Jet Substructure Reconstruction and Application as a Search Tool in ATLAS

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(Werner Heisenberg Institut)
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Preliminaries & Acknowledgements

Results presented today

- Limited to 2011 data with $\sqrt{s}$ = 7 TeV– the results from 2012 analyses are not yet published…
  - Sorry!
- All ATLAS results presented here are – if not stated otherwise – published in **arXiv:1306.4945v1 [hep-ex]** and submitted to **JHEP**!
  - About 64 pages with 54 figures – much more details than can be covered in this talk!
- The results shown here and in the paper reflect an enormous amount of work from a very active group of people in ATLAS
  - Thank everybody who helped with this!
- Every omission or misrepresentation of the findings presented here are mine and not theirs!

This Talk

Introduction

- Motivation
- ATLAS at LHC
- Signals and experimental environment for jet reconstruction in ATLAS
- Jet grooming techniques under consideration

Measuring jet shapes and substructure in ATLAS

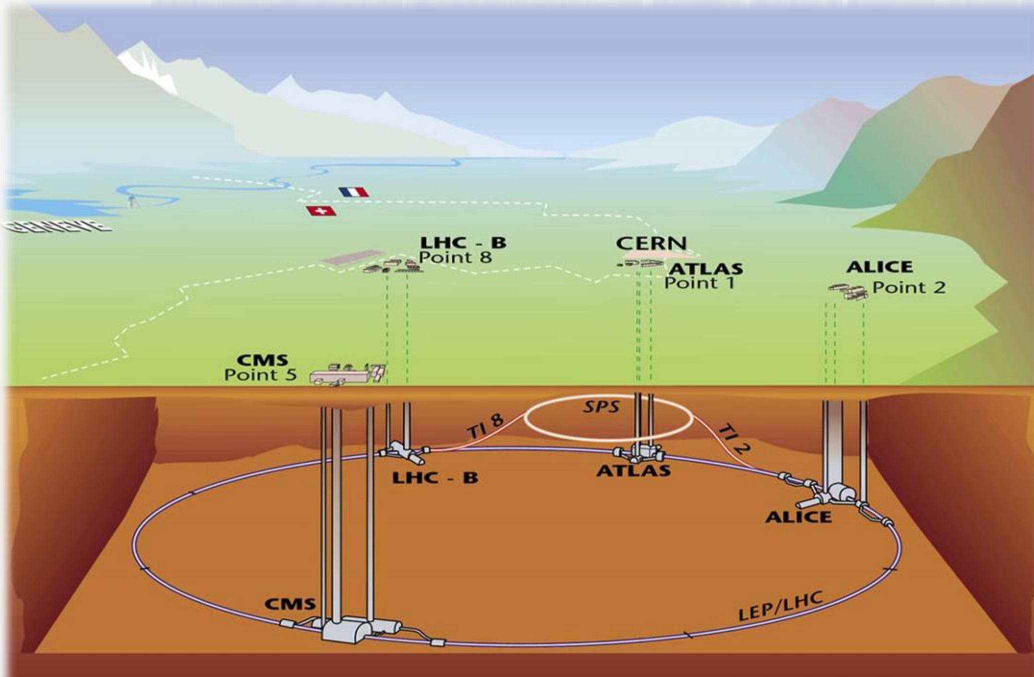
- Jet shape observables
- Jet mass calibration and validation
- Substructure based reconstruction performance in pile-up
- Evaluation of jet substructure modeling

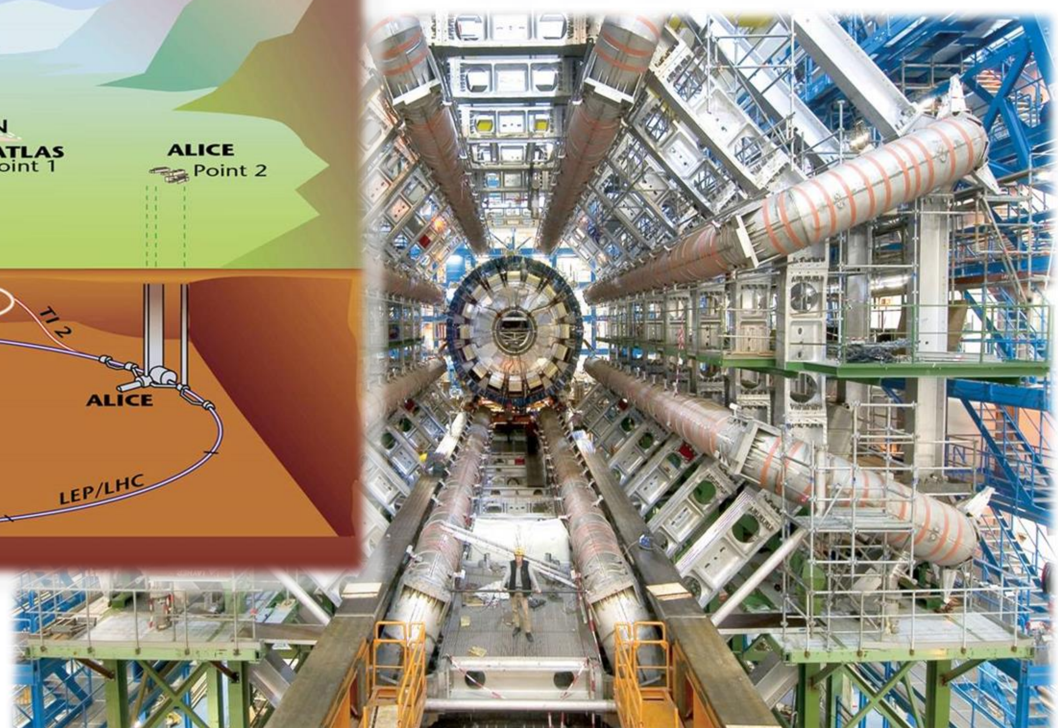
Basics for application in searches for new physics

- Finding the decay products – jet grooming in final states with top quarks and *W* bosons
- First application in searches

Conclusions and outlook

Introduction





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Kinematic reach at LHC

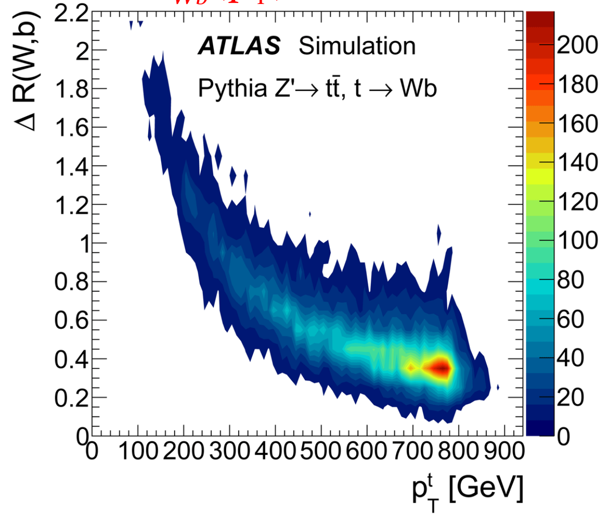
- Allows production of boosted (heavy) particles like W and Higgs bosons, and top quarks decaying into collimated (single-jet like) final states
  - All decay products are collected into one jet with size $R \approx 2m/p_{\mathrm{T}}$
  - Final state not resolvable with standard (narrow jet) techniques anymore
- Searches for new heavy particles with boosted (SM) decay products
  - Single jet mass indicative observable for new particle production

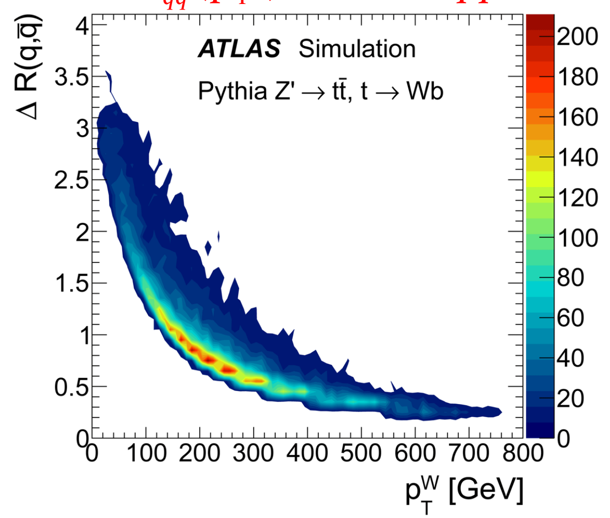
High luminosity

- Presence of additional proton-proton collisions in a bunch crossing can deteriorate single jet mass and shape measurements
  - Needs techniques to extract relevant internal jet energy flow structures for mass reconstruction from diffuse pile-up contributions severely affecting single jet mass scales and resolutions

Jet substructure analysis

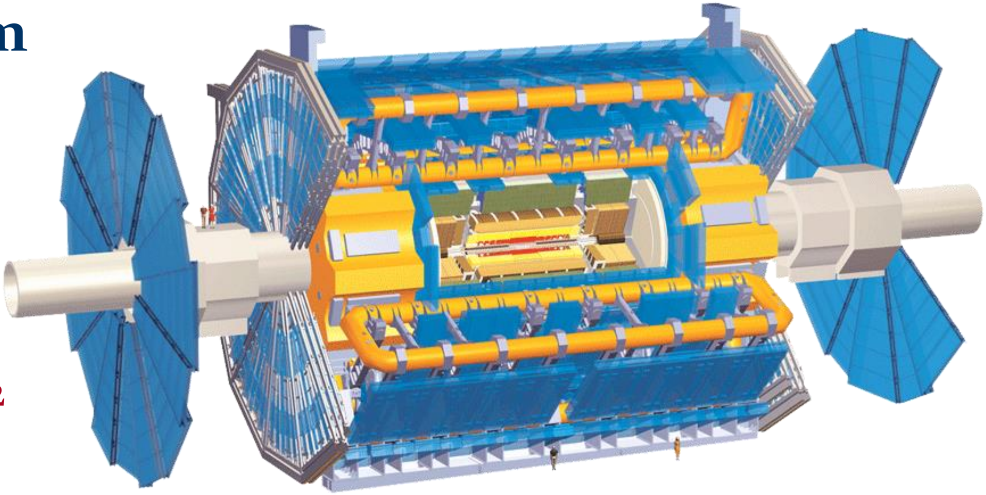
- Collection of techniques aiming at enhancing two- or three-prong decay patterns in single jets
  - Typically leads to suppression of QCD-like backgrounds from quark- and gluon jets with their typical parton shower and fragmentation driven internal flow structure

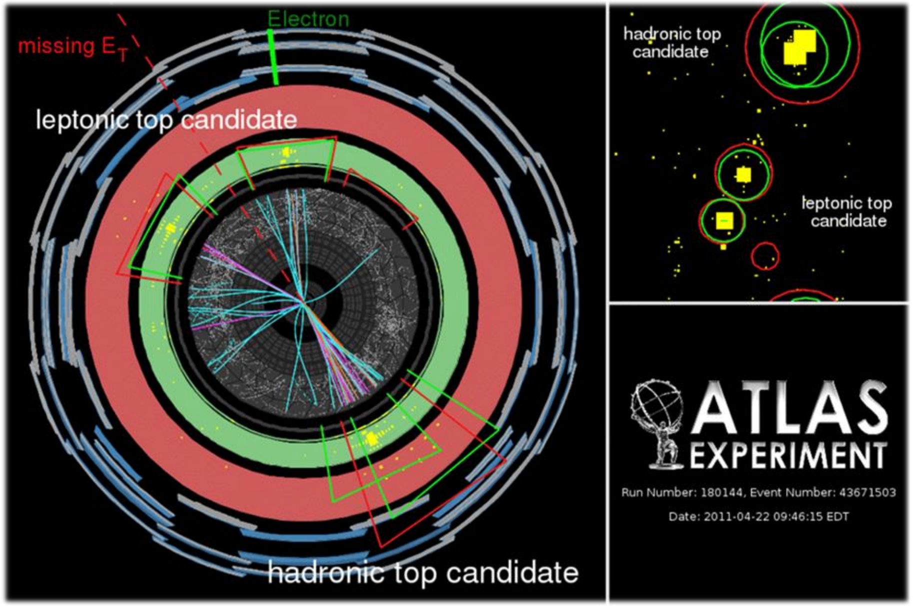




Multi-purpose detector system

- High resolution tracking system
  - High precision charged track reconstruction within |η|<2.5
- Full coverage calorimetry
  - Highly granular electromagnetic (EM) calorimeters within |η|<3.2
  - Full EM and hadronic (HAD) coverage within |η|<4.9
  - About 190,000 independent readout cells
  - 3-7 longitudinal segments for optimal EM and HAD shower reconstruction
- Air toroid muon system
  - High precision muon momentum reconstruction and triggering within |η|<2.7
  - Not used in substructure measurements in 2011 – outside of possible event selections





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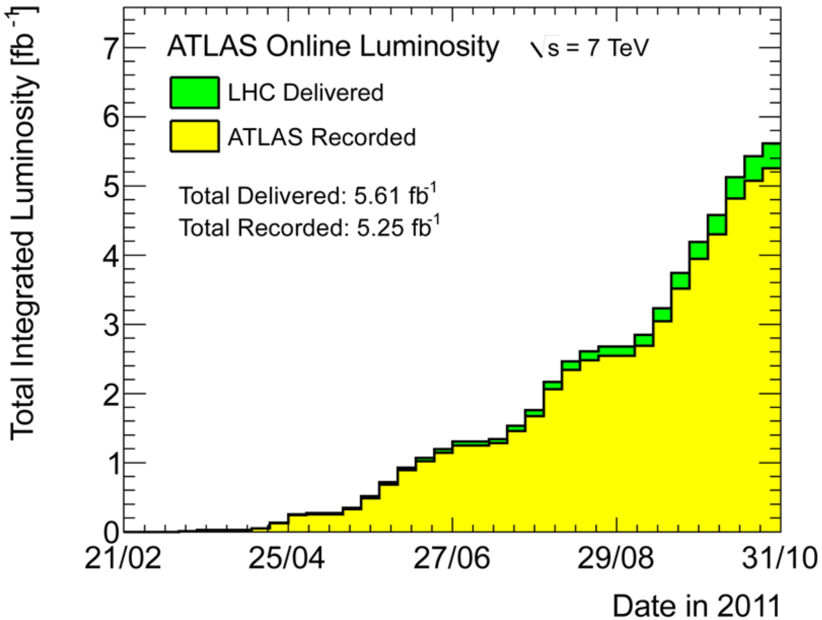
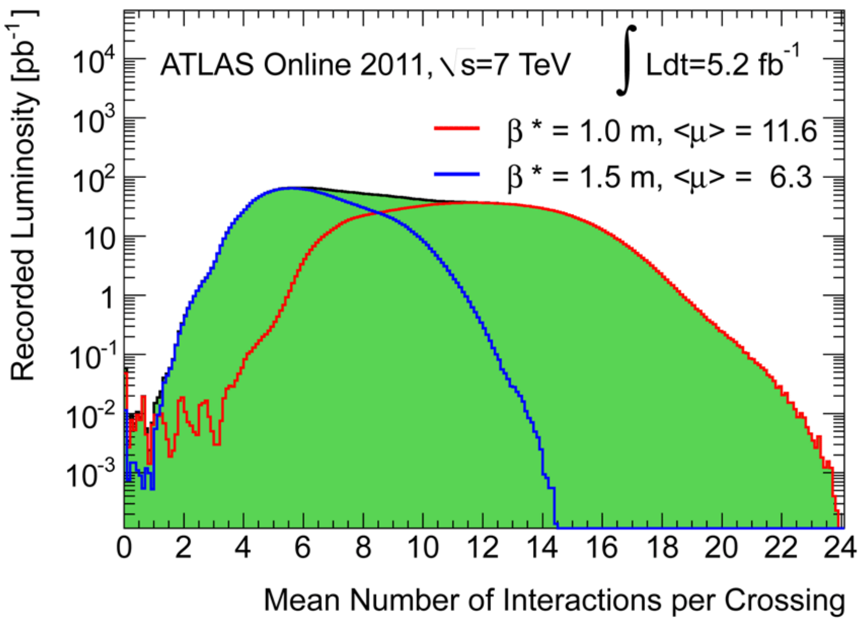
Basic jet signals from ATLAS calorimetry

- Topological cell clusters for jet finding and formation
- ($|\eta| < 4.9$)
  - Defined by calorimeter cell signal significance patterns
  - Locally calibrated
- High quality reconstructed charged particles tracks for jet characterization and validation
  - $p_T > 500$ MeV, $|\eta|<2.5$
  - Jet energy and mass calibration refinements and validation
  - Sub-jet calibration calibration
  - Angular resolution
  - Reference for transverse momentum and mass not affected by pile-up

Experimental conditions at LHC

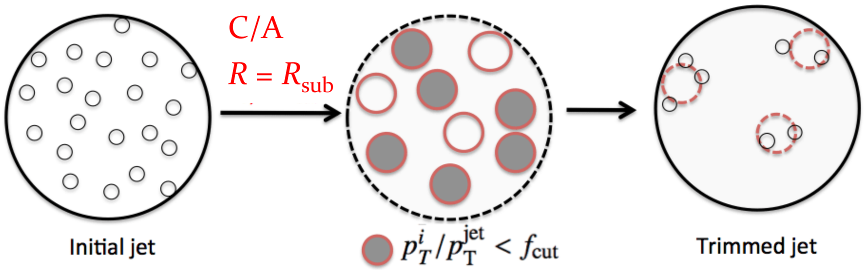
- Data taken 2011 at $\sqrt{s} = 7$ TeV
  - Significant pile-up from additional proton-proton interactions in recorded event (bunch crossing)
  - Significantly affects calorimeter signals – typically requires corrections
- About 4.7 fb^{-1} used for the presented studies





Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84



$$R_{\mathrm{sub}} = \{0.2, 0.3\}$$

$$f_{\mathrm{cut}} = \{0.01, 0.03, 0.05\}$$

$$p_{\mathrm{T}}^{\mathrm{sub}} > f_{\mathrm{cut}} \times p_{\mathrm{T}}^{\mathrm{jet}}$$

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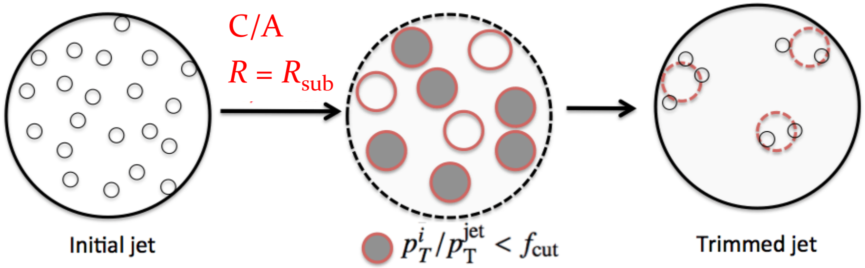
Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84



$$R_{sub} = \{0.2, 0.3\}$$

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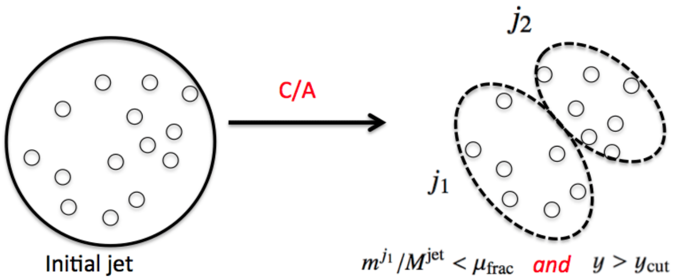
Mass drop…

J.M.Butterworth *et al.*, *Phys.Rev.Lett.* **100** (2008) 242001



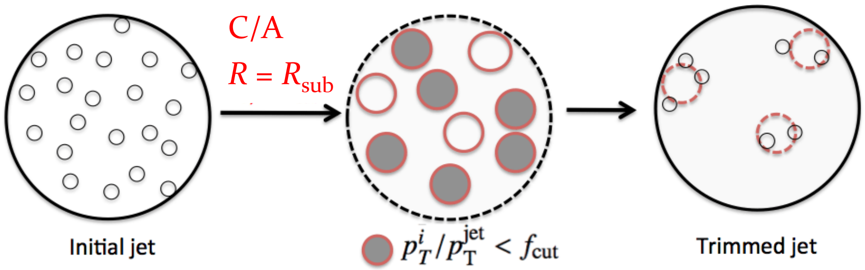
$$m_{j1}/m_{jet} < \mu_{frac}$$

$$y = \frac{\min[p_{T,j1}^2, p_{T,j2}^2]}{m_{jet}^2} \times \Delta R_{j1,j2} > y_{cut}$$

$$\mu_{frac} = \{0.20, 0.33, 0.67\},\ y_{cut} = 0.09$$

Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84



$$R_{\mathrm{sub}} = \{0.2, 0.3\}$$

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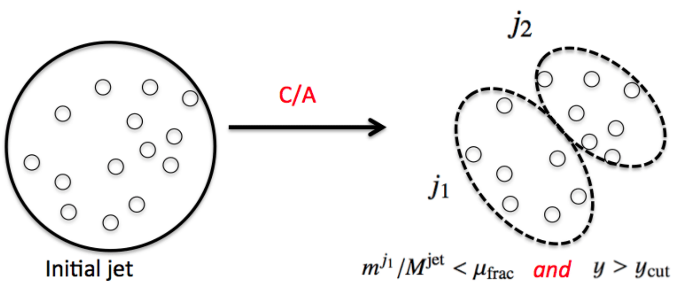
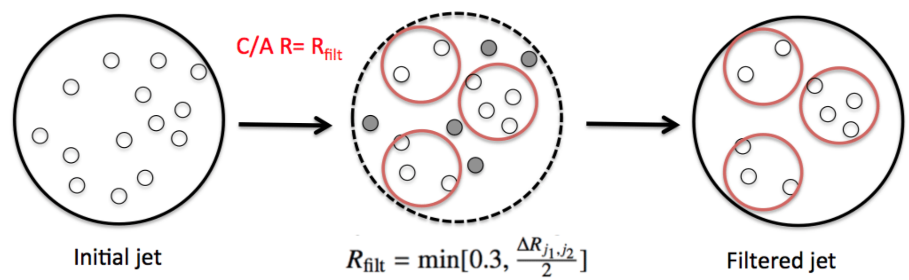
Mass drop…

…filtering

J.M.Butterworth *et al.*, *Phys.Rev.Lett.* **100** (2008) 242001





$$\mu_{\mathrm{frac}} = \{0.20, 0.33, 0.67\},\ y_{\mathrm{cut}} = 0.09$$

$$R_{\mathrm{filt}} = \max[0.3, \Delta R_{\mathrm{j1-j2}}/2]$$

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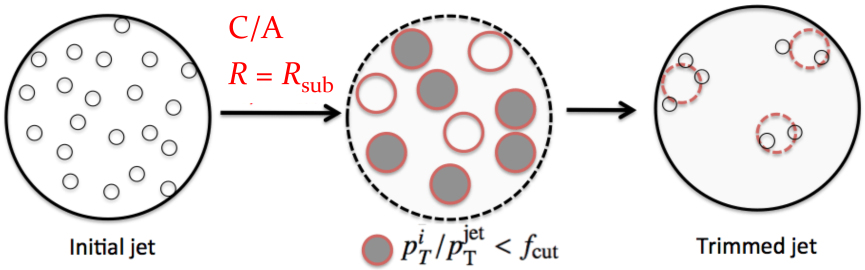
Jet Grooming Techniques

Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84



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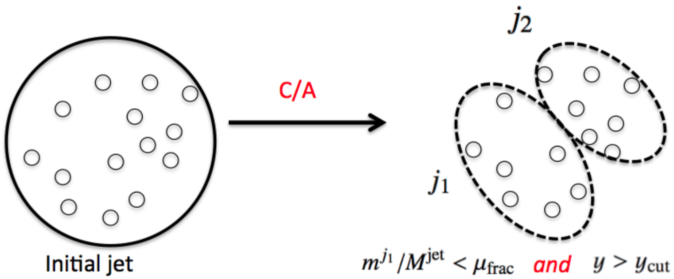

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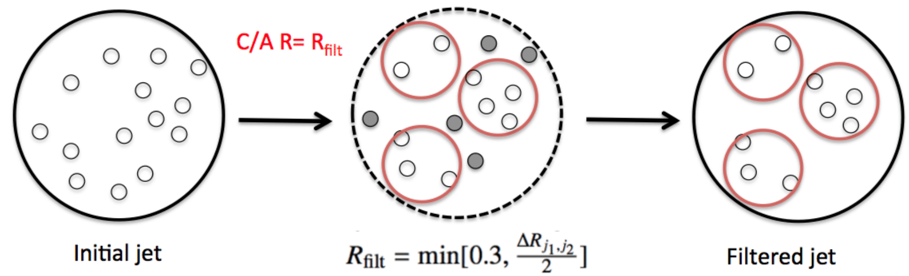
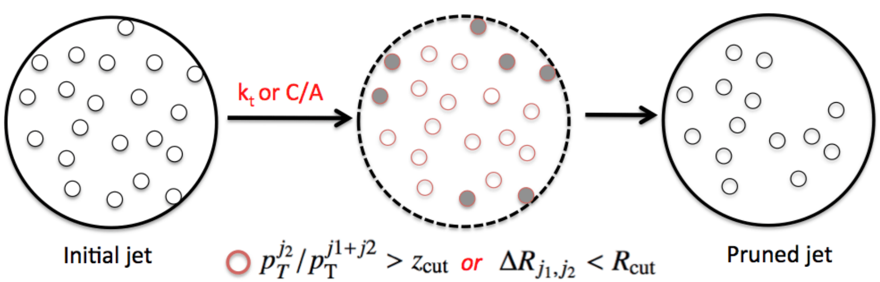


$$\mu_{frac} = \{0.20, 0.33, 0.67\}, \; y_{cut} = 0.09$$

Pruning

S.D.Ellis, C.Vermillion, J.Walsh, *Phys.Rev.* **D80** (2009) 051501 & *Phys.Rev*. **D81** (2010) 094023



$$\Delta R_{j1-j2} < R_{cut} \;\text{ or }\; \frac{p_T^{j2}}{p_T^{j1+j2}} > z_{cut}$$

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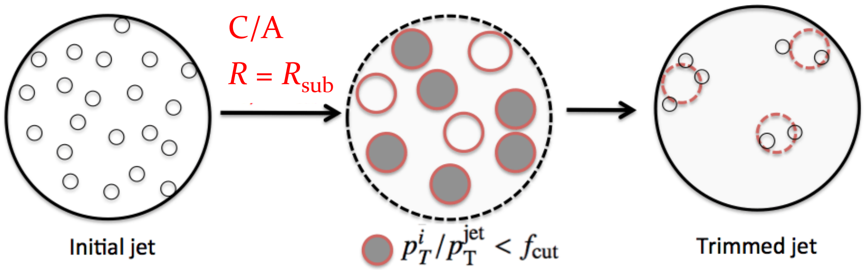
Trimming

D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84



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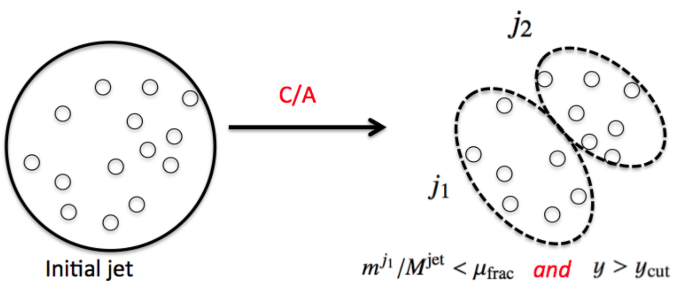

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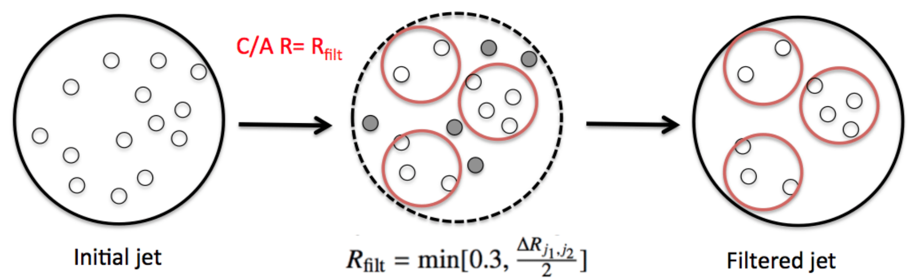

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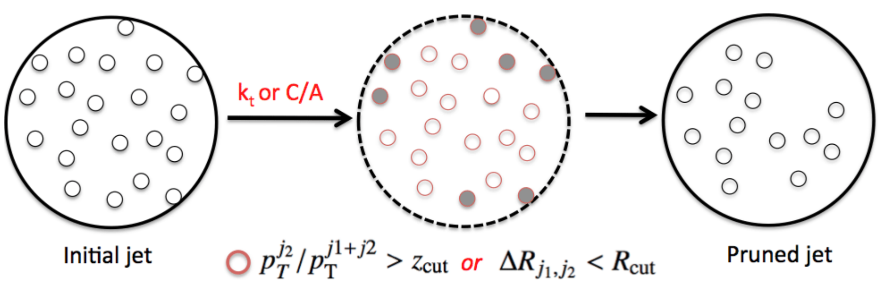
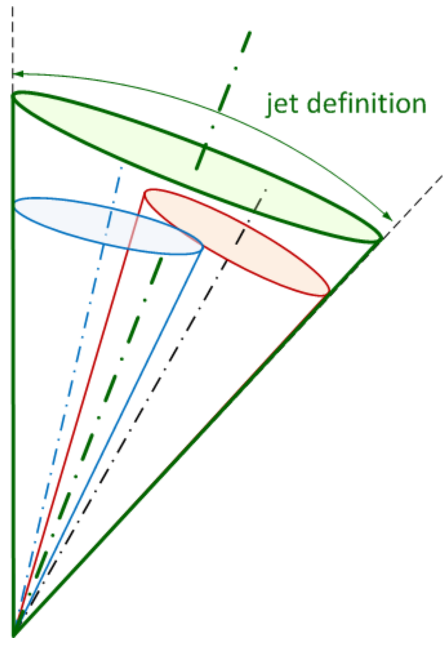
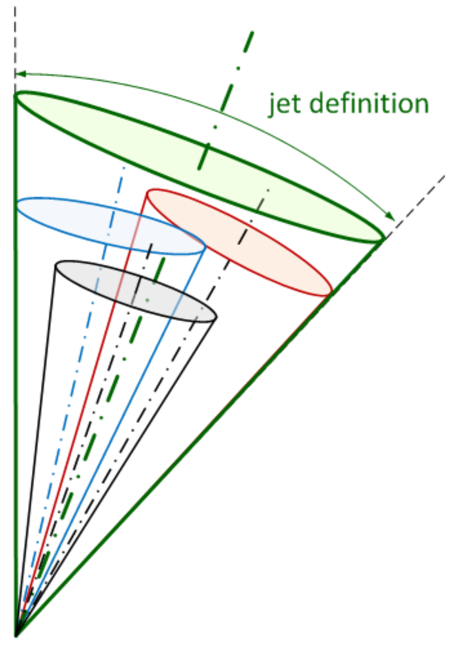


$$R_{\mathrm{cut}} = \{0.1, 0.2, 0.3\}$$

$$z_{\mathrm{cut}} = \{0.05, 0.1\}$$

Measuring Jet Shapes and Substructure with ATLAS





Jet Substructure Observables

Single jet mass

$$m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2}$$

- Deduced from four-momentum sum of all jet constituents
  - Before and after any grooming
  - Constituents can be massive (generated stable particles, reconstructed tracks) or massless (calorimeter cell clusters)
- Can be reconstructed for any meaningful jet algorithm

k_T splitting scales

J.M.Butterworth, B.E.Cox, J.R.Forshaw, *Phys.Rev.* **D65** (2002) 096014

$$\sqrt{d_{ij}} = \min[p_{\text{T},i}, p_{\text{T,j}}] \times \Delta R_{ij}$$

- k_T distance of last (d_{12}) or second-to-last (d_{23}) recombination
  - Typically only hardest and next-to-hardest recombination considered in ATLAS
- Has expectation values for pronged decays
  - $d_{12} \approx (M/2)^2$ for particle with mass M undergoing 2-body decay

N-subjettiness

J.Thaler, K. Van Tilburg, *JHEP* **03** (2011) 15

$$\tau_N = \sum_k p_{\text{T},k} \times \min[\delta R_{1k}, \ldots, \delta R_{Nk}] \Big/ \left(\sum_k p_{\text{T},k} \times R\right)$$

- Measures how well jets can be described assuming N sub-jets
  - Degree of alignment of jet constituents with N sub-jet axes
- Sensitive to two- or three-prong decay versus gluon or quark jet
  - Highest signal efficiencies from N-subjettiness ratios τ_{N+1}/τ_N

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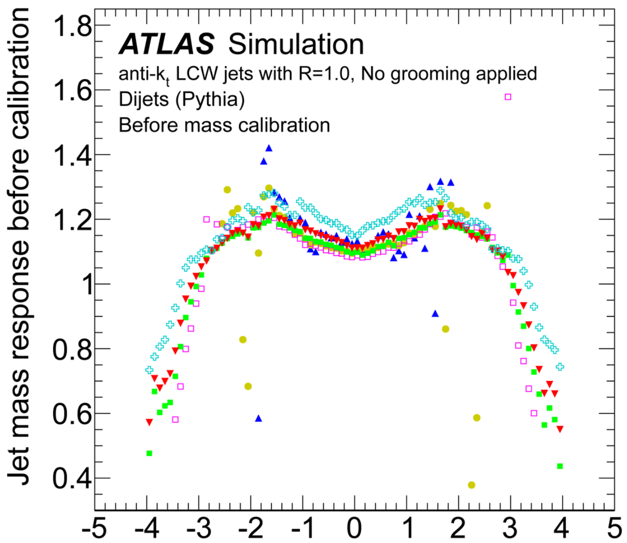
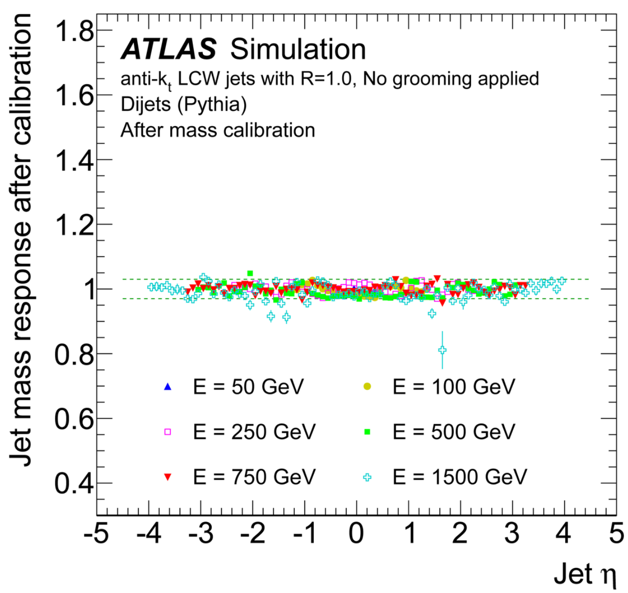
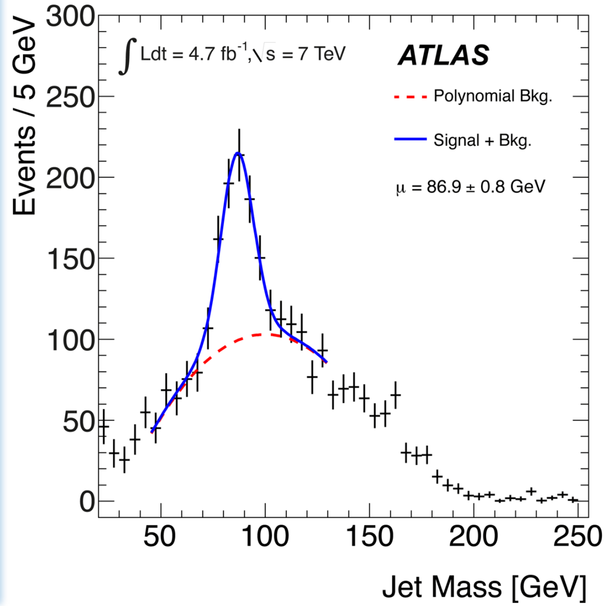
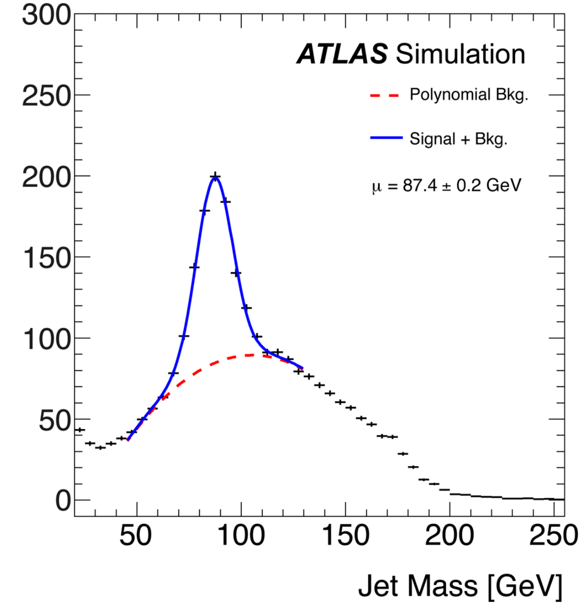
Jet mass calibration in ATLAS

- MC and in-situ based calibrations calibrate energy and p_T
  - Constraints for calibration functions
- Single jet mass is not calibrated automatically
  - Apply dedicated MC based mass calibration
- Validation with MC and data
  - Ratios of masses from calorimeter and tracks
  - *W* boson mass reconstruction
  - Yields 4-6% systematic uncertainty on jet mass scale, depending on grooming technique applied and jet direction









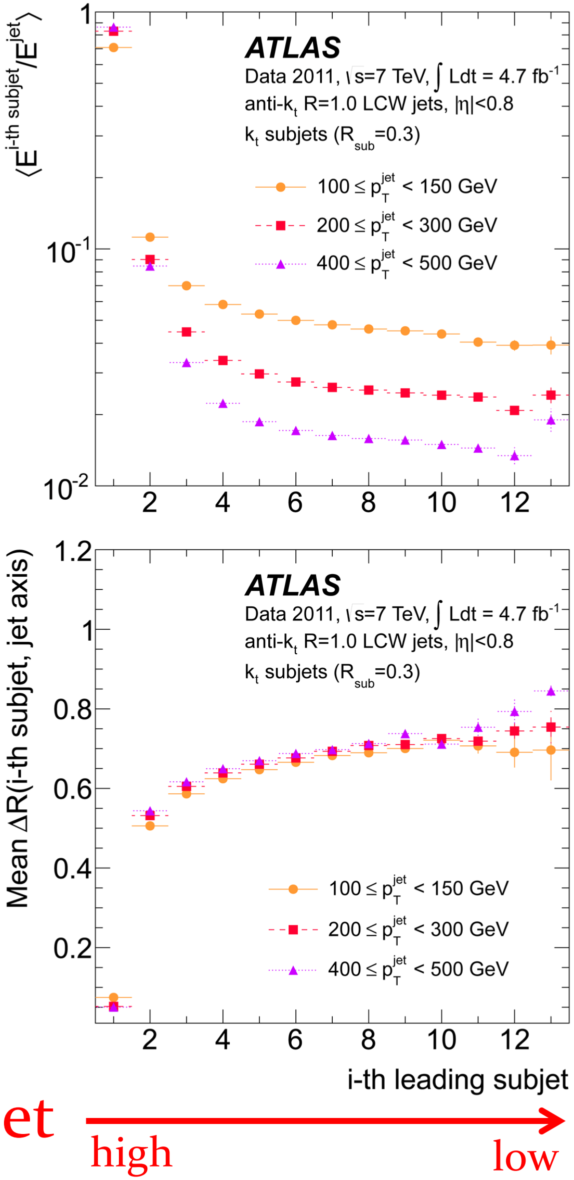
Sub-jet response features

Energy sharing

Fraction of total jet energy carried by sub-jet

Distance to jet axis

Radial dispersion and spatial resolution limitations of ATLAS calorimetry



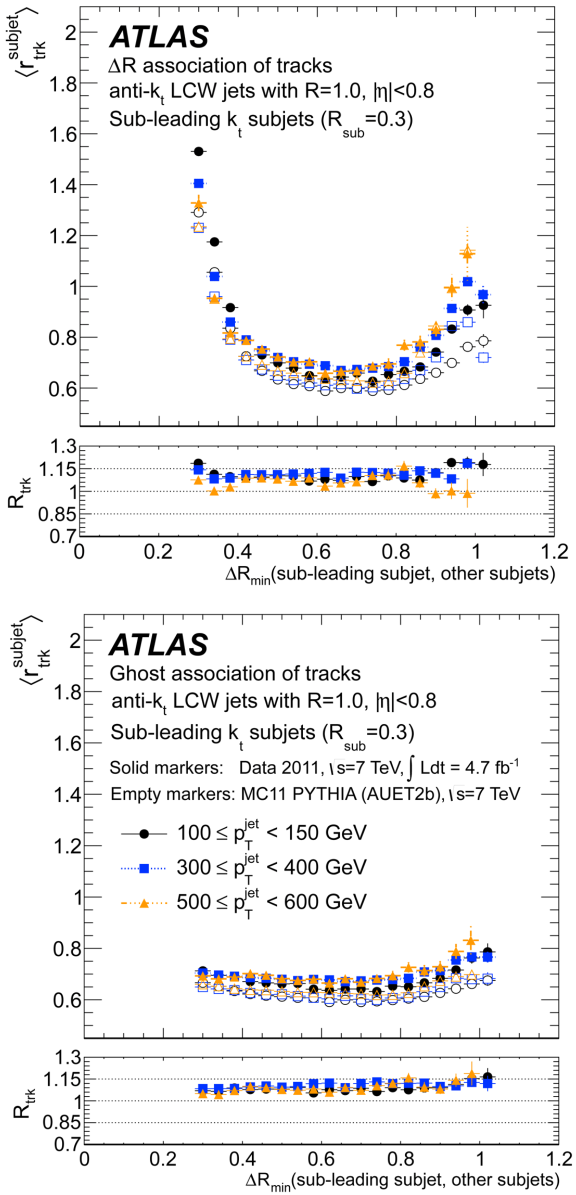
Looking Inside Jets

Sub-jet response reference

- Matching tracks with (calorimeter) sub-jets
  - Traditional method based on angular distance in pseudorapidity and azimuth – matching efficiency depending on sub-jet shapes/shape assumptions
  - "Ghostmatching" clusters tracks into calorimeter sub-jet without interfering with its kinematic ($p_{T,trk}$ set to tiny value O(10^{-100} GeV)) – matching efficiencies ~independent of sub-jet shape
- Calculating response ratios in data and MC

$$r_{\mathrm{trk}}^{\mathrm{subjet}} = \frac{\sum_{\text{matched tracks}} p_{\mathrm{T}}^{\mathrm{track}}}{p_{\mathrm{T}}^{\mathrm{subjet}}}$$

$$\left\langle R_{\mathrm{trk}}^{\mathrm{subjet}} \right\rangle = \frac{\left\langle r_{\mathrm{trk}}^{\mathrm{subjet}} \right\rangle_{\mathrm{data}}}{\left\langle r_{\mathrm{trk}}^{\mathrm{subjet}} \right\rangle_{\mathrm{MC}}}$$



Jet Mass Measurement in Pile-up

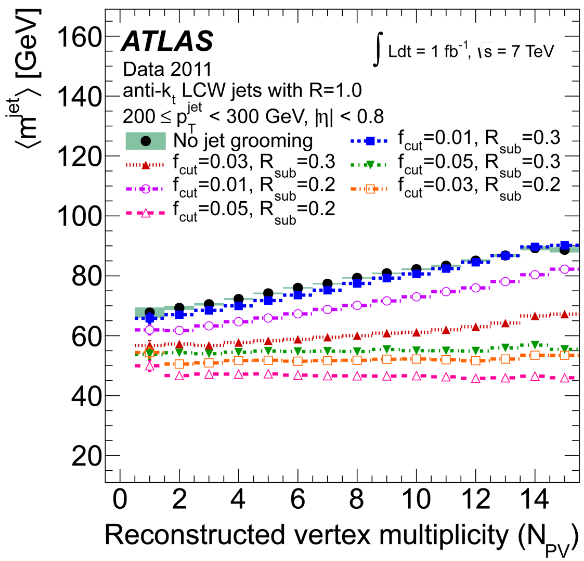
Average effect of jet grooming on the pile-up dependence of the reconstructed single jet mass

Anti-k_T jets, $R = 1.0$

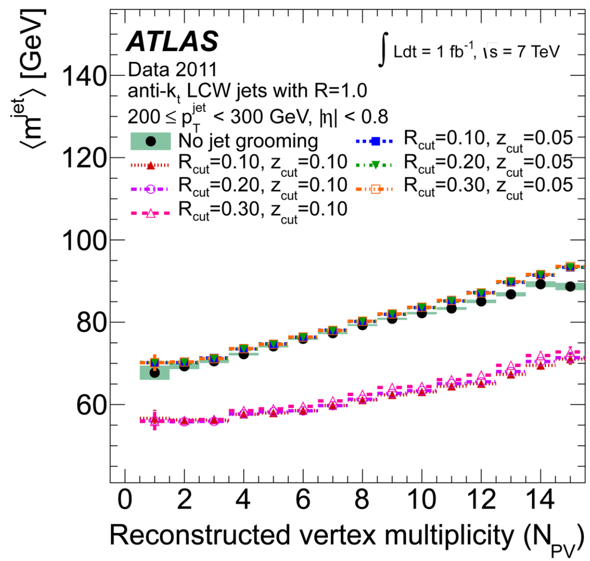
inclusive jet sample:

$200 < p_T^{jet} < 300$ GeV, $|\eta| < 0.8$

Trimming



Pruning



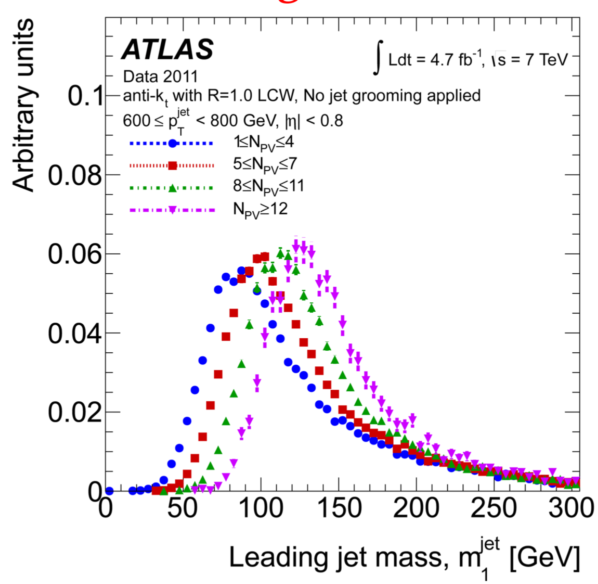
Effect of jet trimming on the spectrum of the reconstructed jet mass

Anti-k_T jets, $R = 1.0$

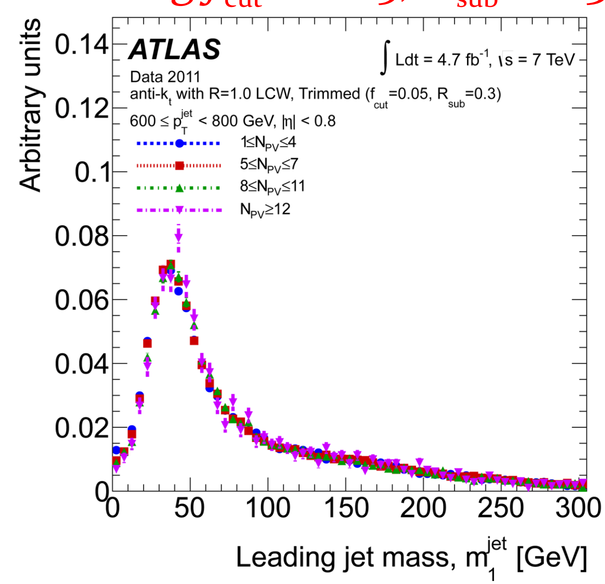
inclusive jet sample:

$600 < p_T^{jet} < 800$ GeV, $|\eta| < 0.8$

Ungroomed



Trimming $f_{cut} = 0.05$, $R_{sub} = 0.3$



Splitting Scales & *N*-subjettiness with Pile-up

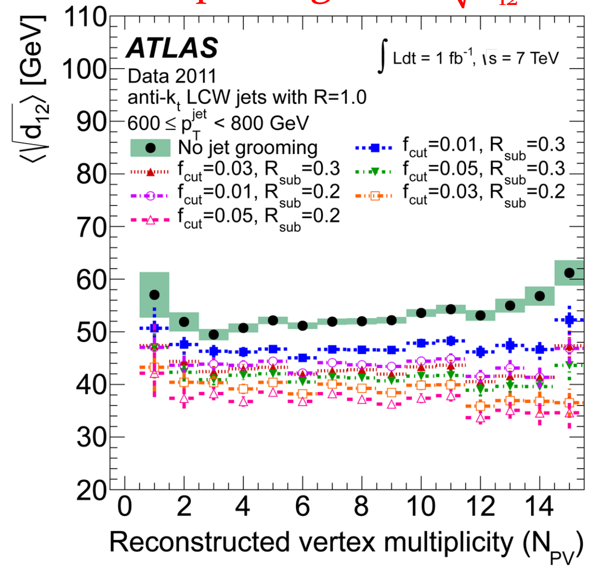
Average effect of jet trimming on the pile-up dependence of the k_T splitting scales

Anti-k_T jets, $R = 1.0$

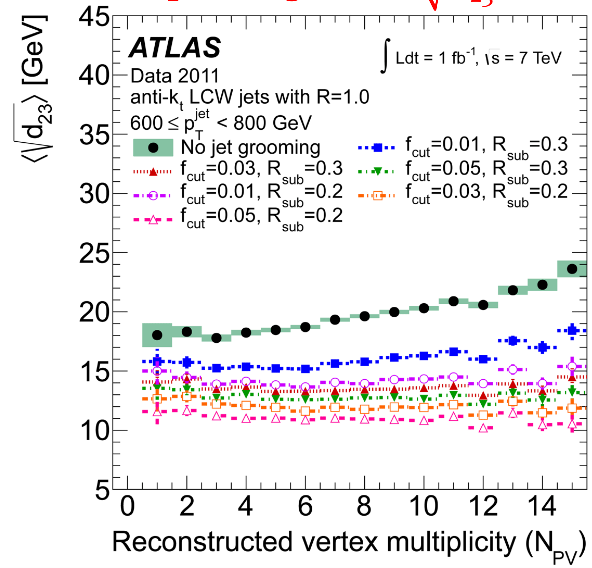
inclusive jet sample:

$600 < p_T^{jet} < 800$ GeV, $|\eta| < 0.8$

Splitting scale $\sqrt{d_{12}}$



Splitting scale $\sqrt{d_{23}}$



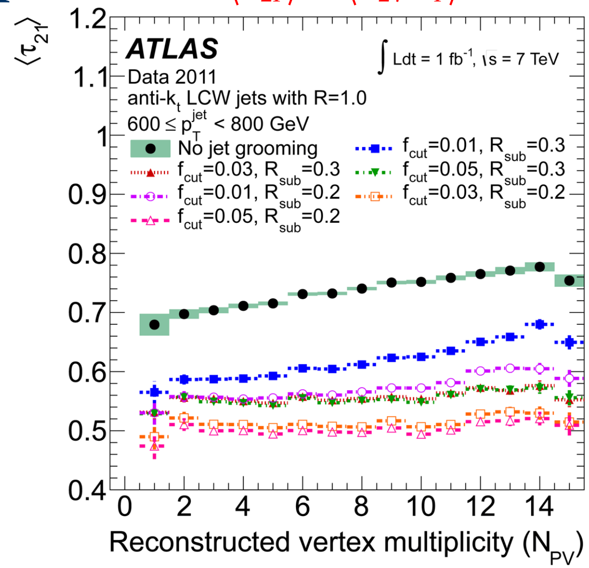
Effect of jet trimming on *N*-subjettiness ratios

Anti-k_T jets, $R = 1.0$

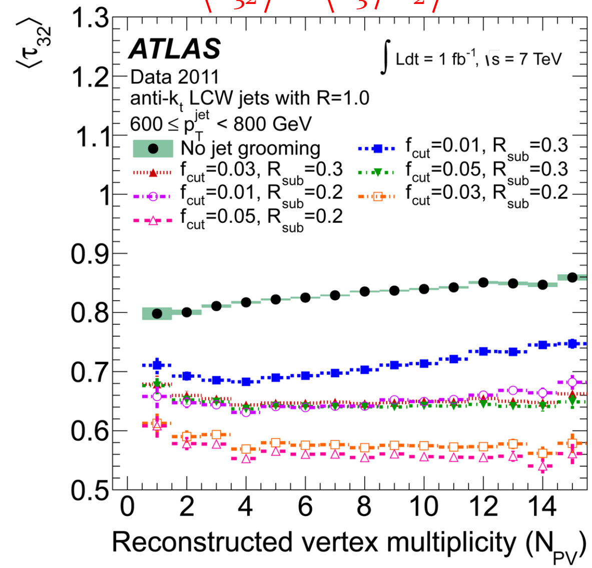
inclusive jet sample:

$600 < p_T^{jet} < 800$ GeV, $|\eta| < 0.8$

$\langle \tau_{21} \rangle = \langle \tau_2 / \tau_1 \rangle$



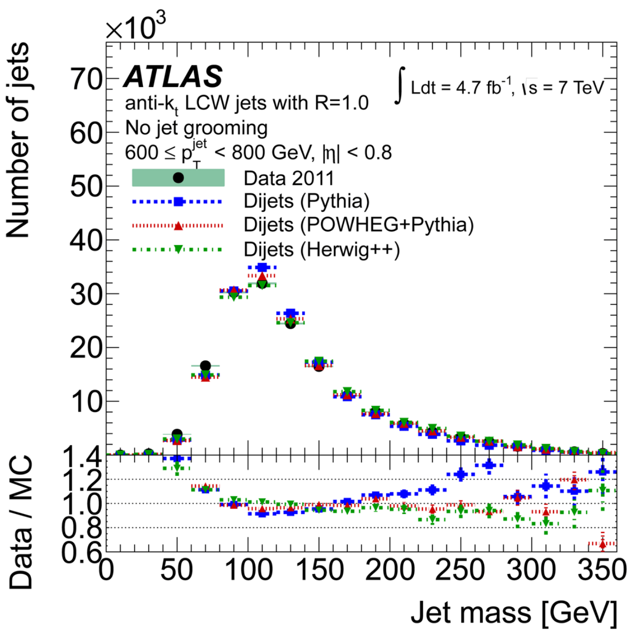
$\langle \tau_{32} \rangle = \langle \tau_3 / \tau_2 \rangle$



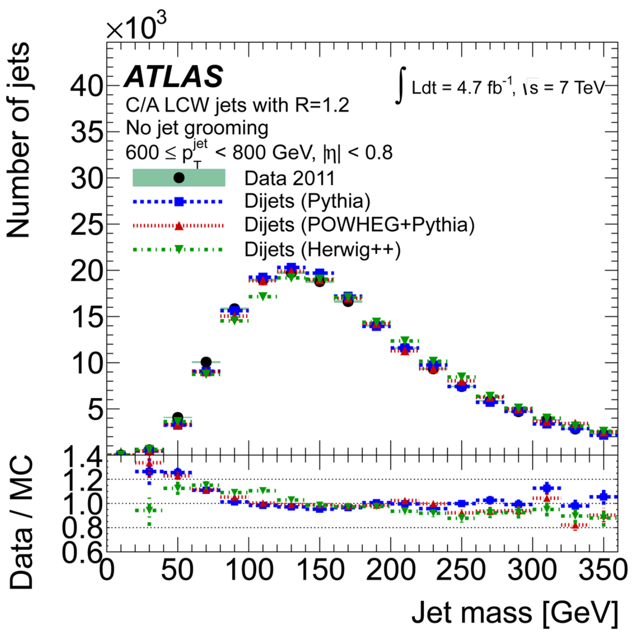
Modeling of Jet Mass

LO versus NLO calculations in MC generation

- Preference for NLO kernel (POWHEG)
  - Additional hard emission in di-jet events determines high mass
  - Detailed effect depends on jet definition – more enhanced in Anti-k_T compared to C/A
- Observed for ungroomed jets



Anti-k_T jets, $R = 1.0$



C/A jets, $R = 1.2$

Evaluation of single jet mass modeling quality for an inclusive sample of ungroomed jets with

$600 < p_T < 800$ GeV, $|\eta|<0.8$

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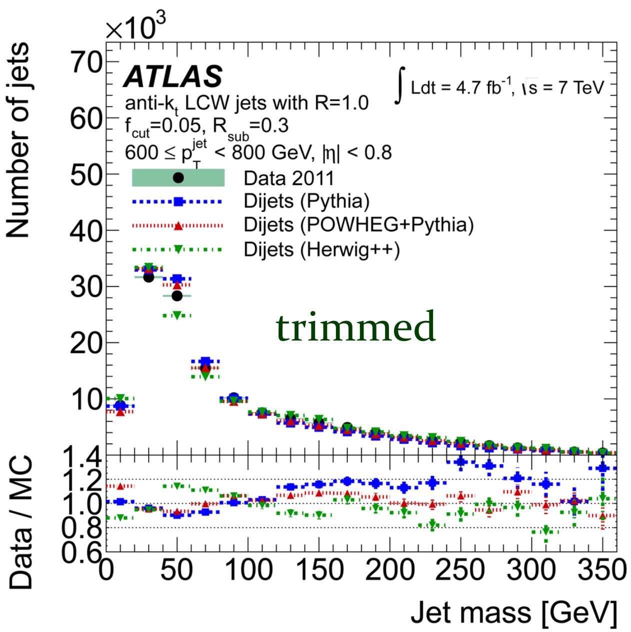
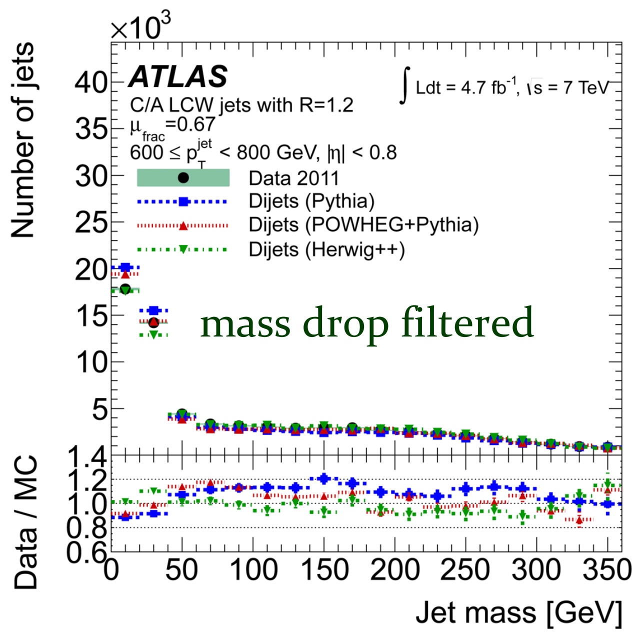
LO versus NLO calculations in MC generation

- Preference for NLO kernel (POWHEG)
  - Additional hard emission in di-jet events determines high mass
  - Detailed effect depends on jet definition – more enhanced in Anti-k_T compared to C/A
- Observed for ungroomed jets and groomed jets
  - Modeling quality depends on grooming technique and jet definition!



Anti-k_T jets, $R = 1.0$



C/A jets, $R = 1.2$

Evaluation of single jet mass modeling quality for an inclusive sample of groomed jets with

600 < p_T < 800 GeV, |η|<0.8

Modeling of Splitting Scales & *N*-subjettiness

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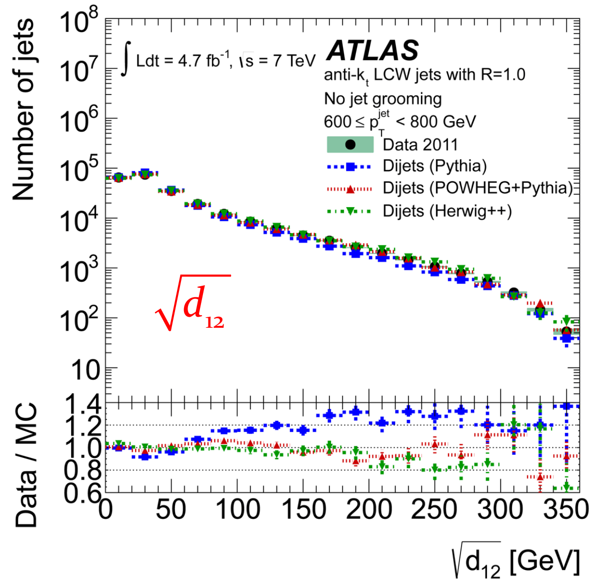
Splitting scale comparisons data/MC – indicate preference for NLO and Herwig++

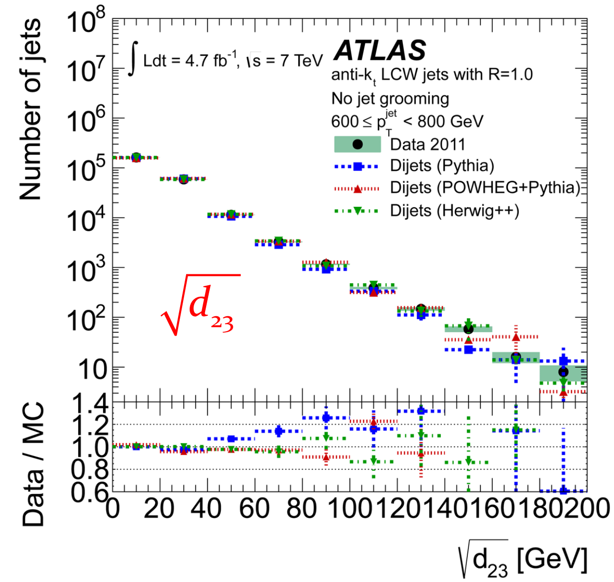
Anti-k_T jets, $R = 1.0$

No grooming - very similar for groomed jets!

inclusive jet sample:

$600 < p_T^{jet} < 800$ GeV, $|\eta| < 0.8$





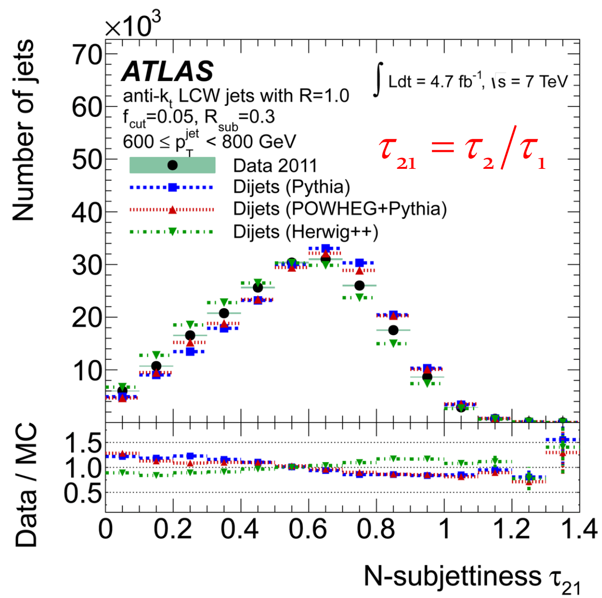
N-subjettiness not too sensitive to LO/NLO kernel choices

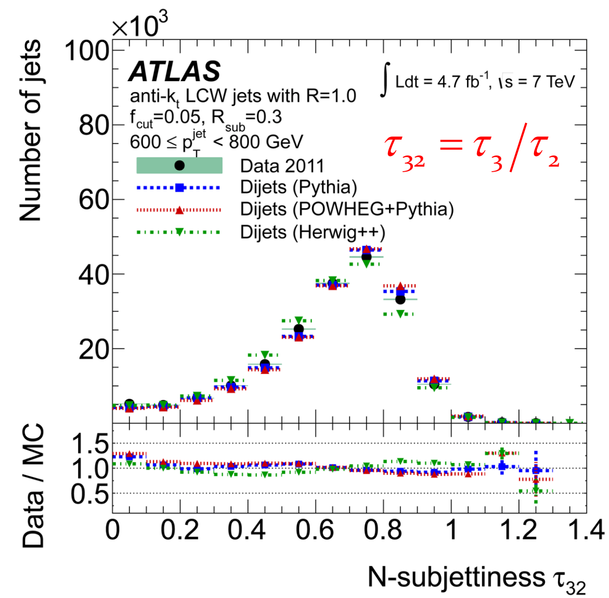
Anti-k_T jets, $R = 1.0$

Trimmed - qualitatively similar for ungroomed jets!

inclusive jet sample:

$600 < p_T^{jet} < 800$ GeV, $|\eta| < 0.8$





Correlations in Substructure

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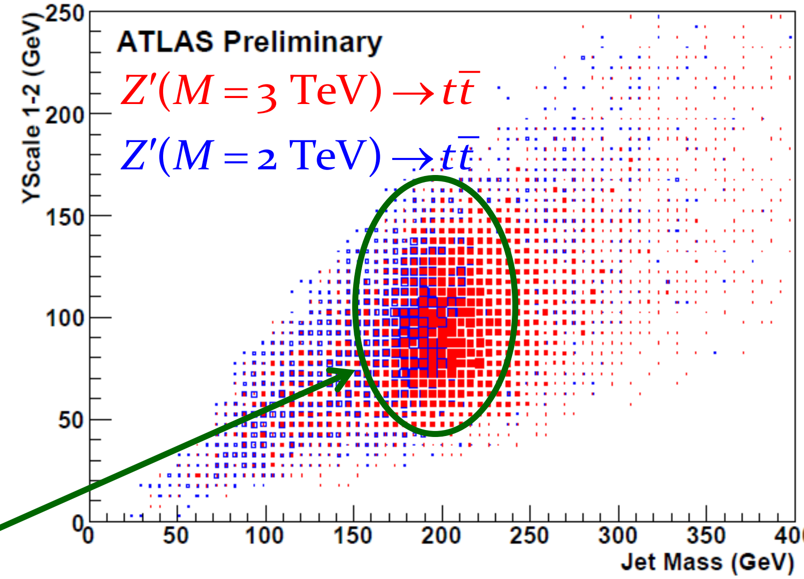
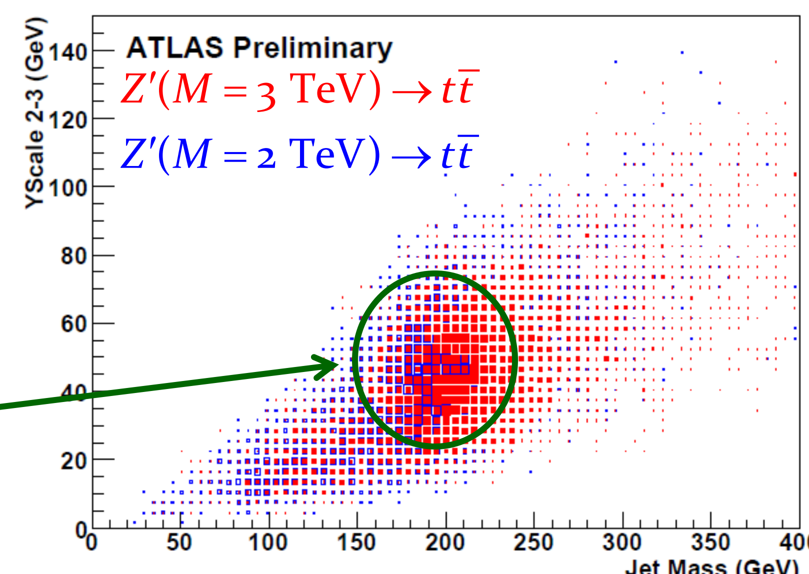
Some substructure observables are expected to be correlated

- Single jet mass and splitting scales
  - Hardest splitting scale from heaviest particle (2-prong) decay
  - Next-to-hardest splitting scale from subsequential lighter particle decay

G.Booijmans, *ATL_PHYS-CONF-2008-008*(2008)



$t \rightarrow Wb$ splitting scale



$W \rightarrow q\bar{q}$ splitting scale

ATLAS MC (Pythia)

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G.Booijmans, *ATL_PHYS-CONF-2008-008*(2008)

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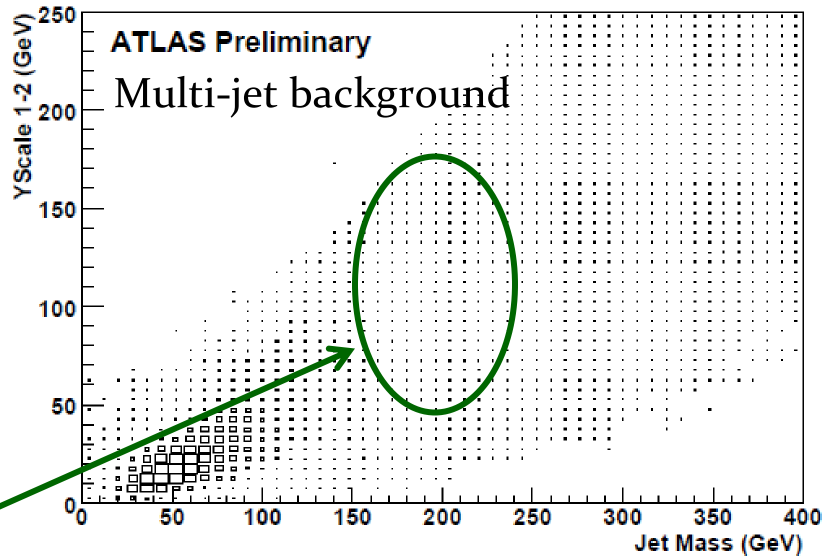
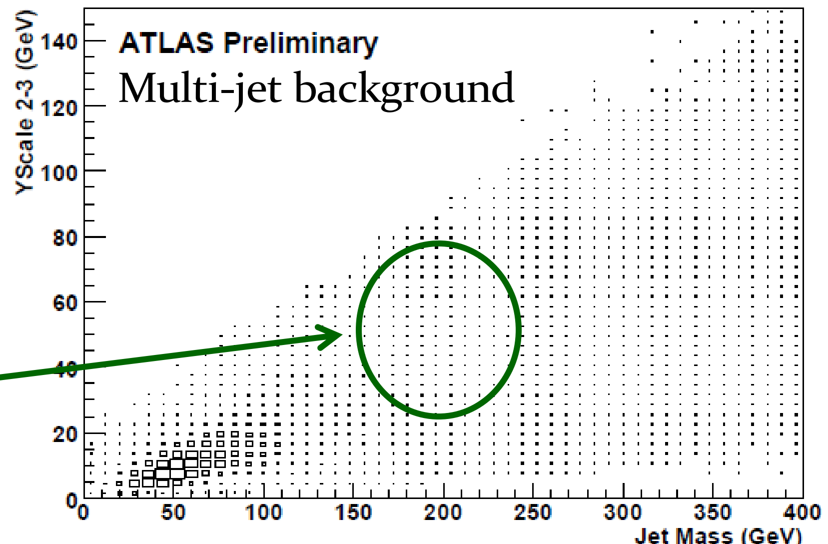


$t \to Wb$ splitting scale

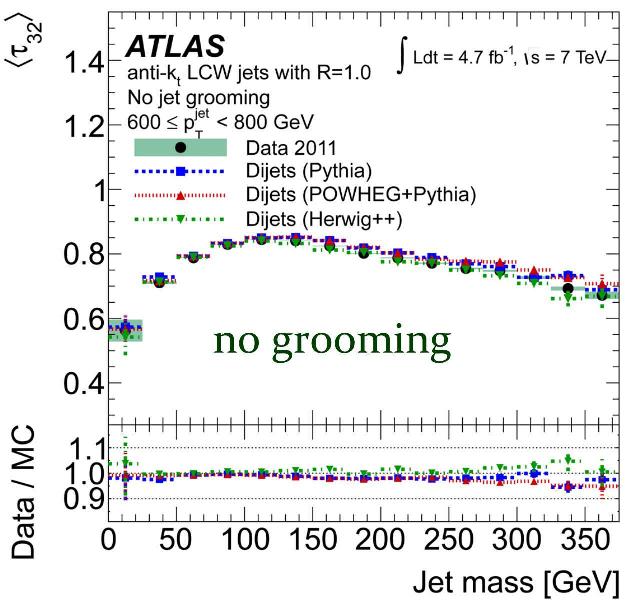


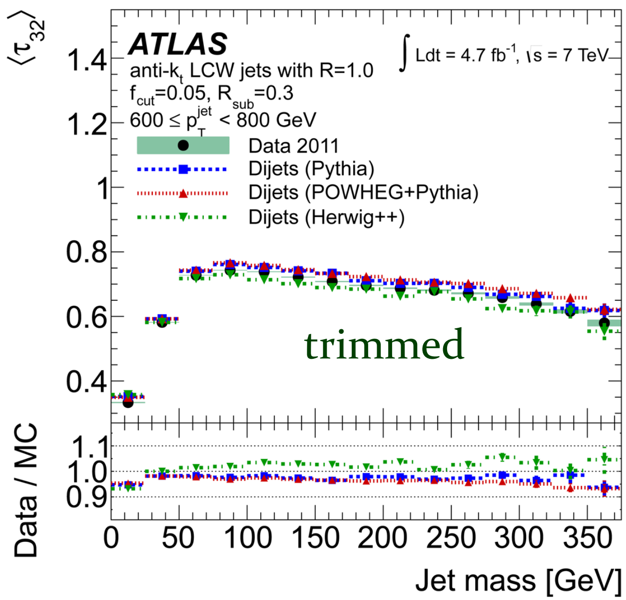
$W \to q\bar{q}$ splitting scale

ATLAS MC (Pythia)

Modeling correlations in single jet structural observables

- Example: evolution of *N*-subjettiness ratio τ_{23} with single jet mass
  - Modeled well within a few percent by all considered generators
  - Qualitatively different behavior of Herwig++
- Observed for ungroomed jets and groomed jets
  - Modeling at same quality with a small increase of differences to Herwig++





Evaluation of modeling quality of average correlation between *N*-subjettiness ratio τ_{23} and single jet mass for an inclusive jet sample with

$600 < p_T < 800$ GeV, $|\eta|<0.8$

Anti-k_T jets, $R = 1.0$

Basics for Application in Searches for New Physics

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Top – Anti-top production

- Most often observed top quark final state at LHC
  - Data collected in 2011 for the first time allowed to study boosted hadronically decaying top
- Large potential background for new physics
  - E.g., *Z'* decaying into top-anti-top pair
- Ideal for performance evaluations of grooming techniques with experimental data
  - Two boosted particles in same final state ($W \rightarrow qq$ and $t \rightarrow Wb$)
  - Performance can be determined for two- and three-prong decays

Hadronic top signal extraction

- Main trigger and event selection from semi-leptonic top decay
  - High p_{T} lepton and large missing transverse momentum
- Typically analysis uses leading jet
  - $p_{\mathrm{T}} > 350$ GeV for jet size $R = 1.0$
- Further refinement for clean sample needed
  - E.g., HepTopTagger – investing more known features of top quarks, like mass windows

T.Plehn, M.Spannowsky, M.Takeuchi, D.Zerwas, *JHEP* **10** (2010) 078

Jet Grooming in Final States with Top Quarks

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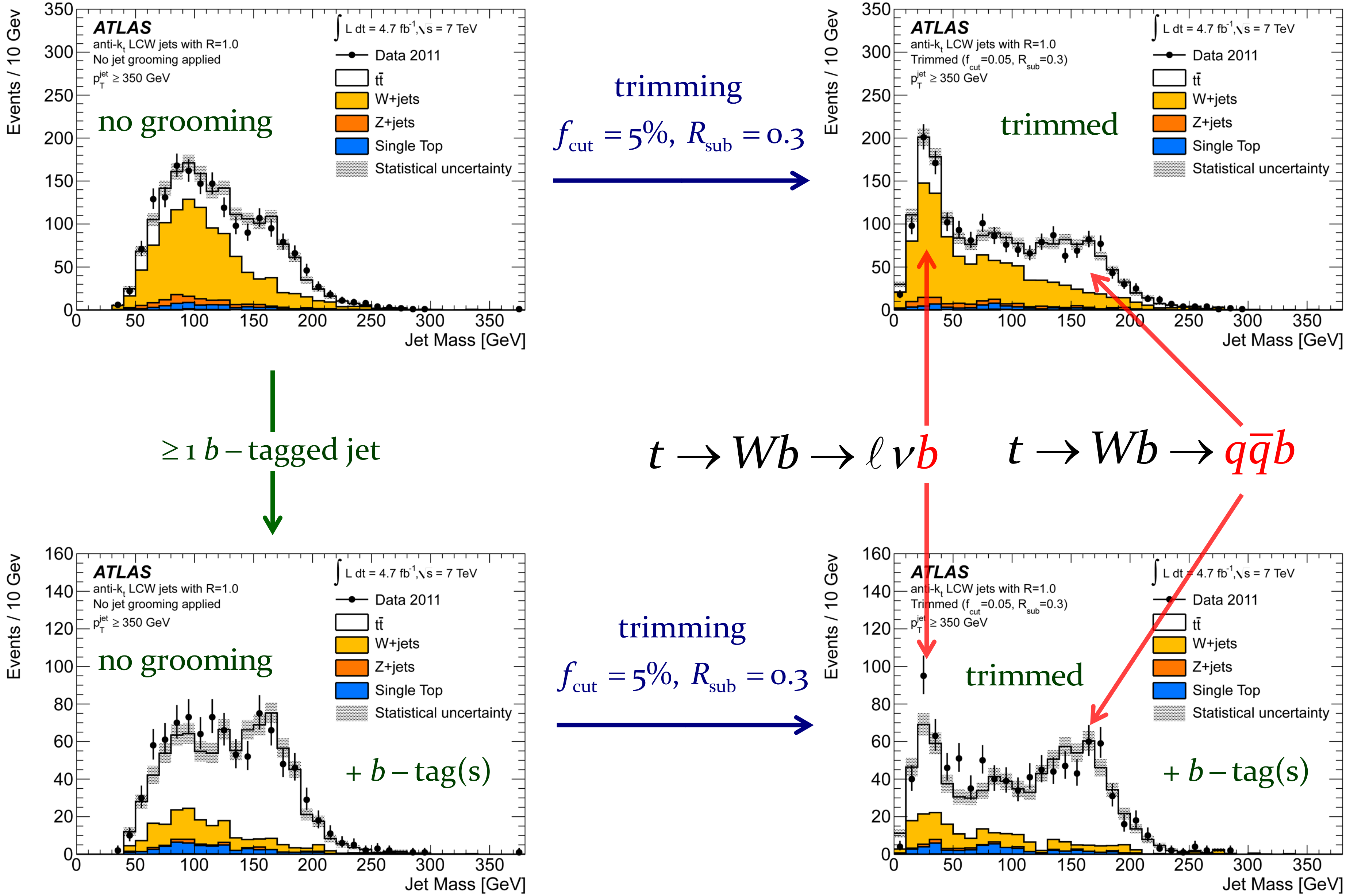
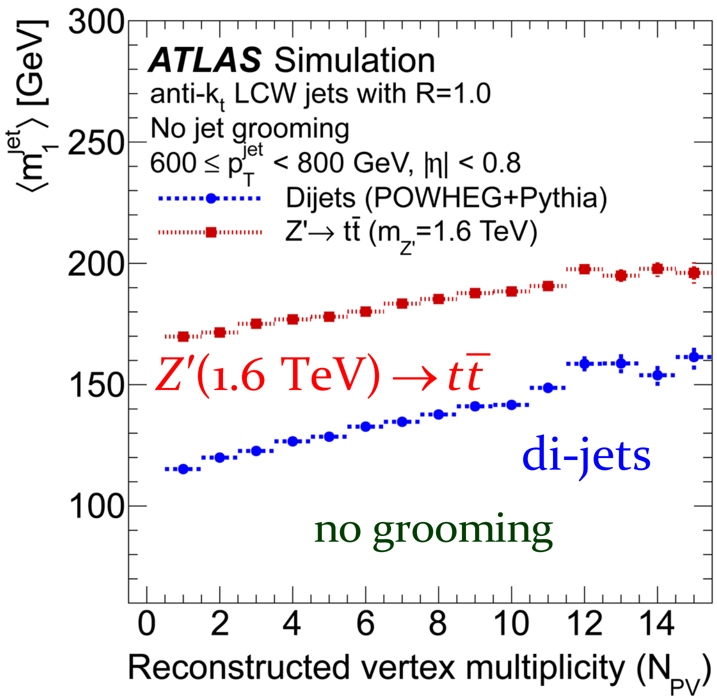
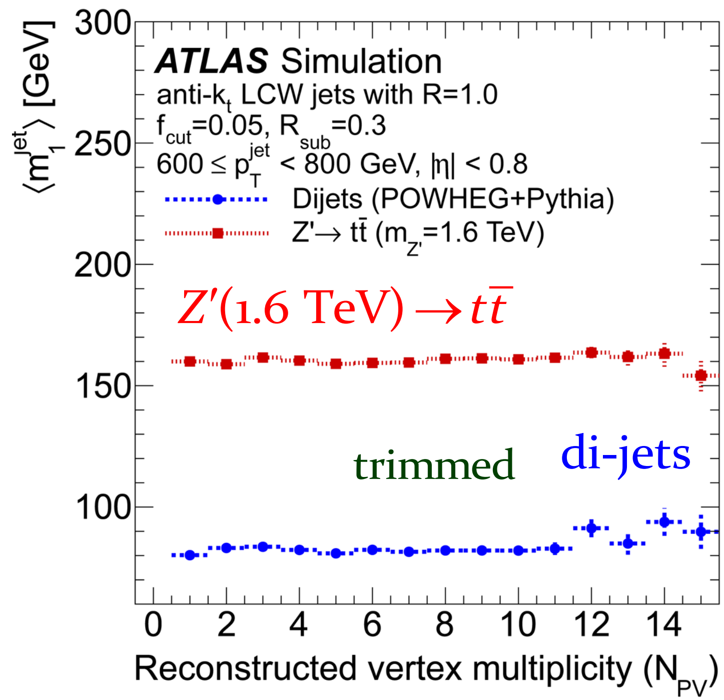


Hadronic top signal extraction (cont'd)

- Check on separation power in other substructure variables
  - Mostly changing background shapes – enhancing top signal significance
- Effects of pile-up on top mass
  - Mitigated well by trimming





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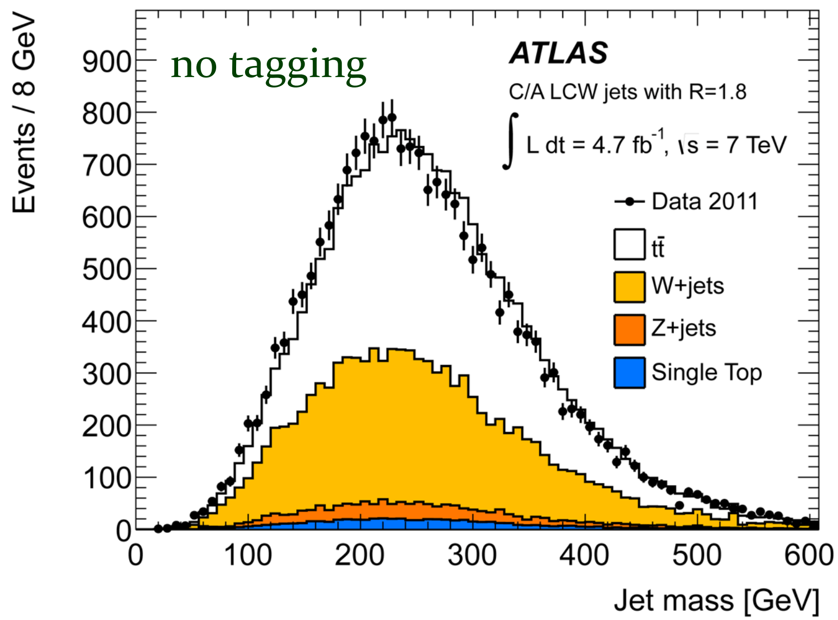
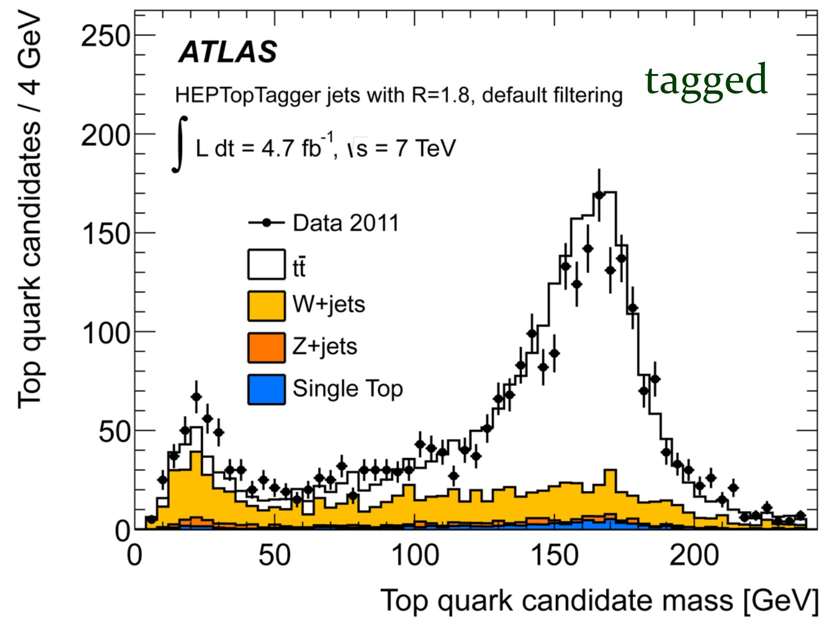
Full hadronic top reconstruction with HepTopTagger

Exploits more exclusive features of final state

- Multiplicities of sub-jets
- Angular distances
- Reconstruction of *W* boson



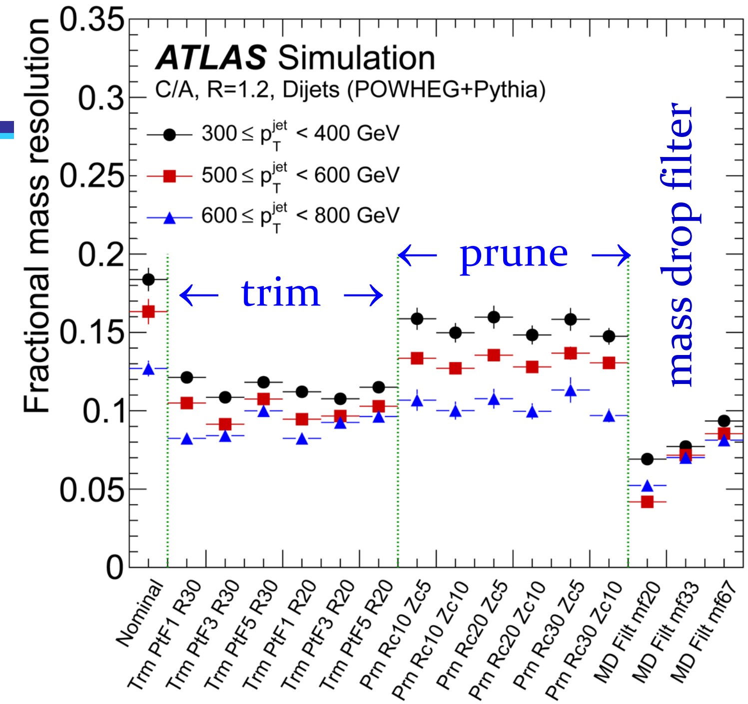


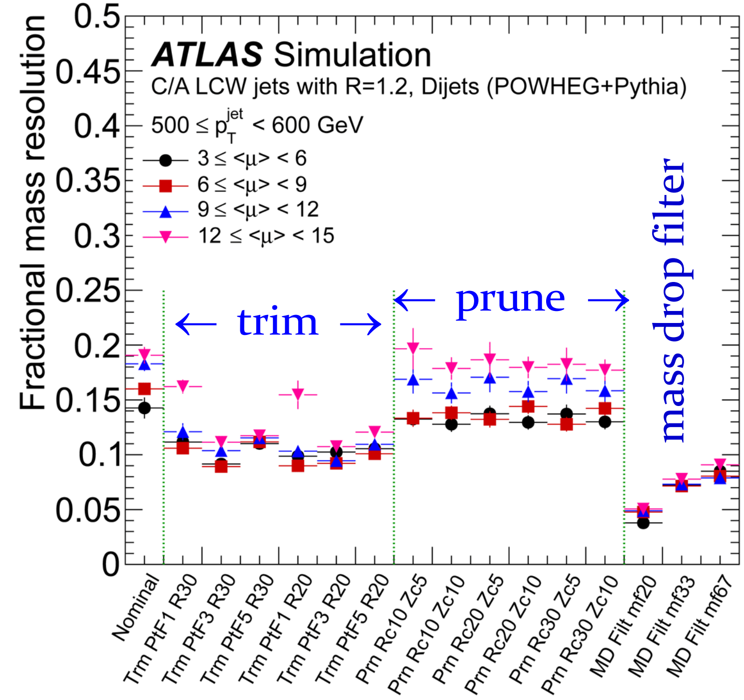
C/A jets, $R = 1.8$

Jet Mass Summary

Single jet mass resolution evaluations

- QCD C/A *R* =1.2 jets (inclusive di-jet sample)
  - Trimming shows best improvement of mass resolution
  - Mass drop filtering has strongest configuration dependence
- QCD C/A *R* =1.2 jets in presence of pile-up
  - Trimming reduces mass fluctuations introduced by pile-up
  - Pruning is least effective with this respect
  - Mass drop filtering effective with stronger configuration dependence

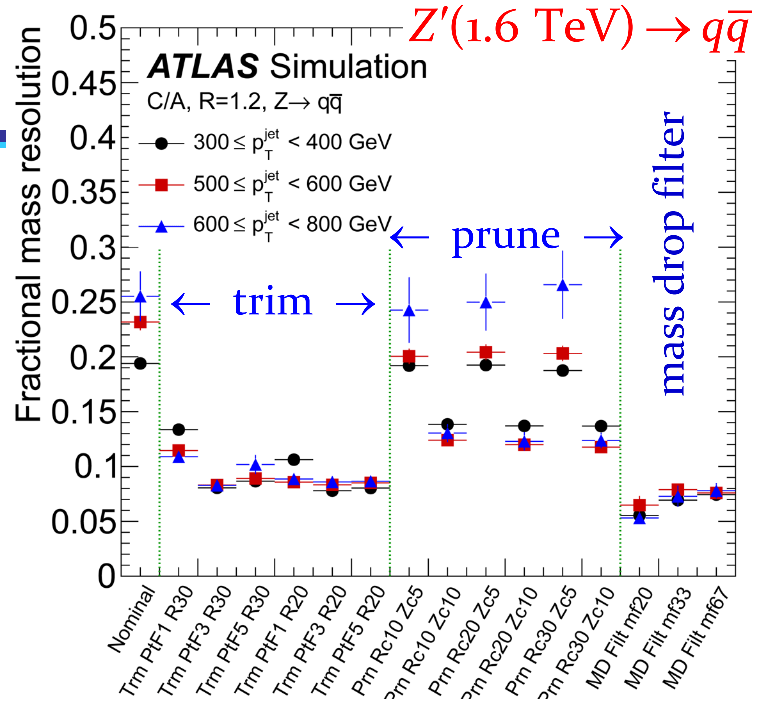


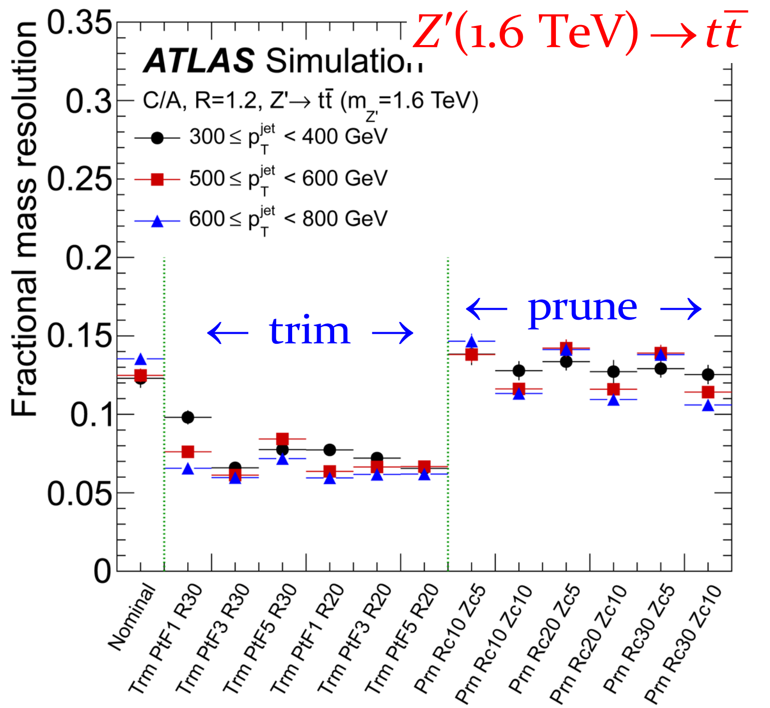


Jet Mass Summary

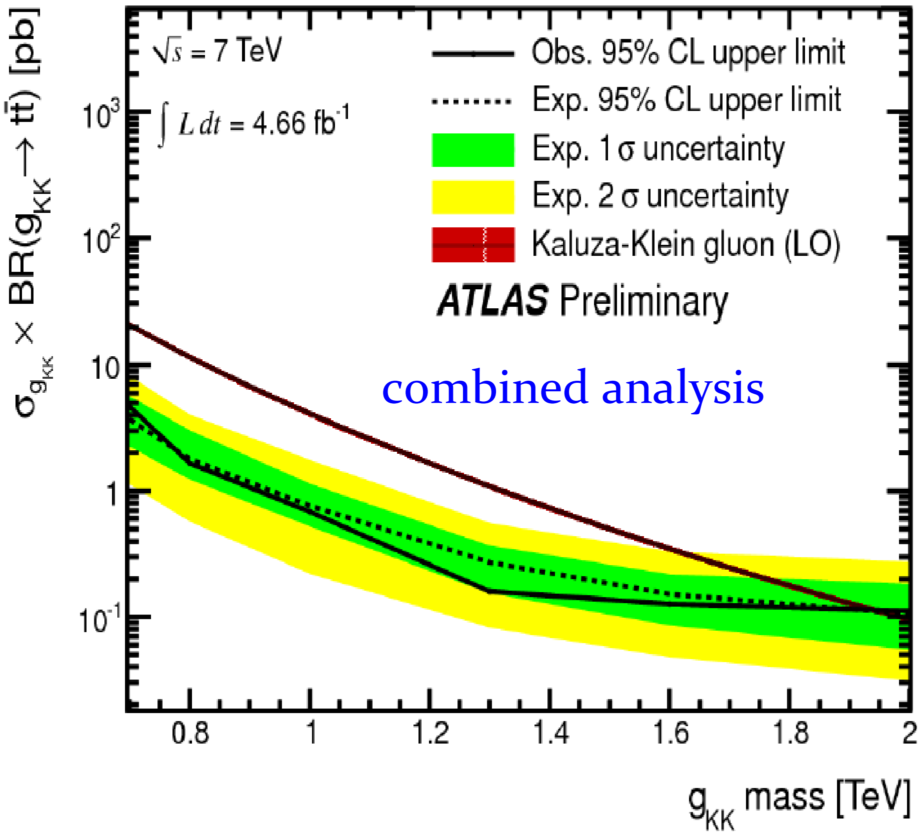
Single jet mass resolution evaluations

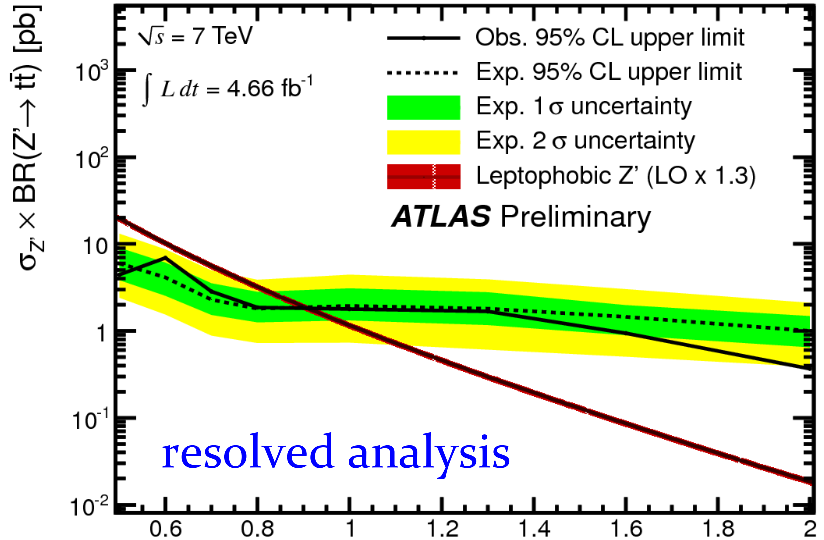
- Two-prong decay C/A R =1.2 jets
  - Trimming and mas drop filtering show best improvement of mass resolution
  - Pruning less effective
- Three-prong decay C/A R =1.2 jets
  - Trimming shows best performance with insignificant dependencies on configurations
  - Pruning shows only little improvement

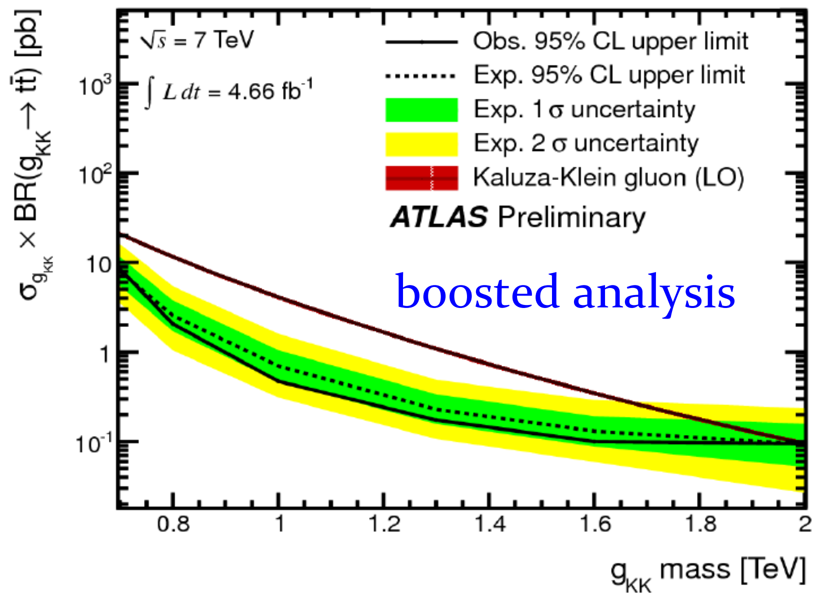




Search top-anti-top resonance







Conclusions & Outlook

- **Jet substructure reconstruction in ATLAS with 2011 data studied in great detail**
  - Large configuration space for jet grooming techniques
    - Trimming, mass drop filtering, and pruning tested with sufficient coverage of corresponding (meaningful) parameter spaces
  - Calibrations for jet masses and sub-jet kinematics available for most performing configurations
    - Systematic uncertainties controlled at typical levels of 5% or better
  - Resolvable angular distance and intrinsic k_T scales for decay structure reconstruction in jet sufficient in kinematic regime accessible with 2011 data
    - Evaluated with boosted *W* bosons and top quarks in data and MC
    - Effects of pile-up at 2011 levels on key observables understood and controlled
    - Most observables can be modeled with sufficient precision – NLO generators are becoming more important for sub-jet distances and single jet mass
  - First applications in searches based on final states with top quarks
    - Extension of exclusion limits with respect to purely resolved analysis
    - (see e.g. ATLAS Coll., JHEP 1212 (2012) 086 or arXiv:1210.4813v2 [hep-ex])
- **Promising tool for 2015 and beyond LHC running**
  - Increase in center-of-mass energy extends accessible kinematic regimes
    - Significant increase of reach for production of heavy particles with highly boosted (Standard Model) decay products
  - Higher intensities expected as well
    - Upcoming results from 2012 data with increased pile-up levels, and MC studies of even higher levels, on jet substructure observables
- **We are looking forward to the new challenges…**