Jet Substructure Reconstruction and Application as a Search Tool in ATLAS

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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
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 $R \approx 2m/p_T$
  - 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 $|\eta|<2.5$

Full coverage calorimetry

Highly granular electromagnetic (EM) calorimeters within $|\eta|<3.2$

Full EM and hadronic (HAD) coverage within $|\eta|<4.9$

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 $|\eta|<2.7$

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

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![Graph](image.png)

**ATLAS Online Luminosity**

\(\sqrt{s} = 7\) TeV

- Total Delivered: 5.61 fb\(^{-1}\)
- Total Recorded: 5.25 fb\(^{-1}\)

**Graph Details**

- **ATLAS Online 2011, \(\sqrt{s}=7\) TeV**
  \(\int L dt = 5.2\) fb\(^{-1}\)

- Red line: \(\beta^* = 1.0\) m, \(<\mu> = 11.6\)
- Blue line: \(\beta^* = 1.5\) m, \(<\mu> = 6.3\)

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![Graph2](image.png)

**Mean Number of Interactions per Crossing**

- 0
- 2
- 4
- 6
- 8
- 10
- 12
- 14
- 16
- 18
- 20
- 22
- 24

**Graph Details**

- Red line: \(\beta^* = 1.0\) m, \(<\mu> = 11.6\)
- Blue line: \(\beta^* = 1.5\) m, \(<\mu> = 6.3\)
Jet Grooming Techniques

Trimming

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

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

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

D. Krohn, J. Thaler, L. Wang, JHEP 02 (2010) 84
Jet Grooming Techniques

Trimming

\[ R_{\text{sub}} = \{0.2, 0.3\} \]

\[ f_{\text{cut}} = \{0.01, 0.03, 0.05\} \]

Mass drop...

\[ \mu_{\text{frac}} = \{0.20, 0.33, 0.67\}, \quad y_{\text{cut}} = 0.09 \]
Jet Grooming Techniques

Trimming

\[ R_{\text{sub}} = \{0.2, 0.3\} \]
\[ f_{\text{cut}} = \{0.01, 0.03, 0.05\} \]

Mass drop... ...filtering

\[ \mu_{\text{frac}} = \{0.20, 0.33, 0.67\}, \ y_{\text{cut}} = 0.09 \]
\[ R_{\text{filt}} = \max[0.3, \Delta R_{j1-j2}/2] \]
Jet Grooming Techniques

**Trimming**

\[ R_{sub} = \{0.2, 0.3\} \]

\[ f_{cut} = \{0.01, 0.03, 0.05\} \]

**Mass drop...**

\[ \mu_{frac} = \{0.20, 0.33, 0.67\}, \quad y_{cut} = 0.09 \]

**...filtering**

**Pruning**

\[ \Delta R_{j_1-j_2} < R_{cut} \quad \text{or} \quad \frac{p_T^{j_2}}{p_T^{j_1+j_2}} > z_{cut} \]


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Jet Grooming Techniques

**Trimming**

\[ R_{\text{sub}} = \{0.2, 0.3\} \]

\[ f_{\text{cut}} = \{0.01, 0.03, 0.05\} \]

**Mass drop...**

\[ \mu_{\text{frac}} = \{0.20, 0.33, 0.67\}, \quad y_{\text{cut}} = 0.09 \]

**...filtering**

**Pruning**

\[ R_{\text{cut}} = \{0.1, 0.2, 0.3\} \]

\[ Z_{\text{cut}} = \{0.05, 0.1\} \]
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

\[ k_T \text{ splitting scales} \]


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

\( k_T \) 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
\( d_{23} \approx (M/2)^2 \) for particle with mass \( M \) undergoing 2-body decay

\( N \)-subjettiness

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

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

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 \( \tau_{N+1}/\tau_N \)
Jet Mass Calibration

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
Looking Inside Jets

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

\[ p_T \text{ ranking in jet} \]

high \rightarrow low
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 ($p_T^{T,\text{trk}}$ set to tiny value $O(10^{-10}) \text{GeV}$) – matching efficiencies ~independent of sub-jet shape

Calculating response ratios in data and MC

\[
 r_{\text{trk}}^{\text{subjet}} = \frac{\sum p_T^{\text{track}}}{p_T^{\text{subjet}}} \\
 \left\langle R_{\text{trk}}^{\text{subjet}} \right\rangle_{\text{data}} = \frac{\left\langle r_{\text{trk}}^{\text{subjet}} \right\rangle_{\text{data}}}{\left\langle r_{\text{trk}}^{\text{subjet}} \right\rangle_{\text{MC}}} 
\]
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:

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

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

Anti-$k_T$ jets, $R = 1.0$

inclusive jet sample:

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

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

**Effect of jet trimming on $N$-subjettiness ratios**

Anti-$k_T$ jets, $R = 1.0$

inclusive jet sample:

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

Evaluation of single jet mass modeling quality for an inclusive sample of ungroomed jets with
\(600 < p_T < 800\ \text{GeV}, \ |\eta| < 0.8\)
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, \( |\eta| < 0.8 \)
Modeling of Splitting Scales & $N$-subjettiness

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

<table>
<thead>
<tr>
<th>Anti-$k_T$ jets, $R = 1.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No grooming - very similar for groomed jets!</td>
</tr>
<tr>
<td>inclusive jet sample:</td>
</tr>
<tr>
<td>$600 &lt; p_T^{\text{jet}} &lt; 800 \text{ GeV},</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Anti-$k_T$ jets, $R = 1.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trimmed - qualitatively similar for ungroomed jets!</td>
</tr>
<tr>
<td>inclusive jet sample:</td>
</tr>
<tr>
<td>$600 &lt; p_T^{\text{jet}} &lt; 800 \text{ GeV},</td>
</tr>
</tbody>
</table>
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
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
Modeling Correlations

Modeling correlations in single jet structural observables

Example: evolution of $N$-subjettiness ratio $\tau_{23}$ 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 $\tau_{23}$ and single jet mass for an inclusive jet sample with $600 < p_T < 800$ GeV, $|\eta|<0.8$
Basics for Application in Searches for New Physics
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 – investing more known features of top quarks, like mass windows

Jet Grooming in Final States with Top Quarks

\[ t \rightarrow Wb \rightarrow \ell \nu b \quad t \rightarrow Wb \rightarrow q\bar{q}b \]

\[ f_{\text{cut}} = 5\%, \quad R_{\text{sub}} = 0.3 \]

no grooming

trimmed

\[ \geq 1 \text{ } b - \text{tagged jet} \]

+ \( b \) - tag(s)

trimmed

Jet Grooming in Final States with Top Quarks

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

**ATLAS Simulation**
- anti-k, LCW jets with R=1.0
- No jet grooming
- $600 \leq p_T^{\text{jet}} < 800$ GeV, $|\eta| < 0.8$
- Dijets (POWHEG+Pythia)
- $Z' \rightarrow t\bar{t}$ ($m_Z=1.6$ TeV)

**Z' (1.6 TeV) → tt**

- **no grooming**
- **di-jets**

**ATLAS Simulation**
- anti-k, LCW jets with R=1.0
- $f_{\text{cut}}=0.05$, $R_{\text{sub}}=0.3$
- $600 \leq p_T^{\text{jet}} < 800$ GeV, $|\eta| < 0.8$
- Dijets (POWHEG+Pythia)
- $Z' \rightarrow t\bar{t}$ ($m_Z=1.6$ TeV)

**Z' (1.6 TeV) → tt**

- trimmed
- **di-jets**
Jet Grooming in Final States with Top Quarks

Full hadronic top reconstruction with HepTopTagger

Exploits more exclusive features of final state

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

\[ C/A \text{ jets, } R = 1.8 \]
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

\[ \sigma_{g_{KK}} \times \text{BR}(g_{KK} \rightarrow t\bar{t}) \text{ [pb]} \]

\( \sqrt{s} = 7 \text{ TeV} \)

- Obs. 95\% CL upper limit
- Exp. 95\% CL upper limit
- Exp. 1 \( \sigma \) uncertainty
- Exp. 2 \( \sigma \) uncertainty
- Kaluza-Klein gluon (LO)

**ATLAS Preliminary**

combined analysis

resolved analysis

boosted analysis

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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...