; subleading jet pT > 250 GeV; Large R jet $\|\eta\| < 2$; **combined mass** > 50 GeV;
dη cut	$\|d\eta(j,j)\| < 1.7$; to reduce QCD background
Resolved Veto	**Veto 4 resolved b-jets (70%** wp**) events, passing resolved SR**
b-tagging	on **0.2** Trackjets (pT > 10 GeV), *Mv2C10*, ***70%*** *wp*

Trigger Turn on

- In MC and 16 data using: HLT_j420_a10_lcw_sub_L1J100;
- In 15 data using: HLT_j360_a10_lcw_sub_L1J100;





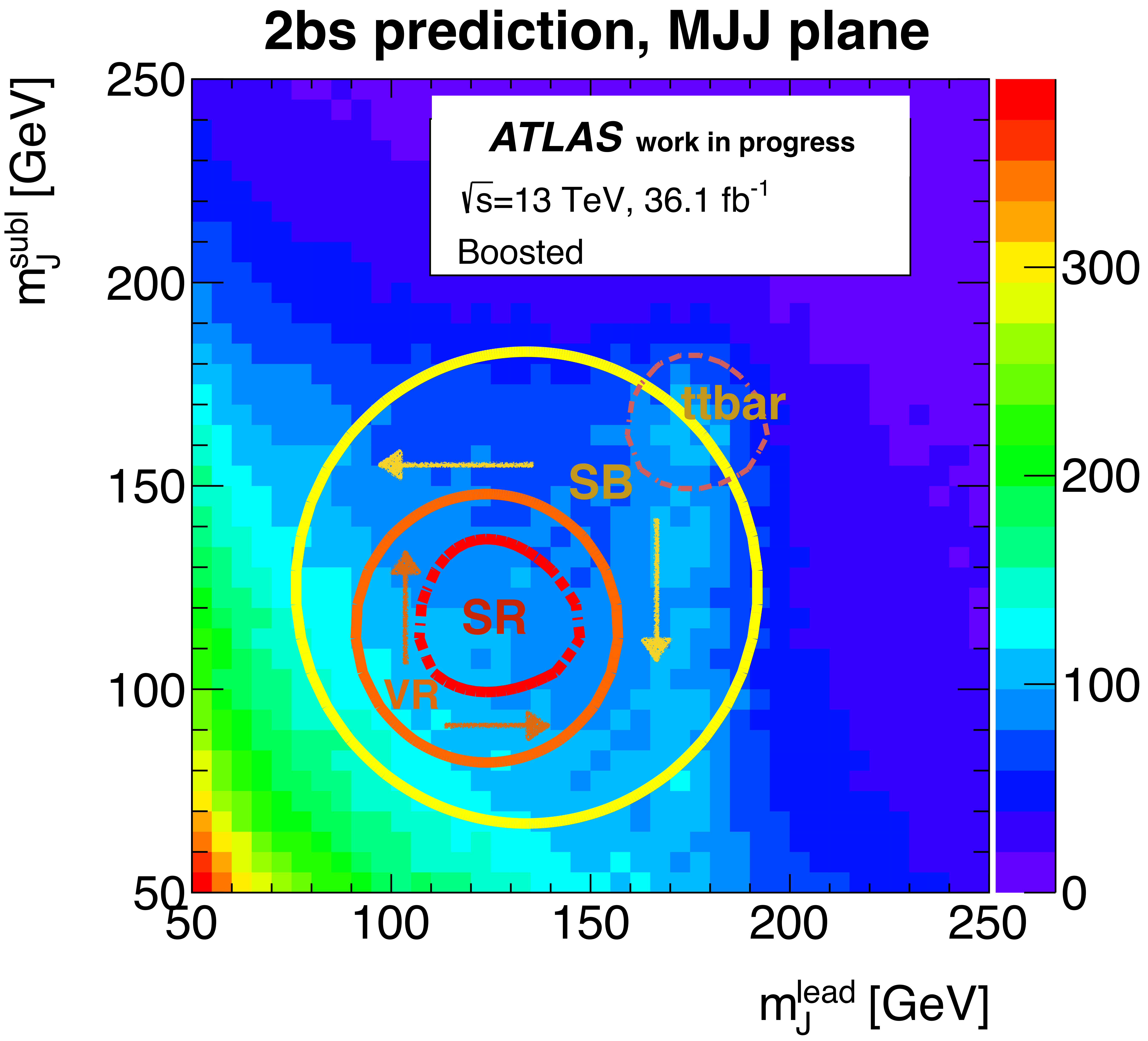
Two Higgs Mass Plane

- **Signal Region** (SR): $X_{hh} < 1.6$
  - "**Egg**" centered at h mass
- **Validation Region** (VR) :
  - $X_{hh} > 1.6$ && $R_{hh} < 33$
  - Ring outside SR (**for validation**)
- **Sideband** (SB):
  - $33 < R_{hh}$ && $R_{hh}^{high} < 58$
  - Ring outside CR (**for modeling**)

$$X_{hh} = \sqrt{\left(\frac{m_J^{lead} - 124\text{ GeV}}{0.1\left(m_J^{lead}\right)}\right)^2 + \left(\frac{m_J^{subl} - 115\text{ GeV}}{0.1\left(m_J^{subl}\right)}\right)^2}$$

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

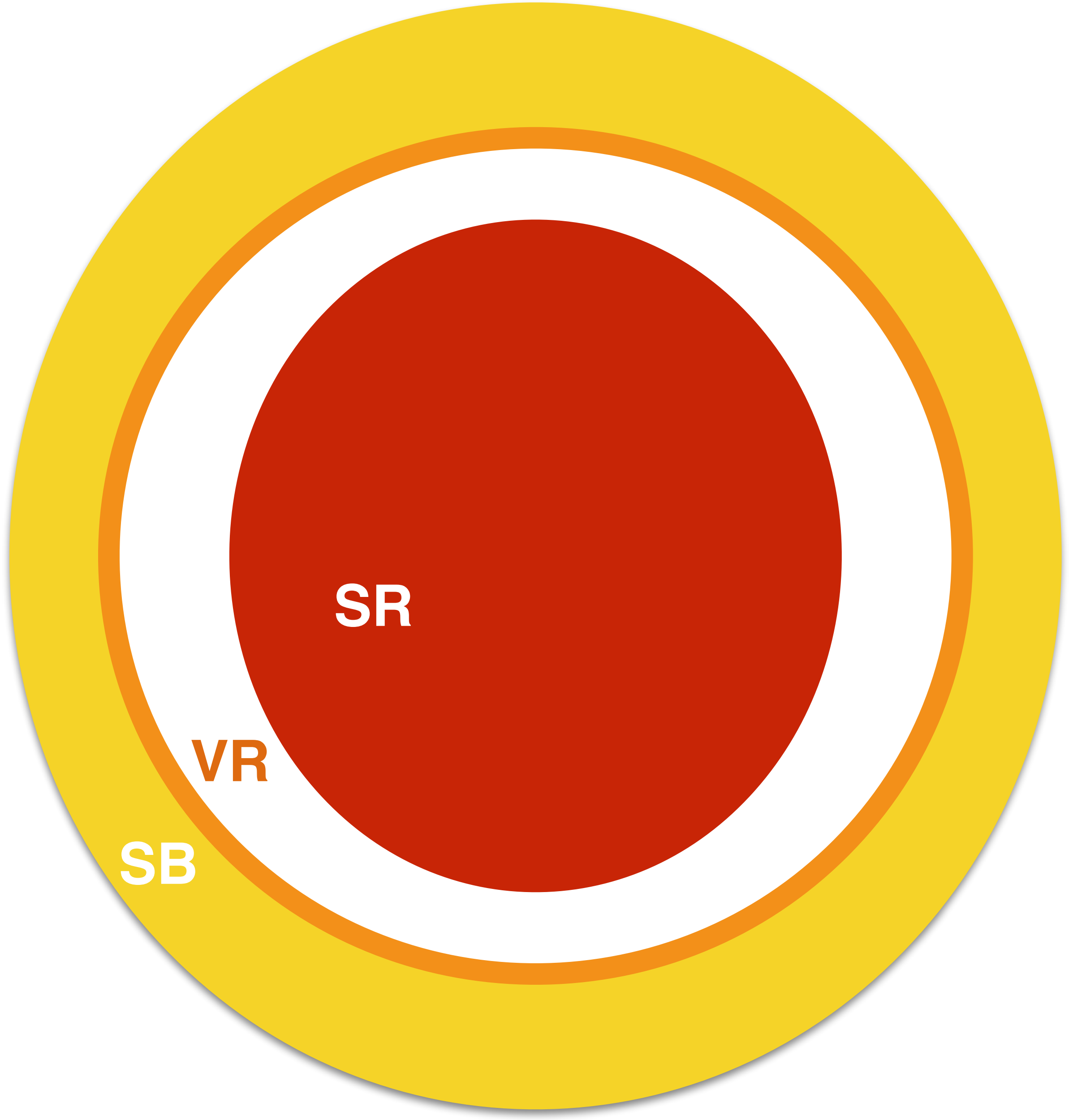
$$R_{hh}^{high} = \sqrt{\left(m_J^{lead} - 134\text{ GeV}\right)^2 + \left(m_J^{subl} - 125\text{ GeV}\right)^2}$$



Background

- Background:
  - 10-15% ttbar—MC
  - 90-85% qcd—data driven
- Need **shape** and **normalization** estimates for qcd events

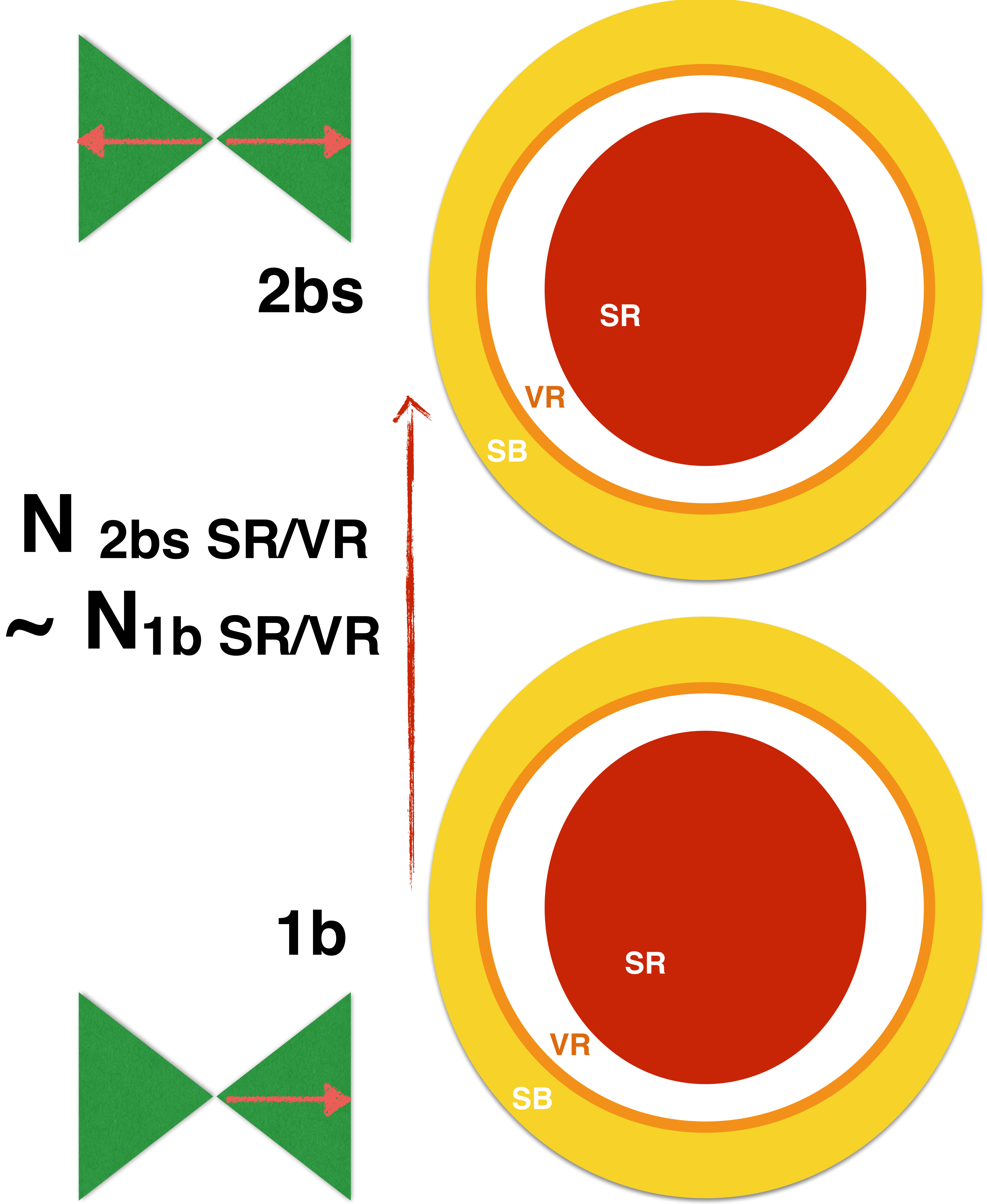
2bs



N 2bs SR/VR
???

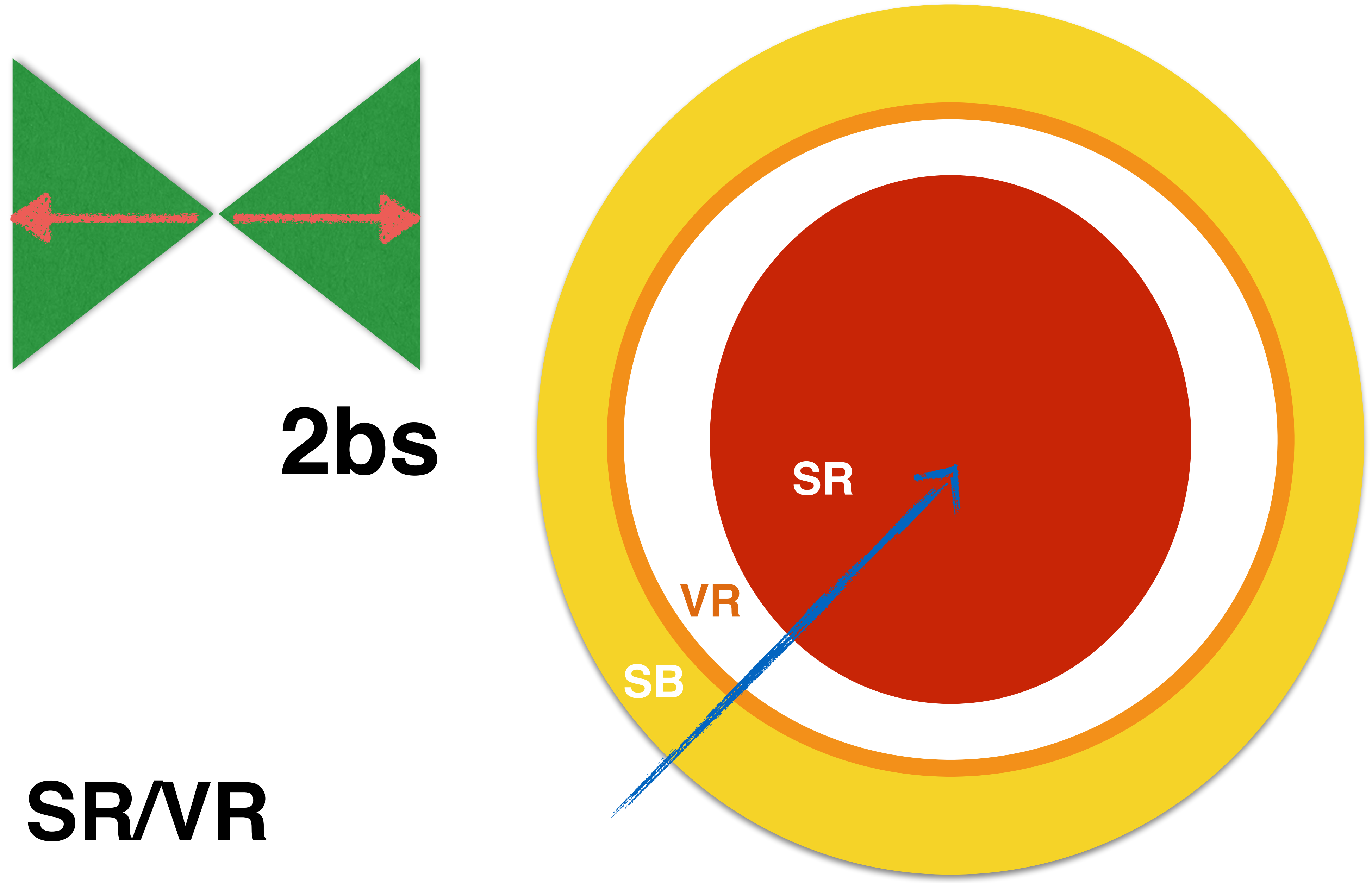
Background

- Background:
  - 10-15% ttbar—MC
  - 90-85% qcd—data driven
- Use lower-b-tag, lower-signal yield region to **model** higher-b-tag regions
  - 2bs — use 1b data
  - 3b/4b — use 2b data

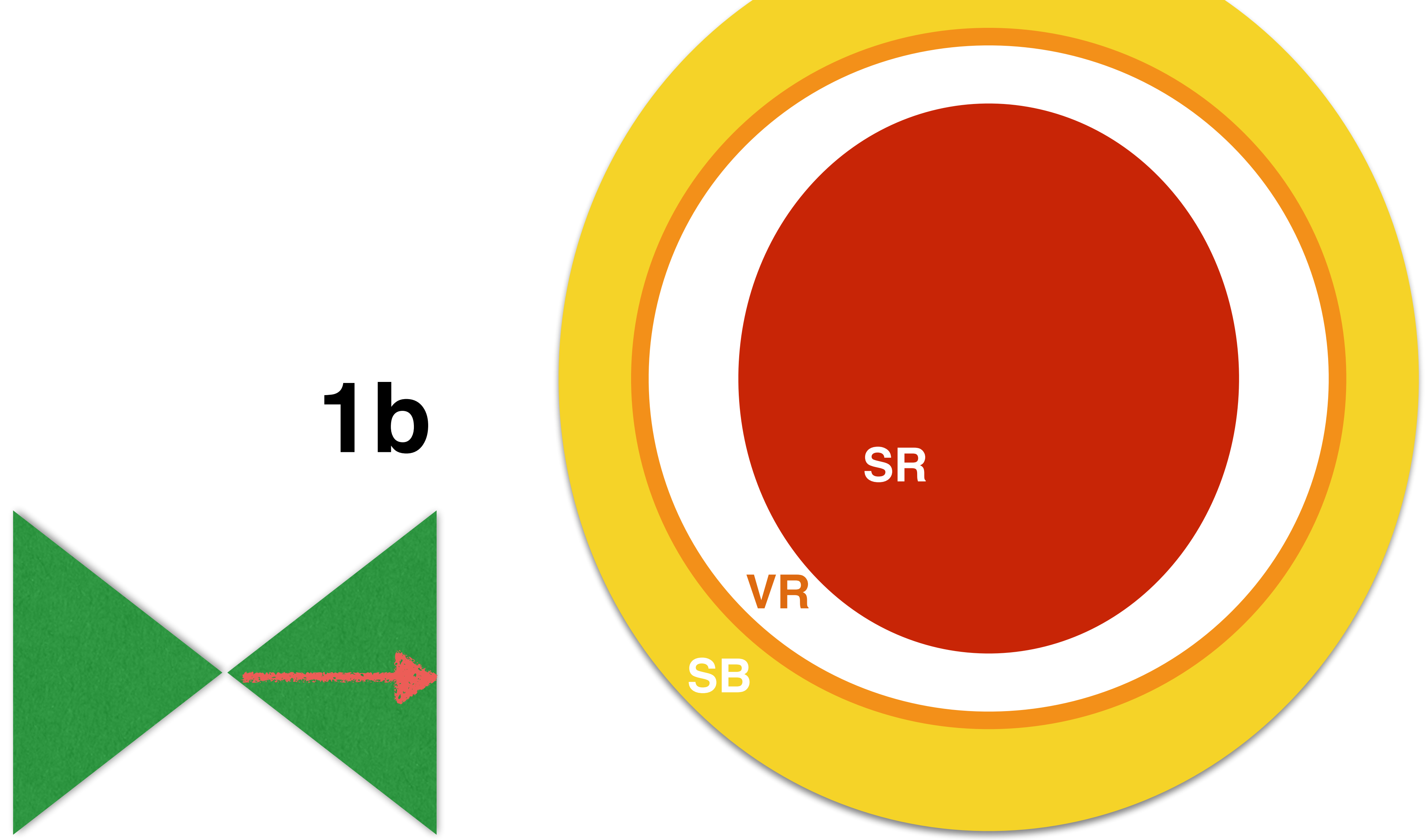


Background

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



$$N_{2bs\ SR/VR} = N_{1b\ SR/VR} * N_{2bs\ SB} / N_{1b\ SB}$$



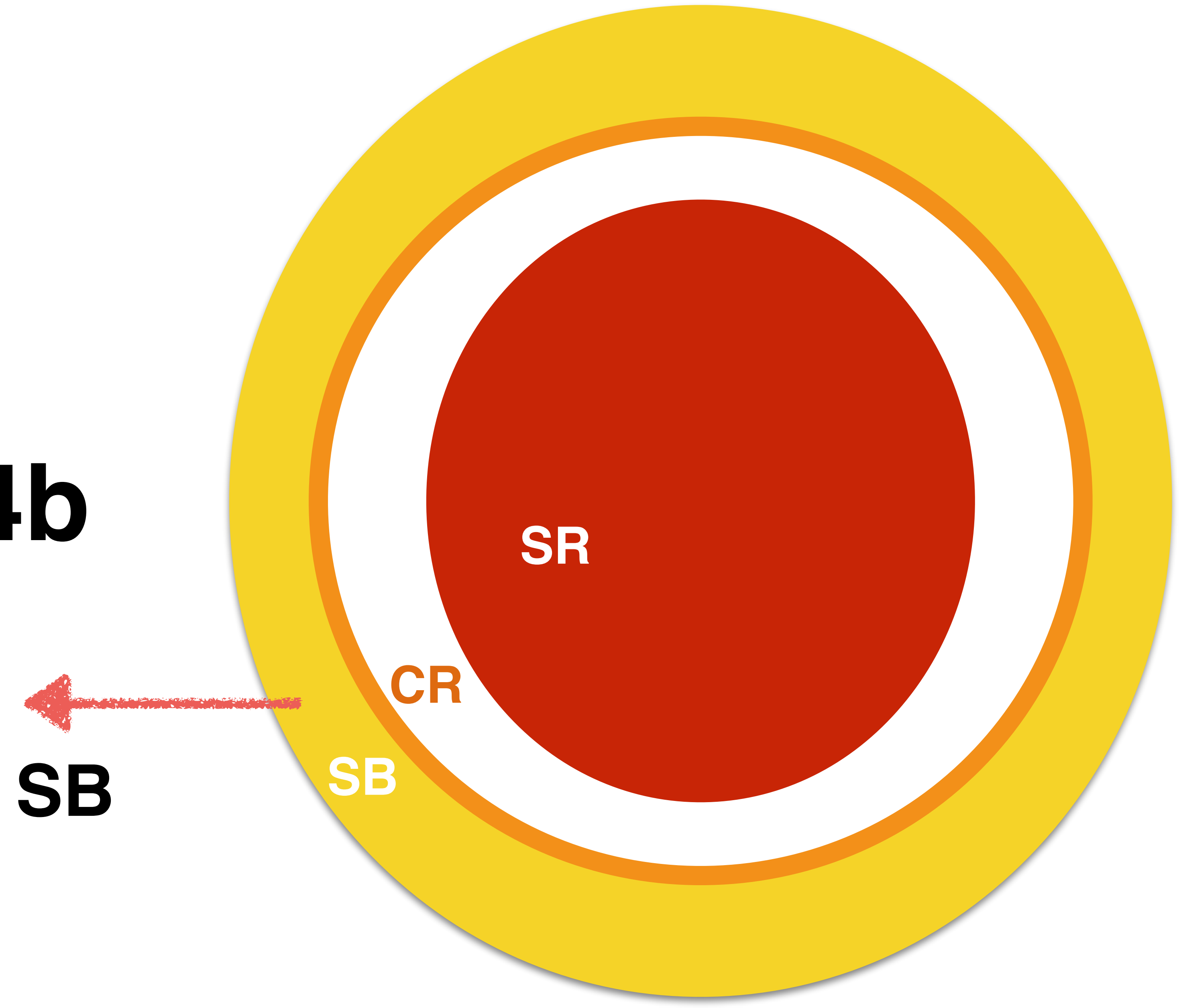
- Use lower-b-tag, lower-signal yield region to model higher-b-tag regions
- Derive the **normalization** factor from the ratio, also apply reweighting to correct composition differences

Boosted 4b Background

- Background composition:
  - ~85% qcd
  - ~15% ttbar

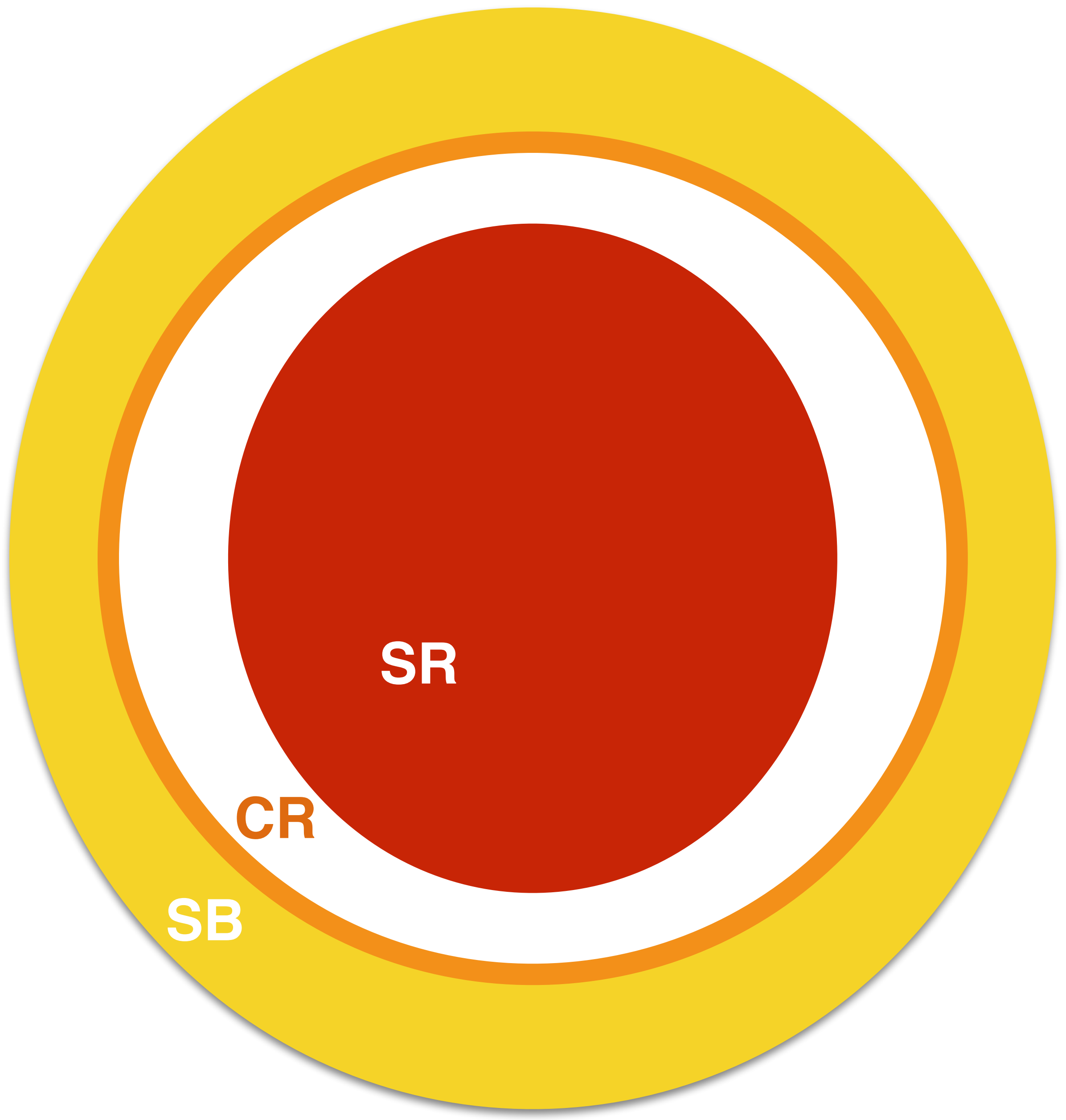
4b

$$N_{4b\ SR/CR} = N_{2b\ SR/CR} * N_{4b\ SB} / N_{2b\ SB}$$



- Background **shape** estimation comes from lower number of b-tagged trackjet regions
  - **2bs: use 1b data**
  - **3b: use ~ 80% 2b data** (2 b-tag on one Jet)
  - **4b: use the other ~ 20% 2b data**
- Fit the leading jet mass in SB to extract ttbar and qcd **normalization** from 1b/2b/2b to 2bs/3b/4b

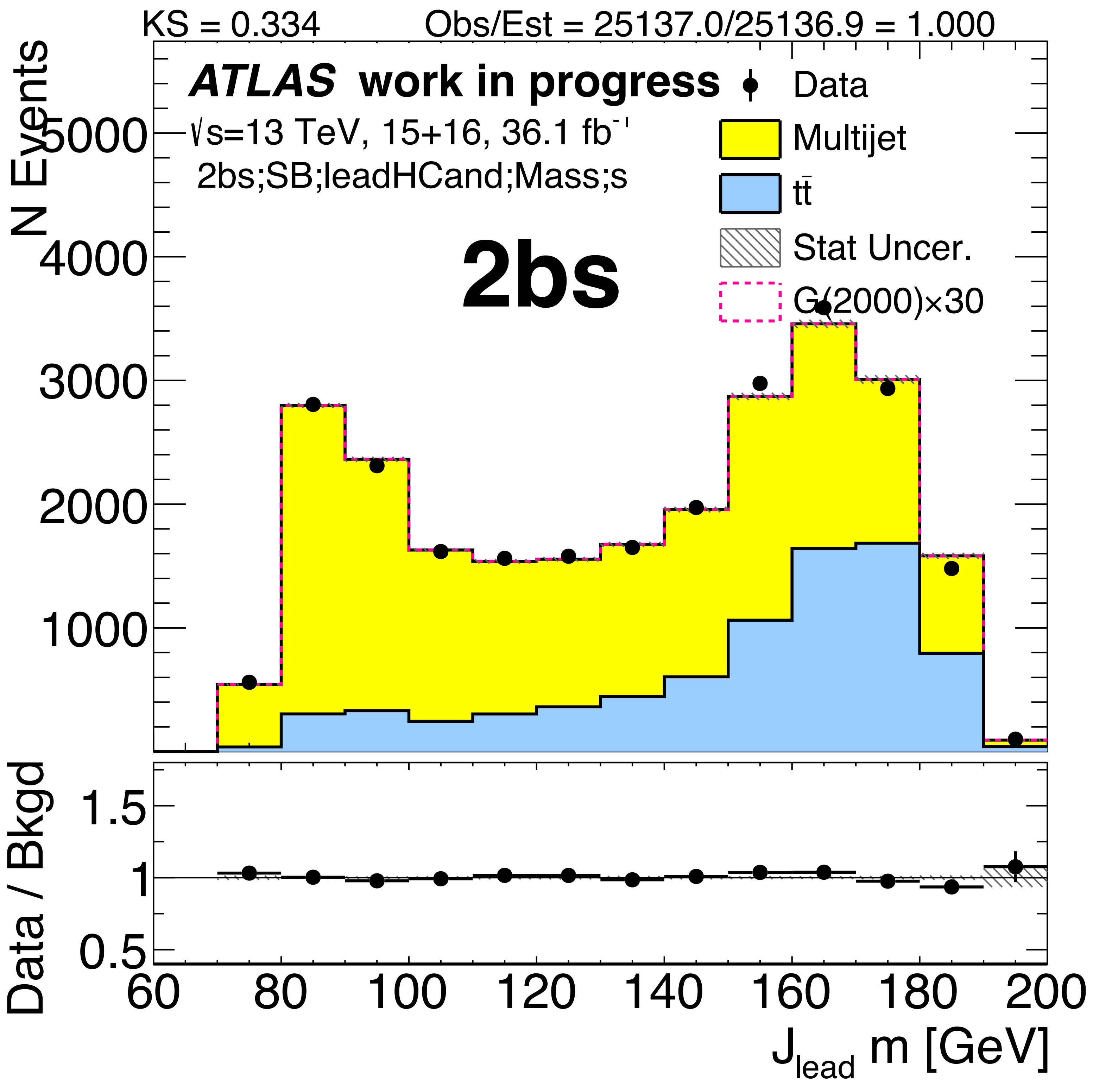
2b

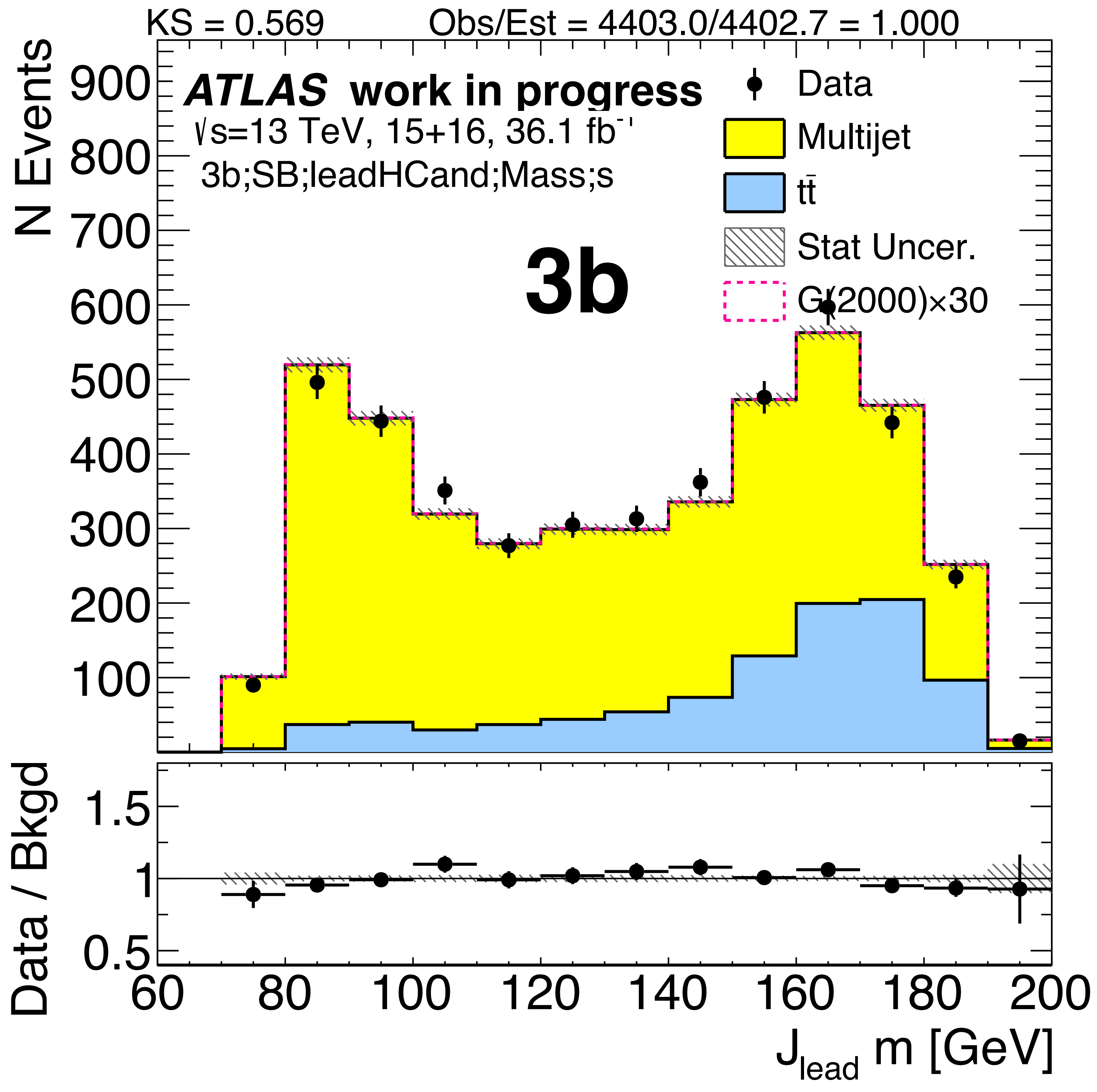


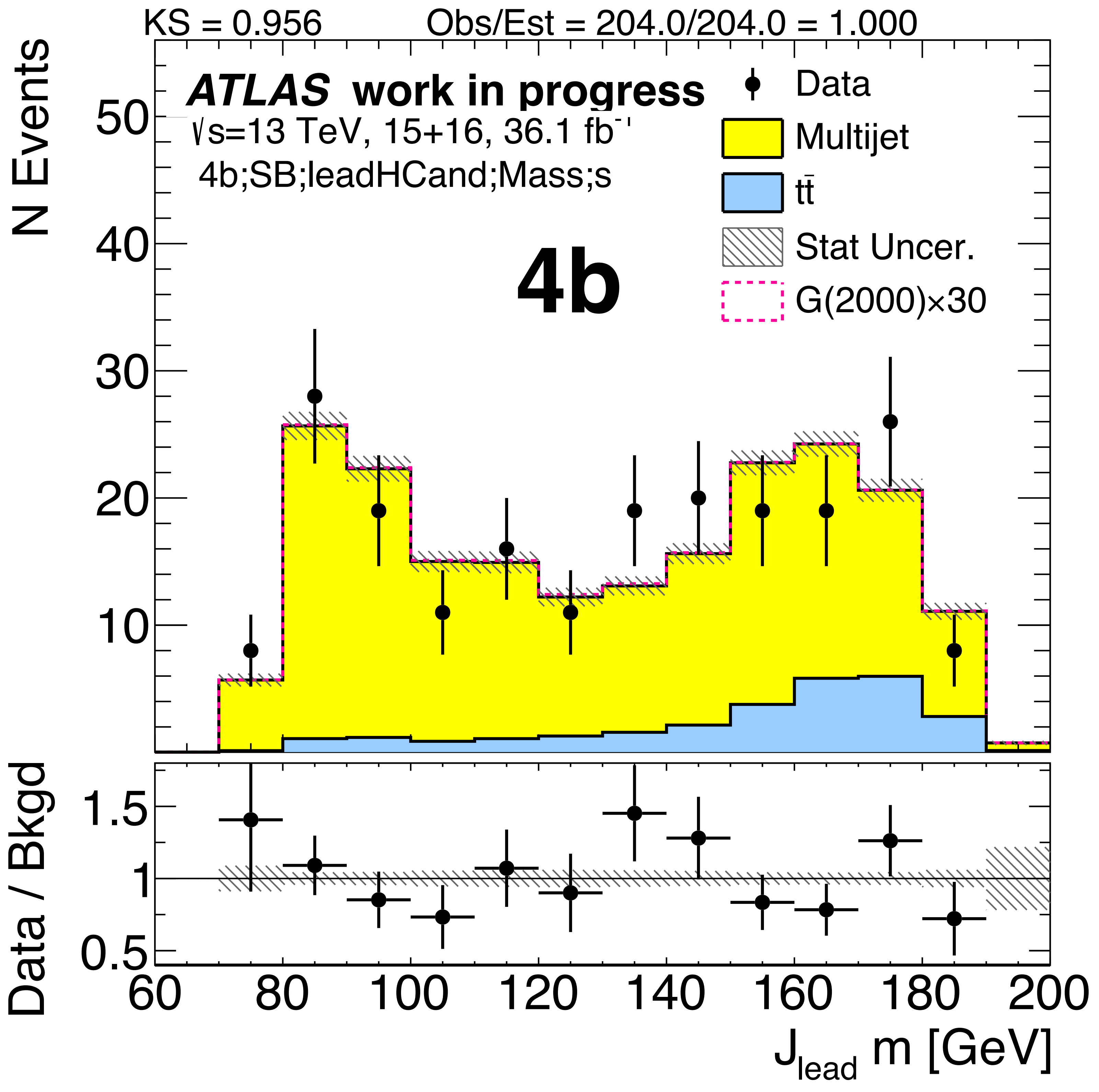
Normalization from Fit on Leading Jet Mass

- Given: $N^{\nu_b}_{data} = \mu^{\nu_b}_{qcd} N^{\nu_b}_{qcd} + \alpha^{\nu_b}_{t\bar{t}} N^{\nu_b}_{t\bar{t}}$
- Simultaneous **fit** to extract μ_{qcd}, a_{tt}

Sample	μ_{qcd}	$\alpha_{t\bar{t}}$	$\rho(\mu_{qcd}, \alpha_{t\bar{t}})$
FourTag	0.0332 ± 0.00423	0.892 ± 0.616	-0.796
ThreeTag	0.158 ± 0.00466	0.895 ± 0.0808	-0.764
TwoTag split	0.0627 ± 0.000857	0.986 ± 0.0265	-0.757





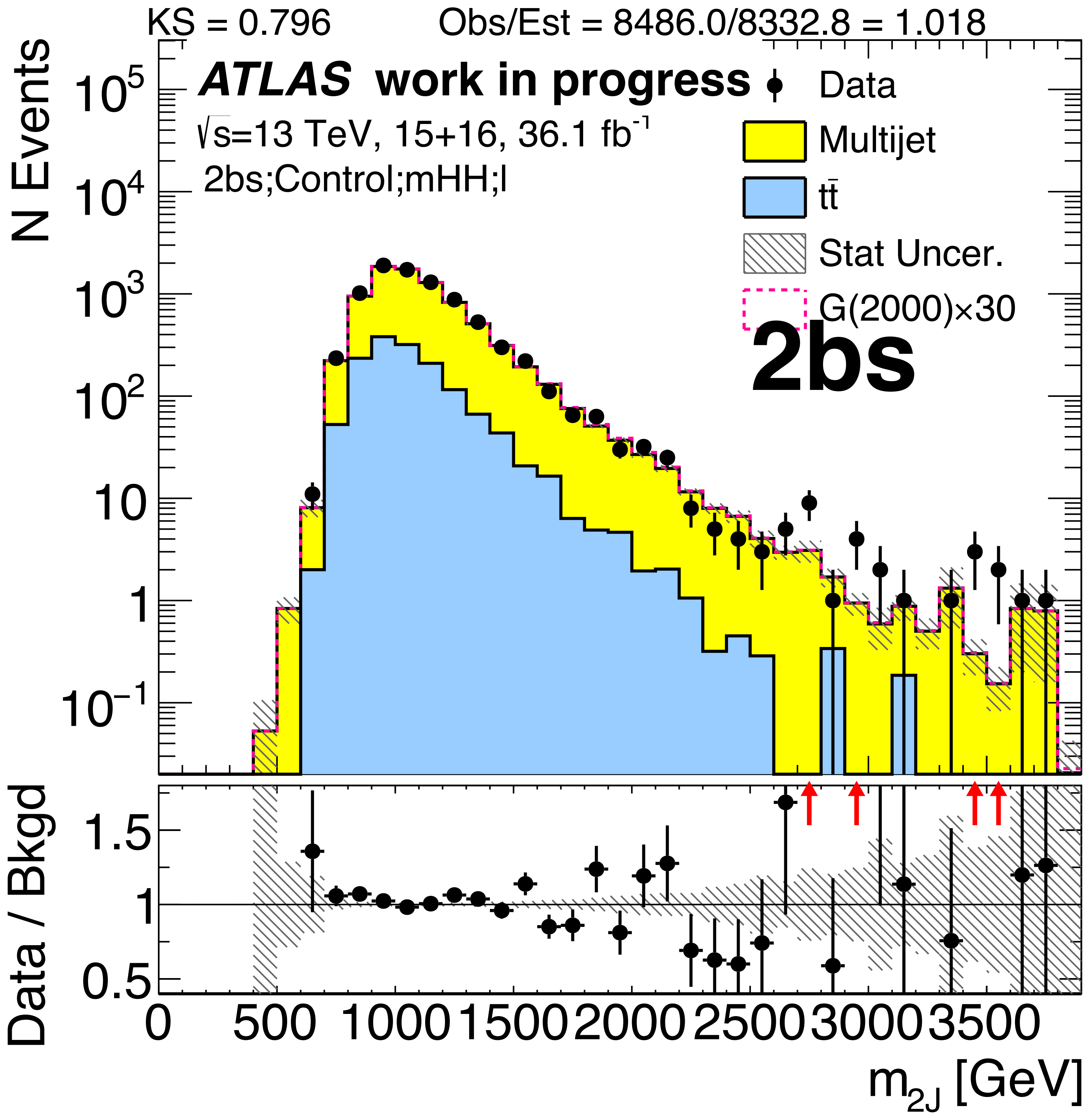


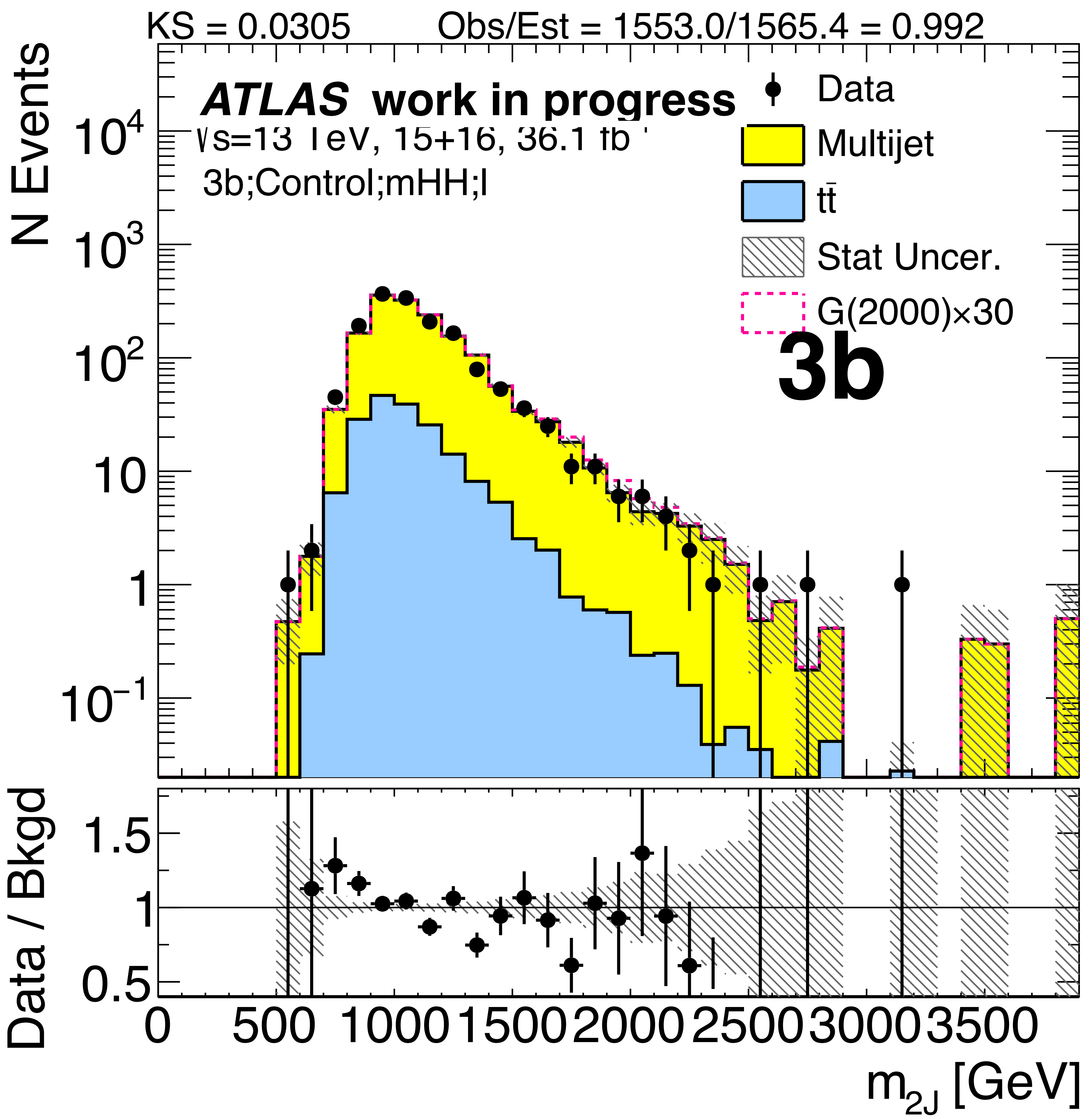
Sideband Region MJJ

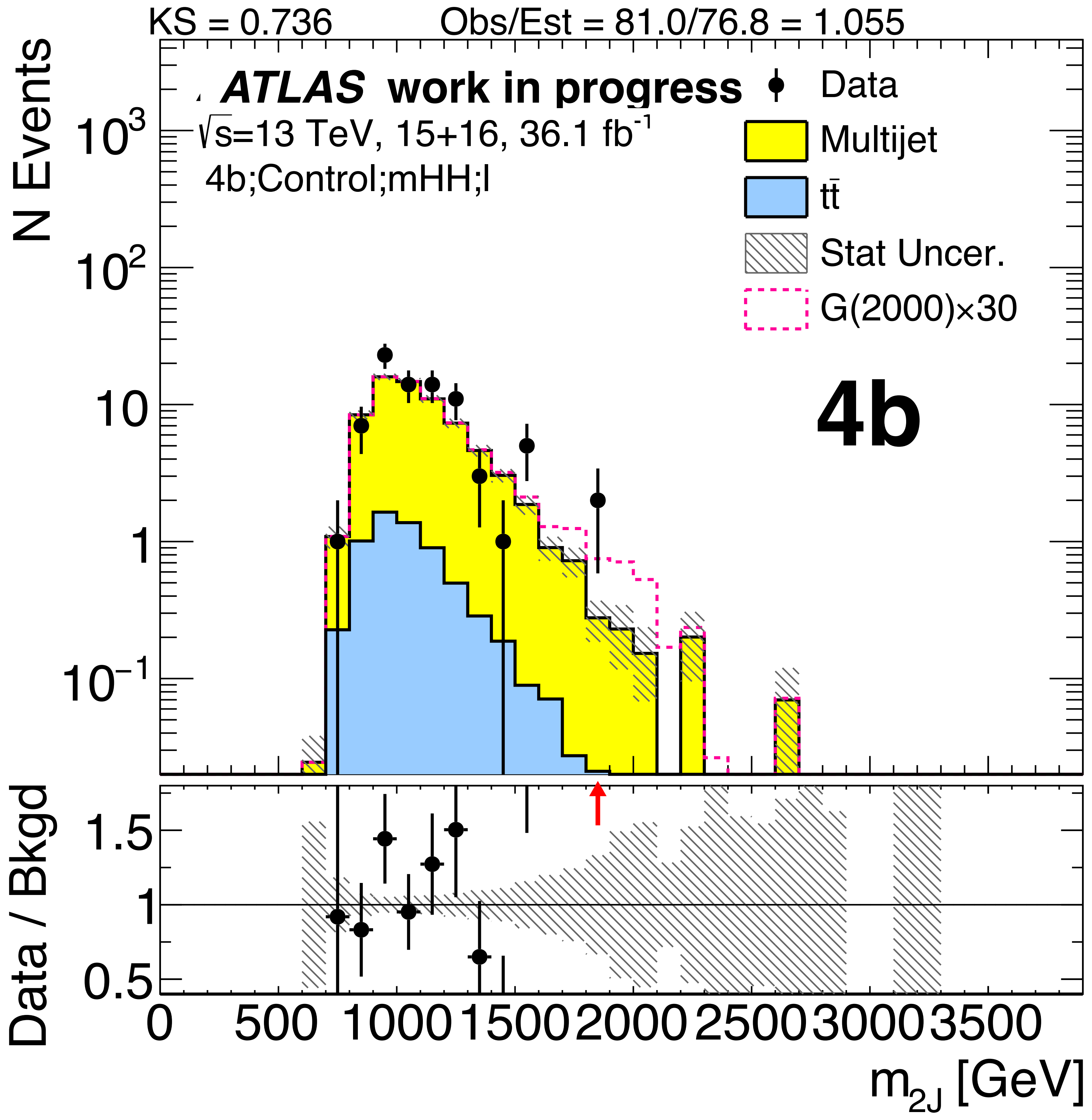
- **Good** agreement in shape; normalization agree by construction

Validation Region MJJ

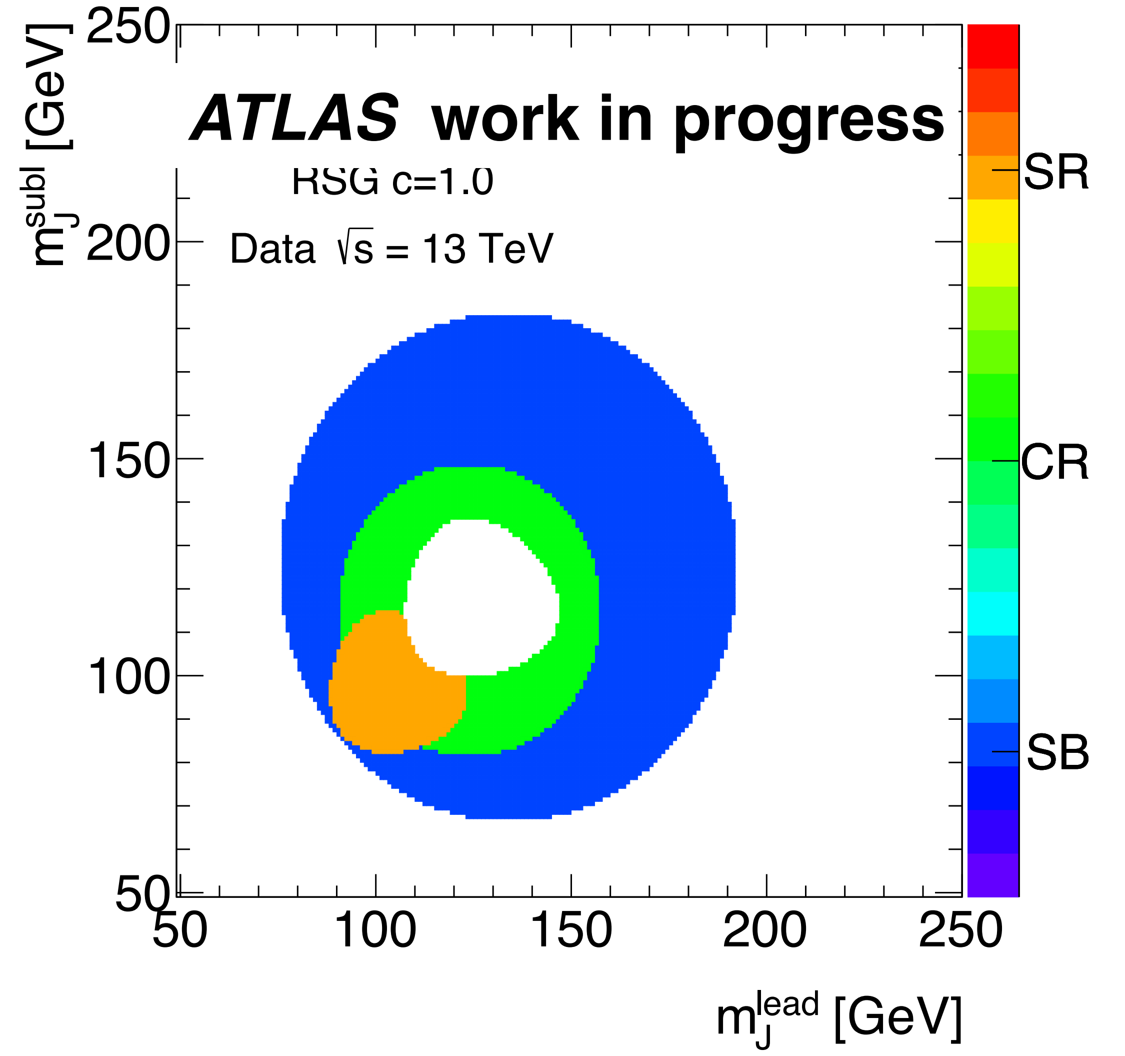
- **Good** agreement in shape and normalization



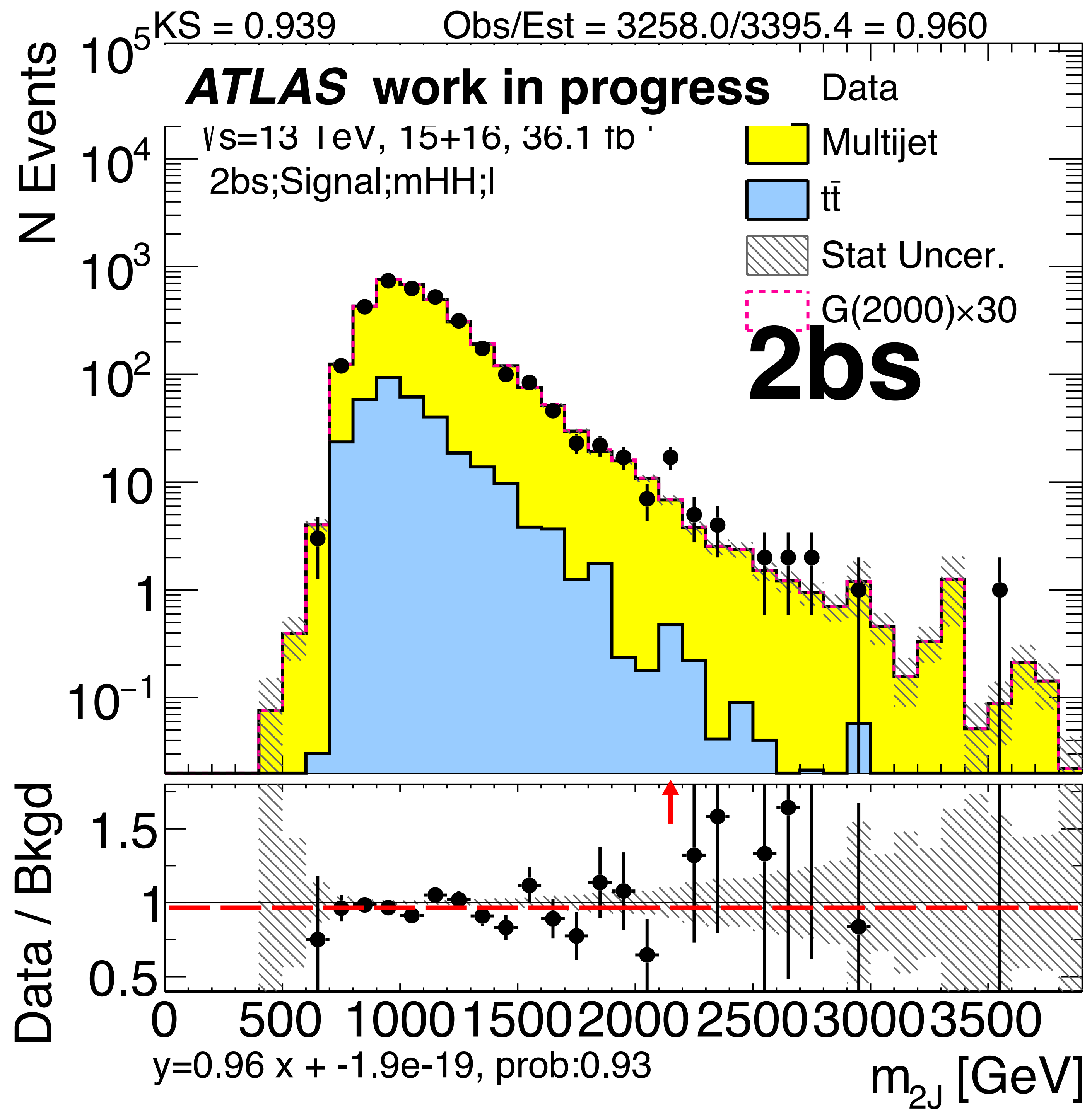


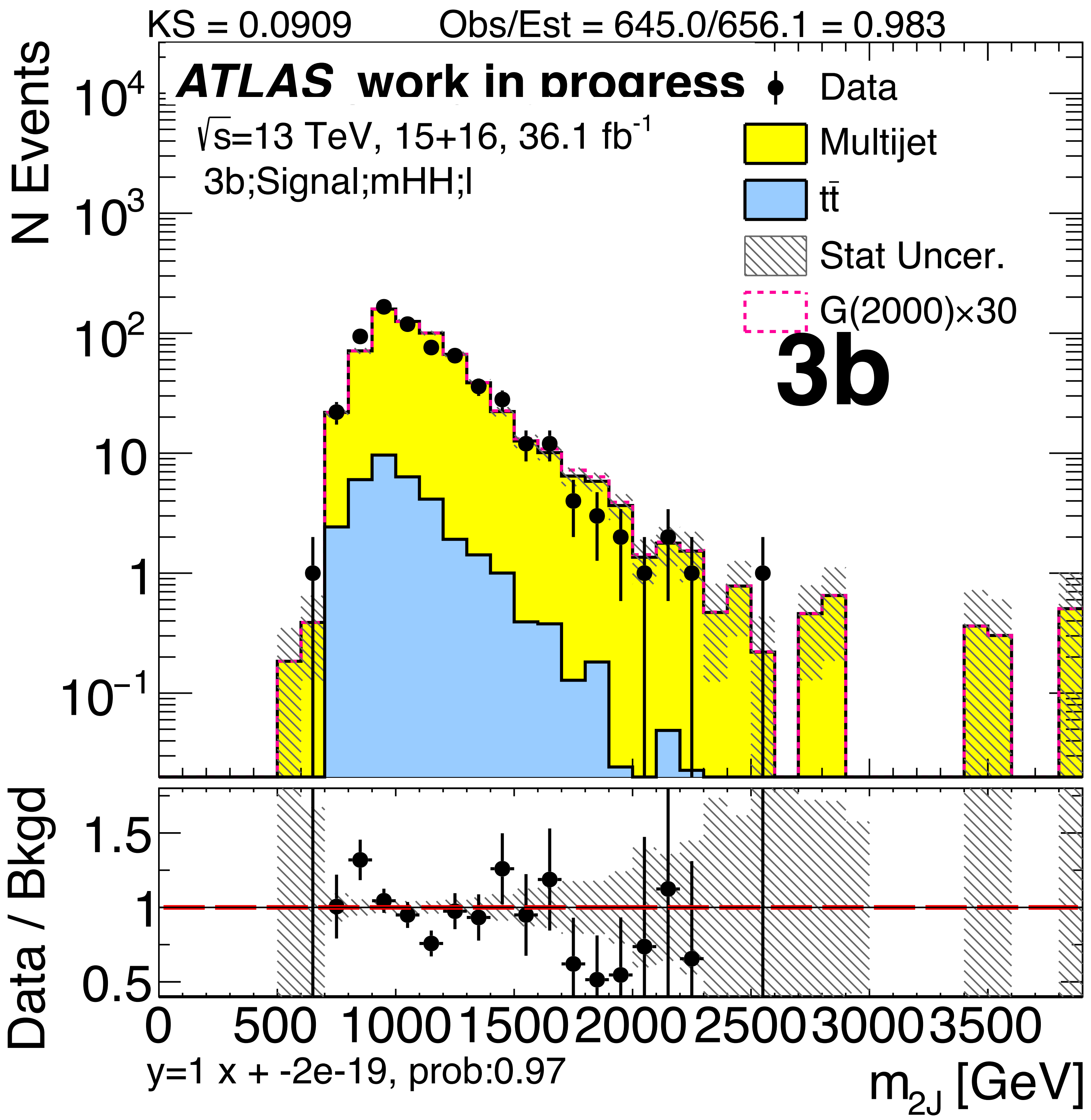


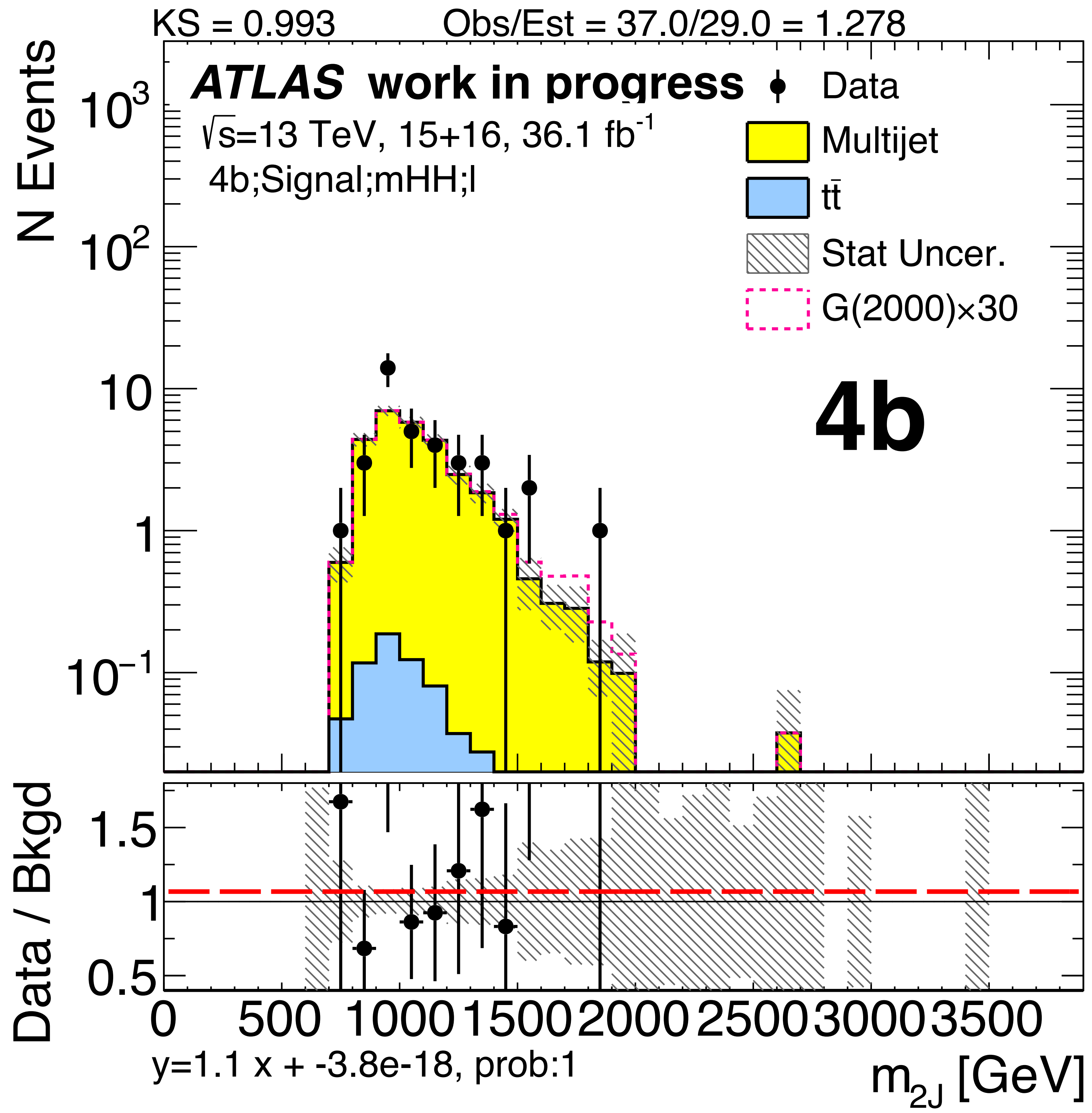
Low Mass Validation Region



- Extra low mass QCD enriched region is used for unblinding tests—looks fine!

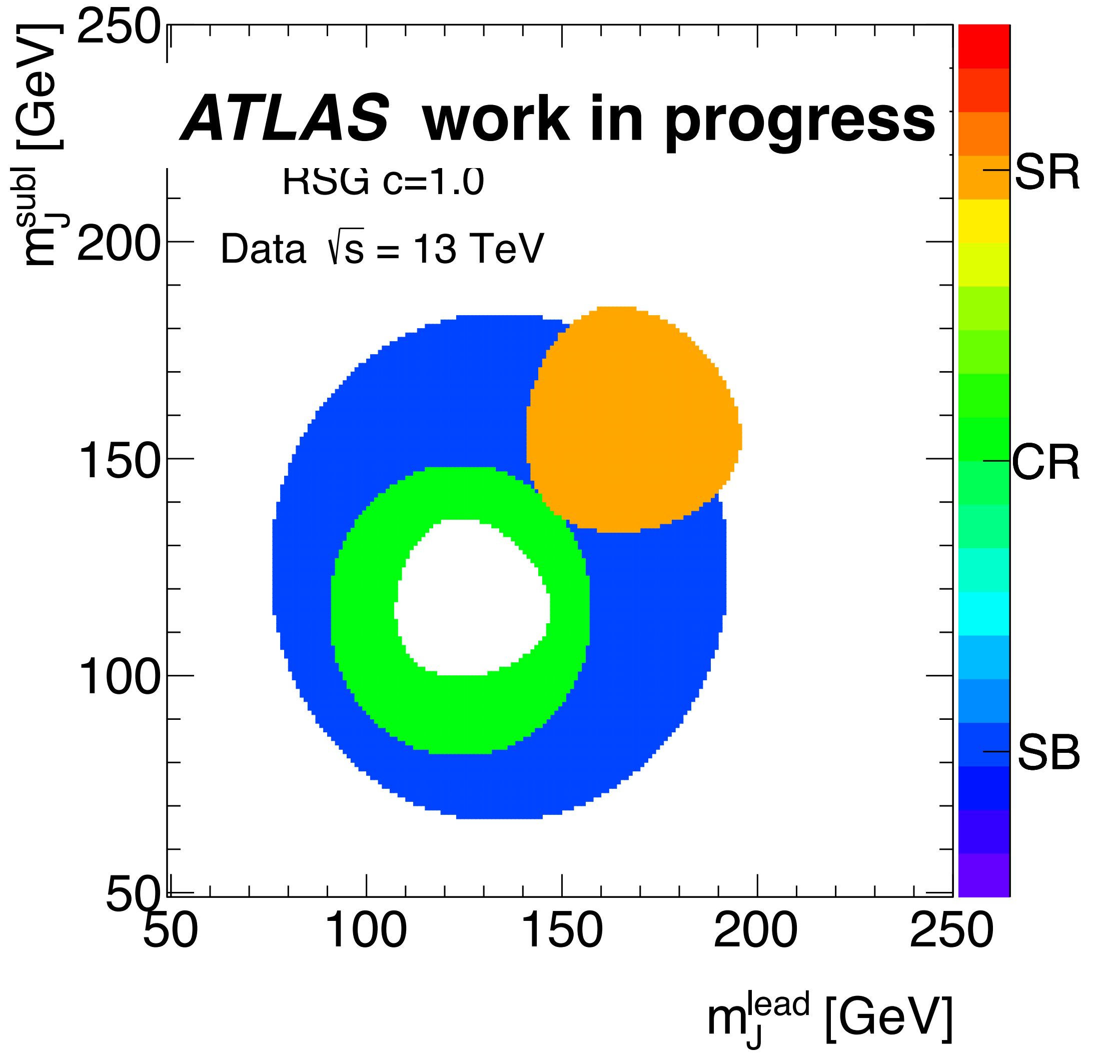


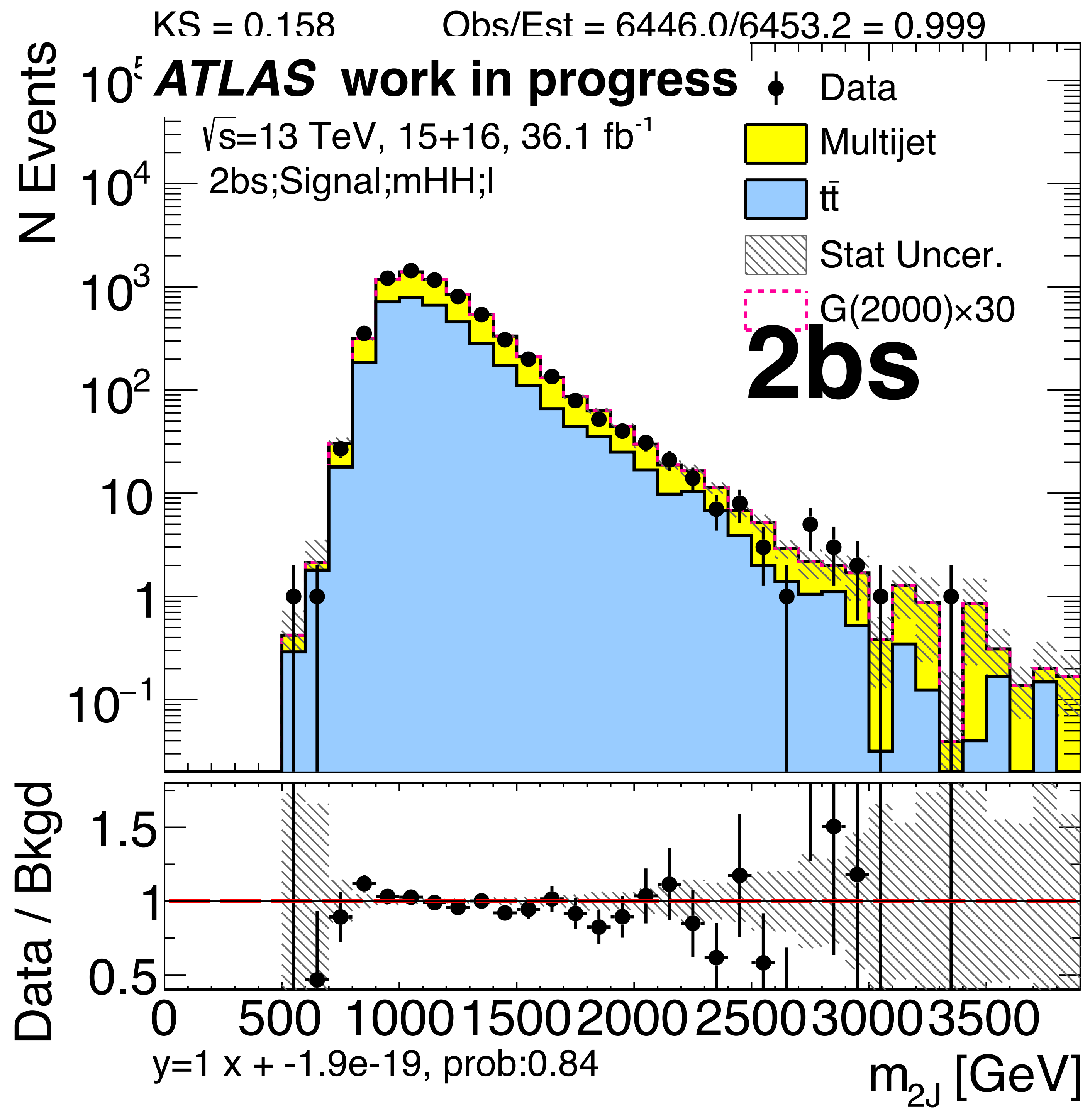


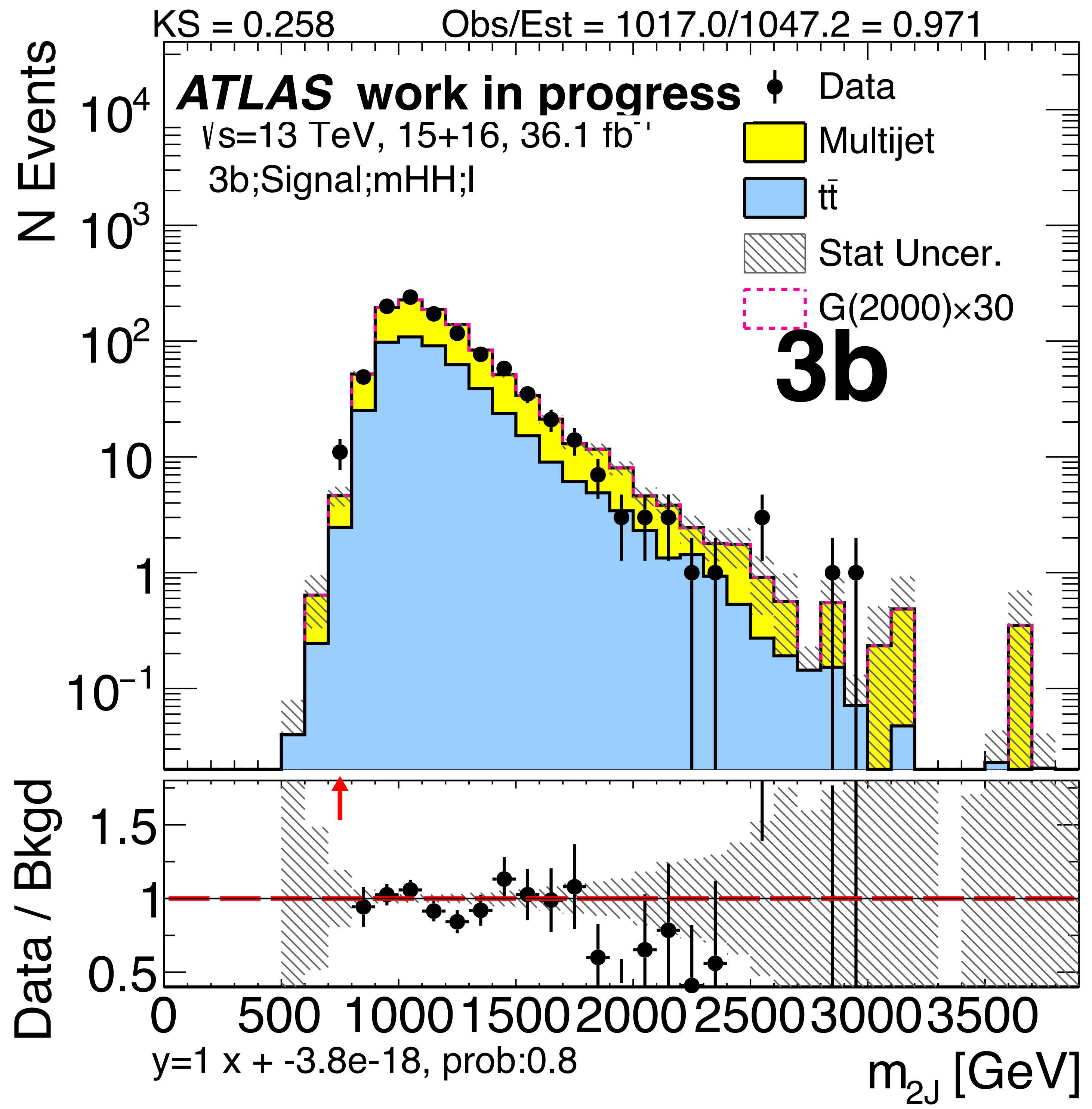


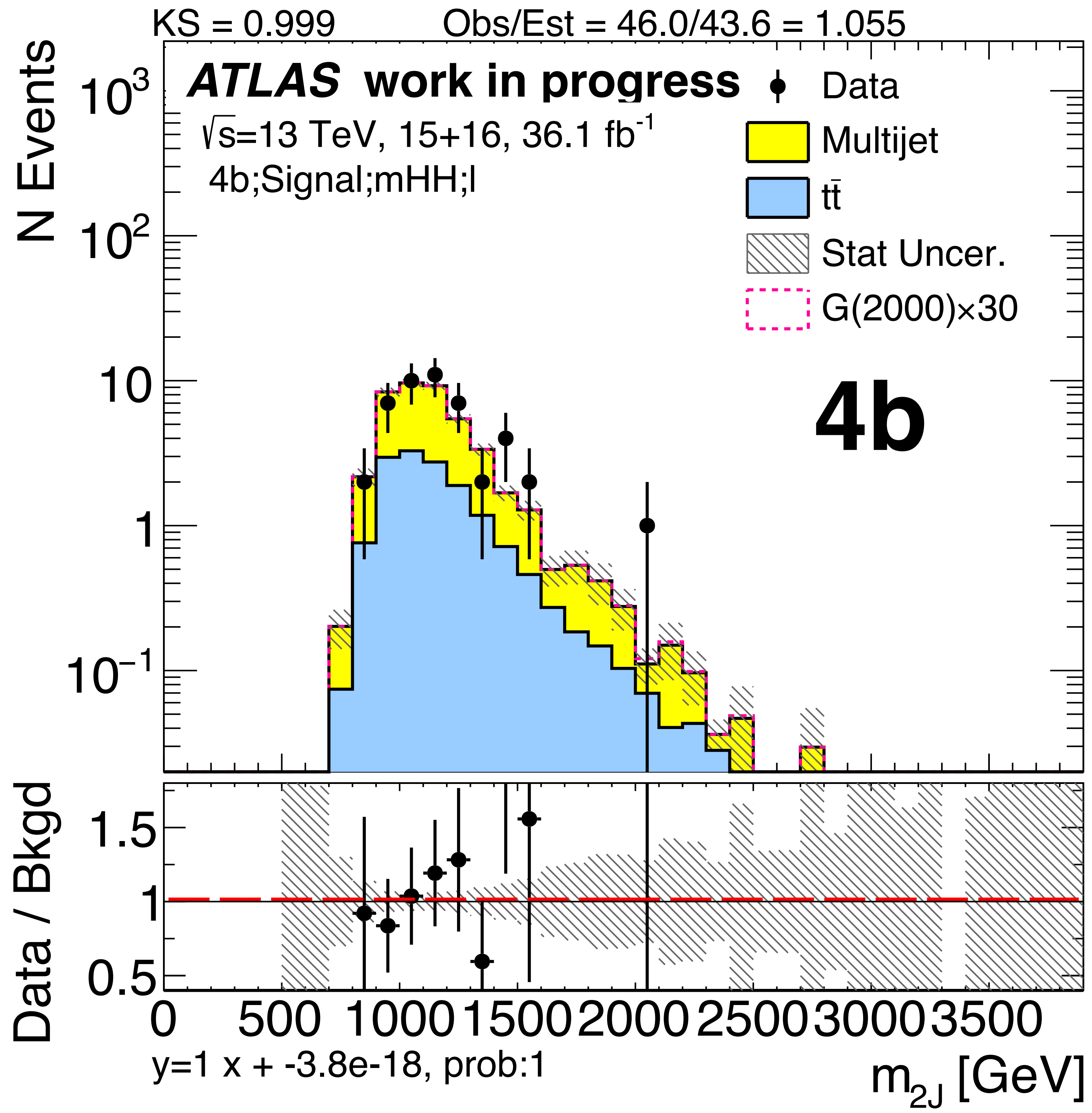
High Mass Validation Region

- Extra high mass ttbar enriched region is also used for unblinding tests—looks fine!





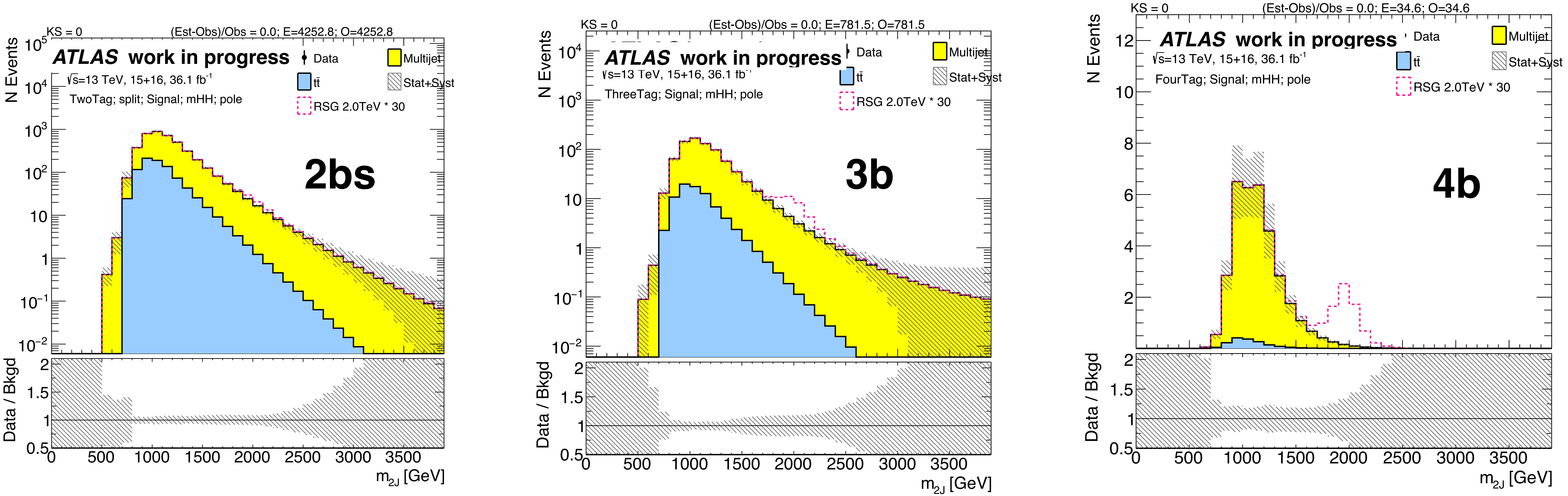




Signal Region: Smoothed

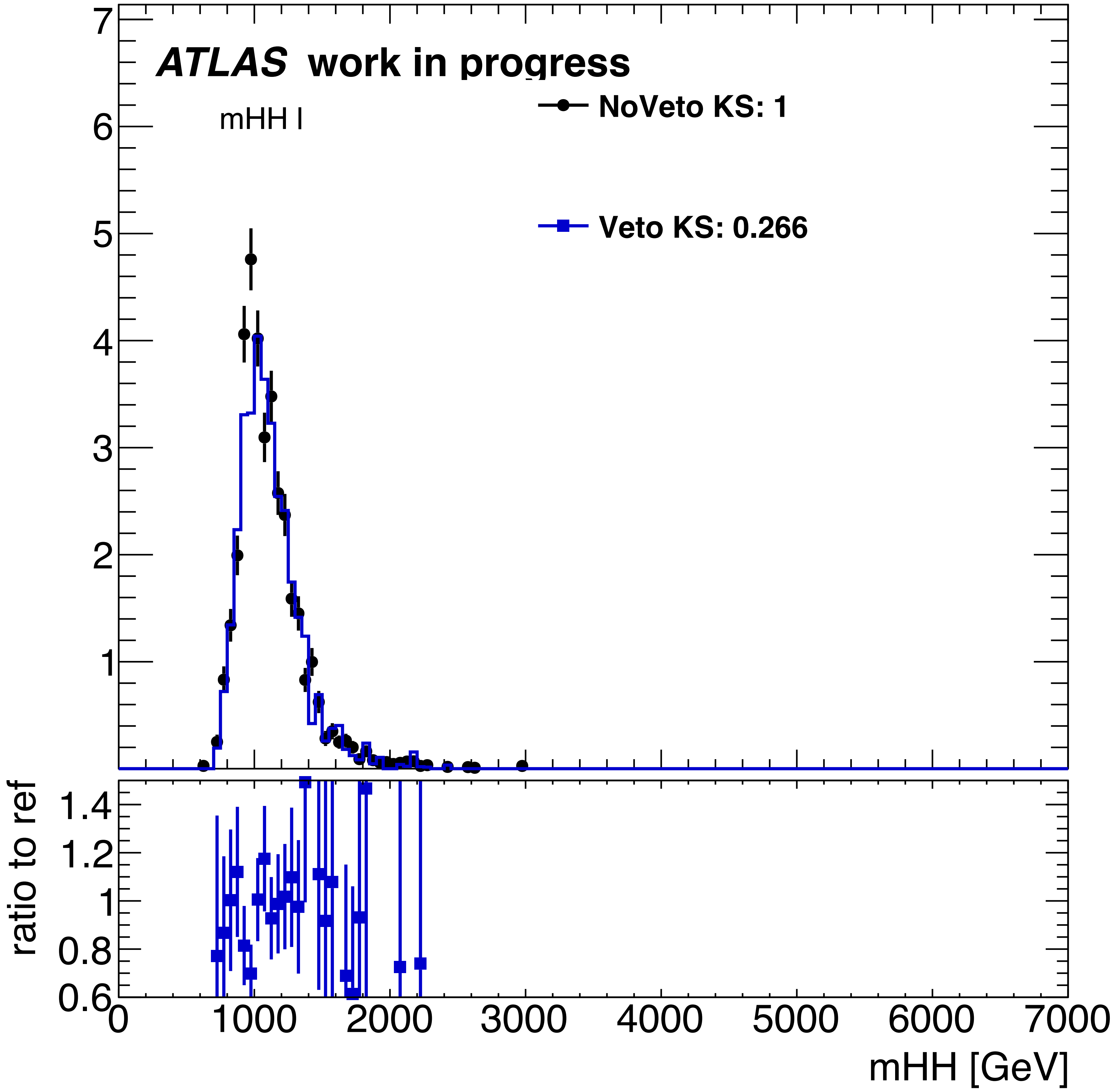
- Smoothing is necessary to compensate for high mass tail fluctuations
- Dijet8 function is used to smooth both QCD and ttbar;

$$y = \frac{a}{\frac{x}{\sqrt{s}}^2}\left(1 - \frac{x}{\sqrt{s}}\right)^{b - c\ \log\left(\frac{x}{\sqrt{s}}\right)}$$



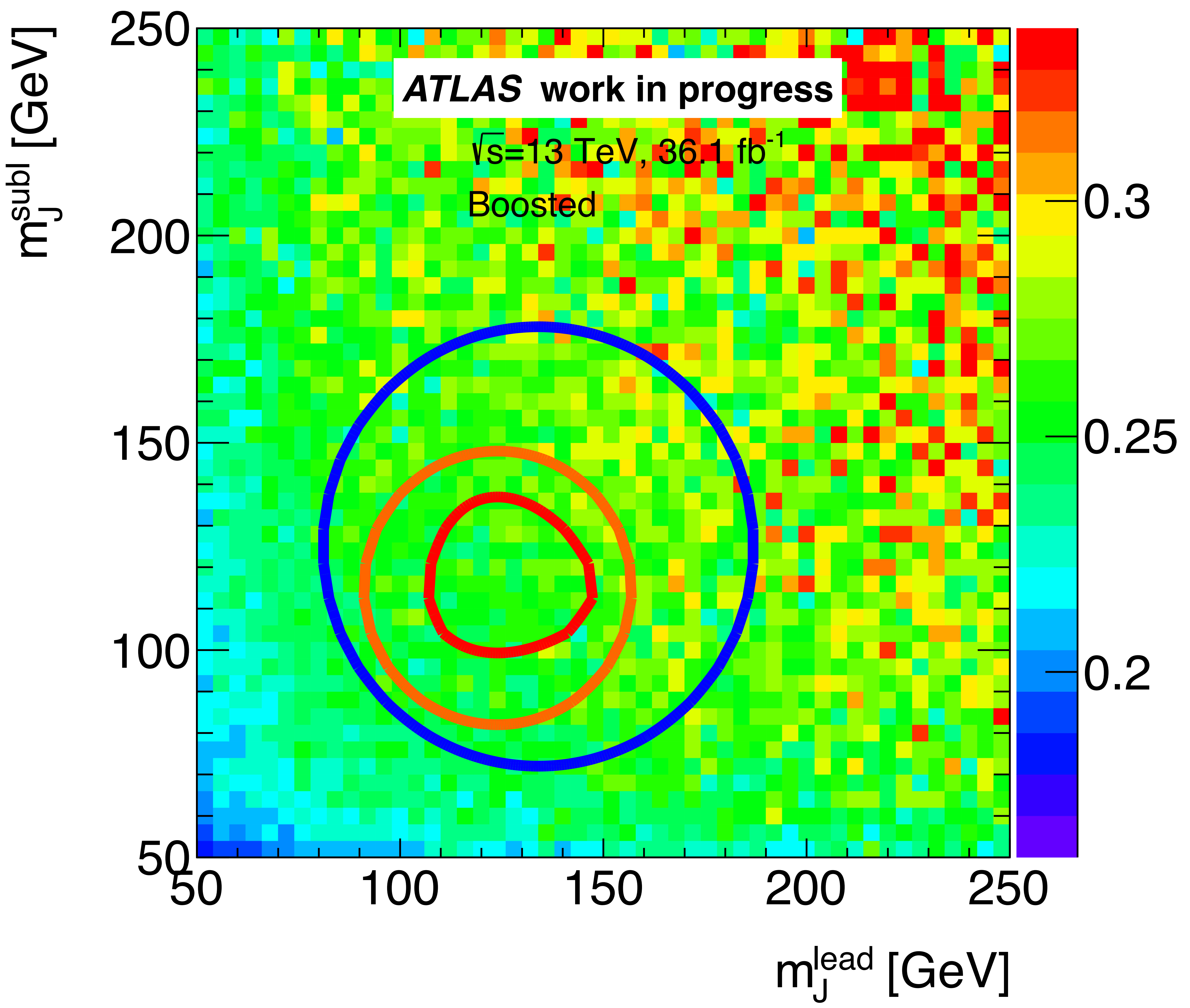
4b bkg prediction

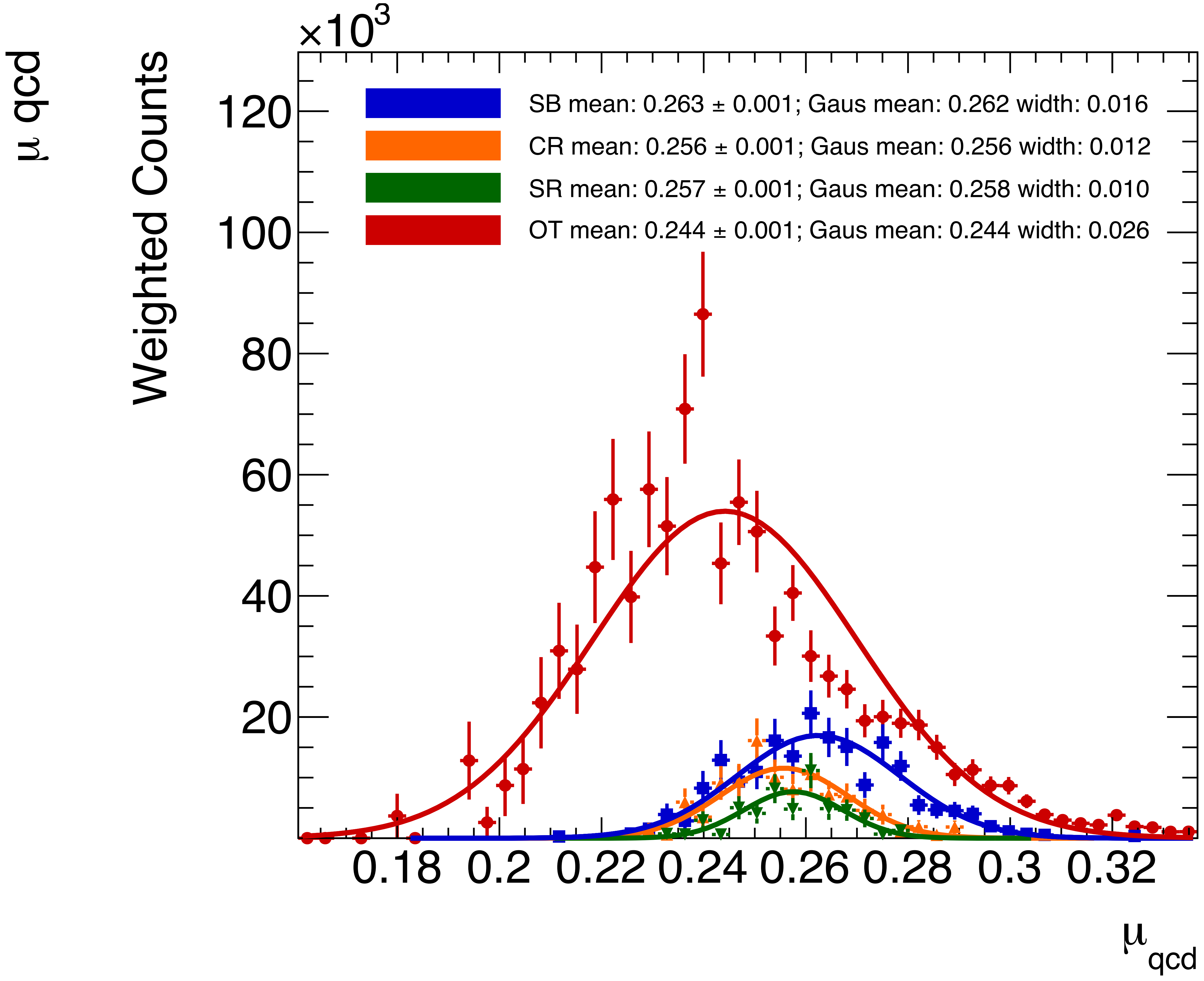
- Use (20%) 2b events to predict 4b distributions
- Resolved veto impacts boosted SR region distribution
- In 2b, also veto events that have 2b jets + 2 non-b jets that can pass the resolved signal region
- Number of events estimate changed from 36.46 to 34.62, turn-on shape changes a bit



OneTag Data / NoTag Data

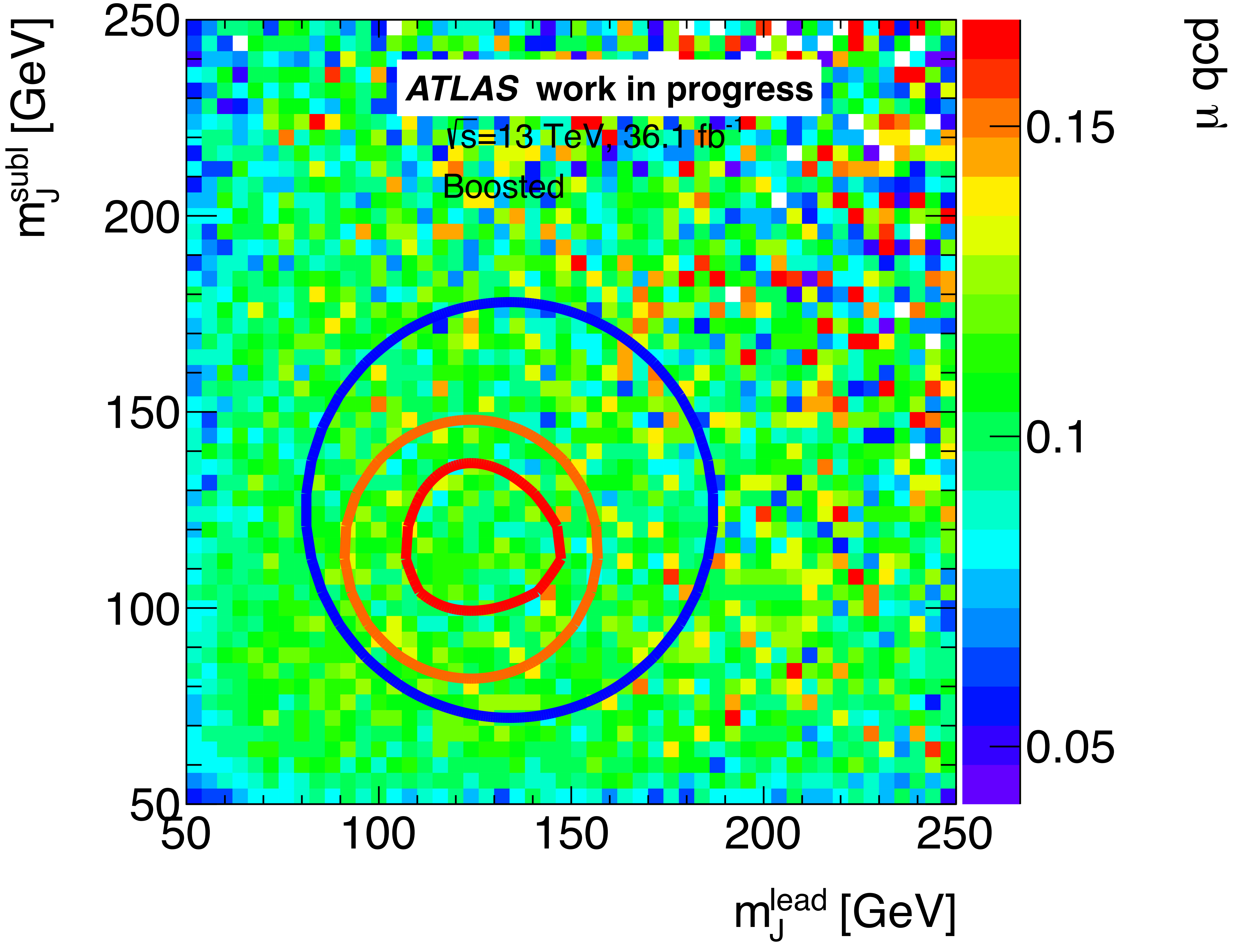
- Moving outside the current SB will cause a bias in muqcd

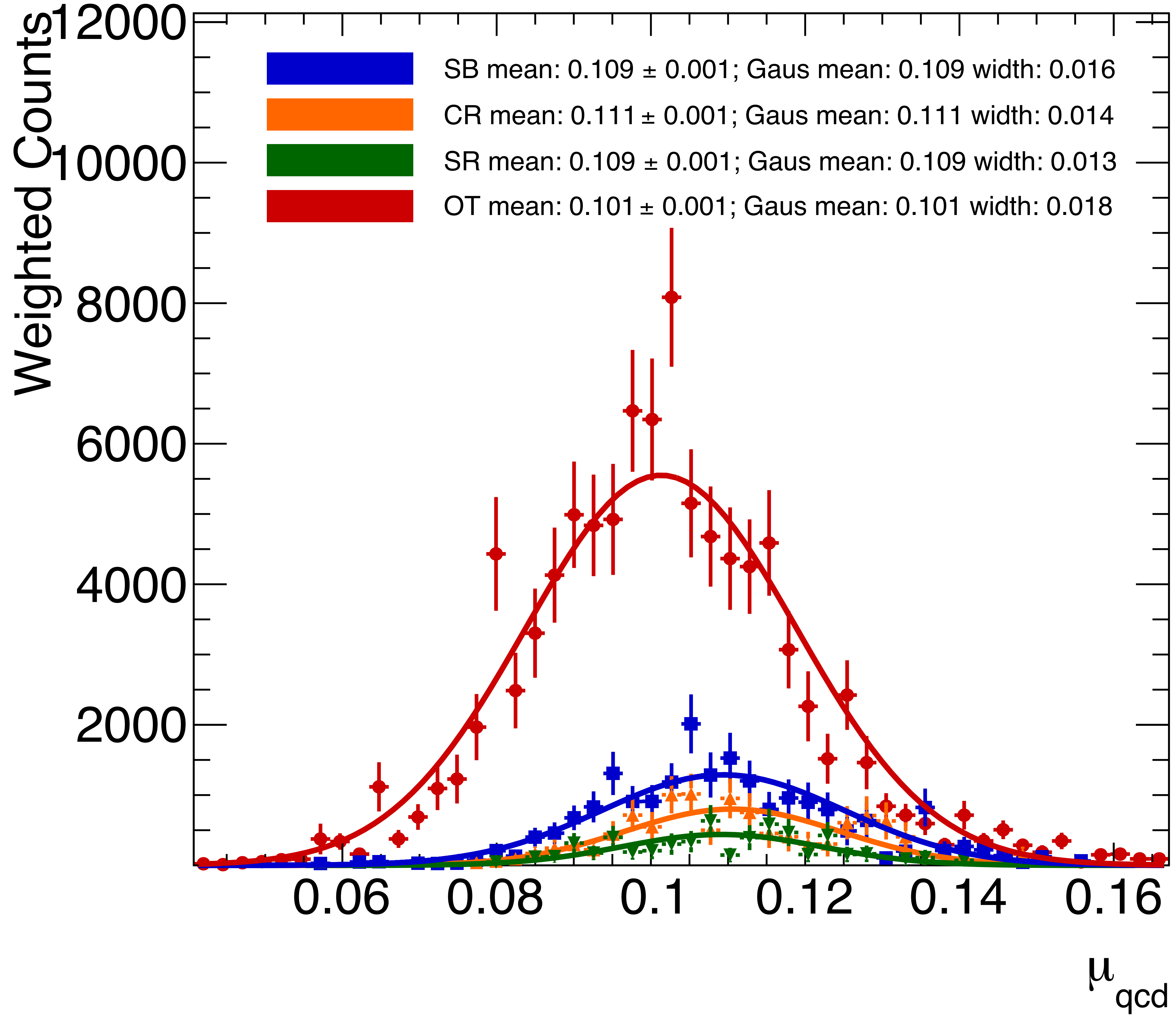




TwoTag Data / OneTag Data

- Similar as OneTag/NoTag ratio





Sideband Region Size

- Scan sideband parameters and find the place where stat uncertainty from fit around one half of the stat uncertainty

- Sideband center and CR size are also justified in this method

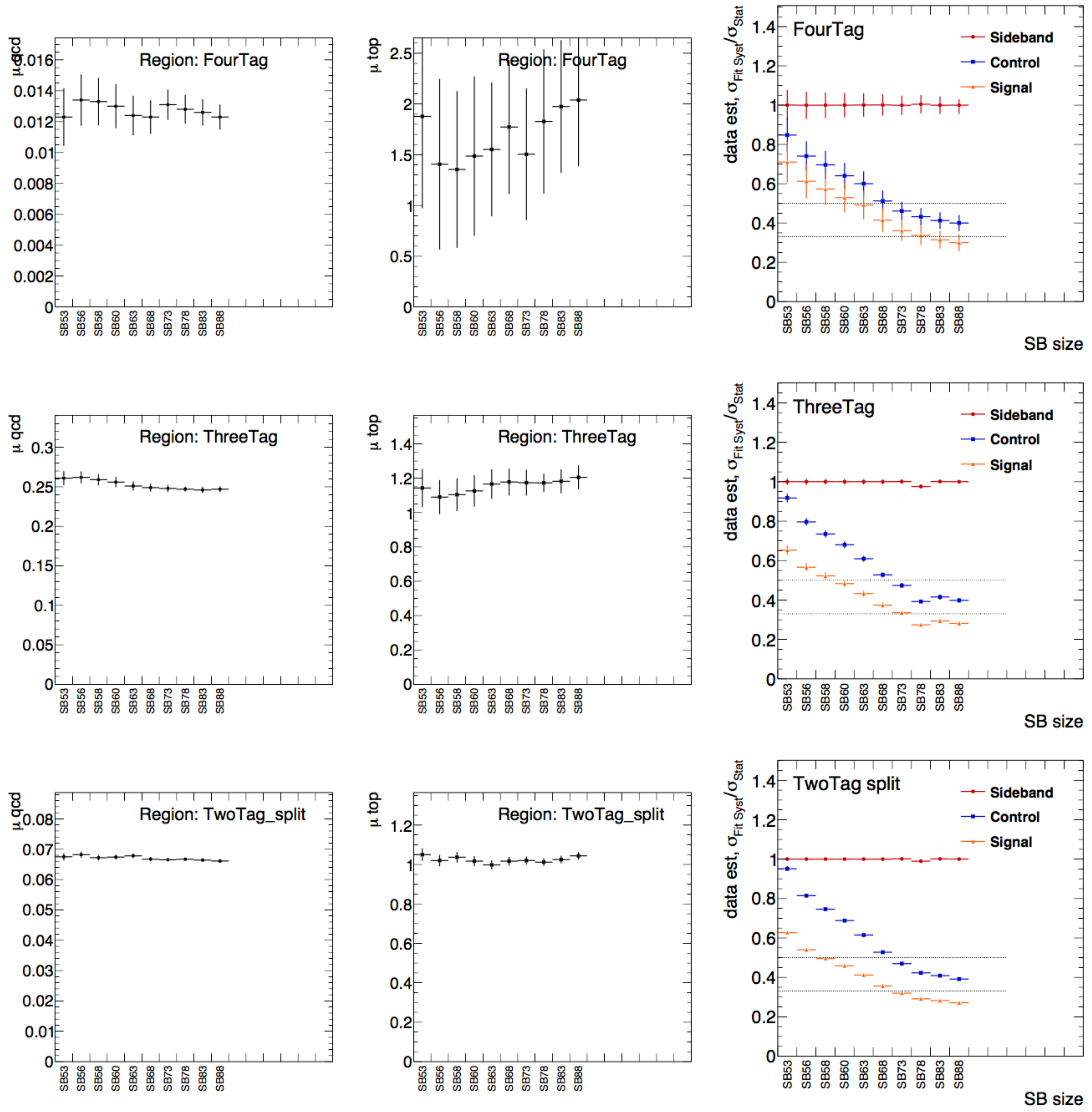


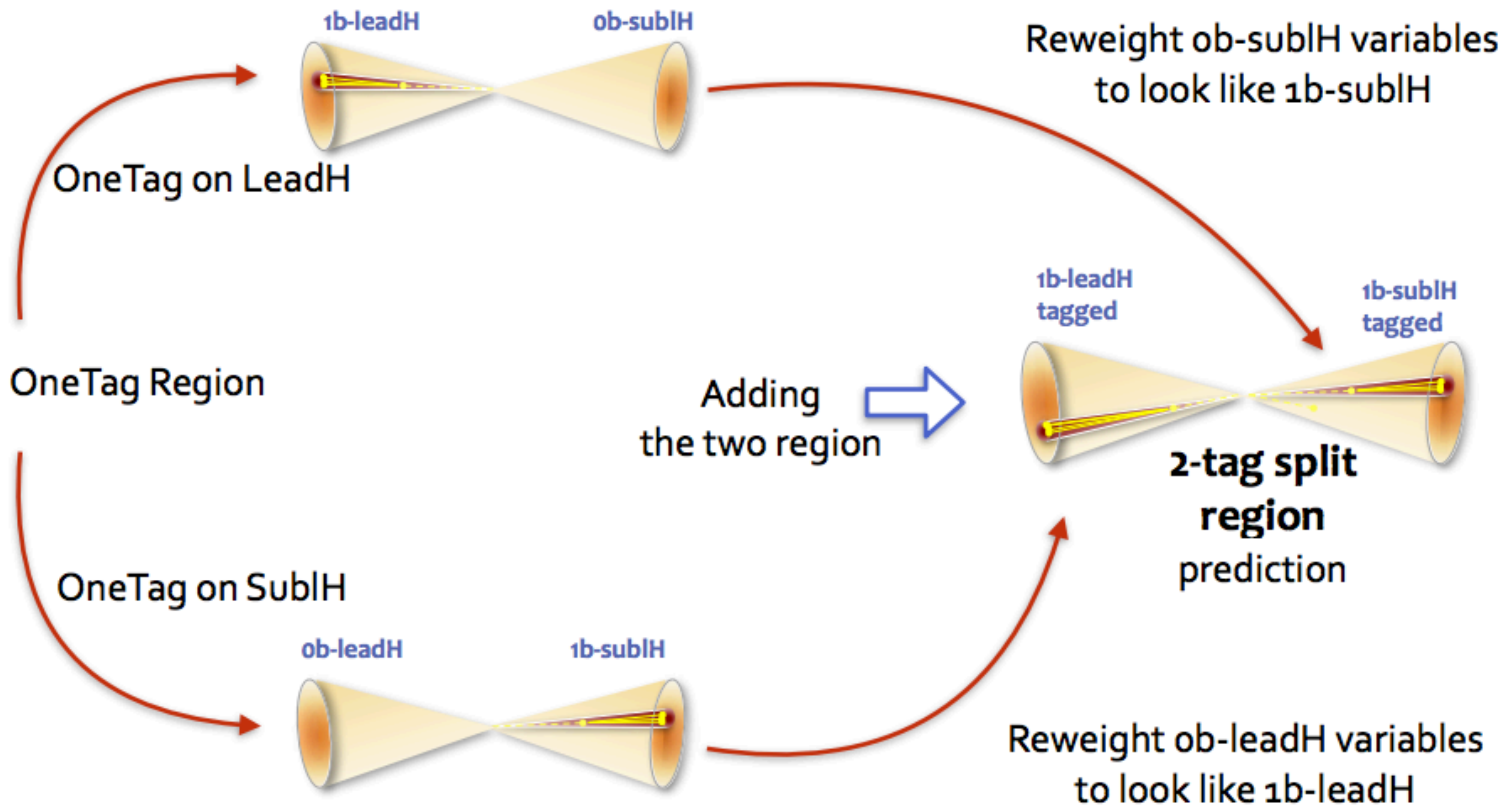
Figure 130: Fit parameters for μ_{qcd} (left), $\alpha_{t\bar{t}}$ (middle), and ratio of fit uncertainty and stat uncertainty as a functioin of different Sideband values (right) , for $4b$ (top) $3b$ (middle) and $2bs$ (bottom). The x-axis indicates different values of SB R_{hh}^{high} cuts.

Current Boosted Reweighting

Improved Reweighting

- Reweighting accounts mainly for:
  - different QCD processes
  - b-tagging efficiency dependence on trkjet pT
- Recently add in a lot of developments, see intro; update;
- Main idea is b-tagging sculpting has similar effects on b-tagged Hcand, in lower b-tagged and higher b-tagged regions

- For example, consider 2bs modeling:



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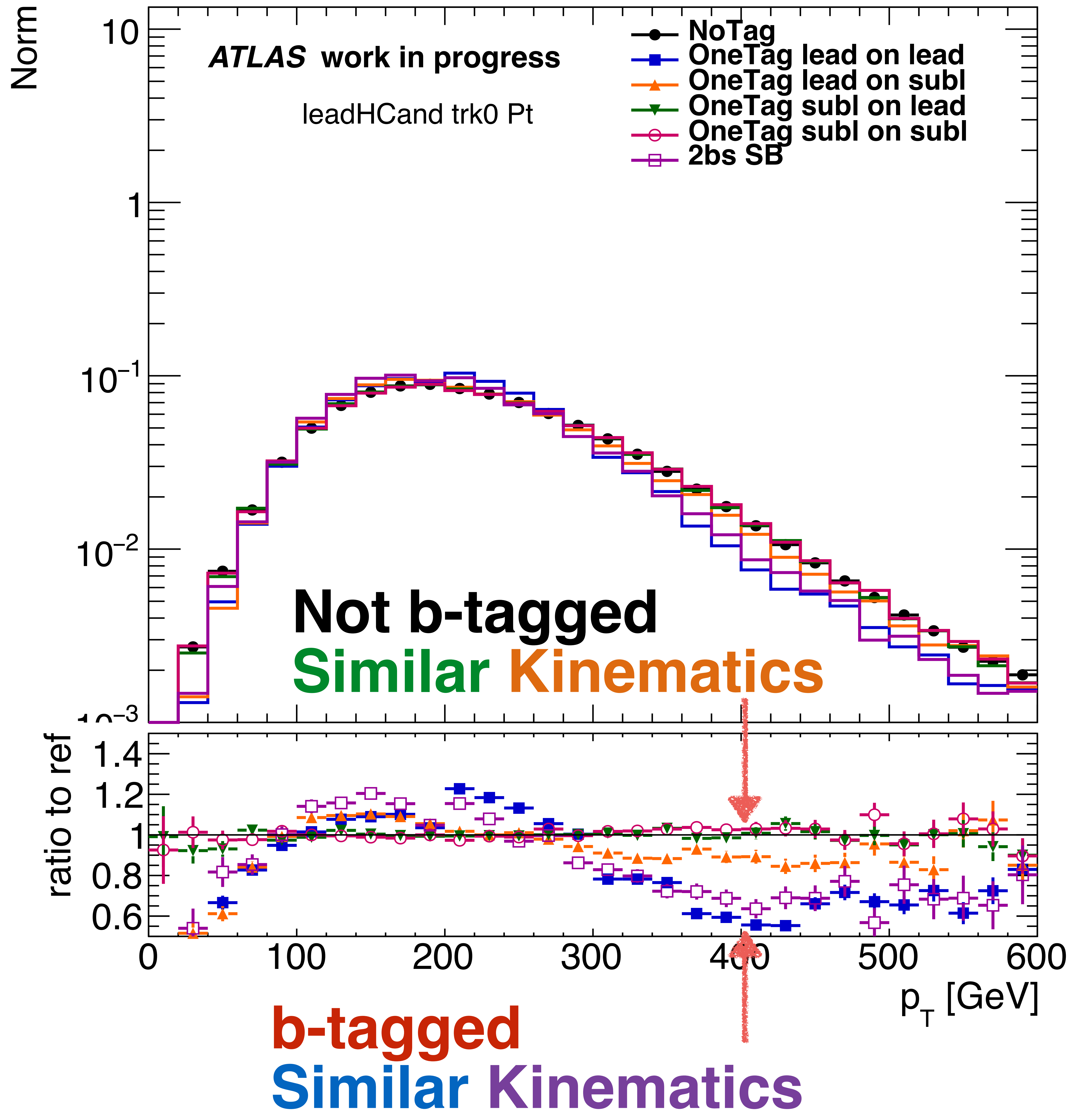
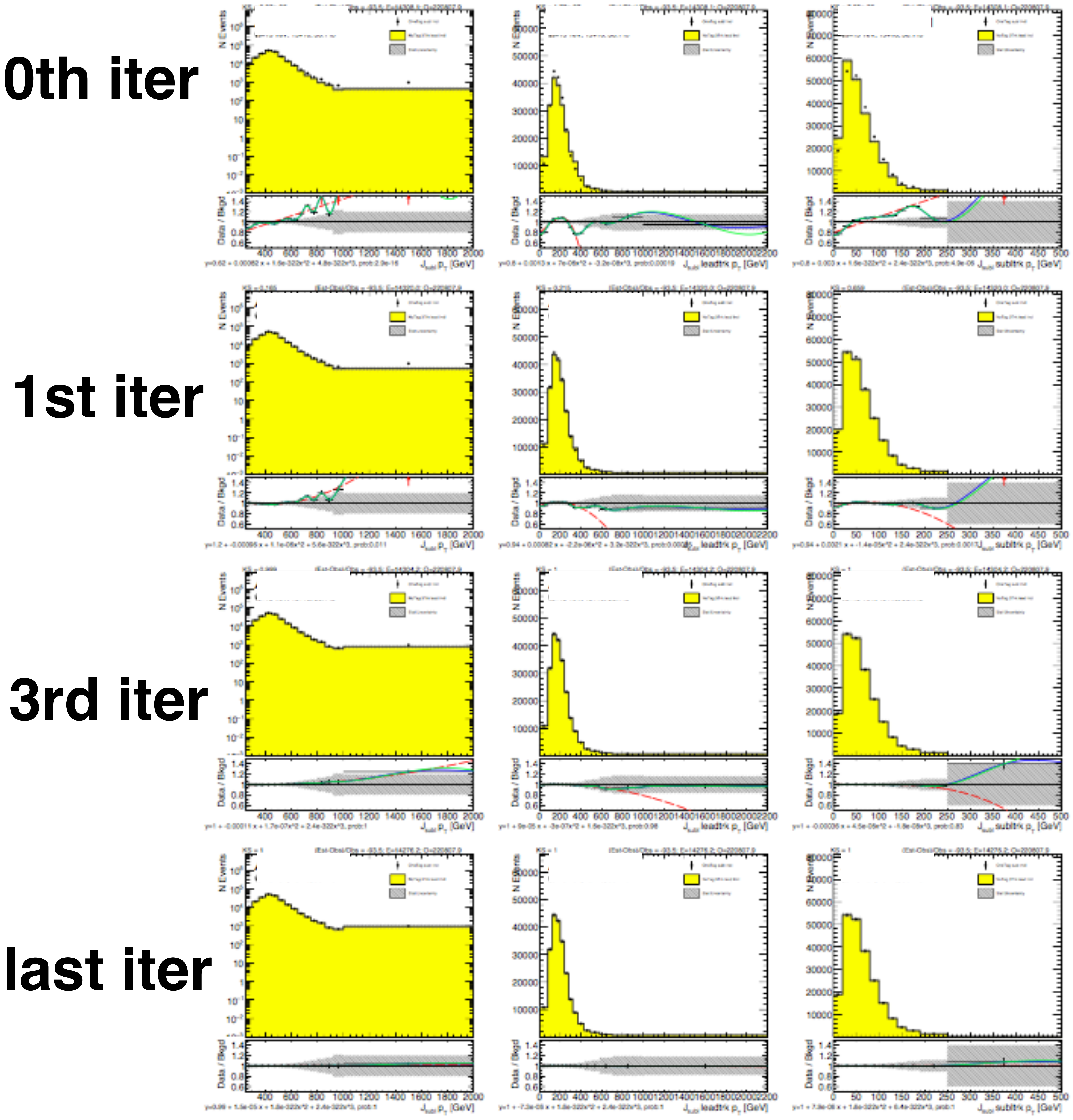


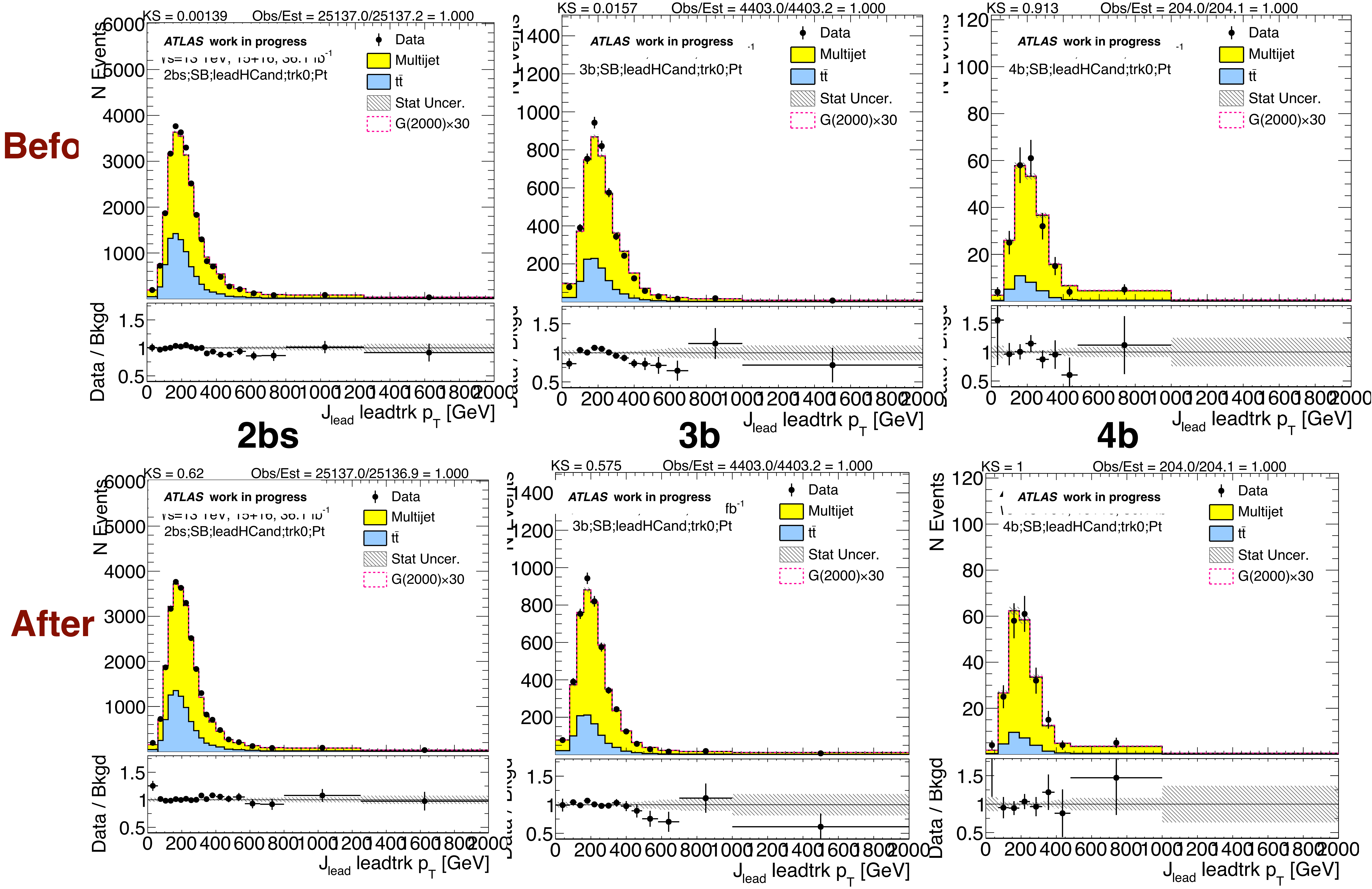
AddTag Reweighting

- Reweight the non-btagged Hcand pT and trackjets pT to be like a b-tagged Hcand pT and trackjets pT
  - 2bs: 1b leadTagged reweight to 1b sublTagged, vice versa
  - 3b: 2b leadTagged reweight to 1b sublTagged, vice versa
  - 4b: 2b leadTagged reweight to 2b sublTagged, vice versa
- Reweight using a spline function, inclusively and iteratively (ten rounds) on lower b-tagged data



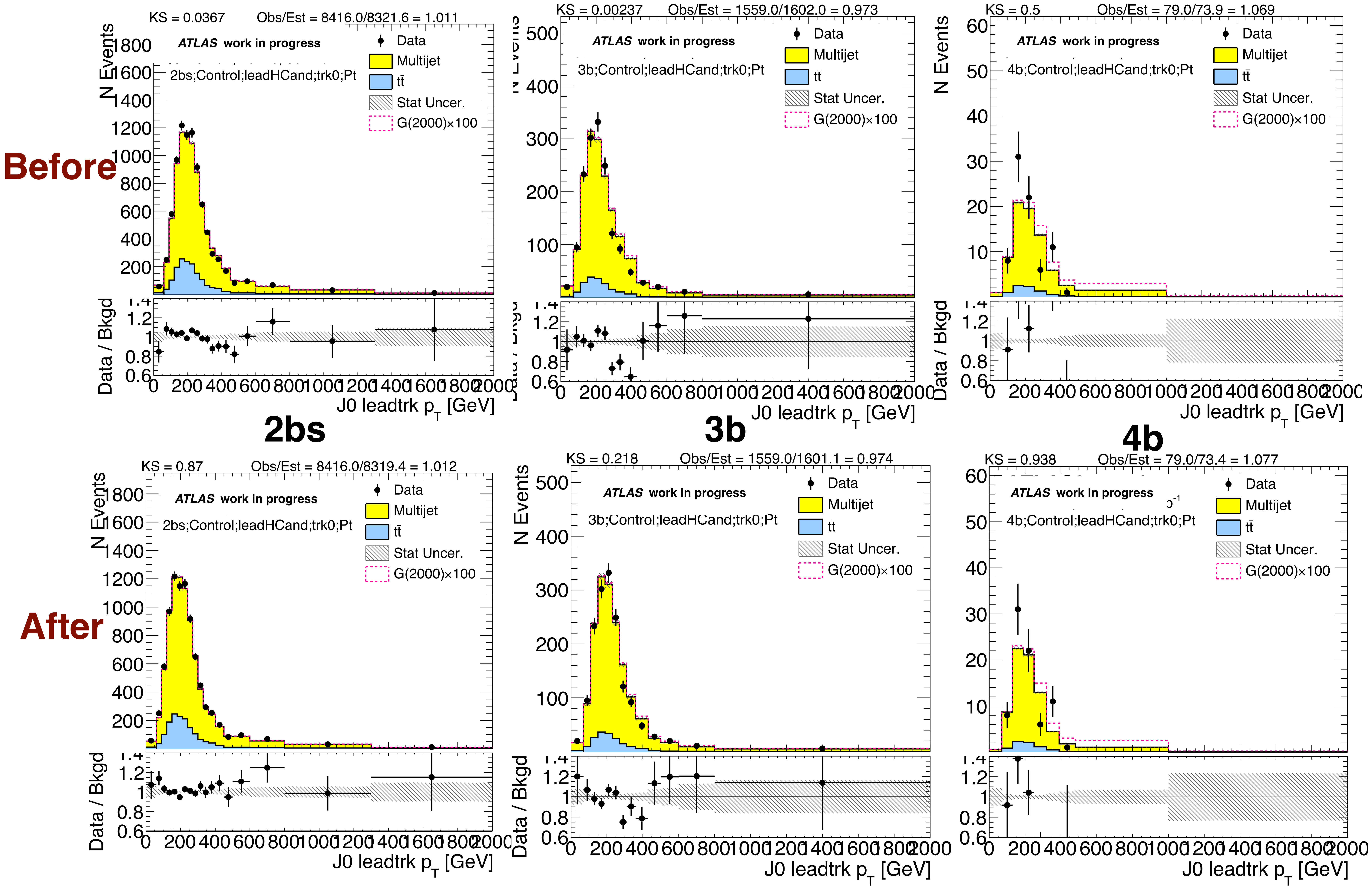
AddTag on background estimation

- Reweight the non-b-tagged Hcand to look like a 1b/2b tagged Hcand
    - Direct shape estimation—can use SB for checks
    - More freedom in modeling, better intuition
    - More confident in predictions in CR/SR



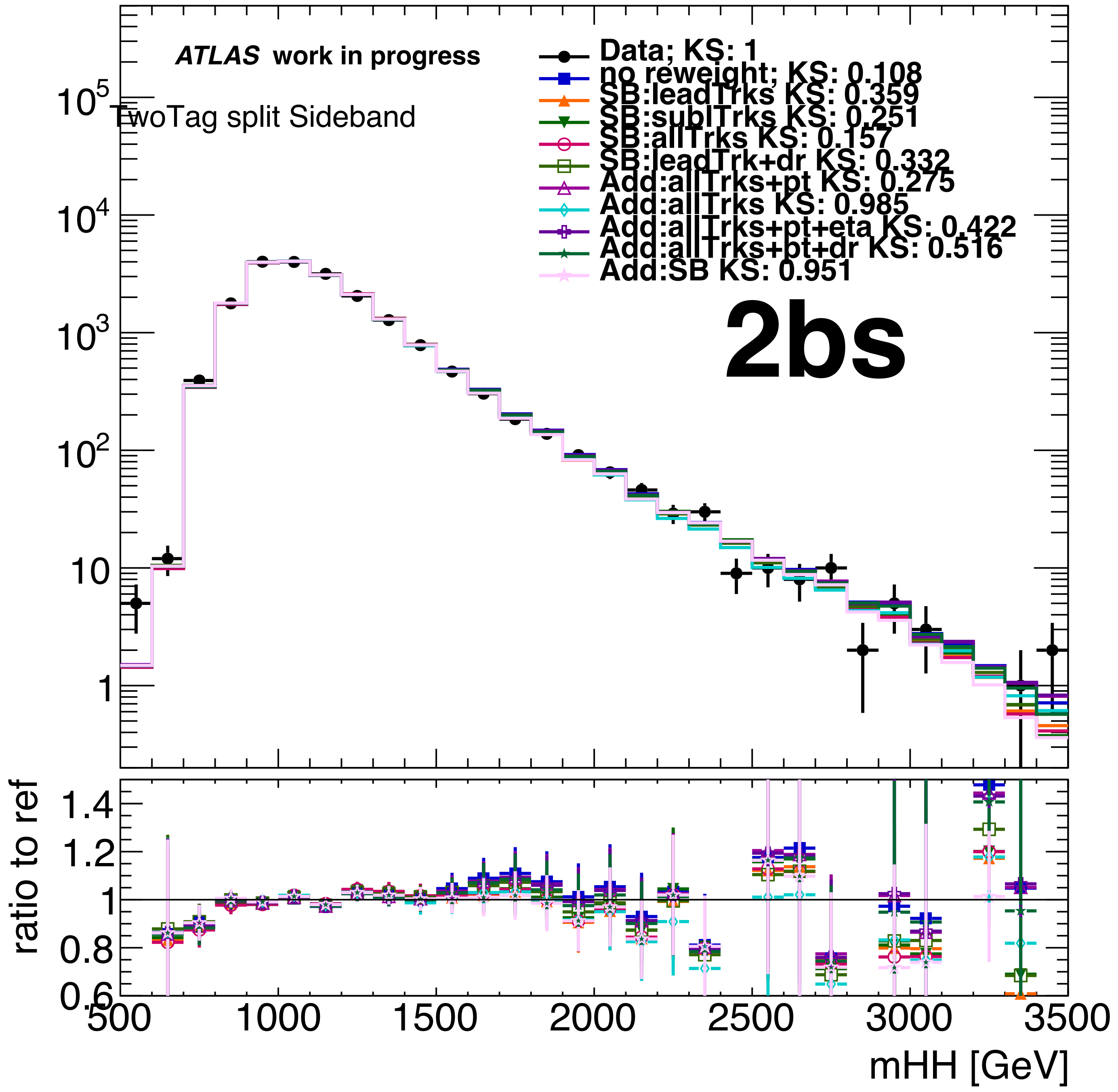
AddTag on Trkjet pT—CR

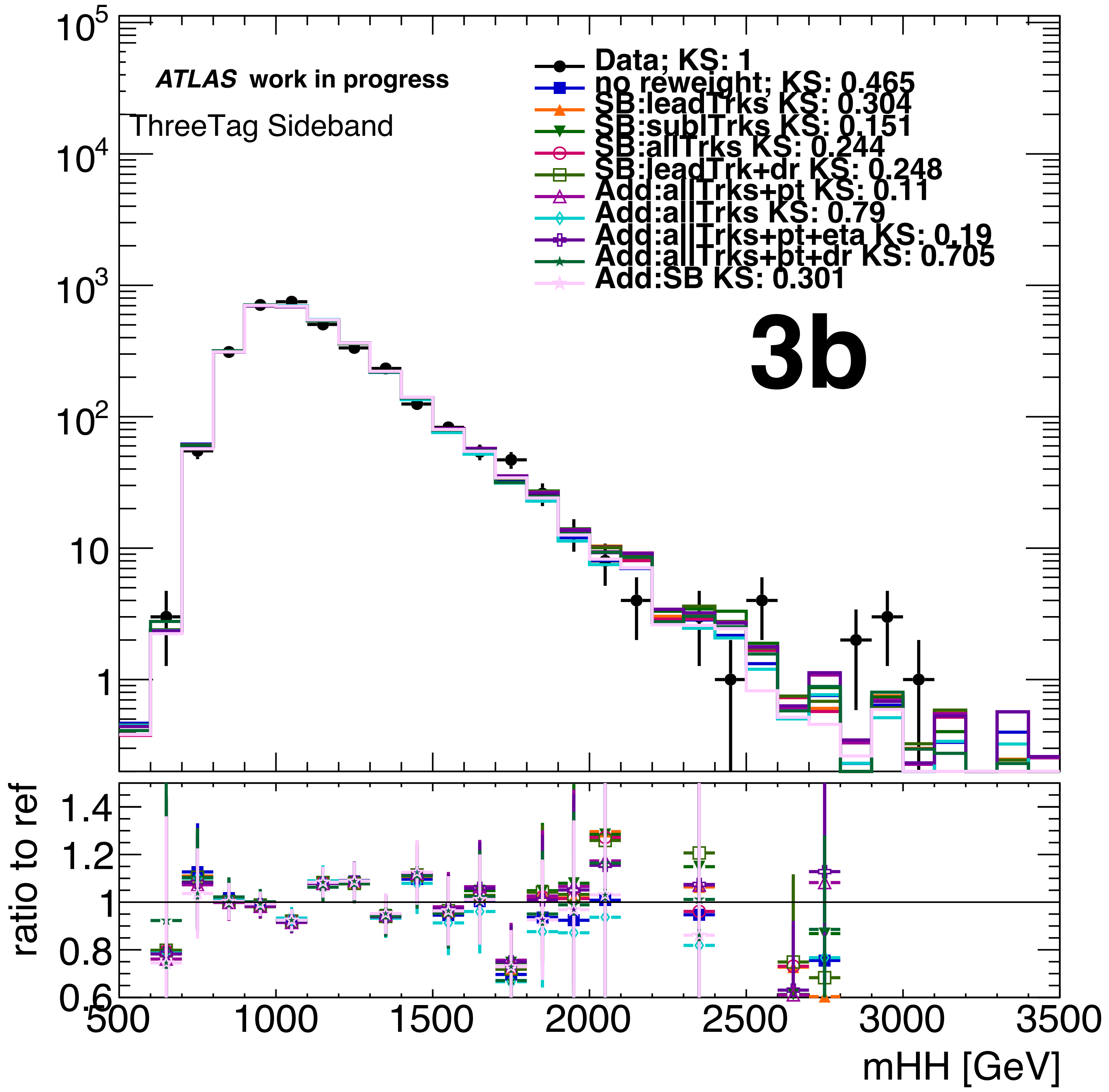
- Much better predictions compare to not reweighting

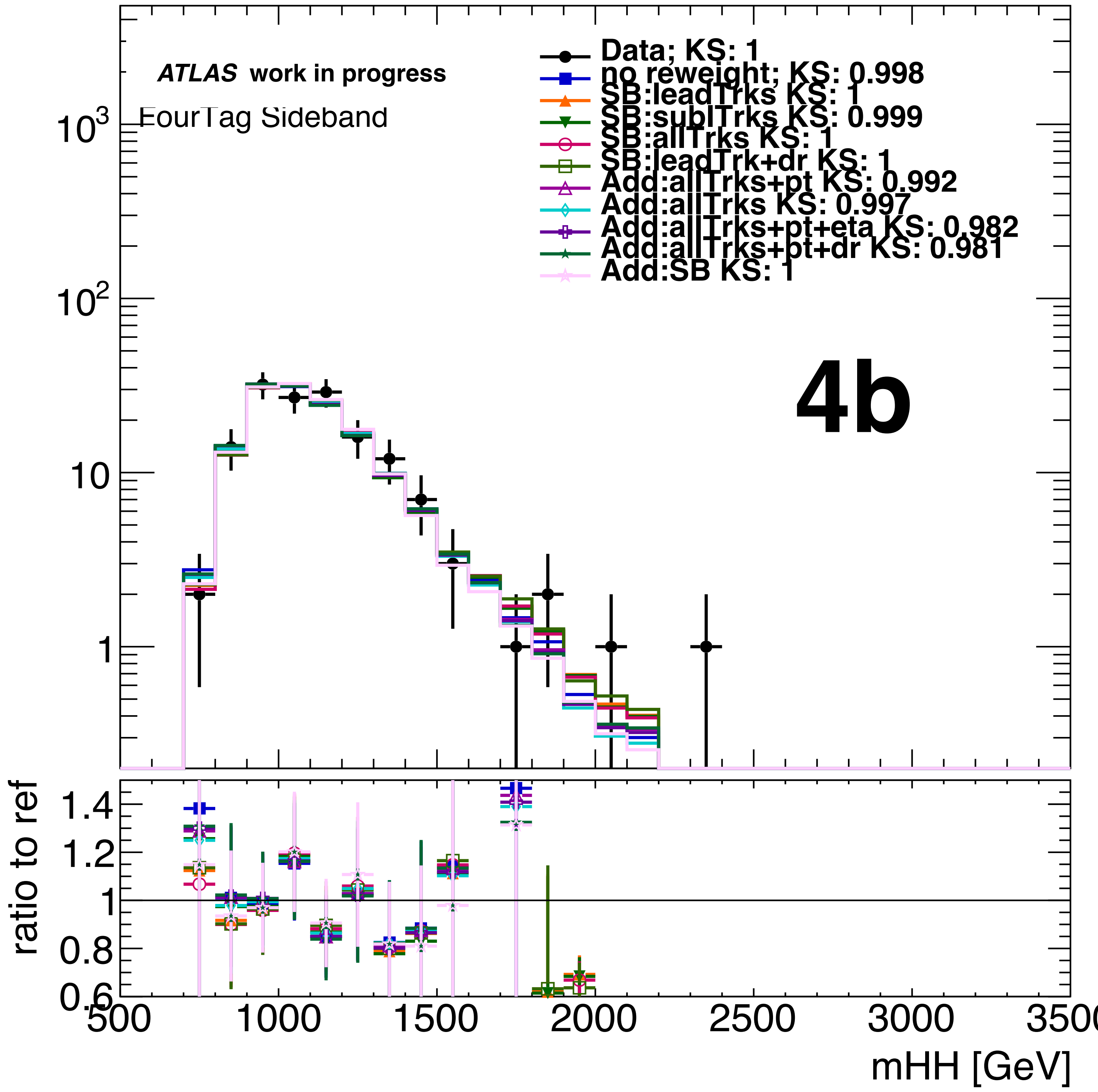


Sideband Region: Boosted

- **Nine different** reweighting methods' mHH shape prediction comparison with the nominal method
- Gives similar results in the distributions

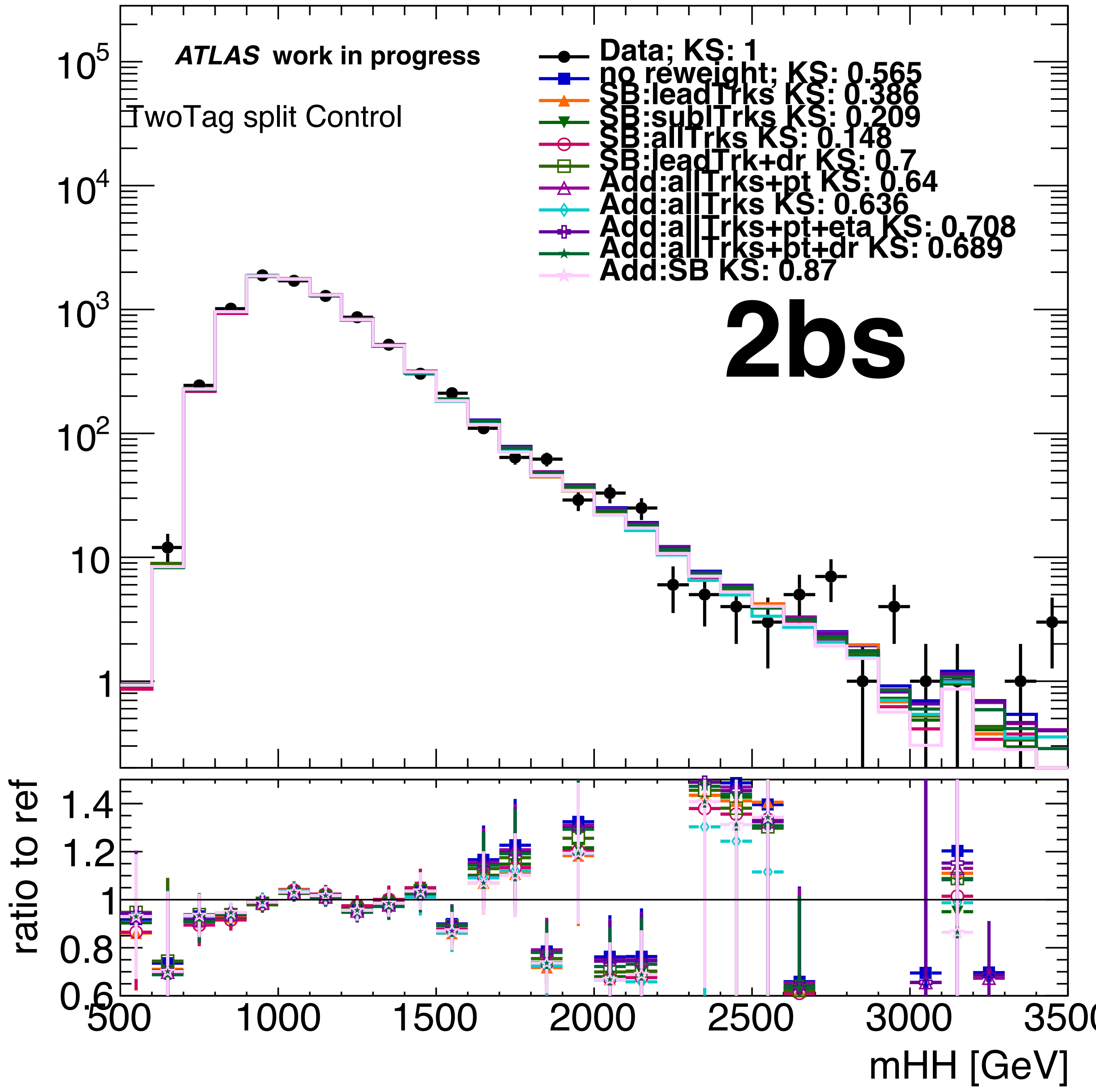


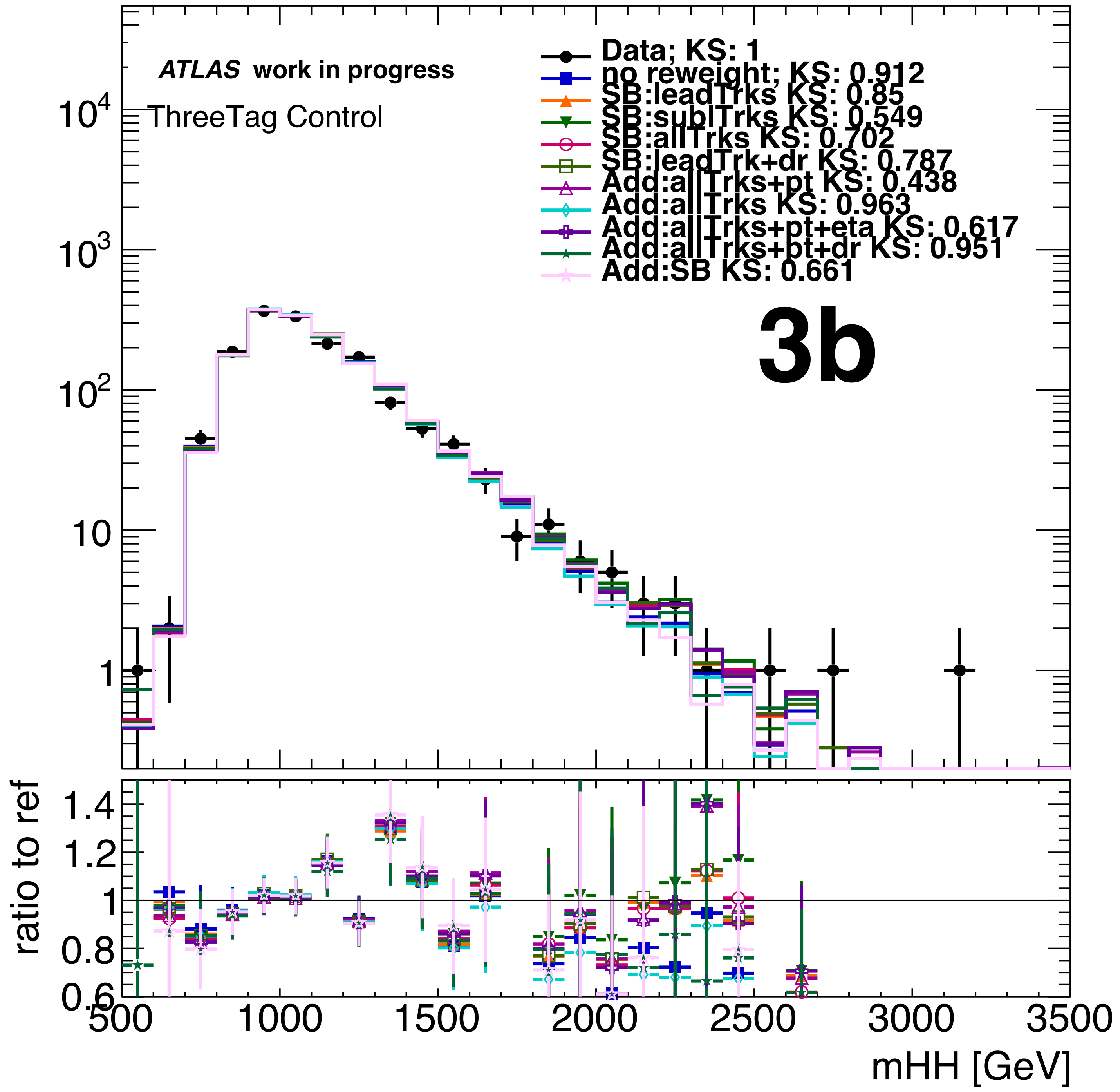


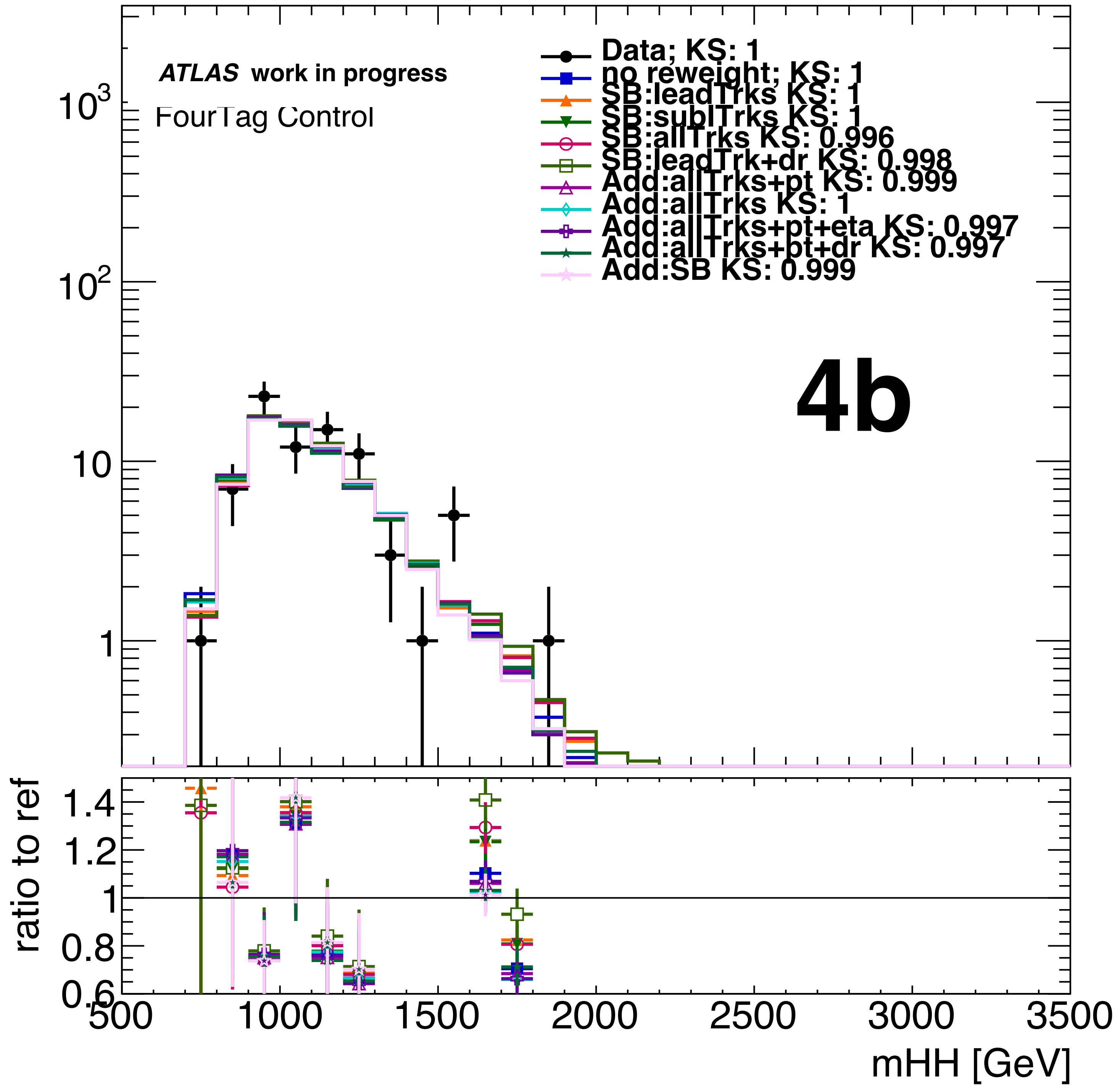


Control Region: Boosted

- **Nine different** reweighting methods' mHH shape prediction comparison with the nominal method
- Gives similar results in the distributions

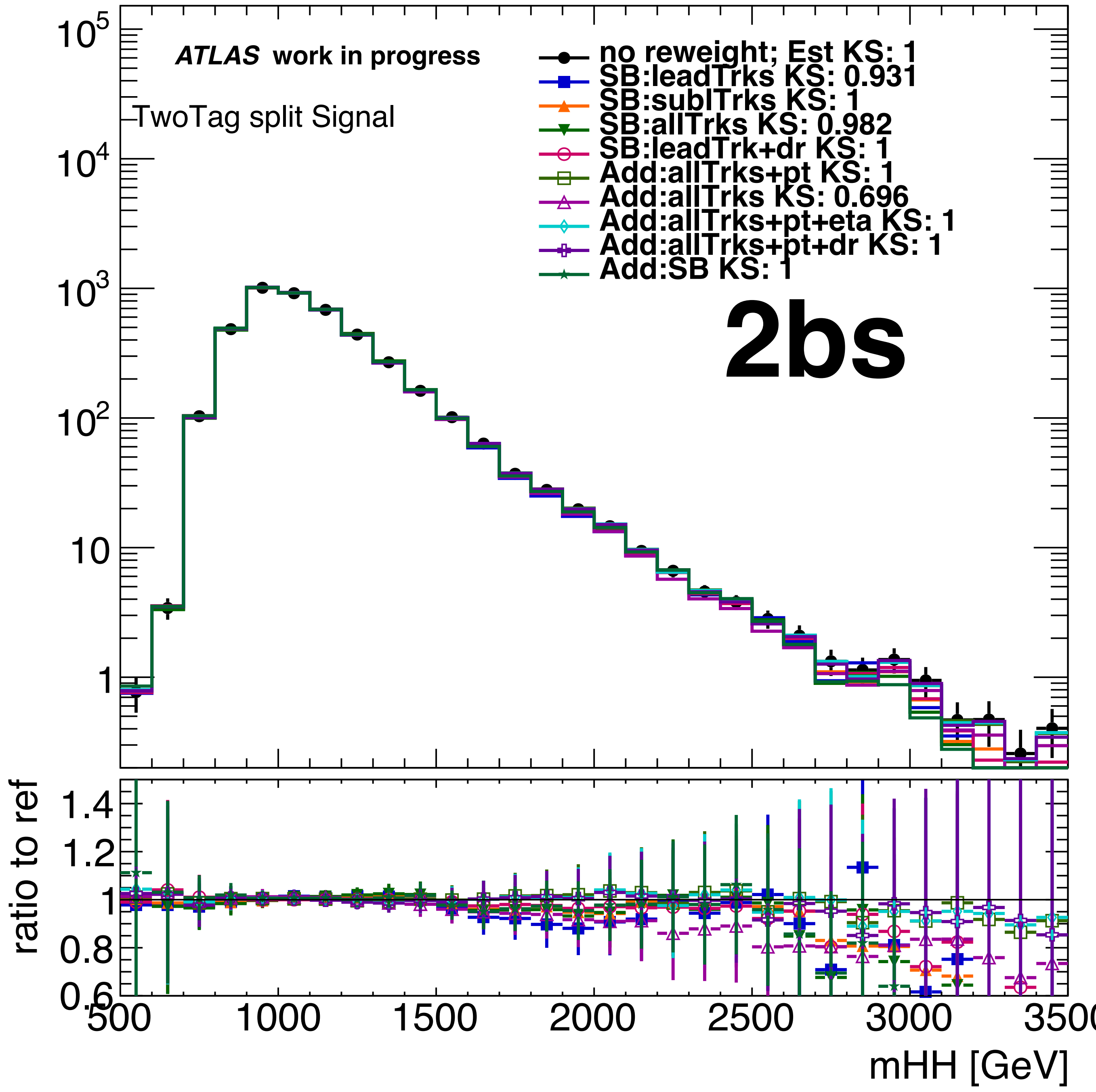


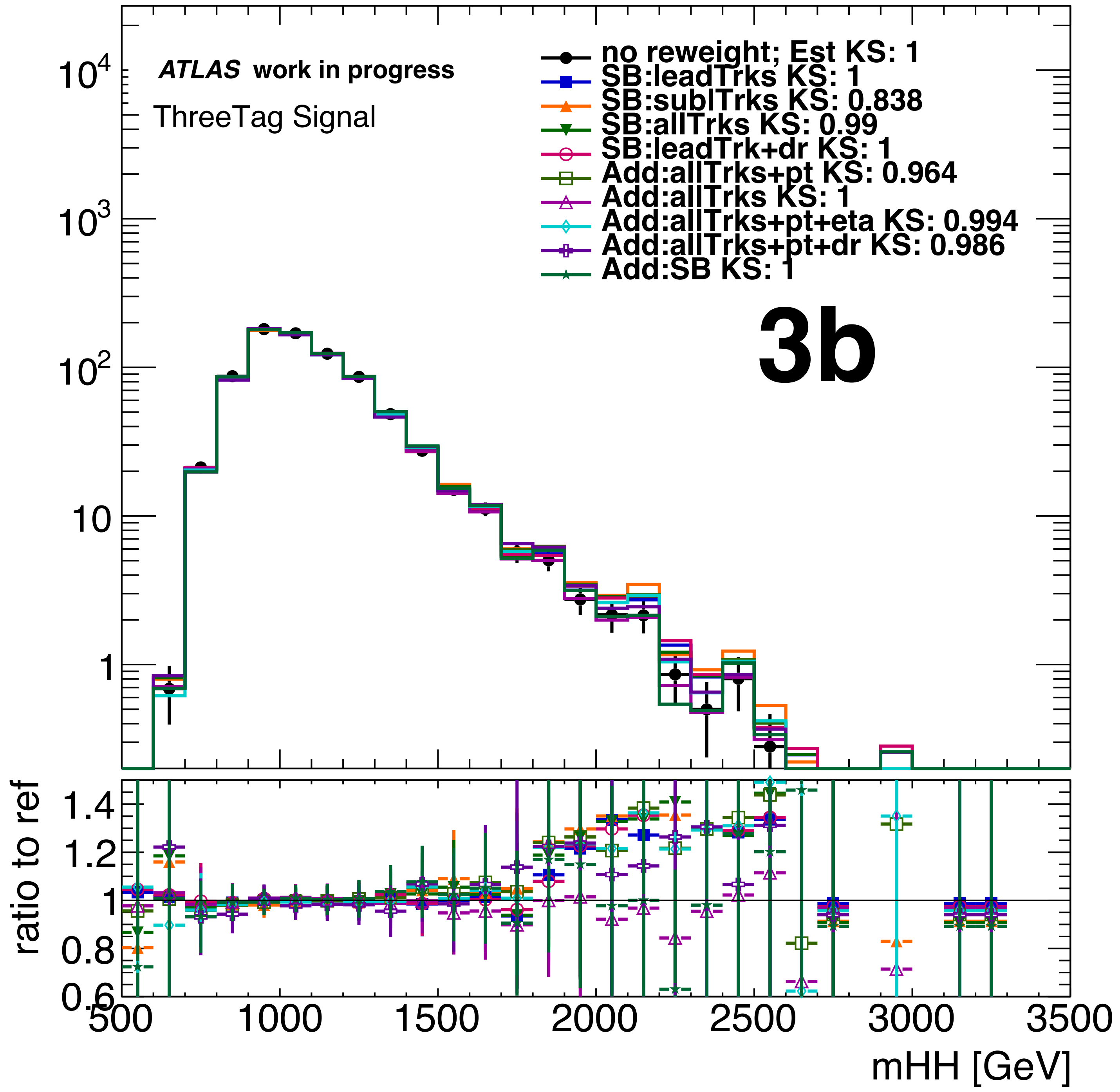


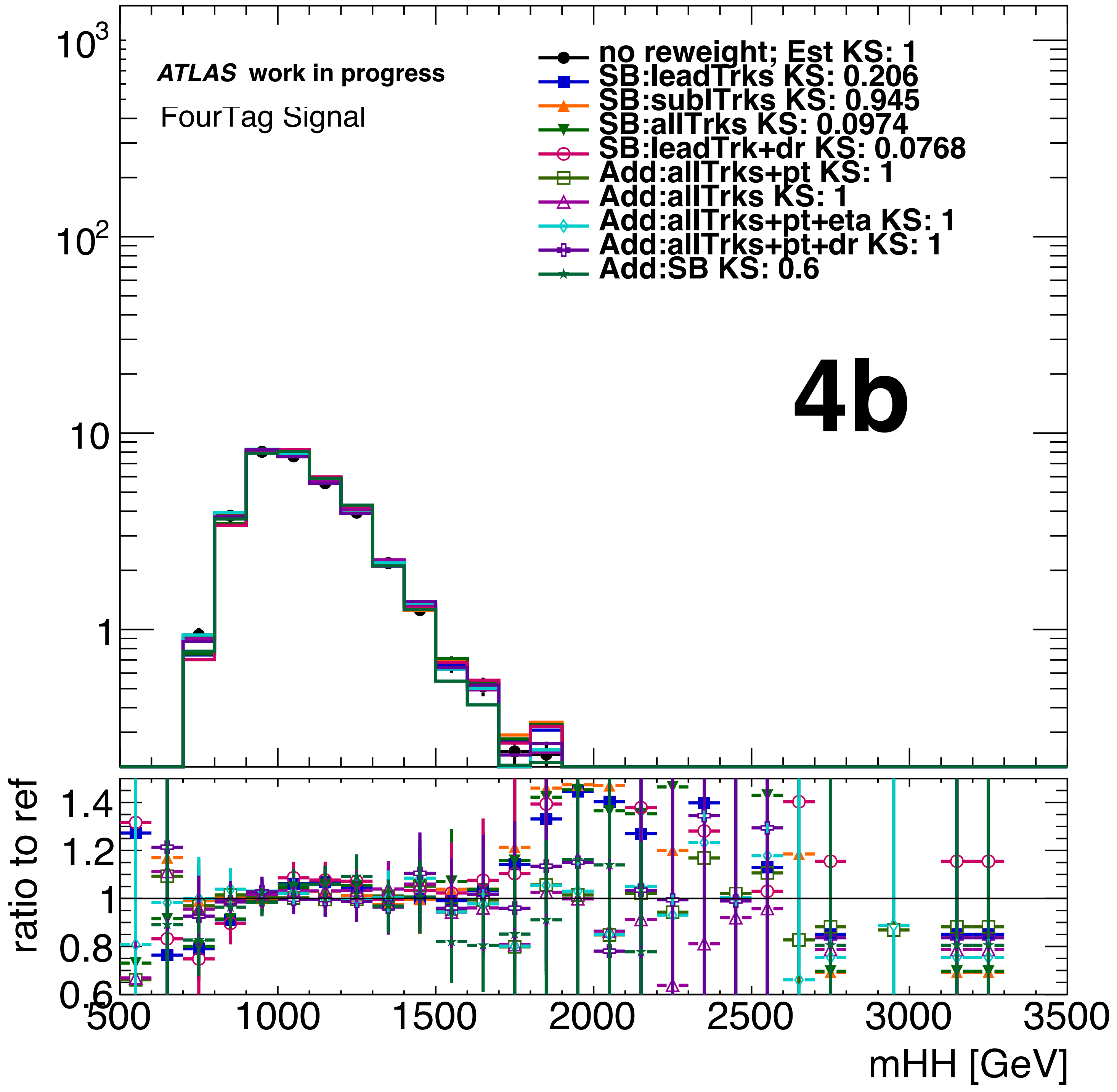


Signal Region: Boosted

- **Nine different** reweighting methods' mHH shape prediction comparison with the nominal method
- Gives similar results in the predictions

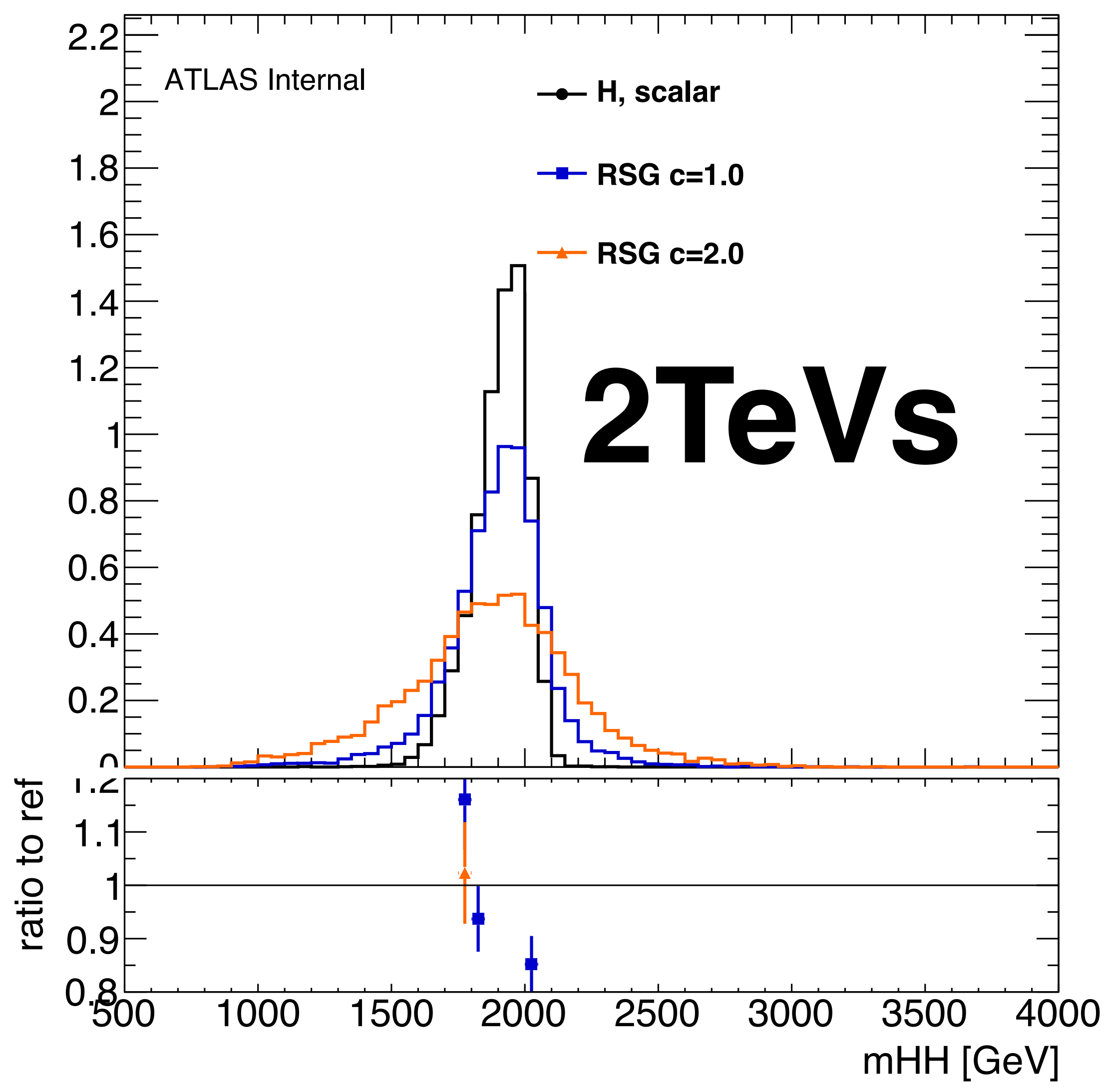


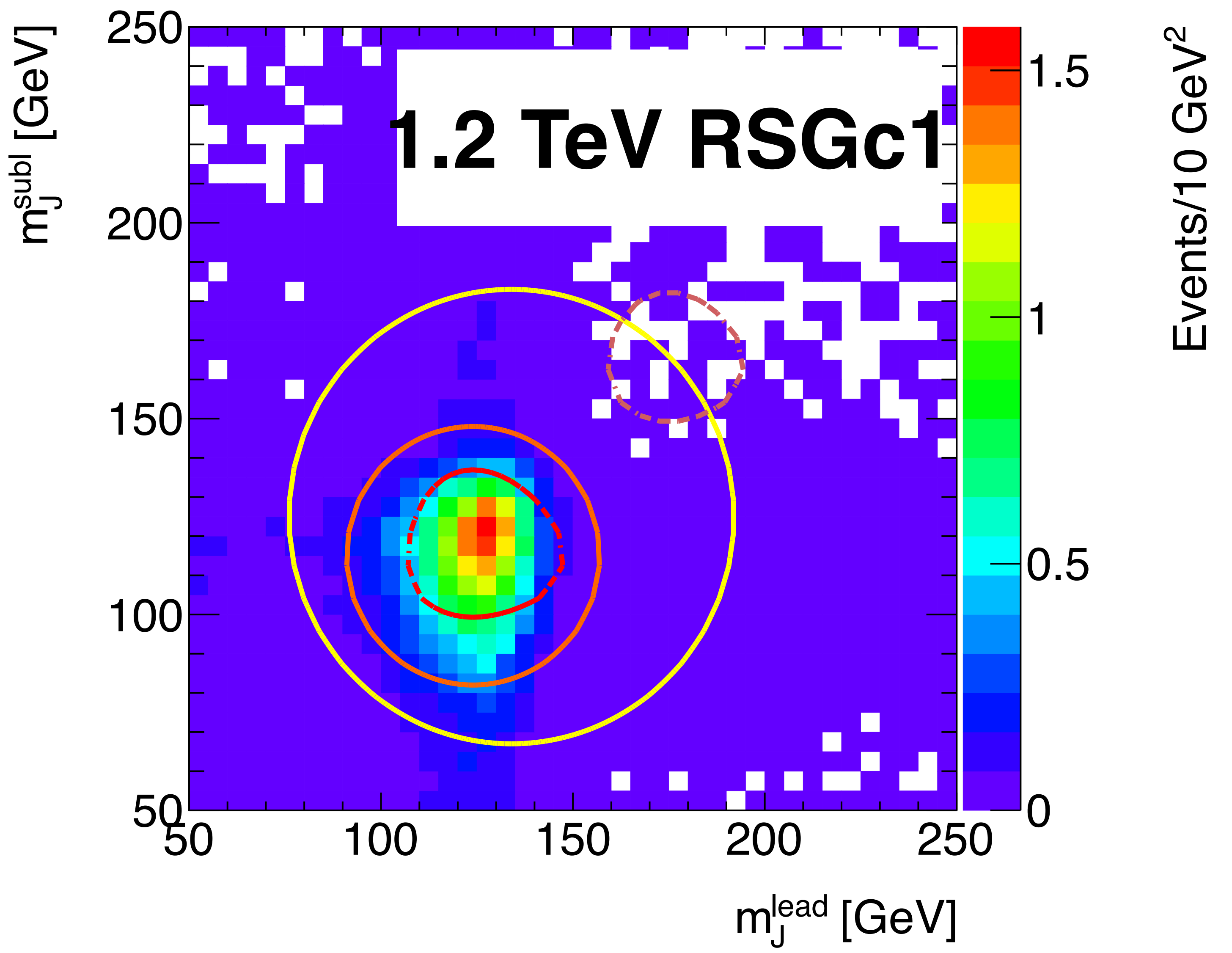


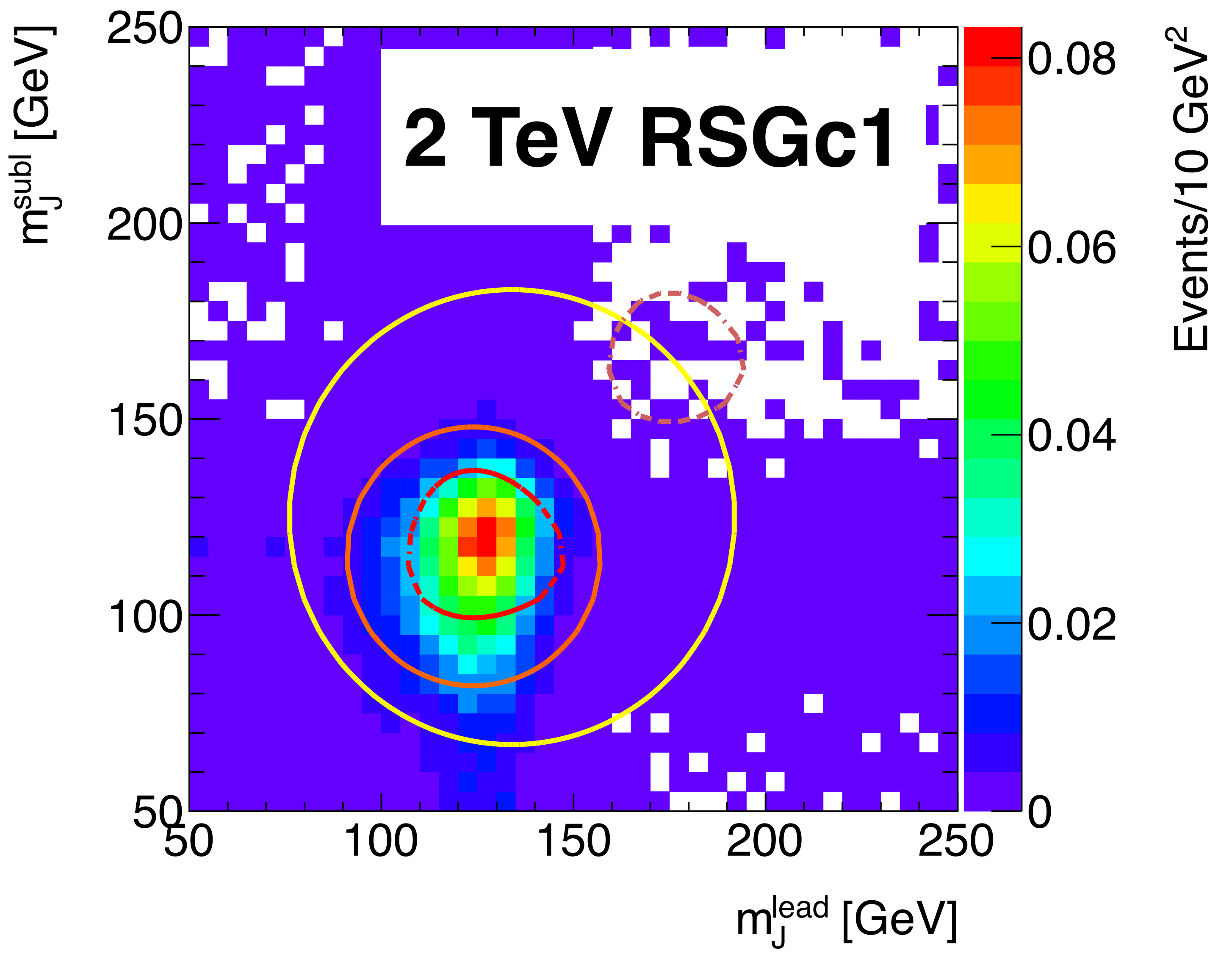


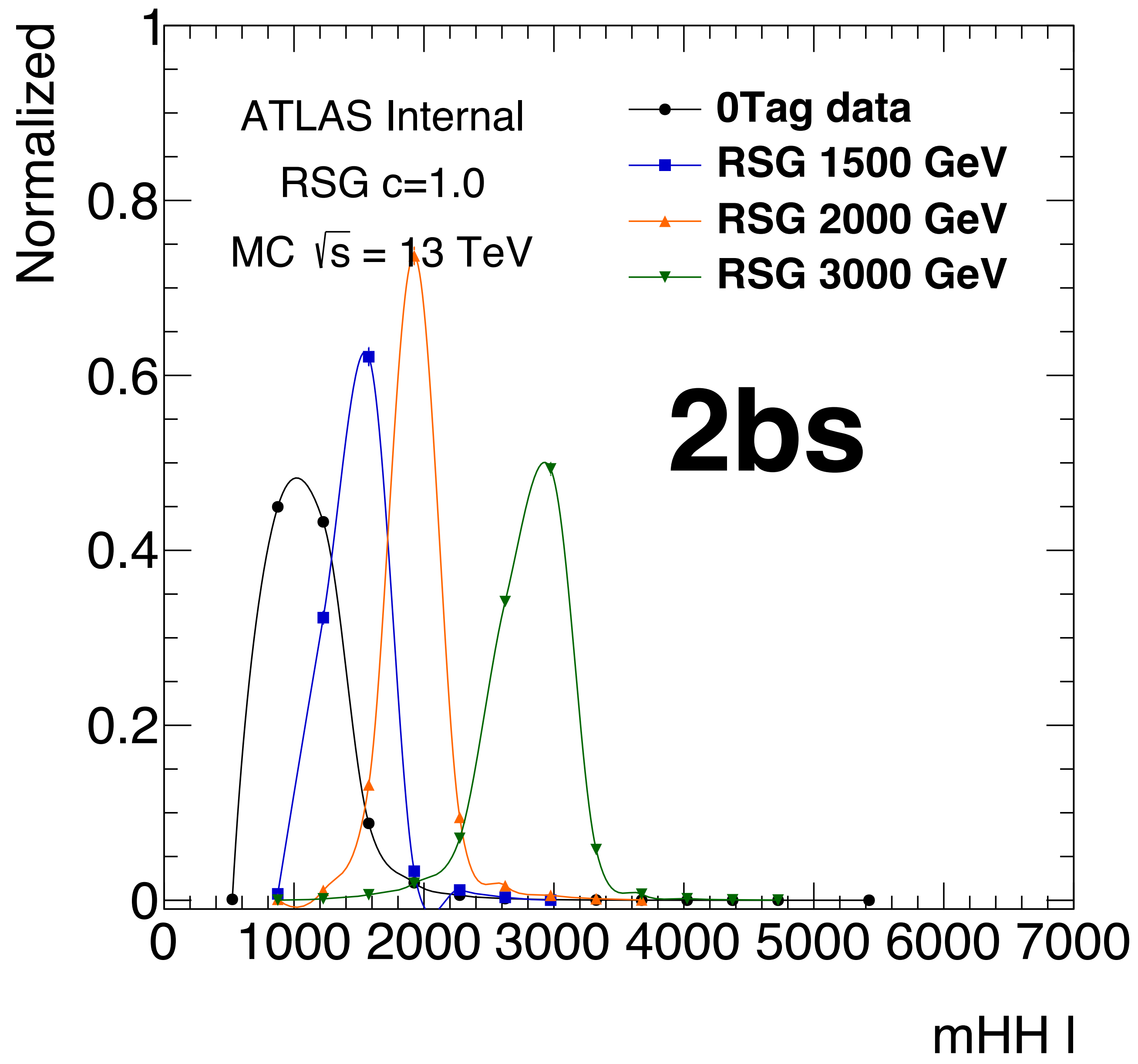
Current Boosted Optimizations

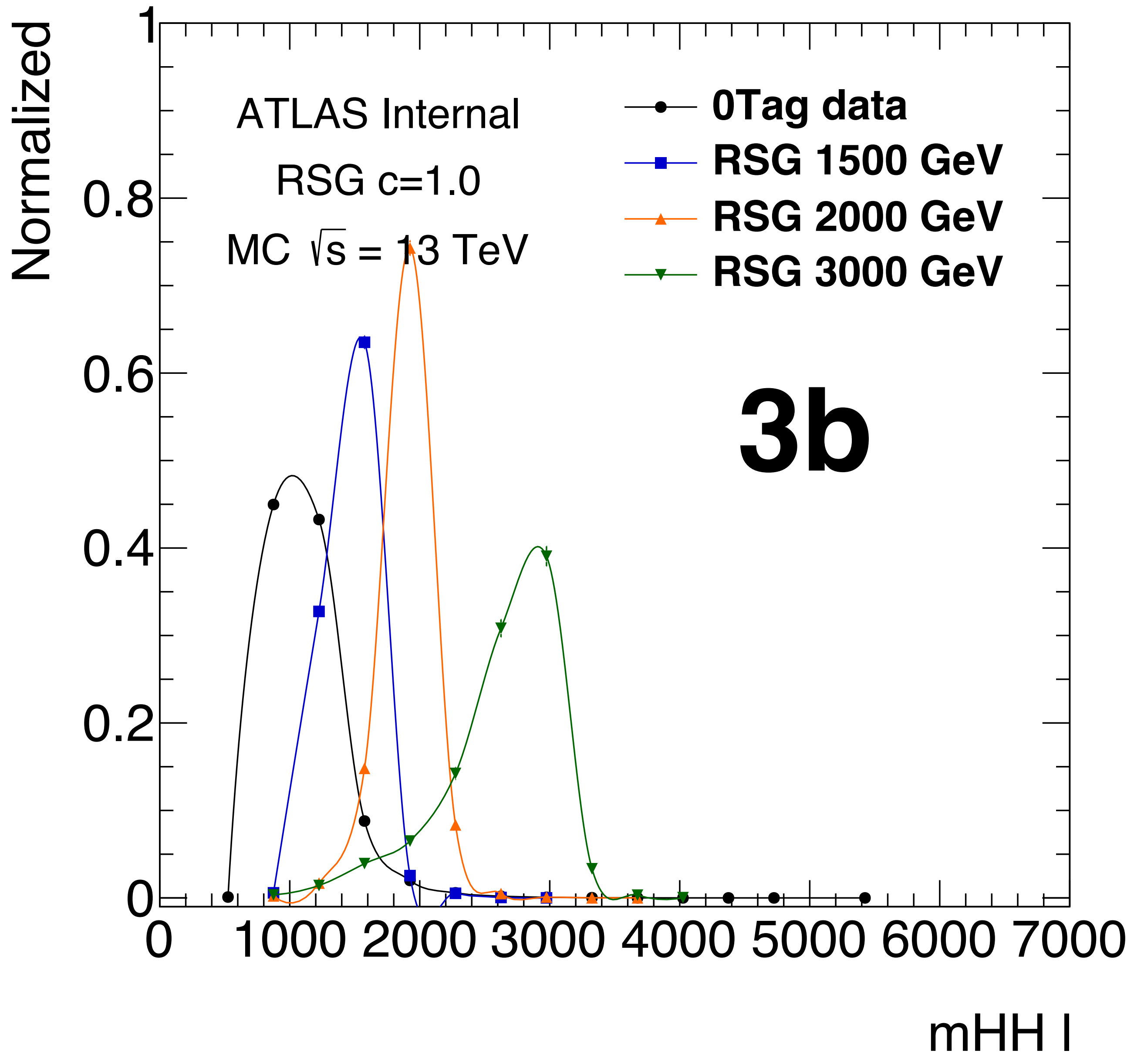
Signal Shapes

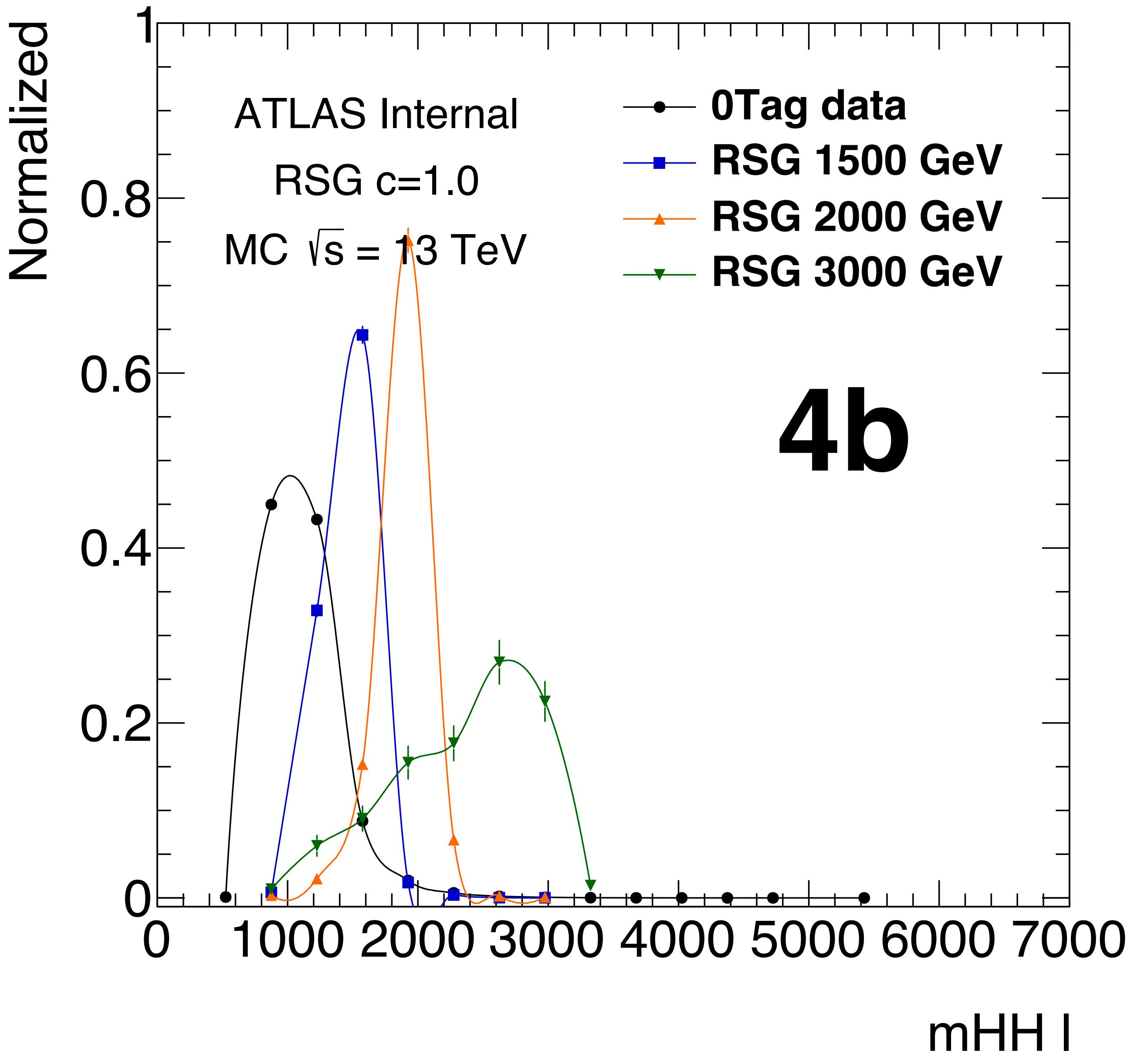






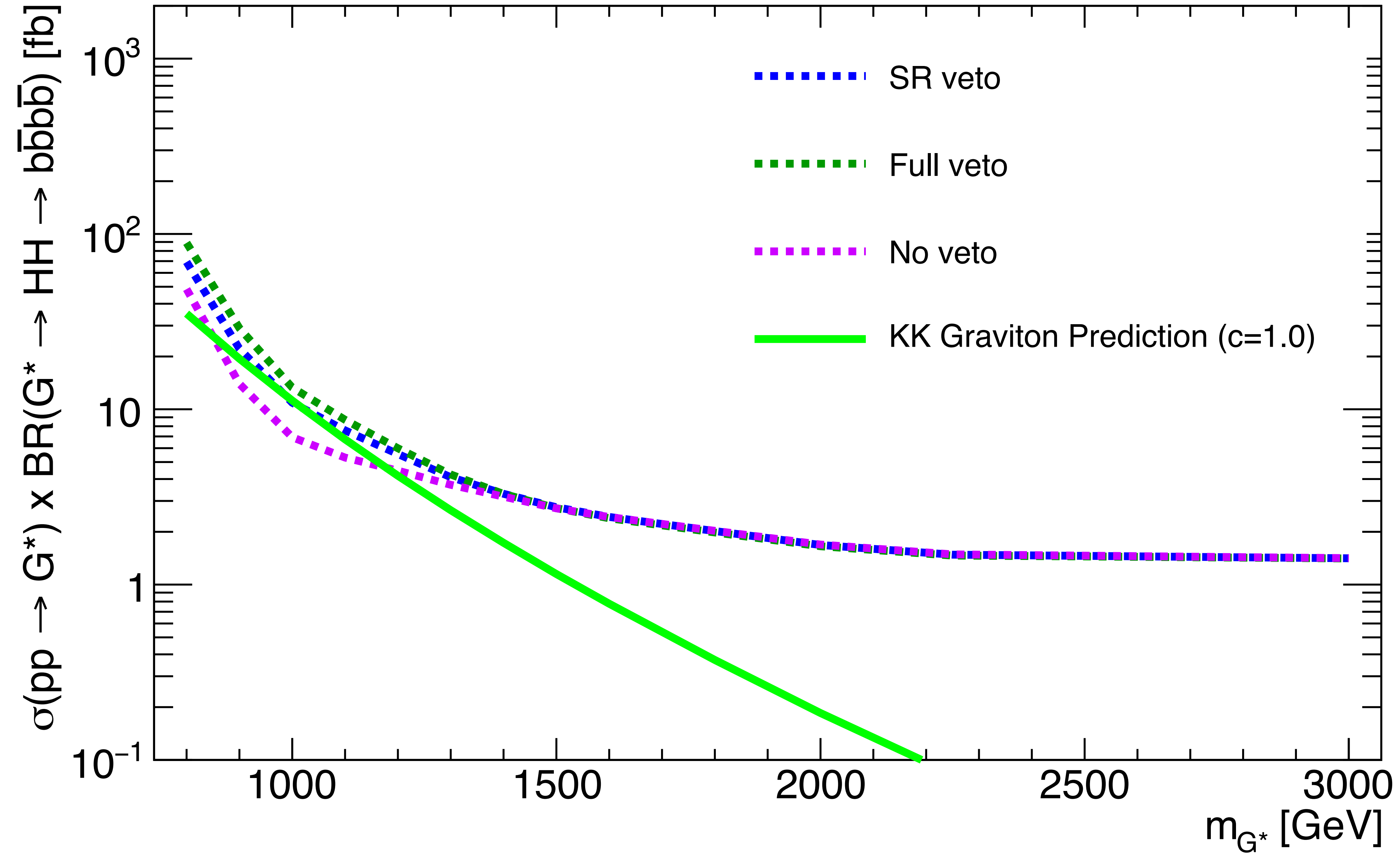


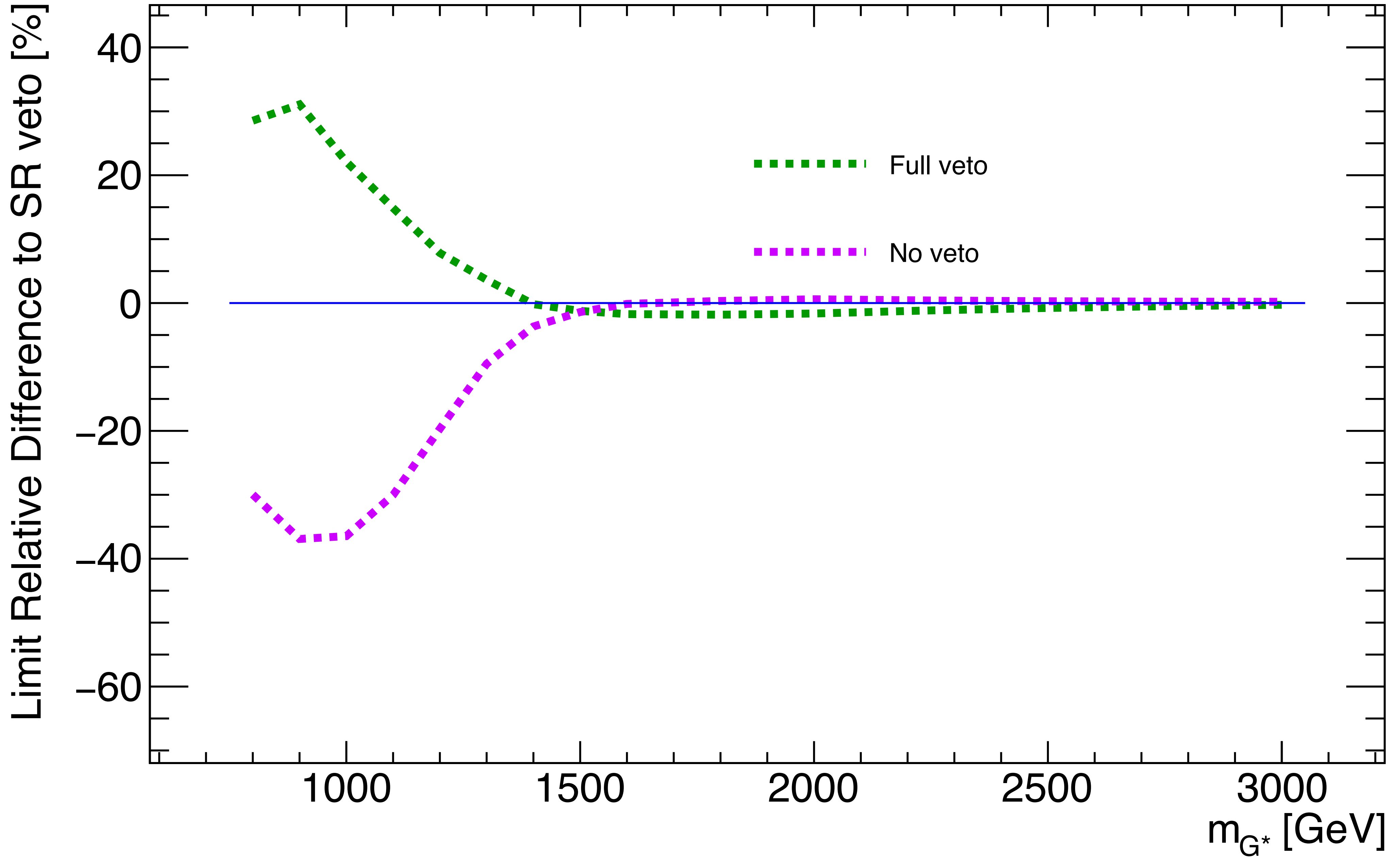




Resolved Veto Impact

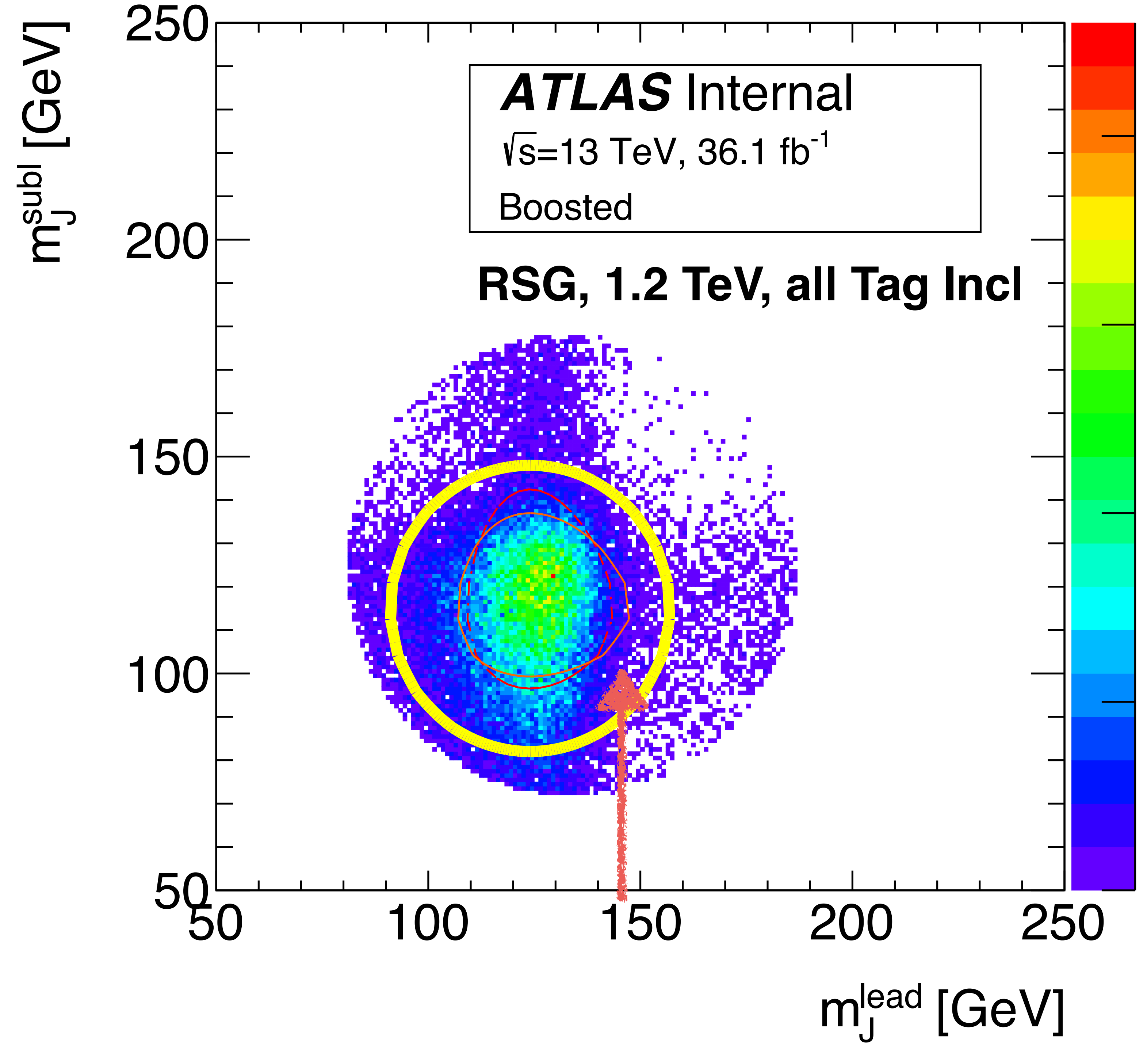
- Three different limits plotted
  - Full veto: veto if there are 4b jets (70%wp)
  - SR veto: Pass current resolved SR selection (without trigger)
  - No veto: no veto at all
- Impact~20-40%, but on the exclusion region
- Will be picked up in the combination, since these events are in resolved SR!

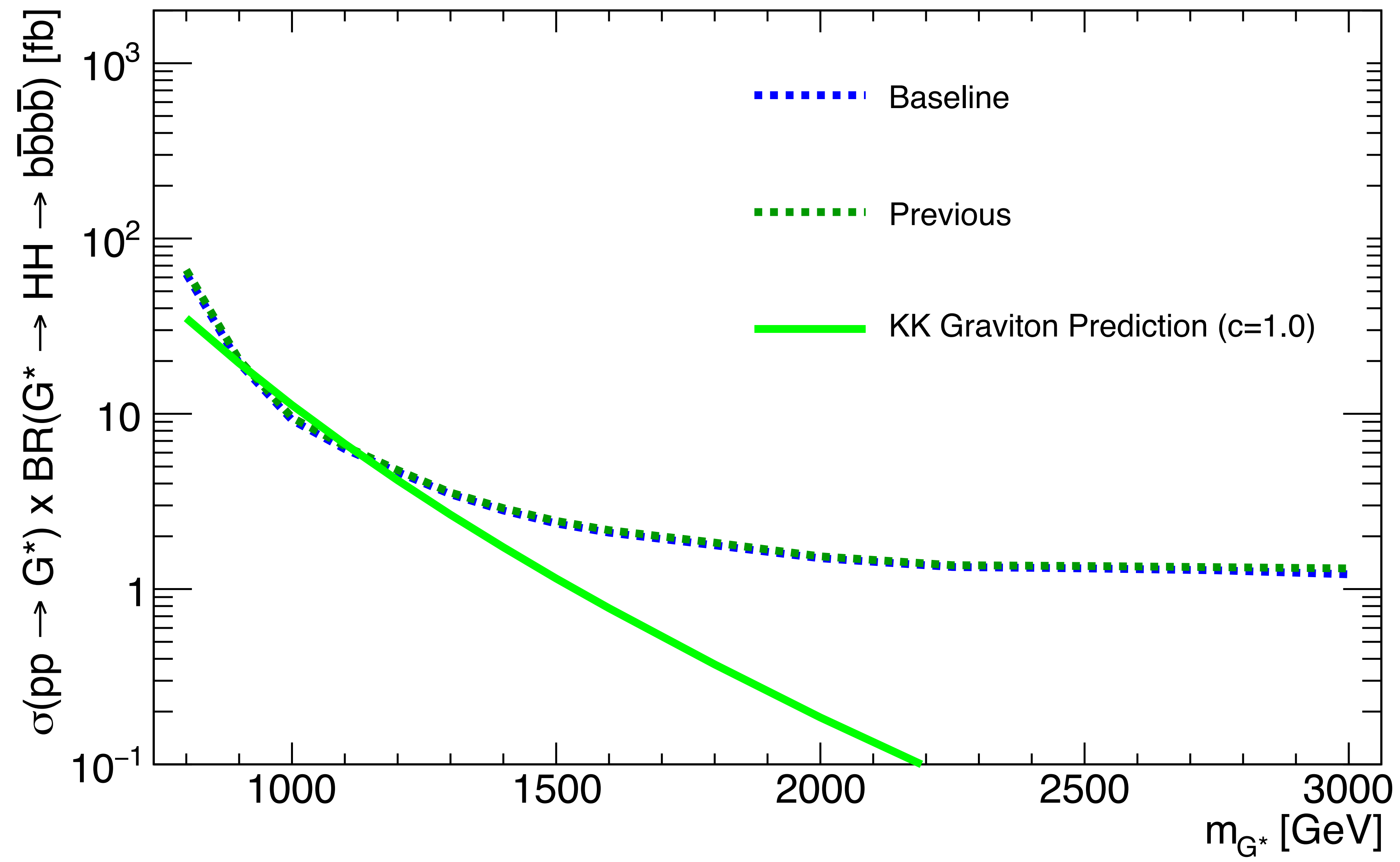


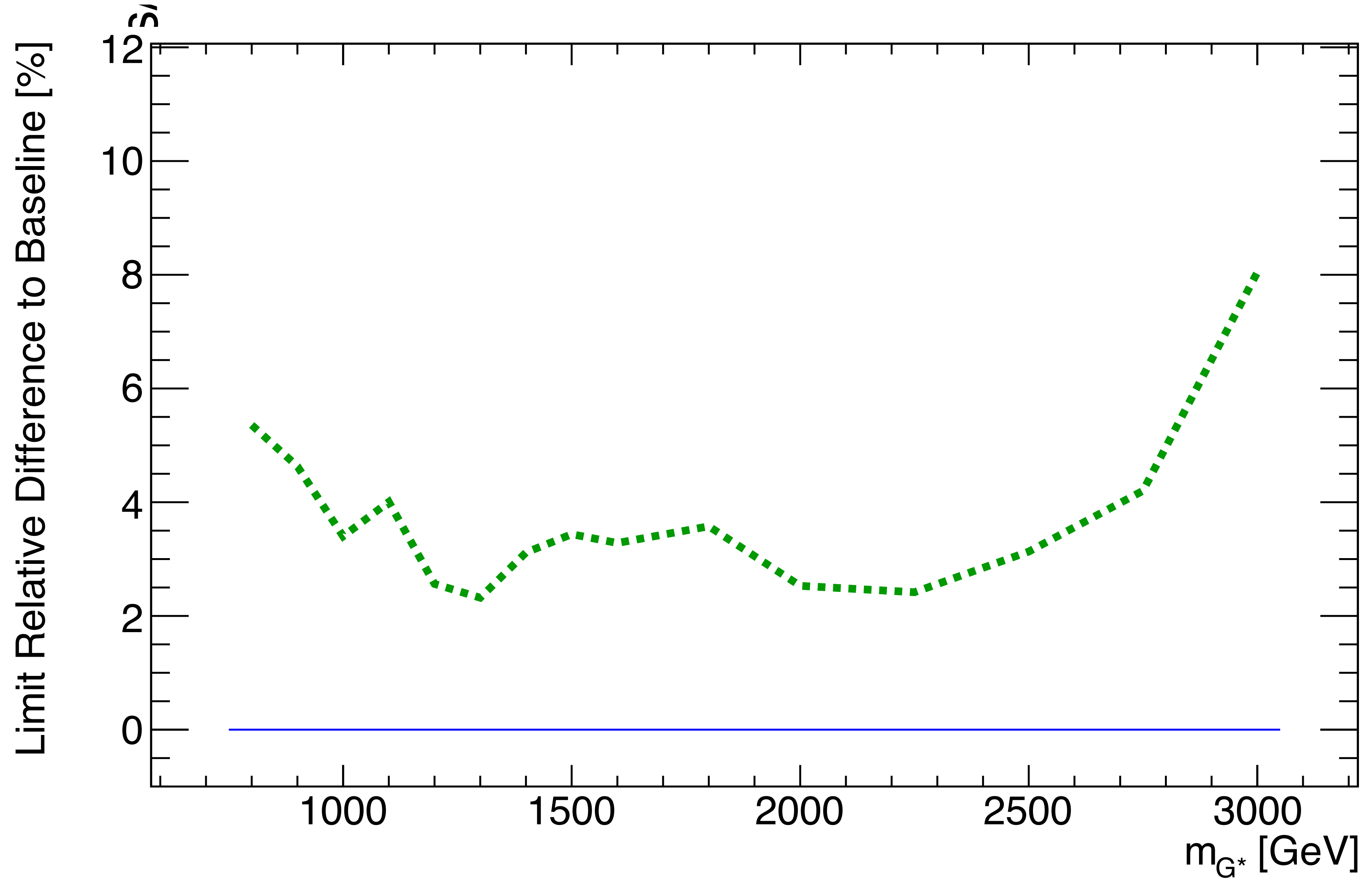


Asymmetric Resolution + pT dependent Xhh

- Sigma used to be
  - 0.1 mJ for lead /subl
- Updated to
  - 0.085 mJlead
  - 0.12 mJsubl
- More like an "**egg**" shape
- Xhh - (leadHpT/900 GeV - 1) * 0.4 < 1.6
  - For 3 TeV signal, with leadHpT ~ 1350 GeV, this gives Xhh < 1.8
- Also see Jana's slides



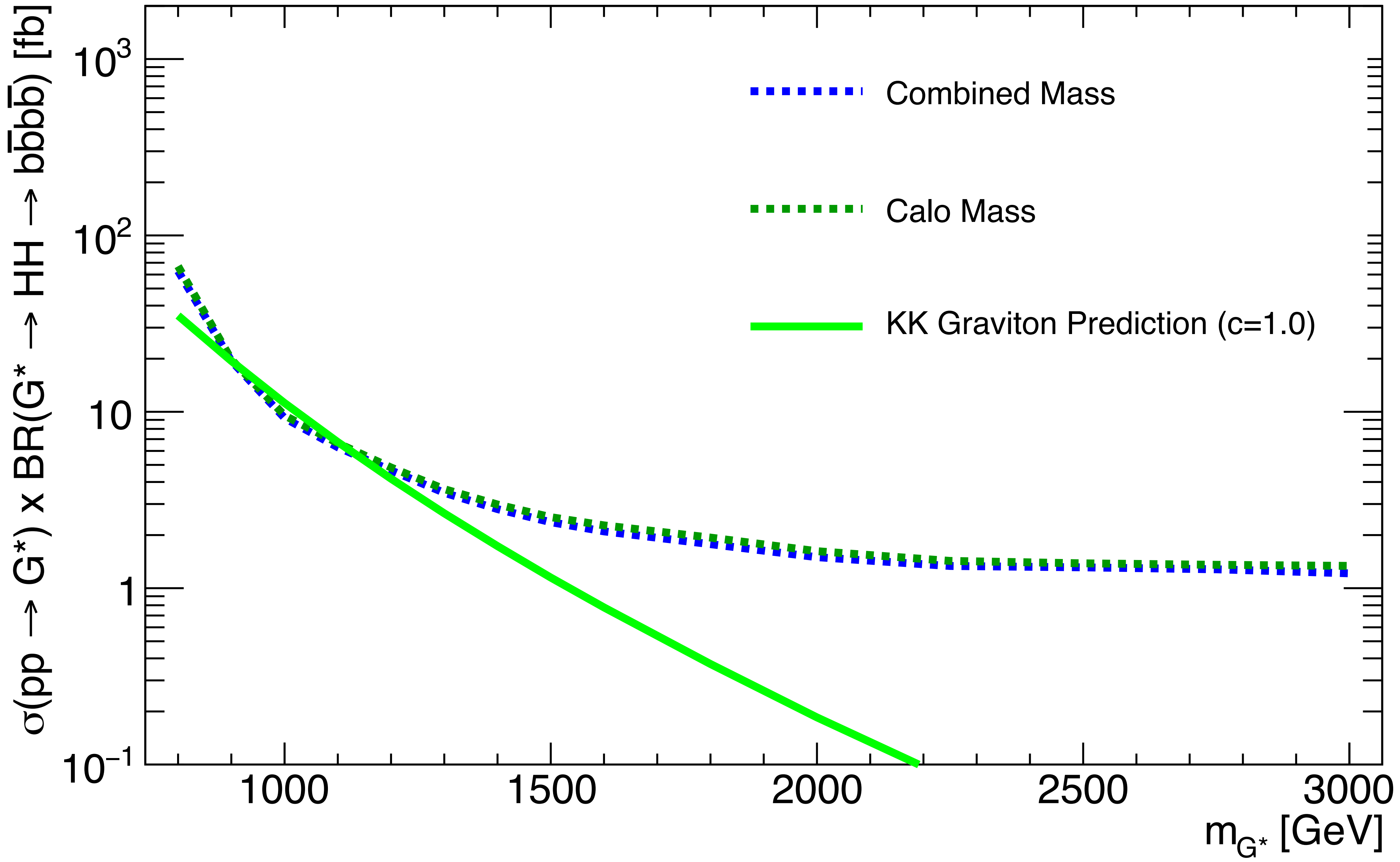


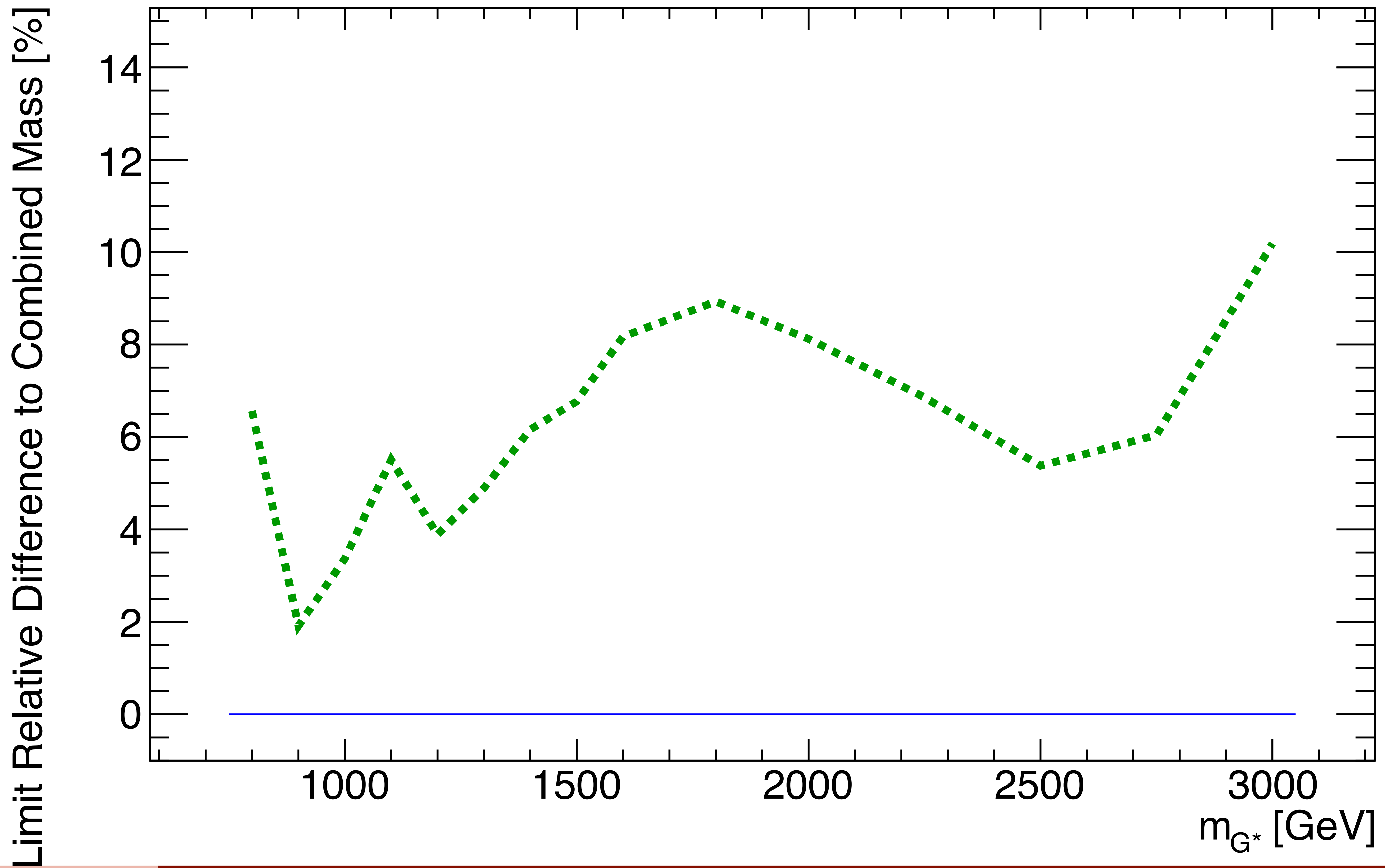


Combined Mass Impact

- Jets are already trimmed at 0.05 pT ratio with cone 0.2
- Pubnote
- Use both the calorimeter and track information
- Gain on mass resolution for high pT **large-R jets**

- Switch to combined mass gains us ~5% in exclusion limits :)





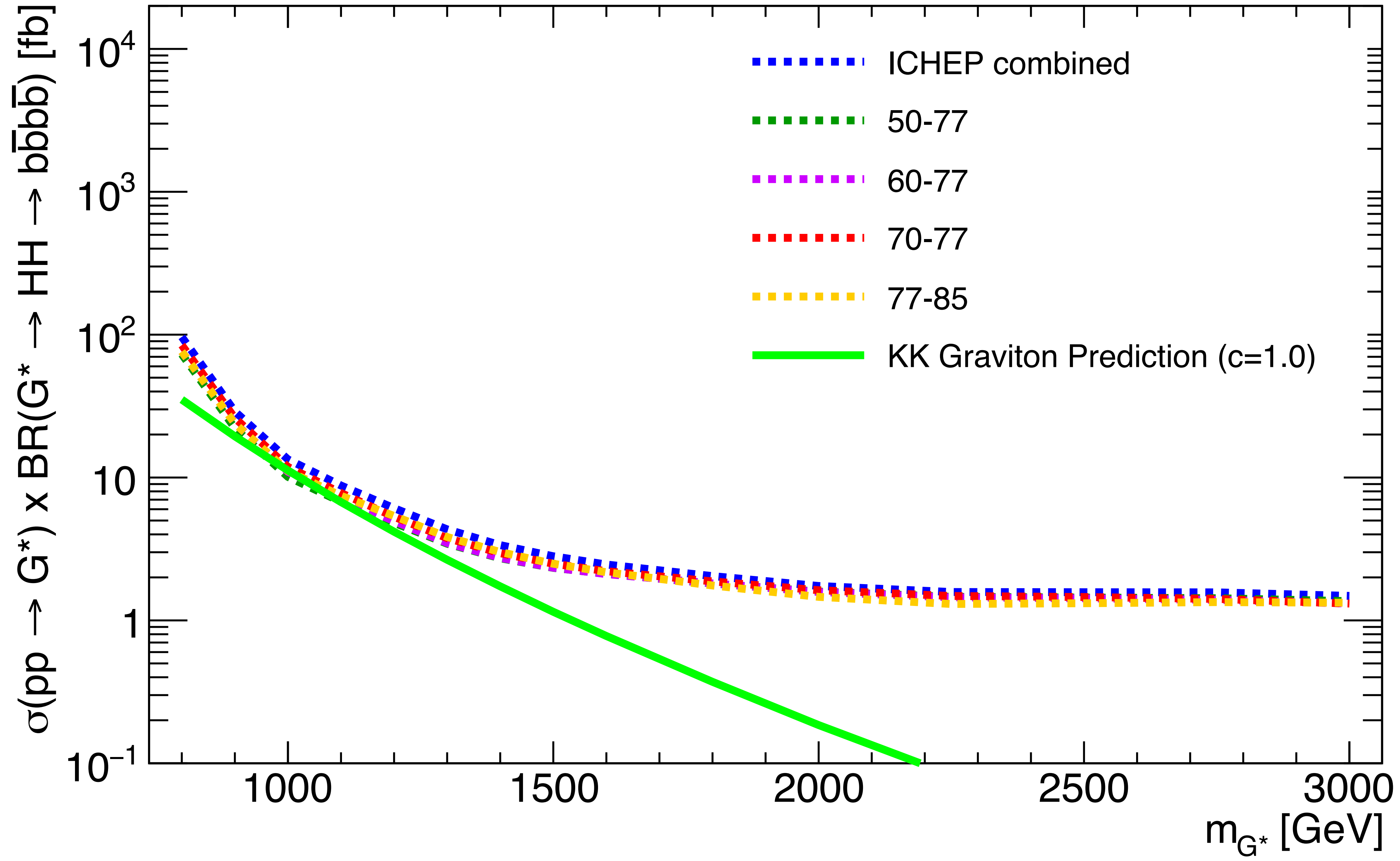
Divide Signal Regions

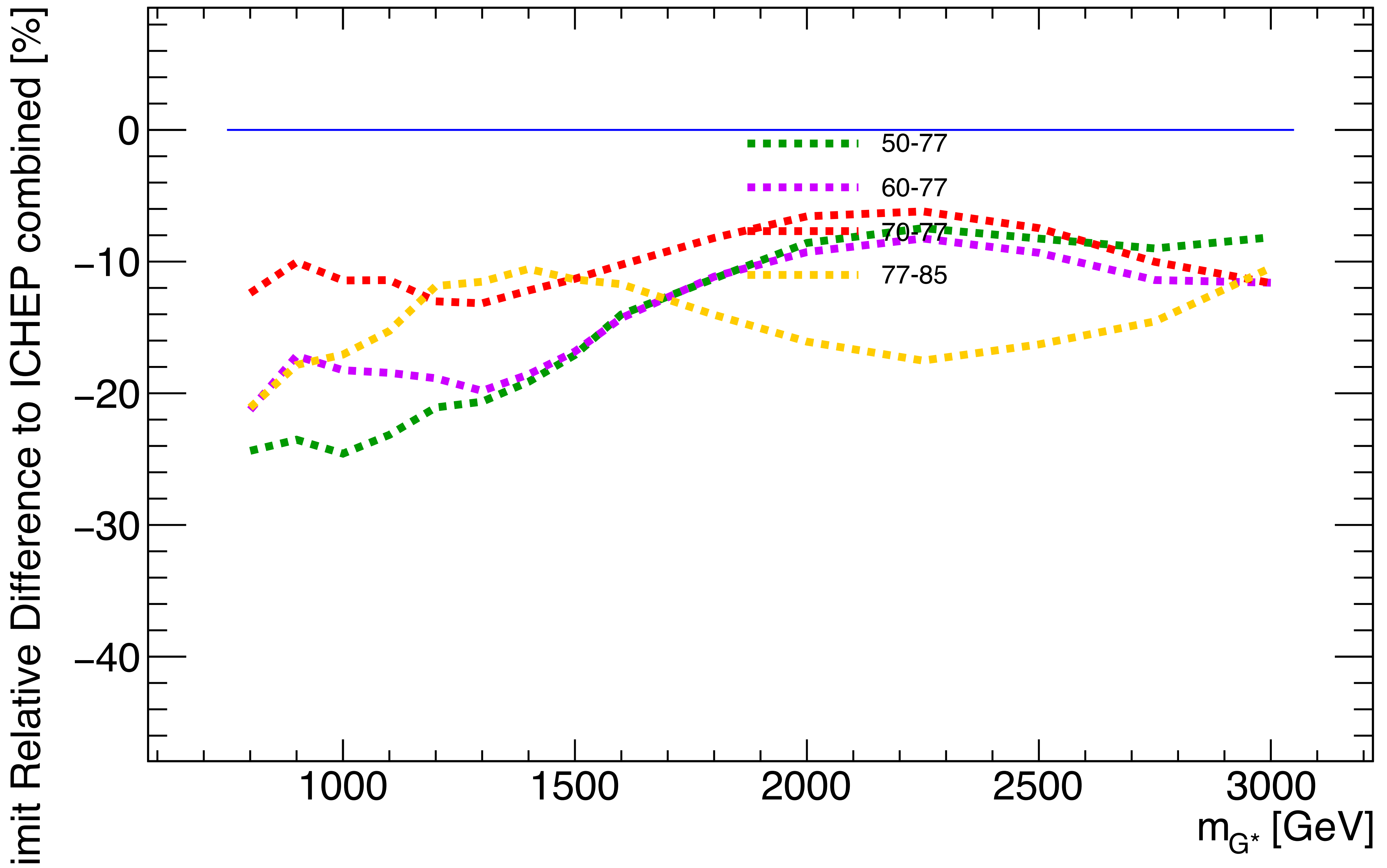
- Use different b-tagging working points to tag the two trackjets
- **Introduce tight-loose categories**
  - Tight: MV2 > higher b-tagging working point
  - Loose: higher b-tagging working point > MV2 > lower b-tagging working point
- Showing 1.5 TeV signal MC, entries are the number of events without weight

1.5 TeV RSG Tight wp - Loose wp	77-77	50-77	60-77	70-77
4 tight	8737	1010	2837	5862
3 tight 1 loose		3193	3863	2456
2 tight 2 loose		3166	1695	393
1 tight 3 loose		1192	326	26
4 loose		176	16	0
Sum	8737	8737	8737	8737

Combined Results

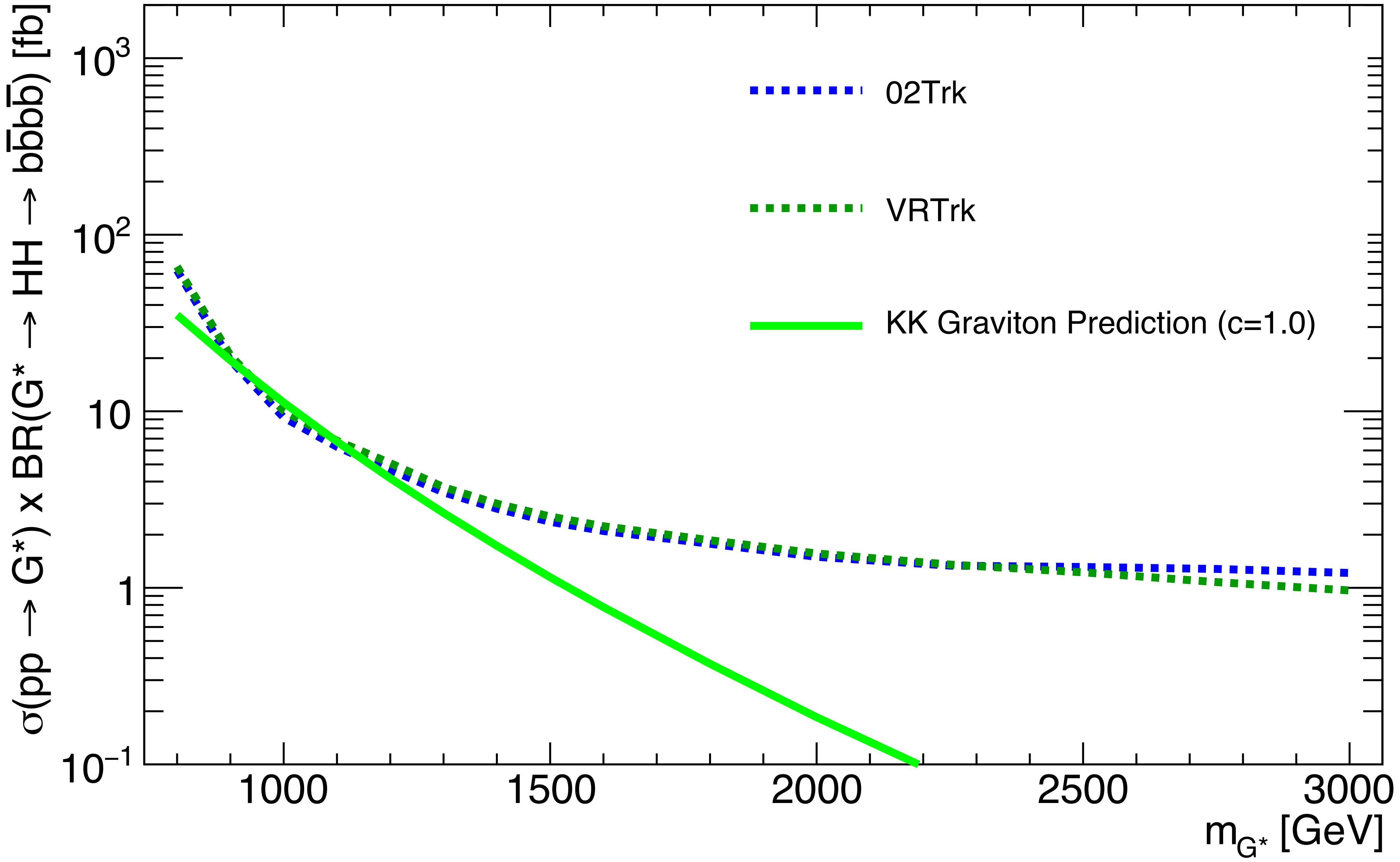
- Combined limits shows improvements
- This is 5+4+3 = 12 signal regions compare to 3 signal regions before
- **Gain 10 - 20 % overall** in exclusion limits
- Could be used in the future analysis once the continuous calibration is available, also when we have more statistics so that each signal region would have a reasonable number of events

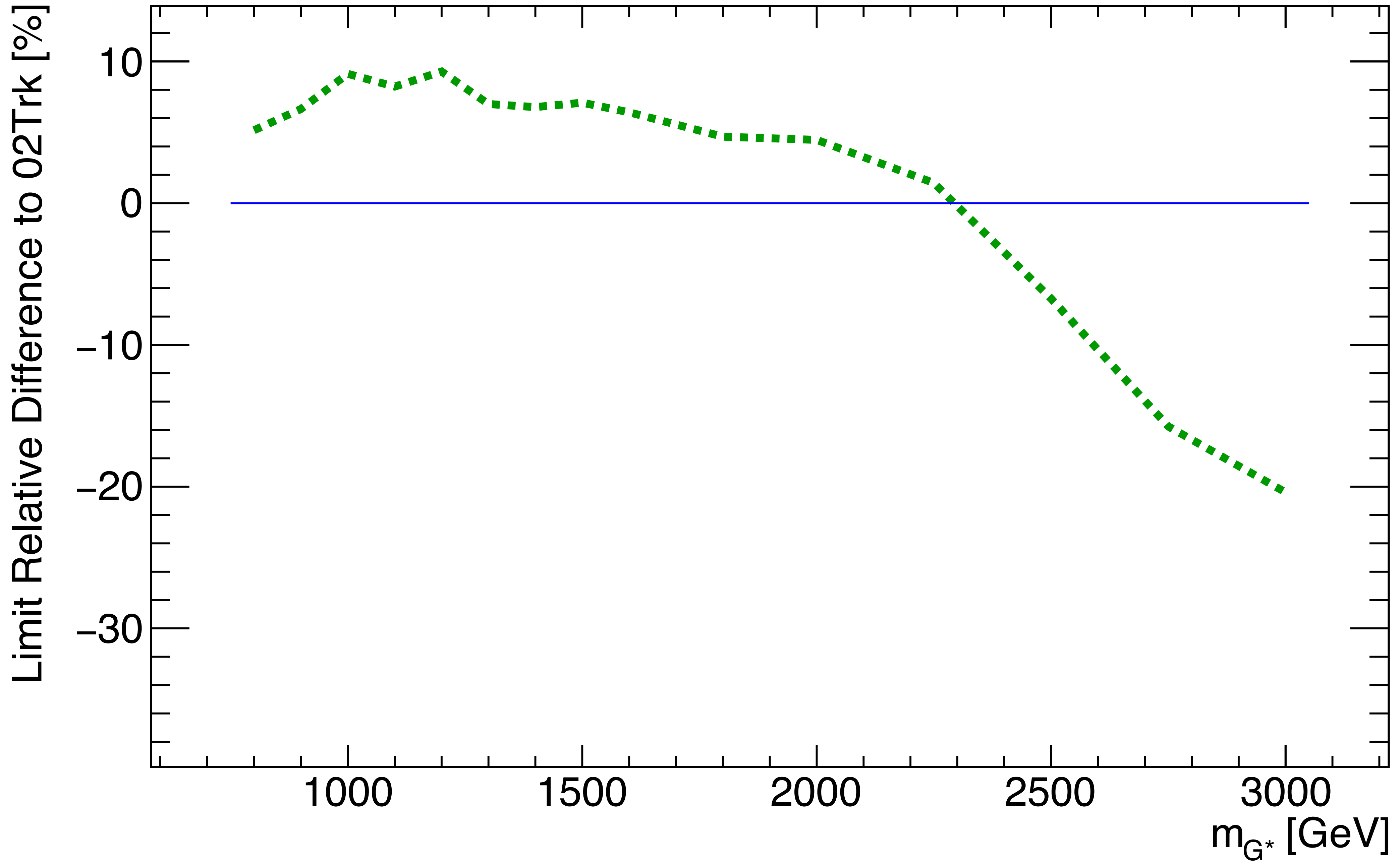




Limit Comparison

- VR analysis has a similar limit compared to 02Trackjet analysis
    - **Above 2.5 TeV, gain in limit ~ 10%-20%**
    - Below 2 TeV, expected limit is worse than fixed radius trackjet, not well understood, could due to increase in background rate
- VR has some potential, once the scale factors are ready, more detailed/careful study is necessary





Current Boosted Systematics

Overview of Systematics

- Signal **MC uncertainty** mainly comes from **b-tagging**
- Background modeling **normalization uncertainty** is dominated by CR non-closure tests
- **Shape uncertainty** is also applied, deriving from control region
- Table with all background systematics in percentage wise countdown
  - 4b ~ 17.6%
  - 3b ~ 5.6%
  - 2bs ~ 2.9%

TwoTag split	totalbkg	qcd	ttbar	RSG1 1000	RSG1 2000	RSG1 3000
JER	0.25	0.48	3.14	1.18	0.74	0.5
JMR	0.52	1.73	9.43	10.96	12.3	13.03
Top	-	-	-	-	-	-
JES/JMS	0.43	1.67	7.17	6.72	1.7	3.55
Bkg Est	2.7	3.32	2.4	-	-	-
b-tag SF	0.83	1.43	1.82	19.28	27.36	2.72
Total Sys	2.92	4.37	12.62	23.2	30.05	13.79
Stat	0.6	0.41	2.47	2.0	1.2	1.07
Estimated Events	4251.49	3392.79	858.7	10.87	0.6	0.039

Table 32: Percent impact of the dominant systematics on the background acceptance and on the signal acceptance of RS $c = 1.0$ graviton predictions in the 2bs signal region.

ThreeTag	totalbkg	qcd	ttbar	RSG1 1000	RSG1 2000	RSG1 3000
JER	1.38	3.52	17.5	1.41	0.93	1.08
JMR	1.35	4.26	24.38	14.3	12.33	15.53
Top	-	-	-	-	-	-
JES/JMS	2.03	1.26	26.22	5.19	1.94	6.35
Bkg Est	4.84	5.62	9.45	-	-	-
b-tag SF	0.47	0.53	8.45	2.45	2.01	9.27
Total Sys	5.61	8.0	41.82	15.47	12.68	19.2
Stat	1.32	1.44	2.47	1.26	1.0	1.83
Estimated Events	780.89	701.52	79.38	26.0	0.76	0.013

Table 31: Percent impact of the dominant systematics on the background acceptance and on the signal acceptance of RS $c = 1.0$ graviton predictions in the 3b signal region.

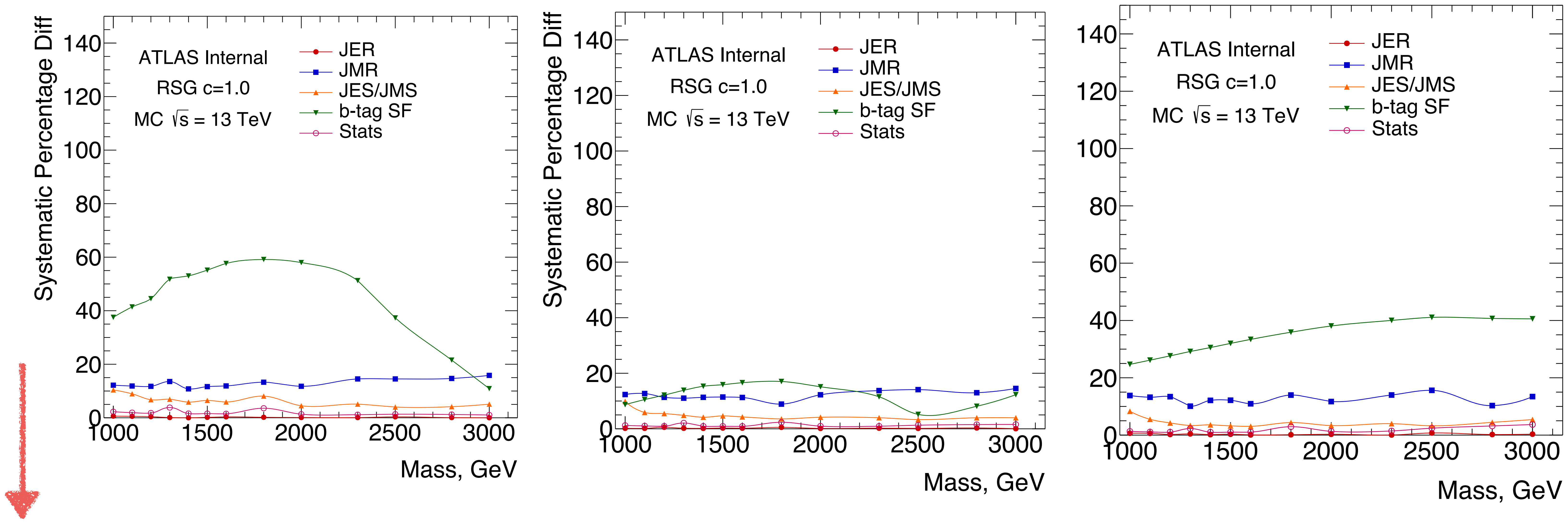
FourTag	totalbkg	qcd	ttbar	RSG1 1000	RSG1 2000	RSG1 3000
JER	0.45	0.27	3.98	2.44	1.07	0.67
JMR	7.9	10.35	39.95	12.33	13.16	15.08
Top	-	-	-	-	-	-
JES/JMS	1.32	1.49	24.36	5.18	3.72	5.62
Bkg Est	15.67	18.19	67.82	-	-	-
b-tag SF	1.11	0.79	18.85	18.34	28.11	27.73
Total Sys	17.64	21.0	84.62	22.83	31.28	32.07
Stat	3.13	3.29	2.47	1.97	1.63	4.9
Estimated Events	34.59	32.91	1.68	10.07	0.25	0.0016

Table 30: Percent impact of the dominant systematics on the background acceptance and on the signal acceptance of RS $c = 1.0$ graviton predictions in the 4b signal region.

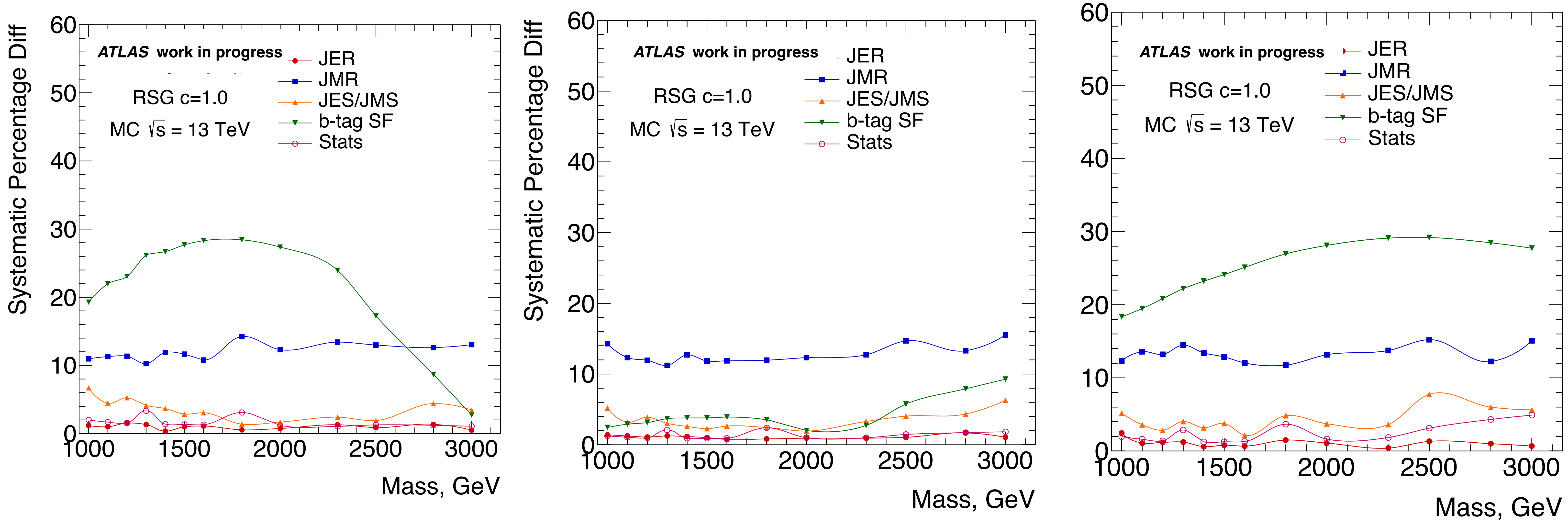
MC Syst

- Significantly smaller signal systematic uncertainties compared with last result

ICHEP **2bs** **3b** **4b**



NEW **2bs** **3b** **4b**

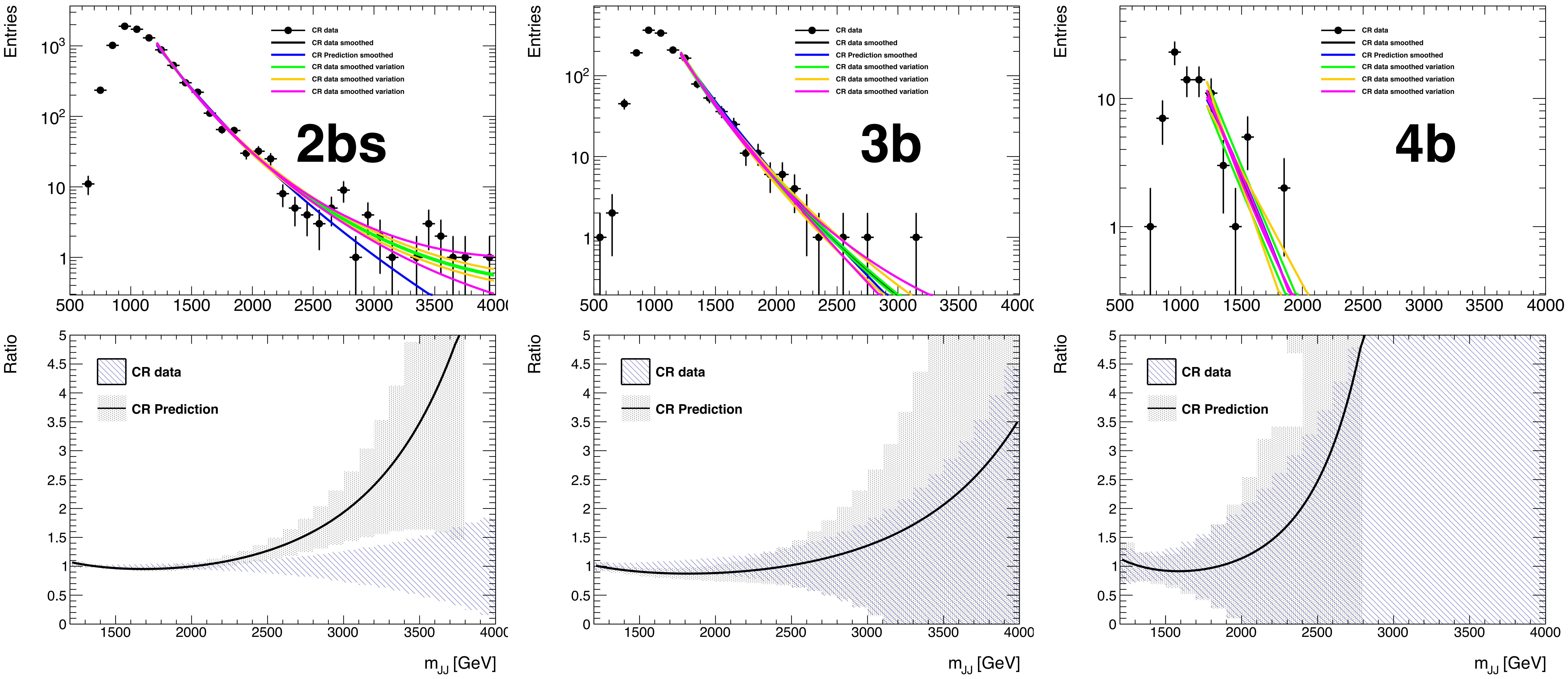


- Updated b-tagging calibrations helped

- This is also applied to ttbar

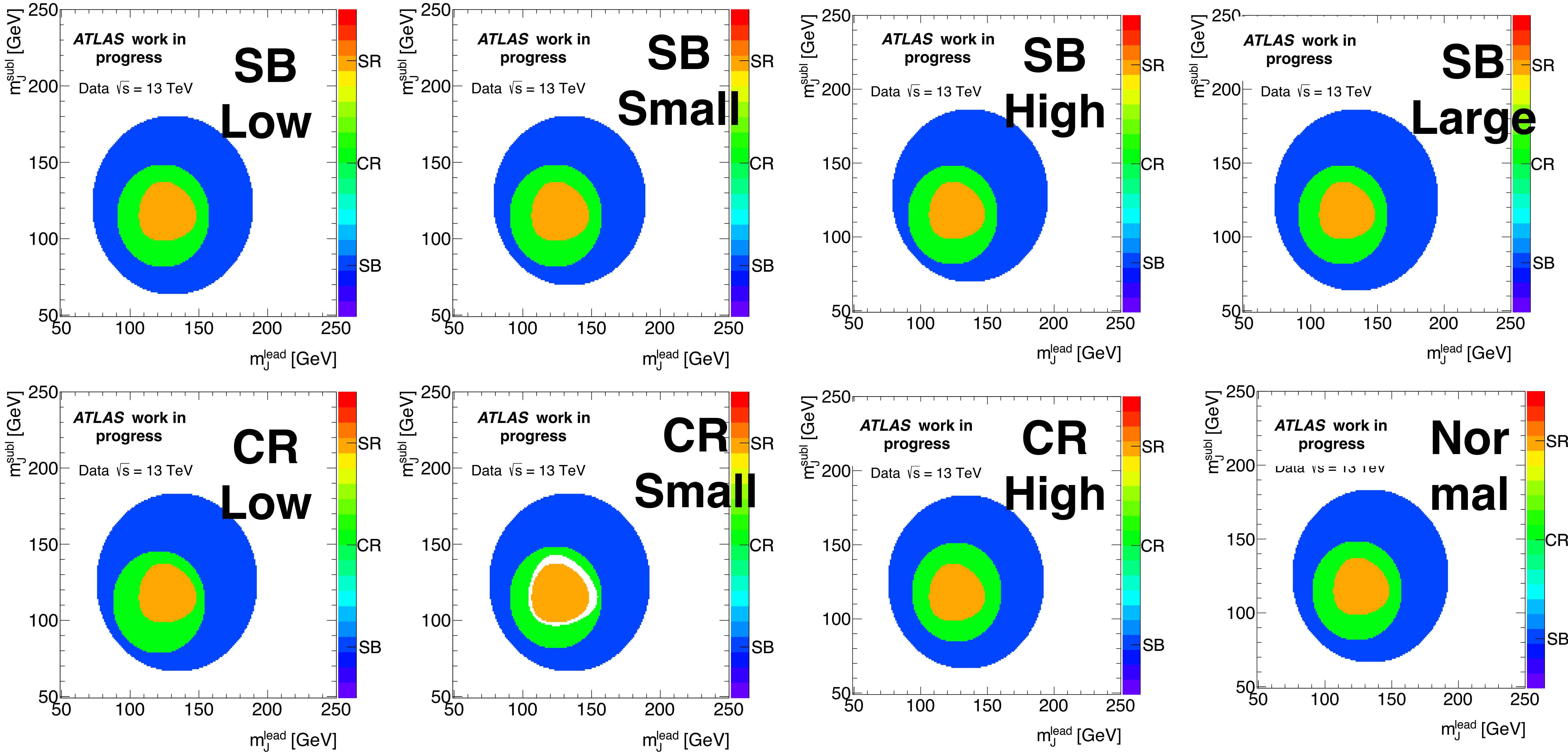
CR Smoothed differences

- **Compare** shapes between prediction after reweighting (blue) and directly smoothed data distribution
- Use the ratio to assign systematics in the signal region
- This ratio is separated: below and above 2 TeV; to have unconstrained pulls for different mass ranges



SB/CR variations

- 7 Different variations:
- SB/CR high/low:
  - center shift up/down in leadH/sublH by 3 GeV
- SB large/small:
  - radius 58 shifted up/down by 3 GeV
- CR small:
  - Xhh > 2.0 (default1.6) && Rhh < 33



SB/CR normalization uncer.

- Largest difference
  - 4b: -12.9%
  - 3b: +2.6%
  - 2bs: -2.8%

- All within one sigma of Data/Prediction statistics only uncertainties
- Will be used as normalization uncertainty

CR Varations FourTag	Data	Prediction	(Predict - Data)/Data
Nominal	81.0 ± 9.0	76.77 ± 5.43	-5.22 % ± 17.23 %
CR High	76.0 ± 8.72	71.12 ± 5.41	-6.42 % ± 17.85 %
CR Low	91.0 ± 9.54	79.87 ± 5.45	-12.2 % ± 15.19 %
CR Small	58.0 ± 7.62	55.96 ± 5.35	-3.52 % ± 21.89 %
SB Large	81.0 ± 9.0	74.73 ± 5.4	-7.74 % ± 16.92 %
SB Small	81.0 ± 9.0	74.17 ± 5.38	-8.44 % ± 16.81 %
SB High	81.0 ± 9.0	78.71 ± 5.46	-2.83 % ± 17.54 %
SB Low	81.0 ± 9.0	76.53 ± 5.38	-5.52 % ± 17.14 %

Table 18: Agreement between data and prediction in 4b tag CR. Showing stat uncertainty only.

CR Varations ThreeTag	Data	Prediction	(Predict - Data)/Data
Nominal	1553.0 ± 39.41	1565.36 ± 18.14	0.8 % ± 3.73 %
CR High	1461.0 ± 38.22	1459.76 ± 17.2	-0.085 % ± 3.79 %
CR Low	1628.0 ± 40.35	1671.45 ± 19.03	2.67 % ± 3.71 %
CR Small	1134.0 ± 33.67	1109.46 ± 15.52	-2.16 % ± 4.27 %
SB Large	1553.0 ± 39.41	1560.38 ± 18.05	0.48 % ± 3.71 %
SB Small	1553.0 ± 39.41	1573.83 ± 18.19	1.34 % ± 3.74 %
SB High	1553.0 ± 39.41	1583.74 ± 18.4	1.98 % ± 3.77 %
SB Low	1553.0 ± 39.41	1558.75 ± 17.99	0.37 % ± 3.71 %

Table 19: Agreement between data and prediction in 3b tag CR. Showing stat uncertainty only.

CR Varations TwoTag split	Data	Prediction	(Predict - Data)/Data
Nominal	8486.0 ± 92.12	8332.78 ± 38.84	-1.81 % ± 1.52 %
CR High	8174.0 ± 90.41	7937.44 ± 39.61	-2.89 % ± 1.56 %
CR Low	8907.0 ± 94.38	8800.44 ± 39.52	-1.2 % ± 1.49 %
CR Small	5999.0 ± 77.45	5873.37 ± 32.31	-2.09 % ± 1.8 %
SB Large	8486.0 ± 92.12	8341.62 ± 38.44	-1.7 % ± 1.52 %
SB Small	8486.0 ± 92.12	8333.08 ± 39.12	-1.8 % ± 1.53 %
SB High	8486.0 ± 92.12	8377.73 ± 38.45	-1.28 % ± 1.52 %
SB Low	8486.0 ± 92.12	8356.68 ± 39.06	-1.52 % ± 1.53 %

Table 20: Agreement between data and prediction in 2bs tag CR. Showing stat uncertainty only.

SB/CR SR prediction

- SR prediction under different variations shows good agreement with the baseline method
- All of the total yield prediction differences are smaller than the control region variations—good sign

FourTag	Prediction	Diff	QCD	ttbar
Nominal	37.19 % ± 0.73 %	0.0057 % ± 3.93 %	0.0021 % ± 4.01 %	0.077 % ± 20.06 %
CR High	37.63 % ± 0.8 %	1.19 % ± 4.13 %	2.31 % ± 4.27 %	-20.6 % ± 15.92 %
CR Low	36.28 % ± 0.77 %	-2.44 % ± 3.98 %	-0.89 % ± 4.13 %	-32.4 % ± 13.55 %
CR Small	37.6 % ± 0.8 %	1.1 % ± 4.13 %	3.16 % ± 4.3 %	-38.9 % ± 12.24 %
SB Large	36.19 % ± 0.76 %	-2.7 % ± 3.97 %	-1.95 % ± 4.09 %	-17.2 % ± 16.59 %
SB Small	35.32 % ± 0.75 %	-5.02 % ± 3.87 %	-5.04 % ± 3.96 %	-4.63 % ± 19.11 %
SB High	38.71 % ± 0.82 %	4.1 % ± 4.25 %	6.92 % ± 4.46 %	-50.7 % ± 9.89 %

Table 37: Varaition in Prediction in 4b SR region.

ThreeTag	Prediction	Diff	QCD	ttbar
Nominal	772.66 % ± 15.95 %	0.00062 % ± 4.13 %	0.0007 % ± 3.92 %	-6.6e-05 % ± 20.31 %
CR High	773.21 % ± 16.04 %	0.071 % ± 4.14 %	1.16 % ± 4.03 %	-8.9 % ± 18.5 %
CR Low	781.85 % ± 16.23 %	1.19 % ± 4.19 %	2.36 % ± 4.08 %	-8.52 % ± 18.58 %
CR Small	776.34 % ± 16.15 %	0.48 % ± 4.16 %	1.5 % ± 4.04 %	-7.97 % ± 18.69 %
SB Large	770.96 % ± 16.1 %	-0.22 % ± 4.14 %	0.43 % ± 4.0 %	-5.56 % ± 19.18 %
SB Small	782.88 % ± 16.36 %	1.32 % ± 4.21 %	2.01 % ± 4.06 %	-4.33 % ± 19.43 %
SB High	787.05 % ± 16.28 %	1.86 % ± 4.21 %	3.29 % ± 4.11 %	-9.92 % ± 18.29 %

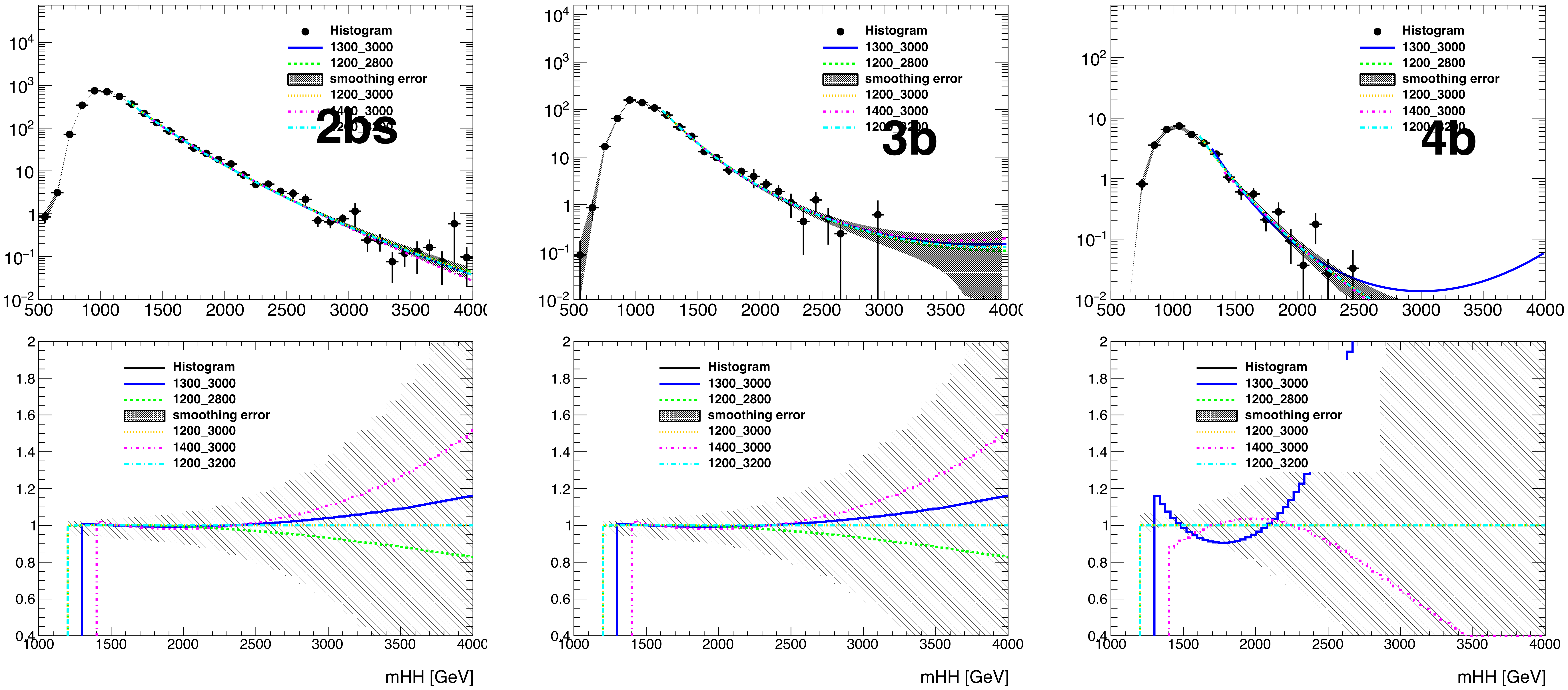
Table 38: Varaition in Prediction in 3b SR region.

TwoTag split	Prediction	Diff	QCD	ttbar
Nominal	4258.01 % ± 27.74 %	7.3e-05 % ± 1.3 %	-9.5e-06 % ± 0.92 %	0.00038 % ± 5.13 %
CR High	4261.42 % ± 27.13 %	0.08 % ± 1.29 %	1.24 % ± 0.94 %	-4.27 % ± 4.91 %
CR Low	4276.75 % ± 27.24 %	0.44 % ± 1.29 %	1.59 % ± 0.94 %	-3.88 % ± 4.93 %
CR Small	4273.59 % ± 27.14 %	0.37 % ± 1.29 %	1.65 % ± 0.94 %	-4.45 % ± 4.9 %
SB Large	4274.69 % ± 26.8 %	0.39 % ± 1.28 %	2.23 % ± 0.95 %	-6.49 % ± 4.79 %
SB Small	4272.43 % ± 27.38 %	0.34 % ± 1.3 %	1.22 % ± 0.94 %	-2.97 % ± 4.97 %
SB High	4288.75 % ± 26.83 %	0.72 % ± 1.29 %	2.65 % ± 0.95 %	-6.51 % ± 4.79 %

Table 39: Varaition in Prediction in 2bs SR region.

Functional Range

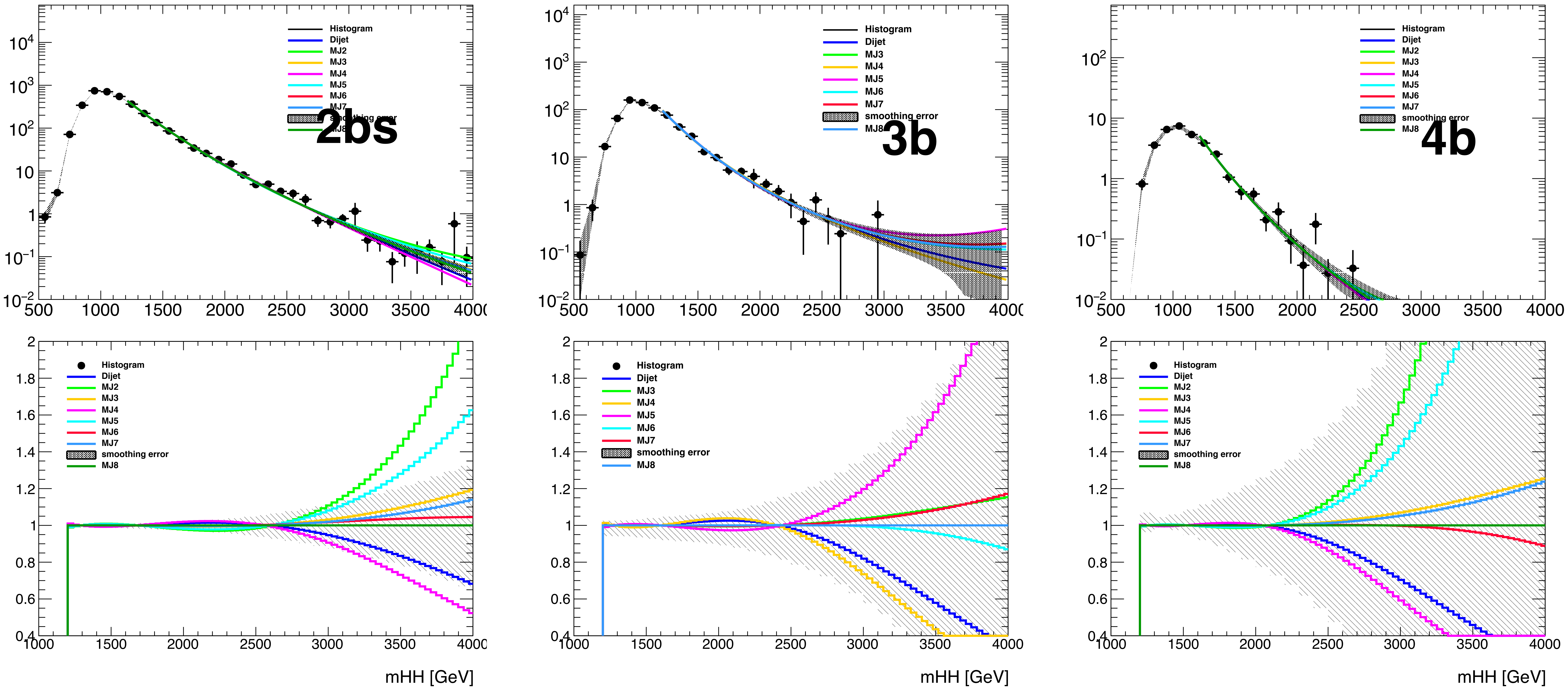
- Default is 1200-3000 GeV, vary range in SR prediction; drop the variations with prob < 0.001 and large normalization differences



Functional Form variations

- Default is MJ8, vary smoothing function in SR prediction

Name	Functional Form
MJ1 (Dijet)	$f_1(x) = p_0(1-x)^{p_1}x^{p_2}$
MJ2	$f_2(x) = p_0(1-x)^{p_1}e^{p_2 x^2}$
MJ3	$f_3(x) = p_0(1-x)^{p_1}x^{p_2 x}$
MJ4	$f_4(x) = p_0(1-x)^{p_1}x^{p_2 \ln x}$
MJ5	$f_5(x) = p_0(1-x)^{p_1}(1+x)^{p_2 x}$
MJ6	$f_6(x) = p_0(1-x)^{p_1}(1+x)^{p_2 \ln x}$
MJ7	$f_7(x) = \frac{p_0}{x}(1-x)^{p_1 - p_2 \ln x}$
MJ8	$f_8(x) = \frac{p_0}{x^2}(1-x)^{p_1 - p_2 \ln x}$



End of Back-ups