Abstract

This paper documents the effects of implementing cuts on jet substructure observables in highly boosted $t\bar{t}$ events. The study used a full ATLAS 2011 dataset, at $\sqrt{s} = 7$ TeV and an integrated luminosity of $4.7 fb^{-1}$. The substructure variables observed were specifically $k_t$ splitting scale and N-subjettiness. All large-R jets have been subjected to the jet trimming algorithm which has been shown to help minimize soft jet components, improve robustness of large-R measurements, and improve the physical potential to search for heavy boosted objects.
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1 Introduction

1.1 The Standard Model

The Standard Model has proven to be the most comprehensive theory in particle physics for explaining what comprises the matter that makes up our visible universe and what mediates the four fundamental forces that mediate the interactions between this matter.[1]

The Standard Model is generally based on Quantum Field Theory (QFT) where particles are described by space pervading fields and forces between particles are described by the exchanging of other particles, referred to as force-mediating particles or more commonly as force carriers.

The force carriers in the Standard Model that mediate three of the four fundamental forces (strong, weak, electromagnetic) in the Universe are known as bosons. The strong, weak, and electromagnetic forces are mediated by the gluon, W and Z bosons, and the photon respectively. The fifth boson in the Standard Model, the Higgs, is related to the Higgs mechanism which accounts for the mass of particles. The theorized graviton, the force mediating particle of gravity, is not included in the Standard Model due to the fact that quantum physics and general relativity are yet to be unified.

The Standard Model proposes twelve matter particles, the fermions. Each of these twelve fermions has its own specific antiparticle. They can be categorized into two groups: quarks and leptons. These fermions are broken down into three generations, 2 particles each. This is depicted in figure 1.

Quarks have color charge, charge, and flavor. This means that they can interact via the strong force, weak force, and electromagnetic force. Due to the properties of the strong force this means that quarks do not exist alone in nature, instead are found in composite particles known as hadrons. Two particle composites are known as mesons and three particle composites are known as baryons. The six known quarks are: up, down, strange, charm, top, and bottom. Each of the generations in the Standard Model has up-type quark with charge $\frac{2}{3}$ and a down-type quark with charge $-\frac{1}{3}$.

Leptons are only electrically charged and do not carry color charge and are thus not subjected to the strong force. The antiparticle of the electron is the positron. The positron has a charge of +1. The other two leptons antiparticles are referred to as neutrinos. These antiparticles carry no charge and this means that they are only subjected to the weak force making them difficult to detect due to the fact that they can pass through matter with very little interaction.
1.2 LHC

The Large Hadron Collider (LHC) is the largest particle accelerator in the world. The LHC is a synchrotron, colliding proton-proton beams in a circular, underground tunnel 27 km long. The LHC is located 100m under the border of France and Switzerland (figure 2). The accelerator is designed to accurately collide proton beams with the use of superconducting magnets. The LHC is designed to run at a center of mass energy $\sqrt{s} = 14$ TeV. Despite this fact, the data taken for this analysis was at half that, $\sqrt{s} = 7$ TeV. When these beams collide particles are projected in all directions; detectors are used to help decode these projections. These detectors are located along the circular ring that makes up the LHC.[2]
1.3 ATLAS

ATLAS (A Torodias LHC ApparatuS) is one of the four particle detectors at the LHC. It is a multi-layered general purpose detector utilized for several focuses of research. ATLAS distinguishes particles produced from the proton-proton collisions by measuring the particles energy, momentum, and charge. ATLAS has three primary detection components: the inner detector, the calorimeters, and the muon spectrometer (figure 3). The detector uses a right-handed cylindrical coordinate system, with the beam-pipe being the z-axis. θ is defined as the angle measured from the z-axis, and pseudorapidity as $\eta = -\log \tan \frac{\theta}{2}$.[3]

Figure 3: Overview of ATLAS detector components

1.3.1 Tracking

The inner detector of ATLAS provides tracking information. It is comprised of three layers: the pixel tracker, silicon microstrip tracker (SCT), and the transition radiation tracker (TRT). All of the components of the inner detector are in a 2 T magnetic field produced by the central solenoid.

Figure 4: ATLAS inner detector

1.3.2 Calorimeter System

The second level of ATLAS detection is the calorimeter system. They measure the energy of particles striking materials in the detector cells. There
are several different types of calorimeters inside this second level. The first calorimeter is liquid argon calorimeter (LAr) which is designed to precisely detect electrons and photons. The next step in the calorimeter system is the TileCal. It utilizes scintillating plastic tiles and detect with a lower resolution. This aspect detects hadron showers (jets) and helps to reconstruct missing energy.

Figure 5: ATLAS calorimeter system

1.3.3 Muon Spectrometer and Muon System

The last layer of the ATLAS detector is for muon detection. Muons pass through the first two layers of the detector without being absorbed so the outermost layer is used for muon detection. The spectrometer identifies and measures the momenta of the particles and the muon system bends the muons for momentum measurement.

Figure 6: depiction of ATLAS muon spectrometer

2 Boosted Tops

The top quark is the heaviest of all the quarks in the Standard Model with a mass of approximately $173 \text{ GeV}$. With an extremely short lifetime on the scale of $10^{-25}$s tops do not form hadrons unlike all other quarks.

2.1 Top Production

Top quarks can be produced in two ways: via the strong interaction or the weak interaction. When top quarks are produced from gluon fusion (the strong interaction), the primary method at the LHC, they form top pairs with the top
and its anti-top or \( \bar{t} \) (t-bar)(figure 7). A single top quark will be produced with the use of the weak interaction (figure 8).

![Figure 7: Top pair production (strong)](image1)

![Figure 8: Single top production (weak)](image2)

2.2 Top Decay

The breakdown of particles into other particles is referred to as decay. With the exception of the top and bottom quarks, quarks do not decay. The top quark decays electroweakly, specifically into a W boson and a b quark (we will assume this \( \sim 99\% \)). After this is where the decay is defined. Our study focused on semi-leptonic decay in the muon channel. This means that one of the W bosons decays leptonically into one muon and one muon neutrino, while the other decays into two quarks. During the decay process, a quark shower, referred to as a jet, forms as a result of quark confinement. Quarks cannot exist by themselves so when they get pulled away from other quarks, all the energy put into separating them results in the production of brand new quarks. As this process repeats itself extremely quick it creates a shower, or jet. When particles have less mass, and thus less momentum, these jets remain singular and separated. At the LHC, an extremely high energy level, the increased momenta of the interaction causes individual jets to overlap. When the top is referred to as boosted or highly boosted, the decay products can no longer be resolved as individual jets. Thus, the final product of our top decay is four quarks (jets), one muon, and one muon neutrino (figure 9). Semi-leptonic decay is more ideal than its alternatives because all hadronic has very high background and all leptonic is very rare and difficult to reconstruct.
2.3 Jets

As defined earlier, a jet is a quark or gluon shower that exists during a decay process. They are complex structures that appear as a multitude of tracks in the detector and are very difficult to accurately reconstruct. To reconstruct the overlapping jets produced in boosted top decays, we must use an algorithm.

2.3.1 Jet Reconstruction Algorithms

ATLAS primarily uses three jet reconstruction algorithms: the anti-$k_t$ algorithm, the Cambridge-Aachen (C/A) algorithm, and $k_t$ algorithm. These are the most widely used infrared and collinear-safe jet algorithms available for proton-proton collider physics. The $k_t$ algorithm clusters the smallest $p_T$ constituents first where as the anti-$k_t$ algorithm clusters the largest $p_T$ jet first providing large, robust, and cone-shaped jets. The C/A algorithm reconstructs entirely off angular separation rather than $p_T$. ATLAS has adopted the anti-$k_t$ algorithm as the standard in all of its physics analyses.

2.3.2 Jet Trimming Algorithm

The jet trimming algorithm was applied to the large-R jets(anti-$k_t$ jets where $R=1.0$) in this study. The jet trimming algorithm helps to remove soft components of the jet. It takes advantage of the fact that contamination from underlying event (UE) and pile-up in the reconstructed jet is usually much softer than the outgoing partons from the hard scatter. The procedure uses a $k_t$ algorithm to create subjets of $R_{sub}$. Any subjets with $p_{T,i}^j / p_{T}^j < f_{cut}$ are removed, where $f_{cut}$ is the parameter in the study and $p_{T}^j$ is the transverse momentum of the $i^{th}$ jet.

Figure 11: Simplistic view of trimming procedure
2.3.3 Jet Properties and Substructure Observables

- **Mass** The jet mass is calculated from the energies and momenta of its constituents, as seen in equation:

\[
(m_{\text{jet}})^2 = (\Sigma E_i)^2 - (\Sigma p_i)^2
\]

where \(E_i\) and \(p_i\) are the energy and momenta of the \(i^{th}\) jet constituent.

- **Splitting scales** The \(k_t\) splitting scales are defined by the reclustering of the subjets inside a jet with the \(k_t\) algorithm. The \(k_t\)-distance of the final step in combining two subjets into the final jet can be used to define a splitting scale variable given in equation:

\[
\sqrt{d_{ij}} = \min(p_{T_i}, p_{T_j}) \times \Delta R_{ij}
\]

where \(\Delta R_{ij}\) is the distance between the last two subjets. This definition means that the last step of the reclustering provides the \(\sqrt{d_{12}}\) observable and so on. For the \(k_t\) splitting scales we expect a steeply falling QCD spectrum. Also, for the first splitting scale we expect a peak at approximately one half the top mass and for the second splitting scale we expect a peak at approximately one half the W boson mass.

- **N-subjettiness** The N-subjettiness variables \(\tau_N\) are observables related to subjet multiplicity. It is calculated by clustering the constituents of the jet with the \(k_t\) algorithm and requiring N subjets to be found. The variables \(\tau_N\) are defined by equation:

\[
\tau_N = \left(\frac{1}{d_0}\right)(\Sigma p_{T_k} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk}))
\]

with \(d_0 \equiv \Sigma p_{T_k} \times R\)

where R is the jet radius parameter in the jet algorithm, \(p_{T_k}\) is the \(p_T\) of the constituent \(k\) and \(\delta R_{Nk}\) is the distance from the subjet \(N\) to the constituent \(k\). The ratios of \(\tau_2/\tau_1\) and \(\tau_3/\tau_2\) can be used to provide discrimination between jets formed from the parton shower of light quarks or gluons and jets containing two hadronic decay products or three hadronic decay products from boosted top quark. These ratios will be referred to as \(\tau_{21}\) and \(\tau_{32}\) respectively.

3 Data and Monte Carlo (MC) Samples

3.1 Data Sample

The data used in this analysis is a Jet stream skim corresponding to 4.7 \(fb^{-1}\) of integrated luminosity, and a center of mass energy \(\sqrt{s} = 7\ TeV\).
3.2 Monte Carlo

Two sources of background were used for this study. The Monte Carlo sample used in this analysis for $W+\text{jets}$ background was generated by ALPGEN, while the QCD background was generated by PYTHIA. There were also two signals in the study: $tt\bar{t}$ and $\rightarrow tt\bar{t}$. The $tt\bar{t}$ is generated by MC@NLO while the $Z'\rightarrow tt\bar{t}$ sample was by PYTHIA. For this analysis $Z'\rightarrow tt\bar{t}$ was chosen to provide a larger sample of boosted tops.

4 Selection

This selection is the standard Columbia semi-leptonic, boosted top selection.[5]

Event-level Trigger and Data Quality Selection  The standard data quality and vertex requirements (First vertex has $\geq 5$ tracks and type=1 or 3) are applied. There is no trigger requirement. Exactly one muon is required for this study.

Event-level Jet Selection  Anti-$k_t$, $R=0.4$ jets are required to have $p_T >30$ GeV and a jet vertex fraction of $|JVF| > 0.75$. The jet vertex fraction is a discriminant which measures the probability that a jet originated from the particular vertex in an event.[4] No LooseBad Anti-$k_t$, $R=0.4$ jets are accepted (jet cleaning). At least 1 Anti-$k_t$, $R=1.0$ (large-$R$) Jet was required. The large-$R$ jet required an $|\eta| < 2.0$ along with $p_T > 350$ GeV. The mass cut window for this large-$R$ jet is $120<\text{mass}<250$ GeV. Finally, the b-tag requirement is $MV1>0.607$.

Muon Selection  Muons must be reconstructed in both the inner detector and muon spectrometer with $p_T >25$ GeV and $|\eta| < 2.5$. Also, the MiniIsolation requirement was $\text{MI}/p_T <0.05$.

Event-level neutrino and leptonic-\textit{W} requirement  Events are required to have a missing energy $E_T > 20$ GeV. Also, the scalar sum of the missing energy and transverse mass of the leptonic W boson must have $E_T+M_W^{T} > 60$ GeV, where $M_W^{T}$ is the combination of the muon $p_T$ and $E_T$ in the event.

4.1 Motivation for New Selection

Sample  The shape and distribution of QCD background against a $Z'\rightarrow tt\bar{t}$ sample is displayed here:

- trimmed, Anti-$k_t$, $R=1.0$ jets, no b-tag, $600 < p_T <800$ GeV
Observations  Relatively uniform distribution for $\tau_{21}$ and decided not to implement a cut based on these plots. Cuts on the $k_t$ splitting scales clearly eliminate high QCD regions, but the N-subjettiness cut is more unclear for this sample.

Sample  Another W+jets sample is displayed here but with no b-tag:

- trimmed, Anti-$k_t$ 10 jets, no b-tag
Observations There is no good place to cut on $\tau_{21}$. This is most likely because the W+jets background appears to be similar to $t\bar{t}$ due to the fact that final state radiation can be present in other Anti-$k_t$, R=1.0 jets and may even appear to have substructure. Again, the splitting scale cuts again would eliminate high W+jets background regions but the N-subjettiness cuts is less conclusive. This is not a surprising result because, in general, N-subjettiness is a better discriminant for eliminating QCD background rather than W+jets. N-subjettiness cuts would be more useful for a hadronically decaying W boson rather than a leptonic one where QCD background is much more prominent.

4.2 Proposed Substructure Selection

- $d_{12} > 40$ GeV
- $d_{23} > 20$ GeV
- $\tau_{32} < 0.8$

5 Results With No b-tag

The results of the substructure cuts will be displayed before and after a b-tagging cut. The results do not include dibosons or single top as background, which could account for Data to Monte Carlo discrepancy. Also, the error bars are statistical uncertainty only, there were no systematics implemented.

The plots on the left-hand side are the substructure variable distributions inside the mass cut window. On the right-hand side shows the mass plot with the current implemented selection along with only the new, specified substructure variable in that section.
5.1 Mass with Current Selection

- Full mass distribution with current selection (no btag, no substructure selection)

5.2 Mass with $d_{12} > 40$ GeV

**Observations**  As seen in the mass plot following the first splitting scale cut (right figure), the region leading up to the mass cut window has been largely eliminated although very little signal or background was lost inside the mass window as a result of this new selection.
• Efficiencies in mass cut window (120-250 GeV)
  - Signal Efficiency : 95.76%
  - Background Efficiency : 95.43%

5.3 Mass with $d_{23} > 20$ GeV

Observations  The mass plot following the second splitting scale cut (right figure), displays the potency of this new selection. It was able to eliminate almost two-thirds of the background while only losing approximate one-third of the signal. This is in addition to eliminating the spike before the mass cut window.

• Efficiencies in mass cut window (120-250 GeV)
  - Signal Efficiency : 62.78%
  - Background Efficiency : 37.46%
5.4 Mass with $\tau_{32} < 0.8$

**Observations** As seen in the mass plot following the $\tau_{32}$ cut (right figure), the region leading up to the mass cut window has been reduced very minimally but the effects inside the window are much more noticeable with a background rejection of over 30%.

- Efficiencies in mass cut window (120-250 GeV)
  - Signal Efficiency : 81.85%
  - Background Efficiency : 68.50%
5.5 Mass with All New Selection

**Observations**  With the new substructure selection it is clear that the sample has become purer. The new selection was able to eliminate approximately 70% of the background while keeping about 58% of the signal in tact.

- Efficiencies in mass cut window (120-250 GeV)
  - Signal Efficiency: 57.88%
  - Background Efficiency: 30.38%

5.6 MV1 Distribution

- Mass efficiencies strictly after b-tag cut (.607):
  - Signal Efficiency: 61.85%
  - Background Efficiency: 11.58%
6 Results with b-tag

The next section shows the mass spectrum with the current selection along with the b-tagging cut and then subsequently displays the effects of implementing individual substructure variable selection. Finally, it will conclude with displaying the effects of all of the current selection, one btag, and all of the substructure selection implemented together.
6.1 Mass with Current Selection and b-tag

- Mass distribution with implemented selection and btag1 (no substructure selection)

6.2 Mass with $d_{12} > 40$ GeV

Observations  The first splitting scale cut had a similar effect after one btag. It was effective in eliminating the region leading up to the mass window but had almost no effect inside the mass cut window (right figure).

- Efficiencies in mass cut window (120-250 GeV)
– Signal Efficiency : 97.43%
– Background Efficiency : 97.96%

6.3 Mass with $d_{23} > 20$ GeV

**Observations** The second splitting scale cut is proving to have the strongest potency in the study. After the btag it was able to eliminate nearly 65% of the background while preserving nearly 70% of the signal

- Efficiencies in mass cut window (120-250 GeV)
  - Signal Efficiency : 69.16%
  - Background Efficiency : 35.58%
6.4 Mass with $\tau_{32} < 0.8$

Observations The $\tau_{32}$ proved to be a relatively effective discriminant again. With the ability to reduce background by almost 30% and only lose approximately 13% of the signal this N-subjettiness cut seems potentially worth while.

- Efficiencies in mass cut window (120-250 GeV)
  - Signal Efficiency : 87.15%
  - Background Efficiency : 72.45%
6.5 Mass with All New Selection

**Observations**  With all of the cuts implemented there is no doubt that the sample is more pure. The ratio of background eliminated to signal lost is $\sim 2$. Even after a powerful discriminant like b-tagging in implemented substructure selection has benefits.

- Efficiencies in mass cut window (120-250 GeV)
  - Signal Efficiency : 66.88%
  - Background Efficiency : 33.54%

7 Conclusion

This paper displayed the effects of substructure selection on highly boosted and trimmed $t\bar{t} \rightarrow WbWb \rightarrow \mu\nu bqqb$ events with and without b-tagging. Some of the selection proved more of an effective discriminant than others. The $k_t$ splitting scale cuts were far more effective in eliminating background before the mass cut window than b-tagging or N-subjettiness, but overall b-tagging is the most powerful discriminant inside the mass window. After observing all of the proposed selection, the $d_{23} > 20$ GeV cut proved to be the most effective substructure variable cut in terms separating signal from background. The other substructure cuts had some effect although not as powerful. After b-tagging, which is an extremely strong discriminant in itself, making substructure selection is up for debate.
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8 Acknowledgements

I would like to thank Emily Thompson my advisor throughout this whole process, Andrew Altheimer for helping me with anything I needed, and John Parsons for the amazing opportunity to work at CERN. I would also like to acknowledge the National Science Foundation for their continuing support of the Research Experience for Undergraduates (REU) program.
9 Bibliography

References


