Boosted Heavy Particles and Jet Substructure

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on behalf of the ATLAS Collaboration

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Introduction

At LHC, $\sqrt{s} \gg$ electroweak scale
Massive particles like top, W, Z and Higgs are often produced with significant boost
E.g. at $\sqrt{s} = 7$ TeV, there are 1000 $t\bar{t}$ events with $p_T > 300$ GeV

Decay products are Lorentz-boosted in the same direction
Separation $\Delta R \approx 2m/p_T$

Hadronic decays cannot be reconstructed using separate jets, since these begin to merge
⇒ use substructure techniques to look inside the merged jet and reconstruct the object of interest

Important to explore this kinematic regime
Extend understanding of the Standard Model
Search for new physics
ATLAS Detector

ATLAS is well suited to reconstructing boosted heavy particles using jet substructure techniques

Excellent tracking
Highly granular, hermetic calorimeter covering $|\eta| < 4.9$

Good jet energy resolution: $\sigma/E \approx 50%/\sqrt{E} + 3\%$ ($|\eta| < 3.2$)

Good longitudinal containment: 9.7 interaction lengths
ATLAS Calorimeter

High granularity
Electromagnetic calorimeter (EMCAL):
\[ \Delta \eta \times \Delta \phi = 0.025 \times 0.025 \]
Hadronic calorimeter (HCAL):
\[ \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \]

Segmentation in depth to track shower development
3 layers for EMCAL and HCAL
Improves energy resolution

Energy of hadrons is reconstructed by forming 3D topological clusters of energy
Jet Reconstruction

Topological energy clusters are combined into jets, using the generalized distance measure:

\[ d_{ij} = \min(p_{t_i}^{2p}, p_{t_j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \]
\[ \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \]

The definition of \( p \) leads to the three algorithms that are commonly used in ATLAS

- \( p = 1: k_T \)
- \( p = 0: \) Cambridge-Aachen
- \( p = -1: \) anti-\( k_T \)

Large R parameters of \( \sim 1 \) are used to reconstruct heavy boosted objects.
Jet Substructure

Jets containing the decay products of a massive particle will be distinct from those typically caused by a light parton

- Significant jet mass
- Hard 2- or 3-body substructure

These differences may be obscured by

- QCD radiation
- Pile-up and Underlying event

Many techniques exist to “tag” and “groom” jets

- identify and retain hard substructure
- reduce impact of soft QCD radiation

![Diagram showing jet substructure](image)

Initial jet → $p_T^j / p_T^\text{jet} < f_{\text{cut}}$ → Trimmed jet

**Graph:**

- ATLAS Simulation
- anti-$k_t$, LCW jets, $600 \leq p_T^\text{jet} < 800$ GeV

**Legend:**

- Ungroomed $Z \rightarrow q\bar{q}$
- Ungroomed Dijets
- Trimmed $Z \rightarrow q\bar{q}$
- Trimmed Dijets
ATLAS Experimental Programme

Measure the jets and their substructure observables

- Required extensive work to calibrate observables and to estimate uncertainties
- Validation of Monte Carlo simulation

Test tagging and grooming techniques in data

- Effective with finite resolution, pile-up etc.?
- Understand their relative performance and correlations

Use as tools for physics measurements

- Standard Model measurements
- Searches for new physics
Jet Mass

Jet mass calibration validated using
Comparison to track-jets reconstructed in inner detector
Hadronic W bosons selected from semi-leptonic ttbar events

Mass scale uncertainties

< 3% in 2011 for hadronic W bosons ($p_T > 200$ GeV)
< 5% in 2012 for hadronic top-jet ($p_T > 500$ GeV)

Precision physics possible with large-R jets!
High instantaneous luminosity causes many interactions per bunch crossing

These pile-up interactions produce many low $p_T$ particles leading to a substantial background energy density, $\rho$

Large-$R$ jets have a large “catchment” area

$\Rightarrow$ suffer from large modifications of kinematics and substructure observables
Mitigating the Effects of Pile-Up: Grooming

Grooming reduces the effective jet area, rejecting soft energy deposits.
This helps to uncover any hard substructure in the jet.
Another Approach: Pile-Up Subtraction

Many fake particles – “ghosts” – with very low momenta, $g_T$, are clustered into each jet
  These mimic soft pile-up particles
  Individual ghost area is $A_g$

Sensitivity to pile-up of a given substructure variable, $V(\rho, g_T)$ is estimated by varying the energy of these ghosts by infinitesimal amount, $\delta$

$$V(\rho, g_T + \delta A_g) = V(\rho + \delta, g_T)$$

Correction is then

$$V \text{corr} = V(\rho = 0, g_T = 0) = V(\rho = \rho_0, g_T = -\rho_0 A_g)$$

$V \text{corr}$ is evaluated using a Taylor expansion

This method can be used for many jet shapes and substructure observables
Pile-Up Subtraction for Substructure

Pile-up subtraction effectively removes pile-up effects from substructure observables

\[ \sqrt{d_{12}} = \text{the } k_T \text{ distance between the two final clusters in jet} \]
Boosted Top

\[ m_{tt} = 2.6 \text{ TeV} \]

ATLAS EXPERIMENT

Run Number: 209995, Event Number: 51048560
Date: 2012-09-09 23:10:22 CEST
Introduction to ttbar Resonance Searches

Many models of new physics predict heavy resonances with large couplings to top quarks. These heavy resonances will decay to boosted tops.

ATLAS has searched for two benchmark models:
- $Z'$: predicted by some leptophobic topcolour models
  - colour singlet
  - narrow resonance: $\Gamma/m = 1.2\%$
- $g_{kk}$ boson: predicted by Randall-Sundrum models
  - colour octet
  - broad resonance: $\Gamma/m = 15.3\%$

ATLAS have tested several algorithms to identify boosted tops:
- HEPTopTagger, Top Template Tagger
- Substructure variable cuts: $k_T$ splitting scales, n-subjettiness, mass

Searches performed in fully- and semi-leptonic channels:
- Fully-hadronic with $\int L dt = 4.7 \text{ fb}^{-1}$ ($\sqrt{s} = 7 \text{ TeV}$)
- Semi-leptonic with $\int L dt = 14.3 \text{ fb}^{-1}$ ($\sqrt{s} = 8 \text{ TeV}$) and $\int L dt = 4.7 \text{ fb}^{-1}$ ($\sqrt{s} = 7 \text{ TeV}$)

N-subjettiness, \( \tau_N \), evaluates how well the jet can be described as containing \( \leq N \) subjets. Ratios \( \tau_{NM} = \tau_N / \tau_M \) give additional rejection power vs light parton jets.
Comparison of Tagging Techniques

Broad spectrum of potential working points
Optimum choice is analysis dependent
HTT, $\sqrt{d_{12}}$ and top template tagger have been used so far

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Search in Semi-Leptonic Channel

Dataset: \( \int L dt = 14.3 \, \text{fb}^{-1} \) at \( \sqrt{s} = 8 \) TeV

\( \geq 1 \) b-tagged \( R = 0.4 \) jet

Selection for Leptonic top decay

W candidate: lepton + ME_T

\( R = 0.4 \) jet, \( \Delta R(\text{jet,lepton}) < 1.5 \)

Selection for hadronic top decay

Trimmed \( R = 1.0 \) jet, \( p_T > 300 \) GeV,

\( m > 100 \) GeV

\( \sqrt{d_{12}} > 40 \) GeV

\( \Delta \Phi(\text{lepton, had. top}) > 2.3 \)

To extend searches to lower resonance masses, a complementary resolved jet is used
No significant excess was seen, so 95% C.L. limits are set
0.5 – 1.8 TeV for narrow, $Z'$-like resonances
0.5 – 2.0 TeV for broad, $g_{KK}$-like resonances

Semi-leptonic search with $\int L \, dt = 4.7 \, fb^{-1}$ at $\sqrt{s} = 7 \, TeV$ (arXiv:1305.2756) set similar limits

A complementary search for fully hadronic $t\bar{t}$ resonances (JHEP01(2013)116) saw no excess either
Conclusions

High LHC collision energy means heavy particles are often highly boosted

- Within the Standard Model and in new physics models

Specialized substructure techniques can be used to reconstruct these highly boosted particles

ATLAS has a comprehensive programme

- To calibrate and understand substructure observables
- To meet experimental challenges such as high pile-up
- To measure Standard Model processes with boosted particles
- To search for new physics with boosted particles

Many interesting studies: these slides are only a selection

Lots of new results coming soon
## Some ATLAS Papers on Substructure and Boosted Heavy Particles

<table>
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<td>ATLAS-CONF-2013-087</td>
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<td>Jet Charge Studies in ATLAS</td>
<td>ATLAS-CONF-2013-086</td>
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<td>Performance of Pile-up Subtraction for Jet Shapes</td>
<td>ATLAS-CONF-2013-085</td>
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<td>Performance of Boosted Top Quark Identification</td>
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<td>Pile-Up Subtraction and Suppression for Jets</td>
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<td>Performance of Jet Substructure Techniques for Large-R Jets</td>
<td>arXiv:1306.4945</td>
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<td>Jet Mass and Substructure of Inclusive Jets</td>
<td>JHEP 05 (2012) 128</td>
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<td>Search for Resonances Decaying into Top-Quark Pairs Using Fully Hadronic Decays</td>
<td>JHEP 01 (2013) 116</td>
</tr>
<tr>
<td>ATLAS Measurements of Properties of Jets For Boosted Particle Searches</td>
<td>Phys. Rev. D 86 072006</td>
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<td>A Search for ttbar Resonances in the Lepton Plus Jets Final State with ATLAS using 14 fb⁻¹</td>
<td>ATLAS-CONF-2013-052</td>
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ADDITIONAL MATERIAL
ATLAS Coordinate System

Right-handed system with x-axis pointing to the LHC centre and y-axis pointing upwards
Polar angle, $\theta$, is measured w.r.t. LHC beamline
Azimuthal angle, $\phi$, is measured w.r.t. x-axis

Rapidity $y = 0.5 \ln [(E + p_Z)/(E - p_Z)]$

Pseudorapidity, $\eta$

is approximation of rapidity, $y$, in high energy limit

$\eta = -\ln \tan(\theta/2)$

$p_T = p \sin \theta$, $E_T = E \sin \theta$
Topoclustering
Different Jet Clustering Algorithms

G. Salam

arXiv:0906.1833v2 [hep-ph]
Mass Calibration Validation using Track-Jets

Jet mass scale validated by comparing to jets reconstructed from tracks
uncorrelated systematics: tracker vs calorimeter
pile-up reduced by using only tracks from hard scatter vertex

\[ r_{\text{track-jet}} = \frac{m_{\text{track-jet}}}{m_{\text{jet}}} \]

\[ R_{\text{track-jet}} = \frac{r_{\text{track-jet}}}{r_{\text{MC-jet}}} \]

jet mass uncertainty
< 5% in 2012 for hadronic top-jet
\( p_T > 500 \text{ GeV} \)

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Mitigating the Effects of Pile-Up: Grooming

By reducing the effective jet area, grooming effectively eliminates the impact of pile-up although at cost of some information about jet
Pile-up Subtraction for Substructure

Pile-up subtraction effectively removes pile-up effects from substructure observables

$$\sqrt{d_{12}} = \text{the } k_T \text{ distance between the two final clusters in jet}$$

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Comparison of Trimming and Subtraction

Both methods perform well
Different advantages/disadvantages
Jet substructure techniques possible in a high pile-up environment
Bodes well for LHC Run 2 and beyond
Jet Mass

Decay product separation $\Delta R \approx 2m/p_T$

For $p_T > 350$ GeV, clear top peak in mass spectrum

From events where all top decay products are contained

$W$ peak from events where $b$ is not contained within $R=1.0$ jet

For $p_T > 500$ GeV, top decay products are contained more often

$W$ peak further suppressed as $R = 0.3$ subjets merge
Dealing with HL-LHC Pile-Up

Planned upgrades of the LHC in the 2020s will see the luminosity increase to $L = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

MC studies indicate that large-$R$ jets and substructure techniques can be used in this environment.

**Signal**

- ATLAS Simulation Preliminary
- $\sqrt{s} = 14$ TeV
- Pythia8 $Z' \rightarrow t\bar{t}$ ($m_{Z'} = 2$ TeV)
- 25 ns bunch spacing
- $0.5 < p_T^{\text{jet}} < 1$ TeV, $0.0 < |\eta| < 0.3$
- $\langle \mu \rangle = 200$, $\sigma^{\text{pileup}}_{\text{noise}} (\mu=200)$
- No jet grooming, no jet pileup correction
- No jet grooming, jet 4-vector pileup correction
- Trimmed, no jet pileup correction
- Trimmed, jet 4-vector pileup correction

**Background**

- ATLAS Simulation Preliminary
- $\sqrt{s} = 14$ TeV
- Pythia8 dijets (QCD 2 $\rightarrow$ 2)
- 25 ns bunch spacing
- $0.5 < p_T^{\text{jet}} < 1$ TeV, $0.0 < |\eta| < 0.3$
- $\langle \mu \rangle = 200$, $\sigma^{\text{pileup}}_{\text{noise}} (\mu=200)$
- No jet grooming, no jet pileup correction
- No jet grooming, jet 4-vector pileup correction
- Trimmed, no jet pileup correction
- Trimmed, jet 4-vector pileup correction
Top Template Tagger

Compares energy flow in jet to 300k simulated top templates

jets with an overlap $OV_3 > 0.7$ are considered tagged

$$OV_3 = \max_{\{\tau_n\}} \exp \left[ - \sum_{i=1}^{3} \frac{1}{2 \sigma_i^2} \left( E_i - \sum_{\Delta R(\text{topo},i)<0.2} E_{\text{topo}}\right)^2 \right]$$

- best template match is used
- parton energy
- cluster energy

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HEPTopTagger
Divides C-A R=1.5 jets into subjets with small R-parameter
Filters out soft contributions
Tests all combinations of three subjets for compatibility with hadronic top quark

ATLAS Preliminary
\[ \int L \, dt = 20.3 \, fb^{-1} \]
\[ \sqrt{s} = 8 \, TeV \]

86% pure
98% pure

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Mini-Isolation

Leptonic decay products of top quark boosted too
Leads to a loss in isolation efficiency if fixed cone used

Define lepton $p_T$ dependent isolation cone to maintain efficiency

Fixed $\Delta R$ isolation cone
Boost
Fixed $\Delta R$ isolation cone

Isolation cone
$\Delta R = 10 \text{ GeV}/E_T$
Lepton Mini-Isolation Performance

Reducing isolation cone size improves signal efficiency
Jet Substructure

Jets containing the decay products of a massive particle will be distinct from those typically caused by a light parton.

- Significant jet mass
- Hard 2- or 3-body substructure

These differences may be obscured by QCD radiation, pile-up, and underlying event.

Many techniques exist to “tag” and “groom” jets, aiming to:

- Identify and retain hard substructure
- Reduce impact of soft QCD radiation

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**Jet Substructure Diagram**

1. **Initial jet**
2. **Trimmed jet**
   - $p_T^i / p_T^{jet} < f_{cut}$

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**Graph**

- **ATLAS Simulation**
  - C/A LCW jets with $R=1.2$, $600 \leq p_T^{jet} < 800 \text{ GeV}$
  - No jet grooming applied $Z \to q\bar{q}$
  - Filtered ($\mu = 0.67$) $Z \to q\bar{q}$

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**Legend**

- **Arbitrary units**
  - $0$ to $0.14$

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**Axes**

- **Jet mass [GeV]**
  - $0$ to $400$

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**arXiv:1306.4945**