Studies of Jet Shapes and Substructure with ATLAS

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This Talk

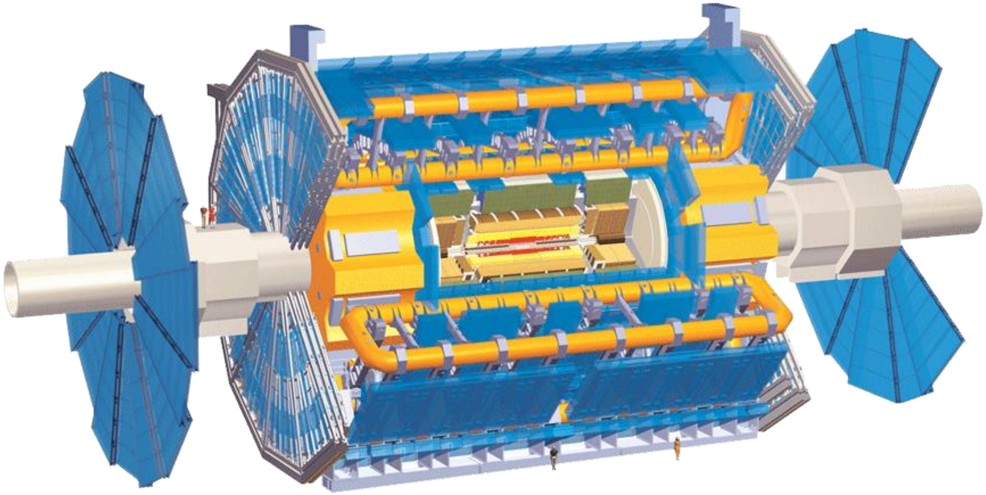
Introduction

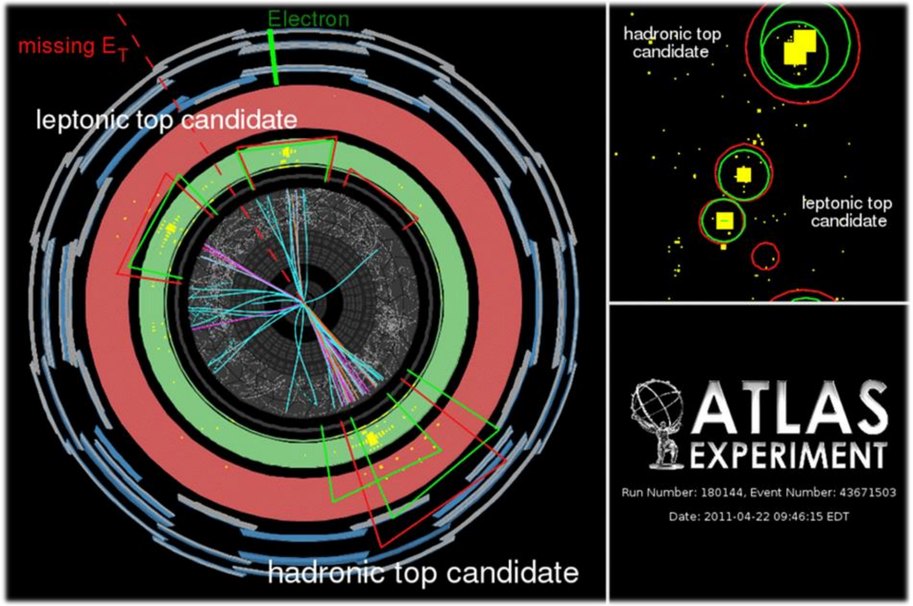
- Motivation
- Jet grooming techniques under consideration

Measuring jet shapes and substructure in ATLAS

- Jet shape observables
- Jet mass calibration and validation
- Substructure based reconstruction performance
- Jet grooming in final states with top quarks

Conclusions and outlook





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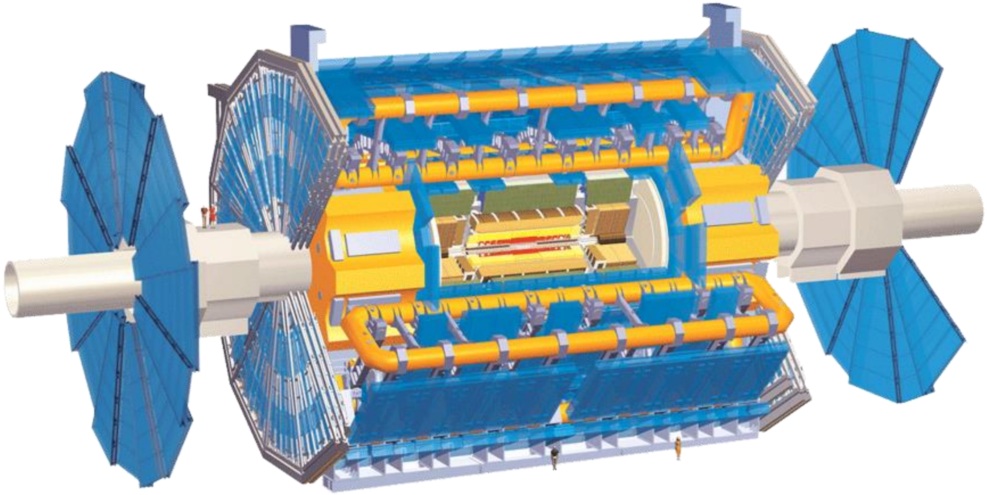


All ATLAS results presented here are published in arXiv:1306.4945v1 [hep-ex] and submitted to JHEP!

Motivation for Jet Substructure Analysis

Kinematic reach at LHC

- Allows production of boosted (heavy) particles decaying into collimated (single-jet like) final states
  - *W* and Higgs bosons, and top quarks
- Searches for new heavy particles with boosted (SM) decay products
  - Single jet mass indicative observable for new particle

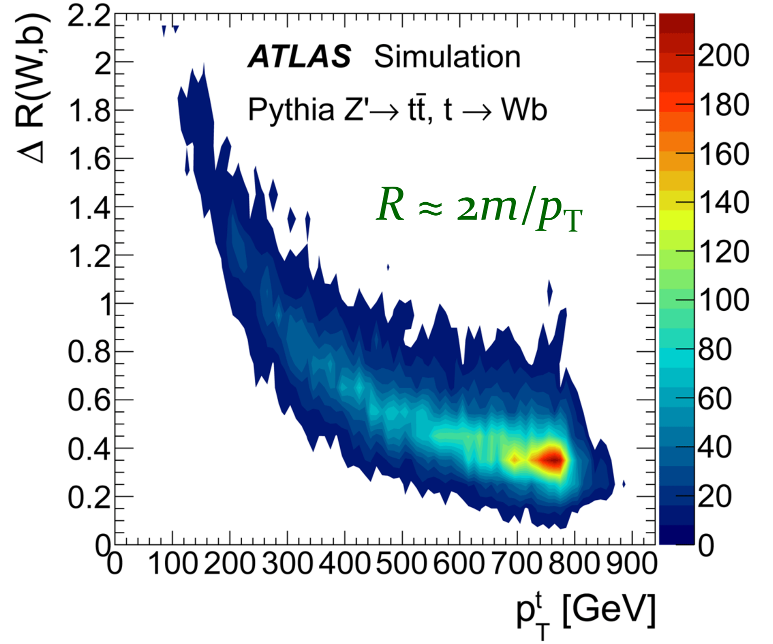
High luminosity pile-up

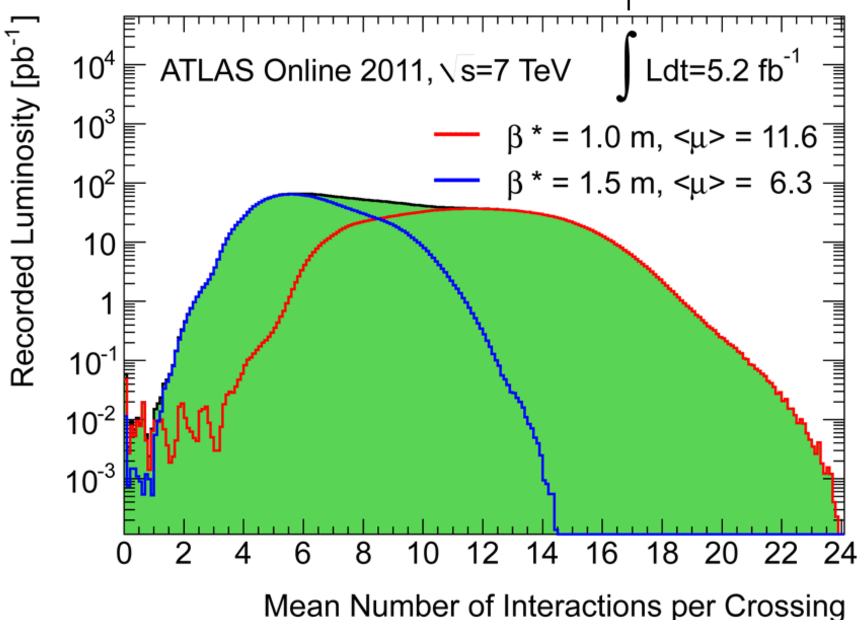
- Presence of additional proton-proton collisions in a bunch crossing can
  - Deteriorates single jet mass and shape measurements

Jet substructure analysis

- Collection of techniques aiming at enhancing two- or three-prong decay patterns in single jets

$\Delta R_{Wb}(p_T^t)$ in $t \rightarrow Wb$

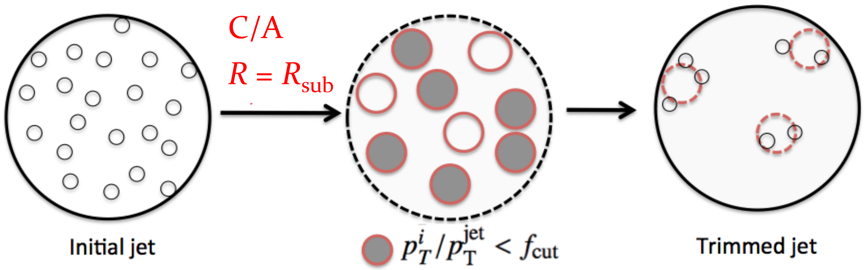




Jet Grooming Techniques

Trimming

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

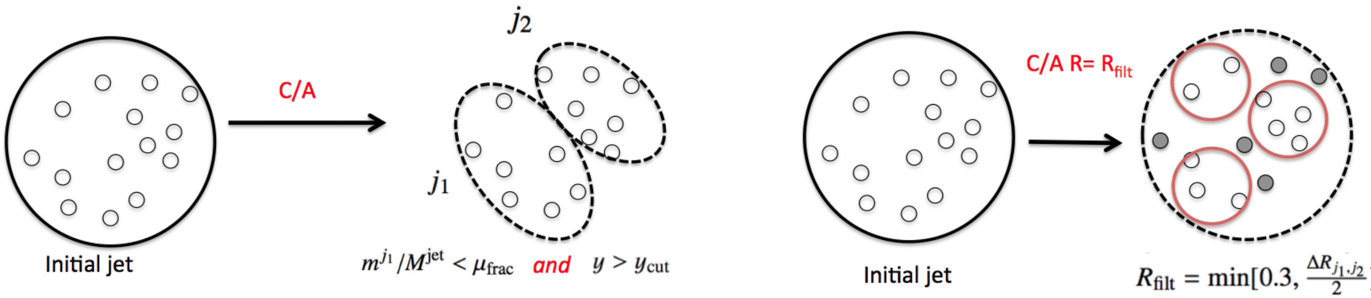


$$R_{sub} = \{0.2, 0.3\}$$

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

Mass drop… … … … … … … …filtering

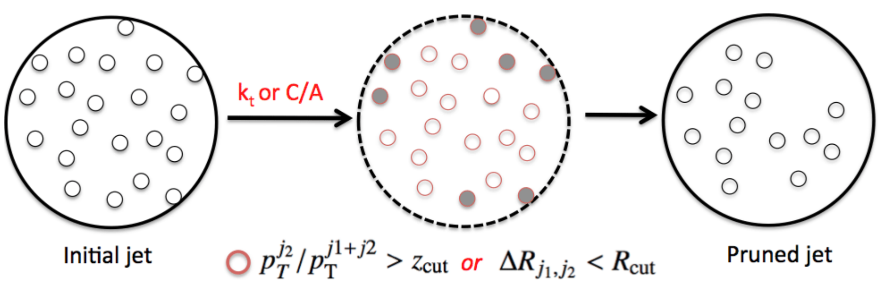
J.M.Butterworth *et al.*, *Phys.Rev.Lett.* **100** (2008) 242001



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

Pruning

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



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

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

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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

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

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

N-subjettiness

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

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

- 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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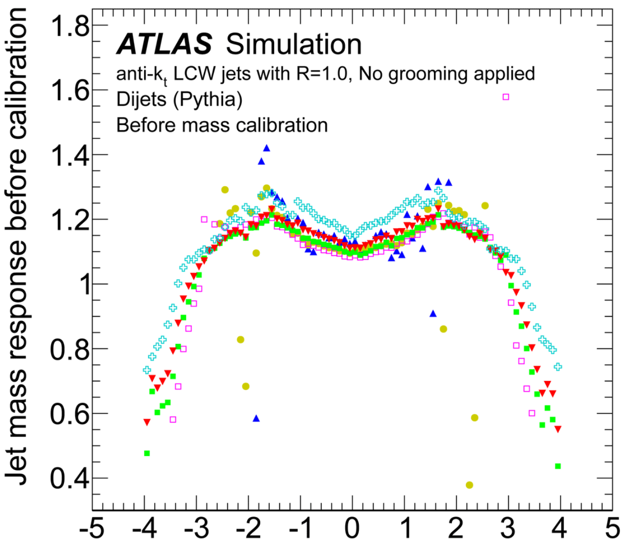
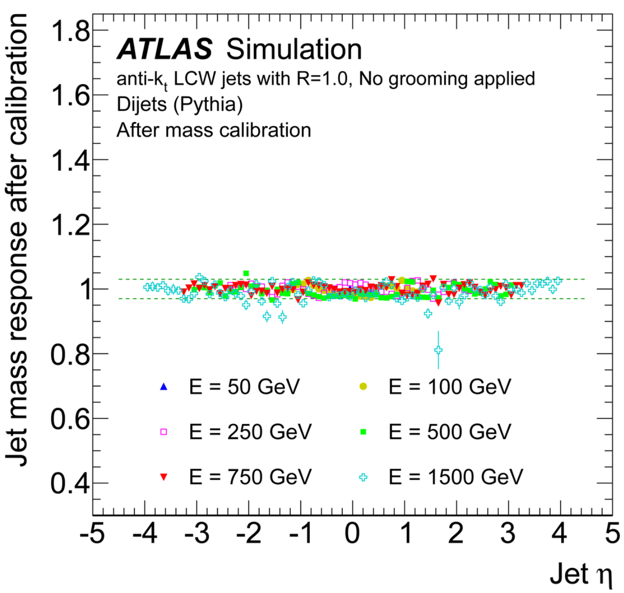
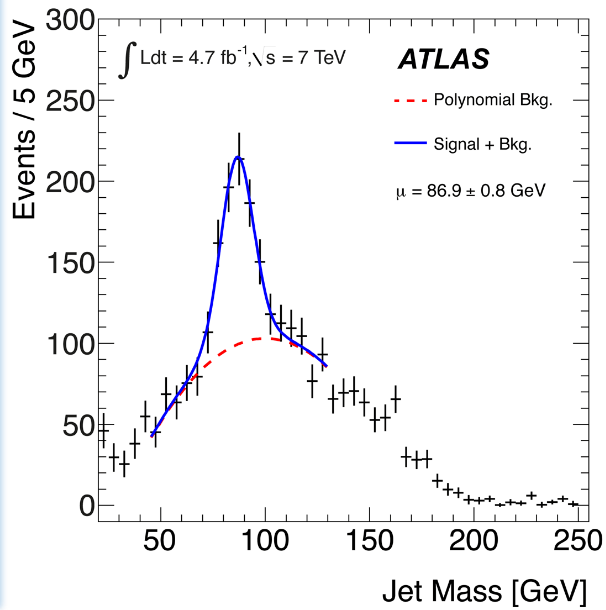
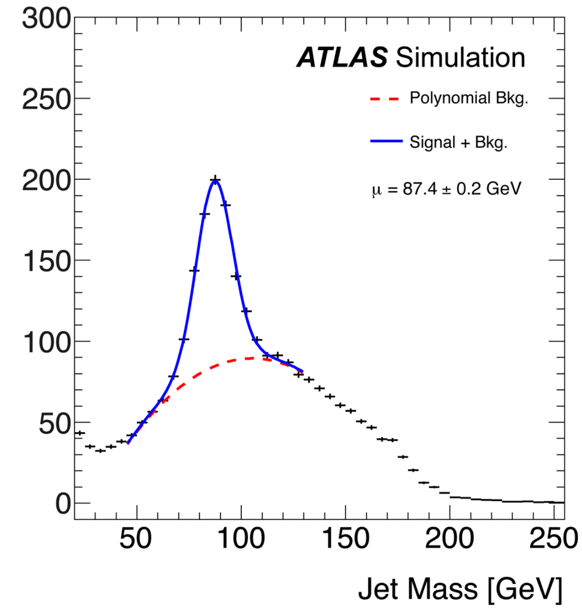




Jet mass calibration in ATLAS

- 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





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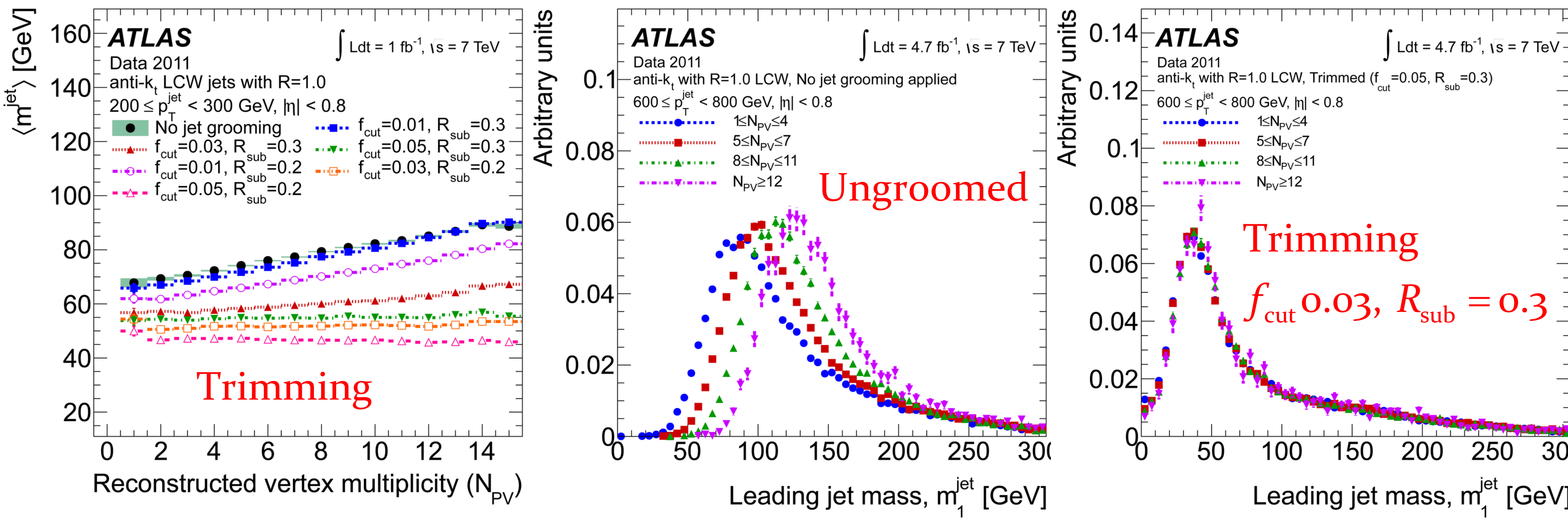
Effect of jet grooming on the pile-up dependence of the reconstructed single jet mass



inclusive jet sample:

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

inclusive jet sample:

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

Anti-k_T jets, $R = 1.0$

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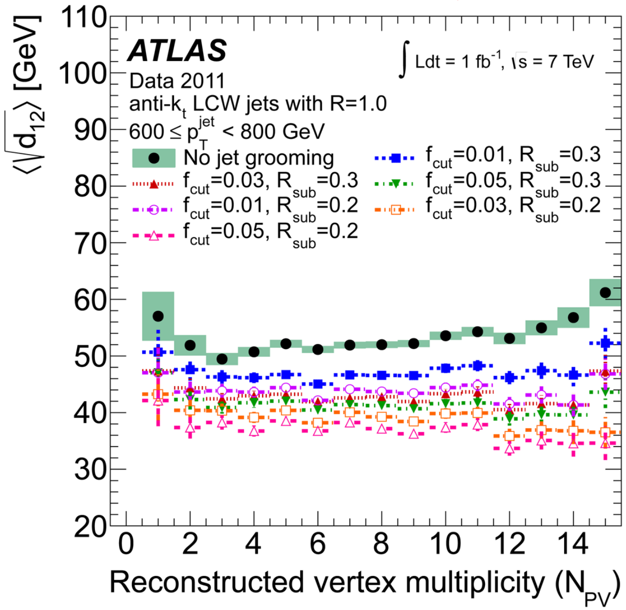
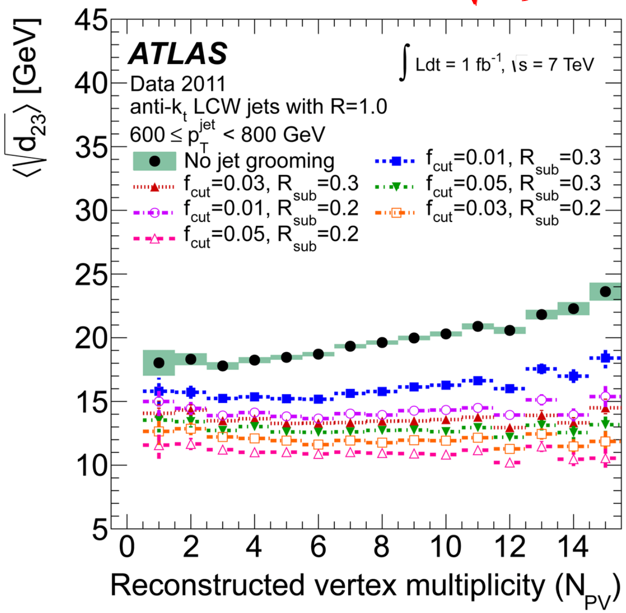
Effect of jet grooming on the pile-up dependence of k_T splitting scales and N-subjettiness

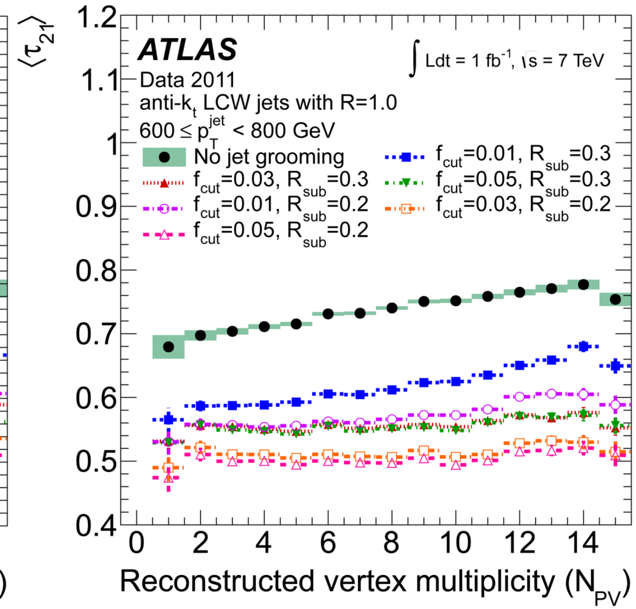
Splitting scale $\sqrt{d_{12}}$



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



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



inclusive jet sample:

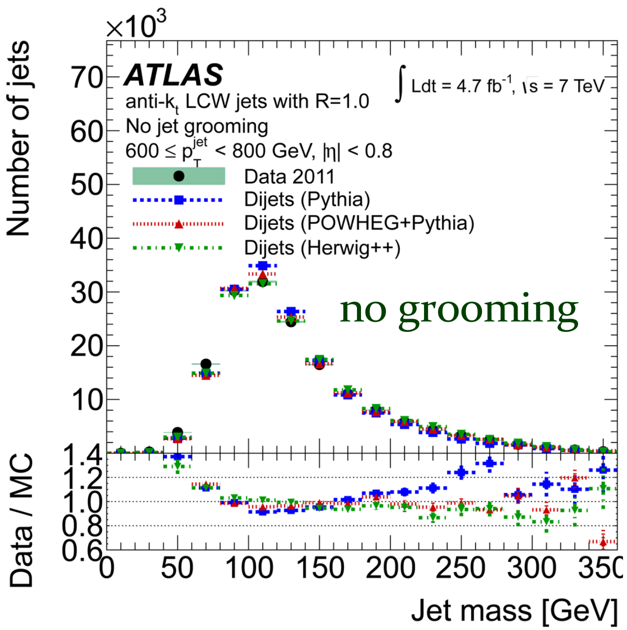
$600 < p_T^{jet} < 800$ GeV, $|\eta| < 0.8$

Anti-k_T jets, $R = 1.0$

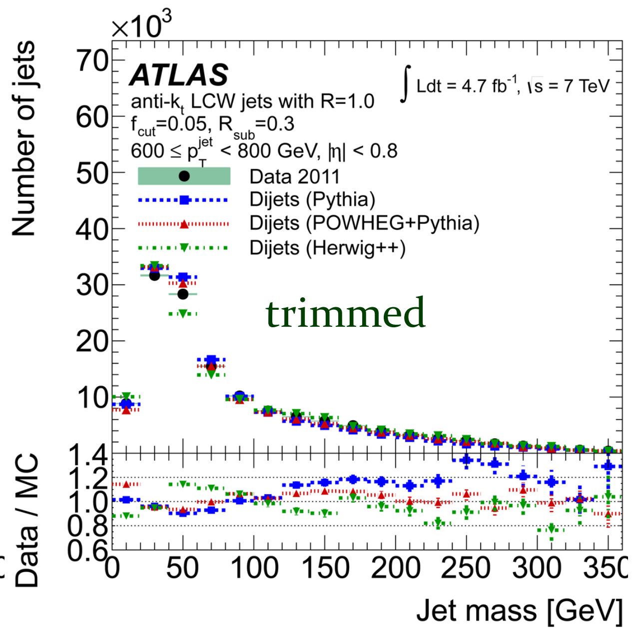
Modeling of Jet Mass

LO versus NLO calculations in MC generation

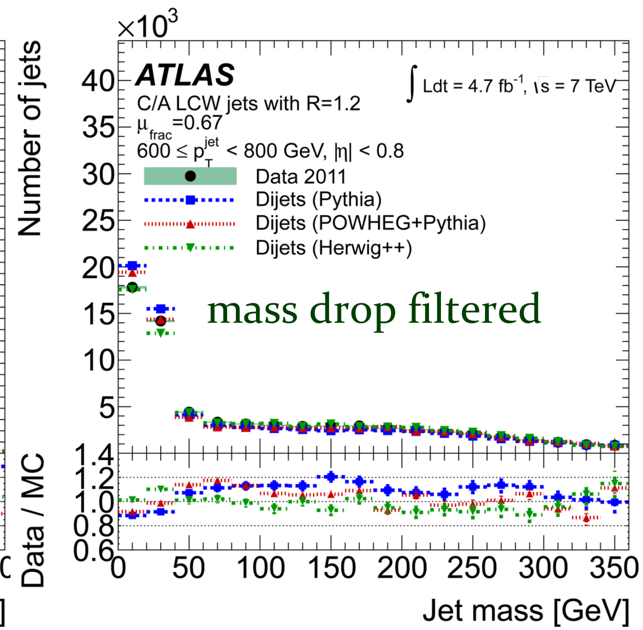
- Preference for NLO kernel (POWHEG)
  - Additional hard emission in di-jet events determines high mass
  - Detailed effect depends on jet definition – more enhanced in Anti-k_T compared to C/A
- Observed for ungroomed jets and groomed jets
  - Modeling quality depends on grooming technique and jet definition!



Anti-k_T jets, $R = 1.0$



Anti-k_T jets, $R = 1.0$



C/A jets, $R = 1.2$

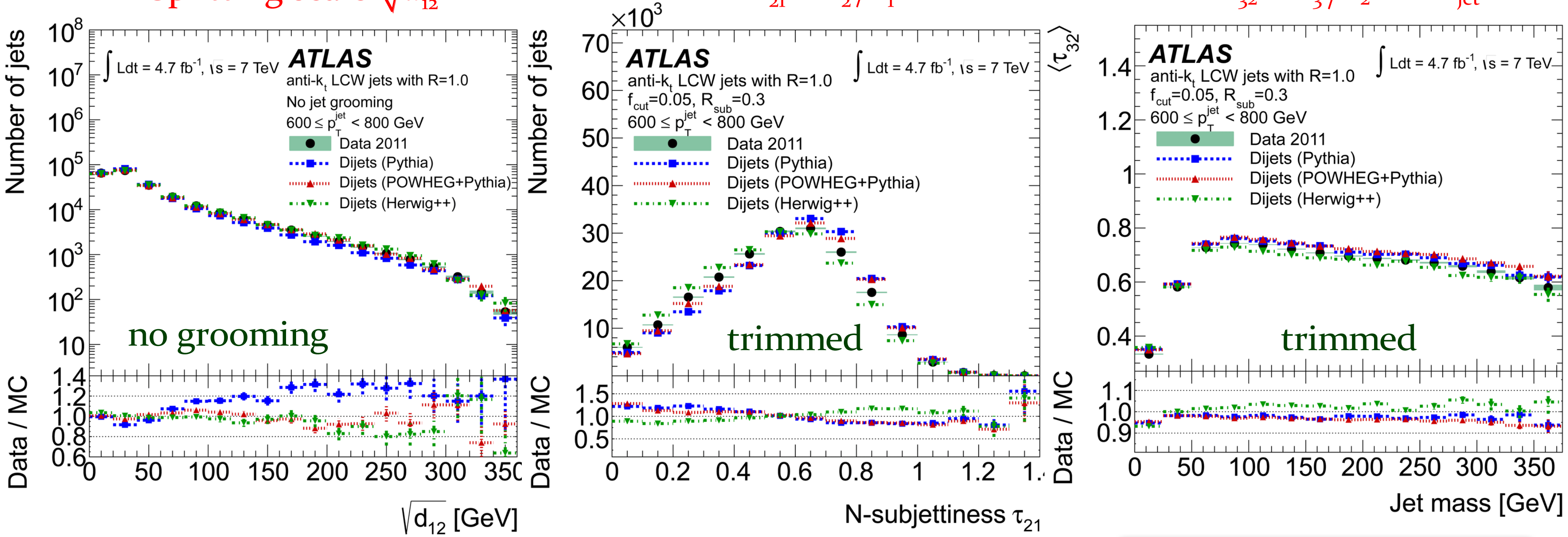
inclusive jet sample: $600 < p_T^{\text{jet}} < 800$ GeV, $|\eta| < 0.8$

Modeling of Splitting Scales & *N*-subjettiness

LO versus NLO calculations in MC generation

- Preference for NLO kernel (POWHEG) in splitting scale modeling
  - Largely correlated with jet mass
  - Observed with and without grooming
- N-subjettiness shows little dependence on LO/NLO modelilng
  - Qualitatively different for Herwig++ featuring cluster fragmentation

Splitting scale $\sqrt{d_{12}}$ $\qquad$ $\tau_{21} = \tau_2/\tau_1$ $\qquad$ $\tau_{32} = \tau_3/\tau_2$ vs $m_{\rm jet}$



Anti-k_T jets, $R = 1.0$

inclusive jet sample: $600 < p_T^{\rm jet} < 800$ GeV, $|\eta| < 0.8$

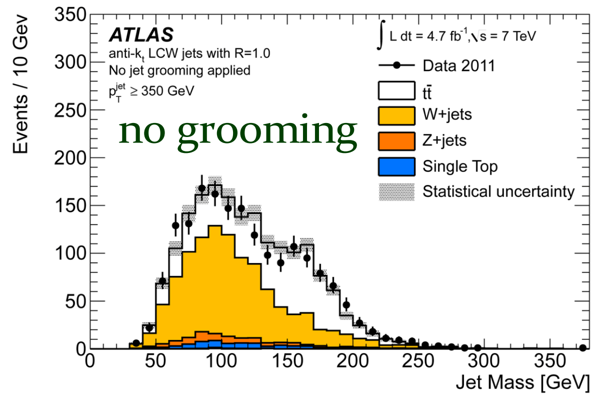
Jet Grooming in Final States with Top Quarks

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

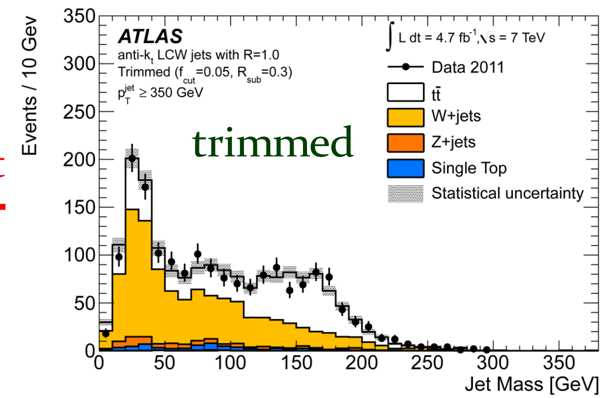
Hadronic top signal extraction

- Main trigger and event selection from semi-leptonic top decay
  - High p_T lepton and large missing transverse momentum
- Typically analysis uses leading jet
  - $p_T > 350$ GeV for jet size $R = 1.0$
- Further refinement for clean sample needed
  - E.g., HepTopTagger

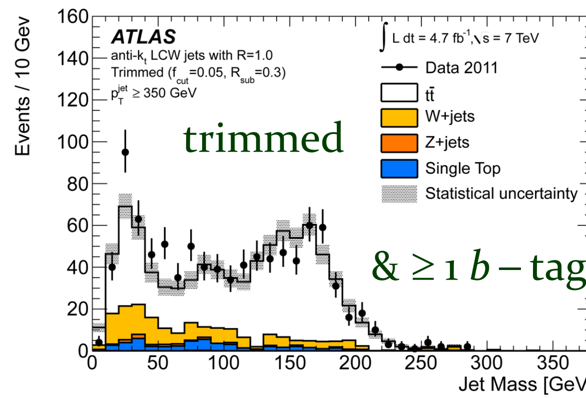


trimming

$f_{cut} = 5\%,\ R_{sub} = 0.3$



$\geq 1\ b-$tagged jet in event



& $\geq 1\ b-$tagged jet

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…