Boosted Hadronically Decaying W and Z bosons

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Introduction

Aim: To measure the production cross section of a boosted, hadronically decaying W/Z boson and use this peak to study the effect of various grooming and substructure techniques

- Reconstructing hadronic decays at the LHC is difficult due to the large backgrounds

  → Look at high p_T where this background rapidly drops off

- Many beyond the standard model theories predict new particles with TeV masses which can decay into W/Z bosons

  → Expect to see boosted (high p_T) W/Z bosons

  → Reconstructing the known W/Z resonance is an important step in developing these boosted techniques

- The observation of this peak provides a standard candle to study the effects of techniques to remove pileup and the underlying event

  → Offers a way to control the jet mass in pileup conditions

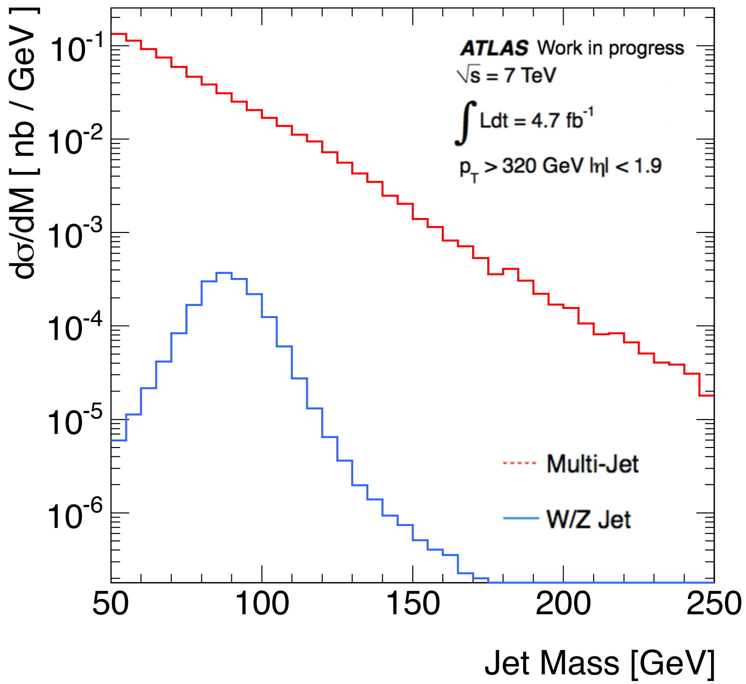
  → Particularly important as the levels of pileup increase

Event Selection

Look for events where the decay products of the W/Z are contained with in a single jet.

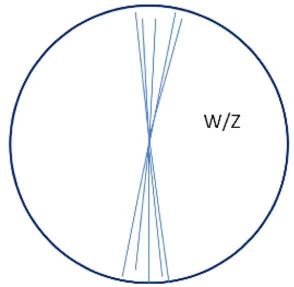
rule of thumb: separation between decay products: $R \sim 2m_X/p_{XT}$

→ Look at Anti-k_T R=0.6 jets, p_T > 320 GeV



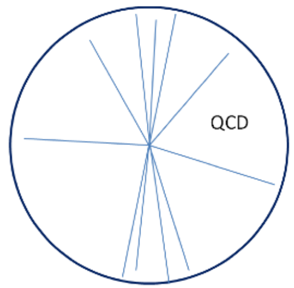
The QCD background is a couple of orders of magnitude higher than the signal…

→ Look at the distribution of energy in the jet



Boost the jet back into its centre of mass frame, we expect:

- W/Z jet to have a back to back topology
- QCD jet to be more isotropic



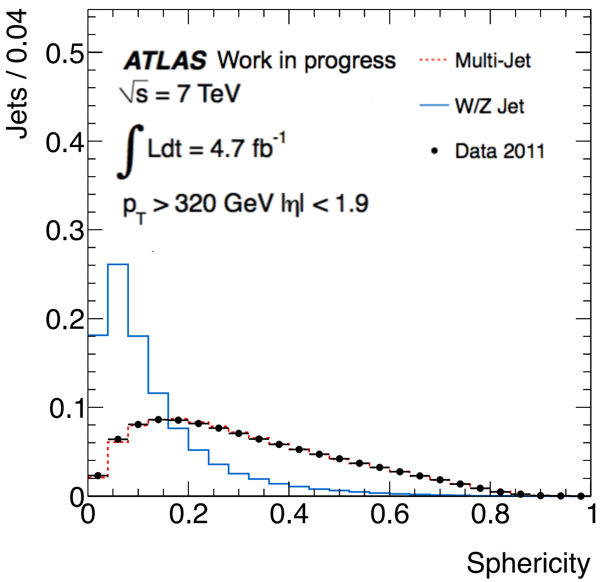
Use jet shapes to distinguish signal from background

Sphericity, Aplanarity, Minor Thrust

Jet Shape Variables

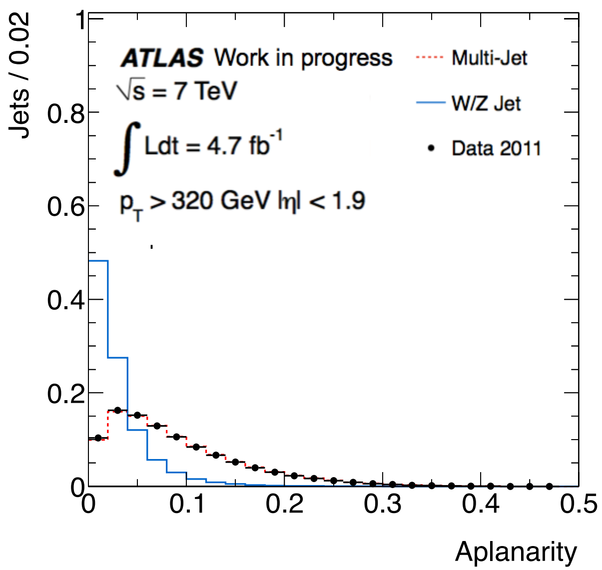
Sphericity

A measure of how well the event lies on a single axis



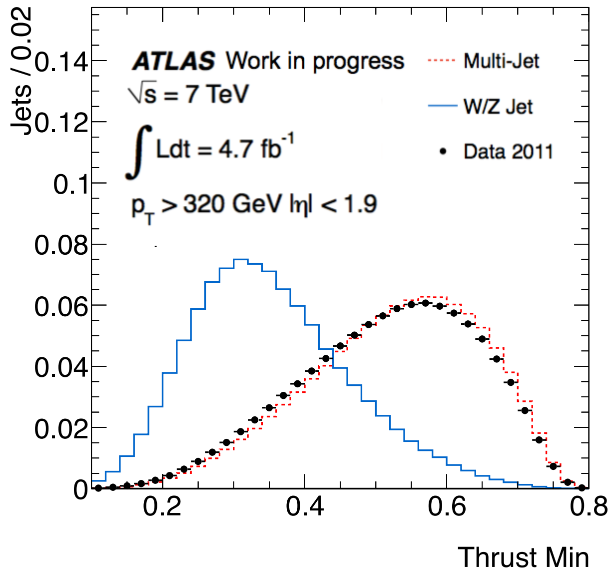
Aplanarity

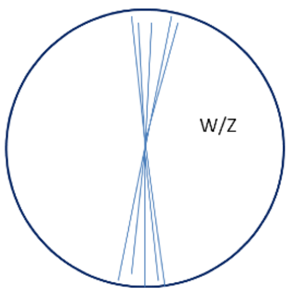
A measure of how well the event is contained within a plane



Minor Thrust

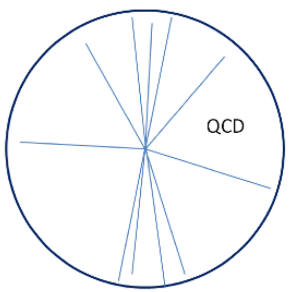
A measure of how much of the momentum lies on the axis minimising the longitudinal momentum





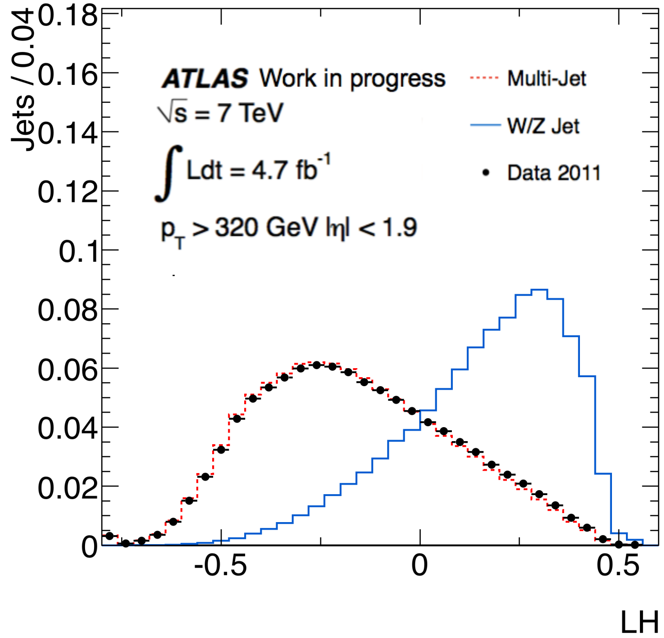
Highly directional events: S, A, T → 0

Isotropic events: S, A, T → 1

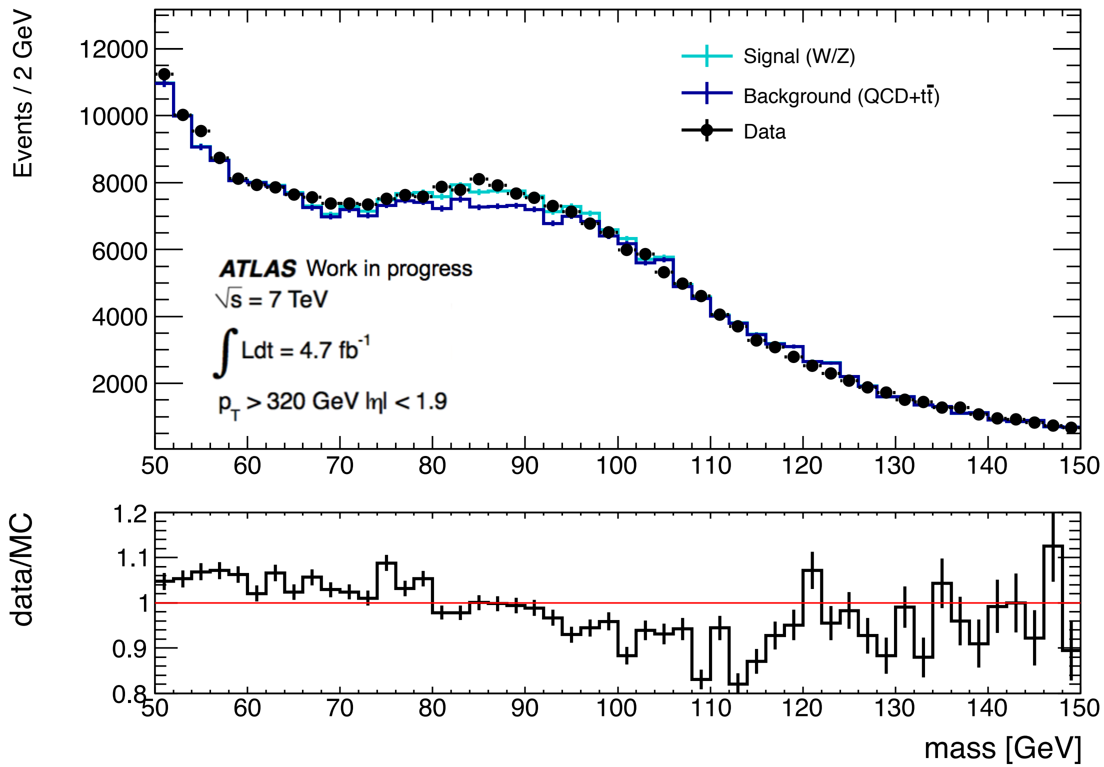


Extracting the Cross Section

Combine the variables into a likelihood and cut on this:
LH > 0.15
Reject ~90% background, keep ~55% signal



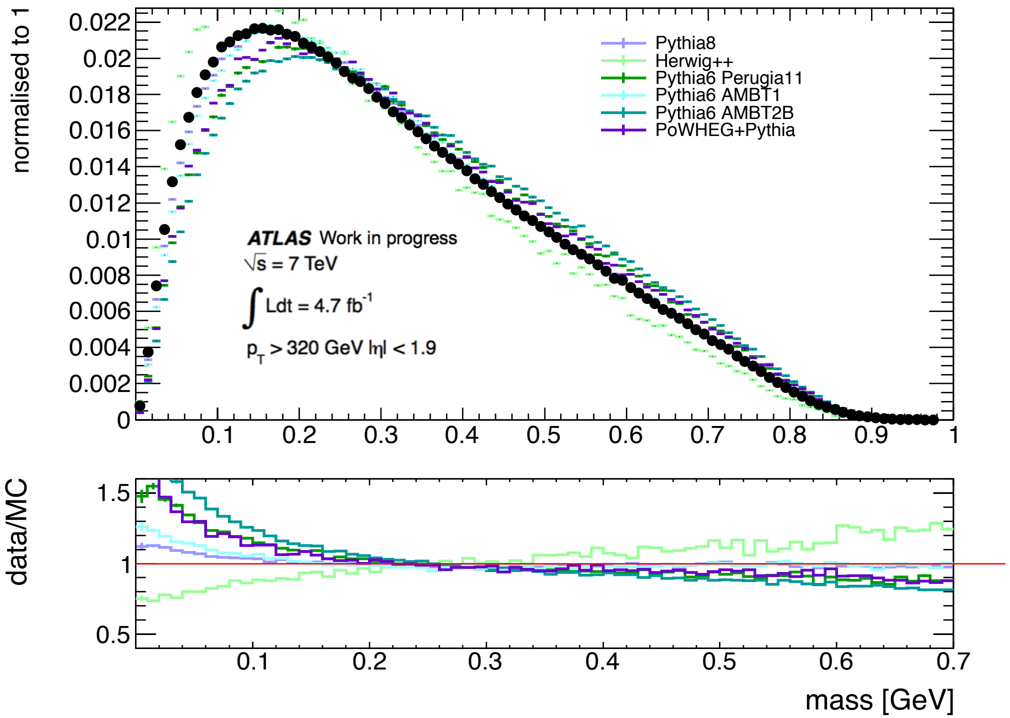
The resulting mass distribution:

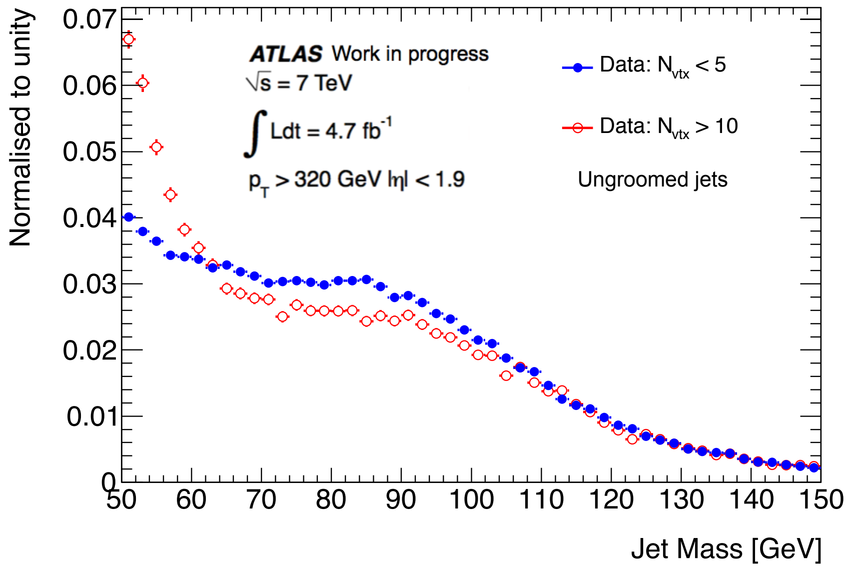


Work is in progress to perform a fit and extract the signal yield and hence perform a cross section measurement.

Take this peak and consider the effect of applying various grooming and substructure techniques:

- **Pruning**
- **Trimming**
- **Area Subtraction**
- **Splitting/Filtering**





Pileup: background from additional proton-proton interactions.

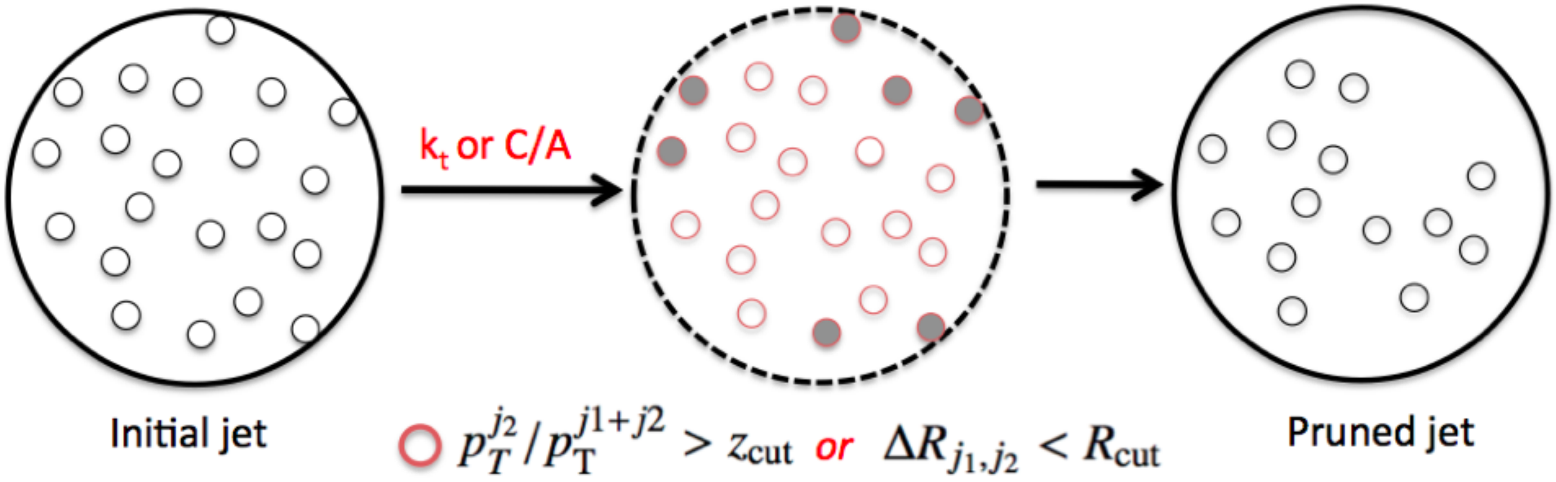
Three main questions – does applying grooming:

Improve the agreement between data and MC?
Improve the s/b that can be achieved?
Help decrease the pileup dependence?

Pruning

Grooming techniques aim to remove the parts of the jet coming from pileup and the underlying event and leave only the hard structure

S. D. Ellis, C. K. Vermilion, and J. R. Walsh, Phys.Rev. **D81 (2010)**



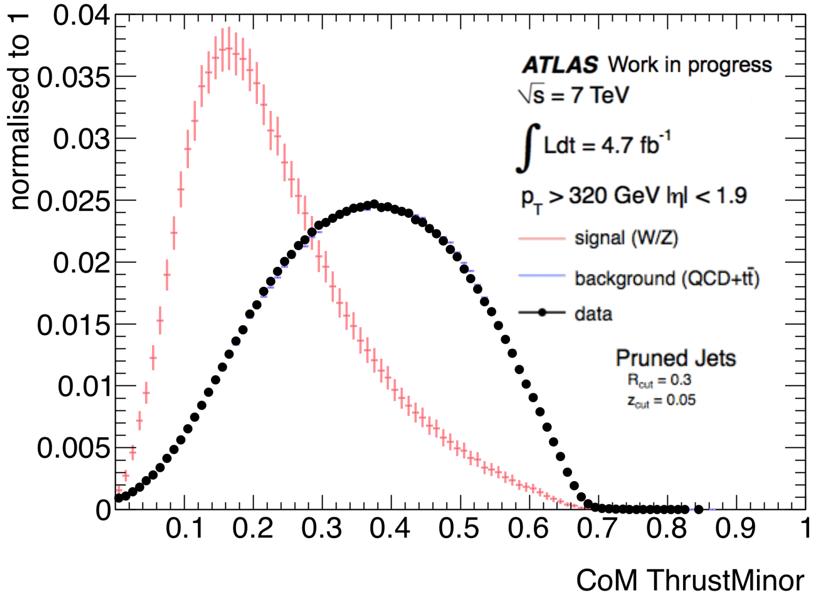
Recluster the jet (using the k_T or C/A algorithm). Remove constituents that are

- Wide angle: $\Delta R_{j_1,j_2} > R_{cut}$
- Soft: $\frac{p_T^{j_2}}{p_T^{j_1+j_2}} < z_{cut}$

Consider $R_{cut} = 0.3$, $z_{cut} = 0.05$

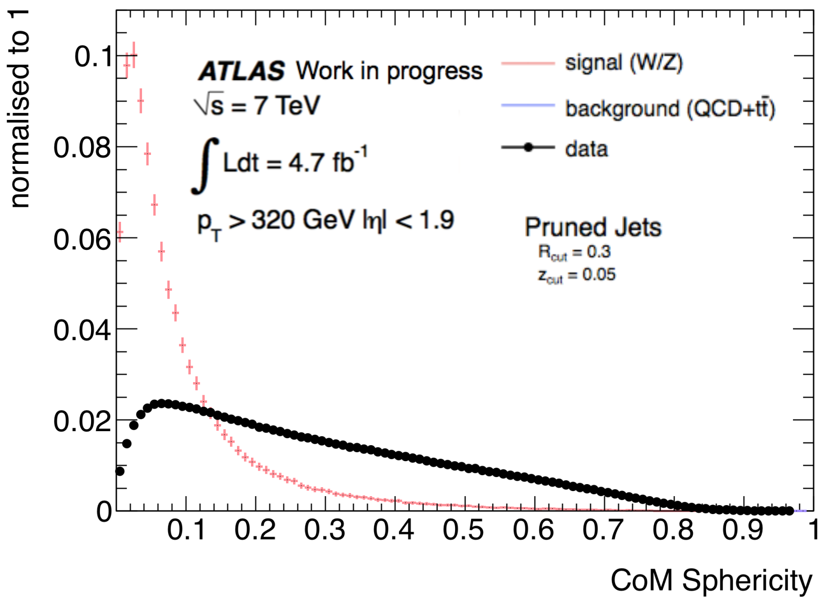
Pruned variables

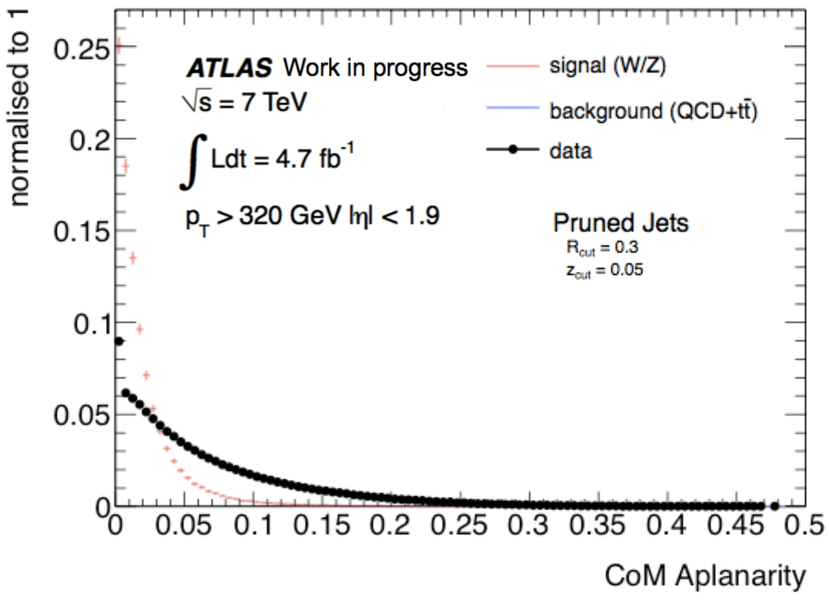
Look at the variables using the pruned constituents:



Improvement in data-MC agreement

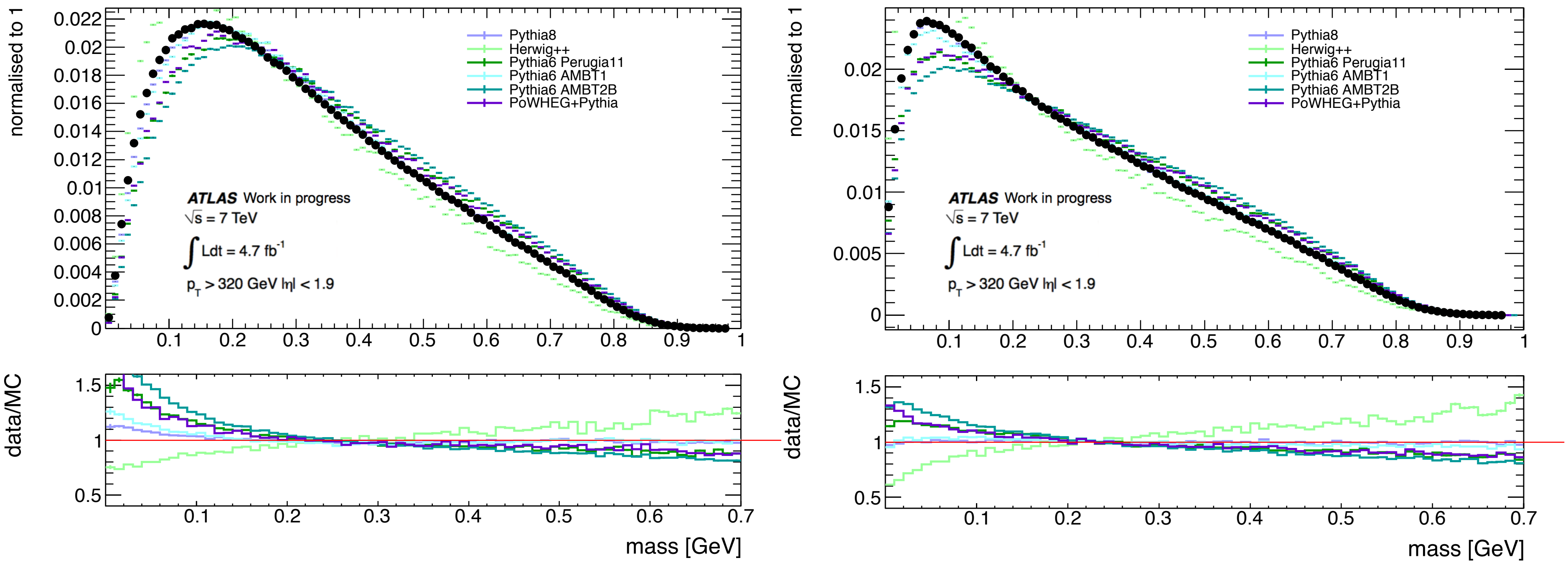
good signal/background discrimination





Pruned variables

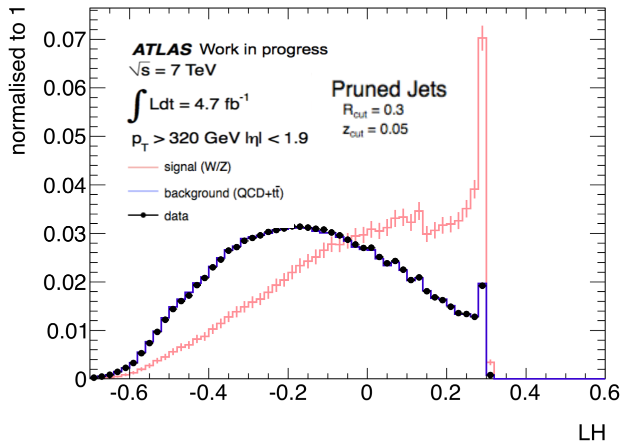
Look how data compares with other MCs:



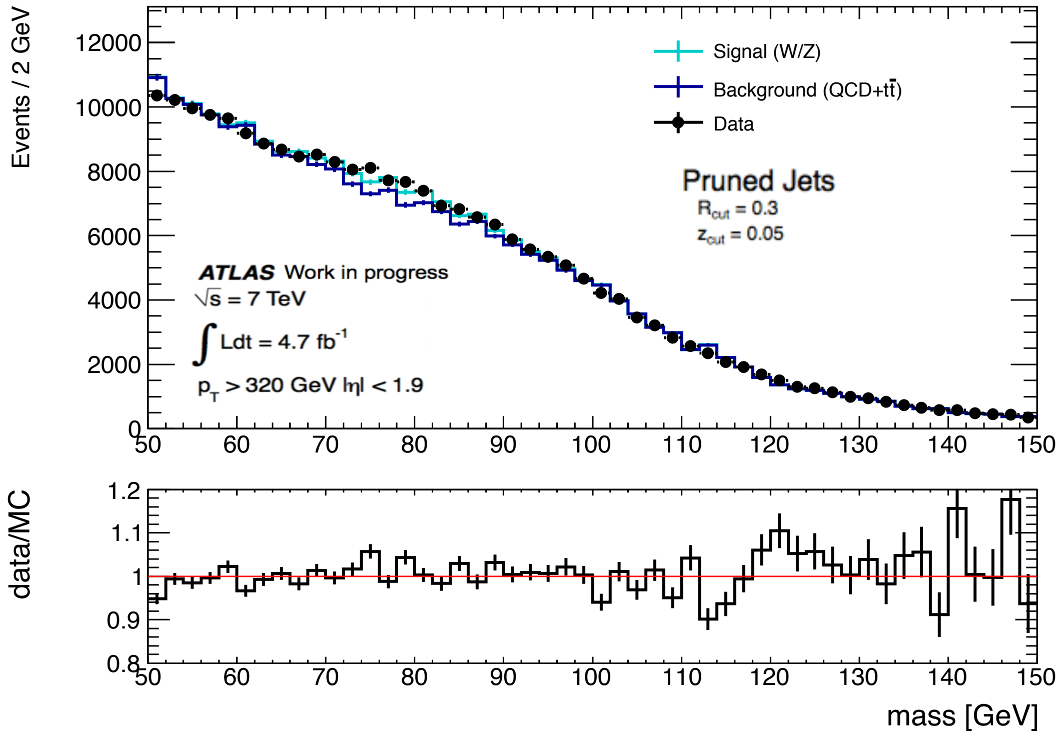
Generally better agreement, particularly for low values of sphericity across all MCs, except Herwig

Pruned mass

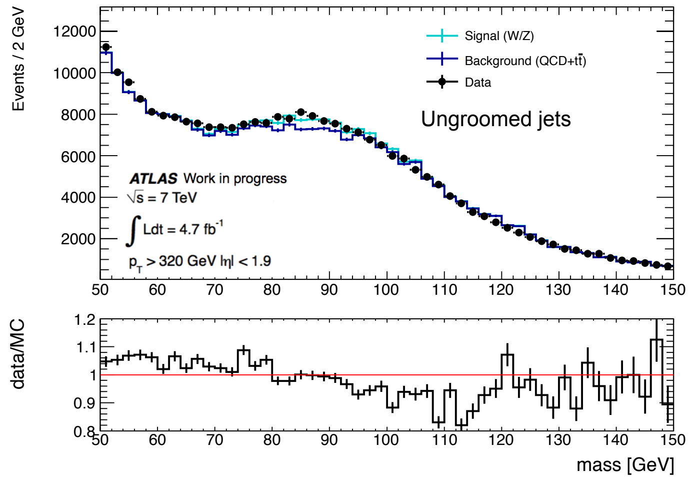
Form a likelihood discriminator from these three pruned variables:



Cut such that 90% of the background is rejected (for comparison to the default)



Ungroomed (for comparison)



Flatter background distribution

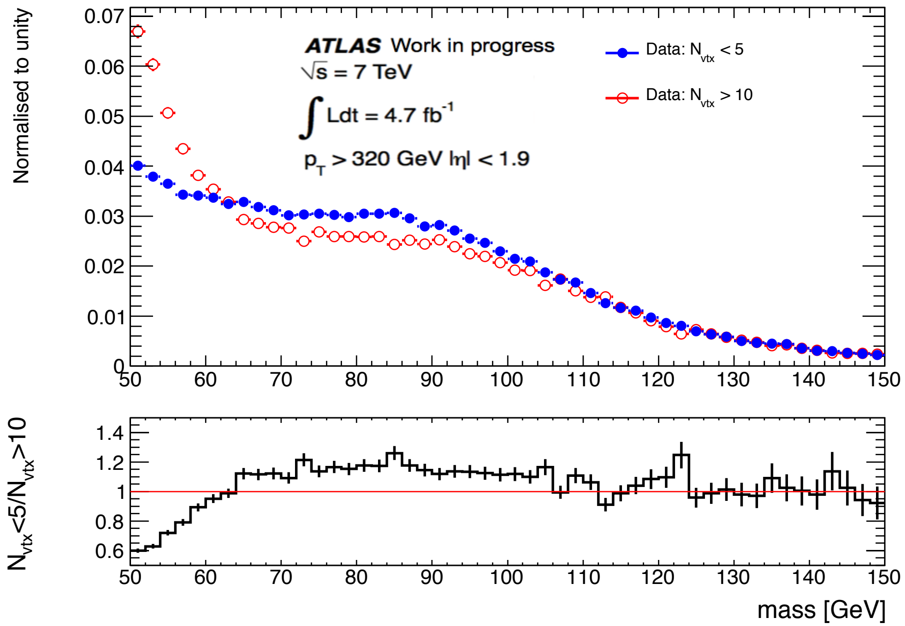
Signal peak shifted to lower mass

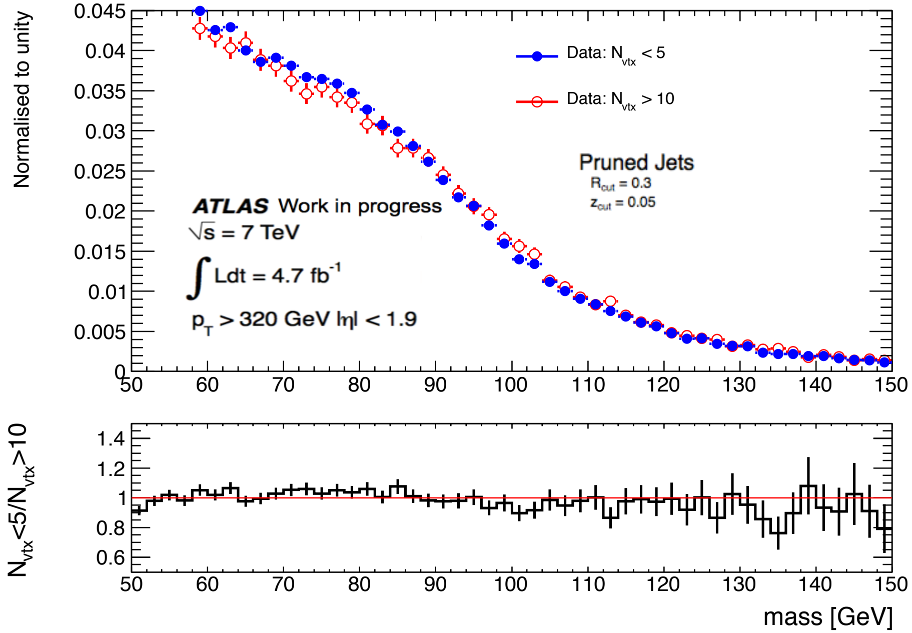
Better agreement between data and MC

Pruning – pileup dependence

Pileup is the contribution from other proton-proton interactions

assess by looking at the distribution as a function of the number of vertices



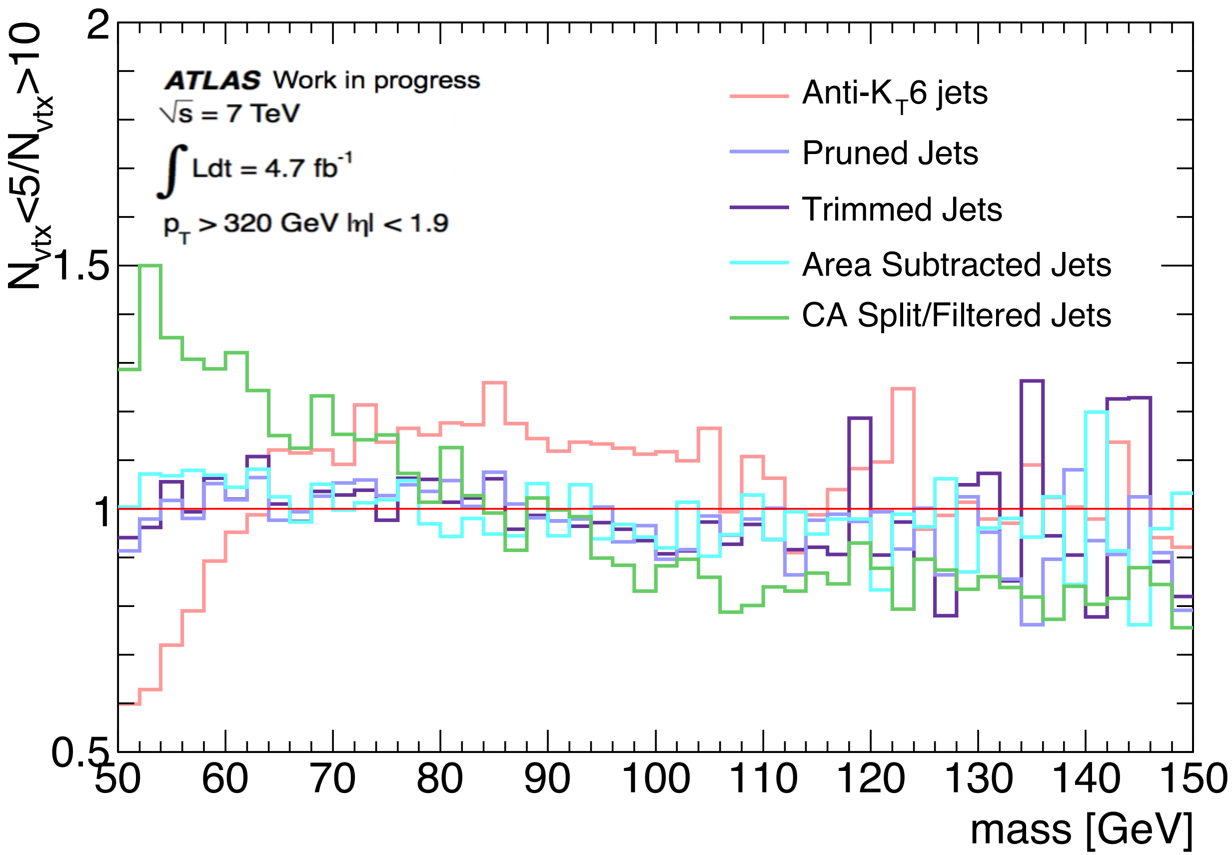


Pileup dependence much reduced

Pileup dependence

Summary for all the grooming/substructure techniques studied:

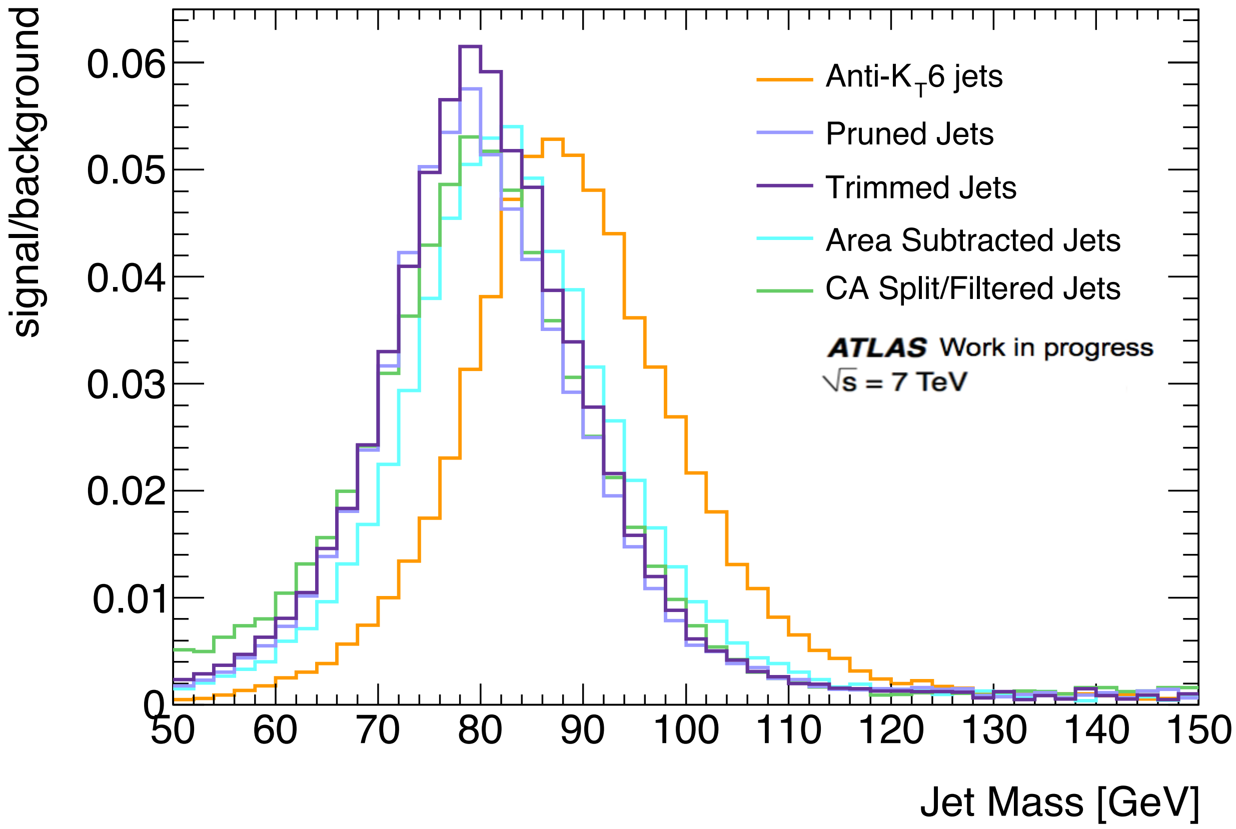
Compare the ratio between low and high numbers of vertices for each technique



Grooming in general reduces the pileup dependence, except in the case of splitting/filtering

Is the s/b improved?

Look at the s/b as a function of the jet mass:



Improvement in s/b, particularly in the case of trimming and splitting and filtering

Conclusion

• The production cross section for a boosted hadronically decaying W/Z boson is in progress.

• The impact of various grooming techniques (Pruning, Trimming, Area Subtraction, Splitting/filtering) were studied using this peak. In general:

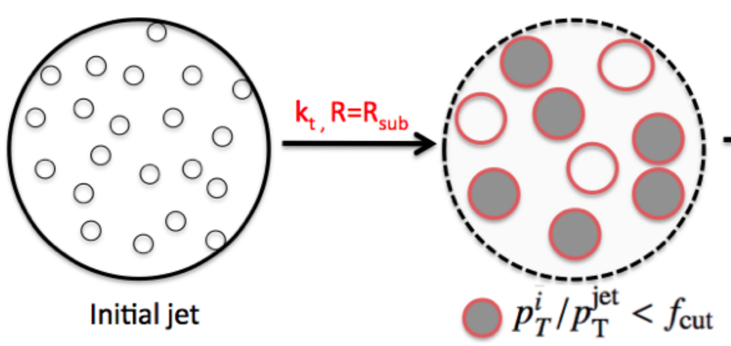
- Grooming improves the agreement between data and MC
- An improvement in the s/b can be made
- Pileup dependence is reduced

• Grooming techniques look promising for controlling the jet mass in future analyses, especially as pileup become more important.

Backup

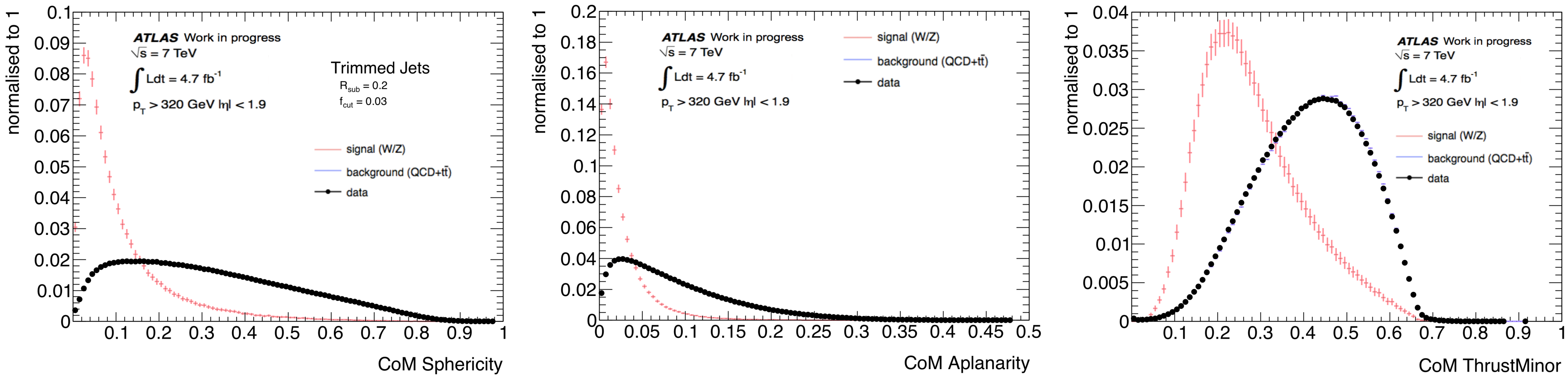
Trimming

Recluster the jet using the k_T algorithm with a smaller radius R_{sub} and remove any subjets with $p_T^{subjet}/p_T^{jet} < f_{cut}$



Consider R_{sub} = 0.2, f_{cut} = 0.03

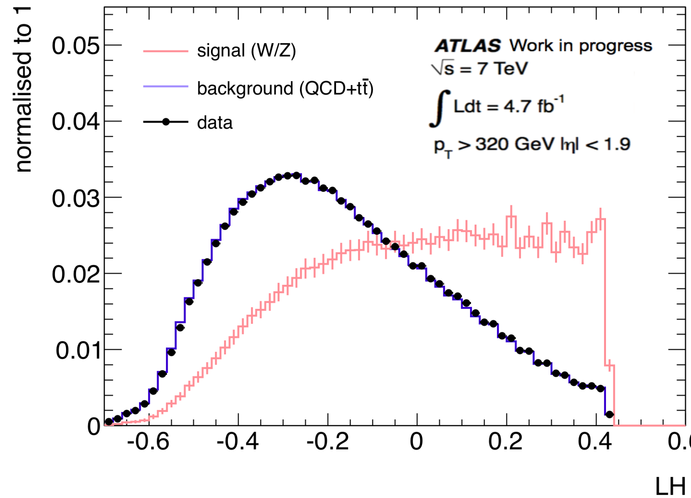
Look at the variables using the trimmed constituents:



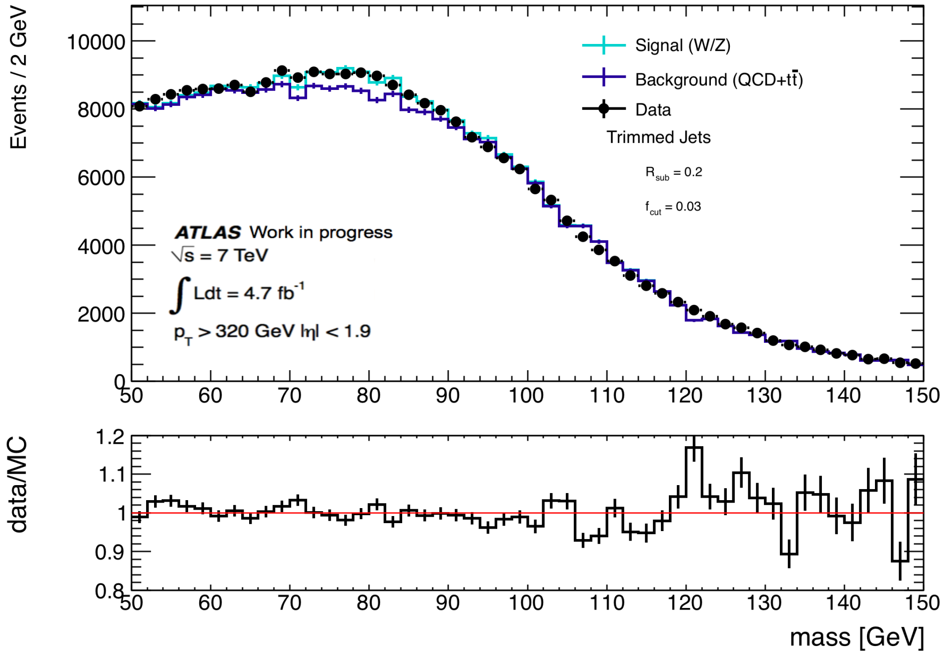
good signal/background discrimination
better agreement between MC and data w.r.t before grooming

Trimming

Form a likelihood discriminator from these three trimmed variables:

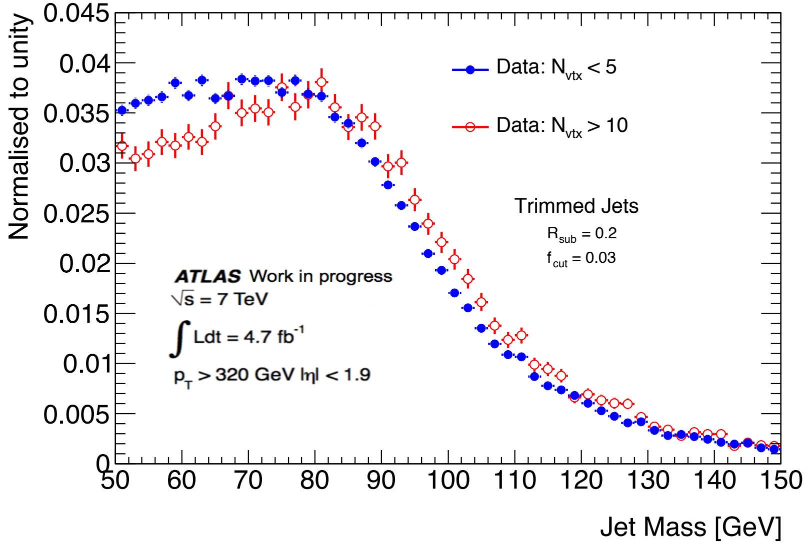


Cut such that 90% of the background is rejected (for comparison to the default)



Look at variation with number of vertices:

Pileup dependence slightly improved



Background slight distorted

Signal peak shifted to lower mass

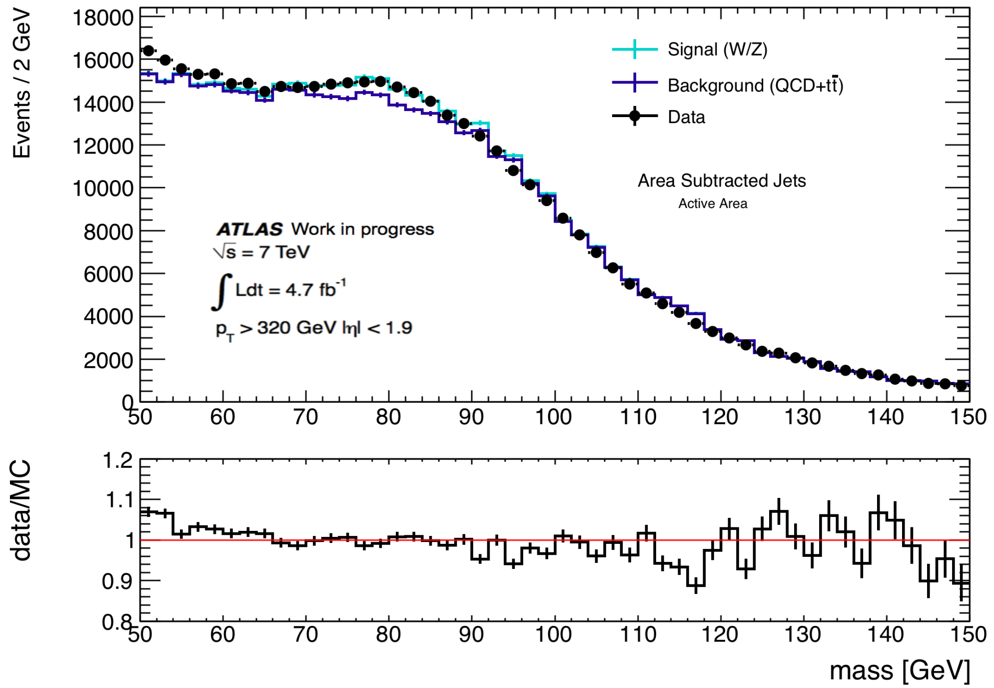
Better agreement between data and MC

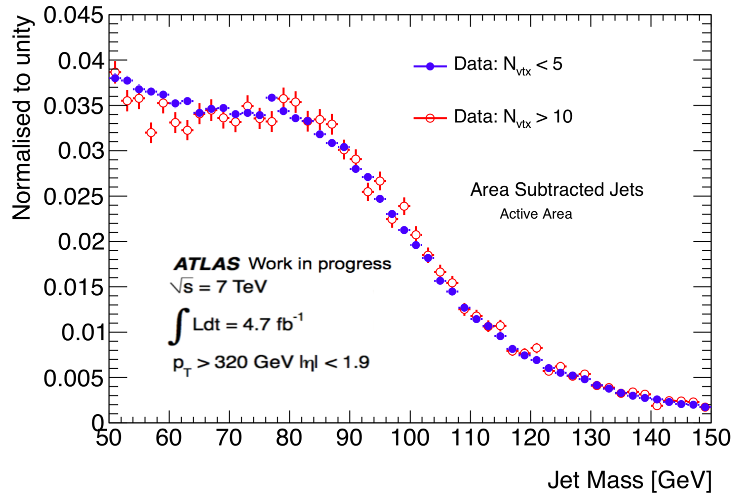
Area Subtraction

Calculate the average level of the background in an event (ρ = median ($p_{T,j}/A_j$)) and subtract this from the hard jets based on their area ($p_{T,j}^{(sub)} = p_{T,j} - A_j\,\rho$)

Where A_j is the area of a jet calculated by adding a uniform background of ghost particles and reclustering.The area of a jet is proportional to the number of ghosts it contains

Apply this to each of the jets in the original selection:





Very good agreement between data and MC

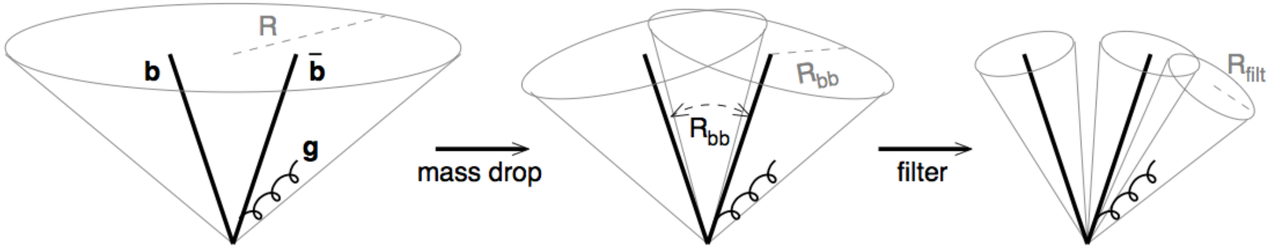
No distortion to the background

Pileup dependence reduced a lot

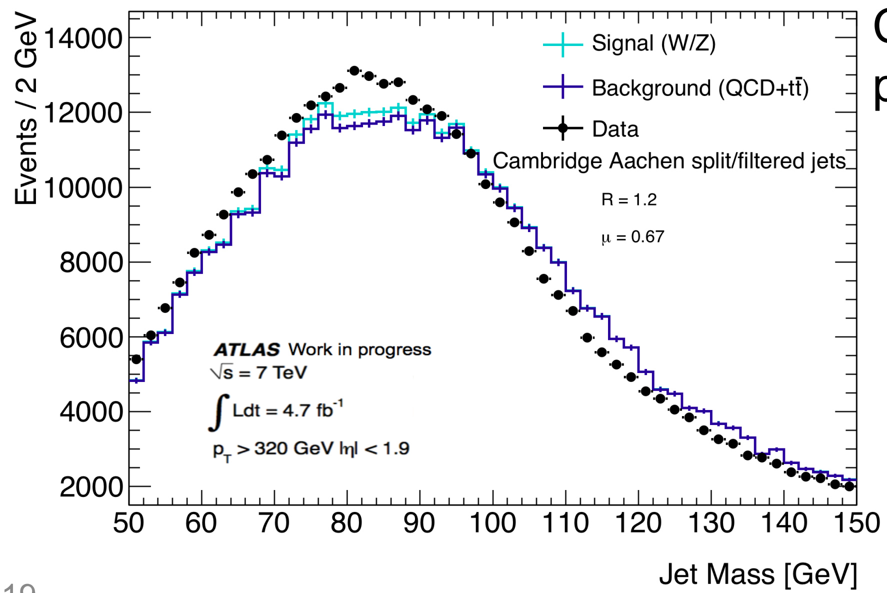
CA split/filtering

Look for hard structure in a jet by

- Undoing the last clustering step in a C/A jet
- Require a sufficient mass drop and symmetric splitting
- Recluster with a smaller radius keeping the largest 3 subjets

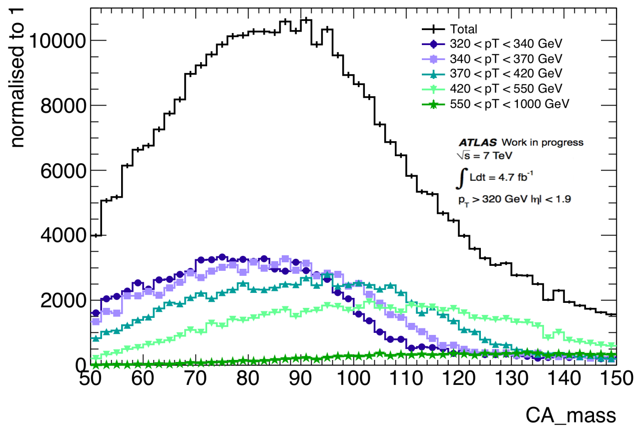


Look at applying splitting/filtering procedure to the jets selected by the default analysis:



Causes the background to peak in the same place as the signal

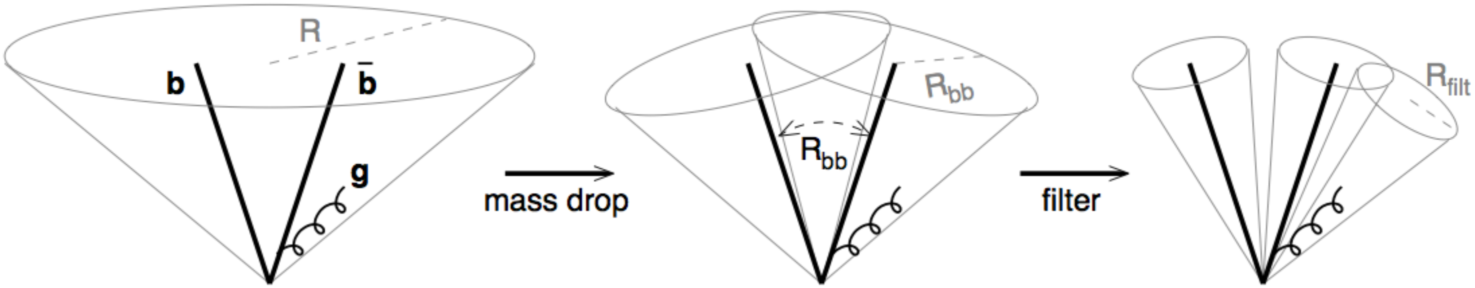
Due to the choice of p_T cut and jet radius



Filtering Technique

The filtering technique (BDRS, Phys. Rev. Lett. 100:242001,2008):

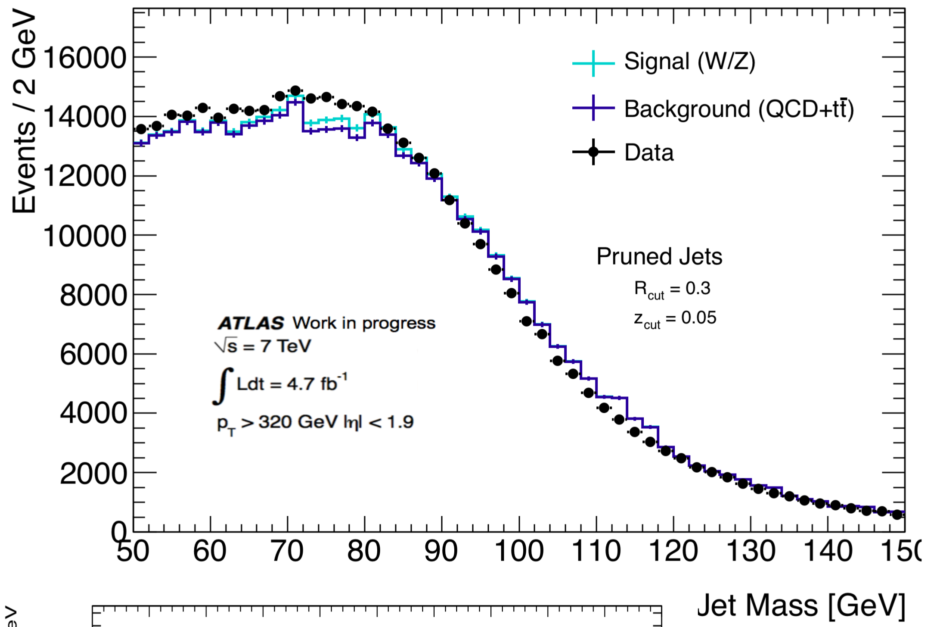
1. Undo the last clustering step : jet j ⟶ subjets j_1, j_2 with mass $m_{j1} > m_{j2}$
   Require: $\delta R_{j1,j2} = \sqrt{\delta y^2_{j1,j2} + \delta\phi^2_{j1,j2}} > R_{split}$
2. If this has mass drop: $\frac{m_{j1}}{m_j} < \mu$ and fairly symmetric splitting: $y_2 = \frac{\min(p^2_{tj1}, p^2_{tj2})}{m^2_j}\delta R^2_{j1,j2} > y_{2,\text{cut}}$
   continue, otherwise set $j = j_1$ and go back to 1
3. Recluster j with Cambridge Aachen radius $R_{filt} = \min(R_{\min}, \delta R_{j1,j2}/2)$
4. Redefine j as the sum of the subjets s_i $j = \sum_{i=1}^{\min(n,3)} s_i$



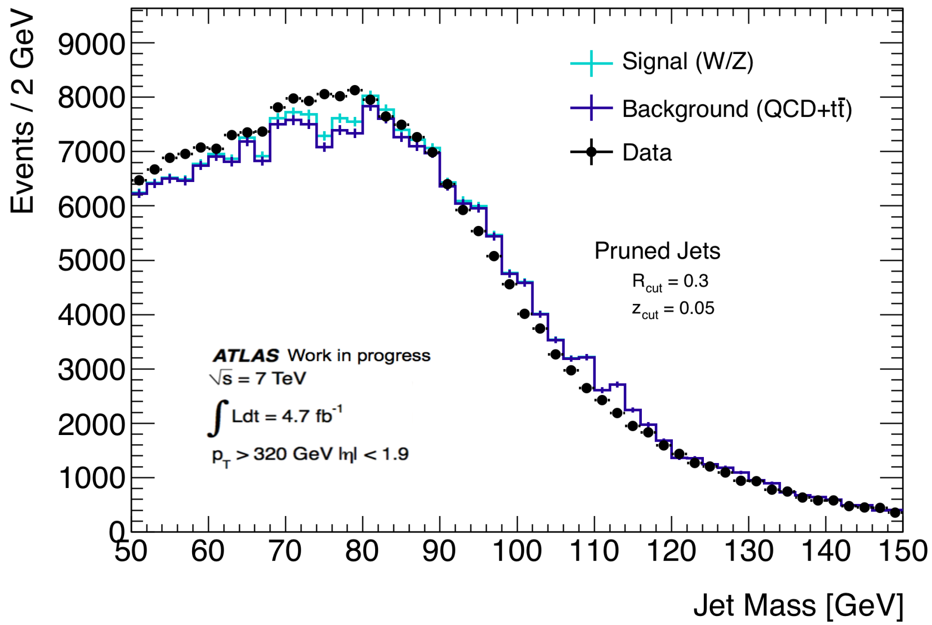
Pruning

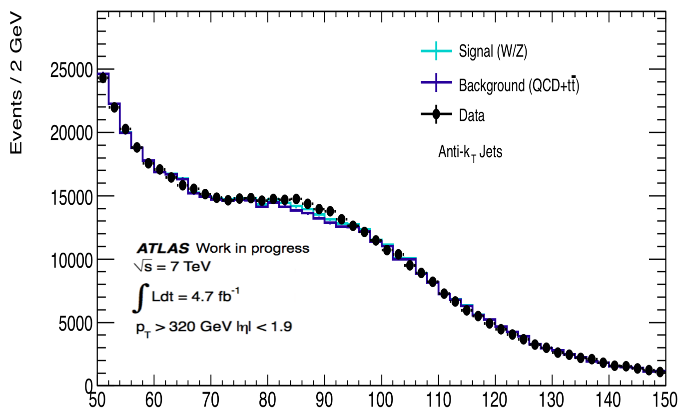
Consider the effect pruning has on the mass distribution using the ungroomed LH:

Default LH cut > 0.16



Tighter LH cut > 0.25
(reject 95% background)



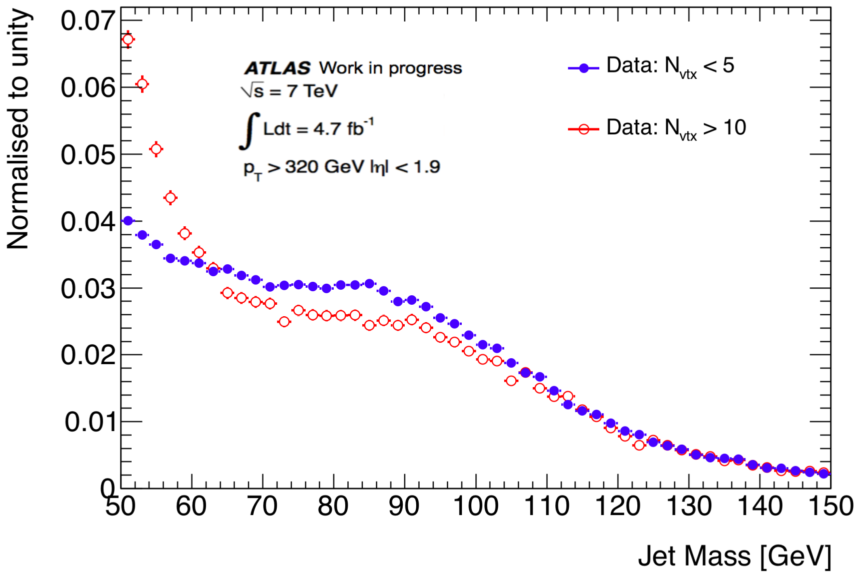


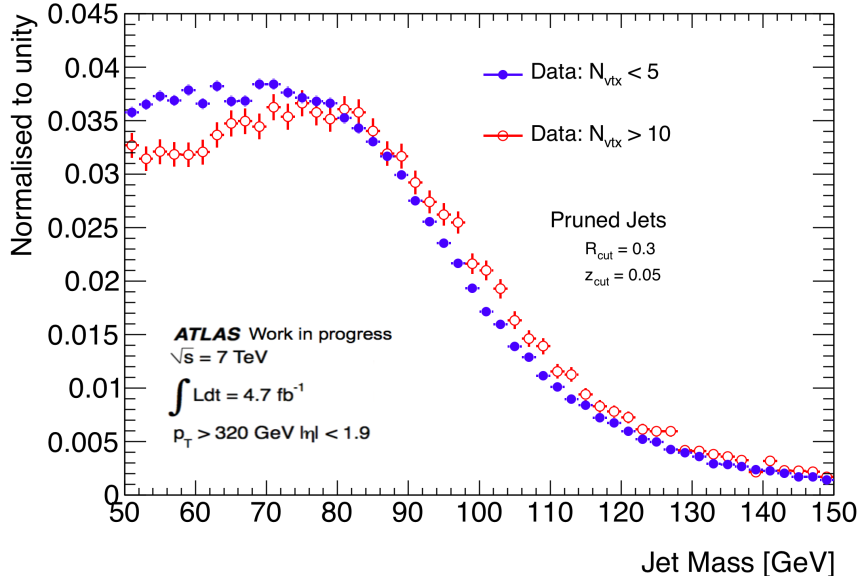
Pruning has a large effect on the background shape, due to:

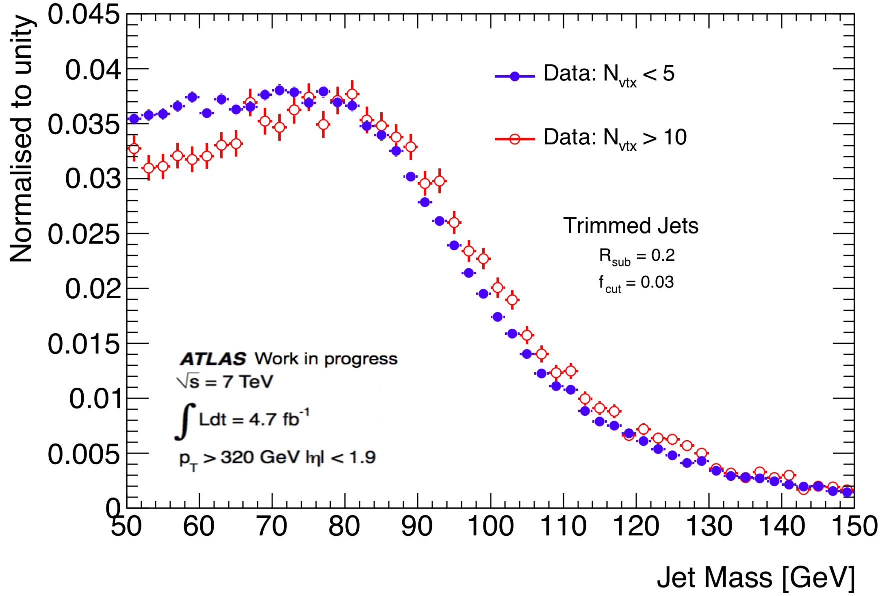
- the p_T cut
- the choice of jet radius

Pileup dependence

Investigate how much the mass is affected by pileup by looking at the mass as a function of the number of primary vertices:



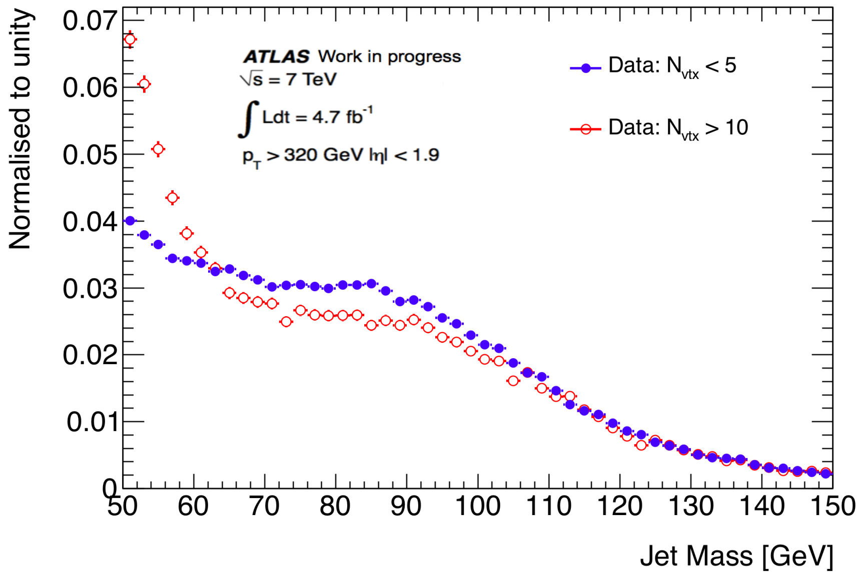


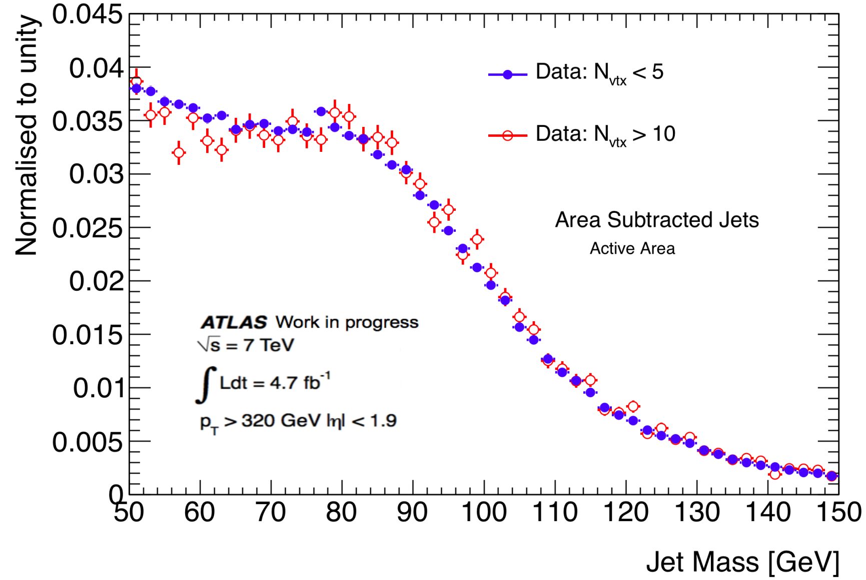


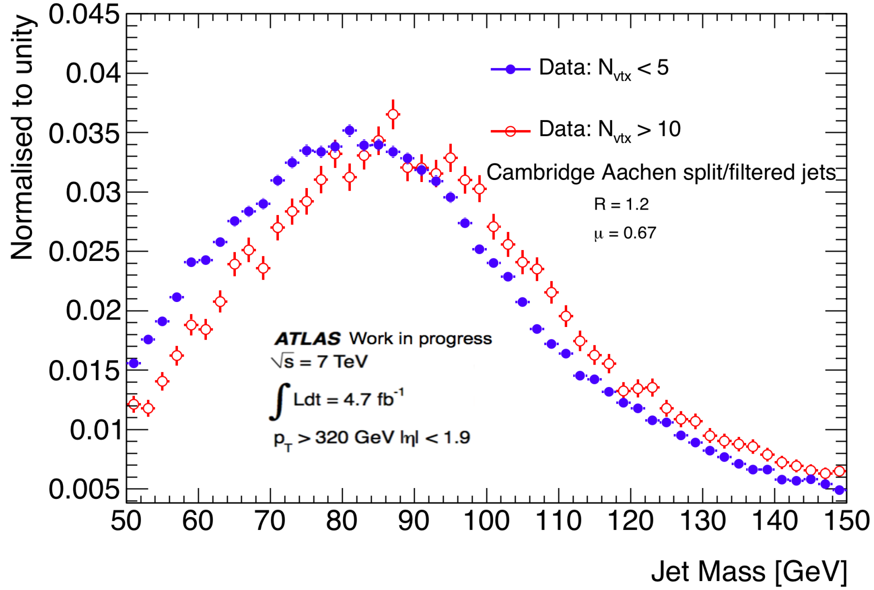
Slight reduction in pileup dependence in the case of pruning and trimming

Pileup dependence

Investigate how much the mass is affected by pileup by looking at the mass as a function of the number of primary vertices:







Pileup dependence much reduced by area subtraction

Shapes

Sphericity is defined as: $S = \frac{3}{2}(\lambda_2 + \lambda_3)$

where λ_3 is the largest eigenvector of the sphericity tensor: $S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\underline{p}_i|^2}$

Highly directional events: sphericity $\longrightarrow$ 0
Isotropic events : sphericity $\longrightarrow$ 1

Thrust: $T = \frac{\sum_i |\hat{T}.\underline{p}_i|}{\sum_i |\underline{p}_i|}$

where the major (minor) thrust axis, T, is the direction which maximises (minimises) the sum of the longitudinal momenta of particles

Directional event: $T_{major} \longrightarrow 1$, $T_{minor} \longrightarrow 0$
Isotropic event: $T_{major} \longrightarrow 0$, $T_{minor} \longrightarrow 1$

Aplanarity is defined as: $A = \frac{3}{2}\lambda_3$

where λ_3 is the largest eigenvector of the sphericity tensor: $S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\underline{p}_i|^2}$

Planar events: aplanarity $\longrightarrow$ 0
Isotropic events : aplanarity $\longrightarrow$ 1