Discriminating Multiprong Jet Substructure

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Abstract. A wide array of jet substructure based techniques have been used to discriminate large-radius jets coming from the hadronic decay of top quarks against those from light quark or gluons. However, discriminating jets with more than three-prongs have been much less explored. In this work, a new physics signal of a boosted right handed heavy neutrino decaying to a top and bottom quark along with a charged lepton is investigated. The aim is to see which jet substructure observables can be sensitive to identify this signal over the top quark pair production background processes.

1 Introduction

1.1 Jet Basics

In collider physics, Jets are the signatures of quarks and gluons in high energy collisions, such as the proton-proton collisions at the LHC (Large hadron Collider). That makes these jet observables extremely important and useful for countless analysis in high energy physics. The strong interactions of quarks and gluons is inherently different from what is seen in weak interactions.

Particles carrying colour charge cannot exist freely as observed by those carrying electroweak charge, this is due to colour confinement in QCD (Quantum Chromodynamics). This ensemble of quarks and gluons are commonly referred to as partons, this results in a collection of partons in a colourless bound state called hadrons. Quarks can radiate gluons, in the same manner as how electrically charged particles can radiate photons, these gluons can then decay to quark anti-quark pairs, as how photons can decay to a lepton pair. This means a single parton may create a shower of partons, resulting in a energy deposits in a number of calorimeter cells in a "cone-like" shape. This collimated collection of bunches of hadrons is what creates our jet, where ideally each bunch would form from a single parton. It is important to note, that jets are not fundamental objects, but a construction of hadrons originating from a single parton [1].

A generic jet forming algorithm is used to construct these jets, which can be described as a set of inputs with four momenta, p^h_N mapped to a set of jets with four momenta, p^j_M. Where these inputs may be hadrons or other detector objects. Thus in the general algorithm we have $p^j = \sum_{i\in j} p^h_i$ where $N > M$. There are more explicit jet algorithms used which in turn decide which objects are inputs for the jet construction, such as energy deposits in calorimeter or tracks. The most commonly used algorithm, and the algorithm used in this study, is the anti-k_T algorithm [2]. It begins with the highest p_T (transverse momentum, momentum along the beam line) object as the initial input and then absorbs all other softer objects around to construct the jet with some radius R_0 (most commonly used radius definitions are $R = 0.4$ for standard jets and $R_0 = 1.0$ for large radius jets). Jets can also be b-tagged and top-tagged, this means the jet has been found to originate from a bottom quark or top quark respectively.

1.2 Jet substructure

Jets can also have "prongs", depending on the origin, these prongs are distinct substructure or "branches" inside a jet, usually tracks or subjets. N-subjettiness refers to the categorisation of how many dominant flows of energy are inside a large radius jet [3, 4]. For a top quark, this would be reconstructed as a large radius top-tagged jet. The top quark decays to a W^+ and a bottom quark ($t \to W^+ b$) the W^+ the decays to a lepton or quark pair.Thus the final state of the top quark decay is a b-tagged jet and quark or lepton pair. This would result in the large radius jet having substructure with three distinctive energy flow directions of tracks and a subjet coming from the individual leptons or quarks and the b-tagged jet.

The radiation patterns and substructure of jets can be unique and distinct for different scenarios, thus jet substructure tools were developed to exploit this information. The τ_N substructure variable can be used to exploit the number of prongs or subjets inside a jet given by [1],

$$\tau_N = \frac{1}{d_0} \sum_{k=N}^{k=0} p_{T,k} \times \Delta R_{min,k}$$

Where k is the subjet constituent and $\Delta R_{min,k}$ is the minimum distance of constituent k and the nearest subjet. The normalisation factor d_0 is the p_T sum of all constituents multiplied by jet radius to ensure $0 < \tau_N < 1$. Using this definition τ_N describes how well a jet can defined as having N or fewer jets, by assessing how well the constituents are aligned to the axis of the subjets. Taking the ratios of different τ_N values can allow us to identify multiprong jets over another. τ_{32} allows us to identify three prong over two prong decay, and in same fashion τ_{21} allows us to identify two prong over one prong decay.

Using jet substructure for jets with more than 3 prongs is scarcely ventured territory. However, in many cases substructure variables are extremely valuable for signal to background discrimination. The aim of this study is to determine whether τ_N variables can be used to discriminate 4 prong structure from 3 prong structure. This would be extremely useful for future analysis considering new topologies and analysis which may not have currently useful discriminating variables.

2 The Model

2.1 Left-Right symmetric models

This study uses simulated samples from MadGraph5 [5] showered with Pythia8 [6], the model used is from the Left-Right symmetric models (LRSMs) [7, 8, 9, 10]. These models predicts a particle spectrum with several extra states such as new charged and neutral gauge bosons, extra (pseudo)scalars and three generations of right handed neutrinos. These models also provide naturally small neutrino masses through the seesaw mechanism. The specific model for this study is the production of a right handed charged gauge boson (W_R) and a right handed heavy neutrino (N_R) [11].

2.2 The signal

The W_R decays to a NR and a lepton, the N_R then decays to a top quark, a bottom quark and an additional lepton. The Feynman diagram in Figure 1 shows the decays and final states.

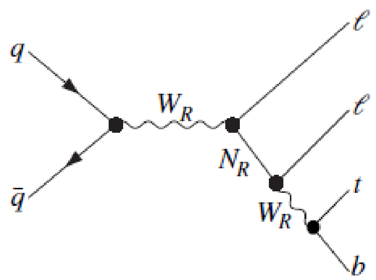

Figure 1: Feynman diagram showing the neutral charged boson decay, and the heavy right handed neutrino decay [11].

In most cases the top quark is highly boosted, this would result in high p_T distribution. Events are only selected if containing two muons, this is due to the fact that muons are a cleaner signature at detector level for a proposed search. Jets can often be misidentified as electrons and vice versa. Thus using muons results in a more efficient final state which allows for a better discrimination of the jet prongs, as well, least one top-tagged jet is required in the fin state. The top jet will be a large radius jet consisting a of a b-tagged jet, thus at least on b-tagged jet is required. This presents us with a final state consisting of two muons, a b-tagged jet and a top-tagged large radius jet. In the sample generated and used in this study, the W_R has a mass of 1.5 TeV and the N_R has a mass of 2.25 TeV.

3 Results

To ensure the correct final state objects are being used to reconstruct the W_R, kinematic variables are plotted. The leading and subleading muon p_T is shown in Figure 2.

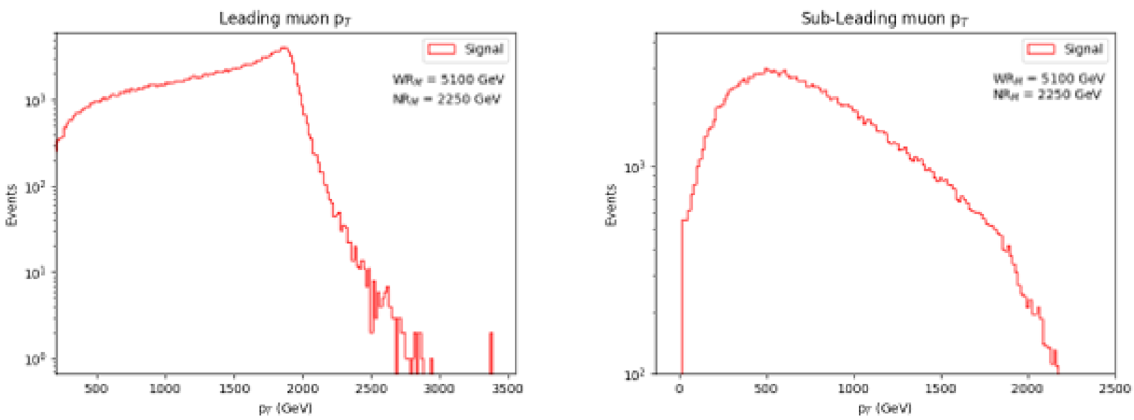

Figure 2: (*left*) Leading muon p_T. (*right*) Subleading muon p_T.

The top-jet is expected to be the leading large radius jet. In Figure 3, it is clear the leading large radius has the mass of the top jet. Thus, we can select the leading large radius jet as our top jet.

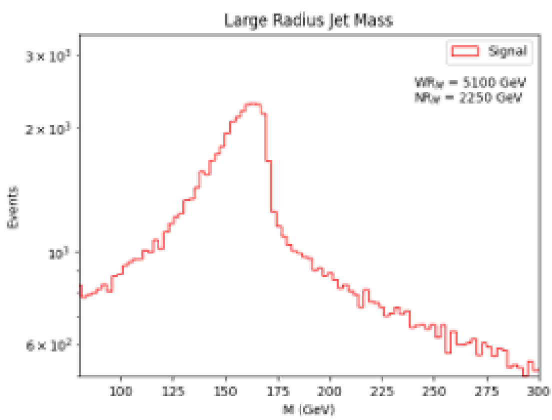

Figure 3: Large radius jet mass.

The bottom jet is chosen by selecting the leading jet that is b-tagged. The p_T of the top jet and b-tagged jet are shown in Figure 4.

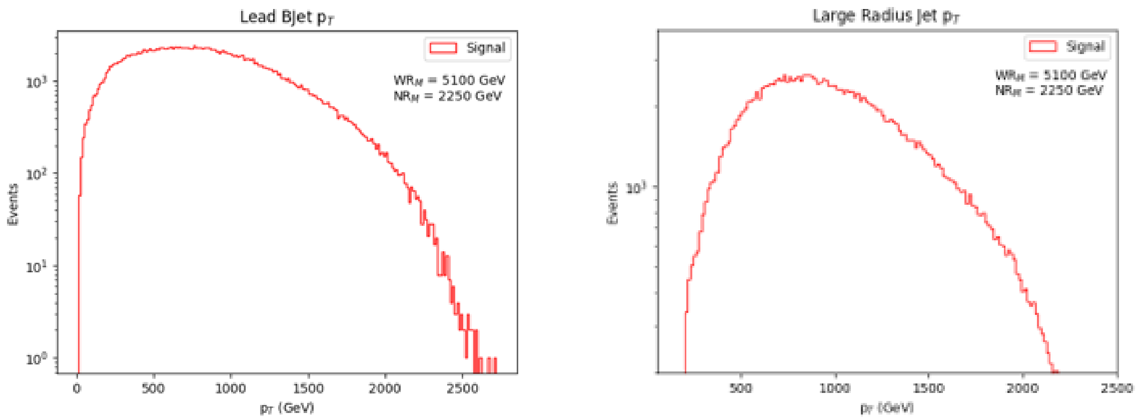

Figure 4: (*left*) b-tagged jet mass. (*right*) Top jet p_T.

The W_R is then reconstructed by taking the invariant mass of the final state objects. We vector sum the four momenta of the leading and sub-leading muons, the leading b-tagged jet as well as the chosen leading large radius jet for the top jet. The invariant mass of the final state objects is shown in Figure 5, from this figure we can see than the invariant mass peaks around the mass of the 1.5 TeV so we are able to reconstruct the W_R.

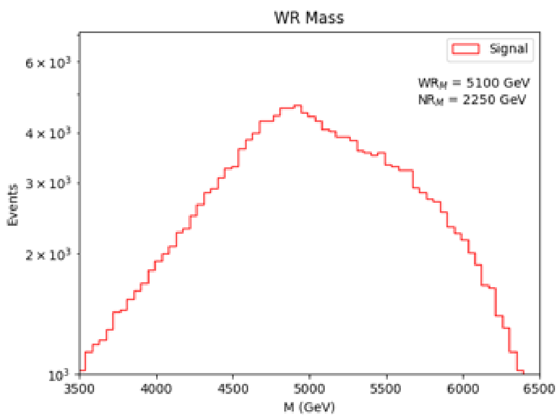

Figure 5: Invariant mass of the leading and subleading muons,the b-tagged jet and the chosen top jet.

4 Discriminating jet prong substructure

In order to compare a 3-prong jet to a 4-prong jet a SM (standard model) semi-leptonic $t\bar{t}$ sample was generated using Pythia8. Various τ_N variables were calculated and the ratios taken for both samples.

Figures 6 to 8 show these variables plotted comparing the signal to the SM semi-leptonic $t\bar{t}$ sample. Although the shapes are similar, there are clear differences between the signal and the SM top sample. This shows promise is using substructure variables to discriminate multiprong jets, with more than 3 prongs.

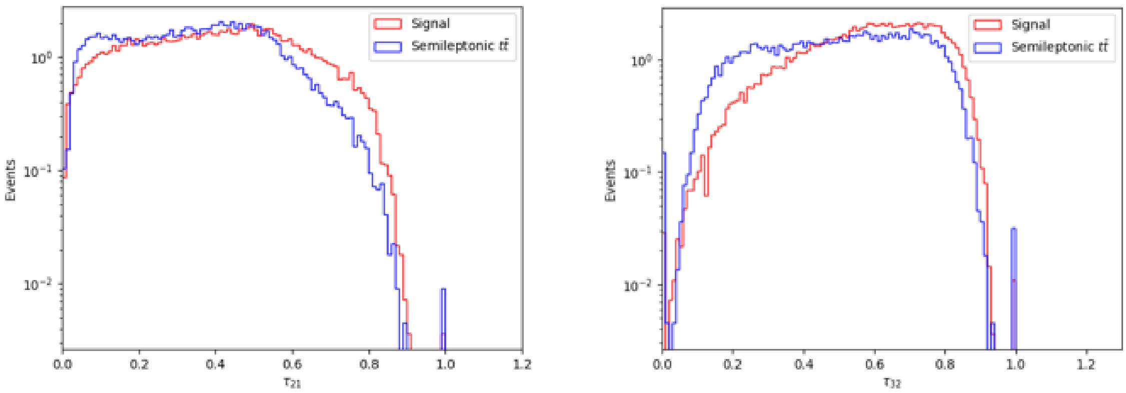

Figure 6: (*left*) τ_{21} comparing 4-prong signal and 3-prong $t\bar{t}$. (*right*) τ_{32} comparing 4-prong signal and 3-prong $t\bar{t}$.

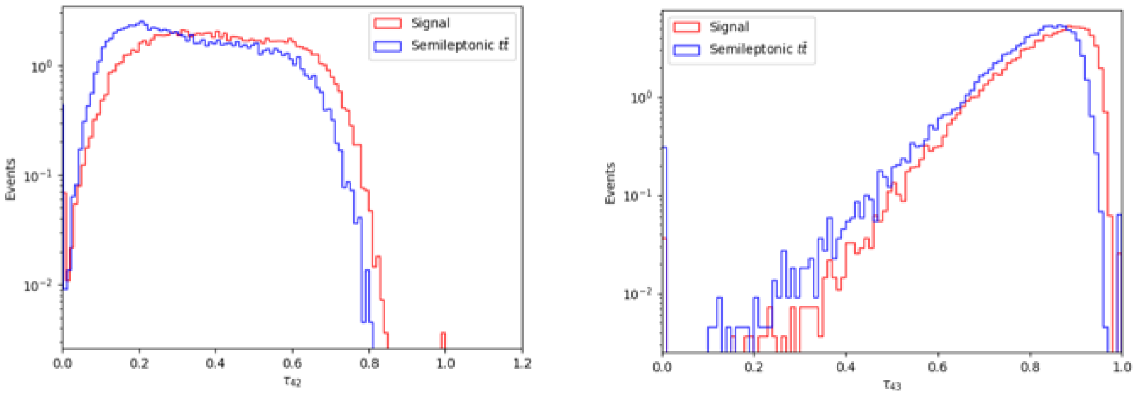

Figure 7: (*left*) τ_{42} comparing 4-prong signal and 3-prong $t\bar{t}$. (*right*) τ_{43} comparing 4-prong signal and 3-prong $t\bar{t}$.

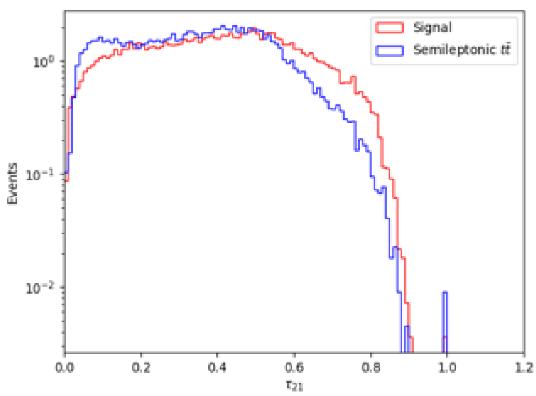

Figure 8: τ_{54} comparing 4-prong signal and 3-prong $t\bar{t}$.

5 Conclusion

This study shows promise for future discrimination of multiprong jet substructure. Using a sample where we are able to reconstruct the neutral charged gauge boson which has a 4-prong substructure. We compare this to a SM semi-leptonic $t\bar{t}$ sample which has a 3-prong jet substructure. Although the discrepancies are not substantial, this still shows that 3-prong substructure can be discriminated from a 4-prong substructure. Future studies would involve calculating τ_N with different jet reconstruction algorithms, as well as investigating and comparing other substructure variables.

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