Jet Substructure Reconstruction and Application as a Search Tool in ATLAS

Peter Loch

Department of Physics
University of Arizona
Tucson, Arizona, USA

Seminar

Department of Physics, Lund University

Lund, November 14, 2013

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

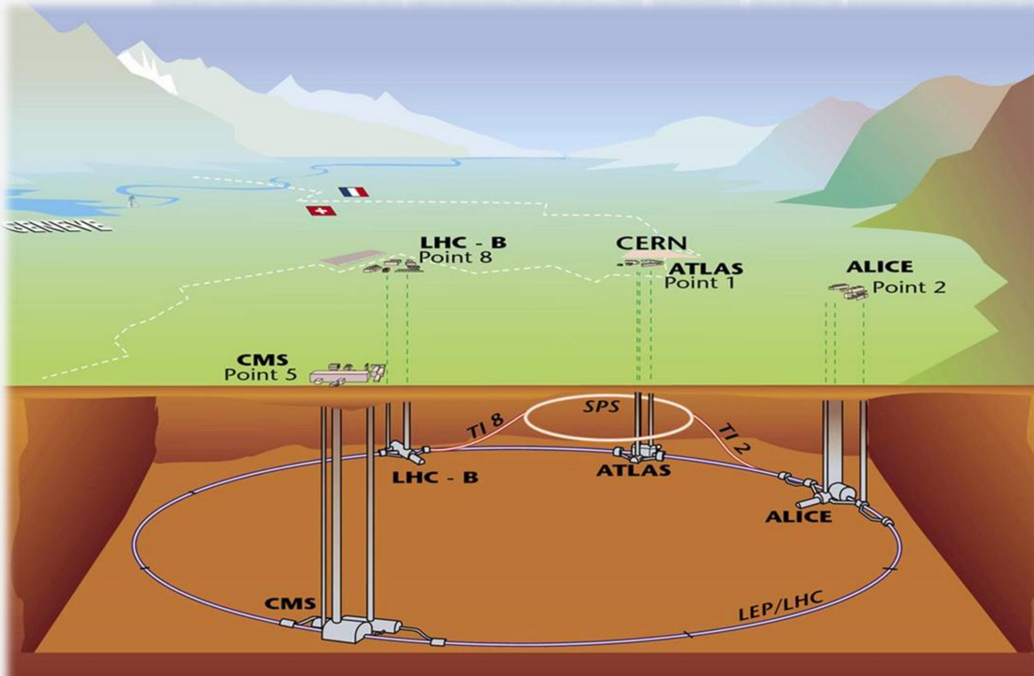
- Jet shape observables
- Jet mass calibration and validation
- Substructure based reconstruction performance in pile-up
- Evaluation of jet substructure modeling

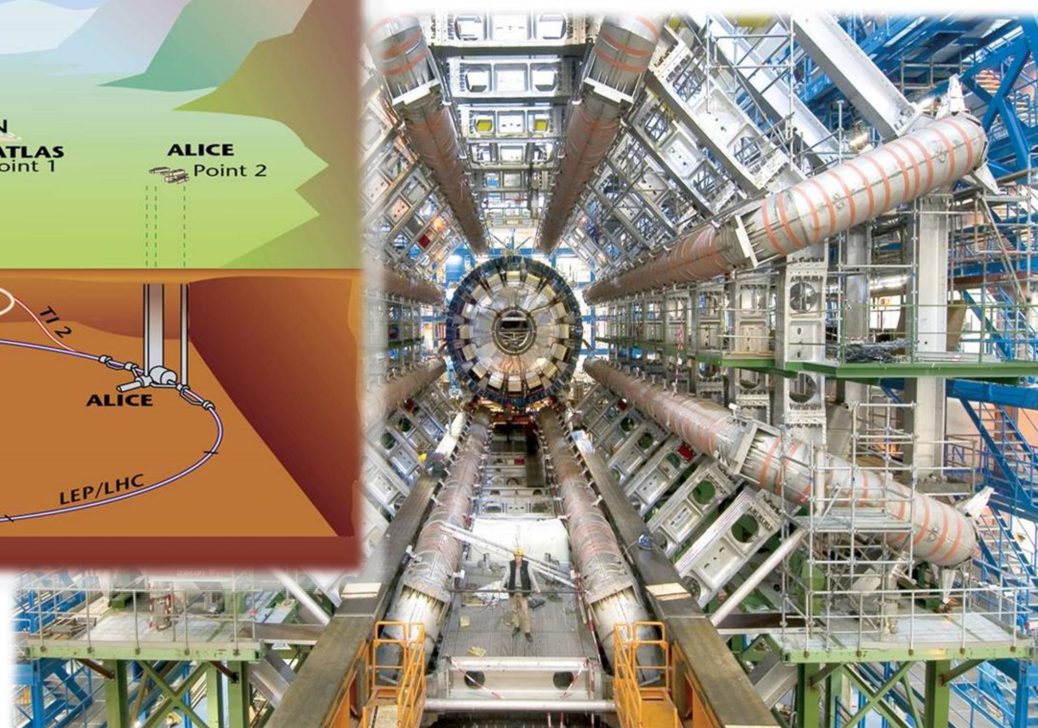
Basics for application in searches for new physics

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

Conclusions and outlook

Introduction





Motivation for Jet Substructure Analysis

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

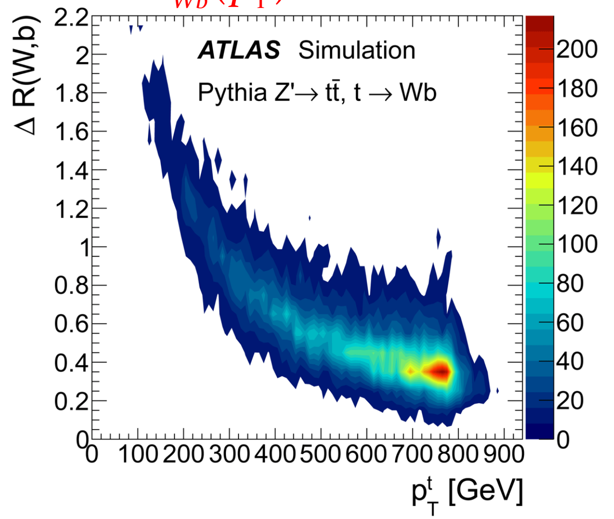
High luminosity

- 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

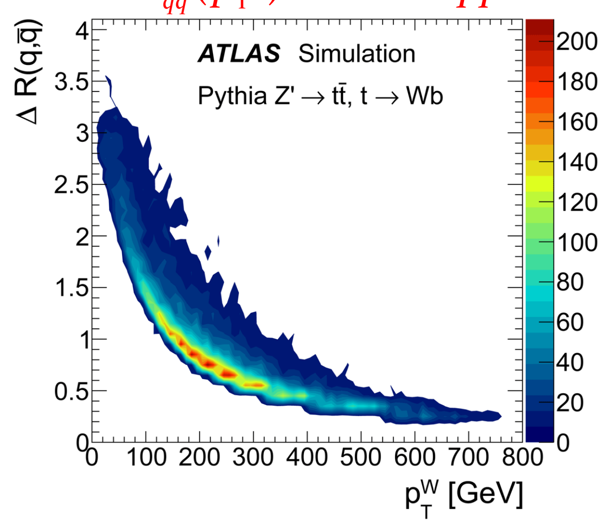
Jet substructure analysis

- 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

$\Delta R_{Wb}(p_{\mathrm{T}}^{t})$ in $t \rightarrow Wb$



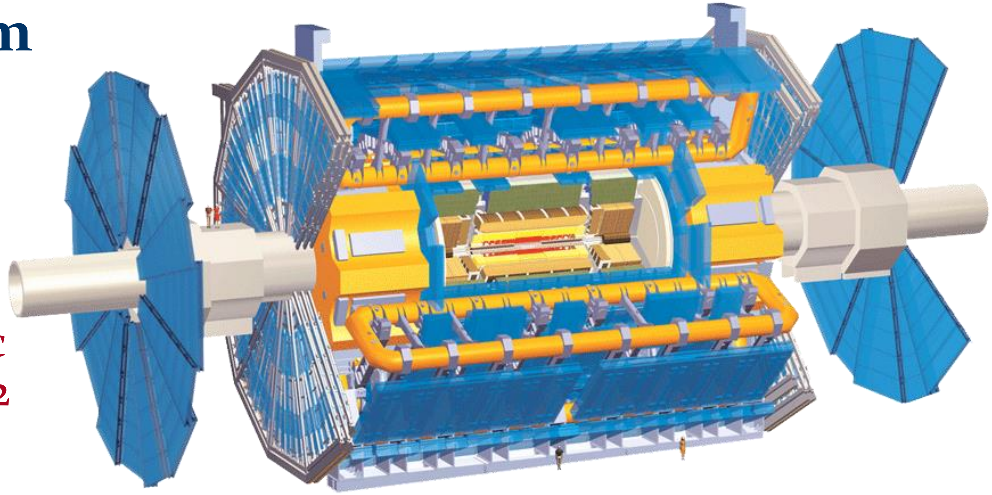
$\Delta R_{q\bar{q}}(p_{\mathrm{T}}^{W})$ in $W \rightarrow q\bar{q}$

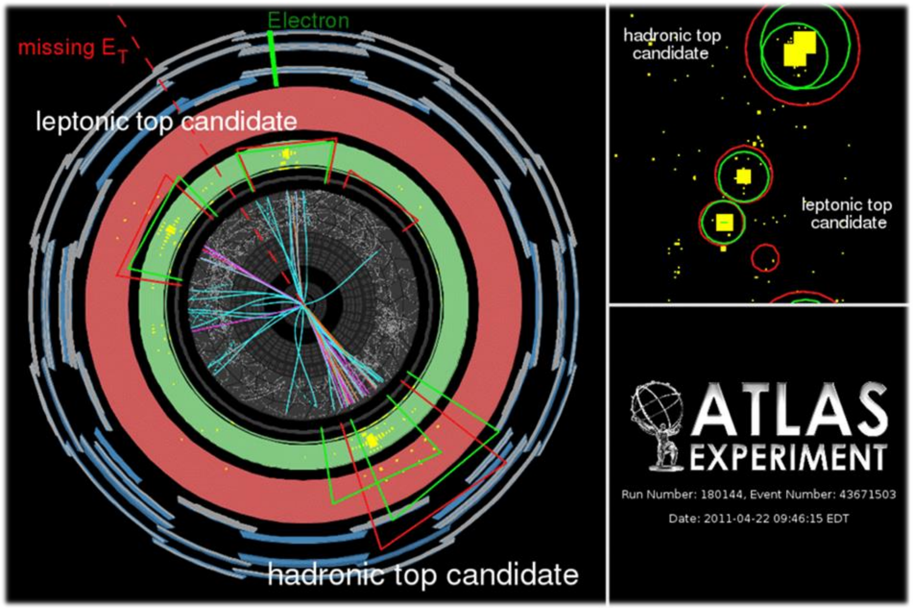


Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA®
College of Science

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





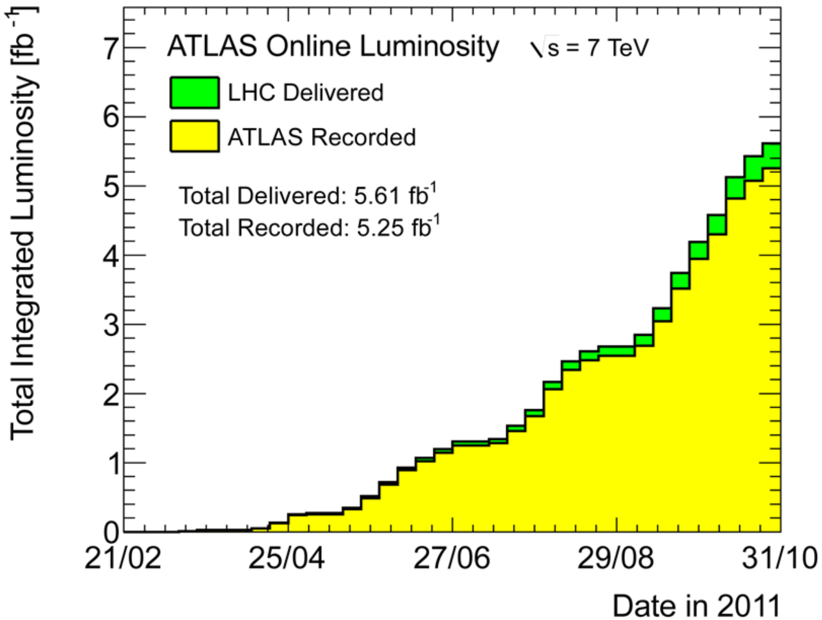
Jet Signals and Conditions at LHC in 2011

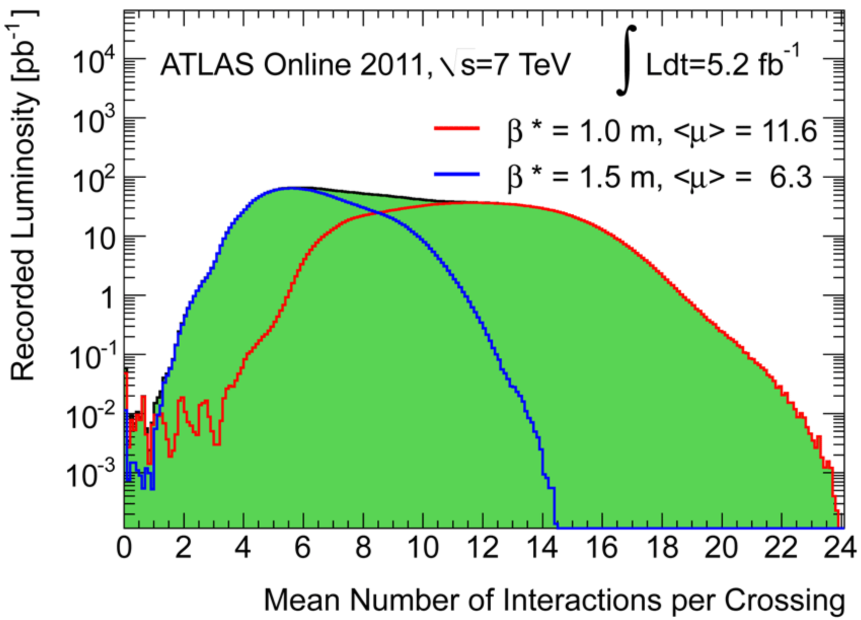
Basic jet signals from ATLAS calorimetry

- 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

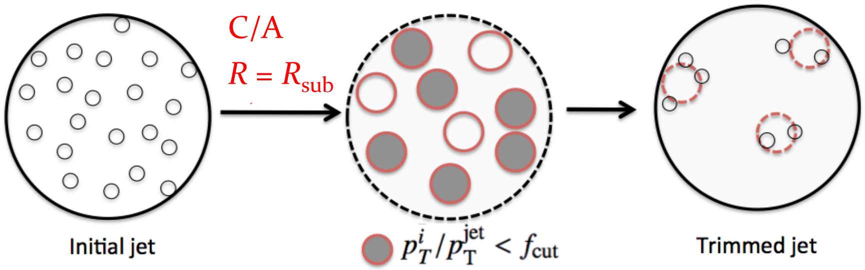
- Data taken 2011 at $\sqrt{s} = 7$ TeV
  - Significant pile-up from additional proton-proton interactions in recorded event (bunch crossing)
  - Significantly affects calorimeter signals – typically requires corrections
- About 4.7 fb^{-1} used for the presented studies





Trimming

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



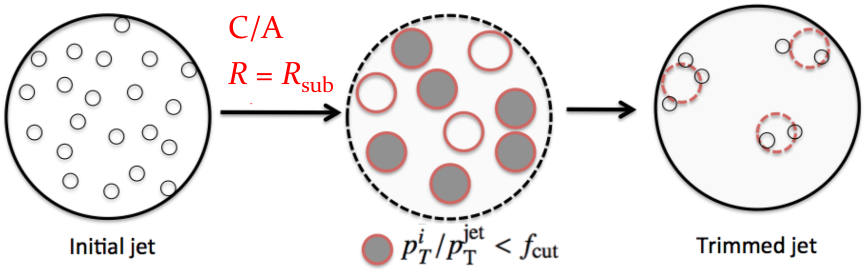
$$R_{sub} = \{0.2, 0.3\}$$

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

$$p_T^{sub} > f_{cut} \times p_T^{jet}$$

Trimming

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

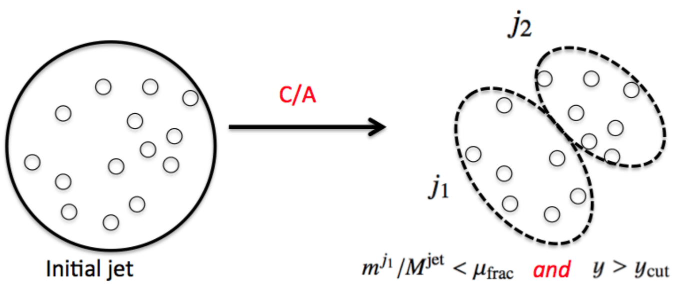


$$R_{sub} = \{0.2, 0.3\}$$

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

Mass drop…

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



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

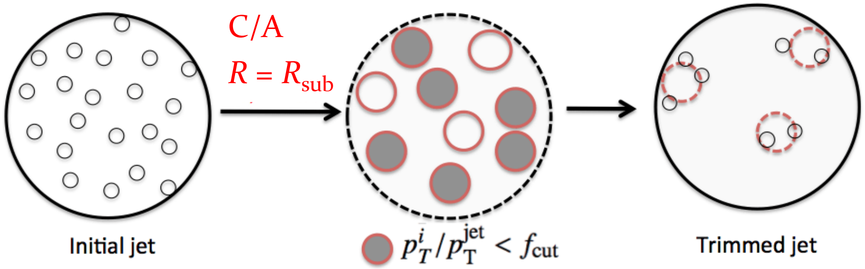
$$y = \frac{\min[p_{T,j1}^2, p_{T,j2}^2]}{m_{jet}^2} \times \Delta R_{j1,j2} > y_{cut}$$

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

Jet Grooming Techniques

Trimming

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



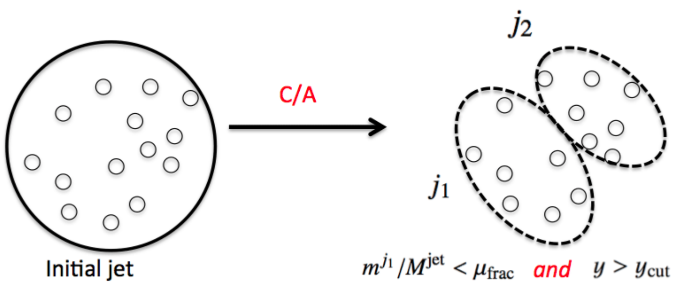
$$R_{\rm sub} = \{0.2, 0.3\}$$

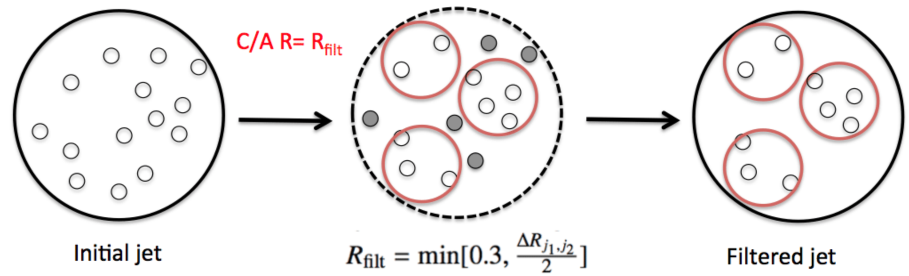
$$f_{\rm cut} = \{0.01, 0.03, 0.05\}$$

Mass drop…

…filtering

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





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

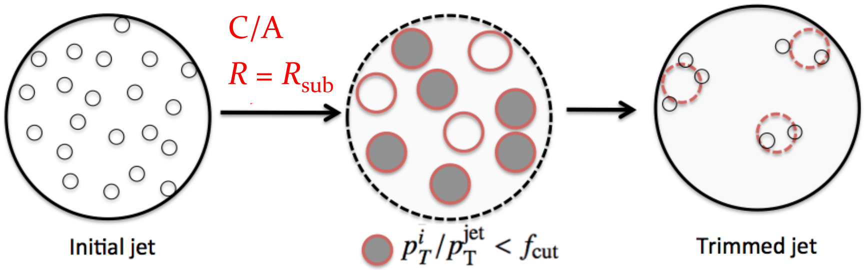
$$R_{\rm filt} = \min[0.3, \Delta R_{\rm j1-j2}/2]$$

Jet Grooming Techniques

Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA®
College of Science

Trimming

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



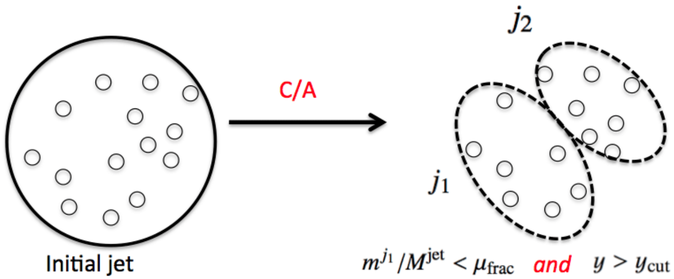
$$R_{sub} = \{0.2, 0.3\}$$

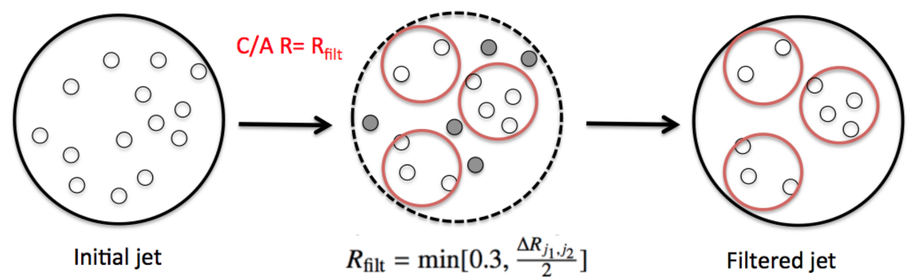
$$f_{cut} = \{0.01, 0.03, 0.05\}$$

Mass drop…

…filtering

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

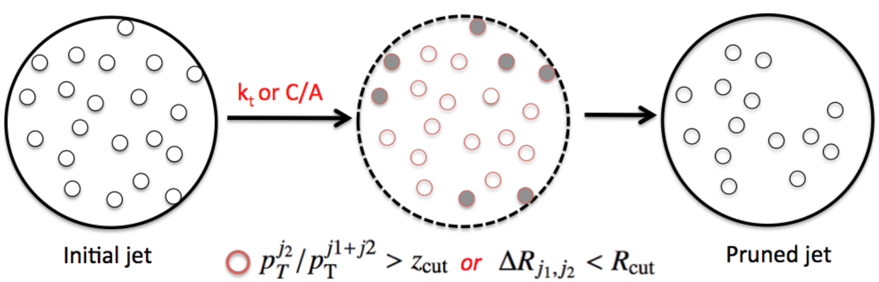




$$\mu_{frac} = \{0.20, 0.33, 0.67\}, \; y_{cut} = 0.09$$

Pruning

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

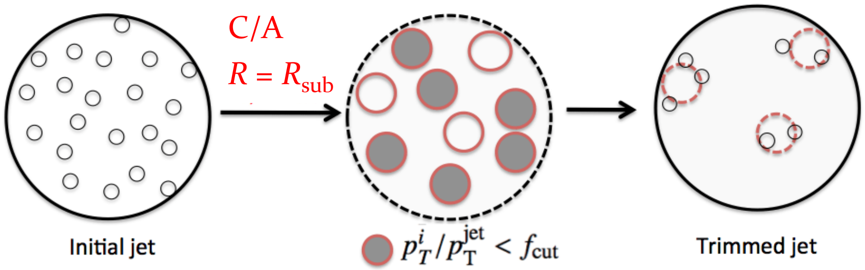


$$\Delta R_{j1-j2} < R_{cut} \text{ or } \frac{p_T^{j2}}{p_T^{j1+j2}} > z_{cut}$$

Jet Grooming Techniques

Trimming

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



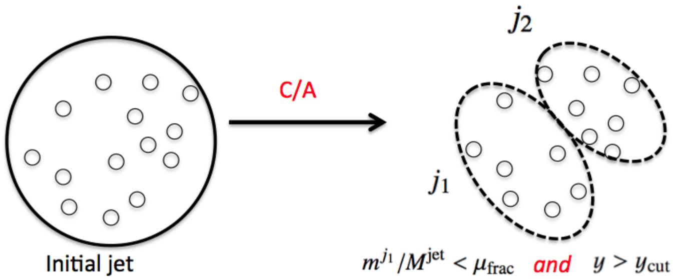
$$R_{sub} = \{0.2, 0.3\}$$

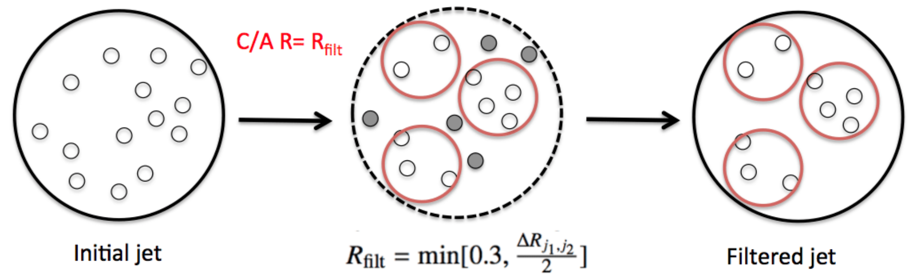
$$f_{cut} = \{0.01, 0.03, 0.05\}$$

Mass drop…

…filtering

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

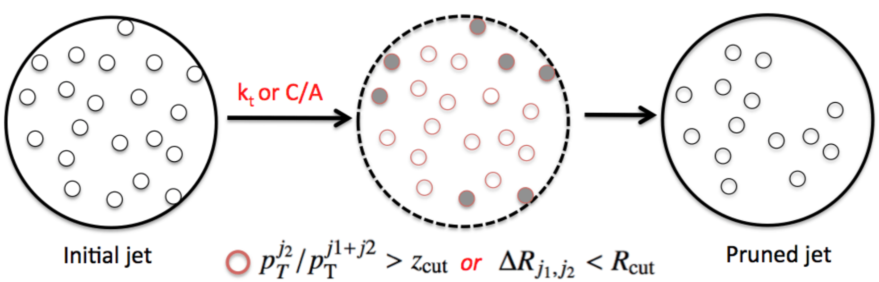




$$\mu_{frac} = \{0.20, 0.33, 0.67\},\ y_{cut} = 0.09$$

Pruning

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



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

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

Pruning Extension: Q-jets

Motivation and implementation

- Test several possible recombination sequences for a given jet
  - Parton showering/fragmentation cannot be exactly undone in experiment – with some respect any jet recombination attempt reflects an arbitrary choice
  - Jet is unchanged if all constituents are always included – need to introduce some randomness in jet grooming to change e.g. the jet mass
- Based on pruning
  - Select random pairs instead of minimum distance pairs – randomness controlled by rigidity parameter α in PDF

PDF with rigidity α:

$$w_{ij}^{(\alpha)} = \exp\left\{-\alpha \frac{d_{ij} - d_{\min}}{d_{\min}}\right\}$$

Probability for recombination:

$$\Omega_{ij} = \frac{w_{ij}^{(\alpha)}}{\sum w_{ij}^{(\alpha)}}$$

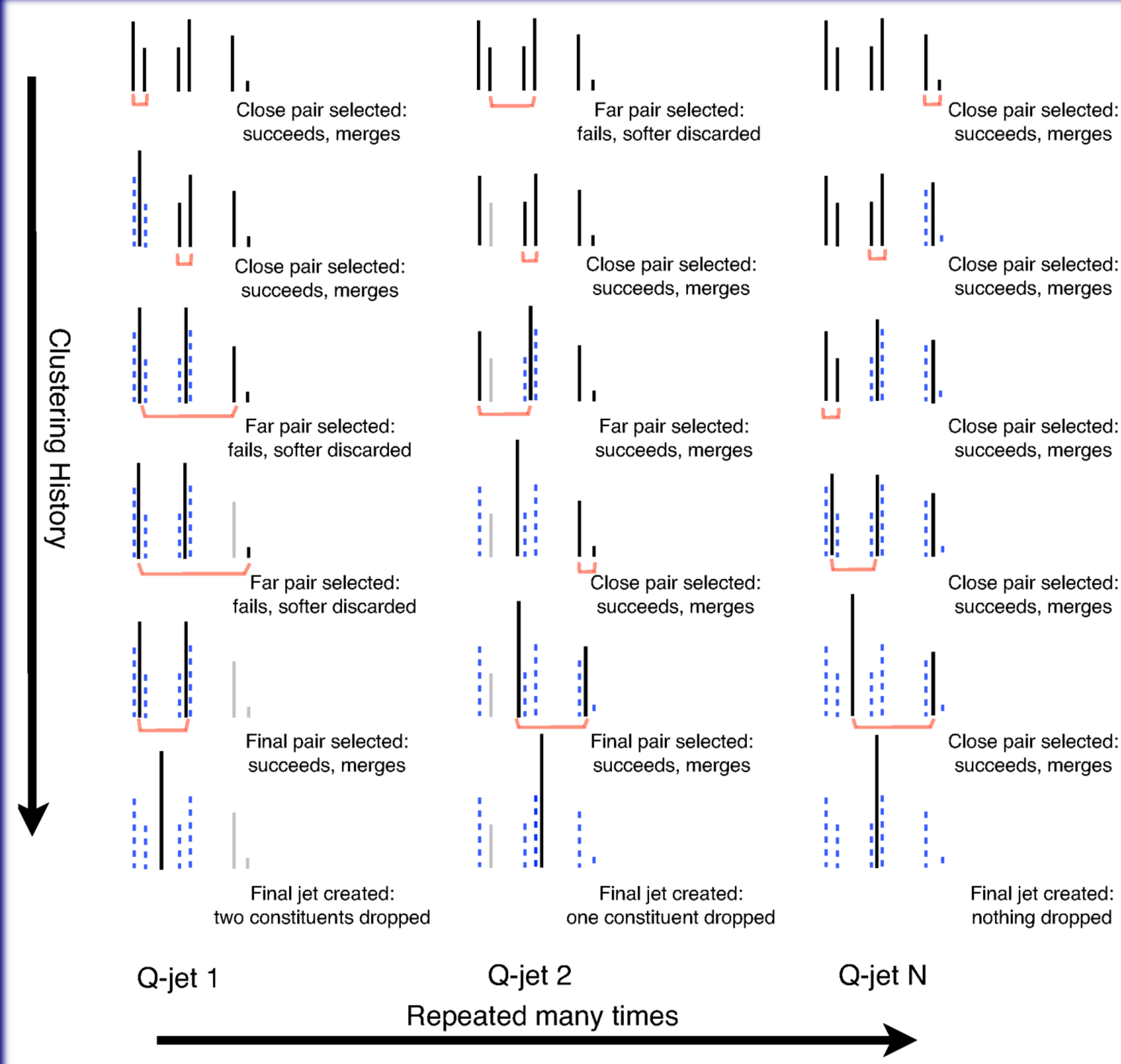
Volatility:

$$\nu = \frac{\Gamma}{\langle m_{\text{jet}}^2 \rangle} = \frac{\sqrt{\langle m_{\text{jet}} \rangle^2 - \langle m_{\text{jet}}^2 \rangle}}{\langle m_{\text{jet}}^2 \rangle}$$

S.D.Ellis *et al.*, *Phys.Rev.Lett.* **108** (2012) 182003

Scoring variable

- Volatility
  - Measures relative width of jet mass distribution arising from chosing N different pruned recombinations for one given jet
- Analysis
  - Distribution of volatilities for a given jet sample sensitive to jet origin – massive particle decay or light quark/gluon jet

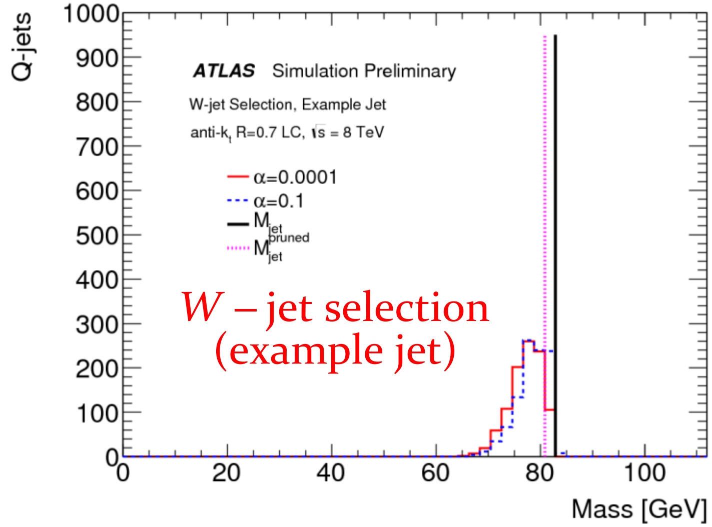


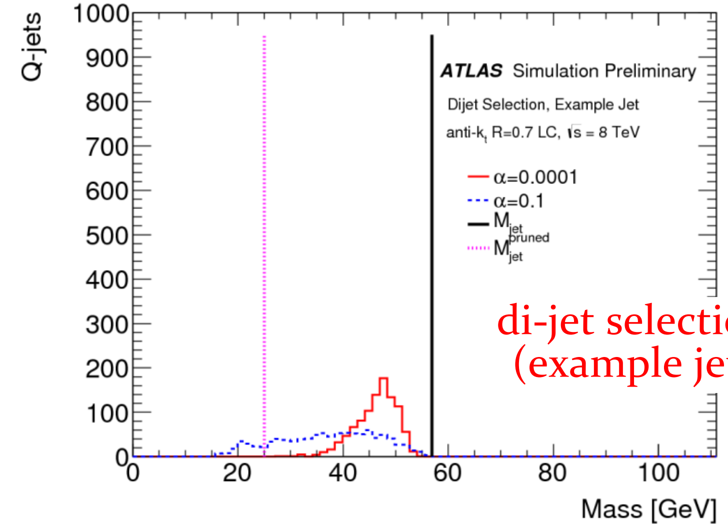
ATLAS Coll., ATLAS-CONF-2013-87 (2013)

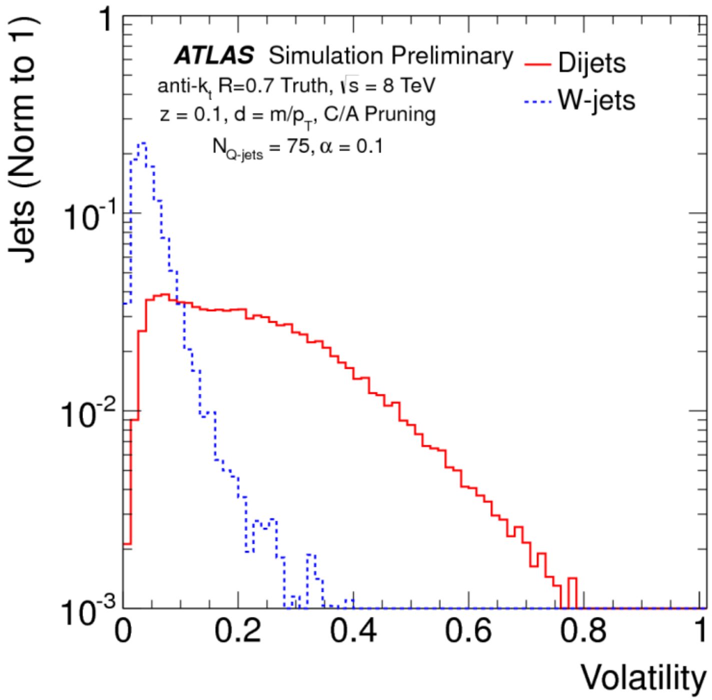
Peter Loch
UAPhysics
The University of Arizona
College of Science

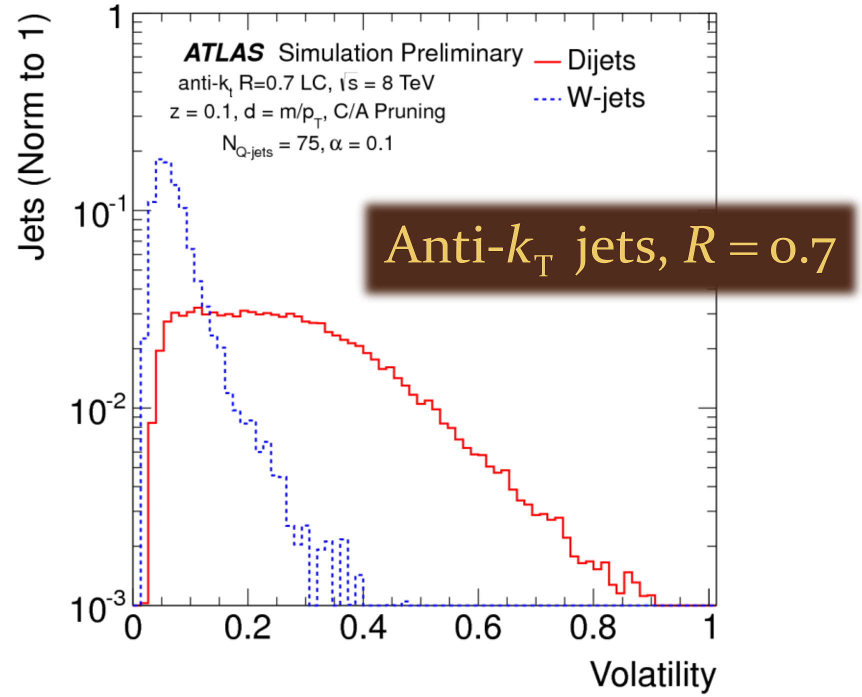
Q-jet masses and volatility

ATLAS Coll., ATLAS-CONF-2013-87 (2013)

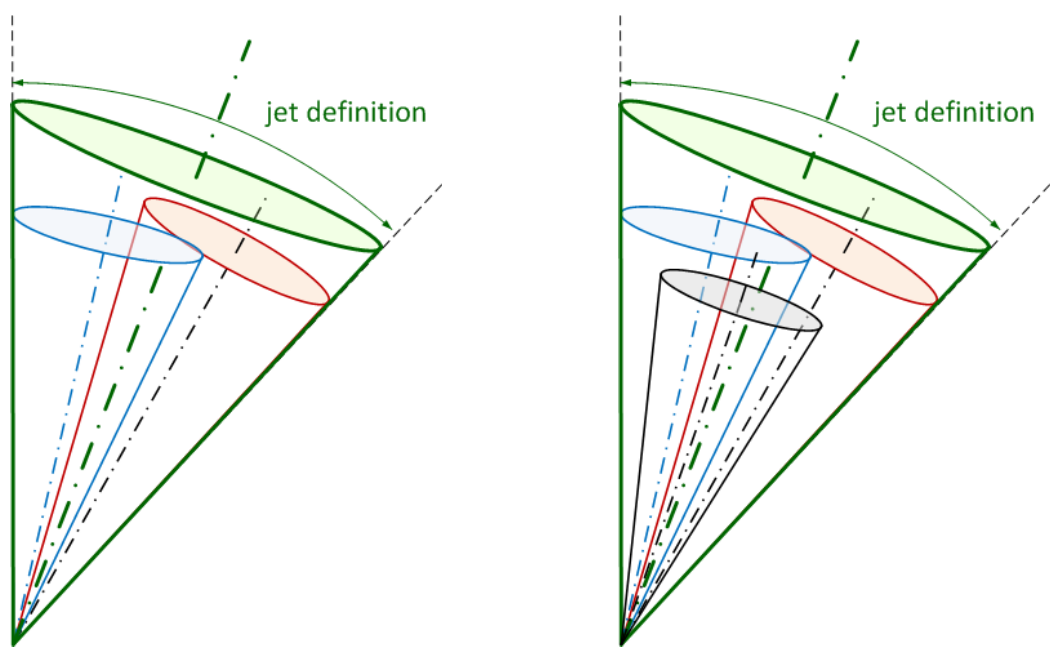








Measuring Jet Shapes and Substructure with ATLAS



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

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

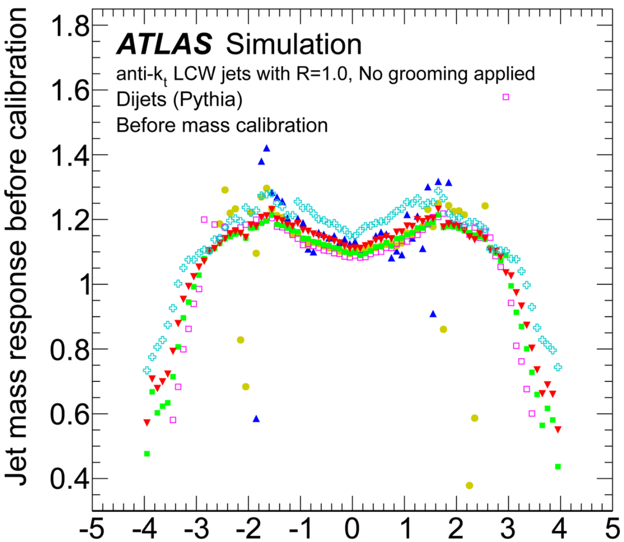
- k_T distance of last (d_{12}) or second-to-last (d_{23}) recombination
  - Typically only hardest and next-to-hardest recombination considered in ATLAS
- Has expectation values for pronged decays
  - $d_{12} \approx (M/2)^2$ for particle with mass M undergoing 2-body decay

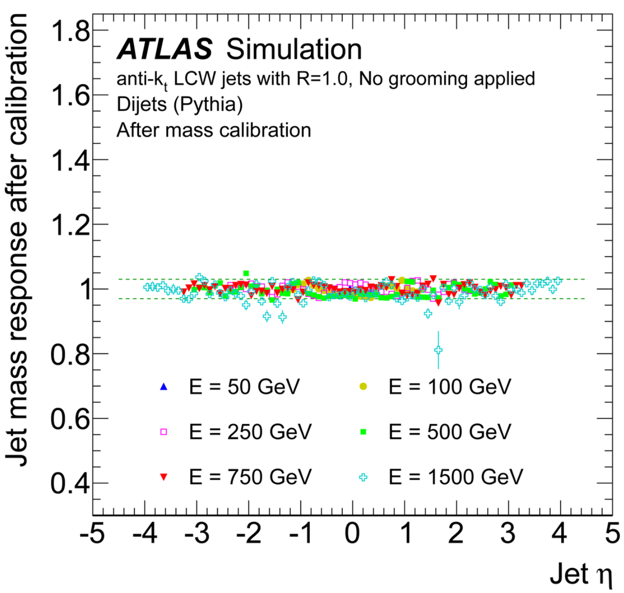
N-subjettiness

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

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

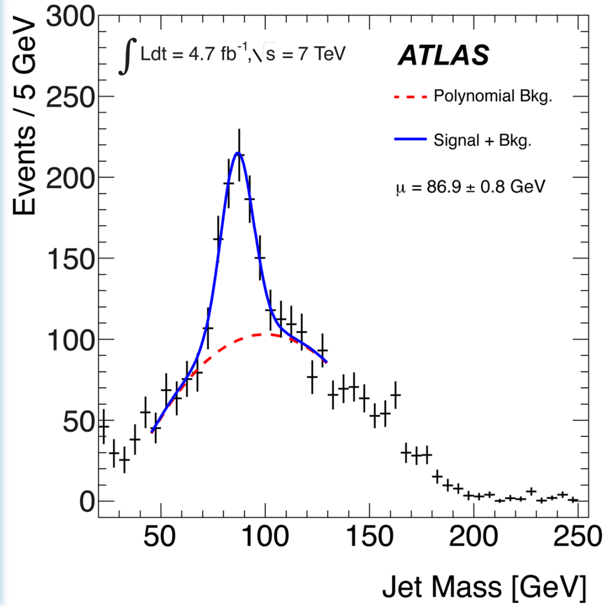
- Measures how well jets can be described assuming N sub-jets
  - Degree of alignment of jet constituents with N sub-jet axes
- Sensitive to two- or three-prong decay versus gluon or quark jet
  - Highest signal efficiencies from N-subjettiness ratios τ_{N+1}/τ_N

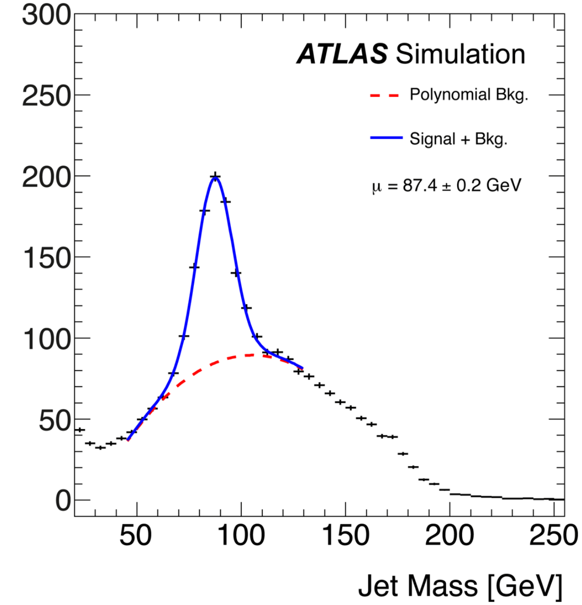




Jet mass calibration in ATLAS

- 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





Jet Mass Measurement in Pile-up

Peter Loch
UAPhysics
The University of Arizona
College of Science

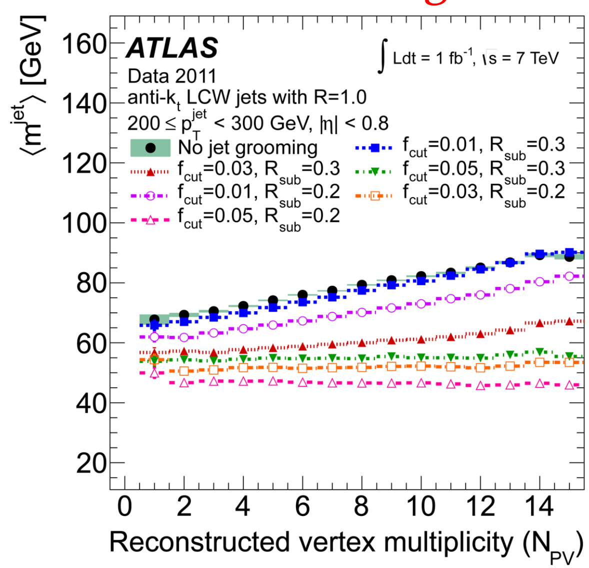
Average effect of jet grooming on the pile-up dependence of the reconstructed single jet mass

Anti-k_T jets, $R = 1.0$

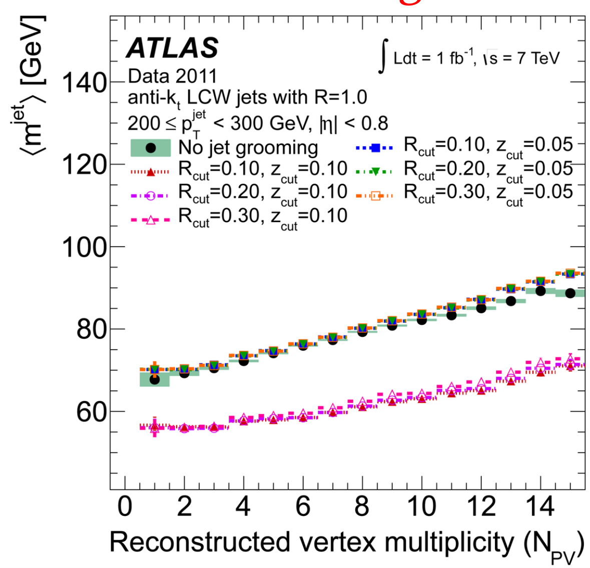
inclusive jet sample:

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

Trimming



Pruning



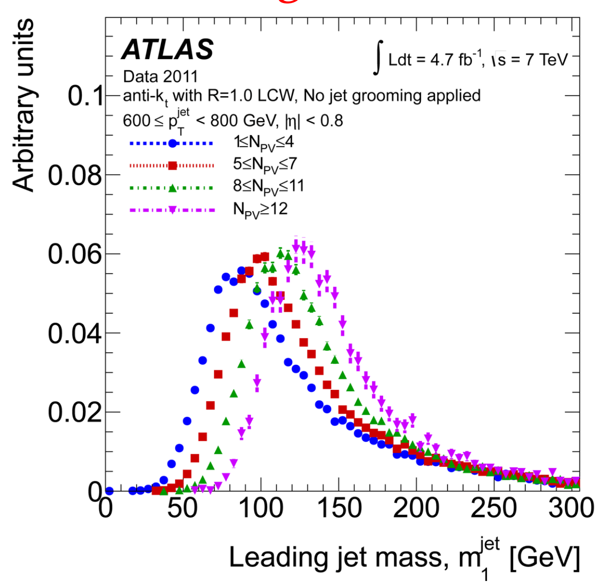
Effect of jet trimming on the spectrum of the reconstructed jet mass

Anti-k_T jets, $R = 1.0$

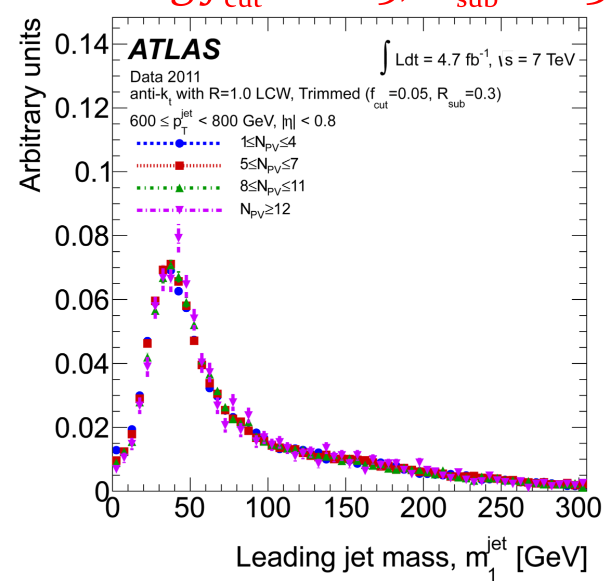
inclusive jet sample:

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

Ungroomed



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



Peter Loch
UAPhysics
The University of Arizona
College of Science

Splitting Scales & N-subjettiness with Pile-up

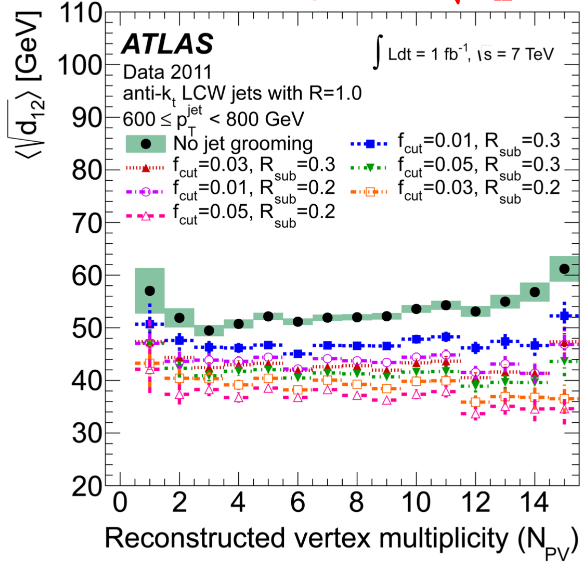
Average effect of jet trimming on the pile-up dependence of the k_T splitting scales

Anti-k_T jets, $R = 1.0$

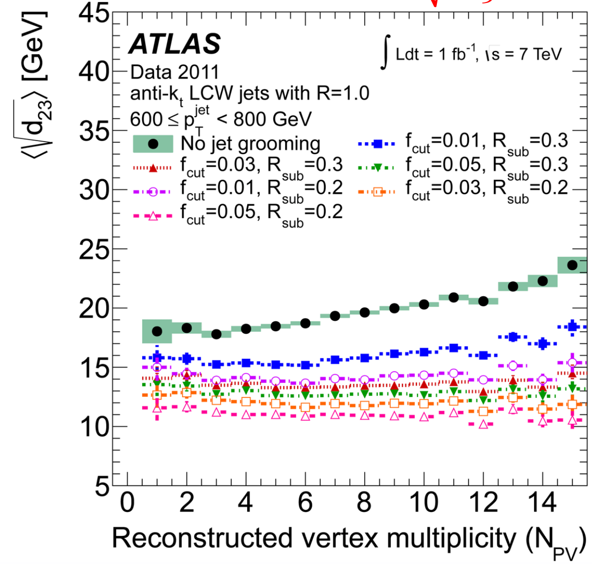
inclusive jet sample:

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

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



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



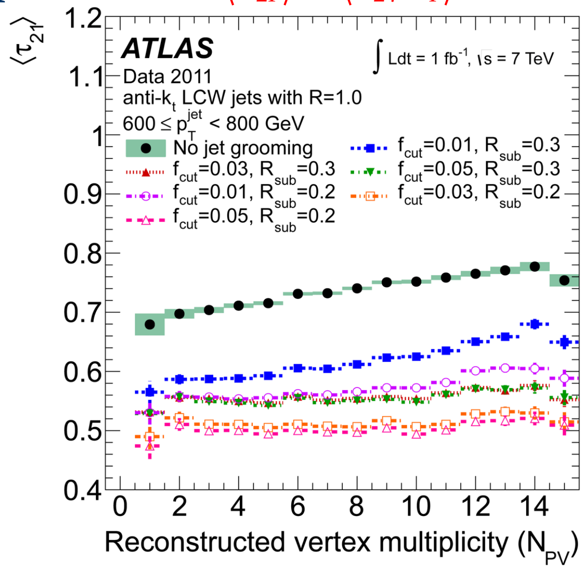
Effect of jet trimming on N-subjettiness ratios

Anti-k_T jets, $R = 1.0$

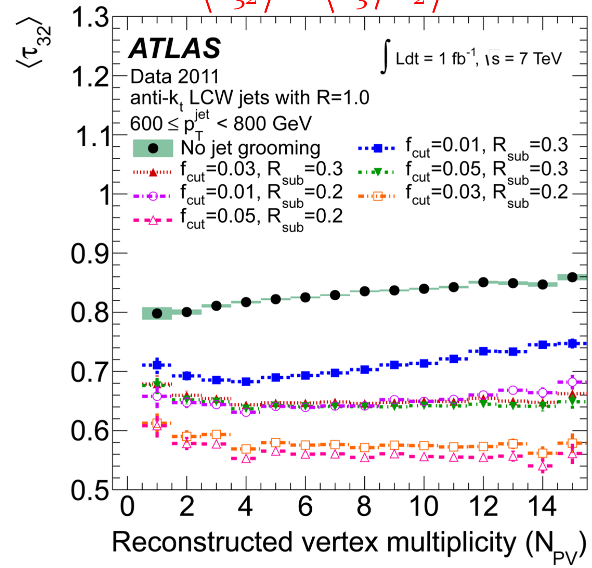
inclusive jet sample:

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

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



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

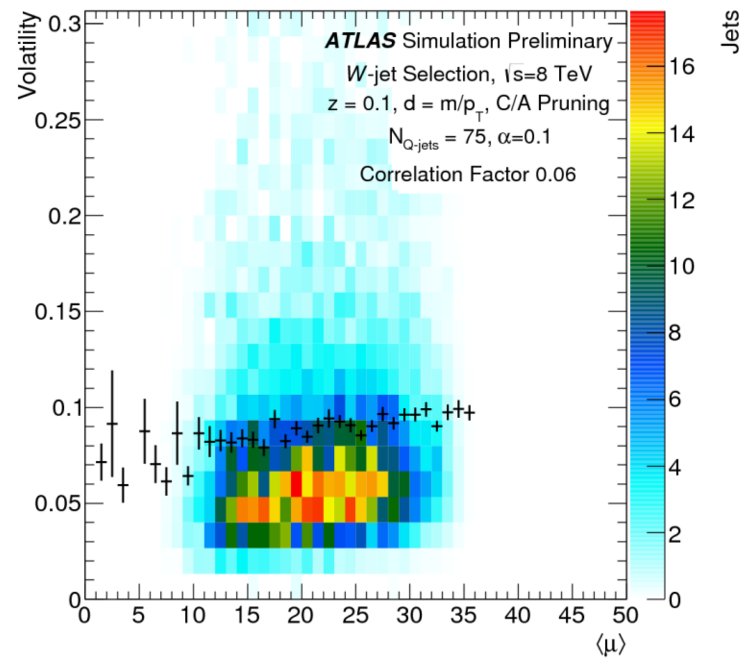


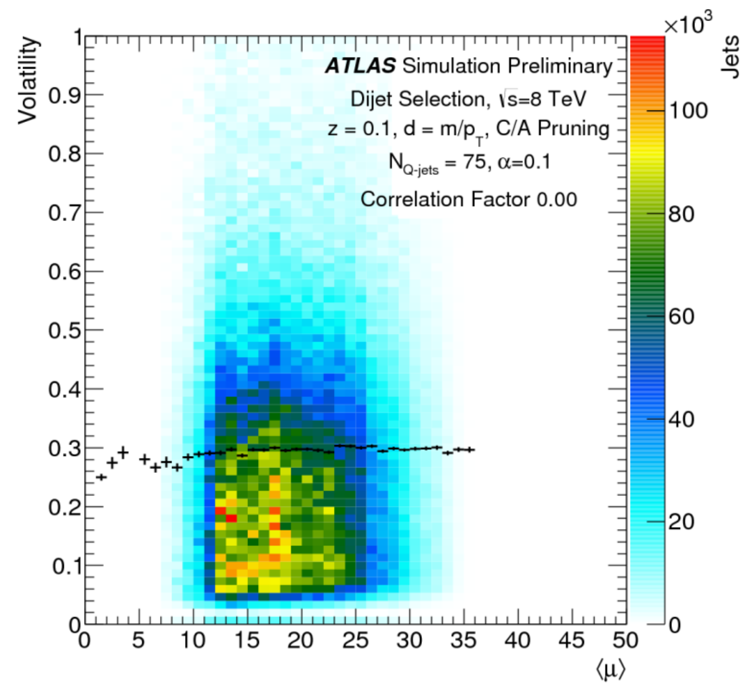
Q-jets with Pile-up

Volatility shows little dependence on pile-up

- Not too surprising as Q-jets are based on pruning – originally designed to suppress soft contributions to jets
  - Includes the diffuse scattering of energy into the jet from pile-up
- Very small effect on jets from *W* decays
  - Small volatility indicates small contribution of recombination to jet mass measurement – expected for 2-prong decay
  - Pile-up introduces more significant fluctuations on this scale than in di-jets where volatility is large to begin with…

Anti-k_T jets, $R = 0.7$



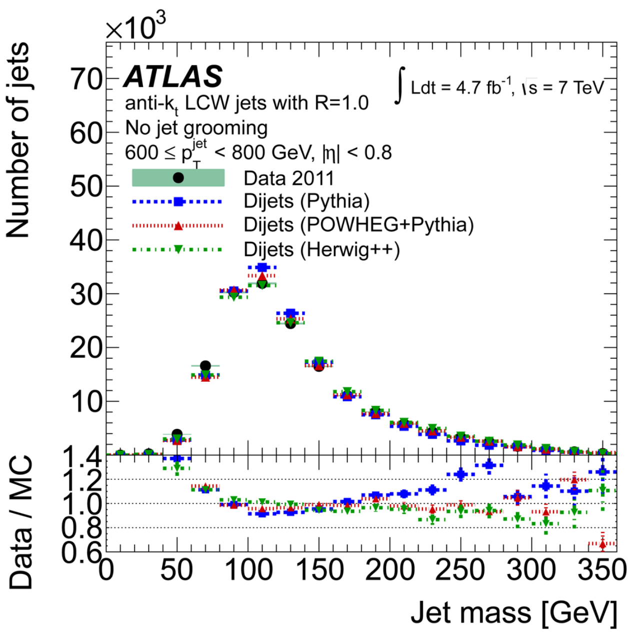


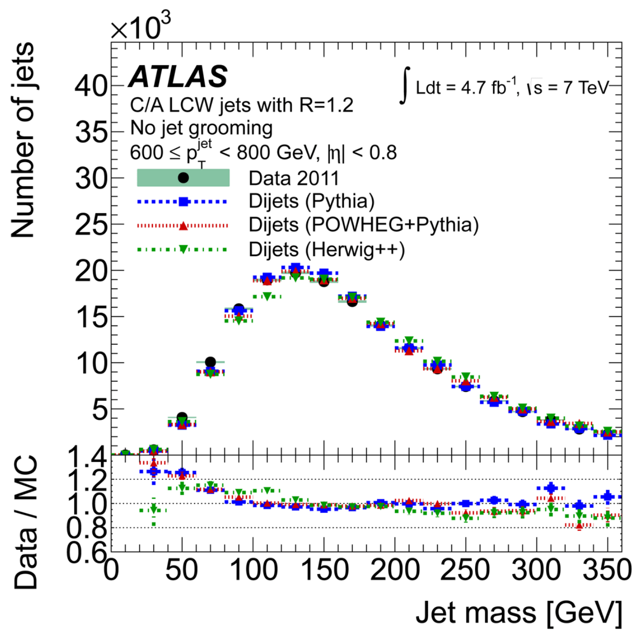
Modeling of Jet Mass

Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA®
College of Science

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





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

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

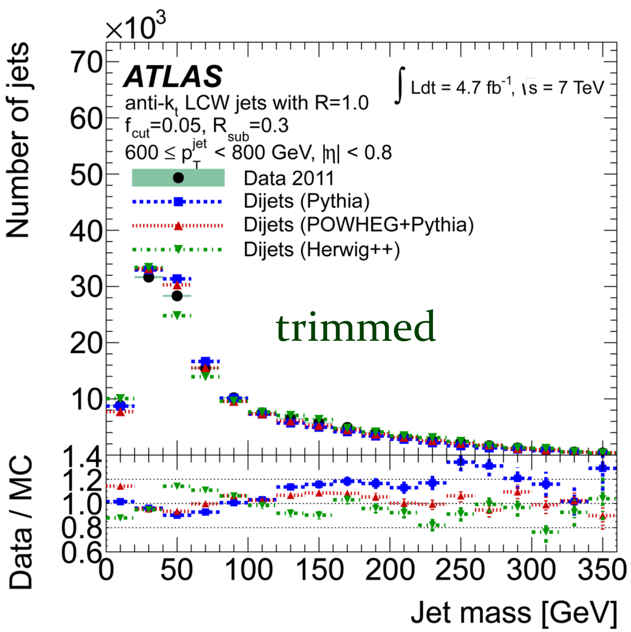
Anti-k_T jets, $R = 1.0$

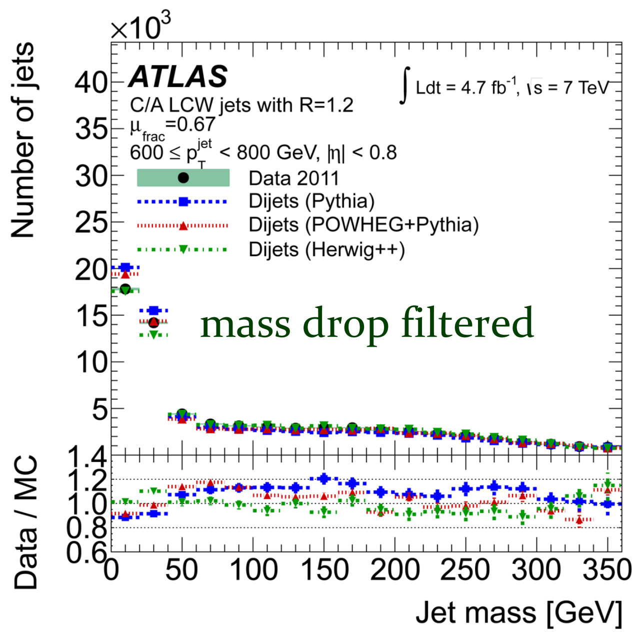
C/A jets, $R = 1.2$

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!





Evaluation of single jet mass modeling quality for an inclusive sample of groomed jets with $600 < p_T < 800$ GeV, $|\eta|<0.8$

Anti-k_T jets, $R = 1.0$

C/A jets, $R = 1.2$

Modeling of Splitting Scales & *N*-subjettiness

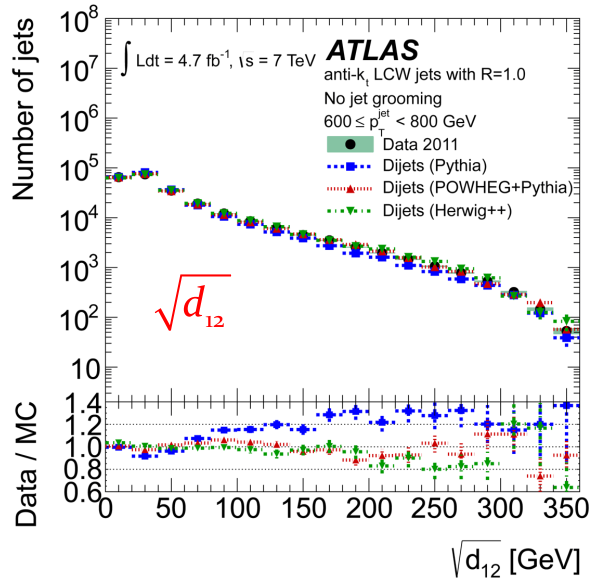
Splitting scale comparisons data/MC – indicate preference for NLO and Herwig++

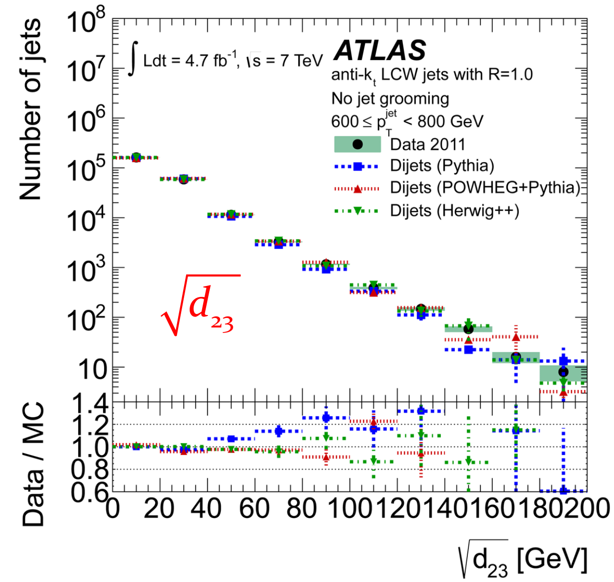
Anti-k_T jets, $R = 1.0$

No grooming - very similar for groomed jets!

inclusive jet sample:

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





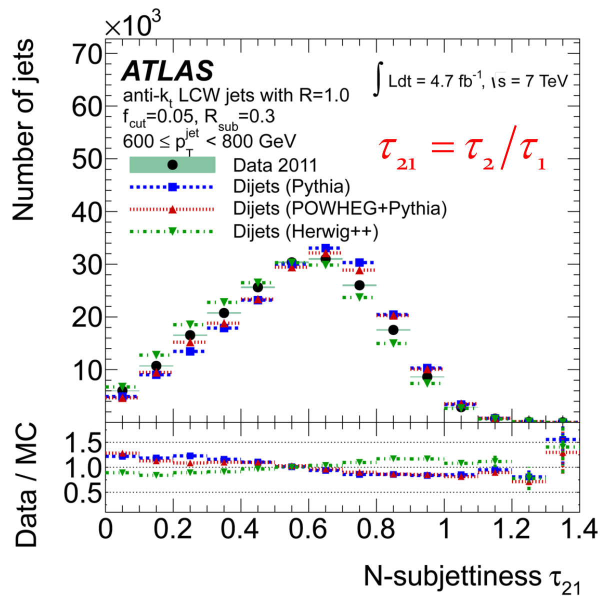
N-subjettiness not too sensitive to LO/NLO kernel choices

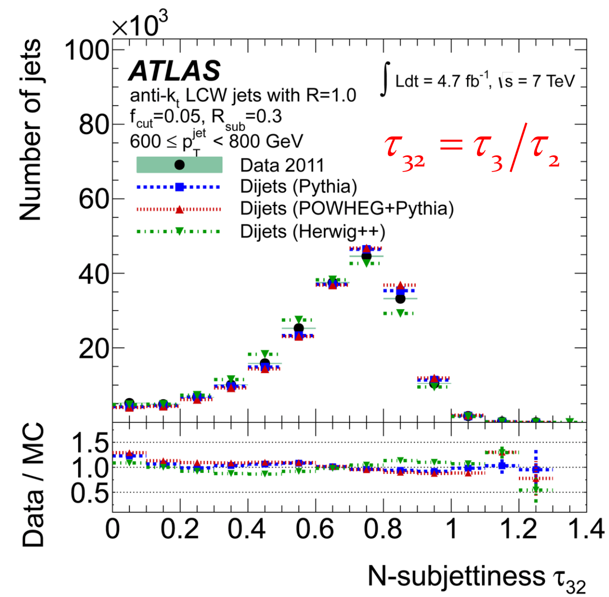
Anti-k_T jets, $R = 1.0$

Trimmed - qualitatively similar for ungroomed jets!

inclusive jet sample:

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



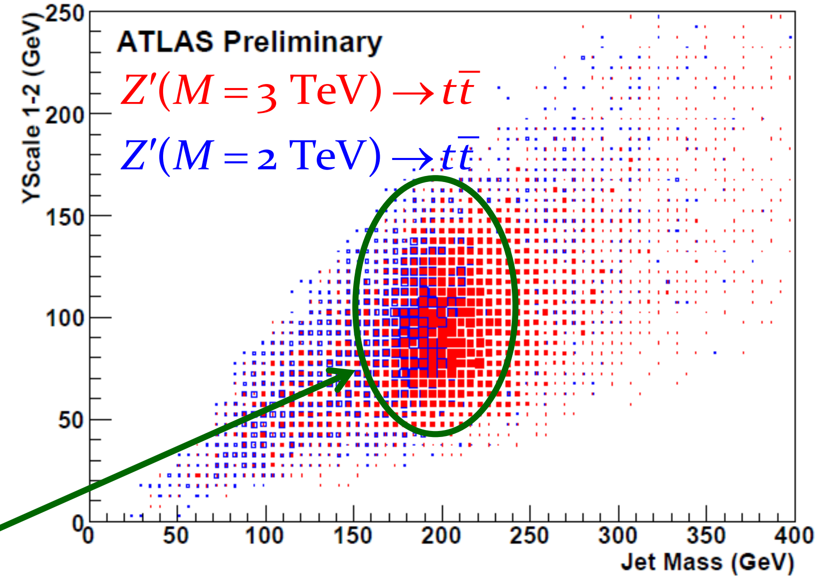


Correlations in Substructure

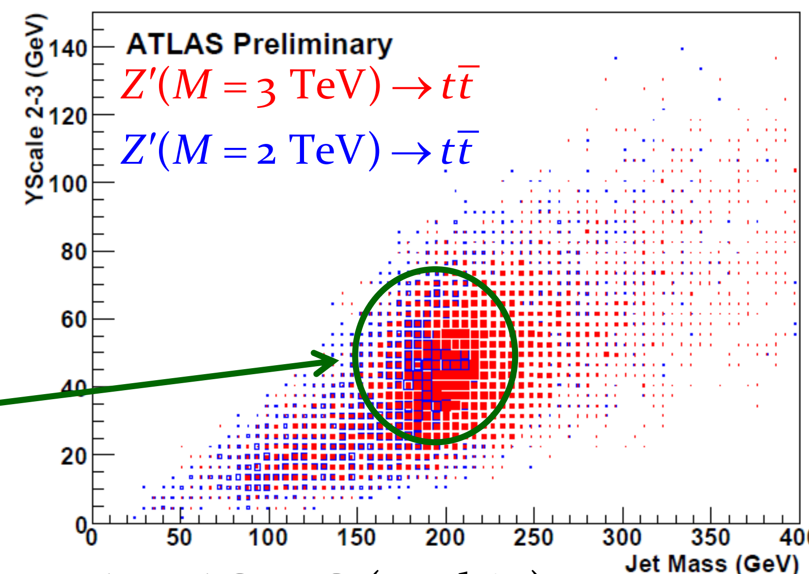
G.Booijmans, *ATL_PHYS-CONF-2008-008*(2008)

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



$t\rightarrow Wb$ splitting scale



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

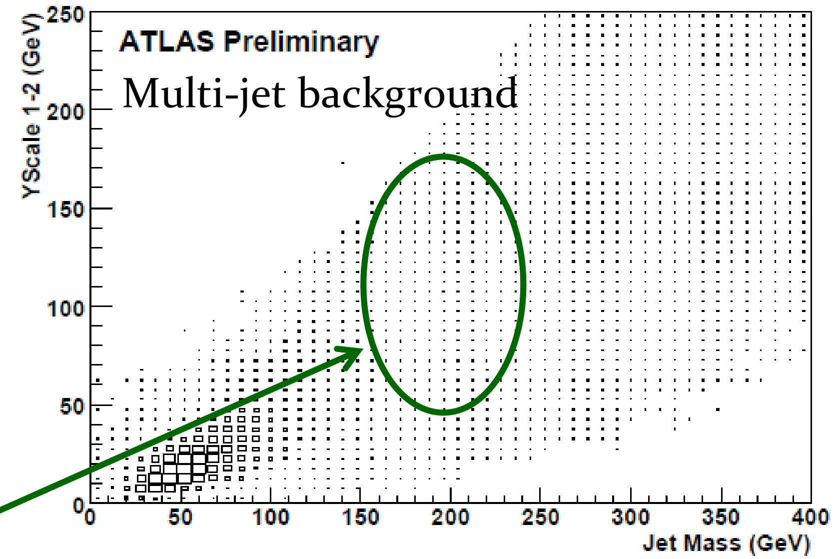
ATLAS MC (Pythia)

Peter Loch
UAPhysics
The University of Arizona
College of Science

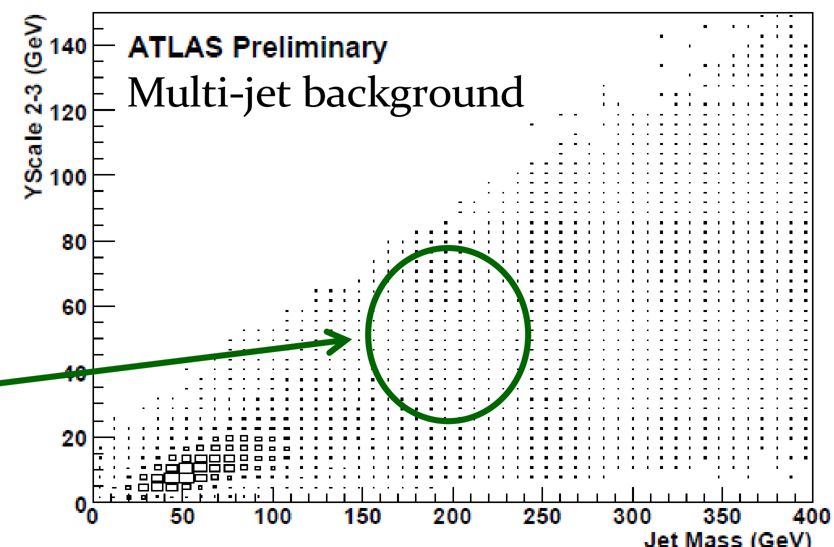
G.Booijmans, *ATL_PHYS-CONF-2008-008*(2008)

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



$t \to Wb$ splitting scale



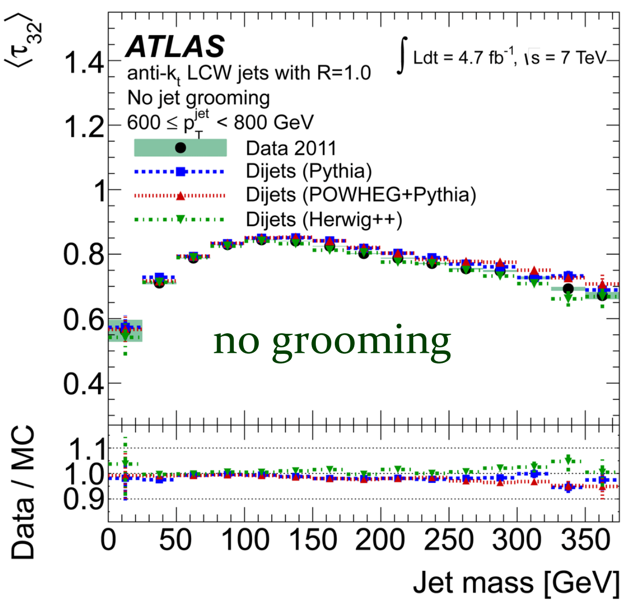
$W \to q\bar{q}$ splitting scale

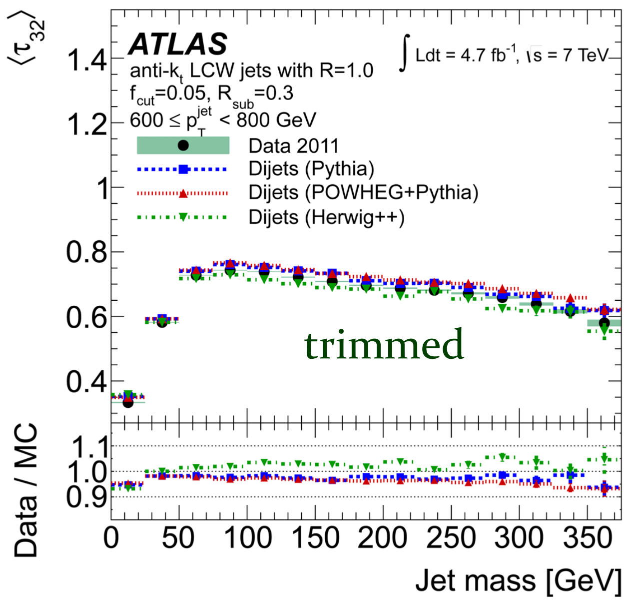
ATLAS MC (Pythia)

Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA®
College of Science

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

Peter Loch
UAPhysics
The University of Arizona
College of Science

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

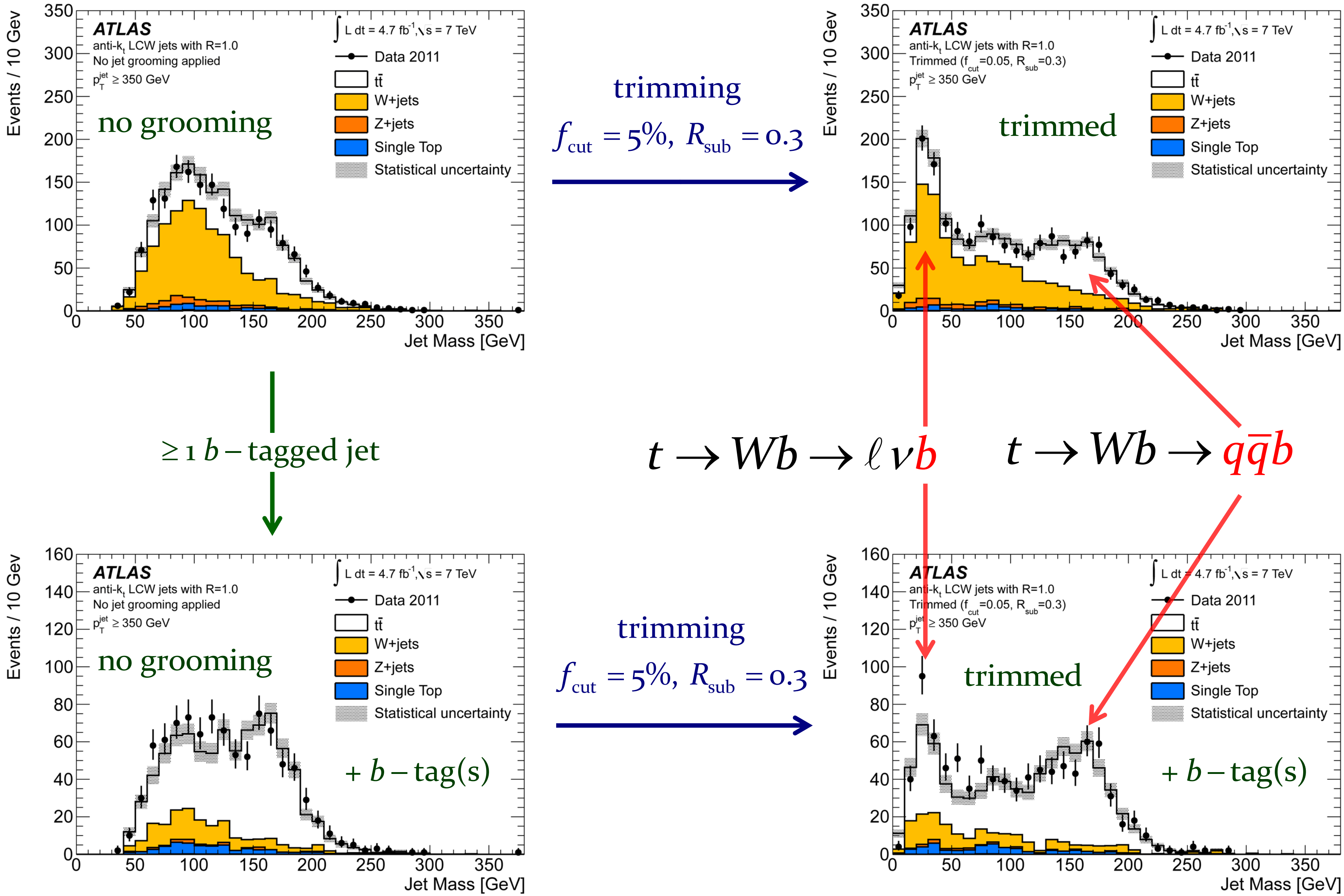
Hadronic top signal extraction

- 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

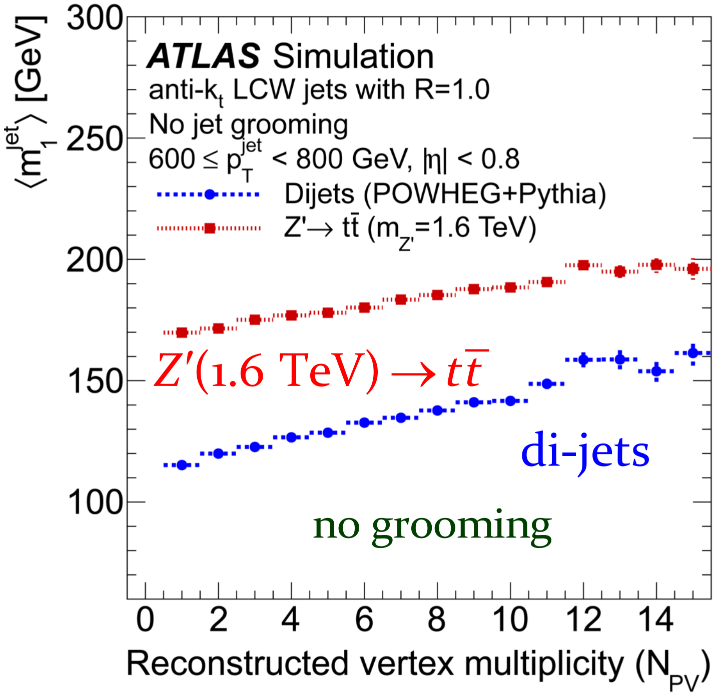
Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA
College of Science

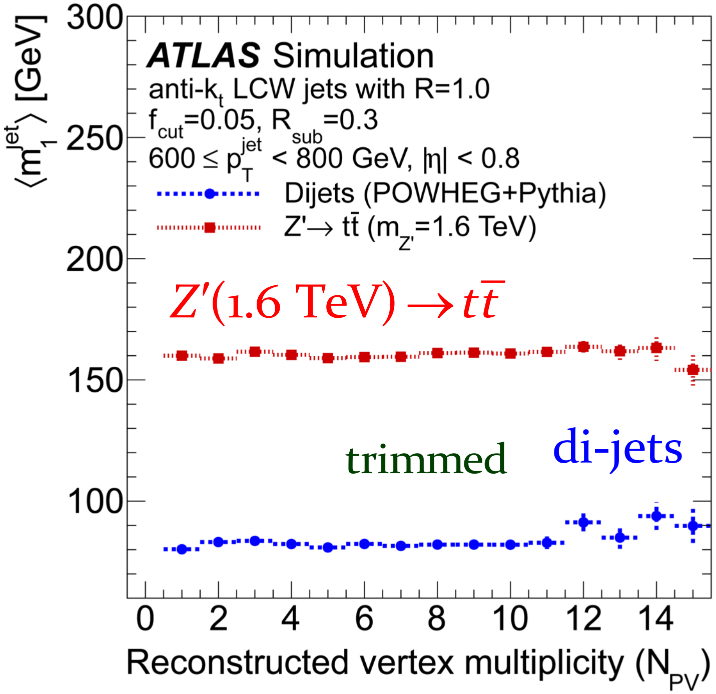


Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA
College of Science

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



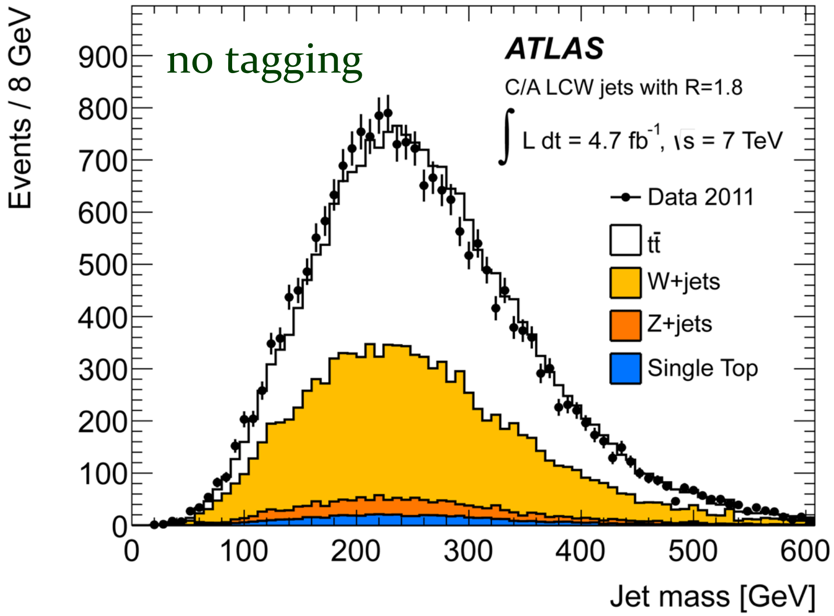


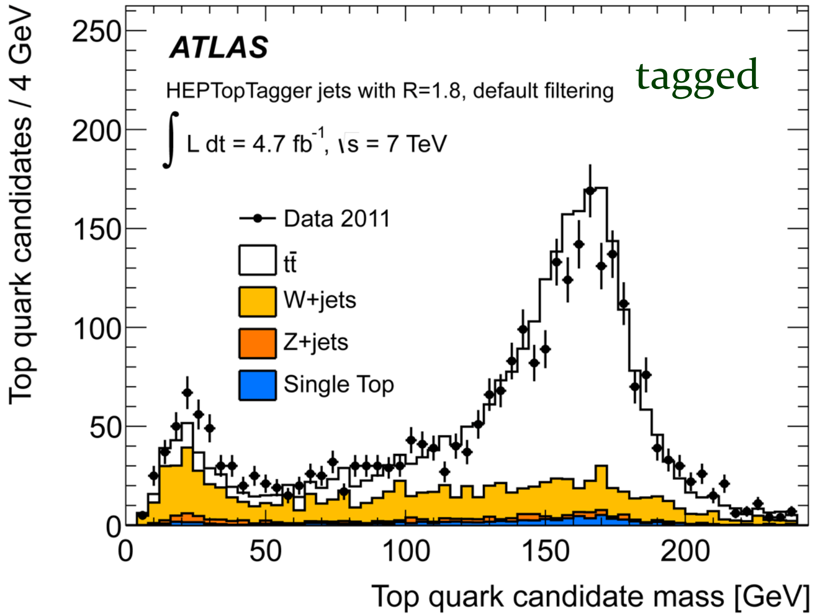
Peter Loch
UAPhysics
The University of Arizona
College of Science

Full hadronic top reconstruction with HepTopTagger

Exploits more exclusive features of final state

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

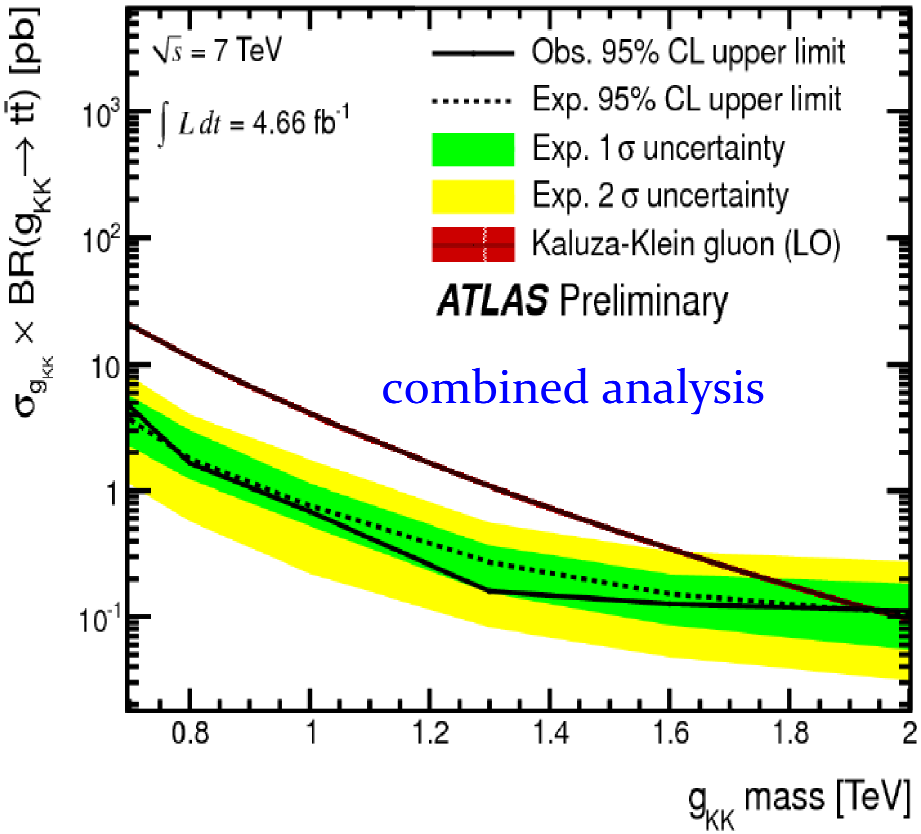


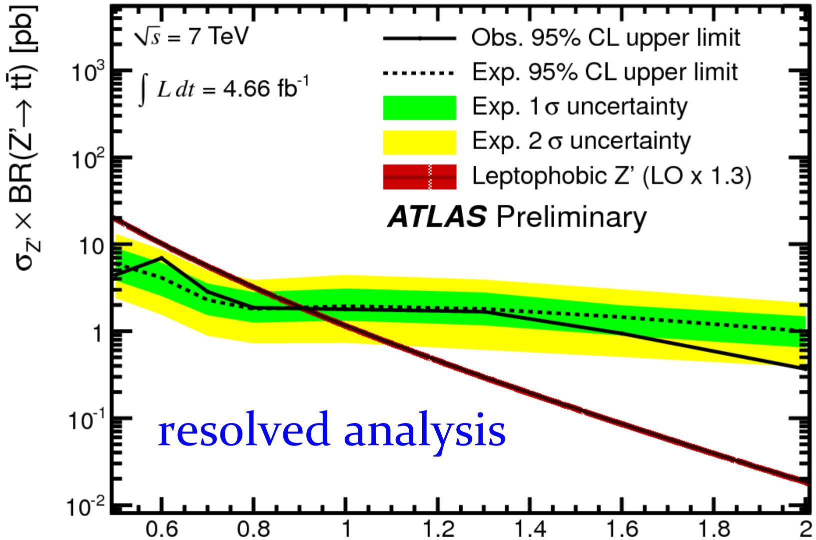


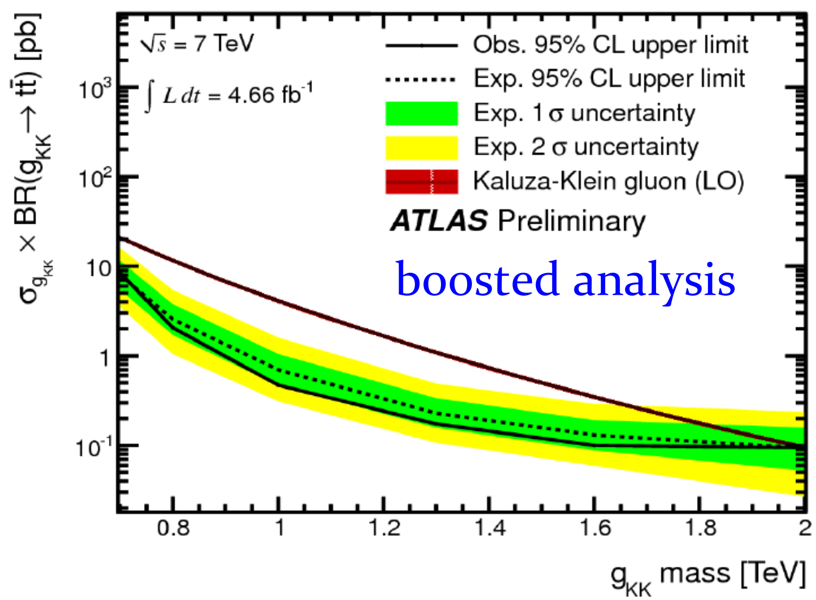
C/A jets, $R = 1.8$

Peter Loch
UAPhysics
The University of Arizona
College of Science

Search top-anti-top resonance



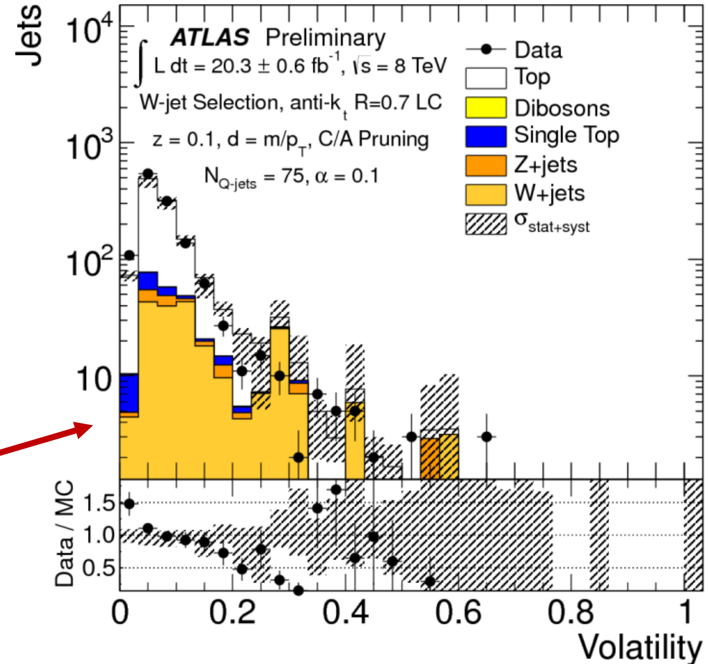


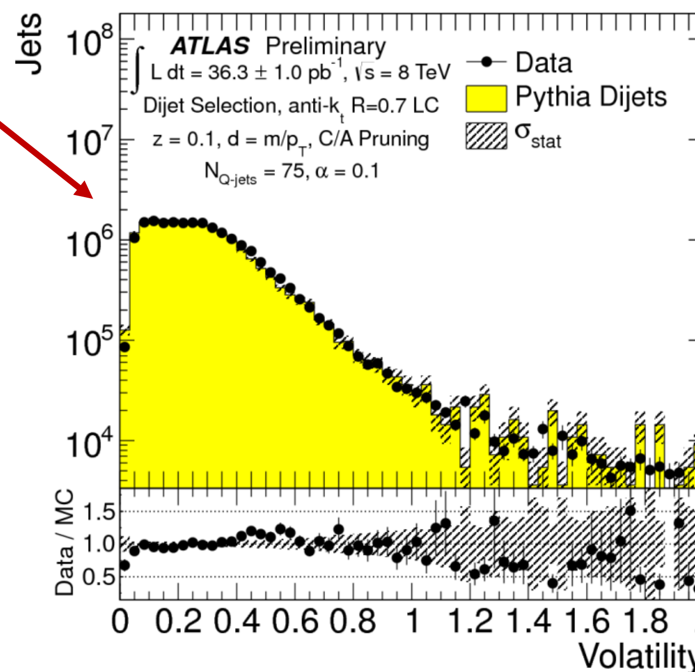


Efficiencies for Q-jets

Measuring efficiency of W reconstruction

- Volatility distributions for signal and background
  - Signals from enriched W-jet samples in data and MC
  - Background from di-jet samples in data and MC
- Efficiency measurement
  - Scanning volatility distributions for background and signal
  - Plot background rejection ($1/\varepsilon_{di\text{-}jet}$) against signal efficiency

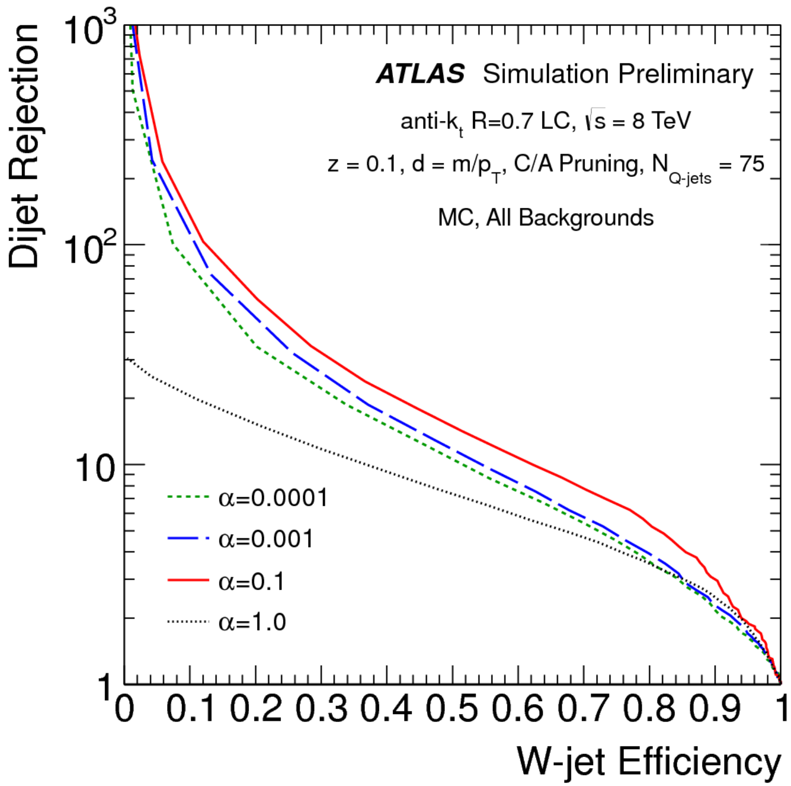


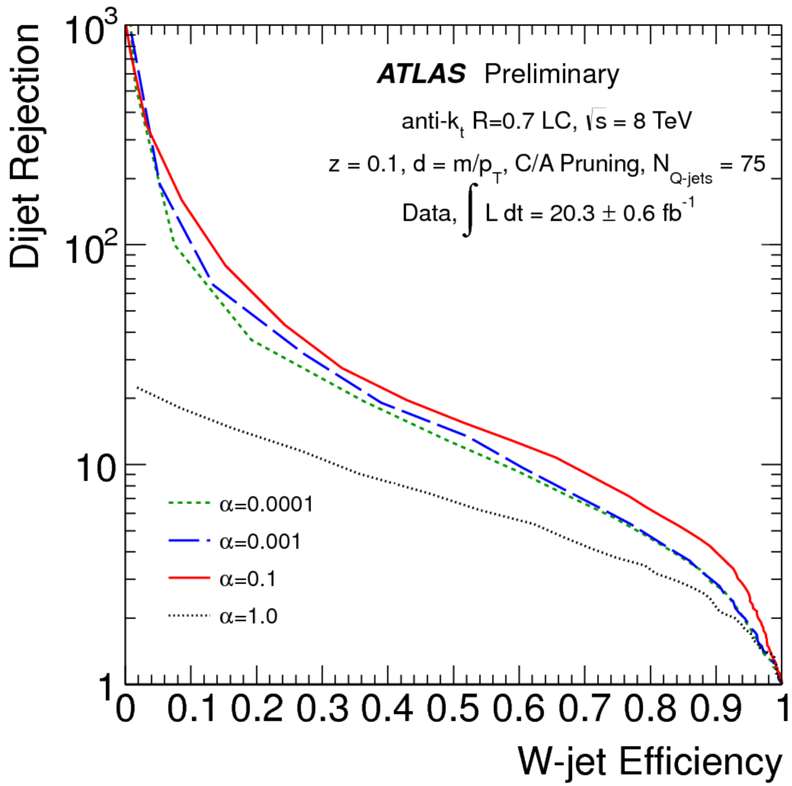


Q-jets ROC Curves for *W*-jet

Dependence on rigidity choice:

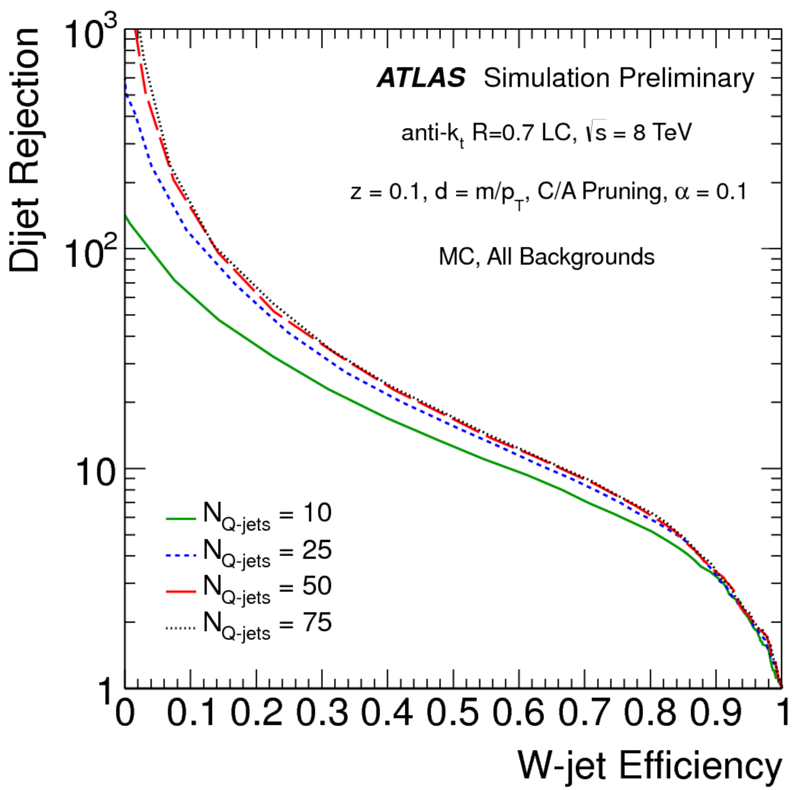
Higher α means closer to minimum distance clustering and pruning

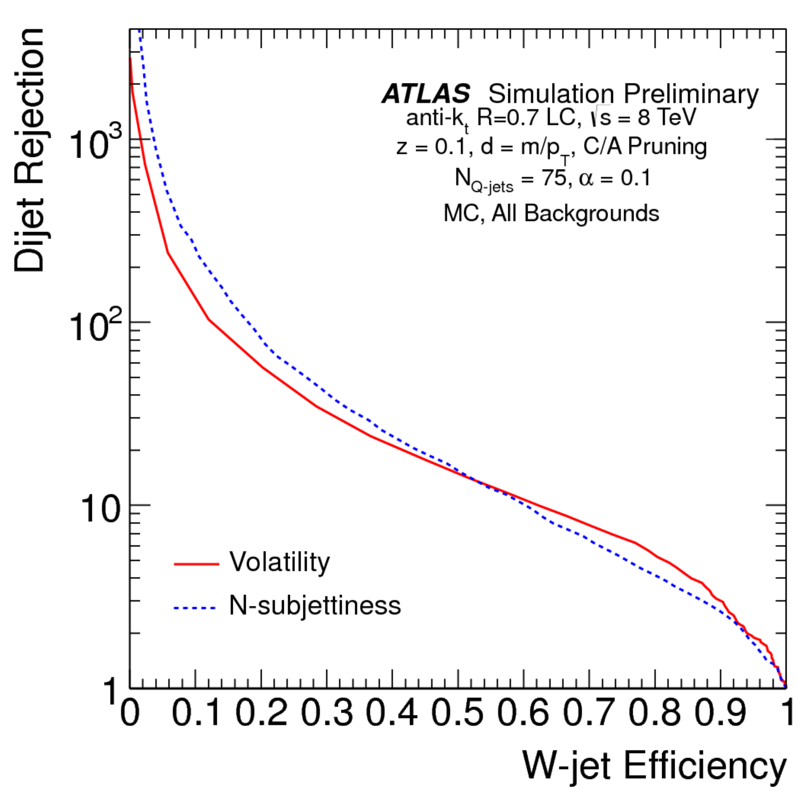




Q-jets ROC Curves for *W*-jet

Dependence on number of Q-jets and comparison to *N*-subjettiness:





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, pruning, and Q-jets 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…

Additional Material

Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA®
College of Science

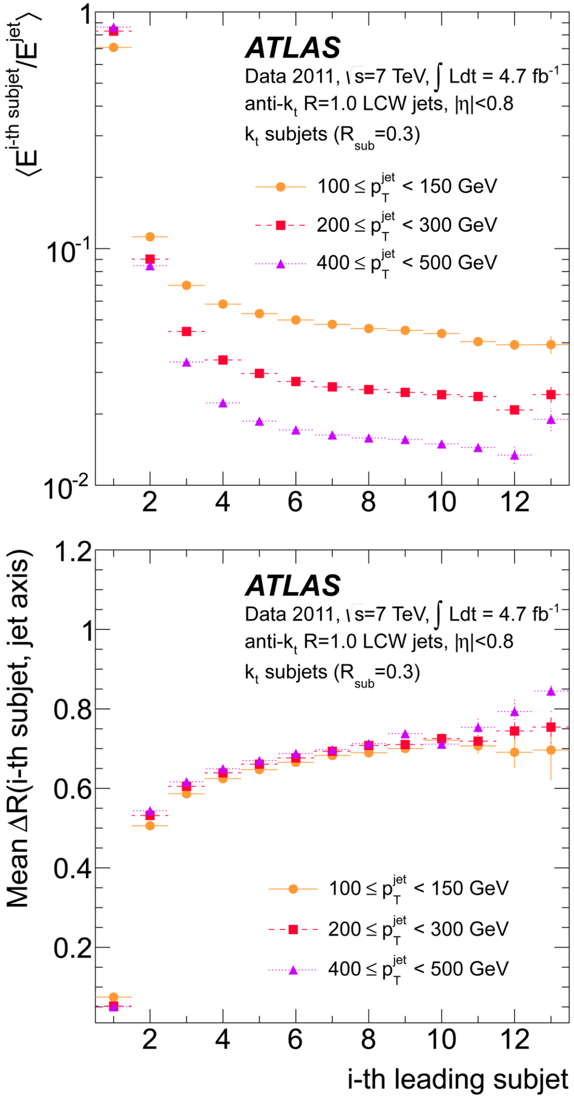
Sub-jet response features

Energy sharing

Fraction of total jet energy carried by sub-jet

Distance to jet axis

Radial dispersion and spatial resolution limitations of ATLAS calorimetry



p_T ranking in jet → high ... low

Peter Loch
UAPhysics
THE UNIVERSITY OF ARIZONA®
College of Science

Sub-jet response reference

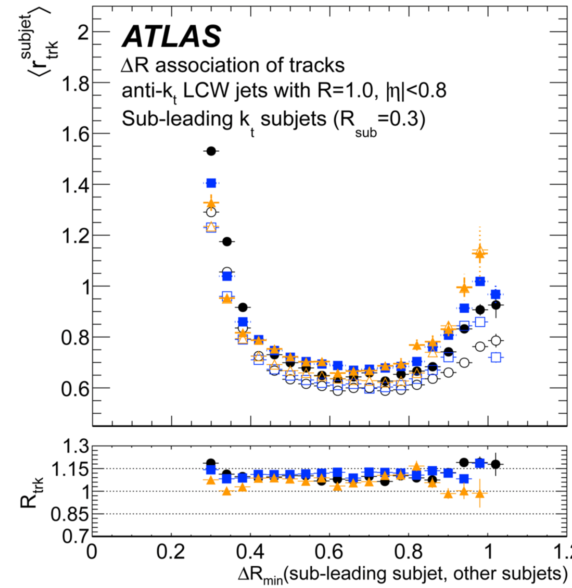
Matching tracks with (calorimeter) sub-jets

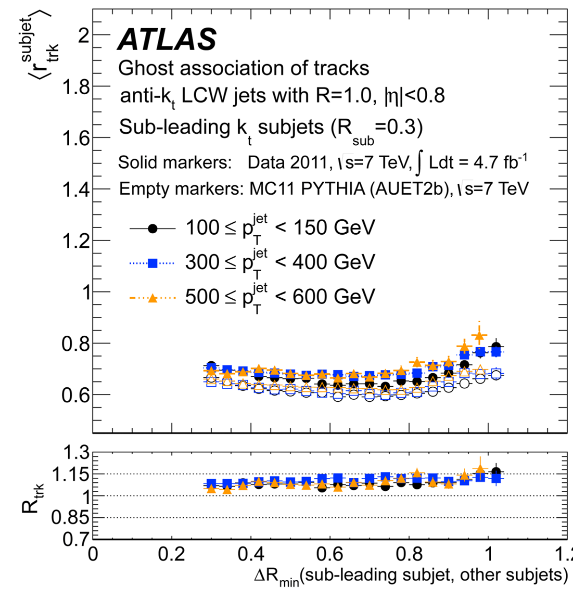
- Traditional method based on angular distance in pseudorapidity and azimuth – matching efficiency depending on sub-jet shapes/shape assumptions
- "Ghostmatching" clusters tracks into calorimeter sub-jet without interfering with its kinematic ($p_{\mathrm{T,trk}}$ set to tiny value $O(10^{-100}$ GeV))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

Calculating response ratios in data and MC

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

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

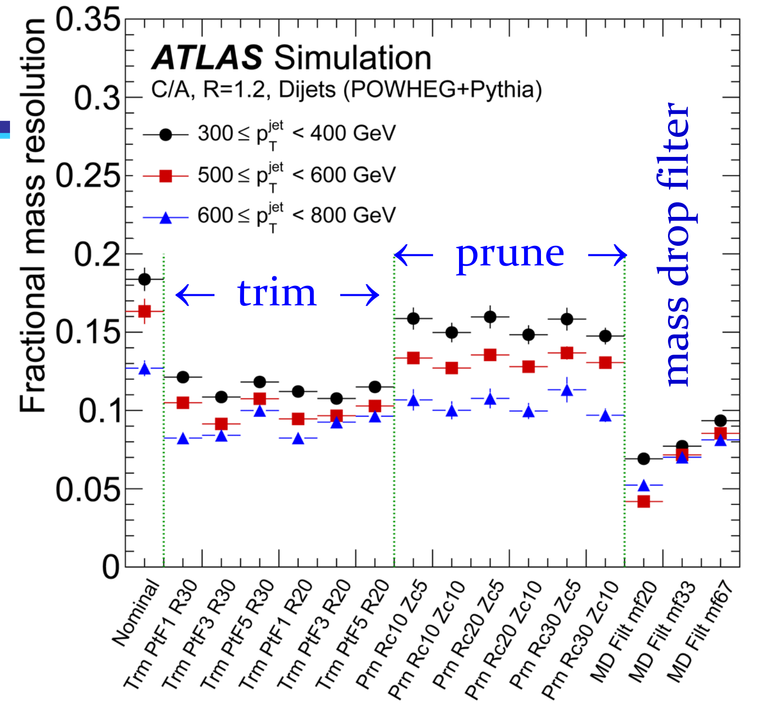


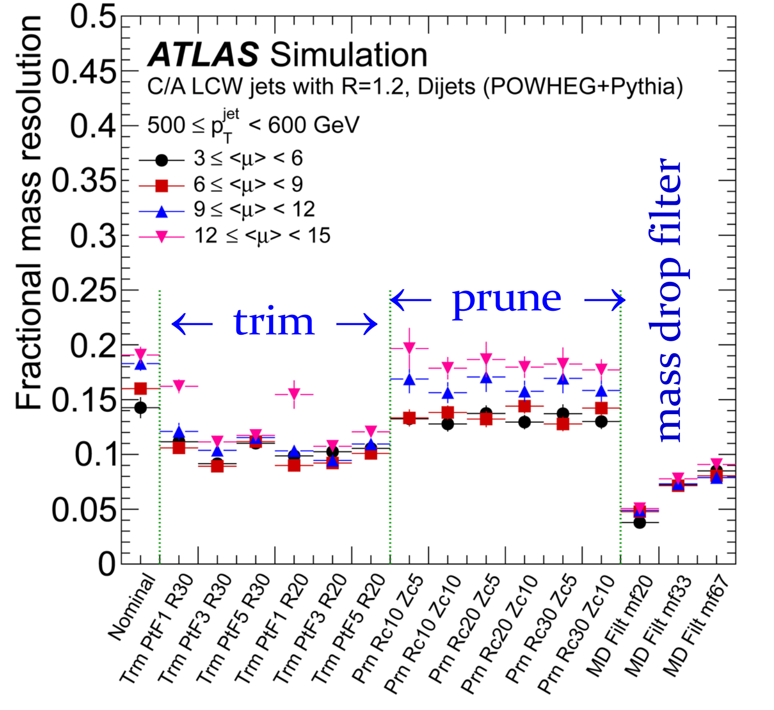


Jet Mass Summary

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