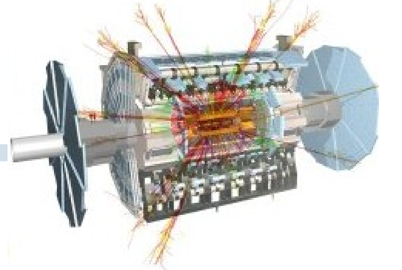
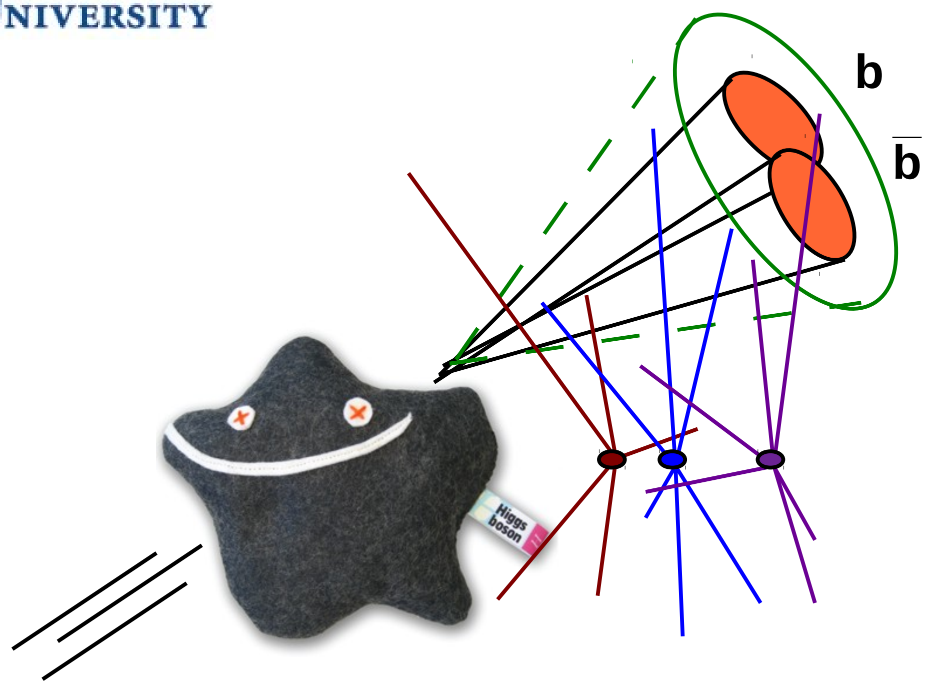


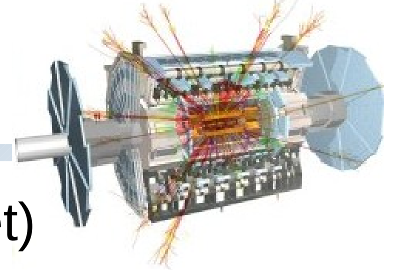



# Jet Grooming in ATLAS

Emily Thompson – *Columbia University*
*on behalf of the ATLAS Collaboration*

- Outline:
  - Update since last year
  - Jet grooming techniques studied and optimizing grooming parameters
  - Performance of grooming on large-R light quark/gluon jets in data
  - MC-based signal background discrimination before and after grooming
  - Jet grooming in ttbar events

# Last year....



- **BOOST'11: ATLAS:** results shown with 42 $pb^{-1}$ of data (2010 dataset)
- Measurement of:
  - anti-kt R=1.0 mass and $\sqrt{d_{12}}$
  - C/A R=1.2 mass before and after mass-drop/filtering (BDRS)
- Our "to-do" list:

  (see Measurable vs Calculable WG Summary here)

## 3 Groomed Jets

An important tool for many new physics searches is jet grooming. There are three grooming algorithms on the market: pruning, filtering and trimming. Filtering and pruning are currently being studied by both ATLAS and CMS. Trimming should be studied too.

It is important to measure

- Measure **both** the groomed **and** ungroomed mass
- Compare the effect of grooming as a function of pileup.
- Try to test grooming as dependent on underlying event, through a measure of the amount of underlying event [Gavin; ref]

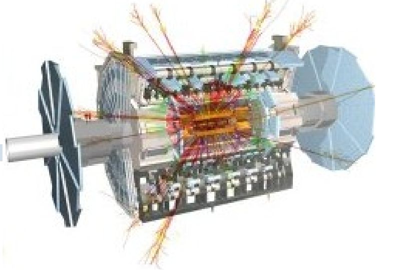
Besides jet mass, it would be good to see the effect of grooming on

- Jet broadening
- N-subjettiness
- using charged tracks only

Experimentalists need input from the theorists on which grooming algorithms would be useful to measure, and for what signals/channels. Are any grooming algorithms useful to measure on jets outside of jet substructure (for general use)? Are there any important theoretical considerations for the calculability/feasibility of the grooming algorithms? What grooming methods can reasonably be measured in the coming year by each collaboration?

- Which algorithms work best?
- What is the best way to determine which algorithms work best?
- Which algorithms are calculable?

# This year....



- **BOOST'12: ATLAS:** 4.7 fb$^{-1}$ of data!
- Showing groomed jet results using:
  - Mass-drop/filtering (C/A), trimming and pruning (anti-kt and C/A)
  - Mass, N-subjettiness ($\tau_{21}$, $\tau_{32}$), kt splitting scales ($\sqrt{d_{12}}$, $\sqrt{d_{23}}$ ) before and after grooming
- Tried to address these questions with full detector simulation

### 3 Groomed Jets

An important tool for many new physics searches is jet grooming. There are three grooming algorithms on the market: pruning, filtering and trimming. Filtering and pruning are currently being studied by both ATLAS and CMS. Trimming should be studied too.

It is important to measure

- Measure **both** the groomed **and** ungroomed mass
- Compare the effect of grooming as a function of pileup.
- Try to test grooming as dependent on underlying event, through a measure of the amount of underlying event [Gavin; ref]

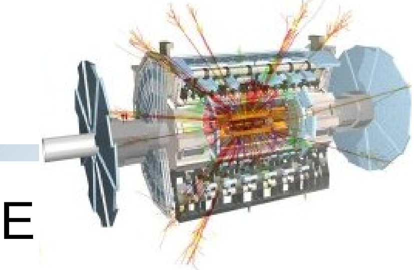
Besides jet mass, it would be good to see the effect of grooming on

- Jet broadening
- N-subjettiness
- using charged tracks only

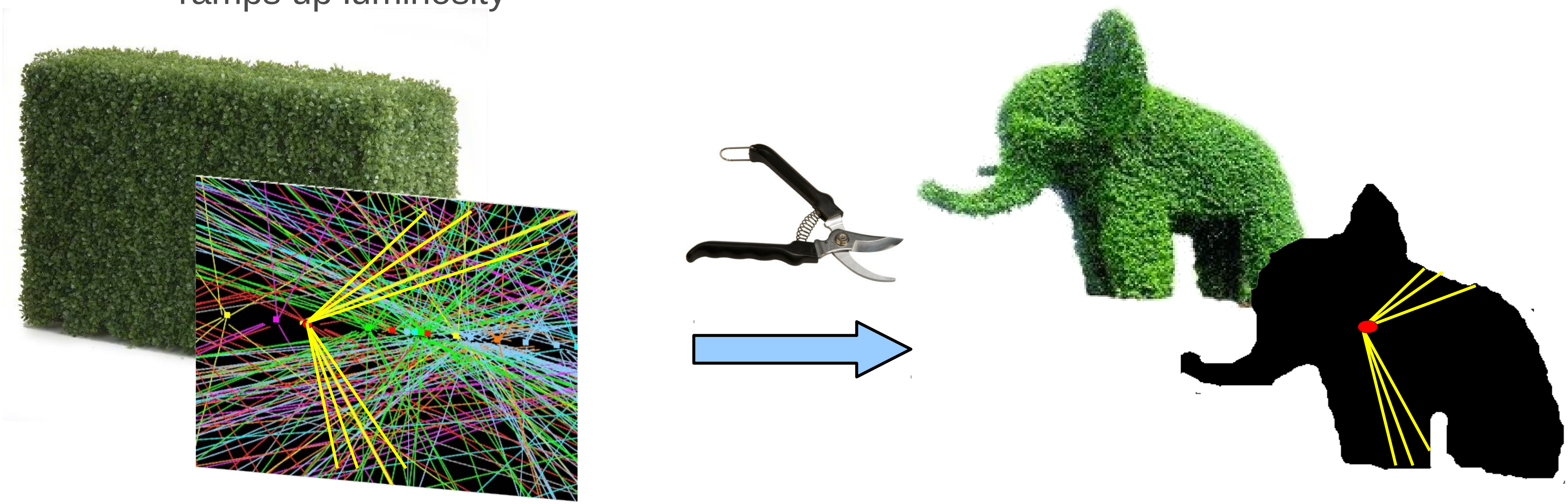
Experimentalists need input from the theorists on which grooming algorithms would be useful to measure, and for what signals/channels. Are any grooming algorithms useful to measure on jets outside of jet substructure (for general use)? Are there any important theoretical considerations for the calculability/feasibility of the grooming algorithms? What grooming methods can reasonably be measured in the coming year by each collaboration?

- Which algorithms work best?
- What is the best way to determine which algorithms work best?
- Which algorithms are calculable?

# Introduction to grooming

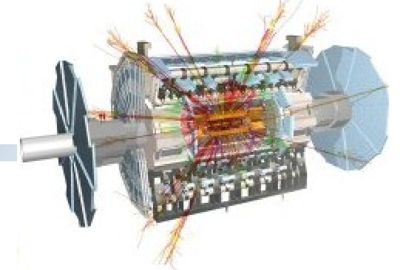


- **Jet grooming:** seeks to get rid of softer components in a jet from UE or pileup and leave constituents from the hard scatter behind
  - Better mass resolution expected after grooming
  - Great for searching for boosted objects contained in a large-R jet!
  - Is especially important to have these studies now so that we are prepared as LHC ramps up luminosity



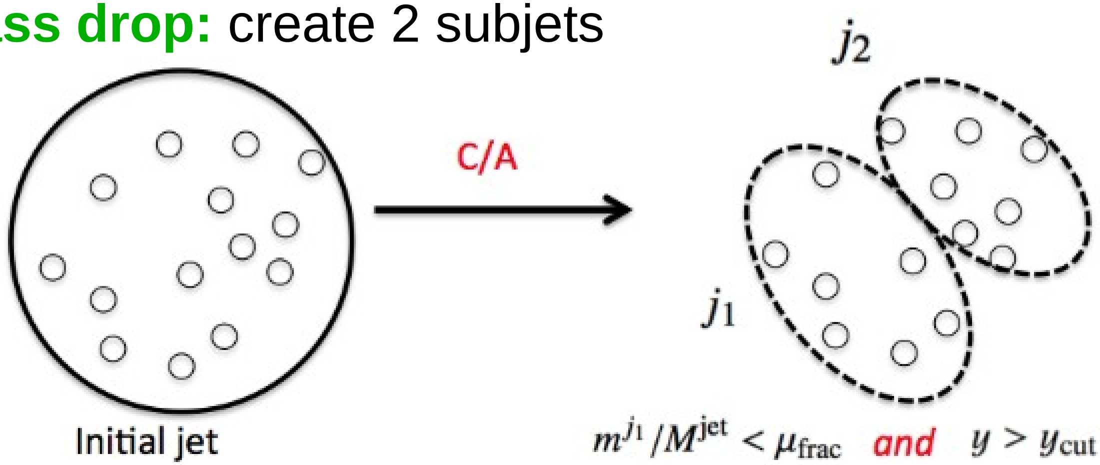
- Three algorithms studied: mass-drop/filtering, pruning, trimming
- **ATLAS results shown today:** summarize the performance between various tunes of groomed algorithms

# Jet grooming



- **"Mass drop/filtering"** http://arxiv.org/abs/0802.2470 (J. Butterworth, A. Davidson, M. Rubin, G. Salam)
  - Identify relatively symmetric subjets, each with significantly smaller mass than their sum
  - Was optimized for H→bb search using C/A jets...**not applied to anti-kt jets!**

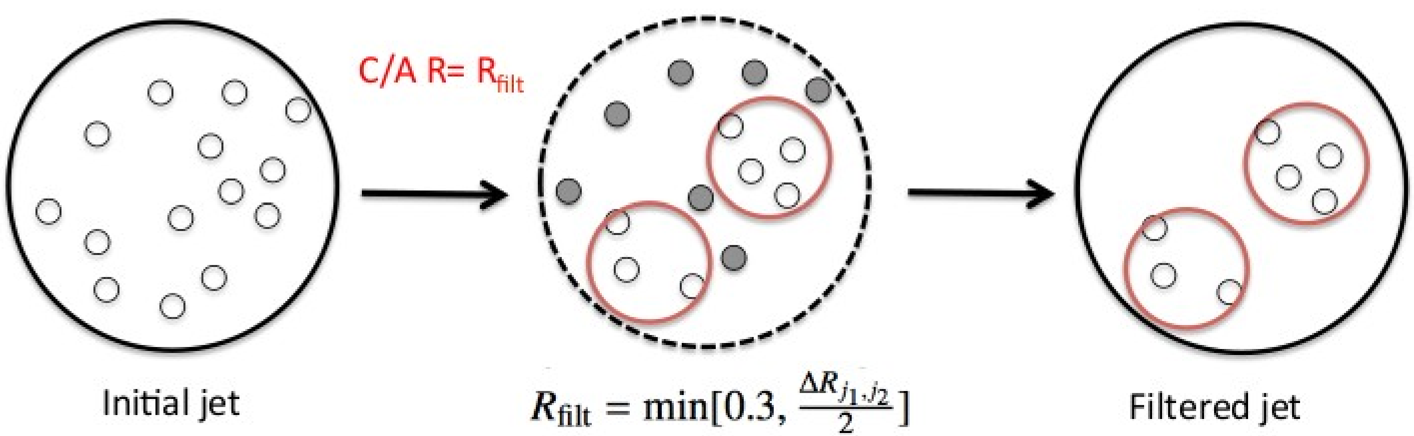
**Mass drop:** create 2 subjets



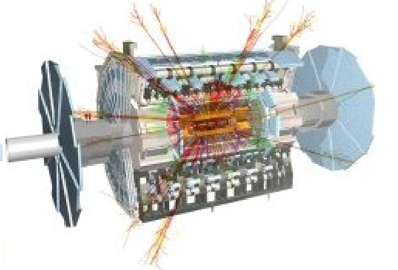

$$\frac{\min[(p_T^{j_1})^2,(p_T^{j_2})^2]}{(M^{\rm jet})^2} \times \Delta R^2_{j_1,j_2} > y_{\rm cut}$$

Tuned parameter: $\mu_{\rm frac}$
($y_{\rm cut}$ set to 0.09)

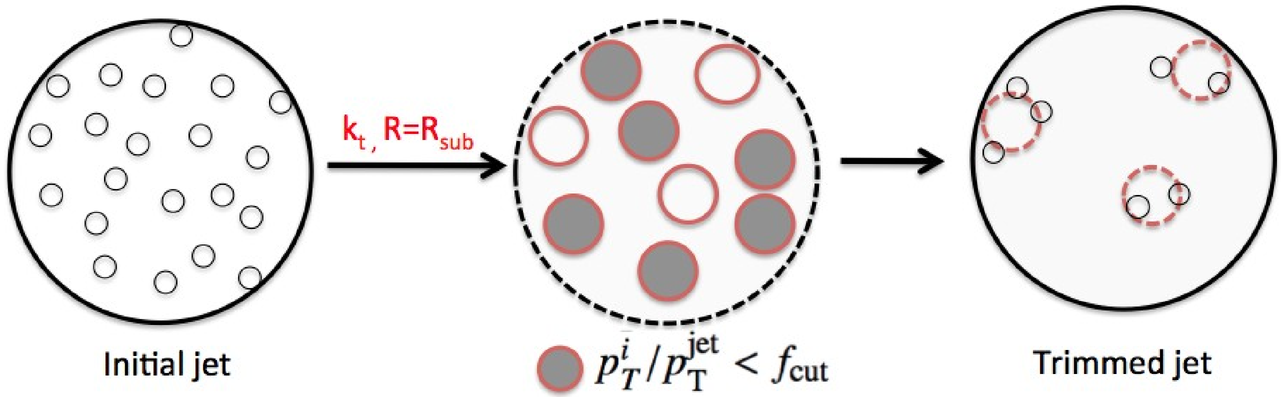
**Filtering:** constituents of j1, j2 are reclustered using C/A



# Jet grooming

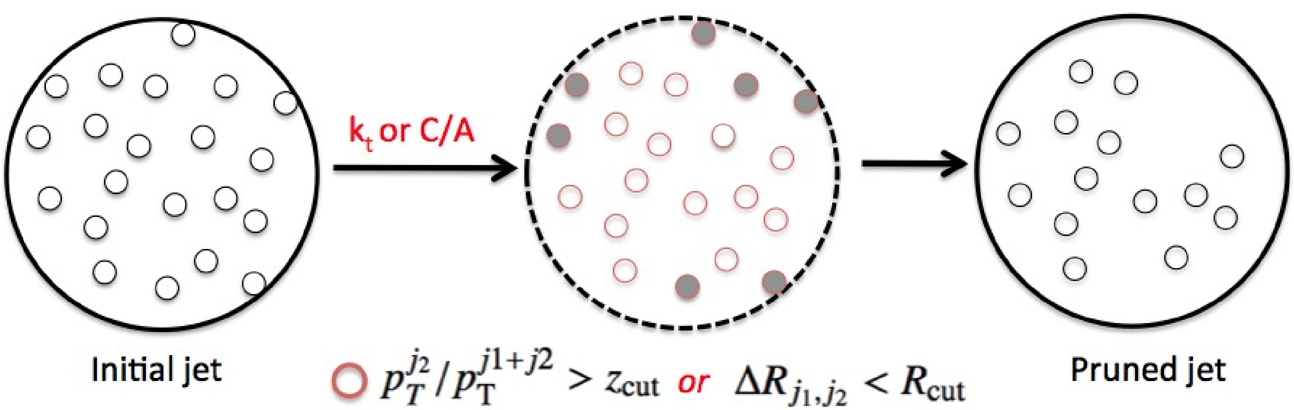


- **"Trimming"** http://arxiv.org/abs/0912.1342 (D. Krohn, J. Thaler, L. Wang)
    - uses $k_t$ algorithm to create subjets of size $R_{sub}$ from the constituents of the large-R jet: any subjets failing $p_T i$ / $p_T < f_{cut}$ are removed



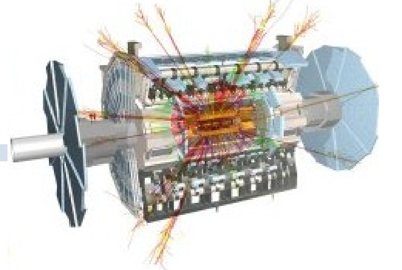

Tuned parameters: $f_{cut}$ and $R_{sub}$

- **"Pruning"** http://arxiv.org/abs/0912.0033 (S. Ellis, C. Vermilion, J. Walsh)
    - Recombine jet constituents with C/A or kt while vetoing wide angle ($R_{cut}$) and softer ($z_{cut}$) constituents. Does not recreate subjets but prunes at each point in jet reconstruction




Tuned parameters: $R_{cut}$ and $z_{cut}$

# Summary of parameters studied



- Large-R jets studied: anti-kt with R=1.0, C/A with R=1.2
- In all, 12 + 15 different grooming configurations

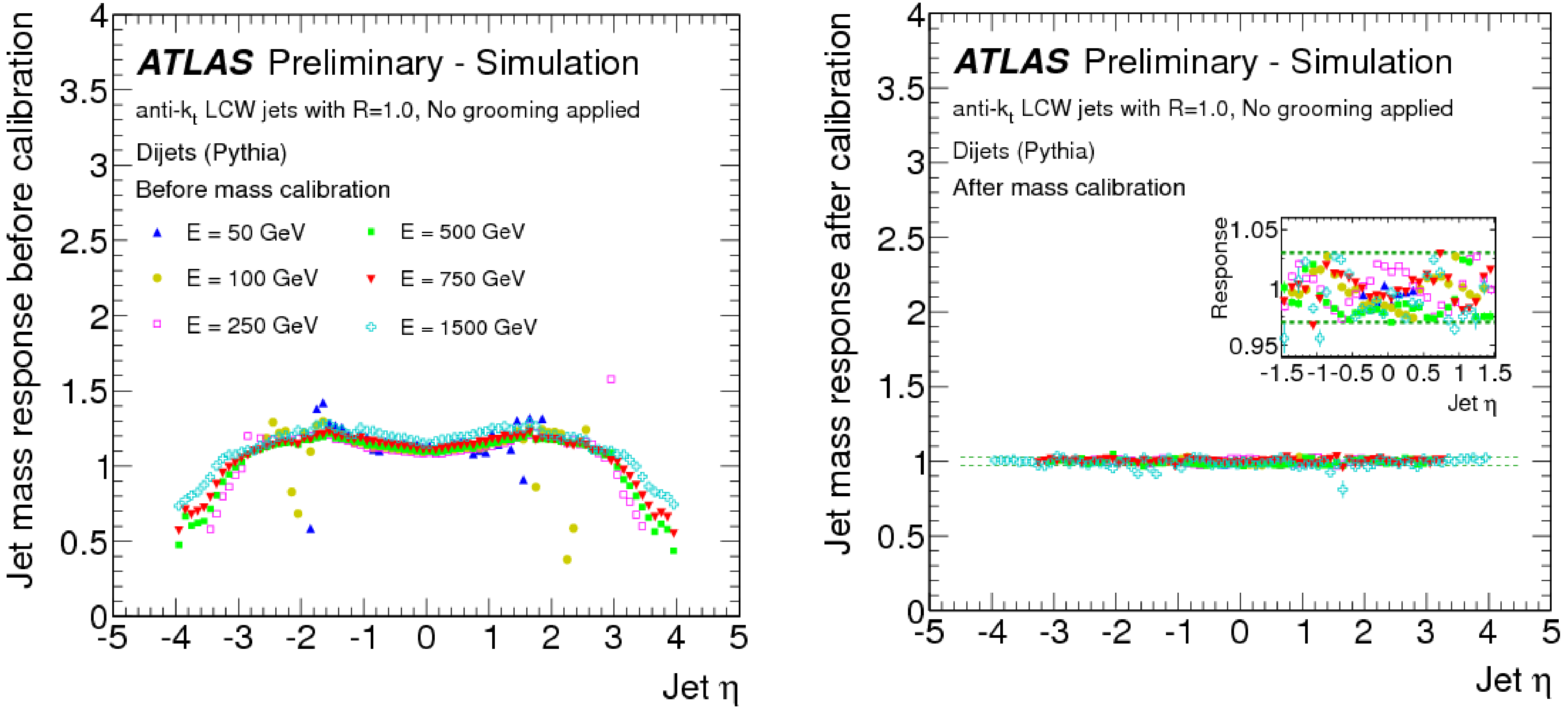
| Jet finding algorithms used | Grooming algorithm | Configurations considered |
|---|---|---|
| C/A | Mass-Drop Filtering | $\mu_{\text{frac}} = 0.20, 0.33, \mathbf{0.67}$ |
| anti-$k_t$ and C/A | Trimming | $f_{\text{cut}} = 0.01, \mathbf{0.03}, 0.05$<br>$R_{\text{sub}} = \mathbf{0.2}, 0.3$ |
| anti-$k_t$ and C/A | Pruning* | $R_{\text{cut}} = 0.1, 0.2, 0.3$<br>$z_{\text{cut}} = 0.05, 0.1$ |

**bold face:** algorithm author recommendations

* Pruning parameters originally studied were changed with discussion with authors after very preliminary studies last fall (were Rcut = 0.05, 0.1 and zcut = 0.05, 0.1, 0.15)

# Jet calibration and selection

- Jets are built from “locally calibrated topological clusters” (LCW)
- Monte Carlo based calibration applied to correct scale
  - Measure calorimeter response with mean of a Gaussian fit to core of distribution of reco jet / truth jet (Pythia)
  - No pileup correction applied before JES/JMS corrections




- Events cleaned for detector noise and non-collision background

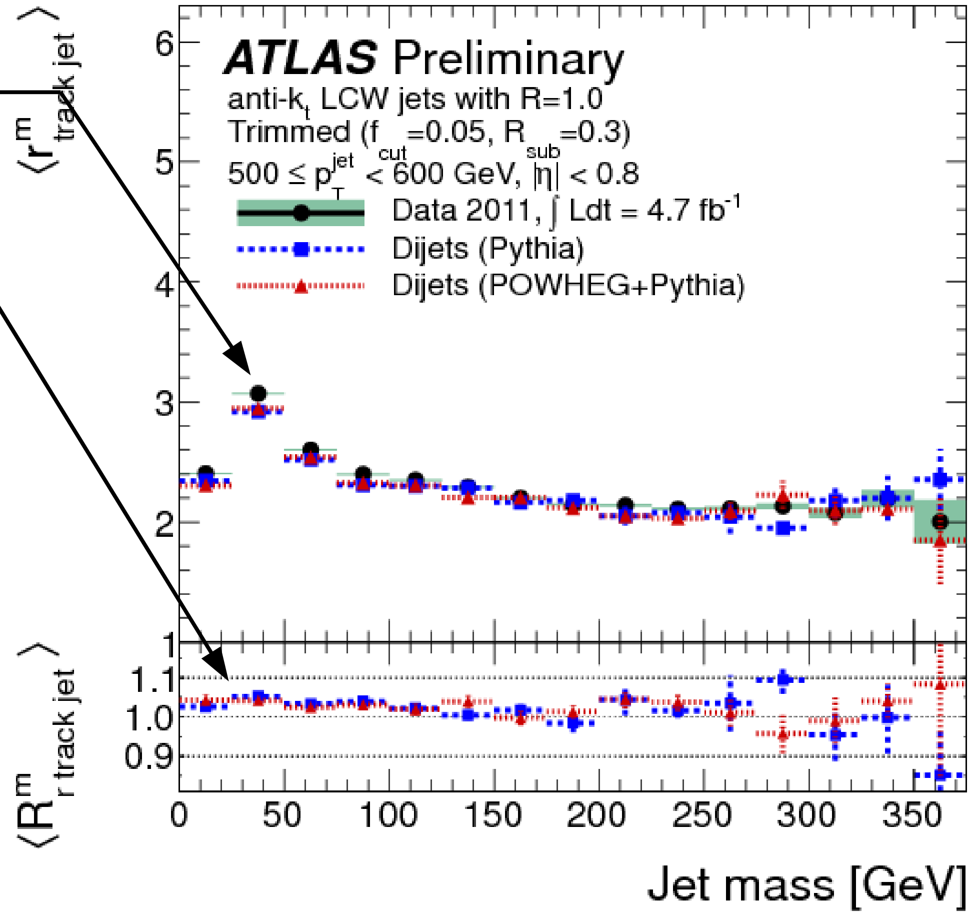
# In situ validation of JES/JMS

- **Double ratio method:**

  $r^m_{\text{track jet}}$ = calo jet / track jet

- Take mean of $r^m_{\text{track jet}} = R_{\text{data}}$ or $R_{\text{MC}}$
- Compute $R_{\text{data}}/R_{\text{MC}}$
- Systematic is deviation from 1, taking the statistical uncertainty of the calo-to-track jet ratio into account
  - weighted average (w_bin is the stat uncertainty):

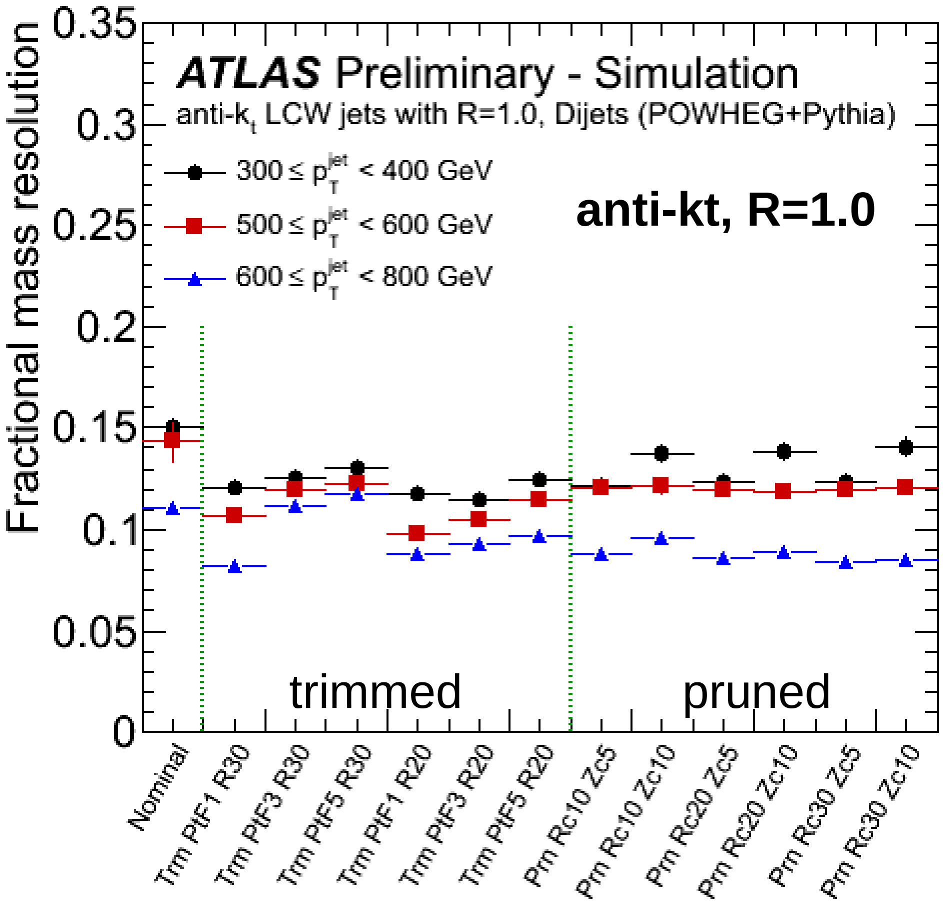
$$\langle \delta_{\text{MC}} \rangle = \frac{\sum_{\text{bins}} w_{\text{bin}} (R^m_{r\text{track-jet}} - 1)}{\sum_{\text{bins}} w_{\text{bin}}}$$

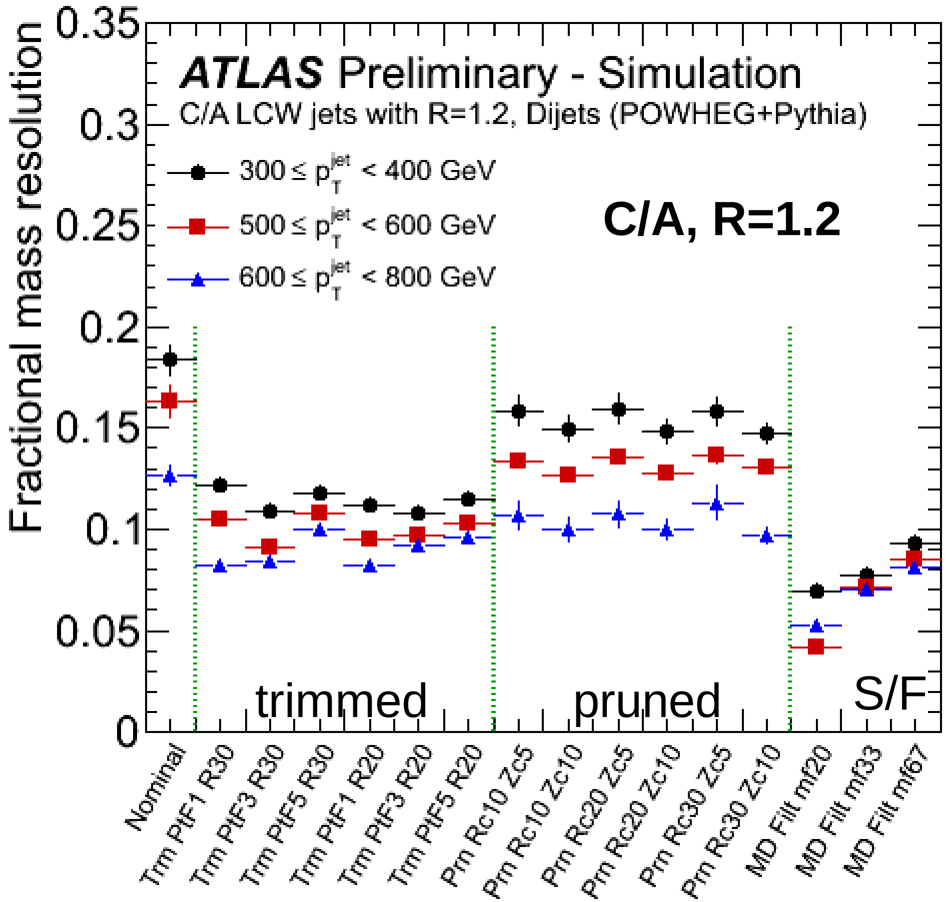



- Take the larger of either the Pythia or POWHEG comparison
- **JMS: fairly stable 4-5% up to pT ~800 GeV**

# Fractional mass resolution

- **Leading jet in Powheg (NLO ME) + Pythia (PS), with pileup:** Reconstructed to truth jet matching within dR < 0.75, and truth jet must pass kinematic criteria




Note: calibration applied only to:

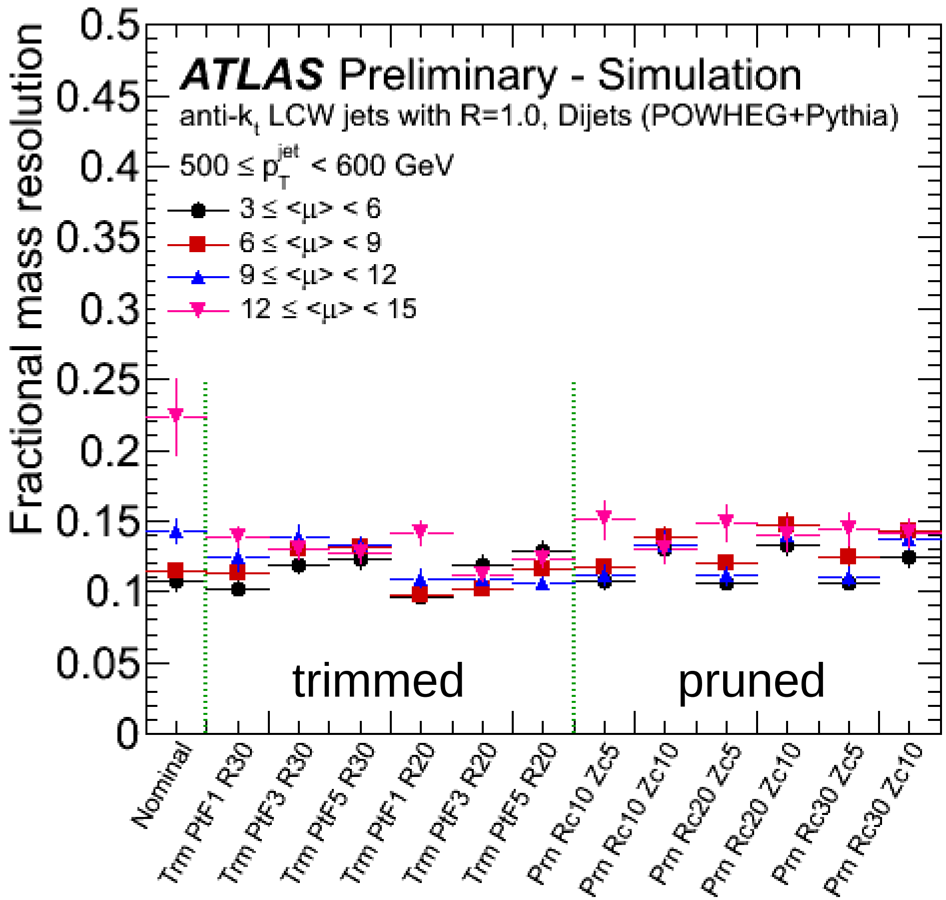
- Ungroomed (“Nominal”) anti-kt R=1.0 and C/A R=1.2
- anti-kt R=1.0 with trimming (fcut = 3%, 5% and Rsub = 0.3)
- C/A R=1.2 with trimming: (fcut = 5% and Rsub = 0.3) and mass-drop/filter (μfrac = 0.67)

# Mass resolution vs pileup

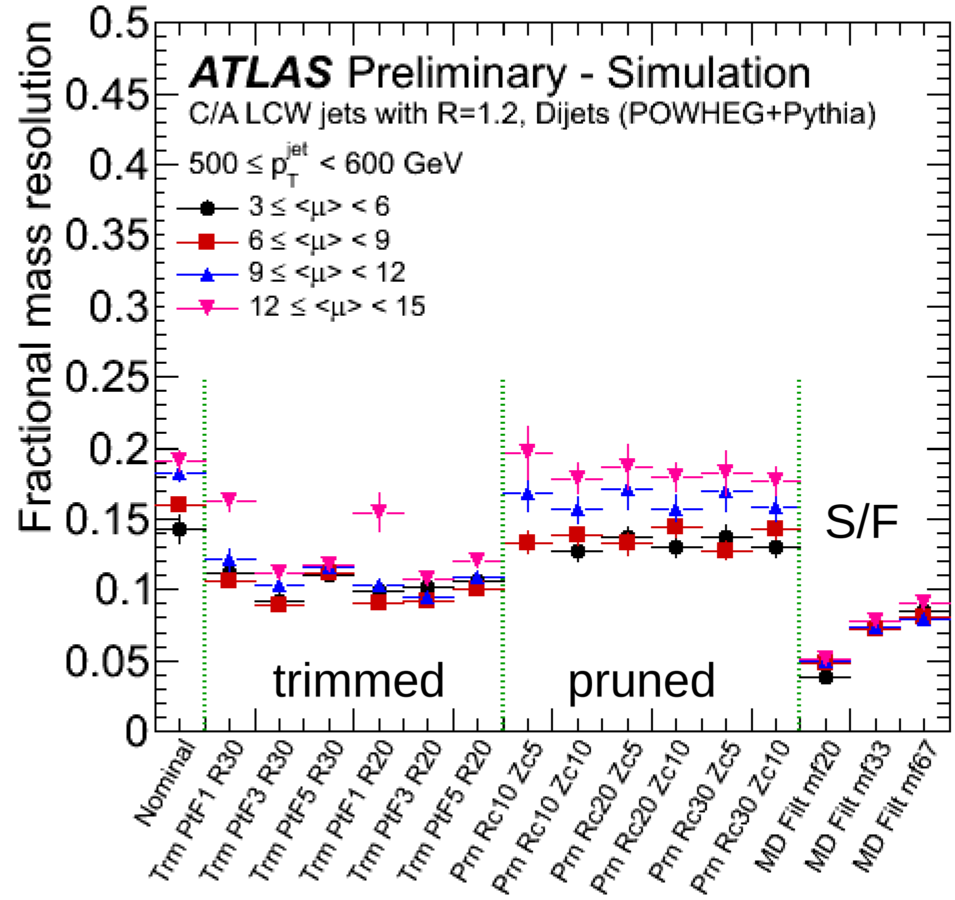
- **Leading jet in Powheg (NLO ME) + Pythia (PS):**

  500 < jet $p_T$ < 600 GeV

**average interactions per bunch crossing**

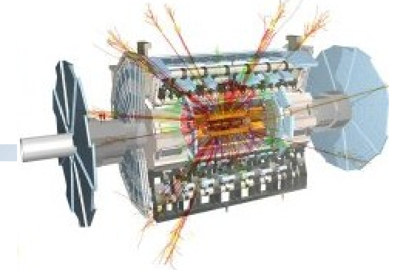



**anti-kt, R=1.0**




**C/A, R=1.2**

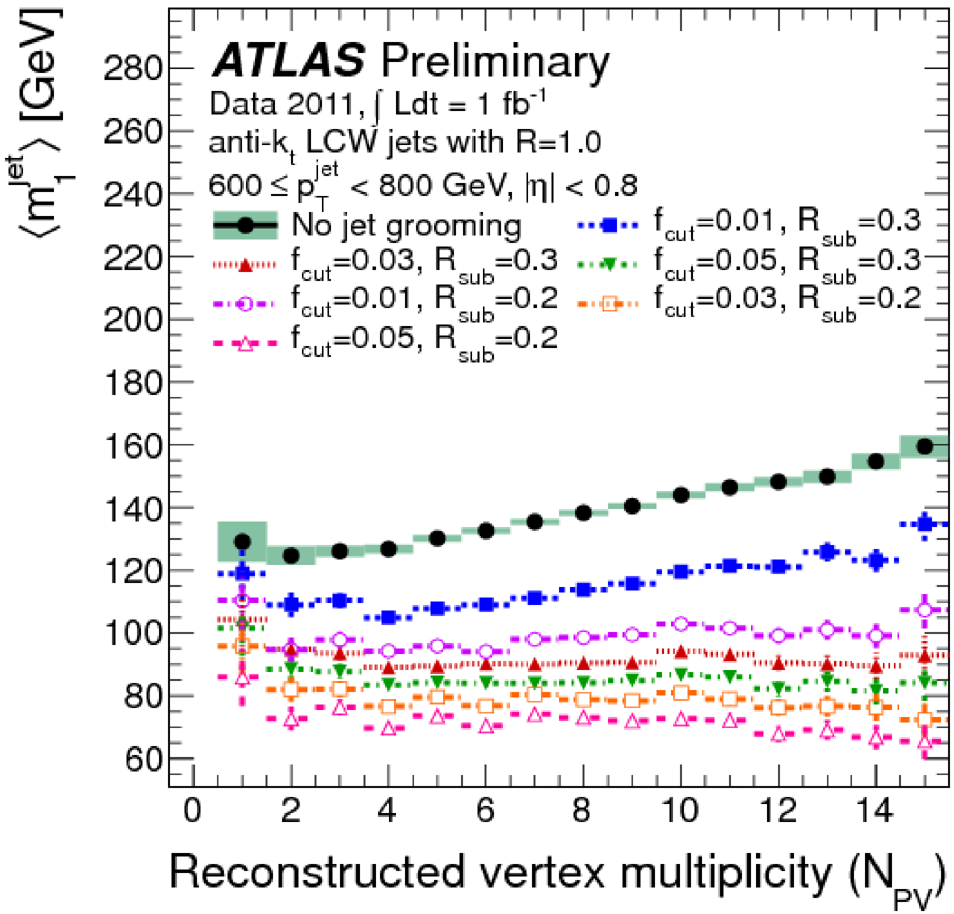
# Mass vs pileup in data



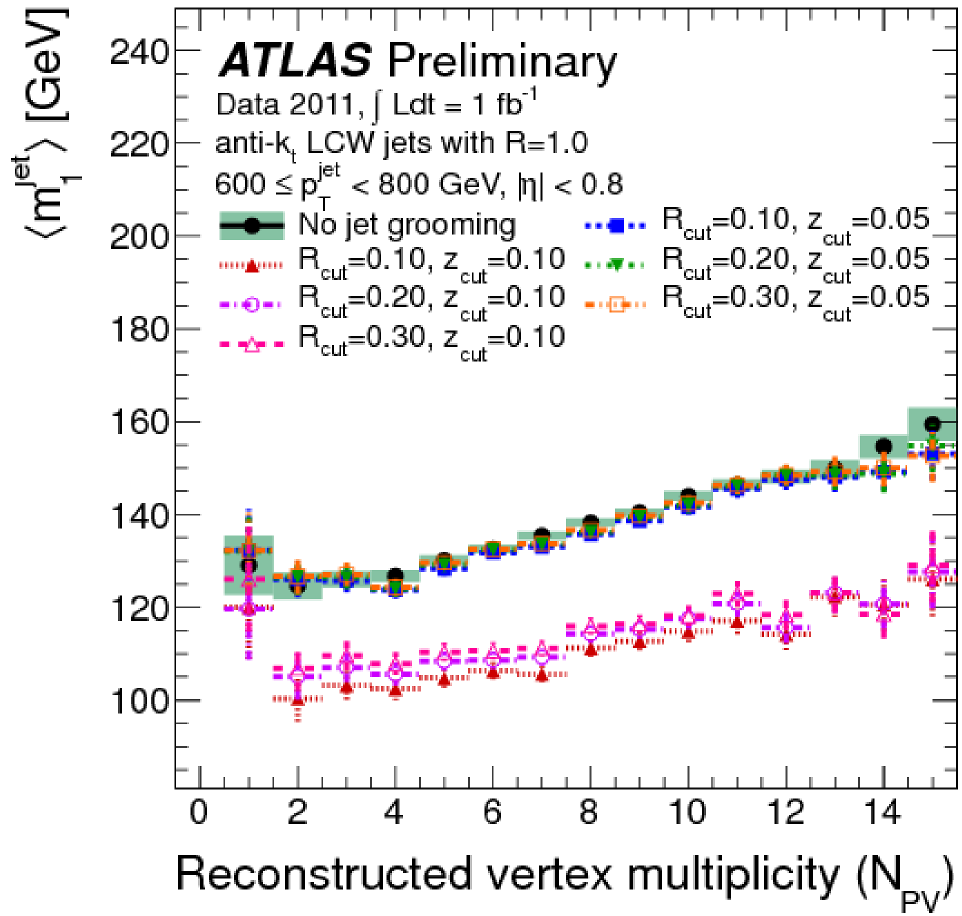
- Mean of mass distribution in data

  600 < jet $p_T$ < 800 GeV

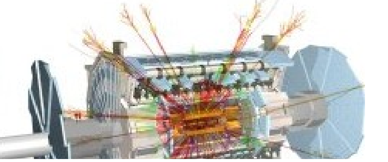
**anti-kt R=1.0, Trimmed**




**anti-kt R=1.0, Pruned**

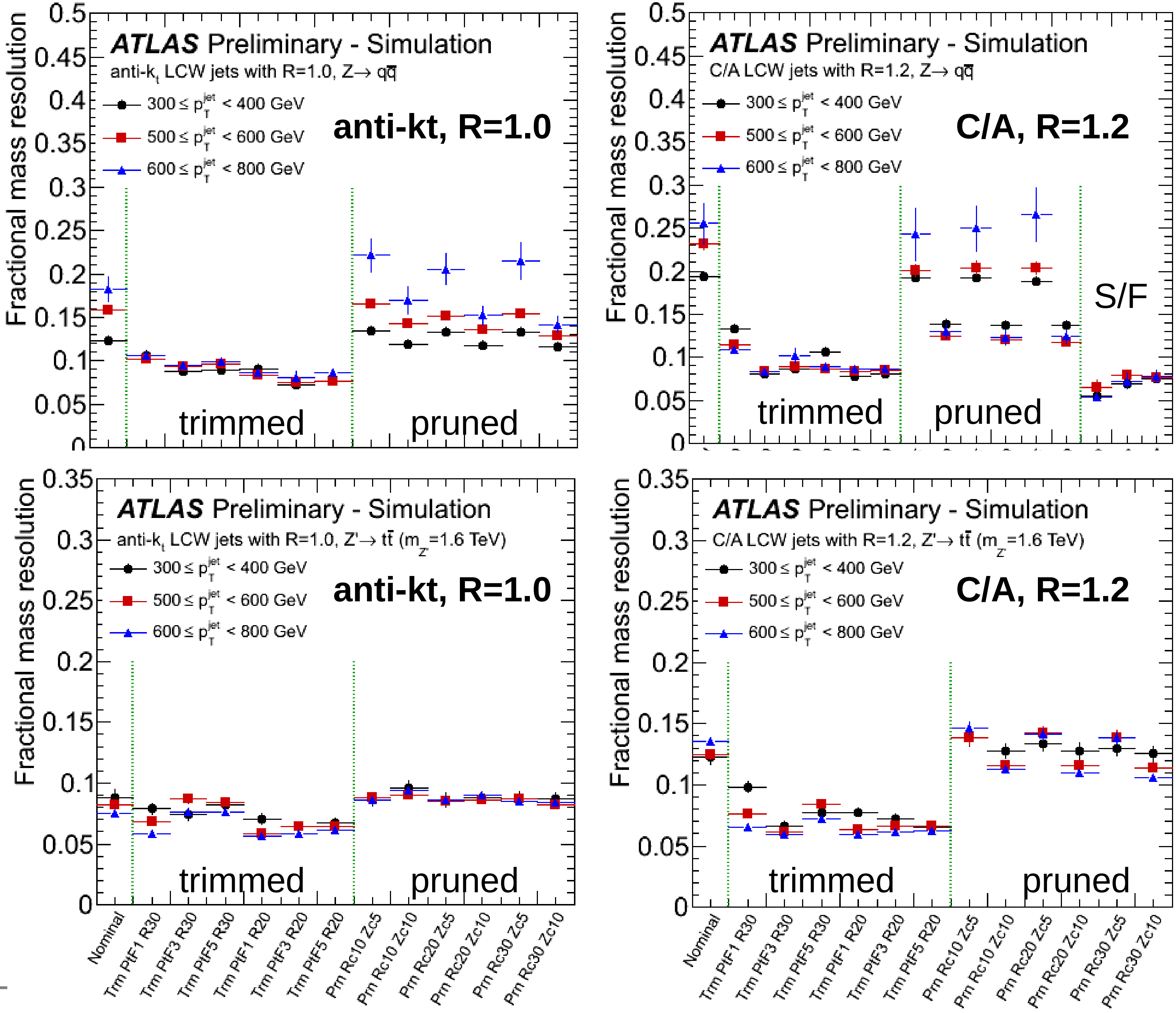


# Resolution in boosted object events

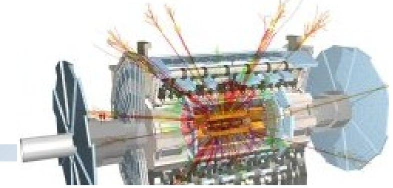


**Herwig (ME)**
**+Jimmy (MPI)**
**Z → qq with pileup**

**Pythia Z' → ttbar (M=1.6 TeV) with pileup**



# Recommendations for ATLAS

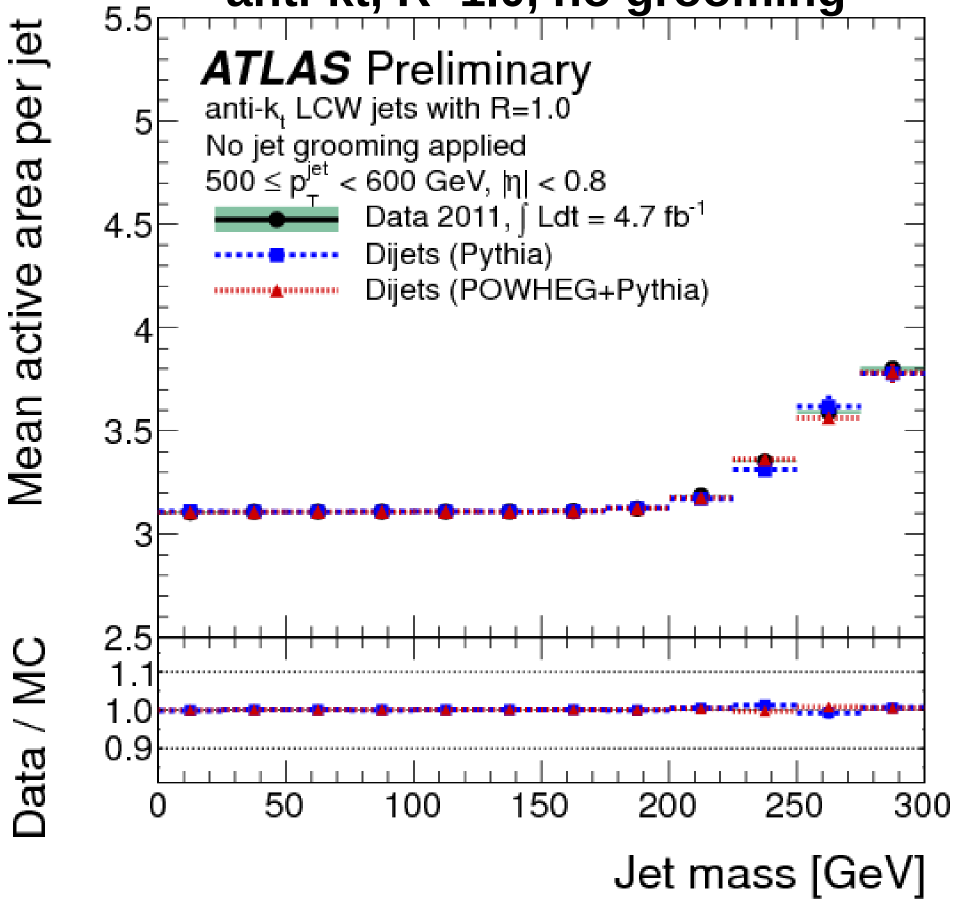


- Based on the above studies (and more not shown here), ATLAS found that **Trimmed anti-kt R=1.0 jets with fcut = 5% and Rsub = 0.3** works best for our boosted top studies.
- **Mass-drop/filtered jets C/A R=1.2 jets with μfrac = 0.67** still show excellent performance and are recommended for two-body hadronic decay channels they were designed for.
- A note on pruning:
  - Most optimization was done as a function of pileup (not original design of algorithm)
  - That being said, initial studies show that a stricter $z_{cut}$ = 0.15 (with $R_{cut}$ = 0.3) looks promising
  - Will also look into event-by-event tuning using NPV, for example.

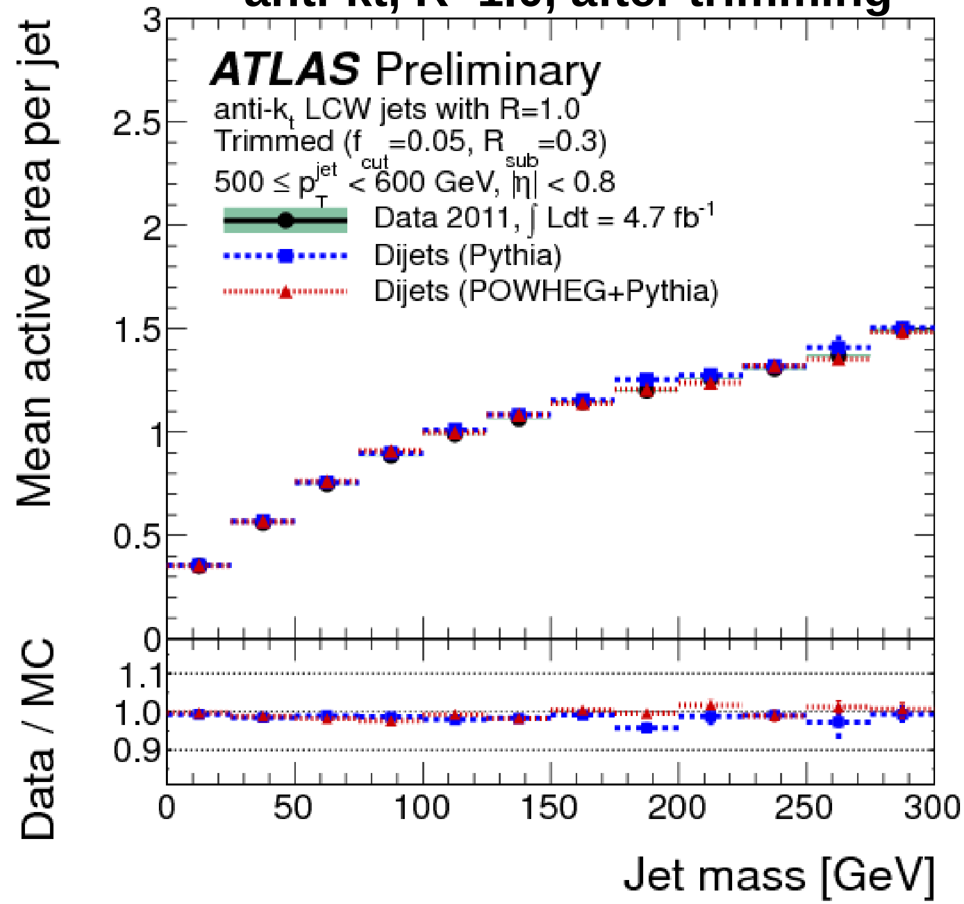
# Impact of grooming in data

- **Jet area**
  - Before trimming: area ~π (R=1.0)
  - After: reduced by factor 3 to 5 (well described in MC)

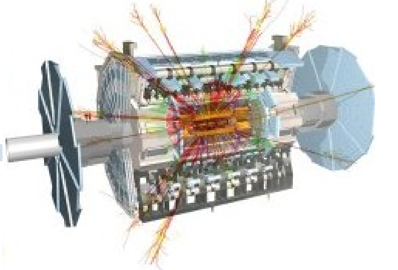
**anti-kt, R=1.0, no grooming**




**anti-kt, R=1.0, after trimming**



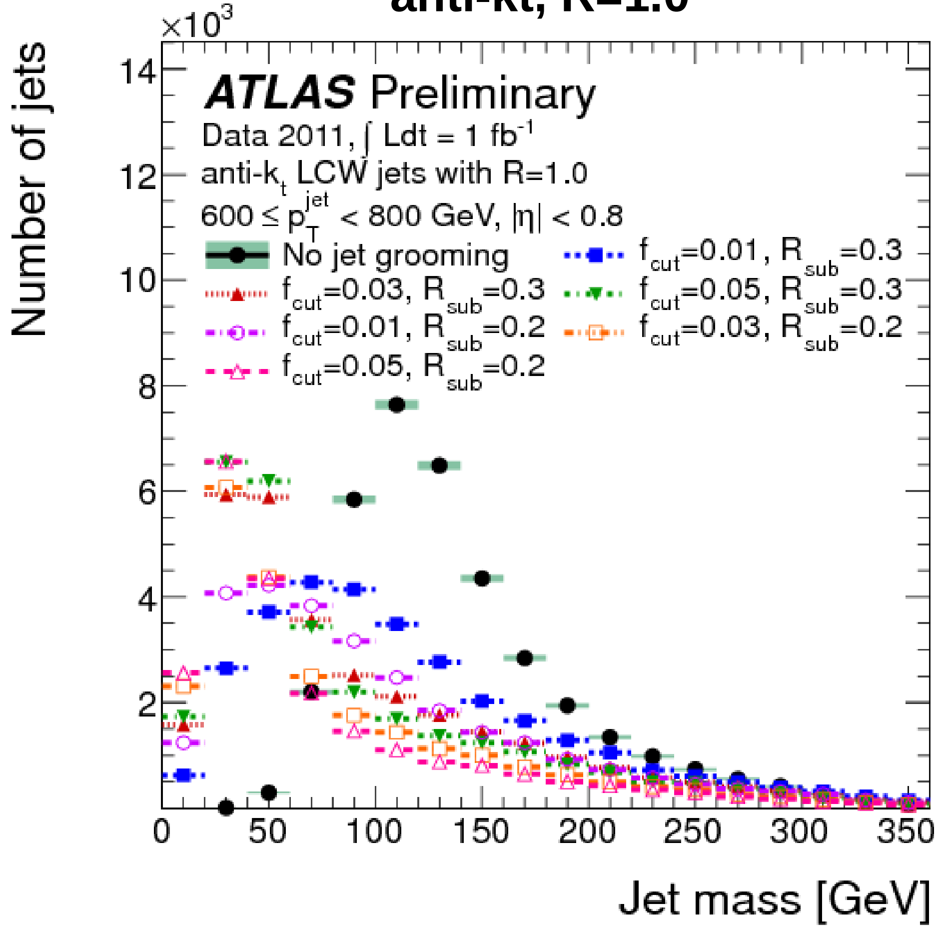
# Impact of grooming in data



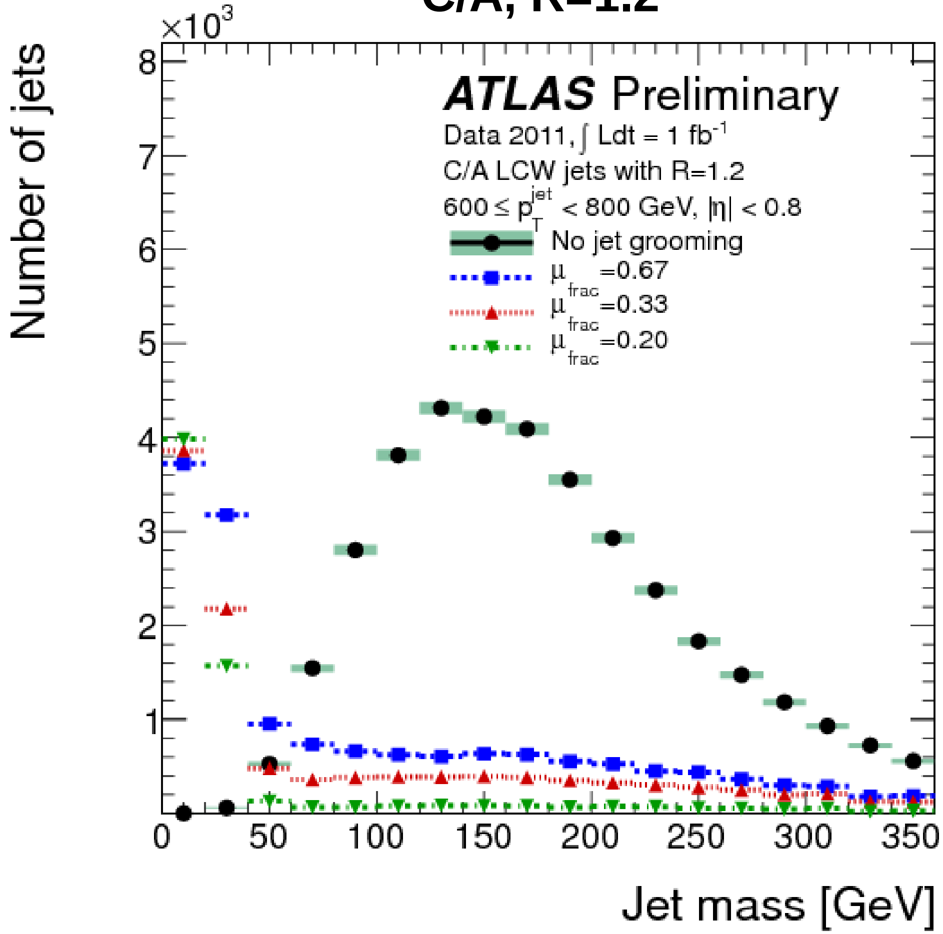
## Jet mass

- ....grooming causes mass to be pushed lower

**anti-kt, R=1.0**




**C/A, R=1.2**

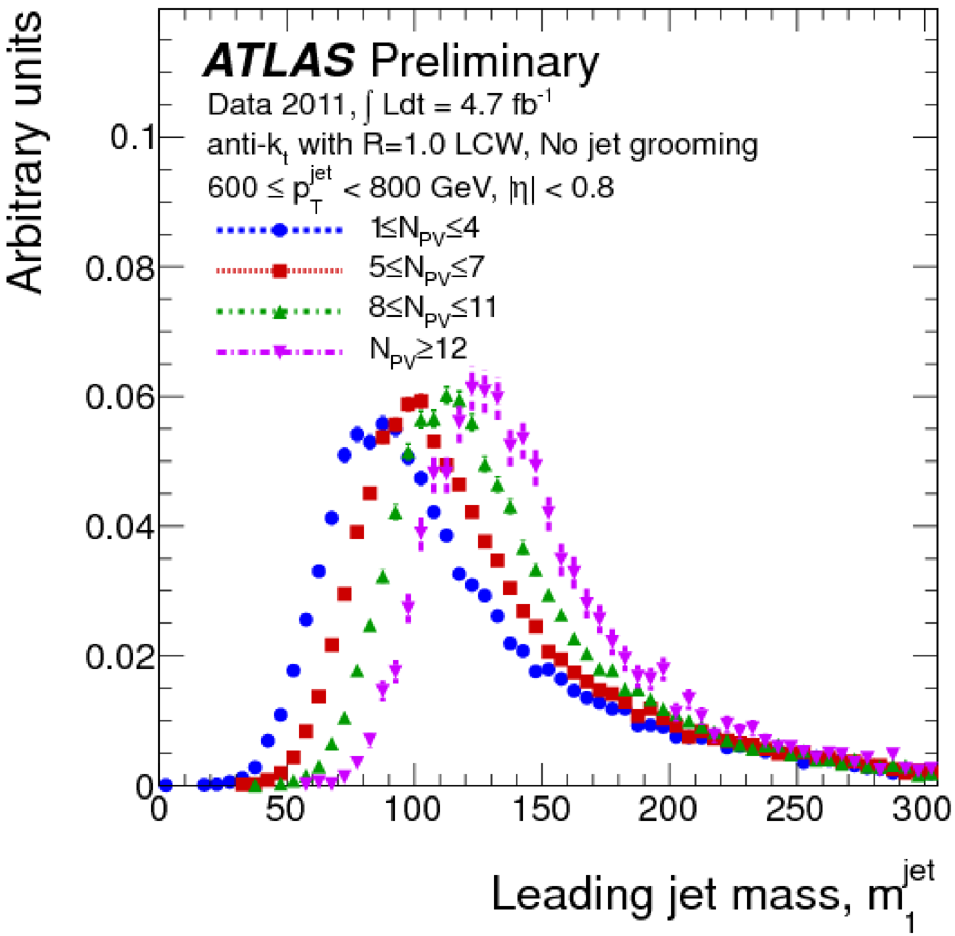


# Impact of grooming in data

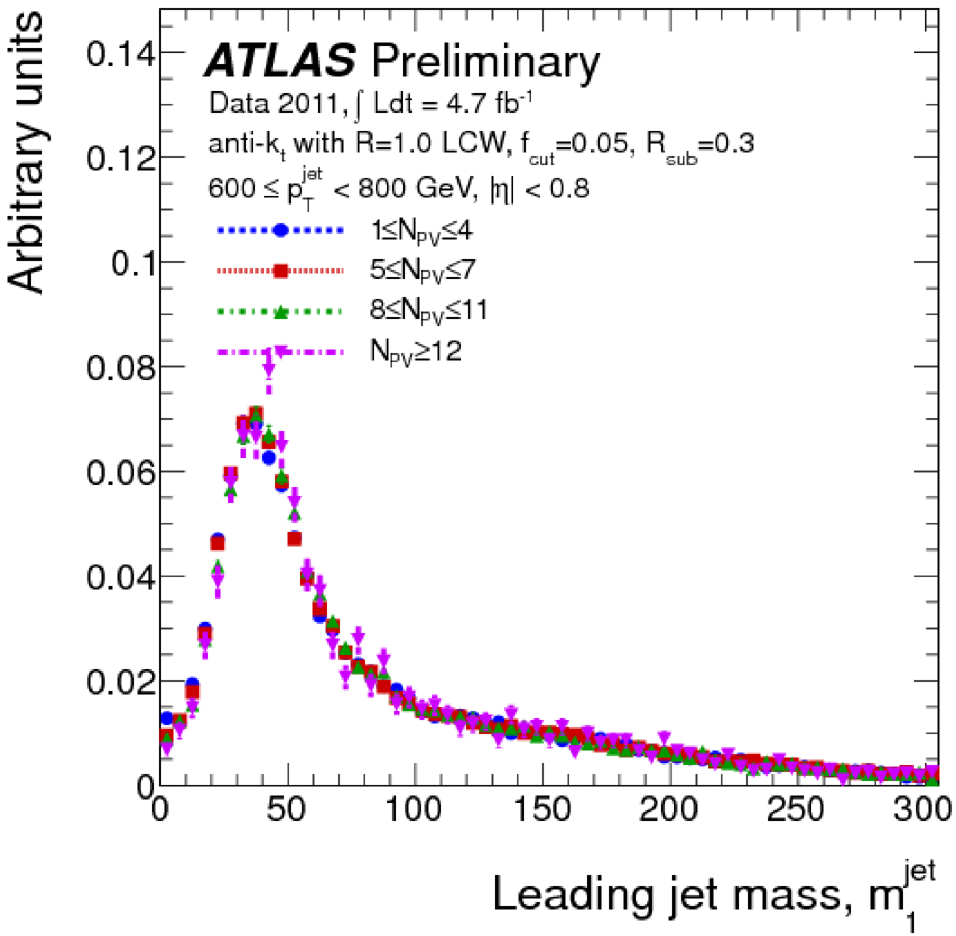
## Jet mass

- Compare ungroomed jets with trimmed vs pileup

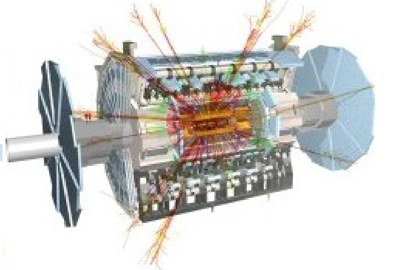
**anti-kt, R=1.0, no grooming**




**anti-kt, R=1.0, after trimming**

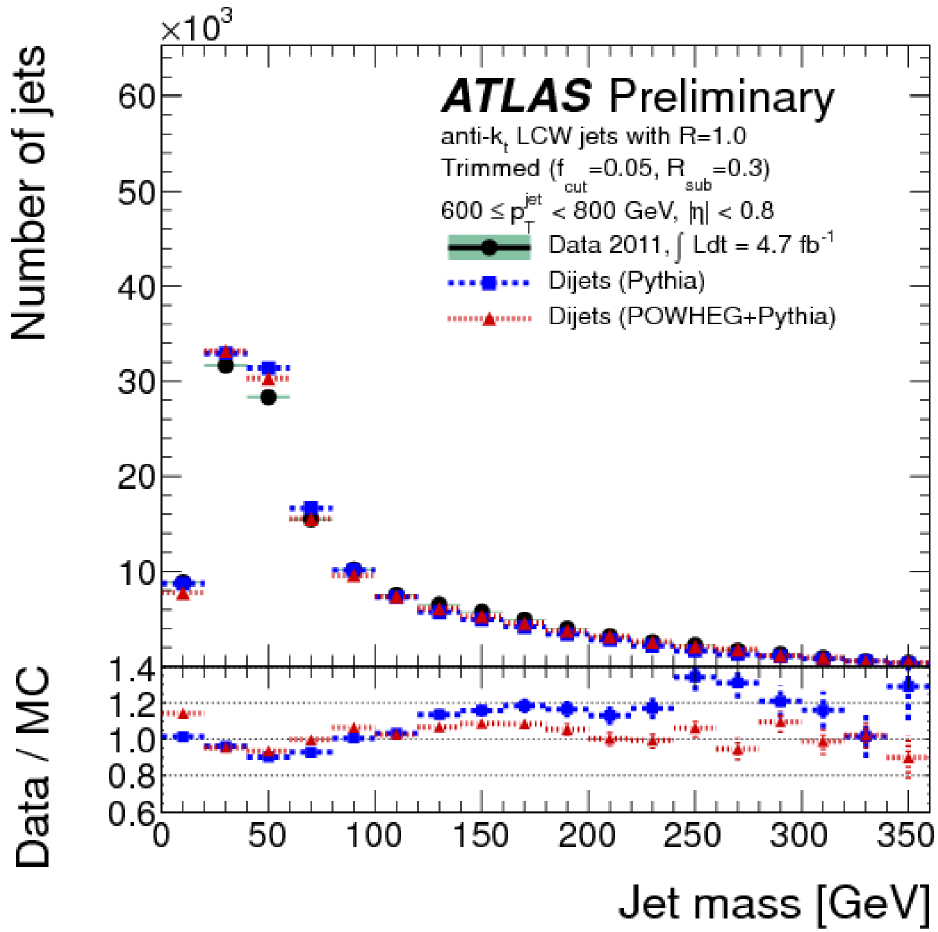


# Impact of grooming in data

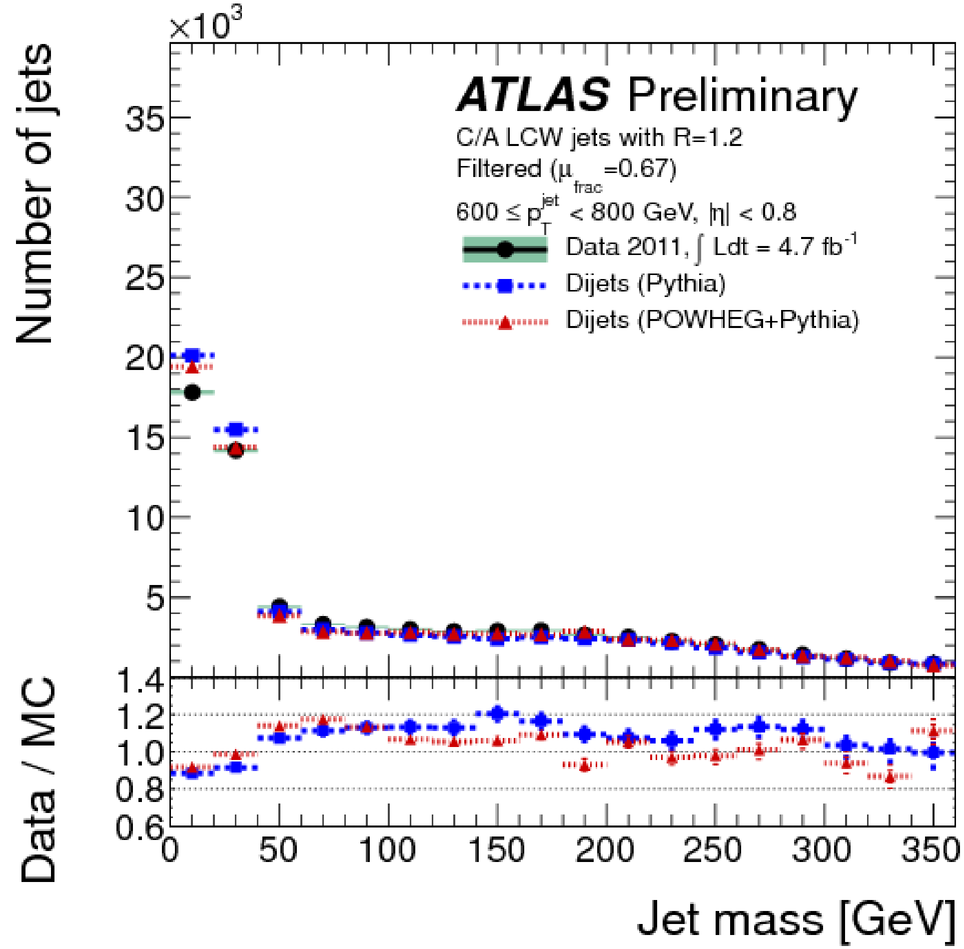


- **Jet mass**
  - LO (Pythia) vs NLO (POWHEG)

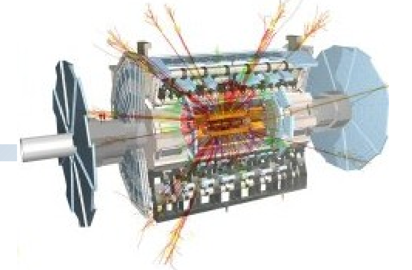
**anti-kt, R=1.0, after trimming**




**C/A, R=1.2, after mass-drop/filtering**



# Impact of grooming in data

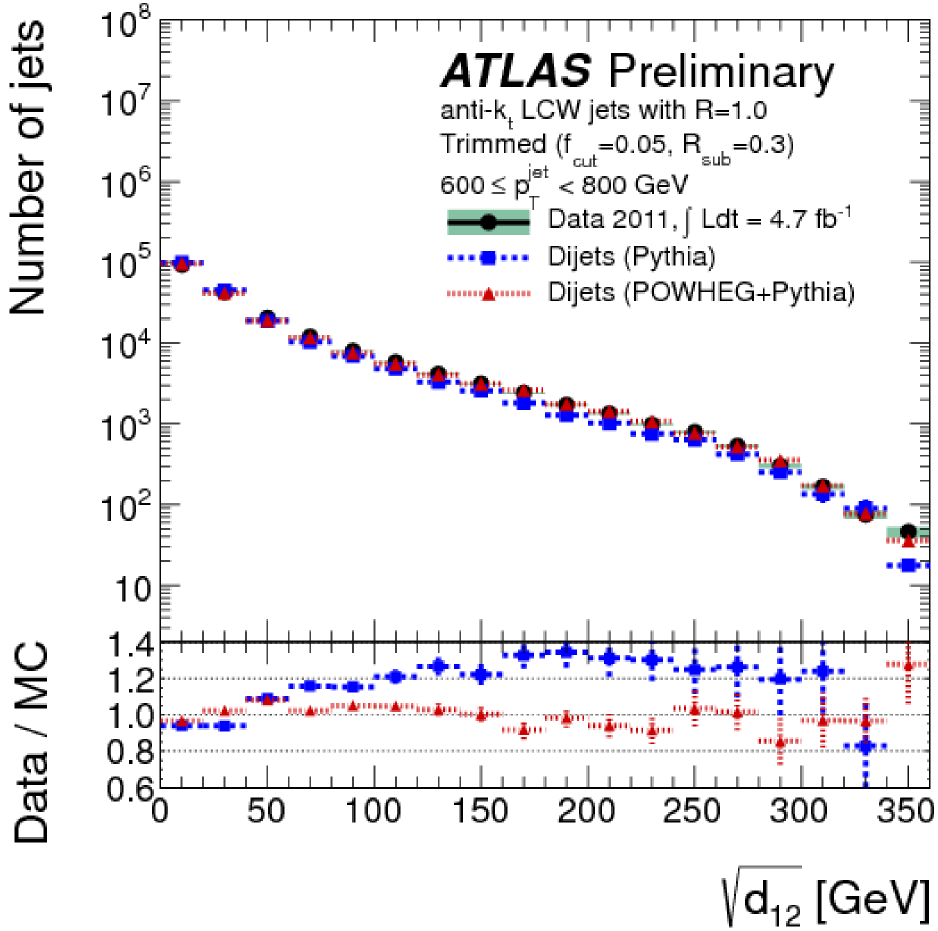


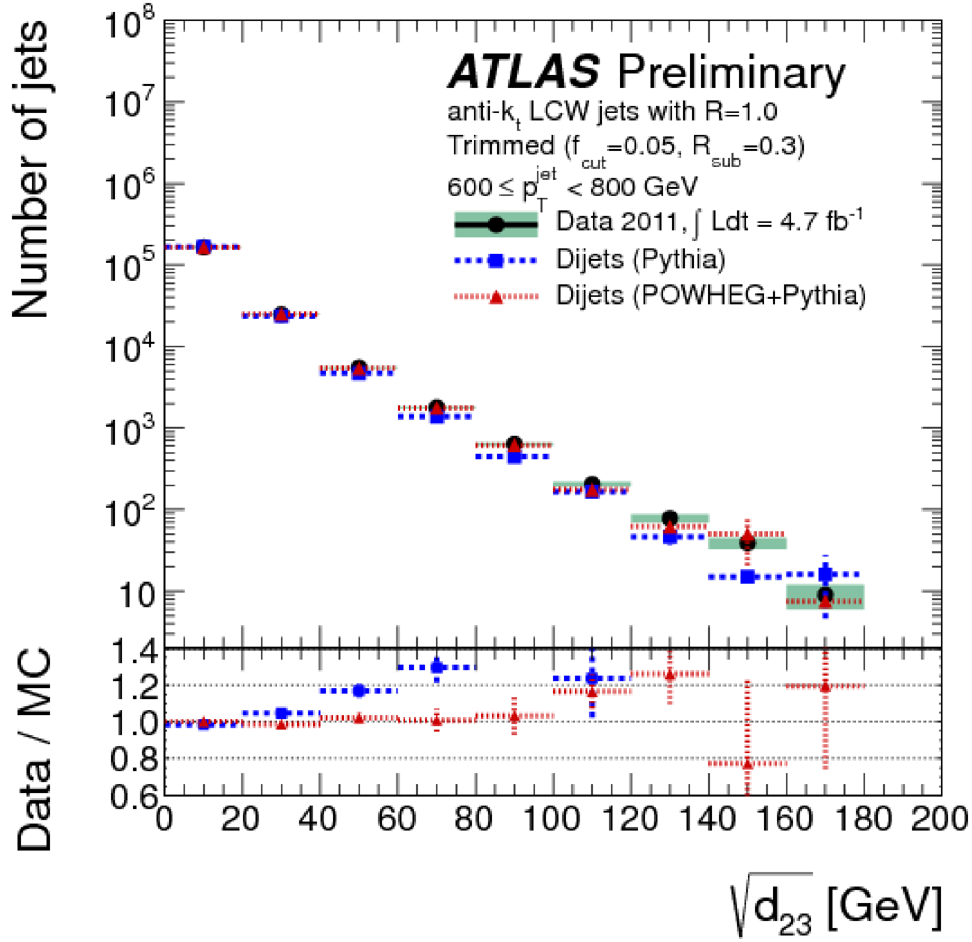
- **kt-splitting scales**

$$\sqrt{d_{ij}} = \min(p_{\mathrm{T}i}, p_{\mathrm{T}j}) \times \Delta R_{ij}$$

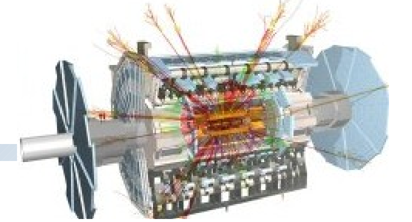
*i, j* = 1, 2: last two constituents before final reclustering
*i, j* = 2, 3: second and third to last constituents

**anti-kt, R=1.0, after trimming**



# Impact of grooming in data



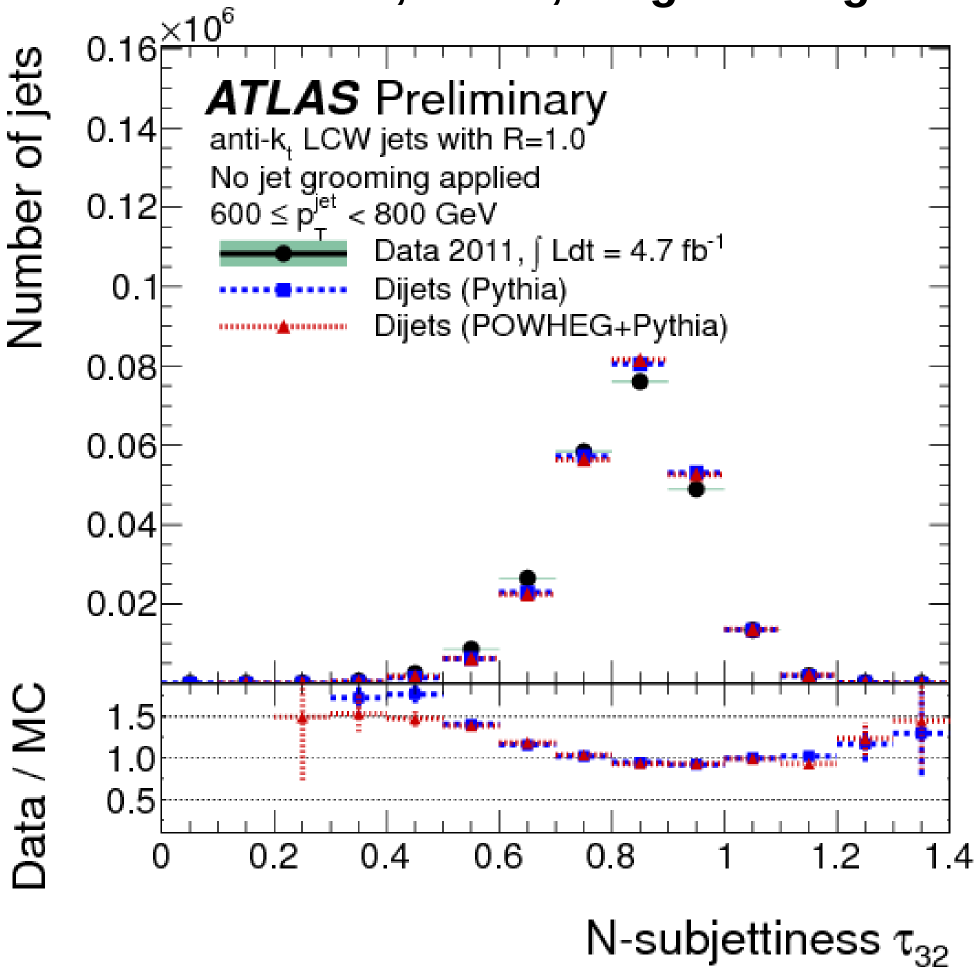
- **N-subjettiness:** Jets with $\tau_N \approx 0$ have all their radiation aligned with the candidate subjet directions and therefore can be considered as having N or fewer subjets

$$\tau_N = \frac{\sum_k p_{T,k} \min\{\Delta R_{1,k}, R_{2,k}, \cdots, R_{N,k}\}^{\beta}}{\sum_k p_{T,k} R_0}$$

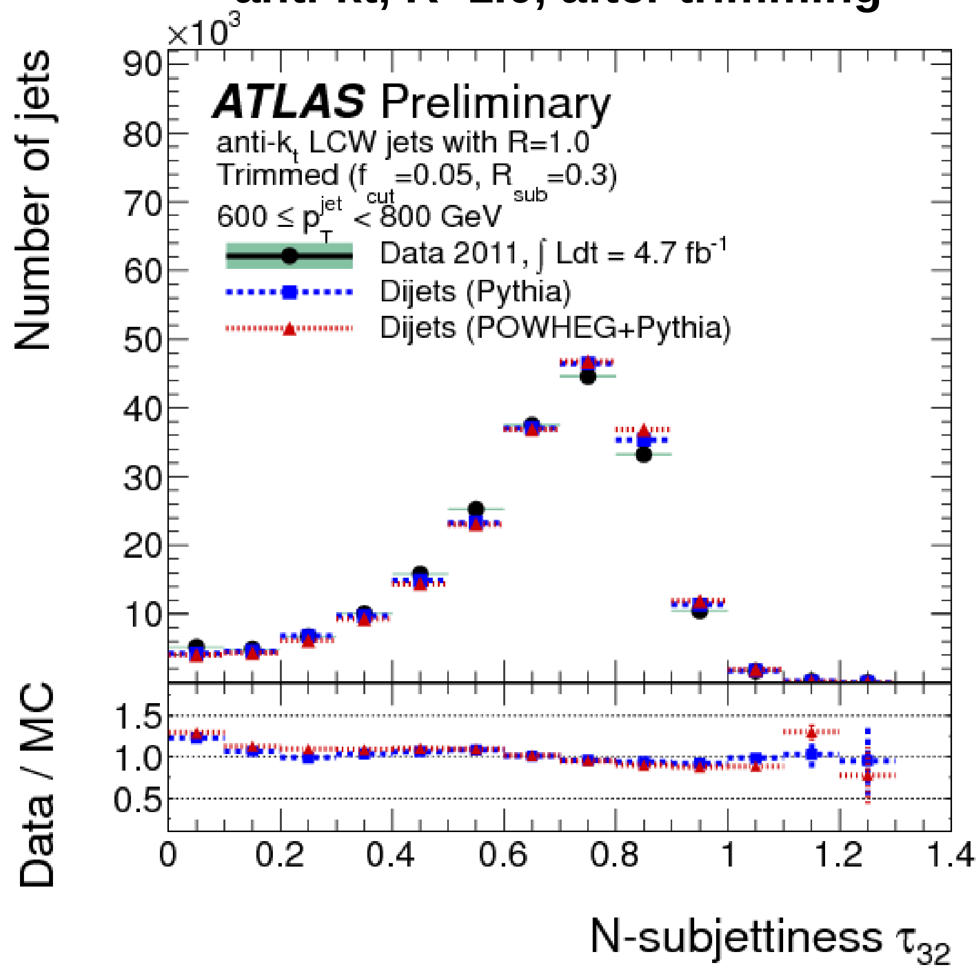
(for k constituent particles)

- Here, kt subjet axes have not been optimized, β=1

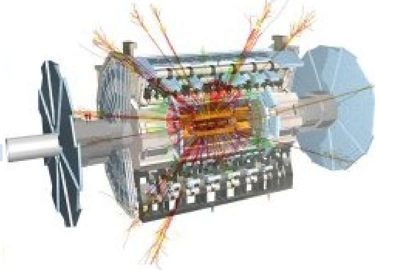
**anti-kt, R=1.0, no grooming**




**anti-kt, R=1.0, after trimming**



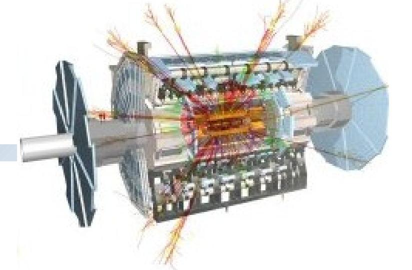
# Signal/background discrimination



- Background: jets from gluons/light quarks
- Signal: jets with real substructure

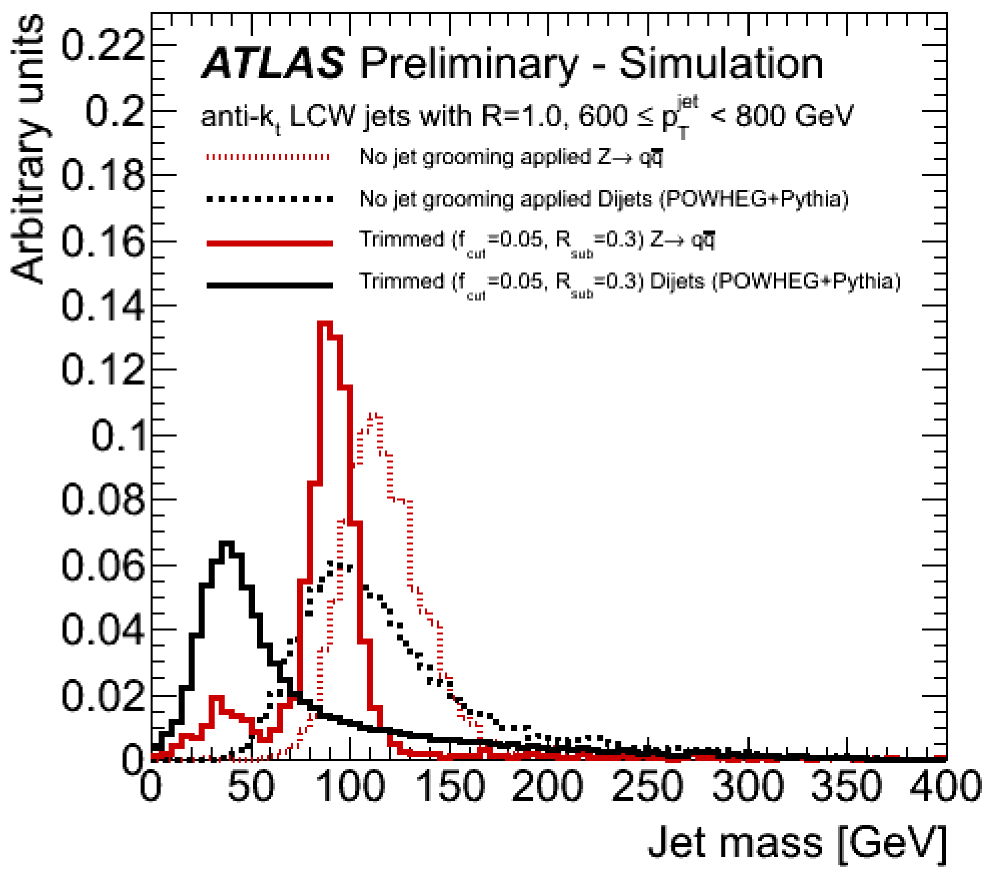
- "Two prong" (hadronic W/Z's, $H \rightarrow bb$)
    - Tried out anti-kt R=1.0 with trimming and C/A R=1.2 with mass-drop/filtering
- "Three prong" (hadronically-decaying tops)
    - Tried out anti-kt R=1.0 and C/A R=1.2 with trimming

# Z→qq events

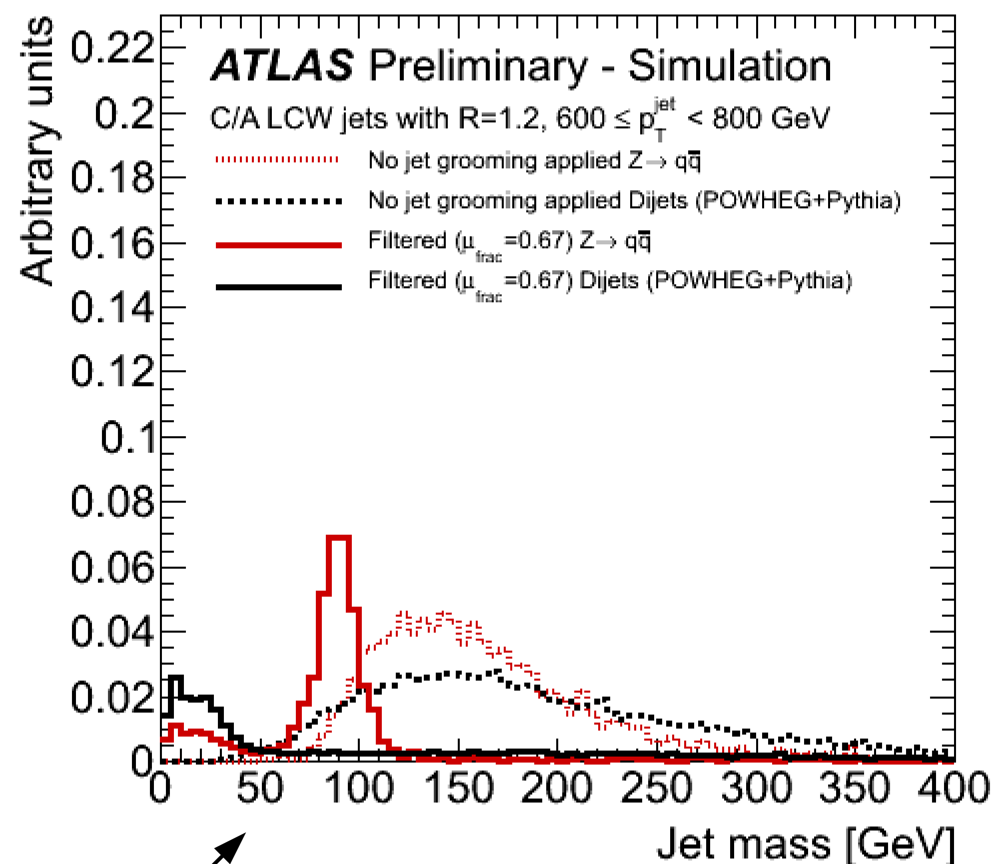


- Background: inclusive dijet sample (Powheg + pythia)
- 600 < jet $p_T$ < 800 GeV

**anti-kt R=1.0, (before/after trimming)**

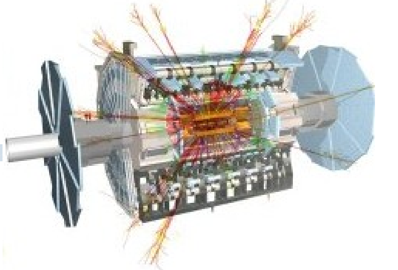



**C/A R=1.2, (before/after mass-drop/filtering)**



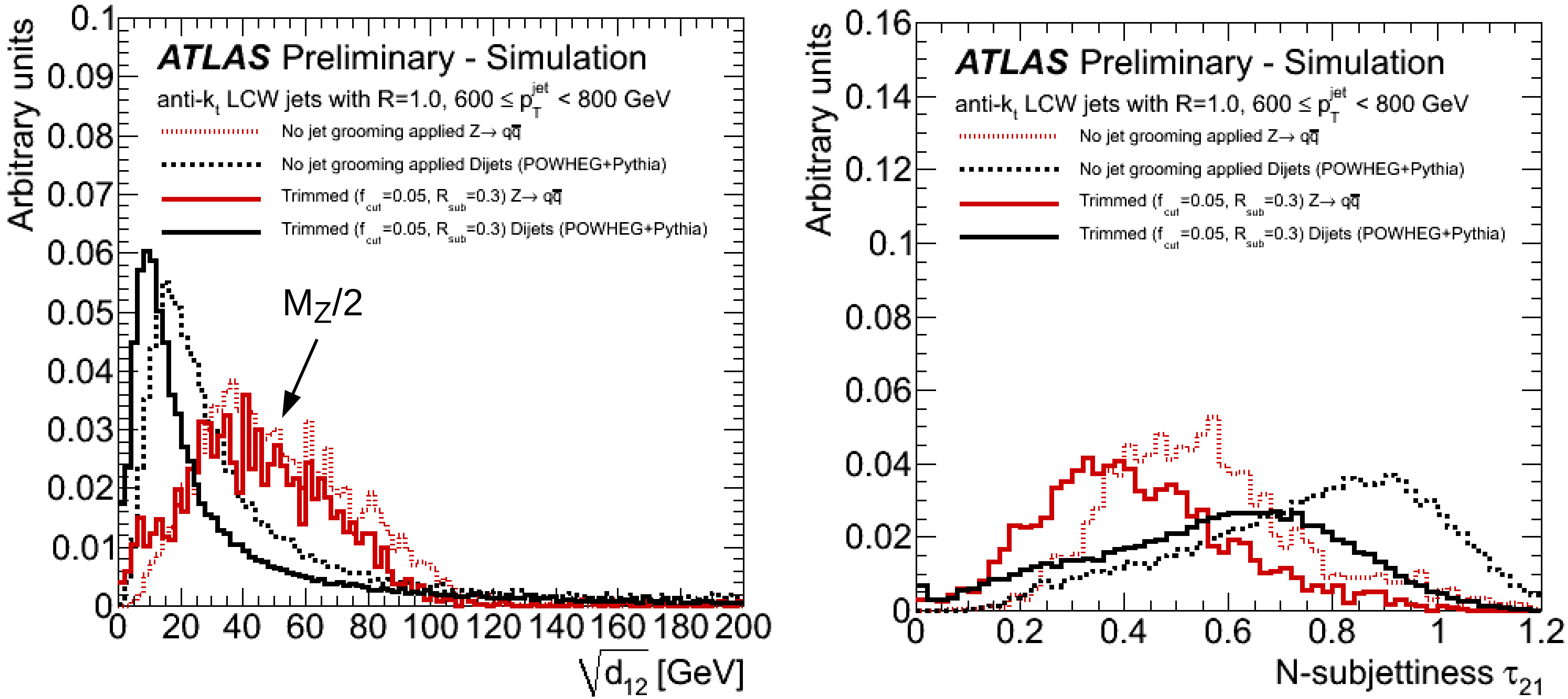

Note strict mass-drop criterion:
~30% efficient for background, ~45% for signal

# Z → qq events

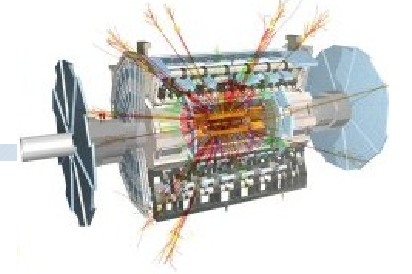


- Background: inclusive dijet sample (Powheg + pythia)
- 600 < jet $p_T$ < 800 GeV

**anti-kt, R=1.0 (before/after trimming)**

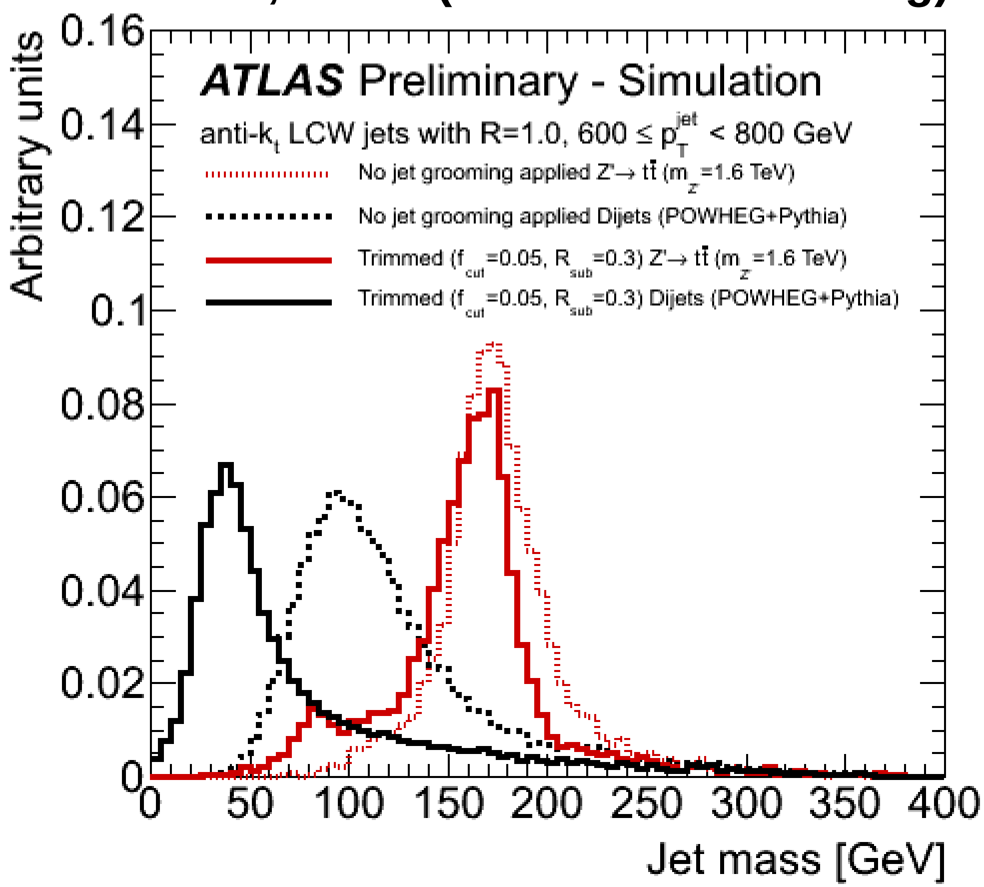


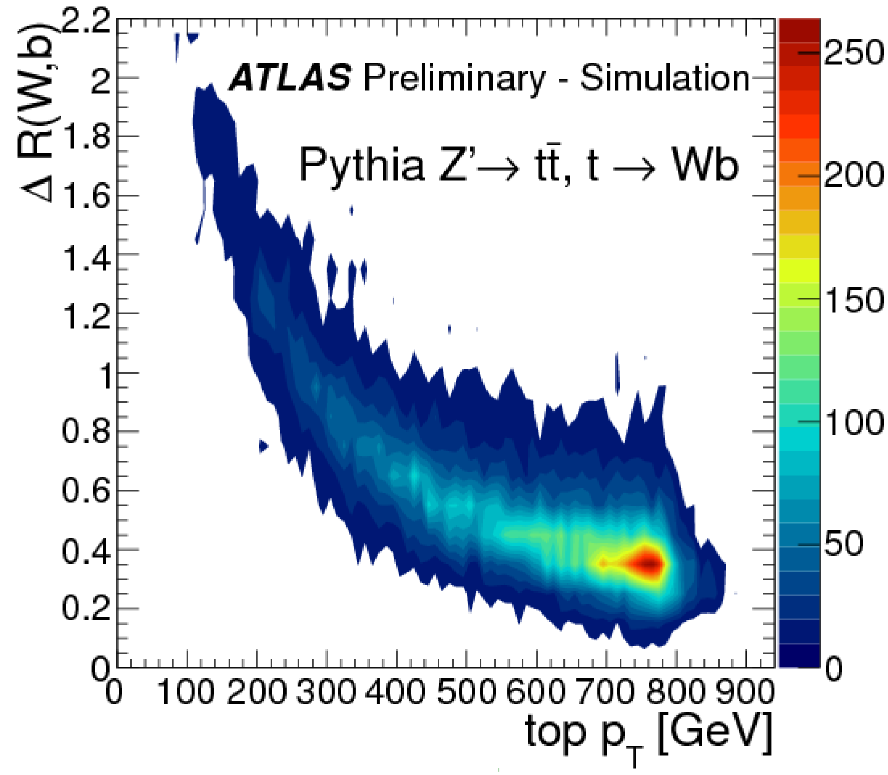
# Z' → ttbar events

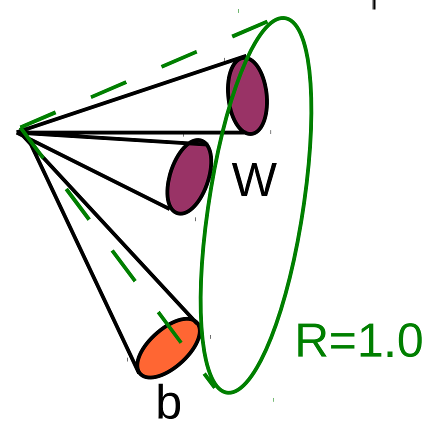


- Background: inclusive dijet sample (Powheg + pythia)
- 600 < jet $p_T$ < 800 GeV

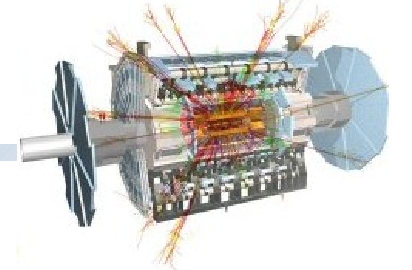
**anti-kt, R=1.0 (before/after trimming)**



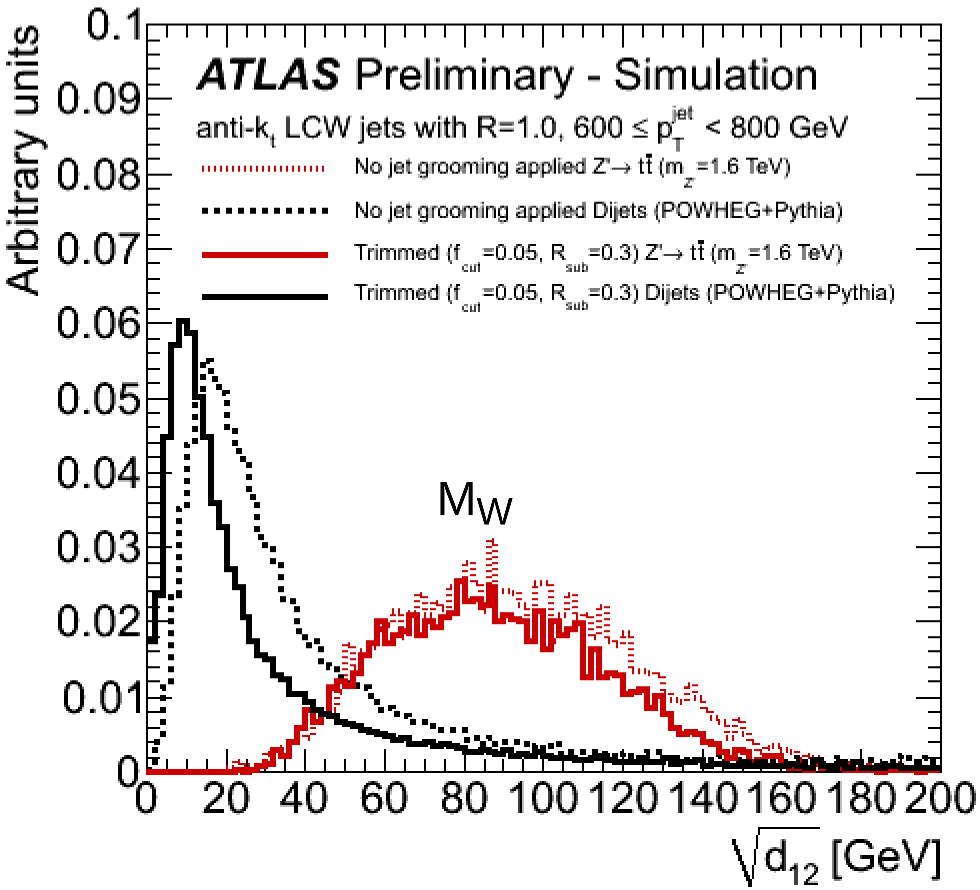



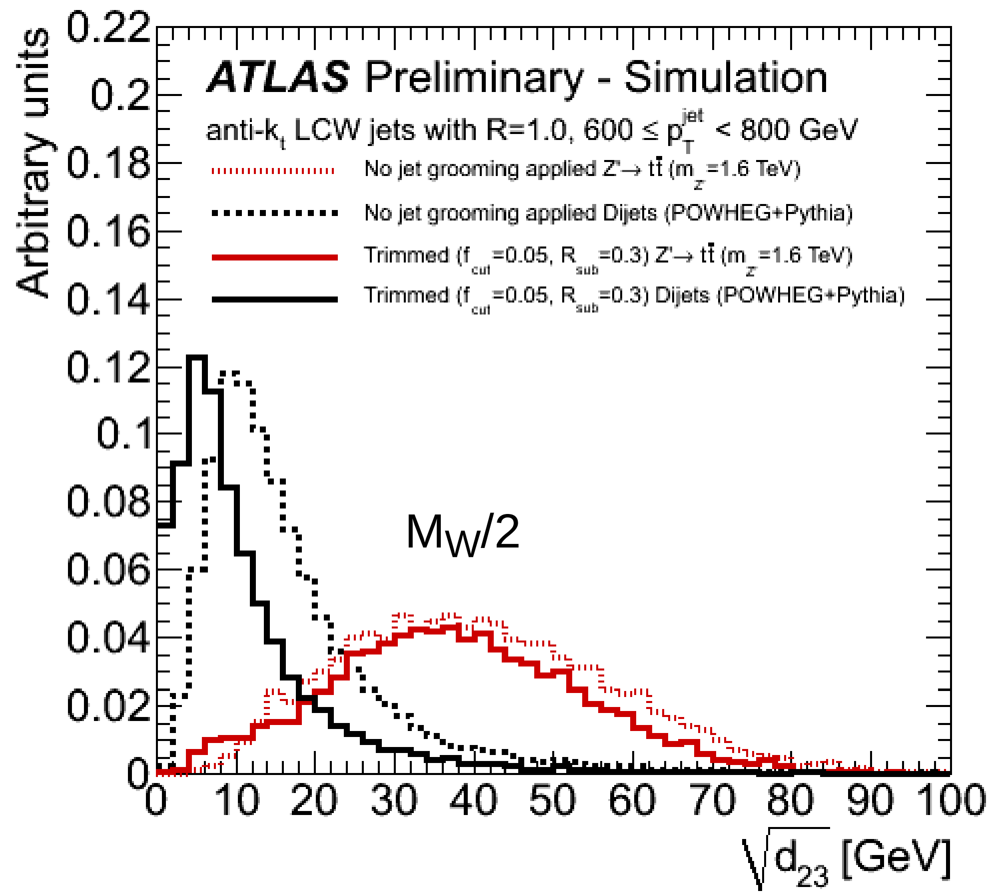
# Z' → ttbar events



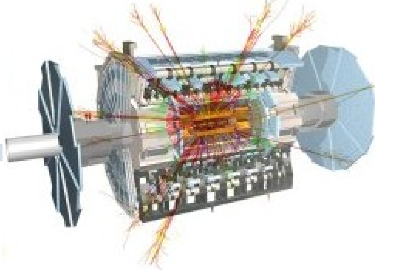
- Background: inclusive dijet sample (Powheg + pythia)
- 600 < jet $p_T$ < 800 GeV

**anti-kt R=1.0, (before/after trimming)**



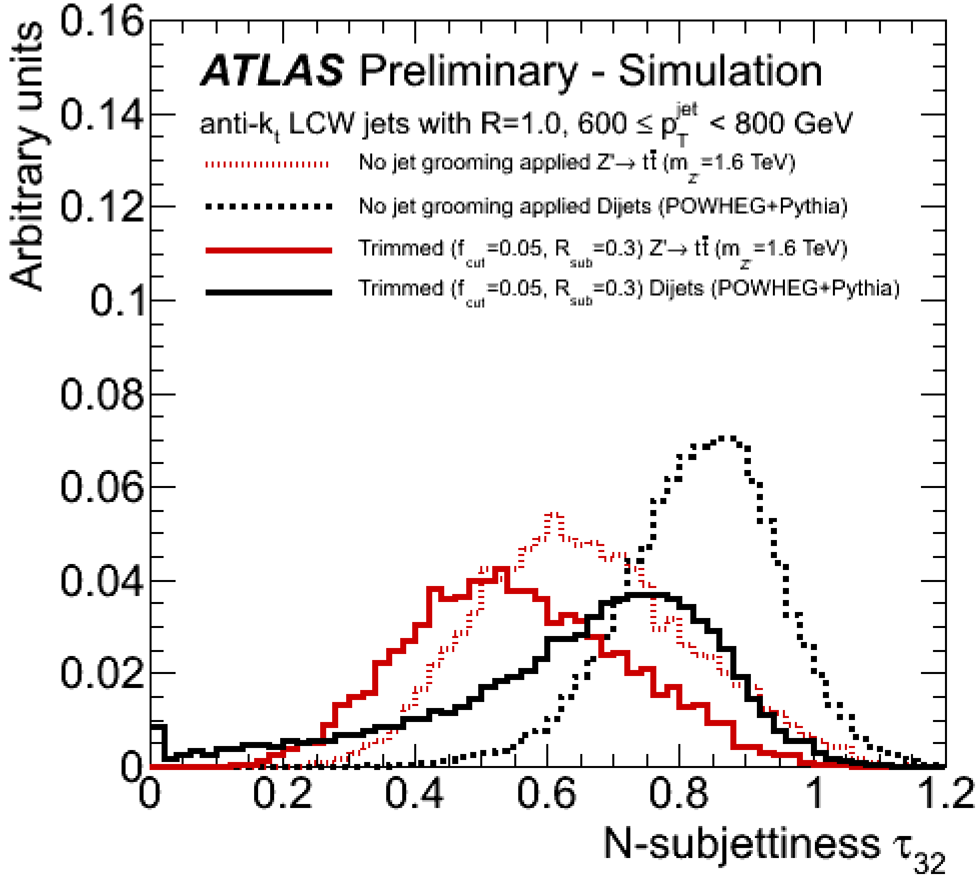



# Z' → ttbar events

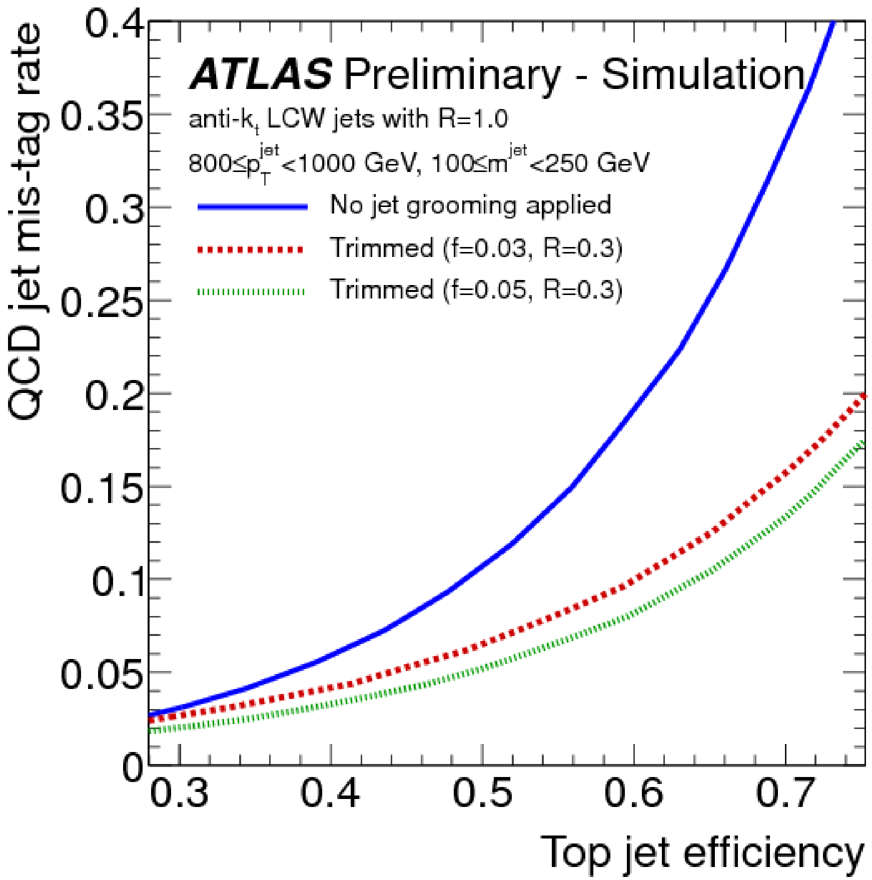


- Background: inclusive dijet sample (Powheg + pythia)
- N-subjettiness, using as a top-tagger:

**anti-kt, R=1.0 (before/after trimming)**

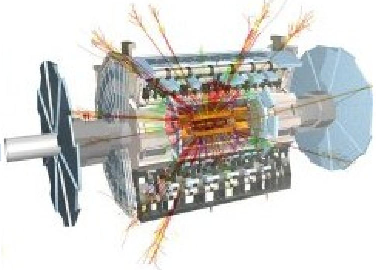



**600 < pT < 800 GeV**
**(no mass cut)**

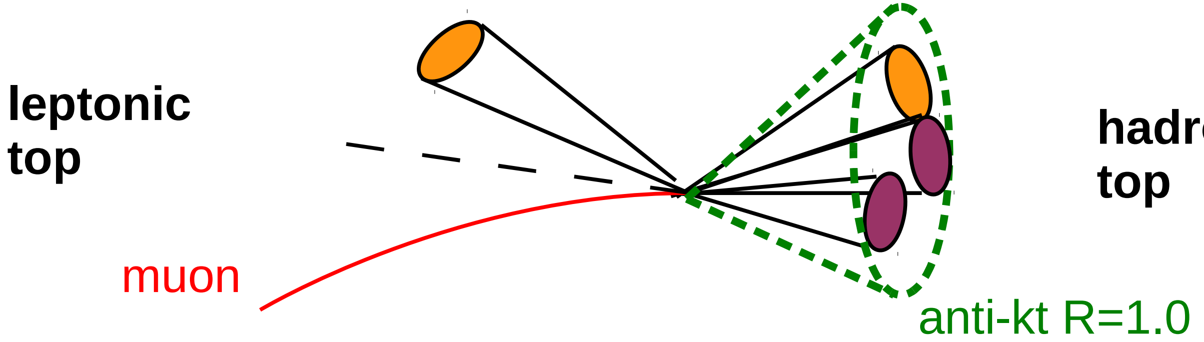



**800 < pT < 1000 GeV**
**(100 < M < 250 GeV)**

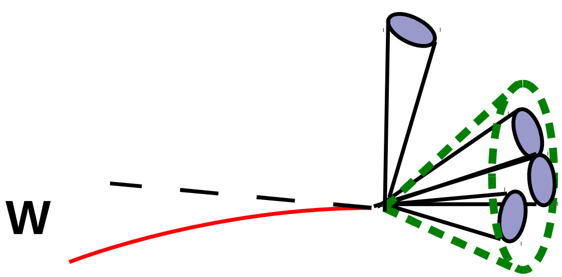
# SM ttbar events in data



- Want to demonstrate the effect of grooming on jets with substructure
- **Enriched ttbar sample:** "tag" a leptonic top → Wb → μυb and study the hadronic top in a large-R jet

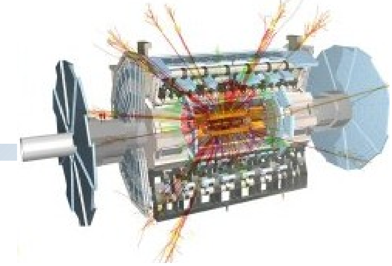



- Event Selection (Note: no data-driven bg estimations or systematics applied):
  - Standard data quality + vertex requirements + muon trigger (EF muon $p_T$ > 18 GeV)
  - Four anti-kt R=0.4 jets with $p_T$ > 25 GeV
  - Isolated muon with combined reconstruction in ID and MS, $p_T$ > 25 GeV, |eta|<2.5
  - Missing energy $ME_T$ > 20 GeV, and $ME_T$+$M_T$(W) > 60 GeV

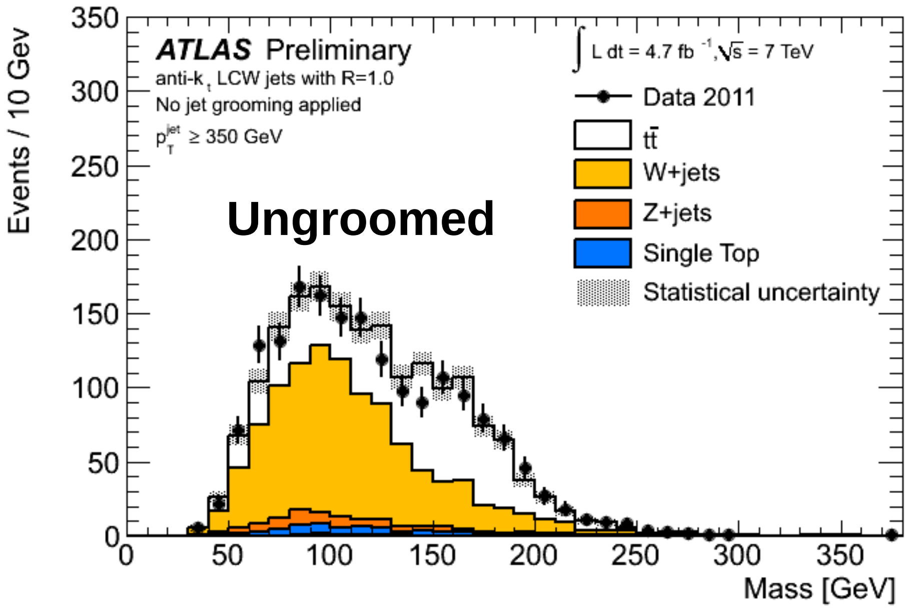


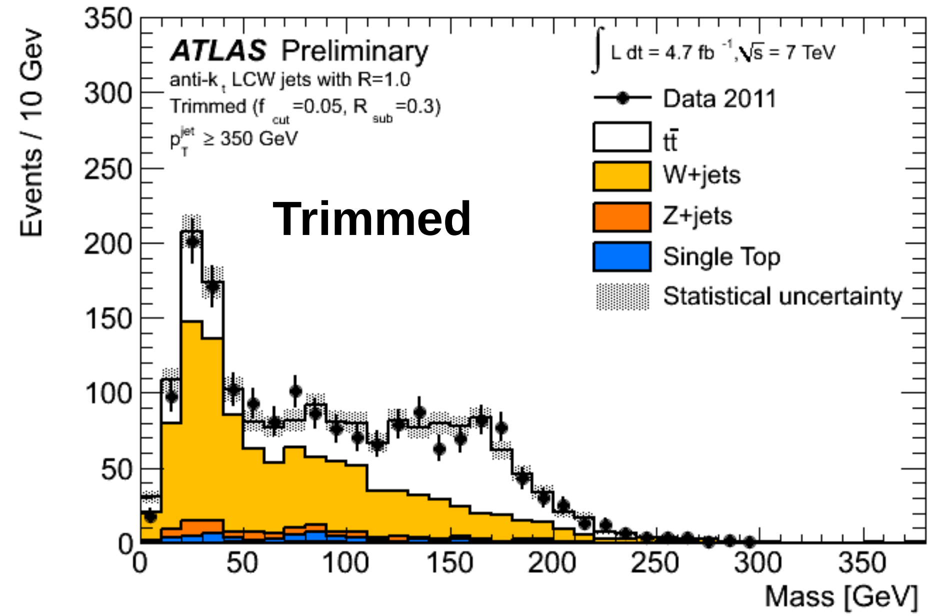

- Very little multi-jet events contamination
- **Main background: W+jets**

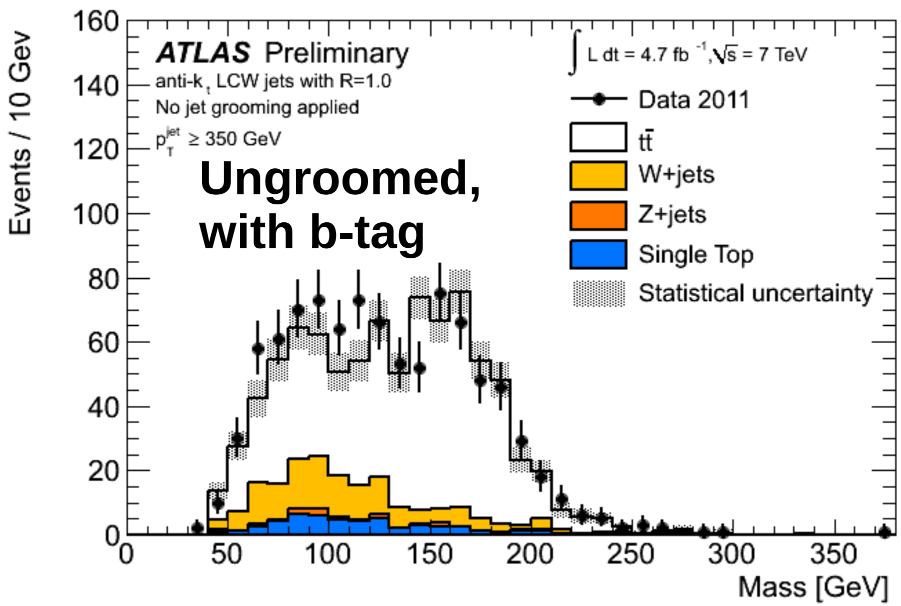
# SM ttbar events in data

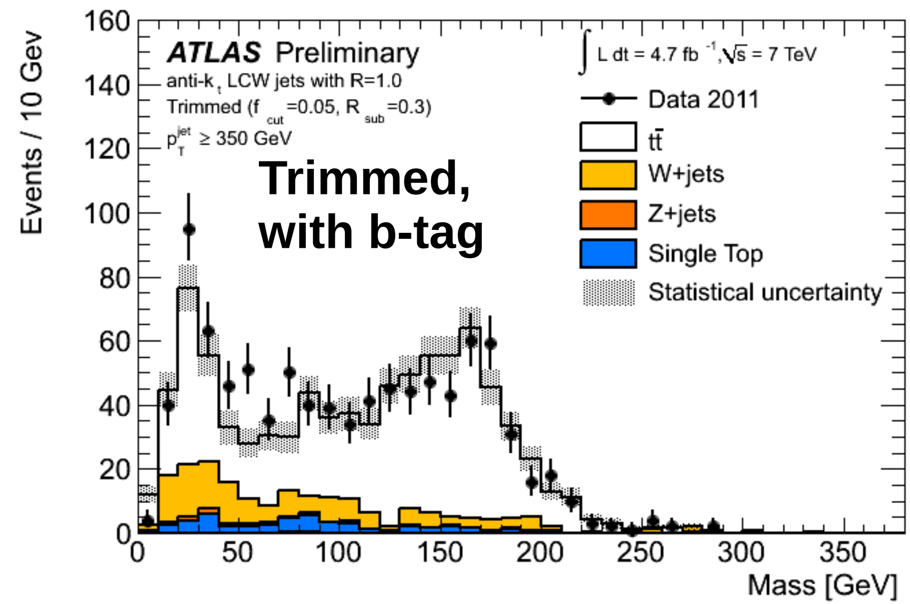


- **Jet Mass** (leading $p_T$ anti-kt R=1.0 jet, $p_T$ > 350 GeV)

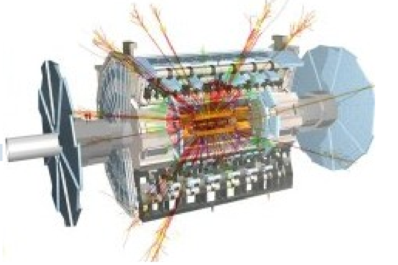


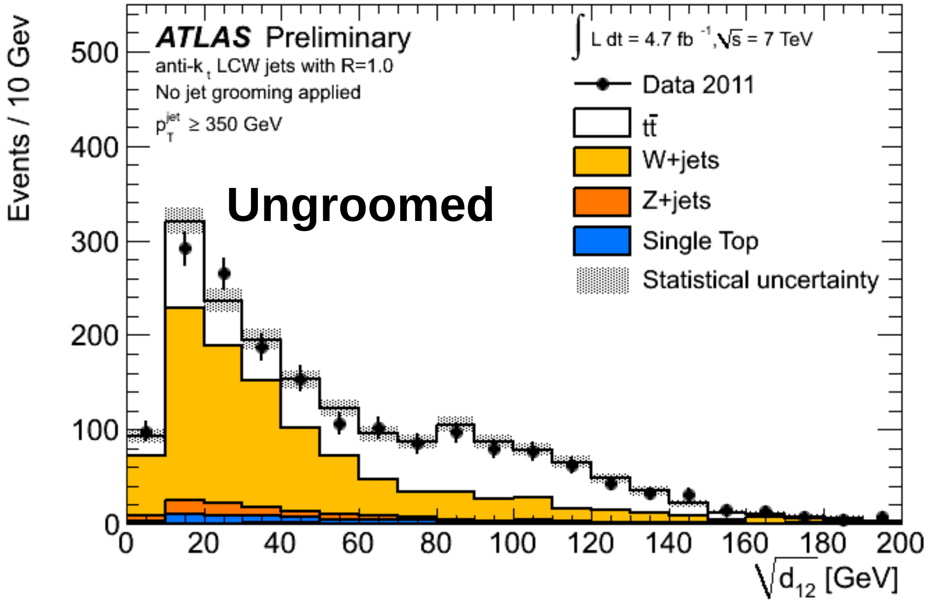



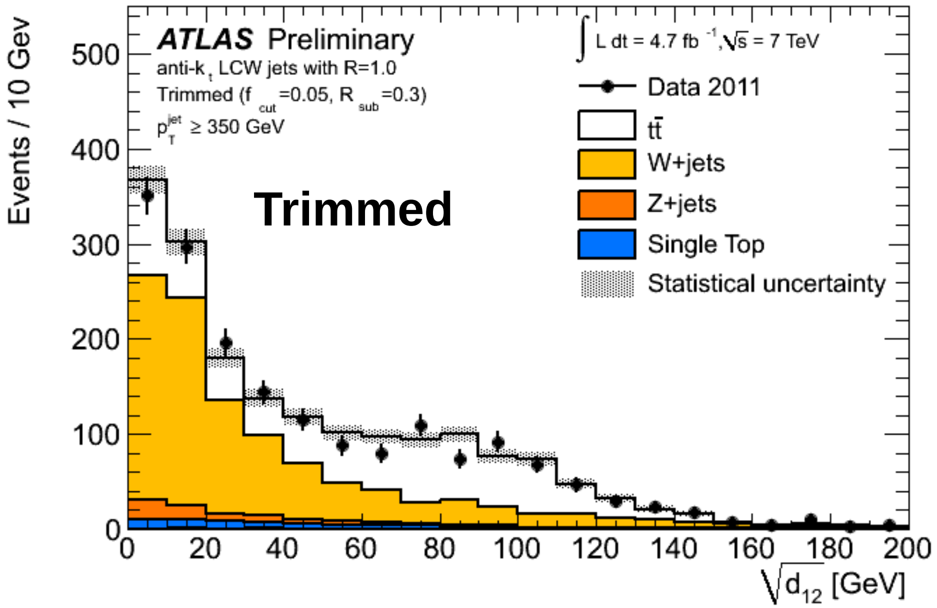



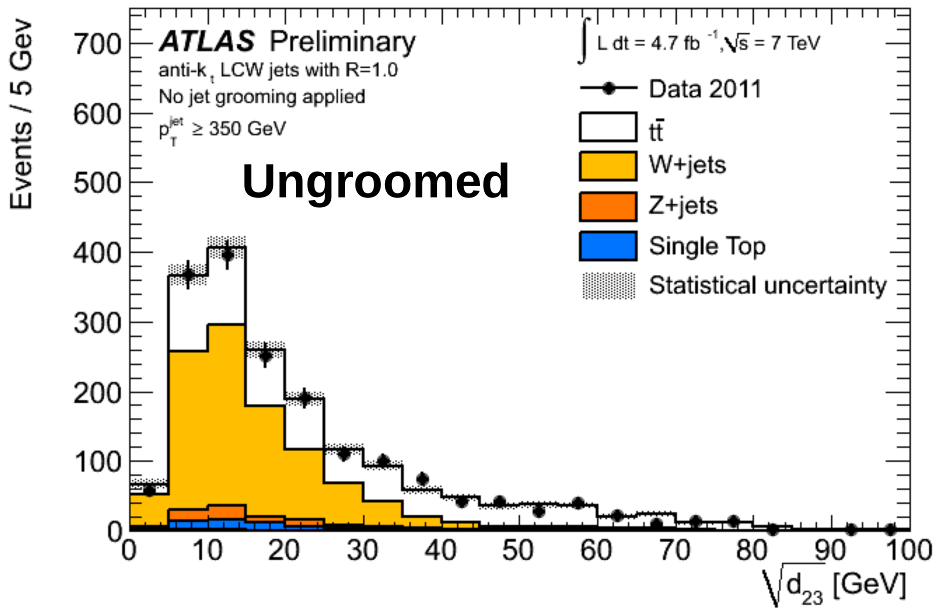
# SM ttbar events in data

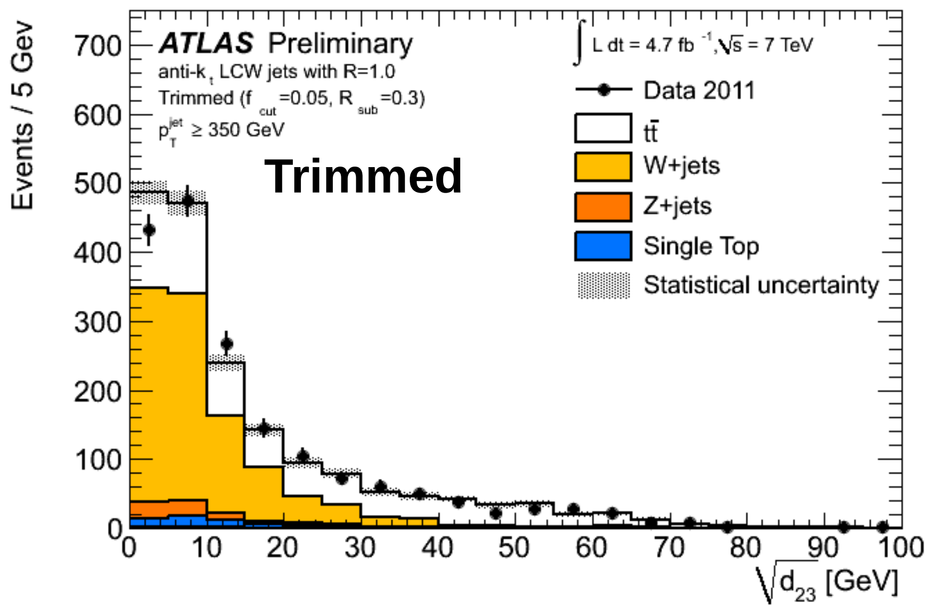


- **kt-splitting scales** (leading $p_T$ anti-kt R=1.0 jet, $p_T$ > 350 GeV)

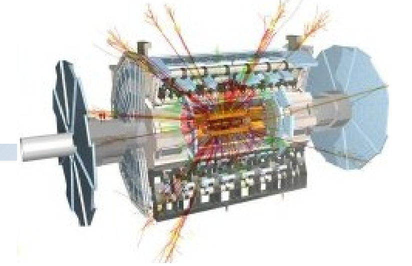


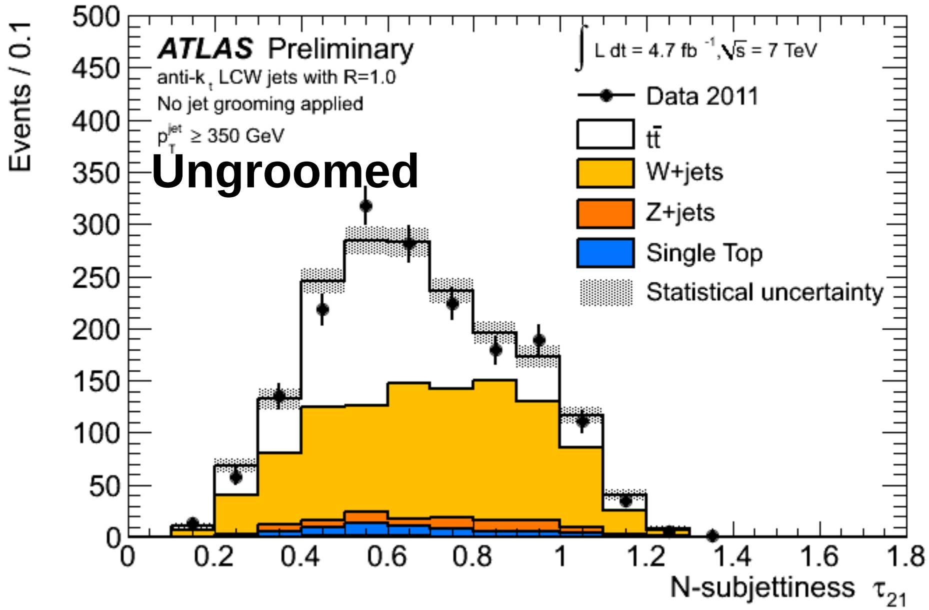



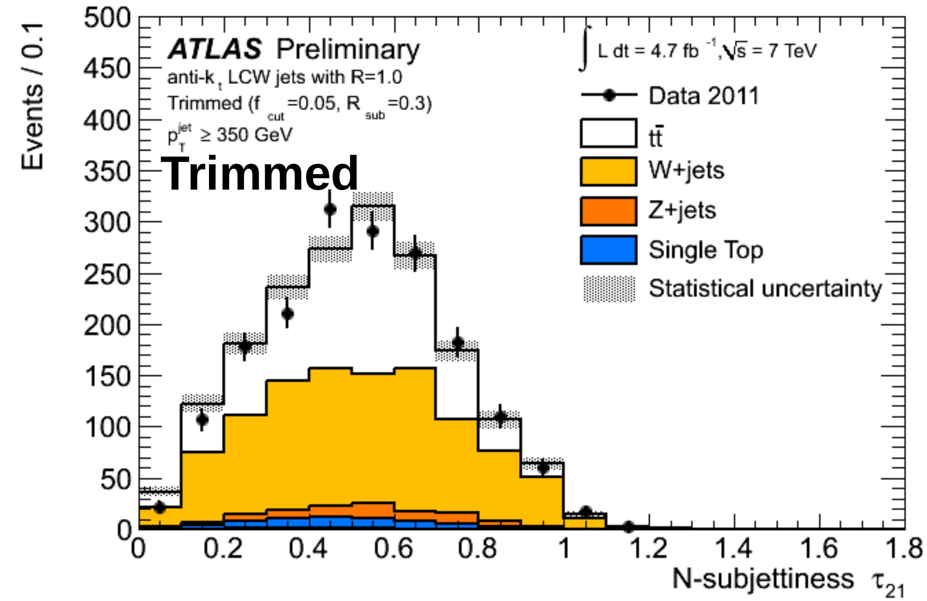



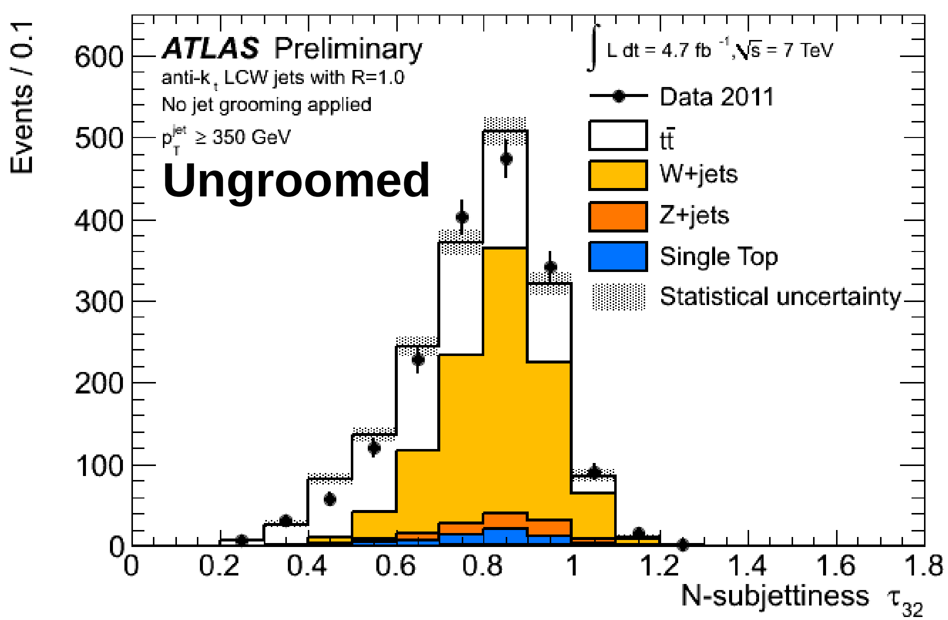
# SM ttbar events in data

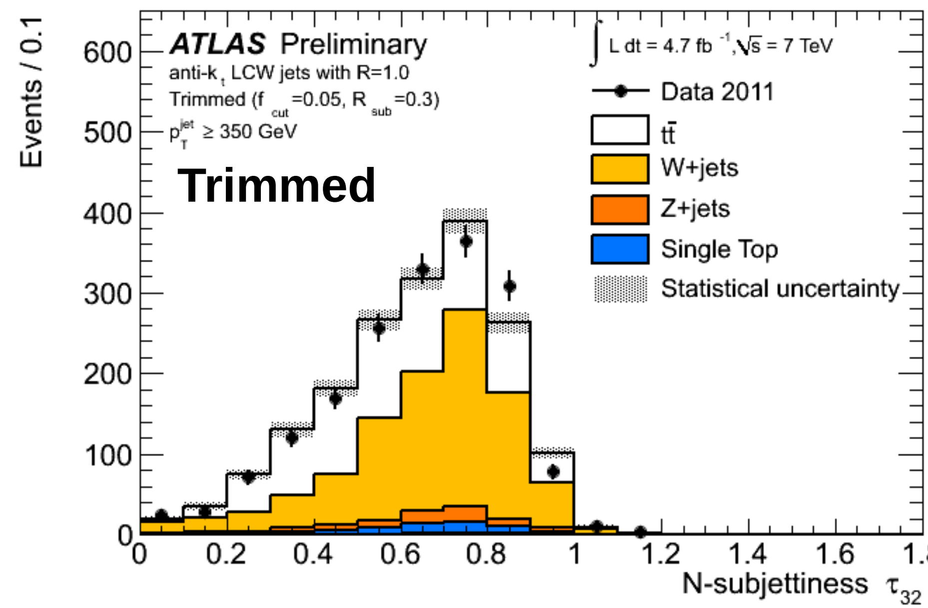


- **N-subjettiness** (leading $p_T$ anti-kt R=1.0 jet, $p_T$ > 350 GeV)

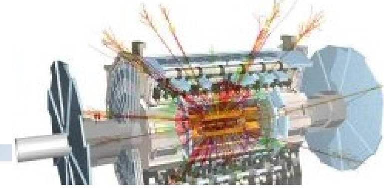


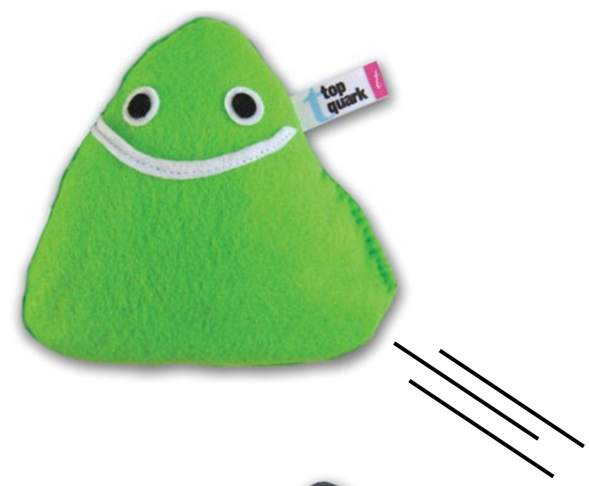



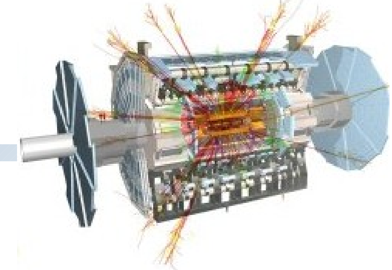
# Conclusions



- Groomed jet properties can be a powerful tool to discriminate between a dominant QCD background and heavy particle reconstruction, increasing signal sensitivity.
  - Reduced sensitivity to underlying event and pileup (see next talk for more)
  - Mass signal peak remains relatively unaffected (and resolution improves!), but background non-substructure jets are systematically shifted lower in mass
- Found that trimming performs well against pileup and has little pT dependence.
- Pruning, while not developed for pileup in particular, may be further tuned in the future to also mitigate pileup effects
- Mass-drop/filtering also performs well for two-pronged decays, but with loss of efficiency
- Data/MC agree well before and after grooming in both inclusive jet sample and in ttbar sample
  - POWHEG (hard matrix element) describes the data better than Pythia, especially in the tails of the distributions




# Conclusions



- ATLAS public notes with many more details than I can show today

  - Performance of large-R jets, jet grooming and jet substructure:

  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-065/

  - Effect of pileup on ungroomed and groomed jets:

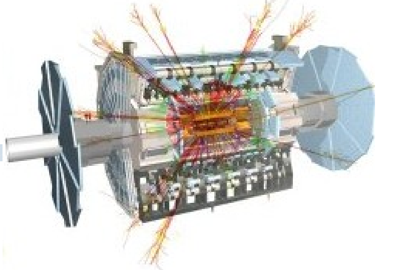
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-066/

**Future work**


- Pileup subtraction on subjets before grooming parameters optimization?
- Optimize $k_t$ axes for N-subjettiness, check β=??
- Look at grooming for smaller-R jets (ie: R=0.4)
- Measure properties of groomed jets containing boosted objects → boosted top tagging
- Can we use quark/gluon discrimination at the subjet level?

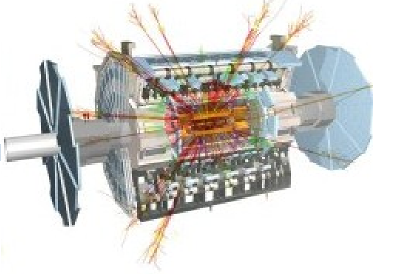
# Backup

# MC samples



- LO ME: Pythia 6.425, AUET2B tune
    - knew from last year that Pythia underestimates tail of mass distribution
- NLO ME: POWHEG 1.0, (patch 4) interfaced to Pythia (for PS, hadronization, UE)

# Large-R jet calibration



Calibrated collections:

- Ungroomed: anti-kt R = 1.0 and C/A, R = 1.2 jets
- Groomed collections:
  - anti-kt R=1.0 with trimming: (fcut = 3%, 5% and Rsub = 0.3)
  - C/A R=1.2 with trimming: (fcut = 5% and Rsub = 0.3) and mass-drop/filter ($\mu_{frac}$ = 0.67)

Calibration procedure:

- Local cluster weighting (LCW)
- Measure calorimeter response with mean of a Gaussian fit to core of distribution of reco jet / truth jet (Pythia)
- No pileup correction applied before JES/JMS corrections

# In situ validation of JMS

- Calo-jet to track-jet double ratios
- JMS: fairly stable 4-5% up to pT ~800 GeV