ATLAS HH → 4b

Analysis Strategy with focus on non-resonant

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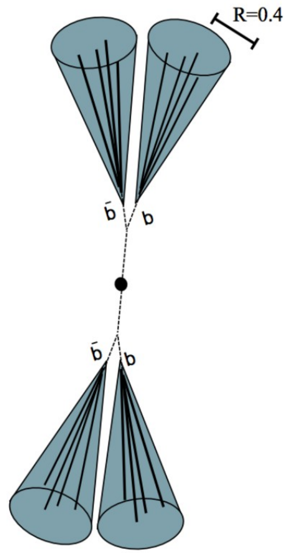
Di-Higgs Workshop September 2018

HH → 4b Overview

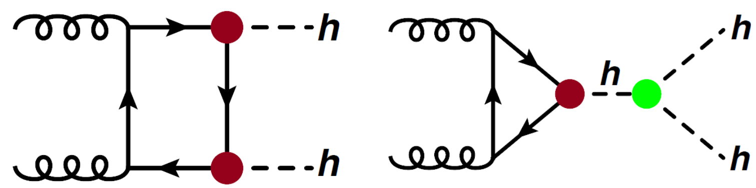
2015+2016 Paper: https://arxiv.org/abs/1804.06174 (submitted to JHEP)

Resolved Analysis

260 – 1400 GeV

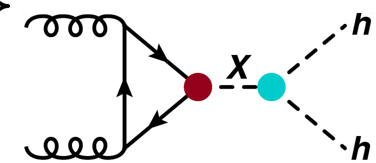


Search for non-resonant



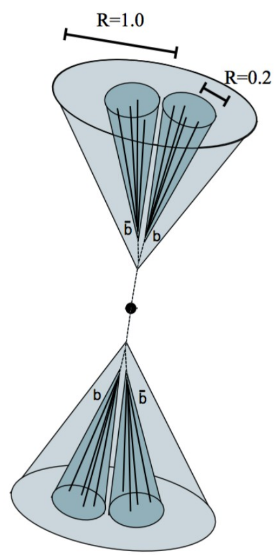
Reconstruction of four small-radius jets
b-tagging applied to all of them

Search for resonances



Boosted Analysis

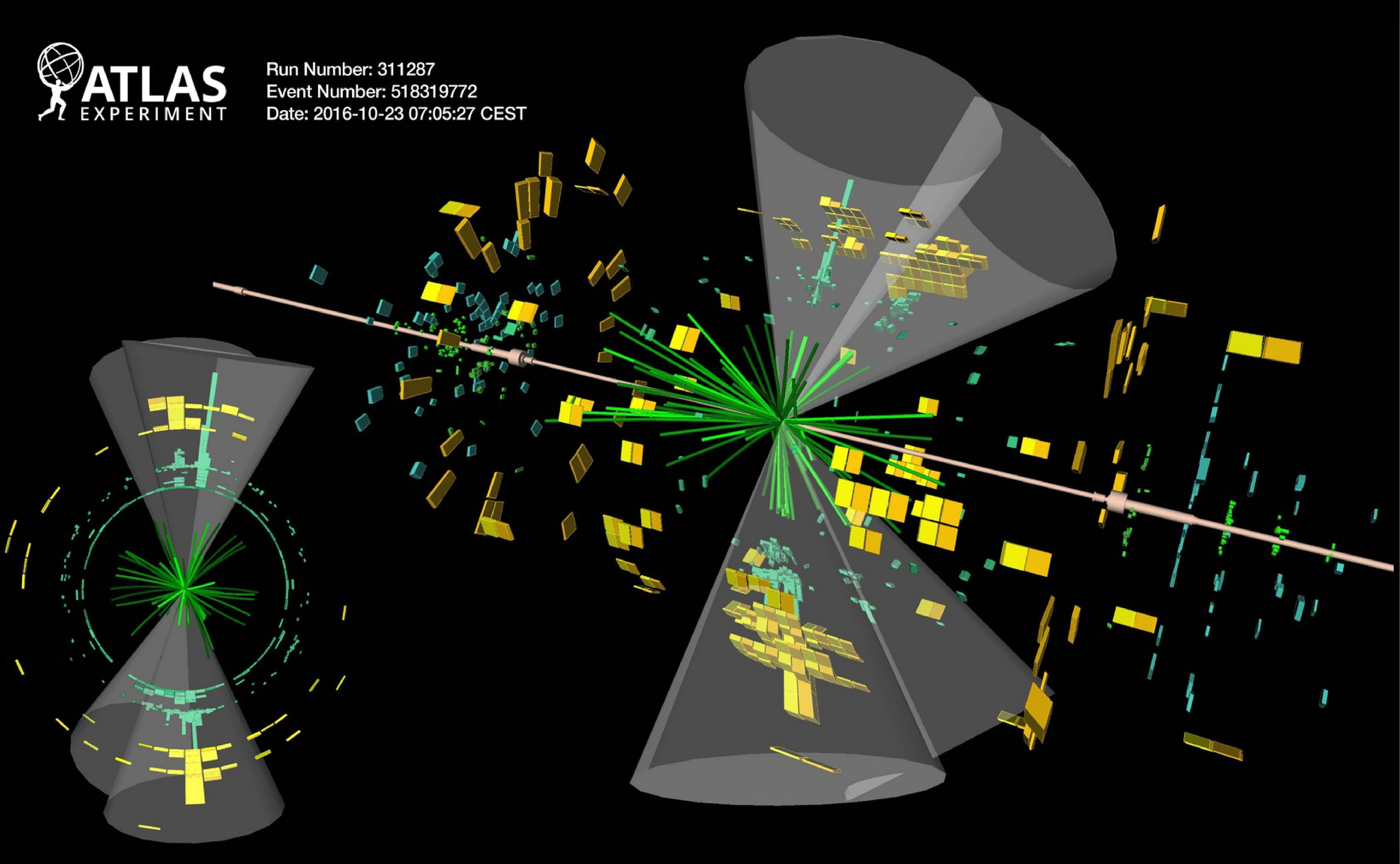
800 – 3000 GeV



Reconstruction of two large-radius jets

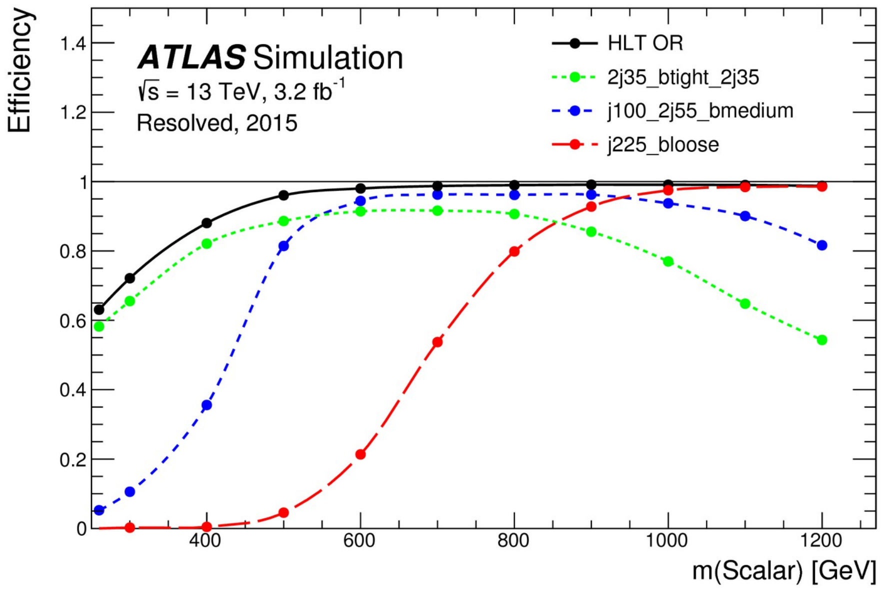
b-tagging of the associated track-jets

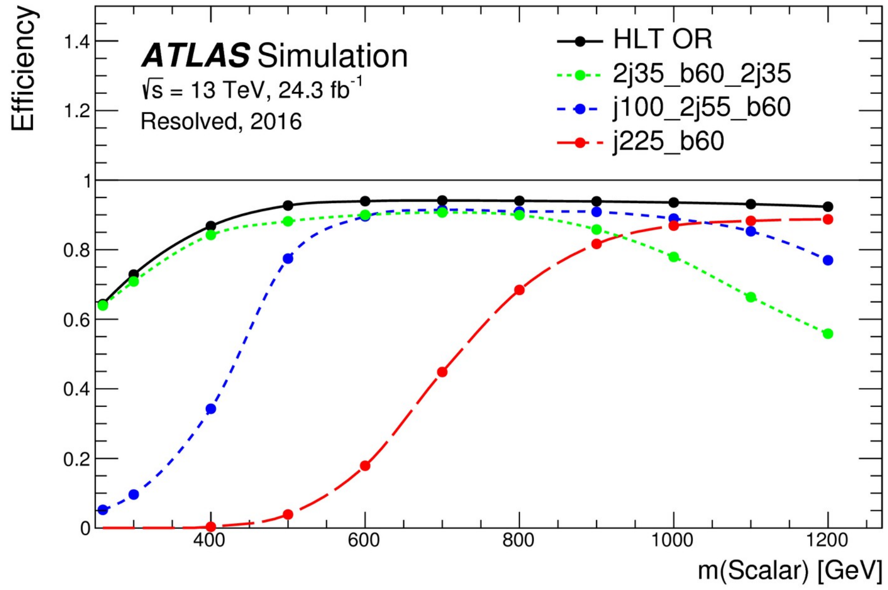
Categories based on number of b-tags


ATLAS
EXPERIMENT
Run Number: 311287
Event Number: 518319772
Date: 2016-10-23 07:05:27 CEST

Resolved: Event Selection

- Trigger: requires one or two jets passing online b-tagging (plus additional non b-tagged jets)





- Trigger is about 65% efficient for low-mass resonant signal, ≥95% efficient for mX > 600 GeV
- Jet reconstruction: anti-kT jets with R=0.4, pT > 40 GeV and |η|<2.5
- Offline b-tagging using the MV2c10 algorithm, 70% efficient for b-jets with pT>20 GeV from ttbar decays
  The four jets with highest b-tagging score are used in the analysis

→ more details on trigger in the talk from John

→ more details on b-tagging in the talk by Luca (and boosted b-tagging in the talk by Michael)

Resolved: Event Selection

Pairing jets to Higgs candidates (HC):

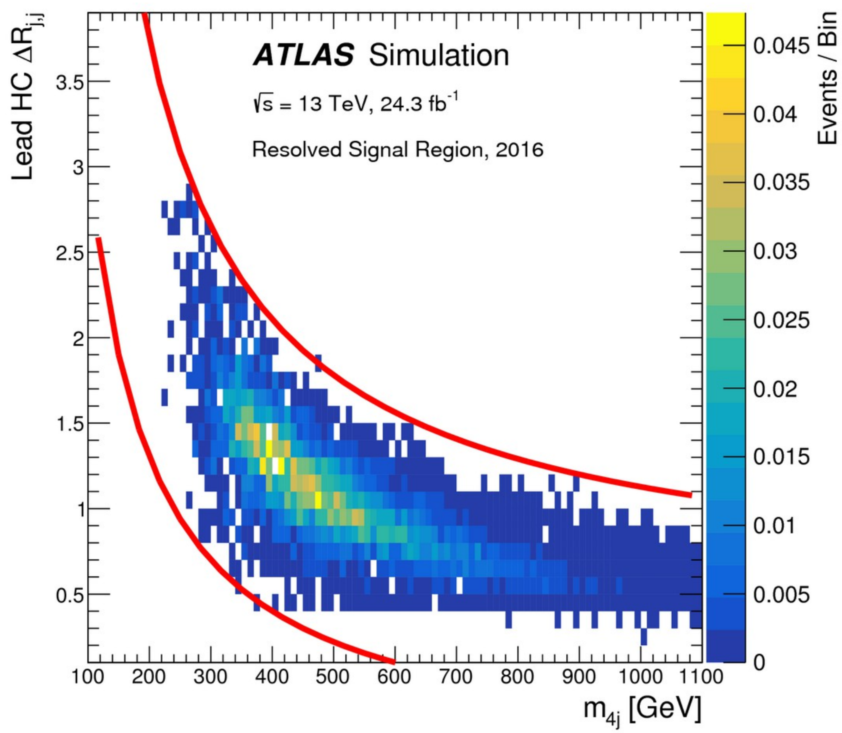
- Angle between the 2 jets from a Higgs boson decay depends on the Lorentz boost and thus m4j

- m4j-dependent requirements on ΔR(j,j) applied, rejects background

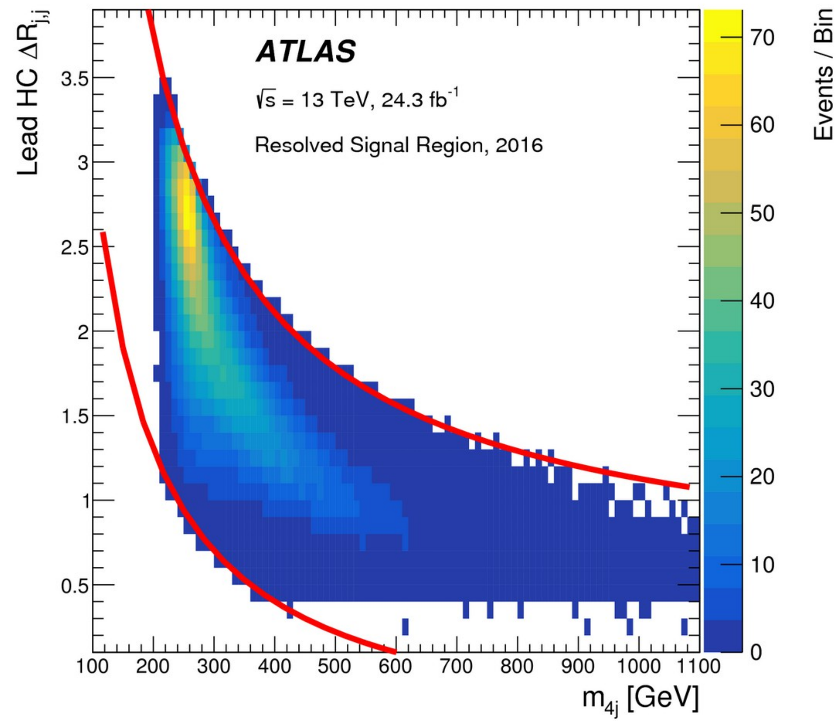
$$\left.\begin{array}{l} \dfrac{360\text{ GeV}}{m_{4\text{j}}} - 0.5 < \Delta R_{jj,\text{lead}} < \dfrac{653\text{ GeV}}{m_{4\text{j}}} + 0.475 \\ \dfrac{235\text{ GeV}}{m_{4\text{j}}} < \Delta R_{jj,\text{subl}} < \dfrac{875\text{ GeV}}{m_{4\text{j}}} + 0.35 \end{array}\right\} \text{if } m_{4\text{j}} < 1250\text{ GeV}.$$

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

Non-resonant signal

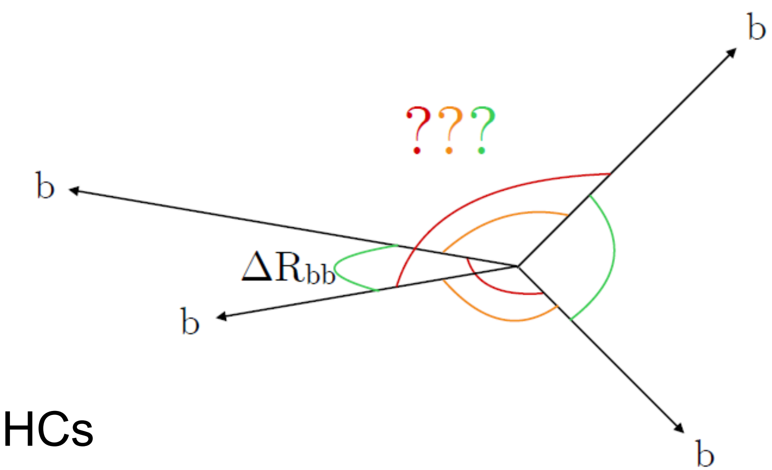


Background



Example: m4j = 300 GeV

leading candidate	$0.7 < \Delta R < 2.6$
sub-leading candidate	$0.8 < \Delta R < 3.3$



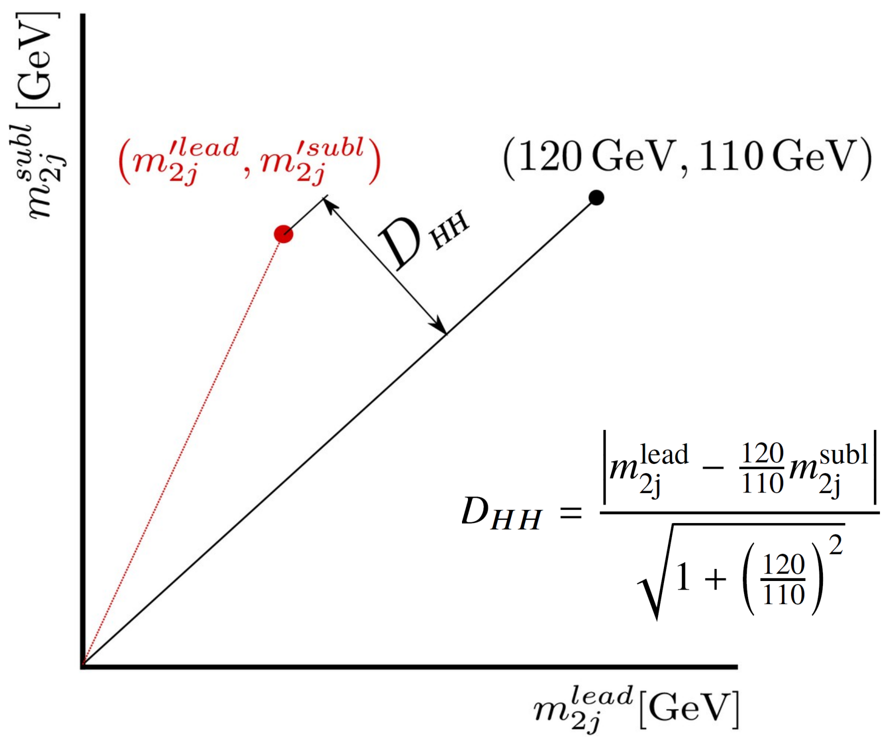
Low m4j means the opening angles can be large → difficult to pair the jets to HCs

Resolved: Event Selection

What if more than two Higgs candidate pairings pass these requirements?

→ Need smart alogithm to pair the jets, that is most consistent with a Di-Higgs topology, ie. the decay of two particles of equal mass

→ Semi-leptonic B-decays lead to energy loss → mass equality needs modification (120 GeV, 110 GeV)



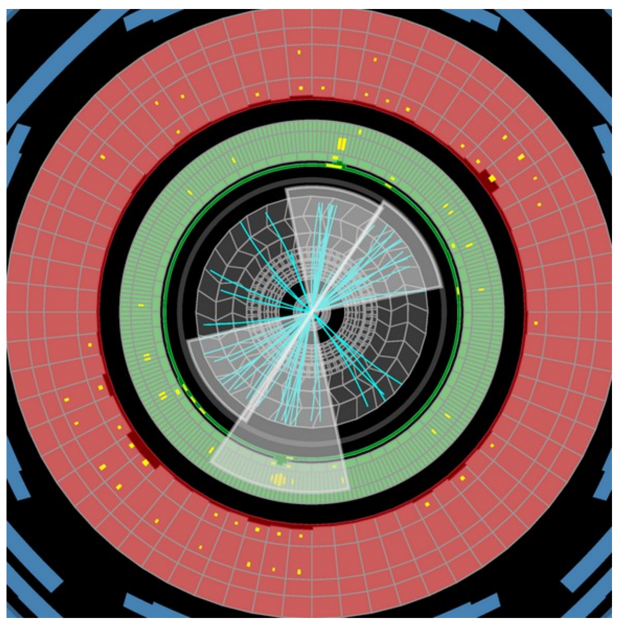
$$D_{HH} = \frac{\left| m_{2j}^{\text{lead}} - \frac{120}{110} m_{2j}^{\text{subl}} \right|}{\sqrt{1 + \left(\frac{120}{110}\right)^2}}$$

Using D_{HH} also prevents background scuplting into the signal region

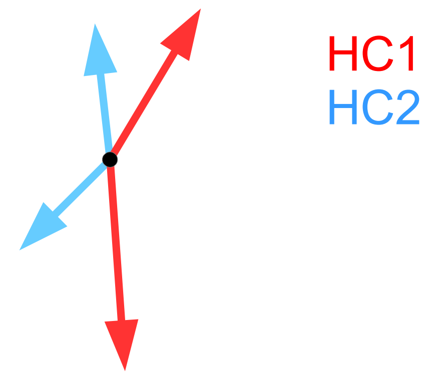
D_{HH} quantifies the distance of the masses from the line connecting (0,0) and (120, 110) GeV (optimized from simulation)

The pairing that minimizes D_{HH} is chosen

In simulation, this leads to at least 90% correct pairings



← 2016 data event, m4j = 272 GeV



Resolved: Event Selection

Further cuts:

m4j-dependent pT cuts on the Higgs candidates:

$$p_{\mathrm{T}}^{\mathrm{lead}} > 0.5 m_{4\mathrm{j}} - 103\ \mathrm{GeV}$$

$$p_{\mathrm{T}}^{\mathrm{subl}} > 0.33 m_{4\mathrm{j}} - 73\ \mathrm{GeV}$$

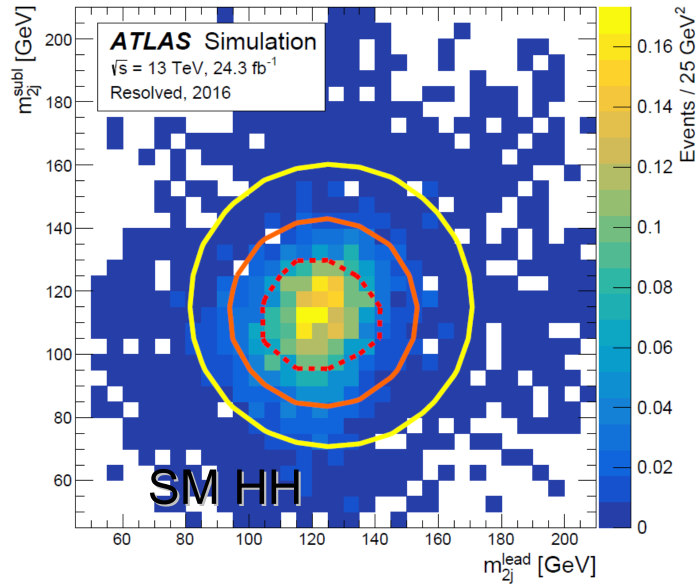
Pseudo-rapidity difference between the HCs:

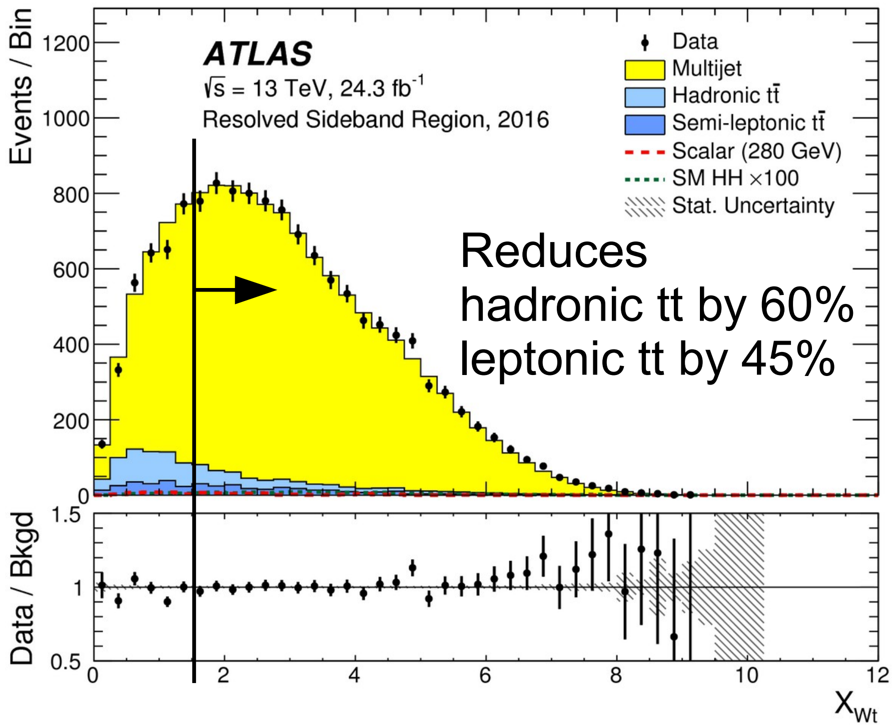
$$|\Delta\eta_{HH}| < 1.5$$

Signal region selection in the 2D HC mass plane:

$$X_{HH} = \sqrt{\left(\frac{m_{2\mathrm{j}}^{\mathrm{lead}} - 120\ \mathrm{GeV}}{0.1 m_{2\mathrm{j}}^{\mathrm{lead}}}\right)^2 + \left(\frac{m_{2\mathrm{j}}^{\mathrm{subl}} - 110\ \mathrm{GeV}}{0.1 m_{2\mathrm{j}}^{\mathrm{subl}}}\right)^2} < 1.6$$

$0.1\ m_{2j}$ represents the HC mass resolution





Top veto:

- Build a hadronic top candidate from any combination of three jets, of which one must be a constituent of a HC

- jet with highest b-tagging score is considered the b from the top decay, the other jets from the W candidate

- The top candidate is that with the smallest X_{Wt}

$$X_{Wt} = \sqrt{\left(\frac{m_W - 80\ \mathrm{GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 173\ \mathrm{GeV}}{0.1 m_t}\right)^2}$$

Top veto requires

$X_{Wt} > 1.5$

Resolved: Event Selection

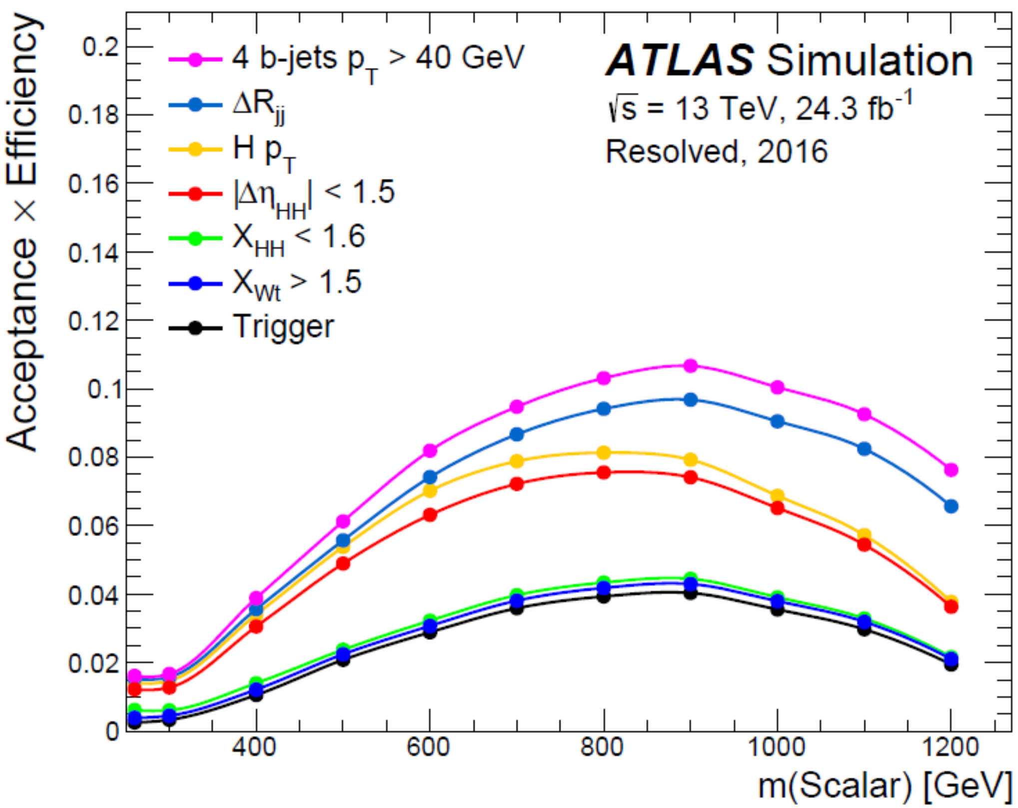
Acceptance x efficiency:

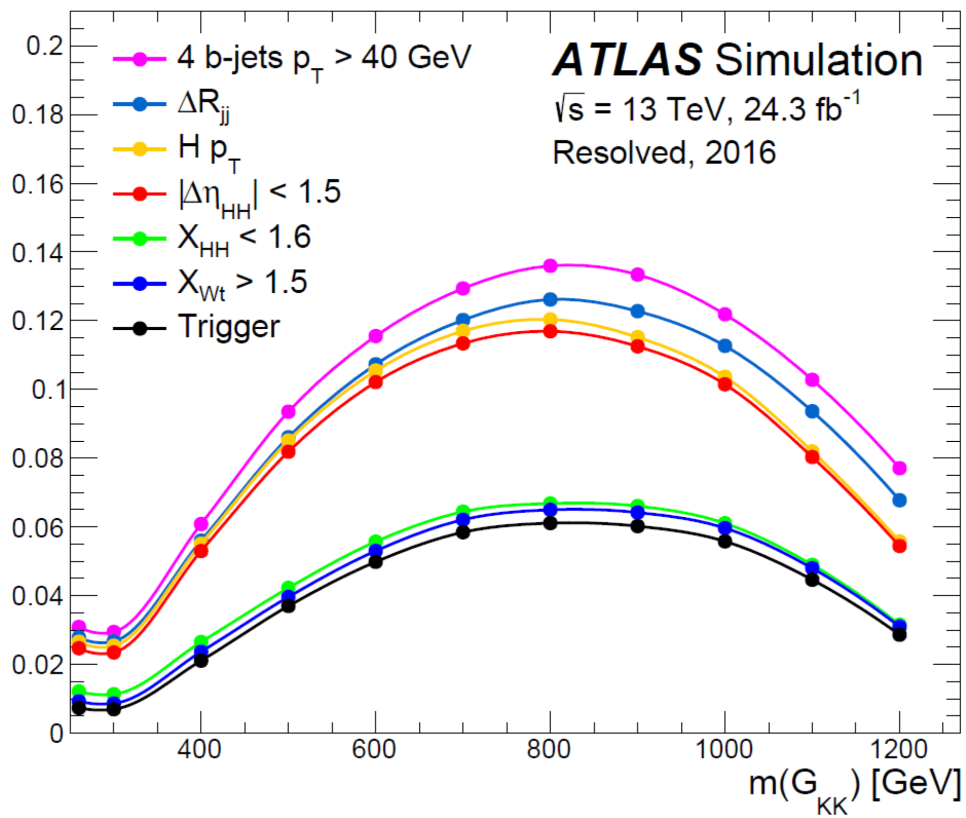
Limited at low mass by the pT requirements on the jets

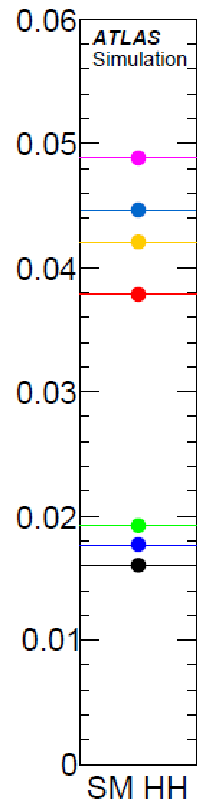
At higher masses the chance to resolve 4 jets decreases (→ boosted regime), b-tagging efficiency deteriorates

1.6% signal efficiency for non-resonant (slightly higher for 2015 dataset due to trigger)

Graviton acceptance a bit higher due to central decay and higher pT jets

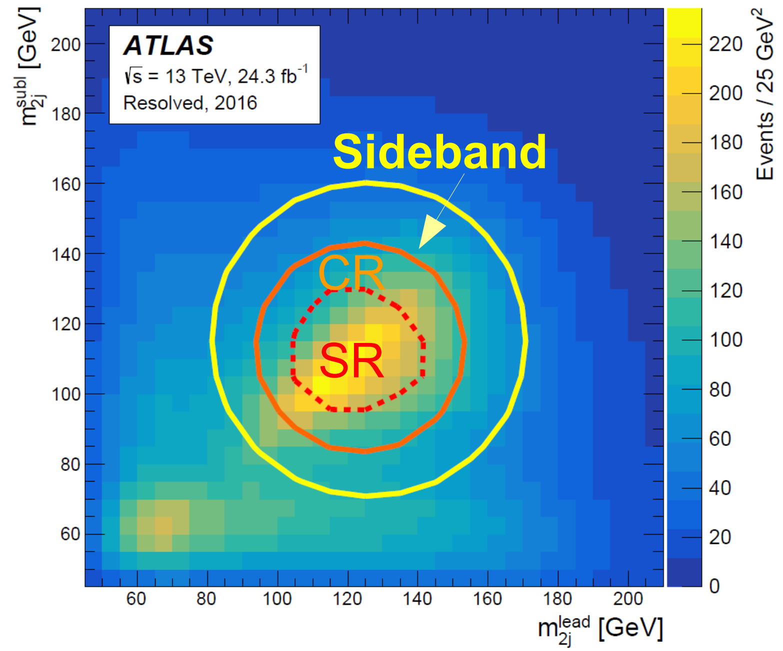






Resolved: Background Estimation

After event selection, 95% of the events are multijet events, remaining 5% is ttbar



Data-driven estimation of the background model:

- Selection of the two-tag sample (contains ≥4 jets, exactly 2 of them b-tagged)

- Application of two weights (combinatorial, kinematic), obtained from the sideband, to make the 2b data look more like 4b data

- Determining the normalization of multijet and ttbar

- An alternative background model is derived from the control region (CR), is used for validation and to derive a systematic uncertainty

Resolved: Background Estimation

(1) Combinatorial weight

To use 2-btag events to model ≥4-btag events, must promote at least two other jets to b-tagged jets („pseudo-tagged“)

If simply pseudo-tagging 2 jets for each event, there is a bias in the model towards lower jet multiplicities :(
Also expect subtle implications from different g → bb rates in both samples.

If an event has more than 2 non-b-tagged jets, there is a combinatorial problem

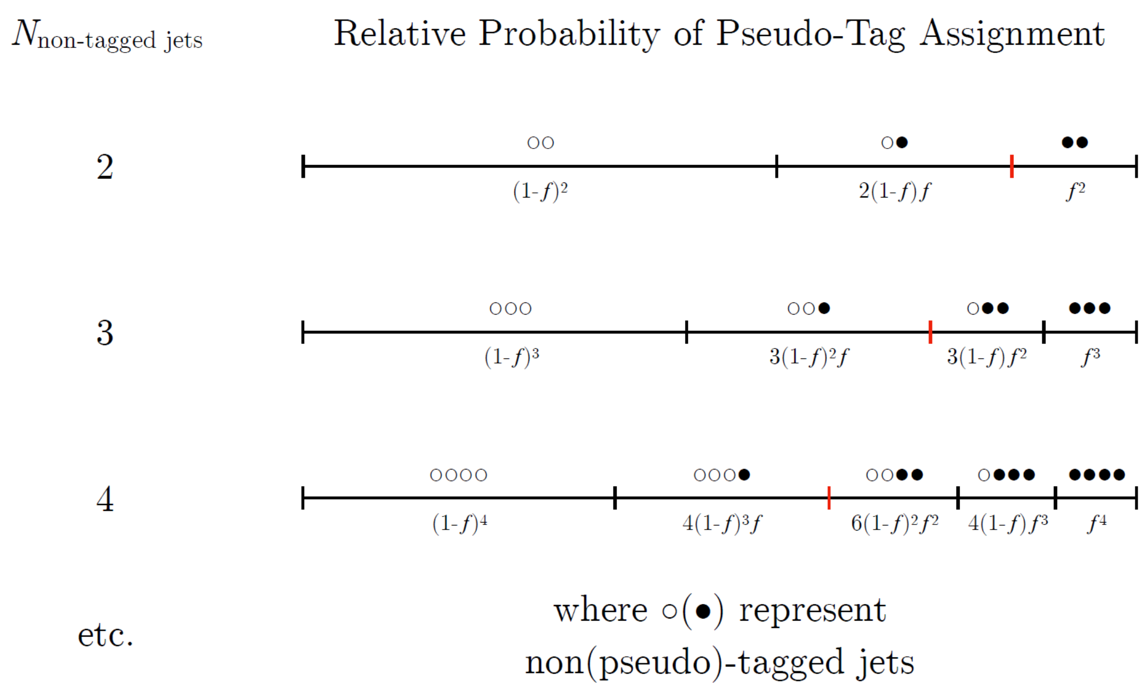
→ All possible combinations are considered (eg. if 4 non-b-tagged jets, there are 11 combinations)

→ Assign a factor f to those jets that get pseudo-tagged, and (1-f) to those which don't get pseudo-tagged, and build a term for each combination

→ Weight the event with the sum of those terms

→ Randomly select one combination and proceed with the event selection

Pseudo-tag rate f is obtained by tuning the agreement of the jet multiplicity between 4b region and the model



Resolved: Background Estimation

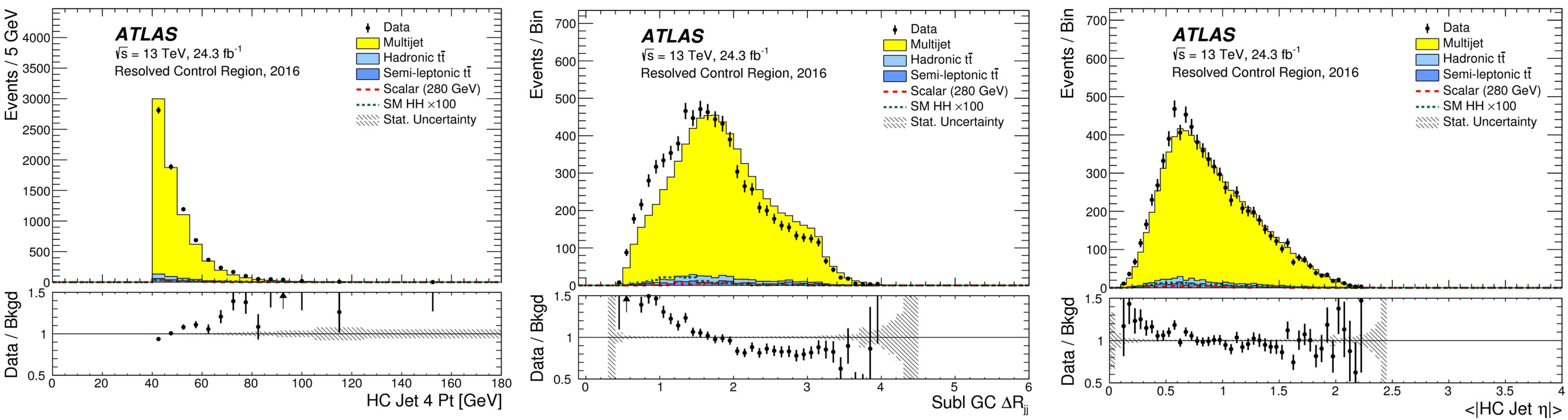
(2) Kinematic weight

Kinematics betwen 2b and the 4b region are not the same, due to:
differences in b-tagging and trigger efficiencies, varying gluon and quark initiated jet fractions

Five sensitive distributions used to iteratively derive weights (fitting cubic splines to the ratios):

- average |η| of the four jets constituting the HCs
- pT of 2nd and 4th leading constituent jet
- smallest ΔR between any two constituent jets
- ΔR between the two other jets

No weights applied:



Resolved: Background Estimation

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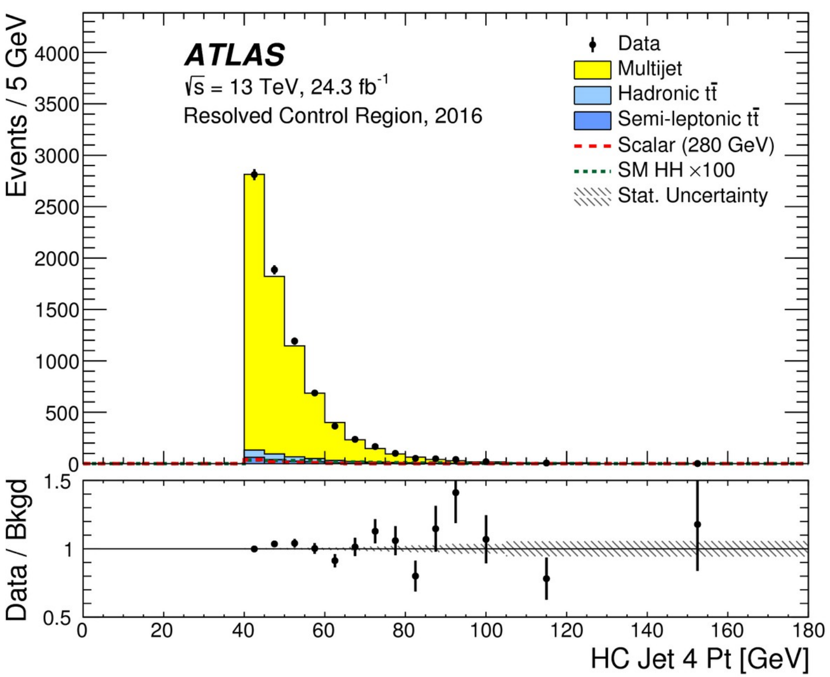
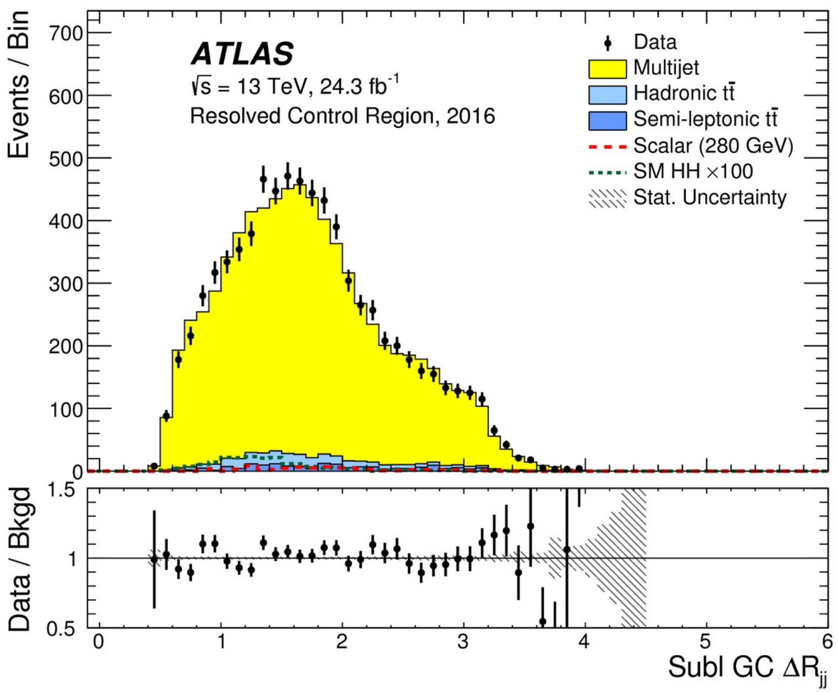
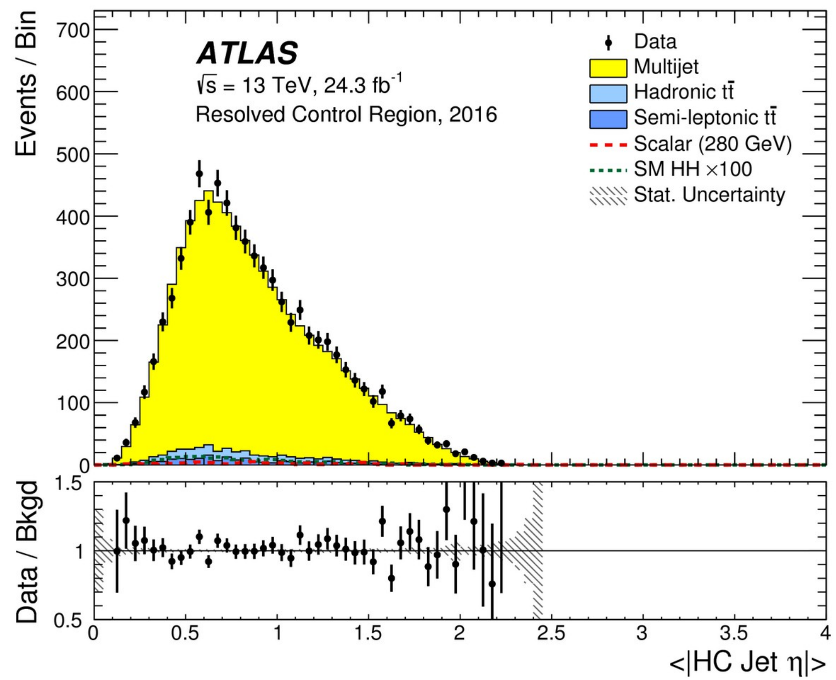
Reweighted:







Resolved: Background Estimation

(3) Normalization of multijet and ttbar

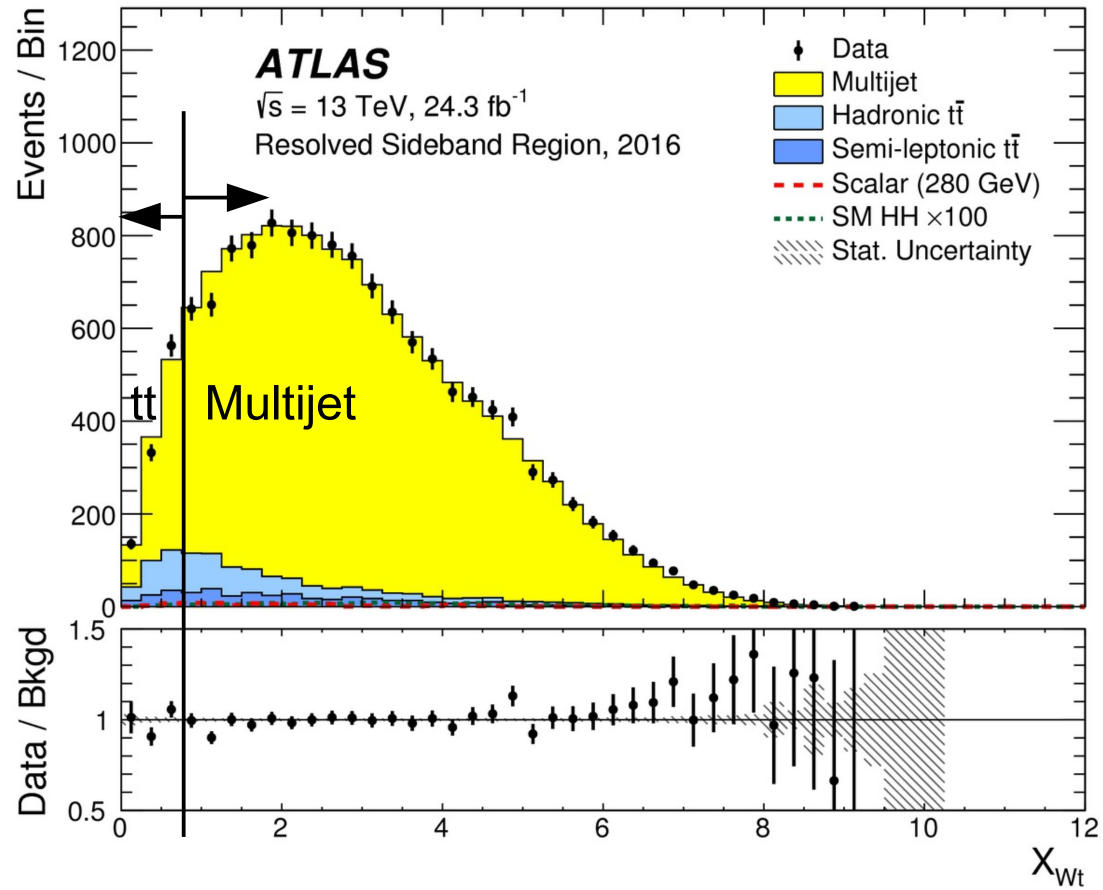
Normalization obtained in a simultaneous fit in three background-enriched regions

(1) „Semileptonic ttbar sample“: $X_{Wt} < 1.5$, presence of an isolated muon with pT > 25 GeV

(2) „Hadronic tt sample“: $X_{Wt} < 0.75$

(3) „Multijet sample“: $X_{Wt} > 0.75$

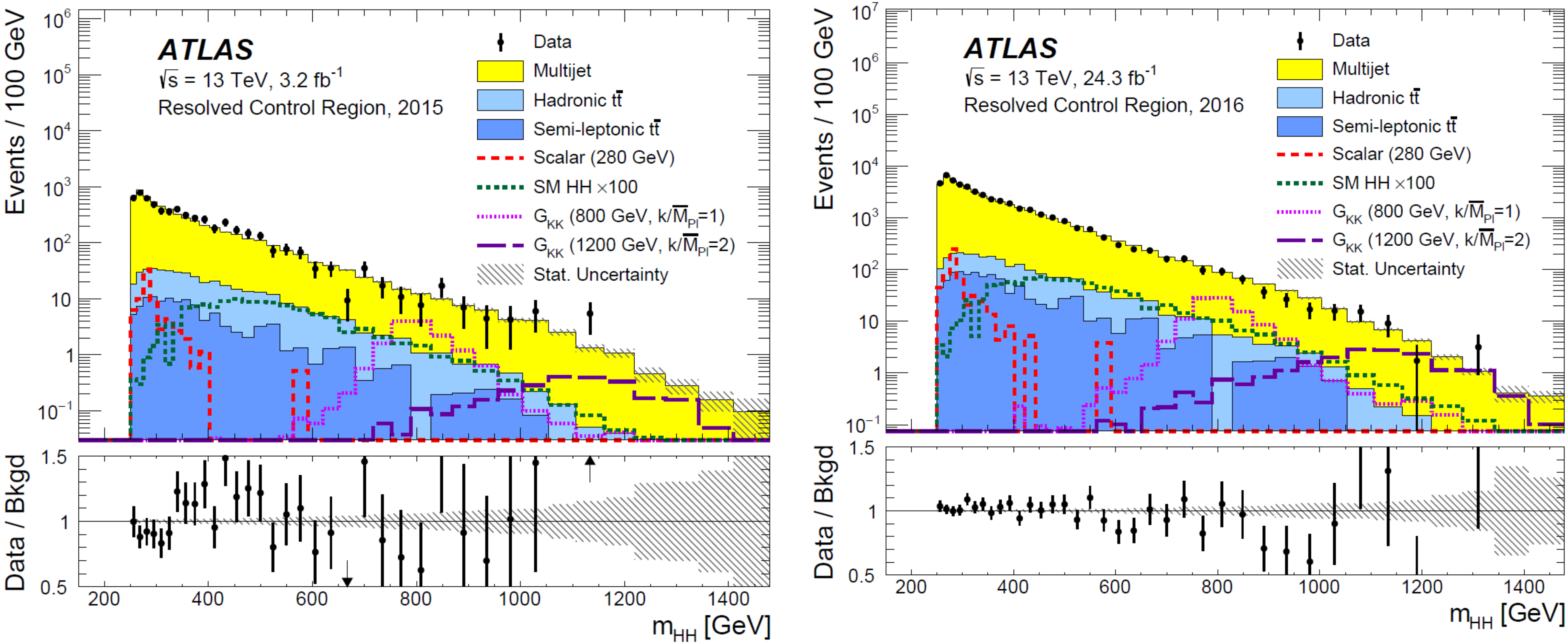
Dataset	f	μ_{multijet}	$\alpha_{t\bar{t}}^{\text{hadronic}}$	$\alpha_{t\bar{t}}^{\text{semileptonic}}$
2015	0.22	0.0838 ± 0.0038	1.19 ± 0.45	1.44 ± 0.48
2016	0.15	0.2007 ± 0.0031	1.15 ± 0.25	1.7 ± 0.19



The three samples are not mutually exclusive, but correlations are considered in the fit.

Resolved: Background Estimation

Validation of the entire background model in the CR



Many kinematic distributions were checked to validate the background model,
in addition also looked at low and high mass validation regions where the mass centers were shifted

For m_{HH} reconstruction, 4-vectors rescaled to force the HC mass to 125 GeV

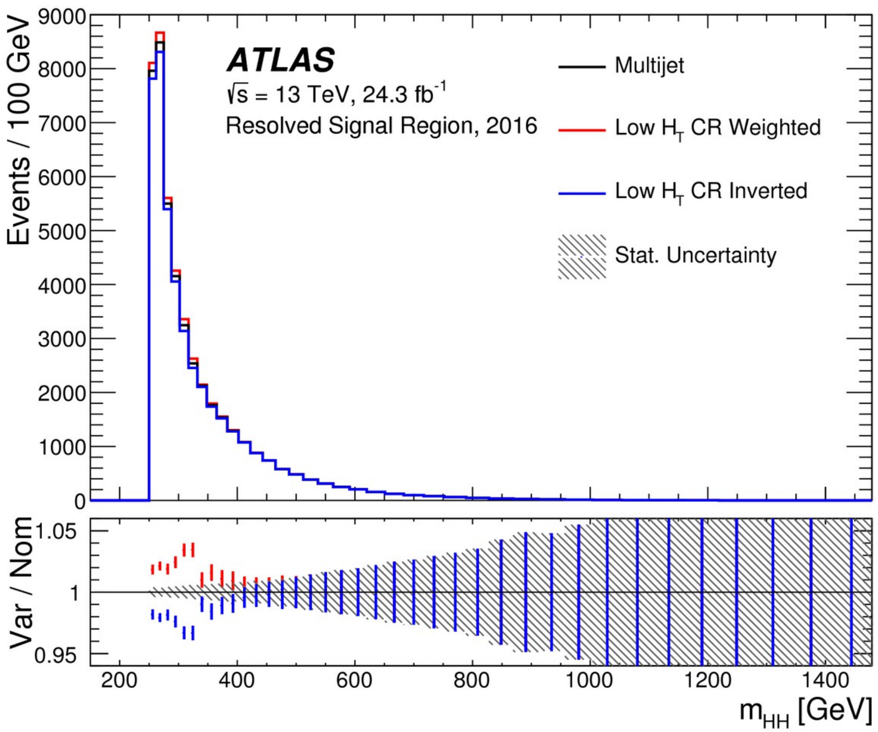
Resolved: Systematic Uncertainties

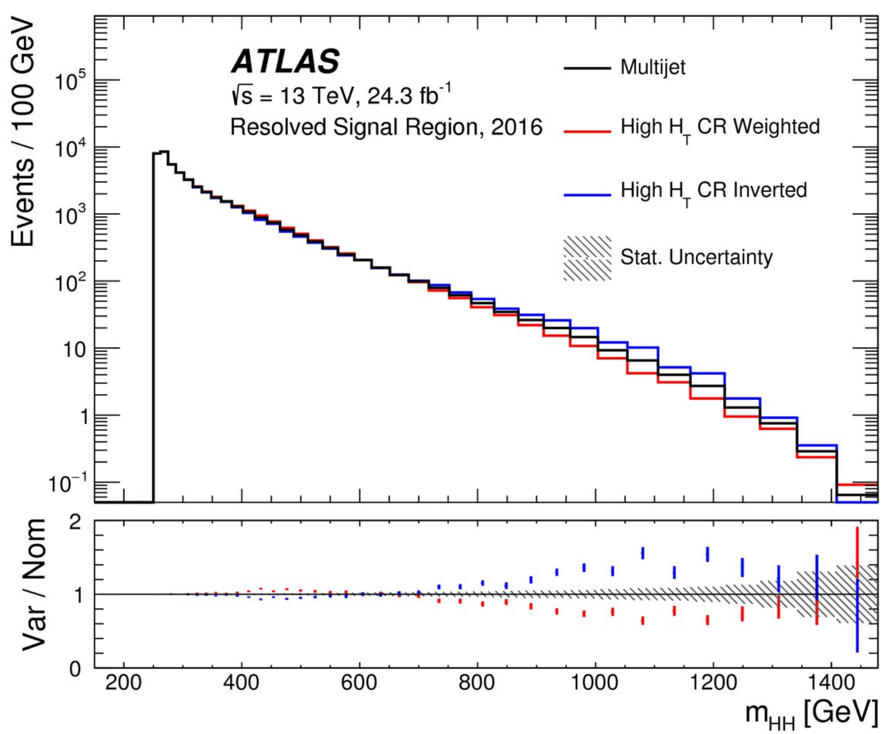
Uncertainties on the signal:

- b-tagging, trigger, jet resolution

- theory uncertainties from varying PDF, scales, parton shower, ISR/FSR

Source	2015 Background	2015 Scalar	2015 SM HH	2015 G_{KK}	2016 Background	2016 Scalar	2016 SM HH	2016 G_{KK}
Luminosity	–	2.1	2.1	2.1	–	2.2	2.2	2.2
Jet energy	–	17	7.1	3.7	–	17	6.4	3.7
b-tagging	–	13	12	14	–	13	12	14
b-trigger	–	4.0	2.3	1.3	–	2.6	2.5	2.5
Theoretical	–	23	7.2	0.6	–	23	7.2	0.6
Multijet stat	4.2	–	–	–	1.5	–	–	–
Multijet syst	6.1	–	–	–	1.8	–	–	–
$t\bar{t}$ stat	2.1	–	–	–	0.8	–	–	–
$t\bar{t}$ syst	3.5	–	–	–	0.3	–	–	–
Total	7.5	31	16	15	1.8	31	16	15

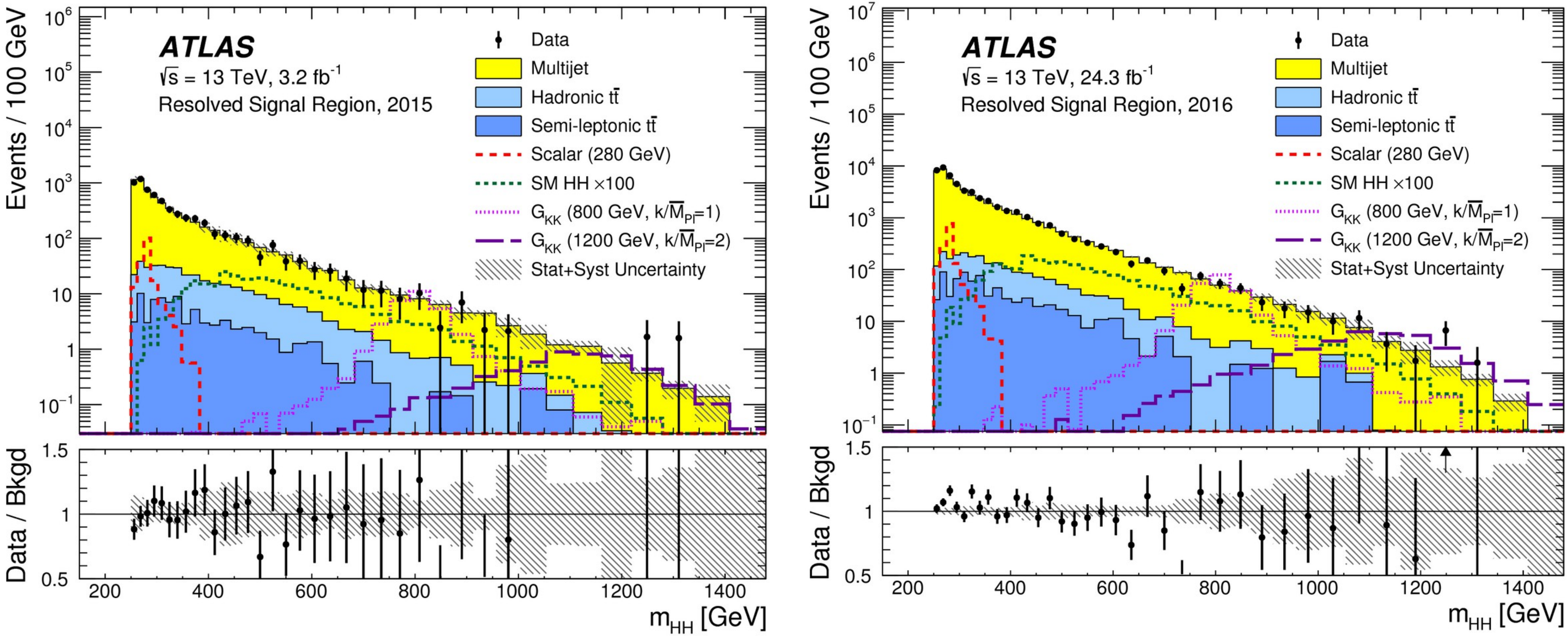




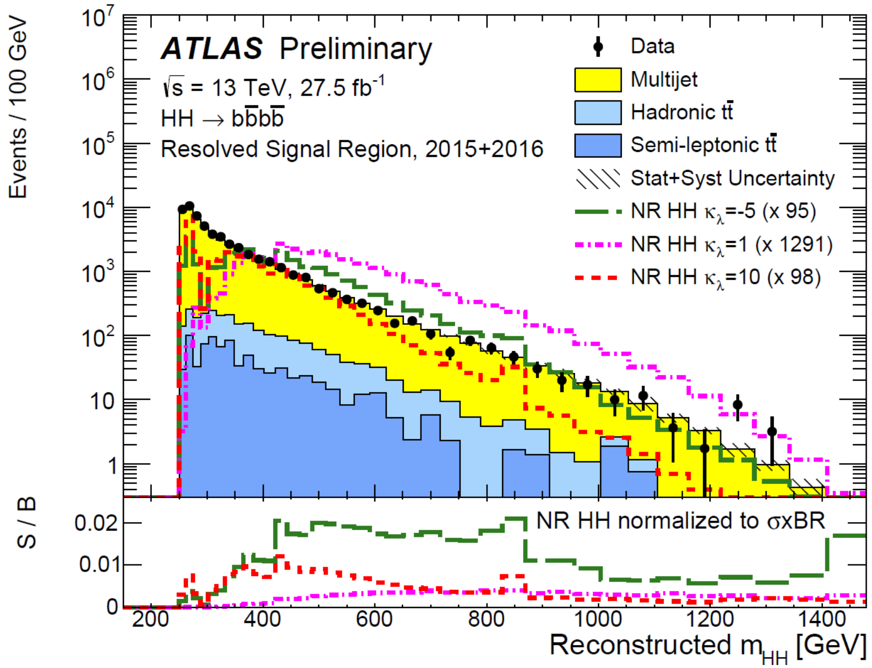
Leading uncertainty is the difference between the SB-derived vs. CR-derived background model

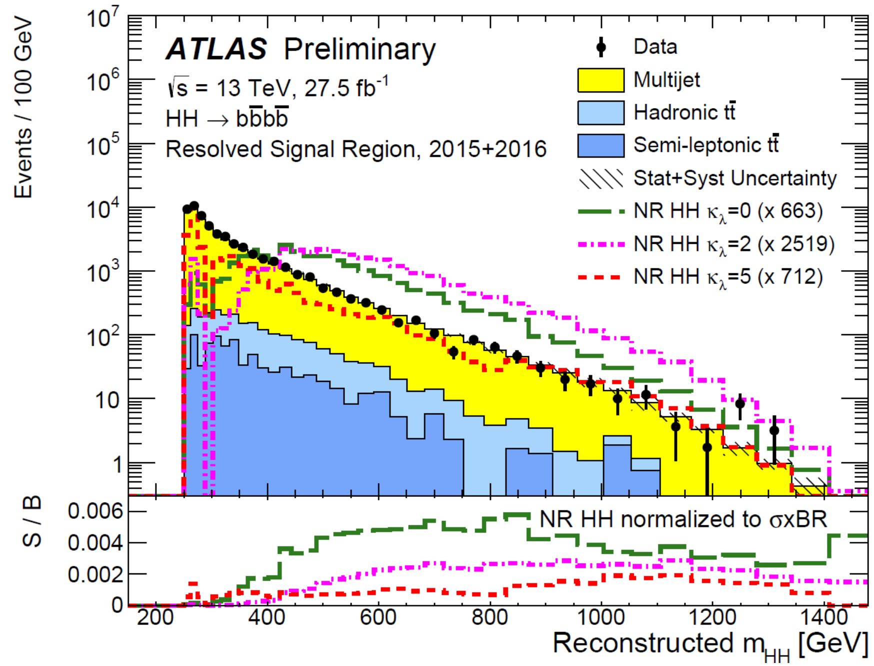
The impact on the shape is split into low and high component to give the fit more flexibility

m4j spectrum in the signal region

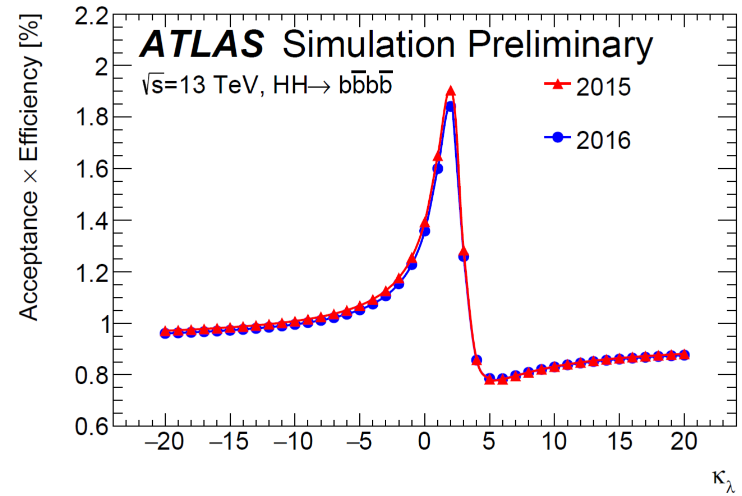


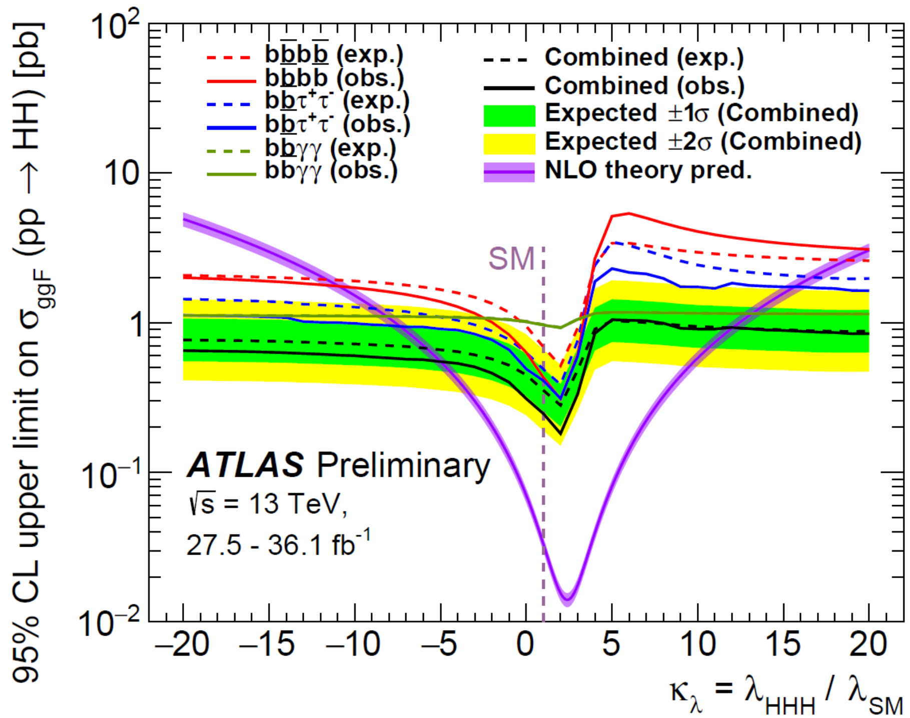
Non-resonant Results (obtained from resolved only)





Signal efficiency vs. κ_λ:





95% CL limits in units of ggF SM HH → 4b prediction (11.3 fb):

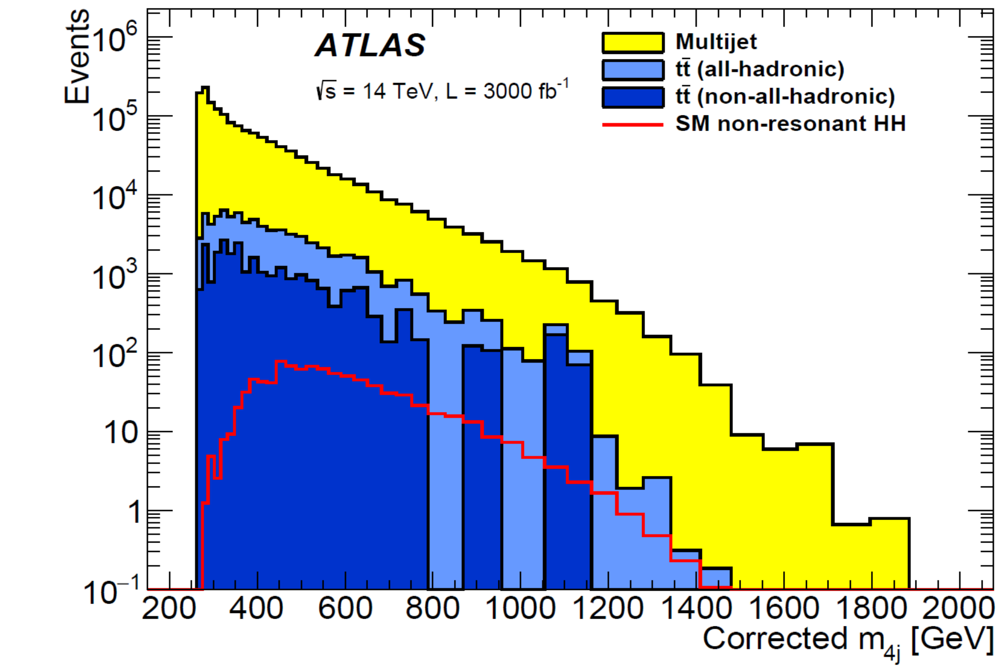
Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
12.9	11.1	14.9	20.7	30.0	43.6

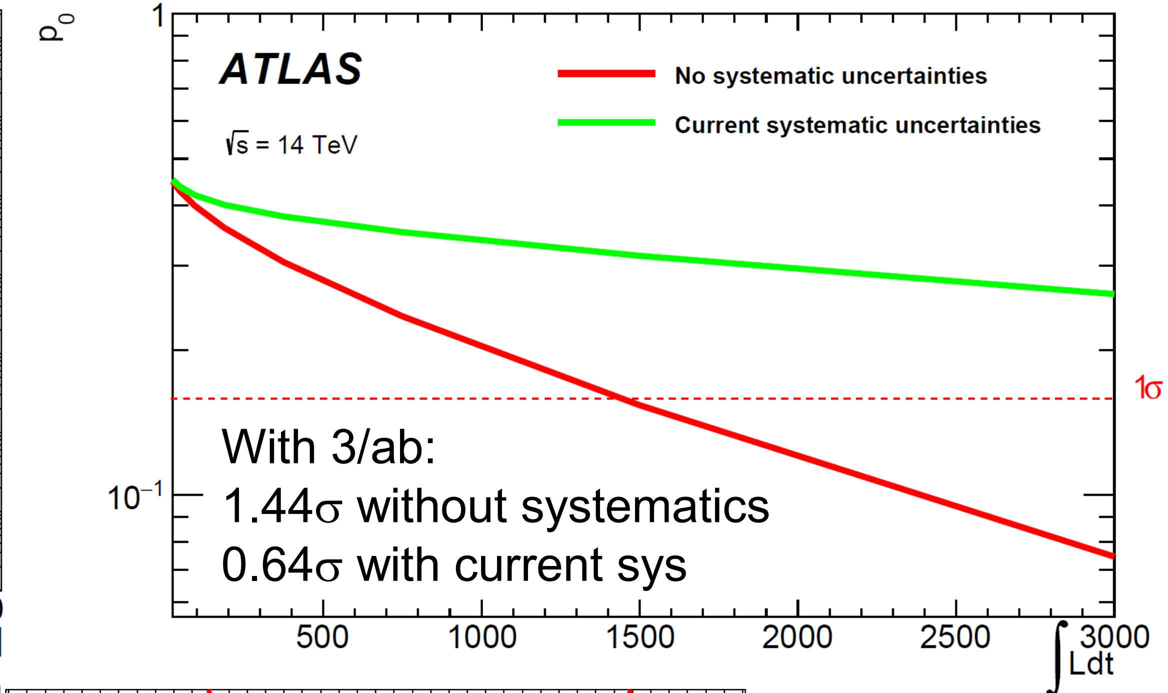
Stat-only expected: 18.5

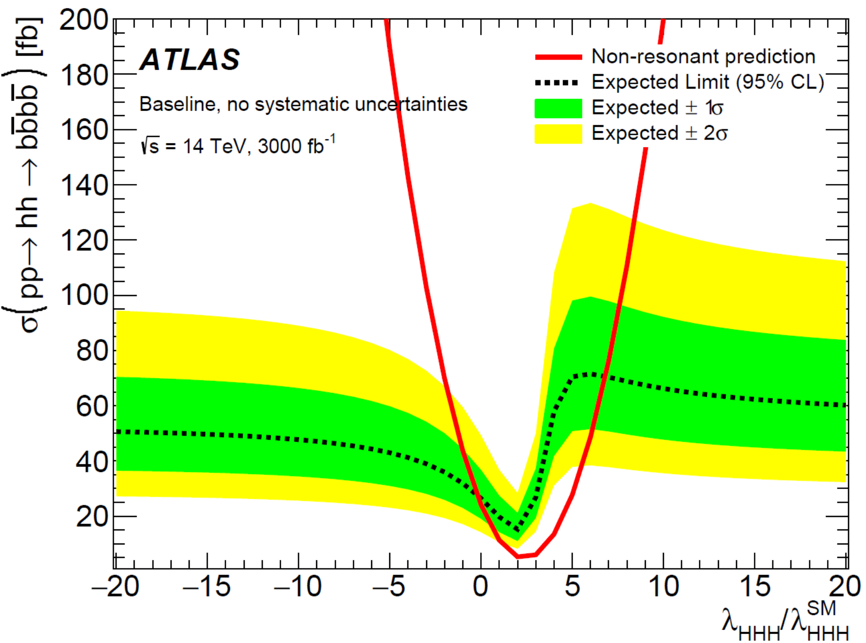
- ATLAS combined non-resonant limit: 6.7 (exp 10.4) x SM
- Truth level reweighted m_{HH} to probe the limit for variations of trilinear Higgs coupling $\kappa_\lambda = \lambda_{HHH} / \lambda_{SM}$
- Very weak limit around lamdba = 5 due to degeneracy of signal and background m4j shapes

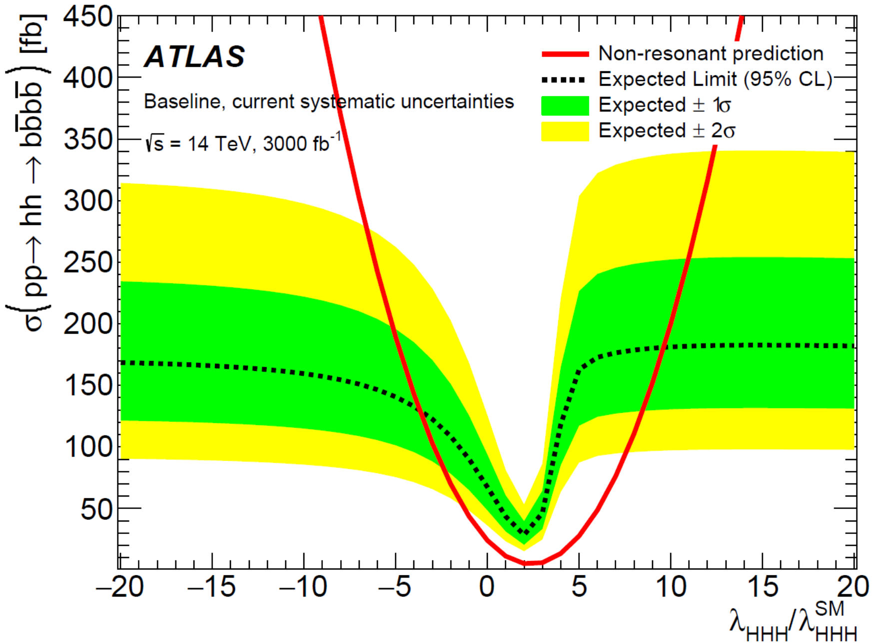
HL-LHC Prospects for non-resonant HH:

Extrapolating the current 4b analysis to 14 TeV and large luminosities:









Self-coupling can be constrained to:

$-1.3 < \kappa_\lambda < 8.0$ (stat-only)

$-4.1 < \kappa_\lambda < 8.8$ (current systematics)

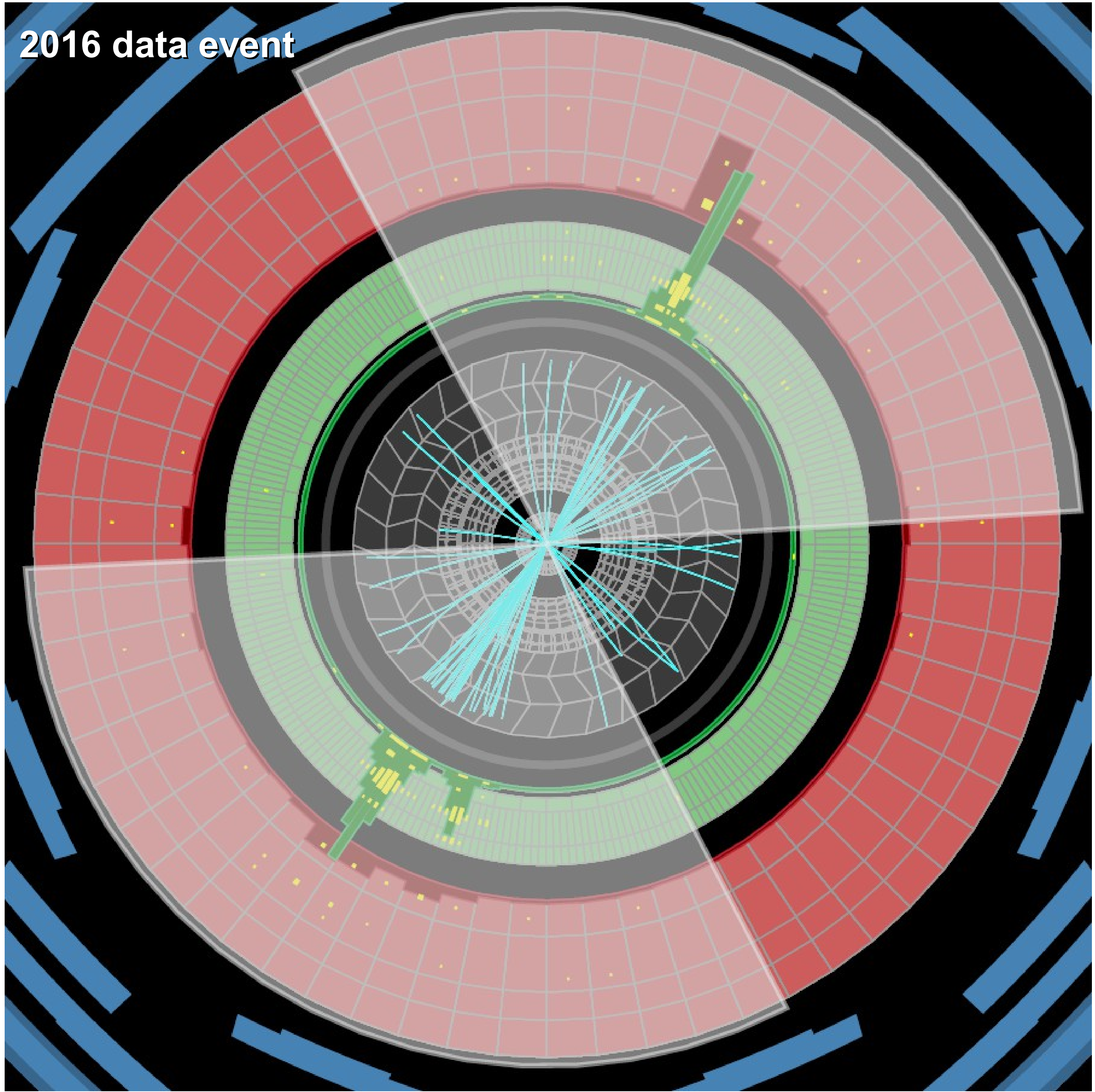
But this might be very optimistic, because the pT threshold of the jets could be raised in run-3 due to trigger limitations

Boosted Analysis

Performed for resonances with masses 800-3000 GeV
In many aspects quite similar to the resolved analysis

Event selection:

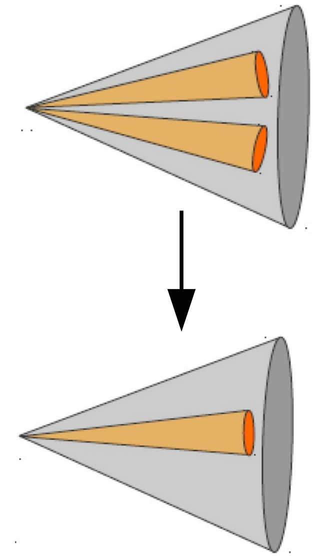
- Large-R jet trigger (pT > 360 or 420 GeV) (100% efficicient for signal passing the selection)
- Reconstruct ≥2 large-R jets (R=1.0) with pT>250 GeV, $|\eta|<2.0$, $m_J>50$ GeV
- Leading jet pT > 450 GeV
- $|\Delta\eta_{JJ}| < 1.7$, $X_{HH} < 1.6$
- Each jet must contain ≥1 ghost-associated track jet (R=0.2)
- B-tagging (70% WP) applied to track-jets (2, 3 or 4 b-tags)
- Remove overlap to resolved selection (priority goes to resolved analysis)

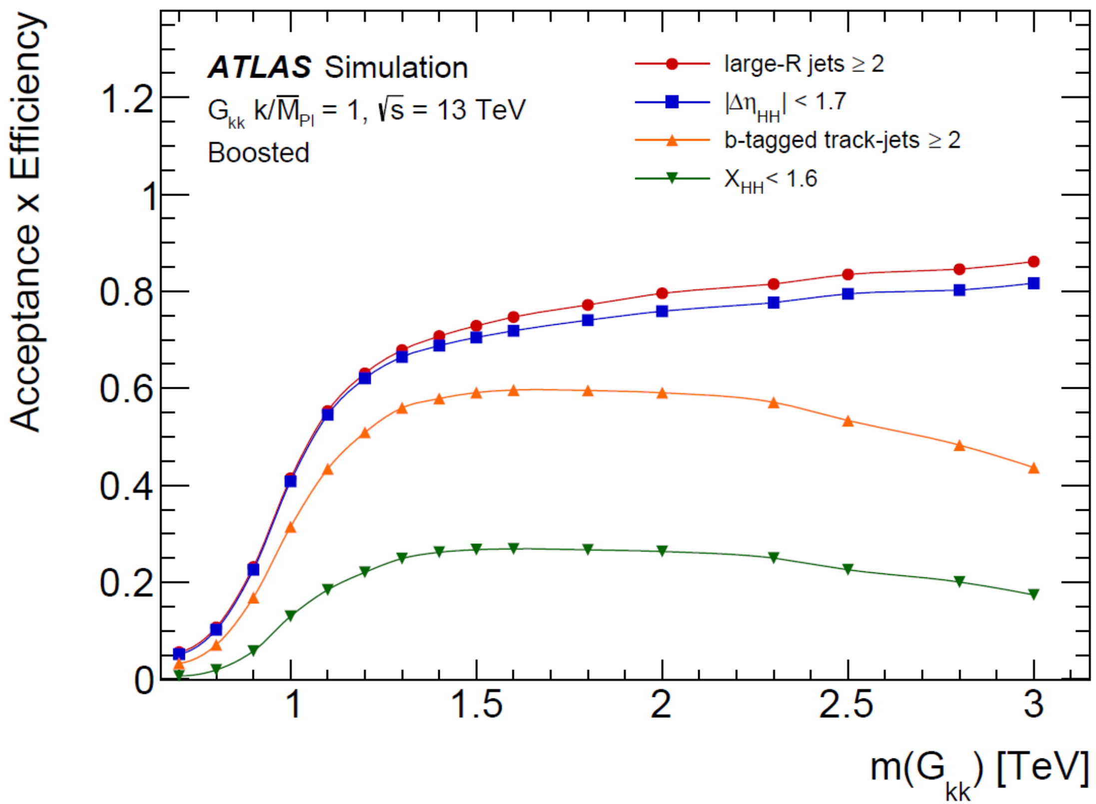


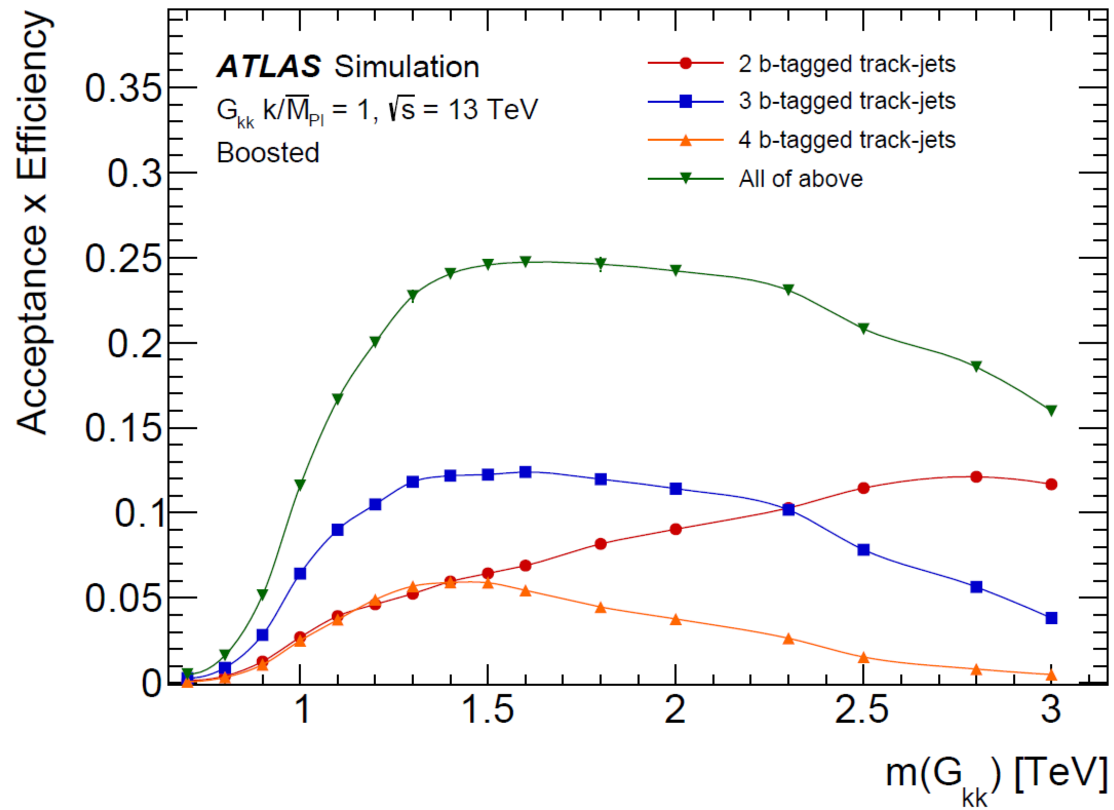
Boosted Analysis: Signal efficiency

Signal efficiency:

- Small efficiency at low mass due to larger separation of the decay products
- Boosted tolopogy becomes important at around 1 TeV resonance masses
- 4b category strong at low masses
- At highest masses, b-tagged track jets start to merge → 2b category has largest efficiency



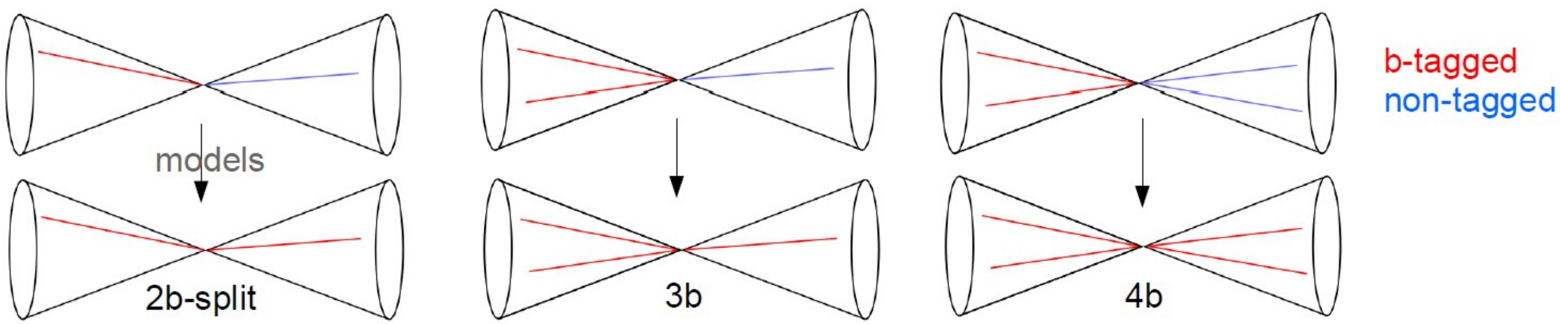




Boosted Analysis Background estimation

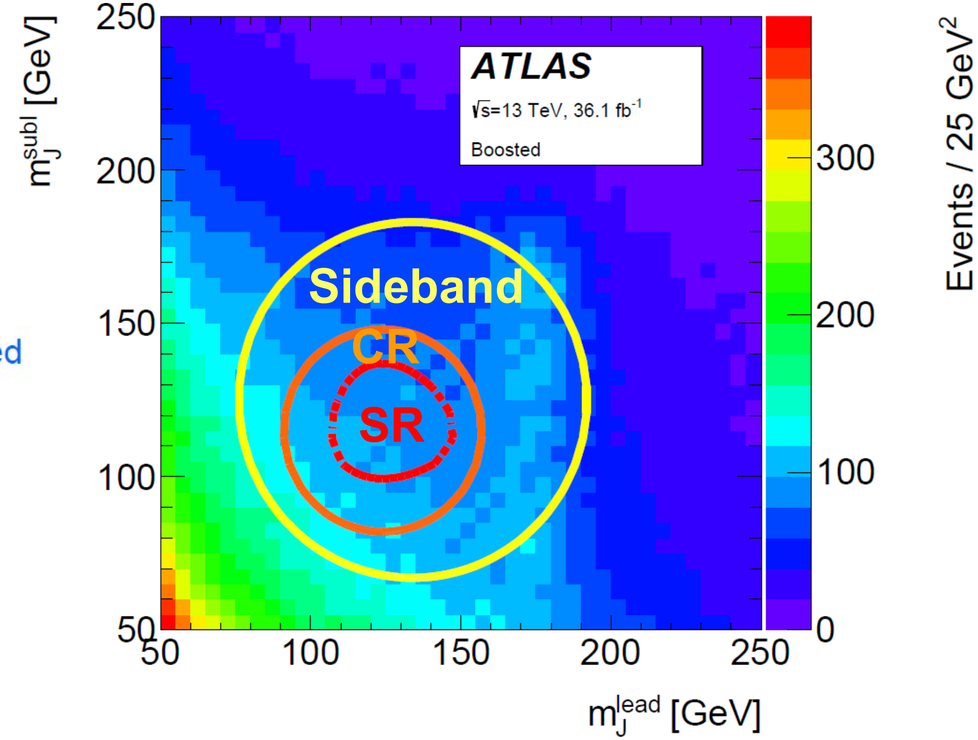
Background estimation steps:

- Background is 80-95% multijet, rest is $t\bar{t}$, depending on the number of b-tags
- Mutually exclusive samples with non b-tagged track jets are defined to model the background of each category:



- Kinematics of the jets are used to derive weights in the inlcusive region (SR+CR+SB), CR is used for validation
- Normalization is obtained in the SB for multijet and ttbar events

Similar to the resolved analysis, different regions are defined in the 2D mass plane:



Signal region:

$$X_{HH} = \sqrt{\left(\frac{m_J^{\text{lead}} - 124\text{ GeV}}{0.1 m_J^{\text{lead}}}\right)^2 + \left(\frac{m_J^{\text{subl}} - 115\text{ GeV}}{0.1 m_J^{\text{subl}}}\right)^2} < 1.6$$

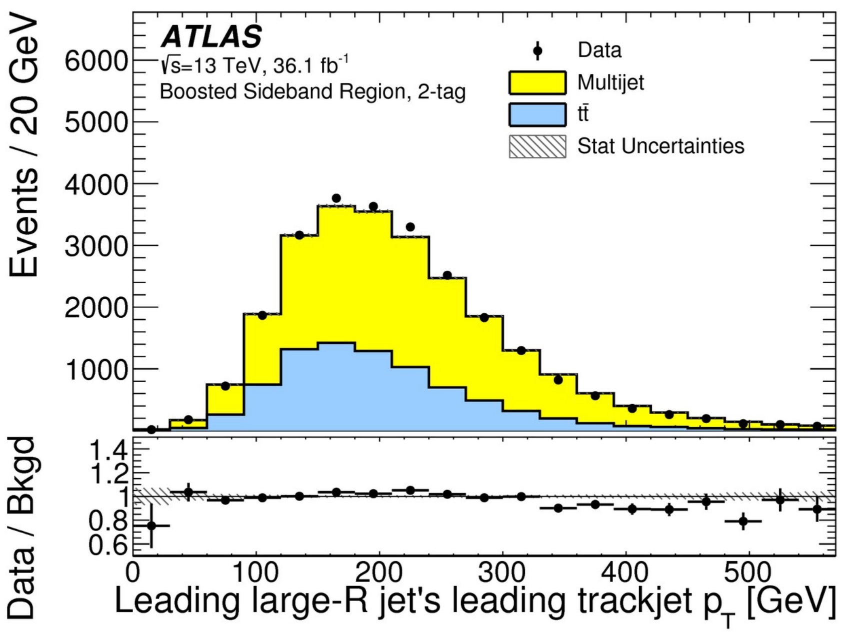
Boosted Analysis Background estimation

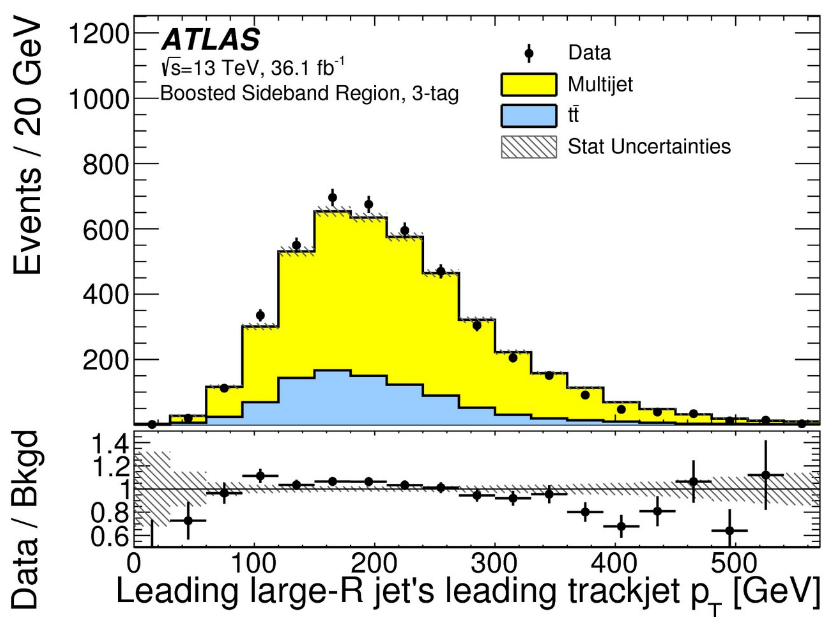
Kinematic reweighting to make the lower-tagged data more similar to the n-tagged data, ie. reweight the non-tagged Higgs candidate to look like the b-tagged Higgs candidate.

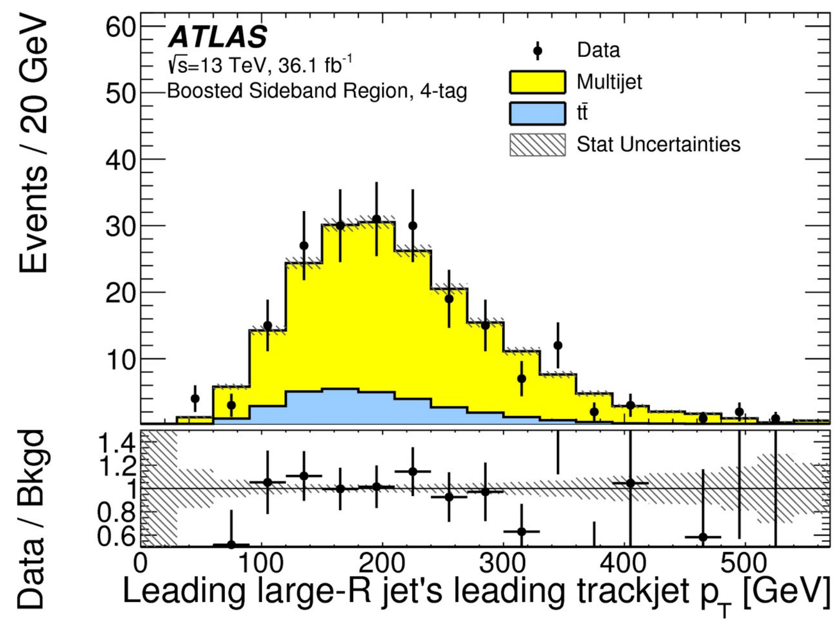
Weights are iteratively derived from 3rd order splines fitted to the ratios of these distributions, after ttbar contribution is subtracted:

- pT of leading track jet associated with leading large-R jet
- pT of leading track jet associated with sub-leading large-R jet
- pT of leading large R-jet

Before reweighting:







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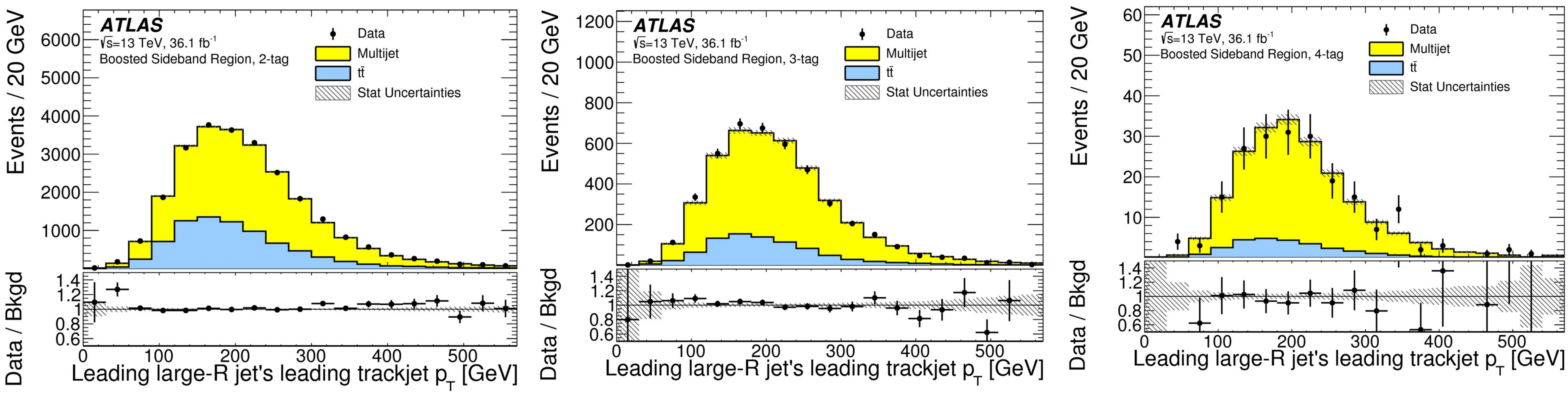


This reweighting method was also validated using Dijet MC.

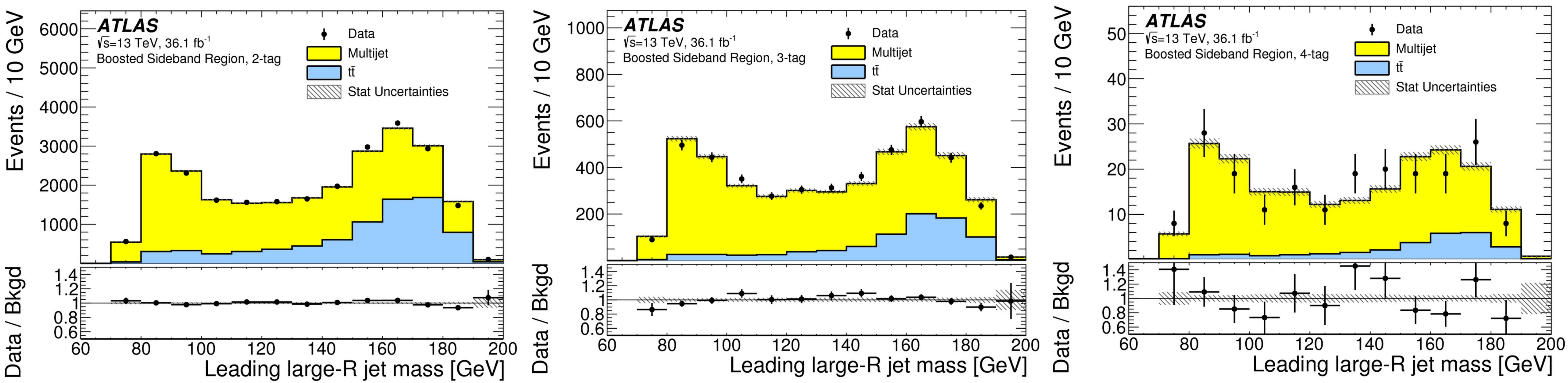
Boosted Analysis Background estimation

Normalization of multijet and ttbar background obtained from simultaneous fit to the leading jet mass:

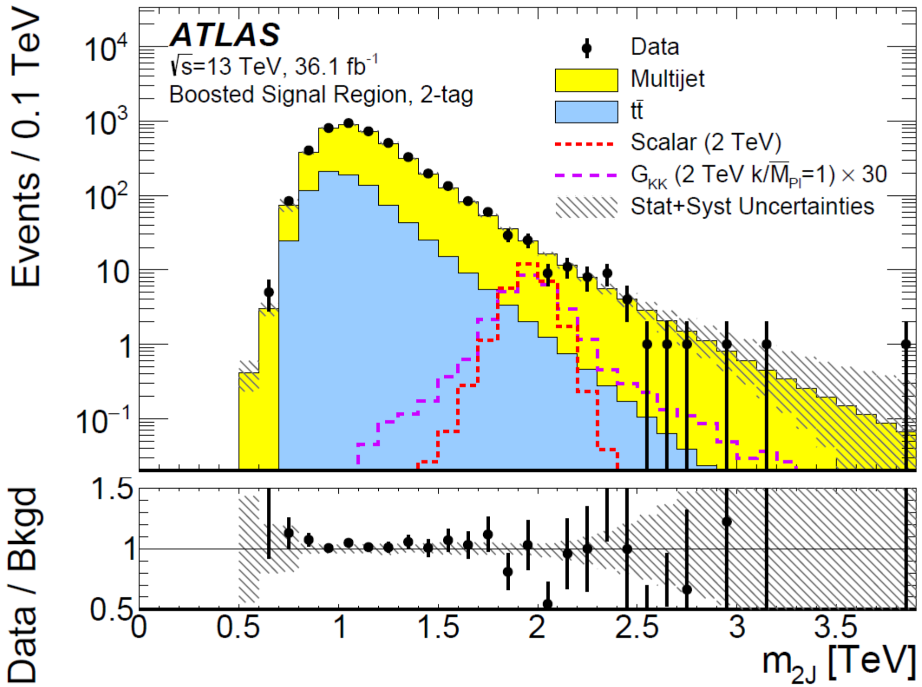
$$N^{n\text{-tag}}_{\text{background}} = \mu^{n\text{-tag}}_{\text{multijet}} N^{\text{lower-tag}}_{\text{multijet}} + \alpha^{n\text{-tag}}_{t\bar{t}} N^{n\text{-tag}}_{t\bar{t}}$$

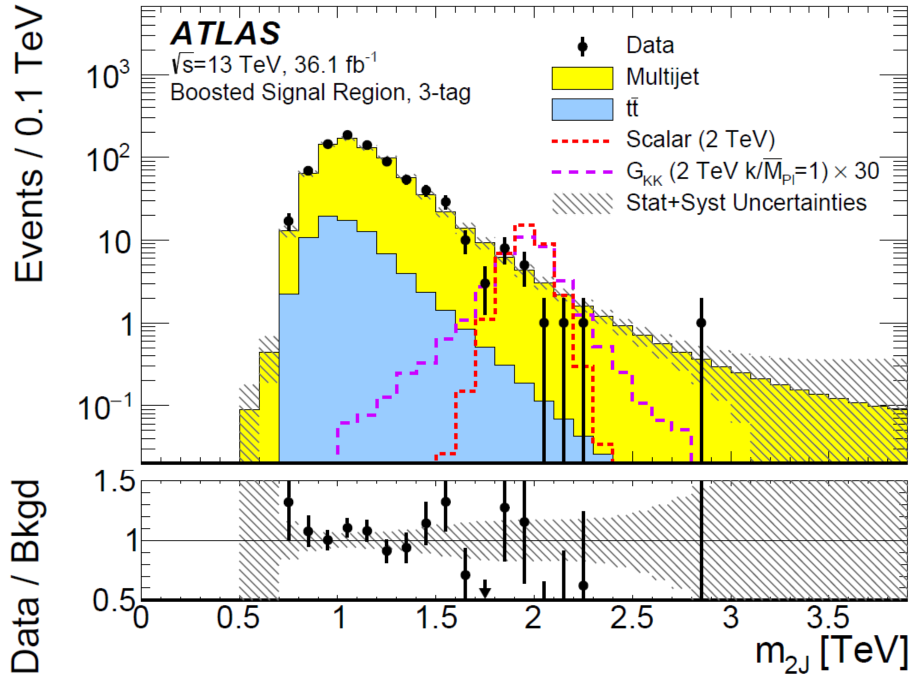
Category	μ_{multijet}	$\alpha_{t\bar{t}}$
Two-tag	0.06273 ± 0.00057	0.986 ± 0.019
Three-tag	0.1626 ± 0.0043	0.800 ± 0.073
Four-tag	0.0332 ± 0.0043	0.89 ± 0.60

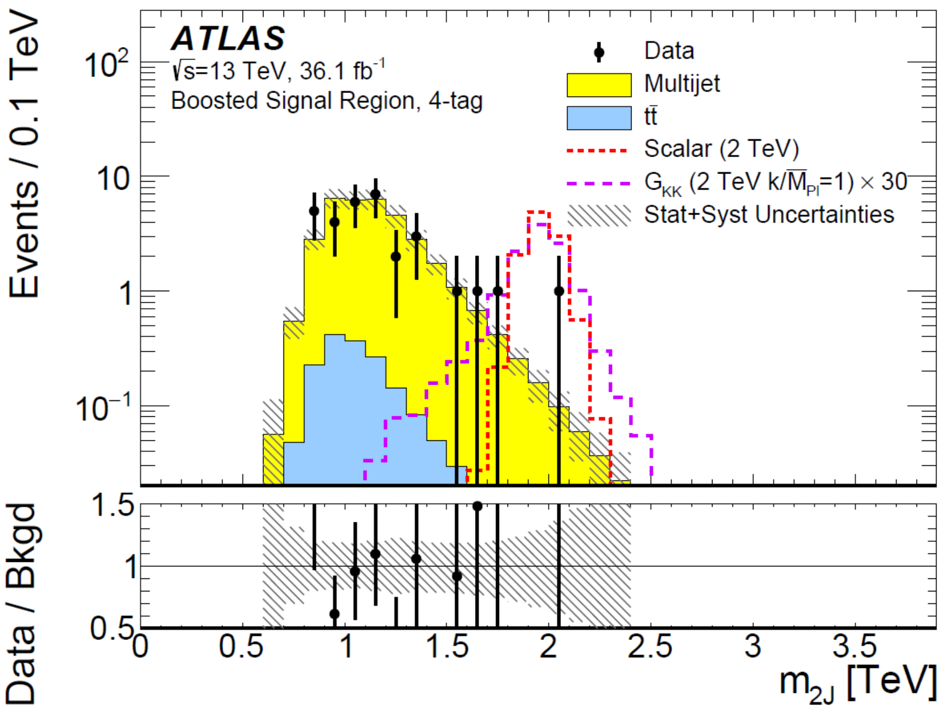
- Mu scales the multijet background from the lower-tagged samples to the n-tagged samples
- alpha is a scale factor of the MC estimate
- Correlations between alpha and mu are fully propagated into the final fit to the m2J mass.



Boosted Analysis: Results





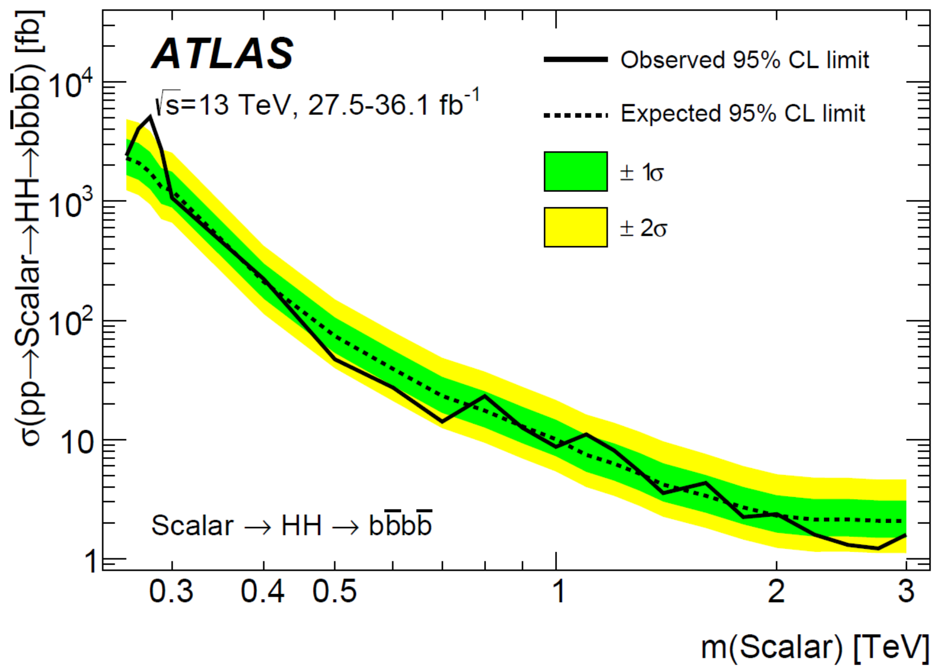


The background templates are smoothed for m2J > 1.2 TeV by fitting the m2J spectrum with an analytical function:

$$f\,(m_{2J}) = \frac{p_1}{\left(\frac{m_{2J}}{\sqrt{s}}\right)^2}\left(1 - \frac{m_{2J}}{\sqrt{s}}\right)^{p_2 - p_3 \ln \frac{m_{2J}}{\sqrt{s}}}$$

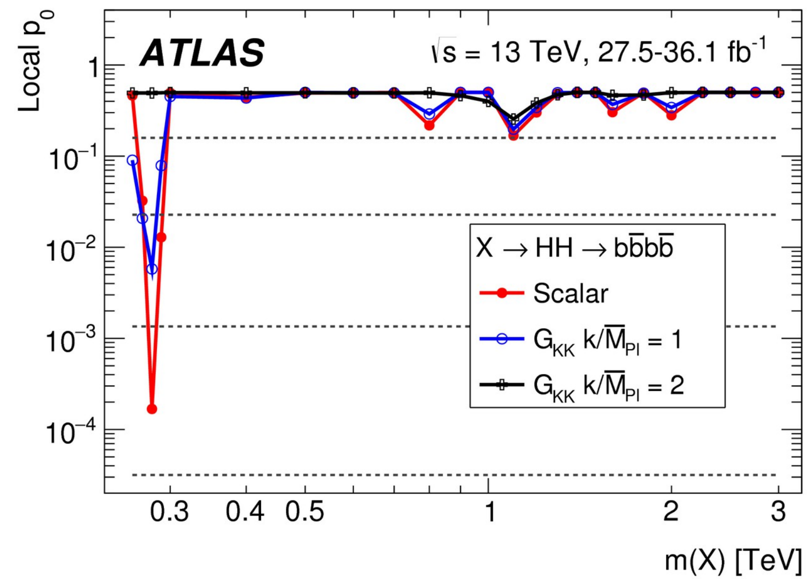
A systematic uncertainty is derived by comparing smoothed background to the smoothed data in the CR, split into low and high mass component for more flexibility in the fit

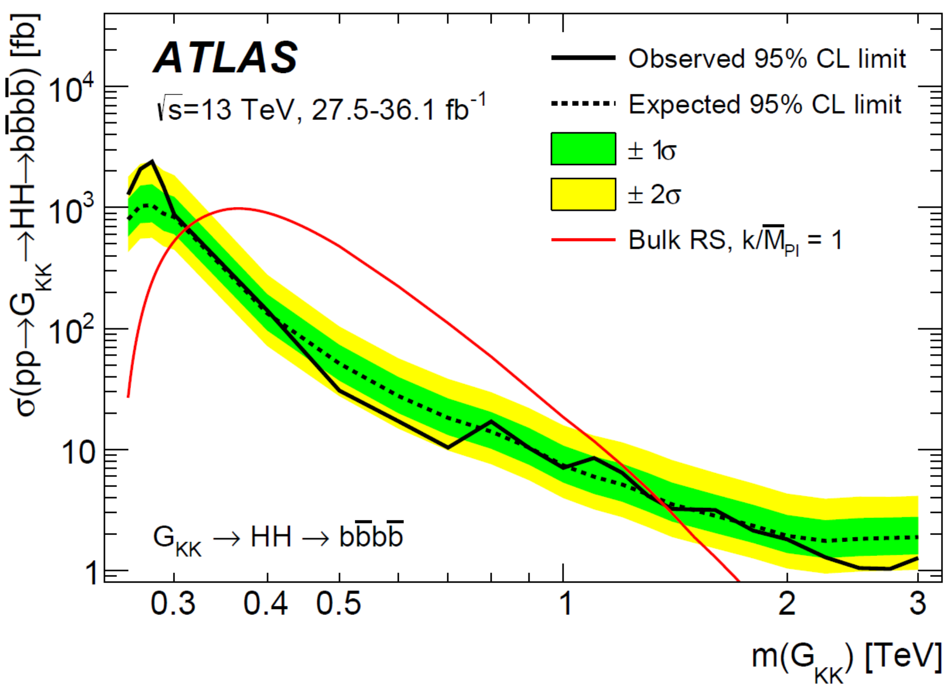
Resonant Results (combination of resolved and boosted)

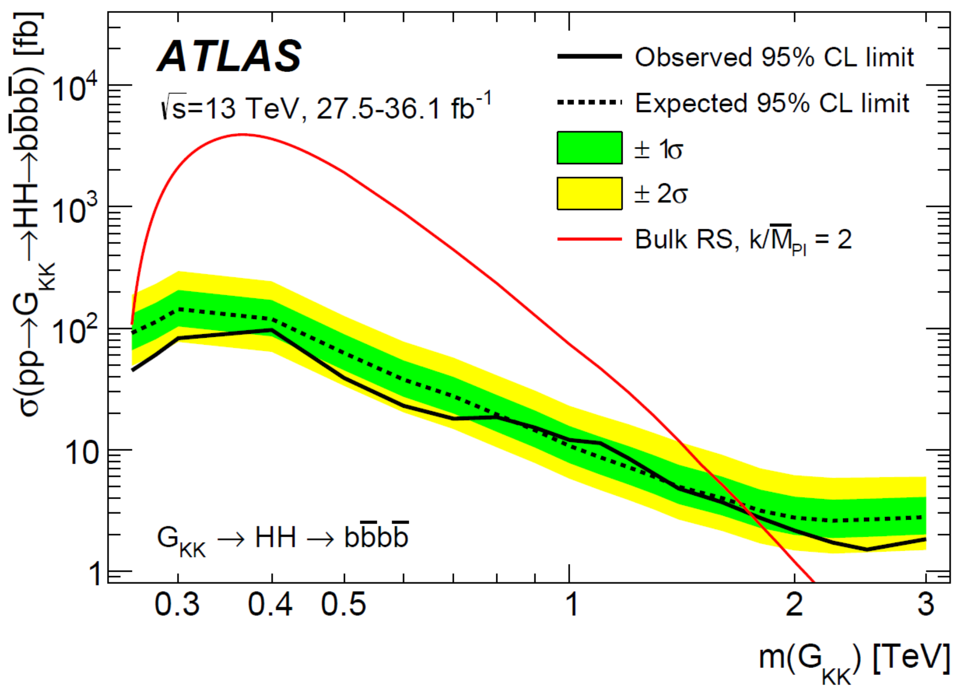


Narrow-width excess at 280 GeV (one bin in m4j histogram)

Global significance: 2.3σ







$k/\overline{M}_{Pl}=2$ limits better due to higher signal acceptance and m4j shape deformation at low resonance masses

Conclusions

HH → 4b channel is very powerful channel because of

- easy mass reconstruction (once the combinatorics are figured out)
- large branching ratio
- most sensitive HH channel at high resonance masses (>1 TeV)
- Competetive channel for low mass and non-resonant due to efficient b-jet triggers and smart reconstruction algorithms

But difficult to estimate the overwhelming background, which is also hard to simulate.
With more data, will be even more sensitive to mismodellings and systematics of the data-driven backgrounds.

Many ideas to expand the search, for both analysis and performance aspects.

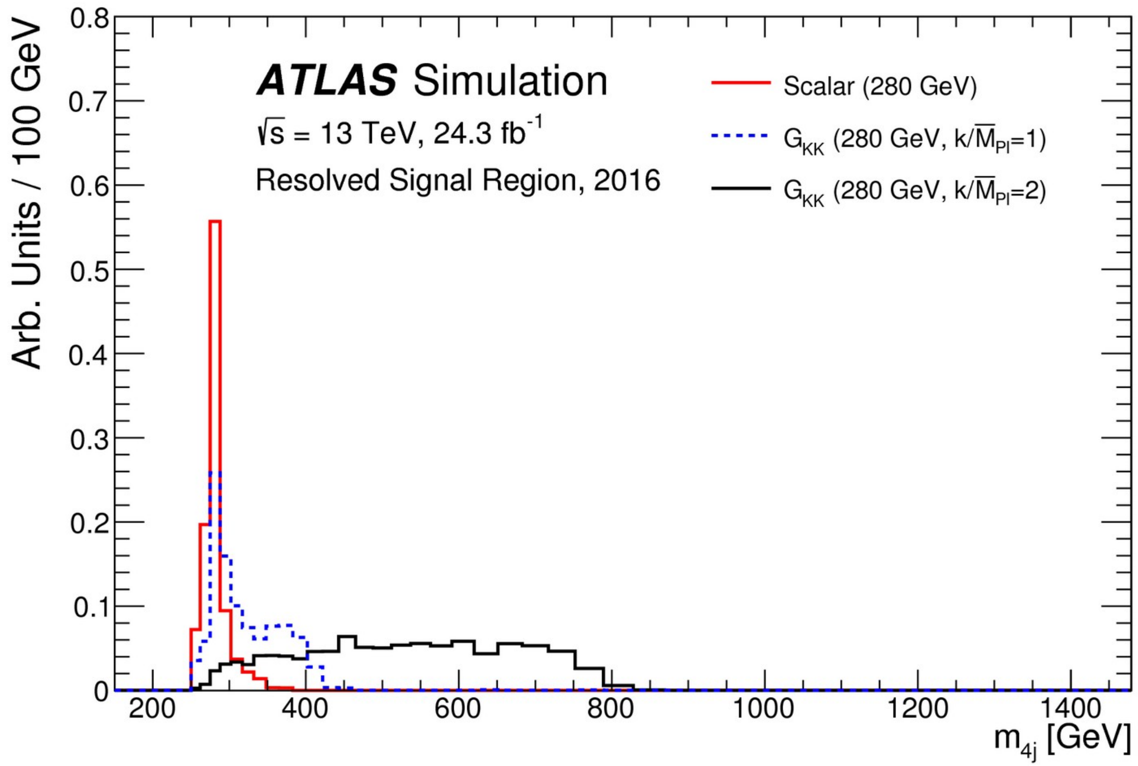
Few possible improvements:

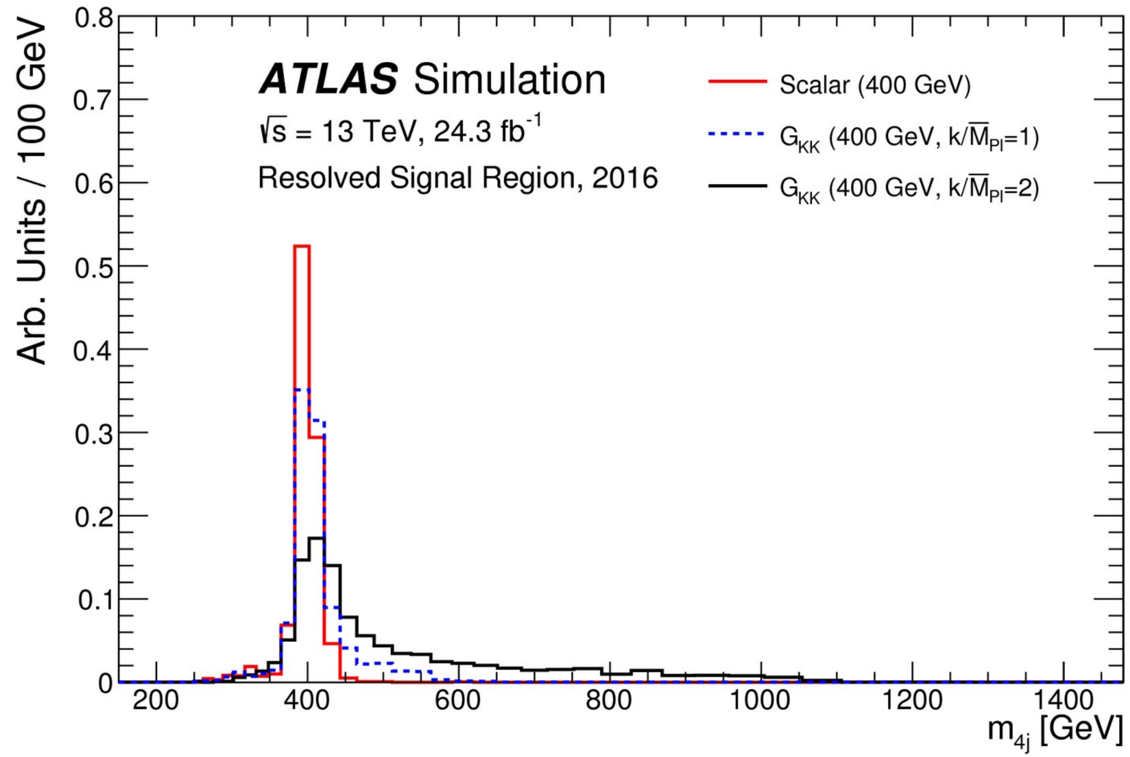
- BDT reweighting instead of spline-based reweighting, as used in SUSY 4b+MET search (arXiv:1806.04030)
- New boosted b-tagging methods as used in mono H→bb (ATLAS-CONF-2018-039) (ie. variable-radius track jets)
- b-jet energy regression (see the talk by Alex)

Backup

Deformation of m4j for finite-width graviton samples at low mass

width: 3% (6%) for low mass up to 13% (25%) for high mass for c=1 (c=2)





Sample	2015 SR	2016 SR	2015 CR	2016 CR
Multijet	866 ± 70	6750 ± 170	880 ± 71	7110 ± 180
$t\bar{t}$, hadronic	52 ± 35	259 ± 57	56 ± 37	276 ± 61
$t\bar{t}$, semileptonic	13.9 ± 6.5	123 ± 30	20 ± 9	168 ± 40
Total	930 ± 70	7130 ± 130	956 ± 50	7550 ± 130
Data	928	7430	969	7656
G_{KK} (800 GeV)	12.5 ± 1.9	89 ± 14		
Scalar (280 GeV)	24.0 ± 7.5	180 ± 57		
SM HH	0.607 ± 0.091	4.43 ± 0.66		

	Two-tag	Three-tag	Four-tag
Multijet	3390 ± 150	702 ± 63	32.9 ± 6.9
$t\bar{t}$	860 ± 110	80 ± 33	1.7 ± 1.4
Total	4250 ± 130	782 ± 51	34.6 ± 6.1
G_{KK} (2 TeV)	0.97 ± 0.29	1.23 ± 0.16	0.40 ± 0.13
Scalar (2 TeV)	28.2 ± 9.0	35.0 ± 4.6	10.9 ± 3.5
Data	4376	801	31