ATLAS NOTE

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Observing Boosted Hadronically Decaying W and Z bosons with Jet Substructure

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Abstract

Recent phenomenological and experimental studies have demonstrated the potential of analysis techniques involving jet substructure for the discovery of new heavy particles. These techniques have been validated with realistic detector simulations, but such is their novelty that ATLAS needs to confront them with data as soon as possible. In this note we present a simple particle-level study of the capabilities of a jet substructure technique in relation to observing W and Z bosons in the coming LHC run.

1 Introduction

At the LHC for the first time large numbers of heavy standard model particles such as W and Z bosons will be produced with significant Lorentz boosts. When such particles decay hadronically, the large boosts mean the decay products tend to be close together and reconstructed as a single jet. The flow of energy within the resulting jets has structure which can be used to identify the presence of the heavy particle. Further analysis can then be applied to reduce the contamination from effects such as underlying event and pile-up. Such techniques have been shown to be effective in a variety of new physics scenarios [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

One particular approach [10] takes advantage of the angular ordering of the Cambridge-Aachen (C-A) jet finder [12, 13]. After finding jets with this algorithm, the clustering can be undone one step at a time. This particuar method finds large radius jets then undoes the clustering, looking for steps where two light objects were combined to make one heavy object. Such a splitting is indicative of the presence of a two-body decay of a heavy particle. The constituents of these two "sub-jets" are then further filtered by clustering with a smaller radius.

This technique has been shown to be effective for identifying Higgs decays to $b\bar{b}$ at the hadron level [10] and at the ATLAS experiment [11]. It has two tunable parameters;

- μ, the fraction by which the mass of the jet must drop to be considered a hard splitting and
- y, the minimum allowed $k_\perp$ between the two sub-jets.

The y requirement helps to select only symmetric splittings.

Here events have been generated with HERWIG 6.510 [14, 15] using the Rivet [16] framework. Samples of QCD dijets, W+jets and Z+jets events were generated corresponding to the amounts expected for 1 fb^{-1} of integrated luminosity at the LHC.

2 Results

Initially we define jets using C-A jets with a radius parameter $R = 0.7$. Some basic kinematic variables are shown in Fig. 1 and Fig. 2. Fig. 1a shows that before applying any jet mass or substructure requirement, the background is around two orders of magnitude above the signal. Fig. 1b shows that the jets are back-to-back, that is the structure of the events is dijet-like. In Fig. 2 the rapidity and pseudorapidity distributions are shown, after applying a $p_\mathrm{T} > 400$ GeV cut. The jets are central in the detector.

We next apply the procedure as described in [10] with the parameters set to $\mu = 1/3$ and $y = 0.09$. Significances are calculated by counting the number of jets in a mass window of 75 GeV to 95 GeV. Jets from W+jets or Z+jets events are considered to be signal (S), while jets from QCD dijet events are considered to be background (B).

In performing the subjet analysis we scan across the relevant parameters. First we adjust the p_T requirement, the effects on S/B and $S/\sqrt{B}$ can be seen in Fig. 3. Higher p_T cuts tend to offer somewhat better S/B but worse $S/\sqrt{B}$. Tuning this cut offers some ability to trade-off between statistical and systematic uncertainties as necessary. Based on this we choose 400 GeV as a reasonable benchmark cut and also sufficiently high as to be relatively free from experimental effects such as trigger limitations. The distribution of heavy-particle candidate masses after a $p_\mathrm{T} > 400$ GeV cut but before any subjet analysis is shown in Fig. 4.

The results of tuning μ can also be seen in Fig. 3. It is observed that lower cuts (i.e. stricter mass drop requirements) tend to offer better S/B. However at very low values the significance starts to be affected by strongly falling signal statistics. Based on this graph, we choose two benchmark points, one conservative one where $\mu = 1/3$ and one somewhat more aggressive one where $\mu = 1/5$. These two

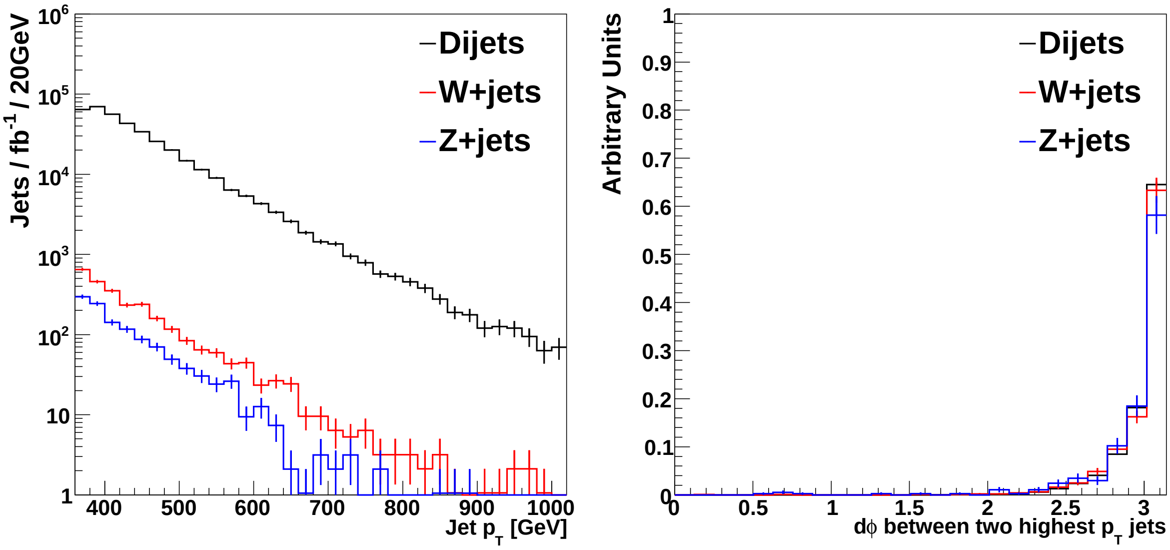

Figure 1: Kinematic distributions for C-A jets with $R = 0.7$, p_T (left) and $d\phi$ between the two leading jets where the leading jet has $p_T > 400$ GeV (right)

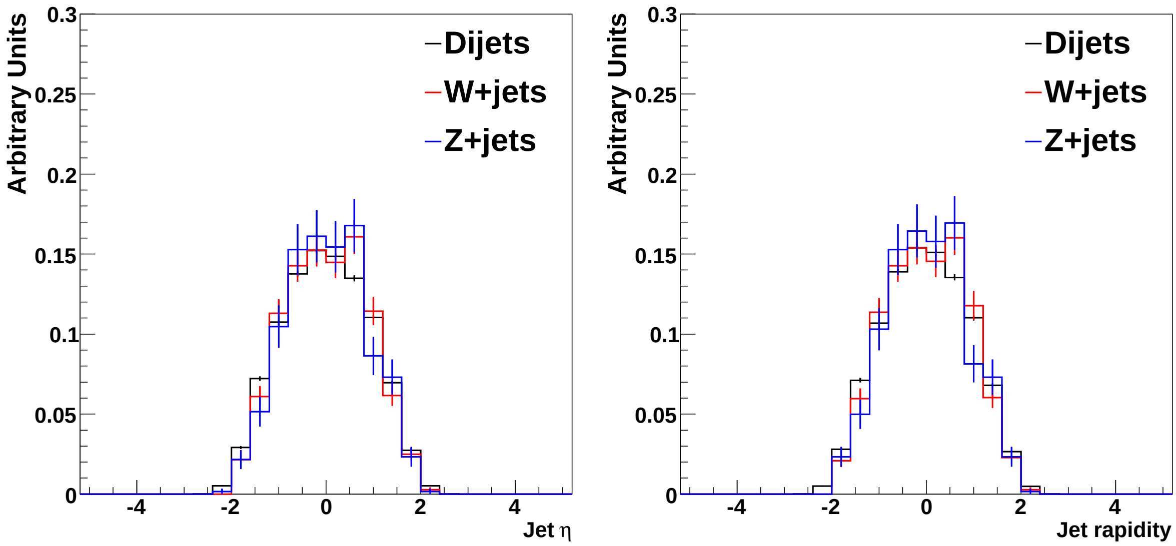

Figure 2: η (left) and rapidity (right) for C-A jets with $R = 0.7$ and $p_T > 400$ GeV

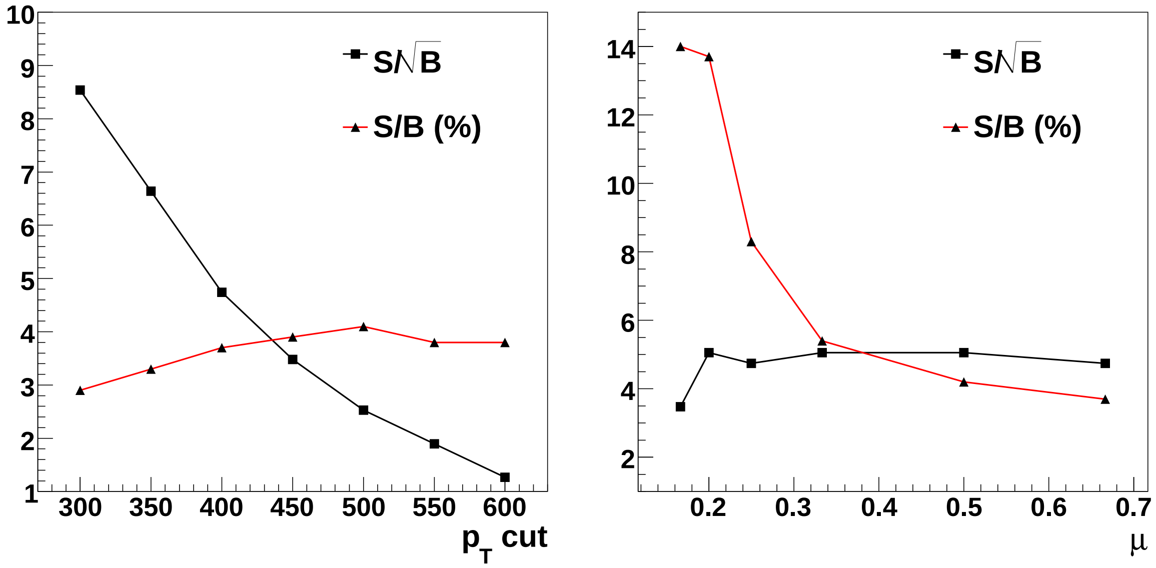

Figure 3: Scan of possible values of p_T cut (left) and μ cut (right)

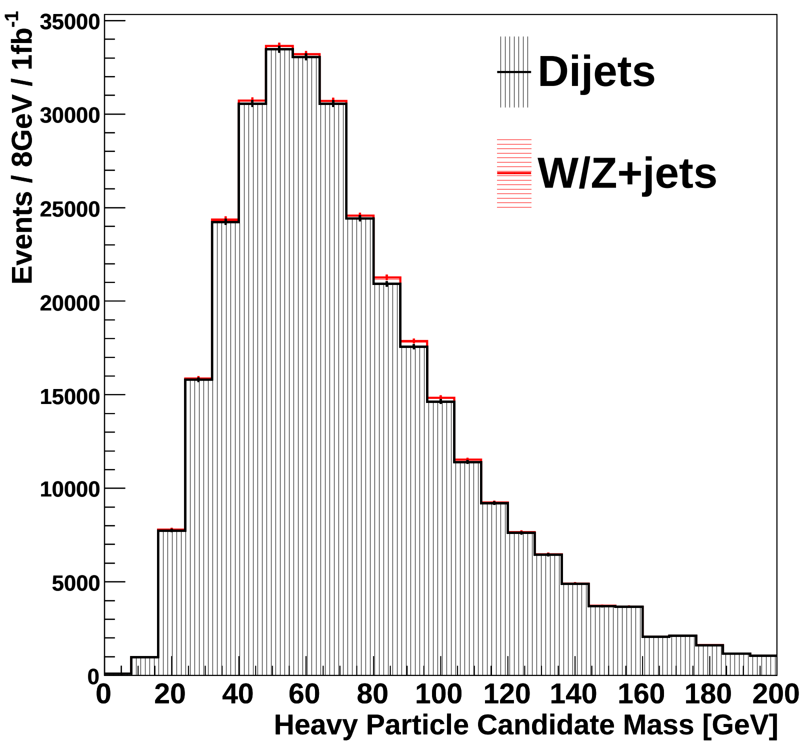

Figure 4: Mass of heavy particle candidates from C-A R=0.7 jets with $p_T > 400$ GeV where no jet substructure procedure has been applied.

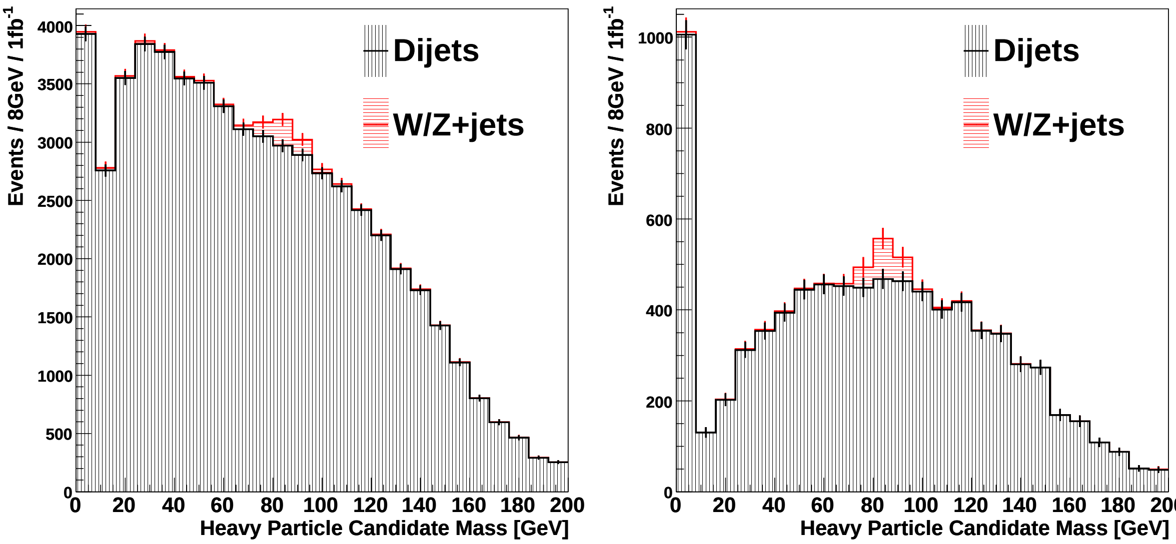

Figure 5: Mass of heavy particle candidates after jet substructure analysis on C-A R=0.7 jets with $p_T >$ 400 GeV for two scenarios, $\mu = 1/3$ (left) and $\mu = 1/5$ (right).

points offer hadron-level significances of around 5σ with 1 fb^{-1} of LHC data with S/B of around 5% and 13% respectively.

The distributions after the two choices of subjet analysis described above, are shown in Fig. 5. Clearly the signal is greatly enhanced compared to Fig. 4. The plots are binned in 8 GeV intervals, a value believed (based on full detector simulation [11]) to broadly approximate the experimental resolution effects. In both, the peaks are clearly visible above the QCD background although the background shape is very different between the two. The slightly peaked background for $\mu = 1/5$ may be disadvantageous from a systematic point of view although this may be compensated by the higher S/B.

One further tuning that can be explored is to increase the radius parameter R of the initial jet finding from 0.7 to 1.2. The effects of this change can be seen in Fig. 6. Although the signal region is largely unaffected, the shape of the background in the high mass tail is strongly flattened. This ability to choose a flatter background shape may well be useful in a full study. Overall these plots show that by tuning the available parameters there is a great deal of flexibility in terms of background shape.

The shape of the signal distribution can be seen in Fig. 7, plotted with both 8 GeV binning as the above plots and with 4 GeV binning. Although experimental resolution will probably not reach 4 GeV, the large signal statistics may make it possible at somewhat higher luminosities to obtain information about the relative rates and positions of the W and Z boson peaks.

3 Conclusion

Extracting the singly-produced hadronically decaying W and Z bosons in W+jets and Z+jets events is a challenging task which has never been accomplished at high p_T at a hadron collider (although unboosted decays were seen in [17]). Subjet techniques such as this offer a possible approach, here showing that with minimal tuning at the hadron-level it is possible to extract a significance of around 5σ within 1 fb^{-1} of LHC luminosity. A full study with detector simulation is required to more accurately evaluate the sensitivity of this technique but the available evidence and current LHC schedule suggests a promising outlook for this measurement in the 2010/2011 run.

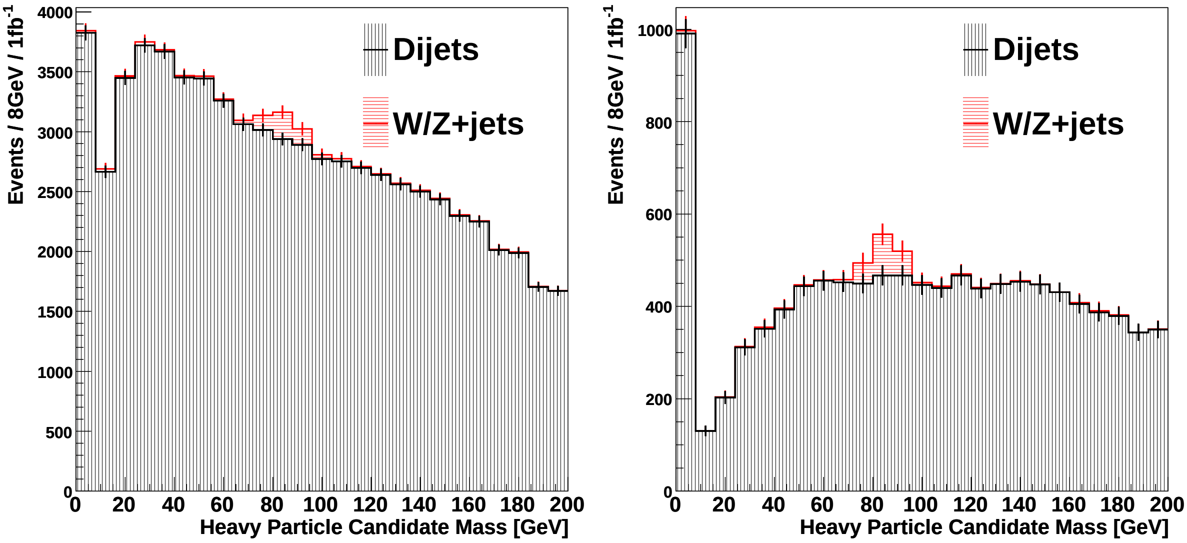

Figure 6: Mass of heavy particle candidates after jet substructure analysis on C-A R=1.2 jets with $p_{\mathrm{T}} >$ 400 GeV for two scenarios, $\mu = 1/3$ (left) and $\mu = 1/5$ (right).

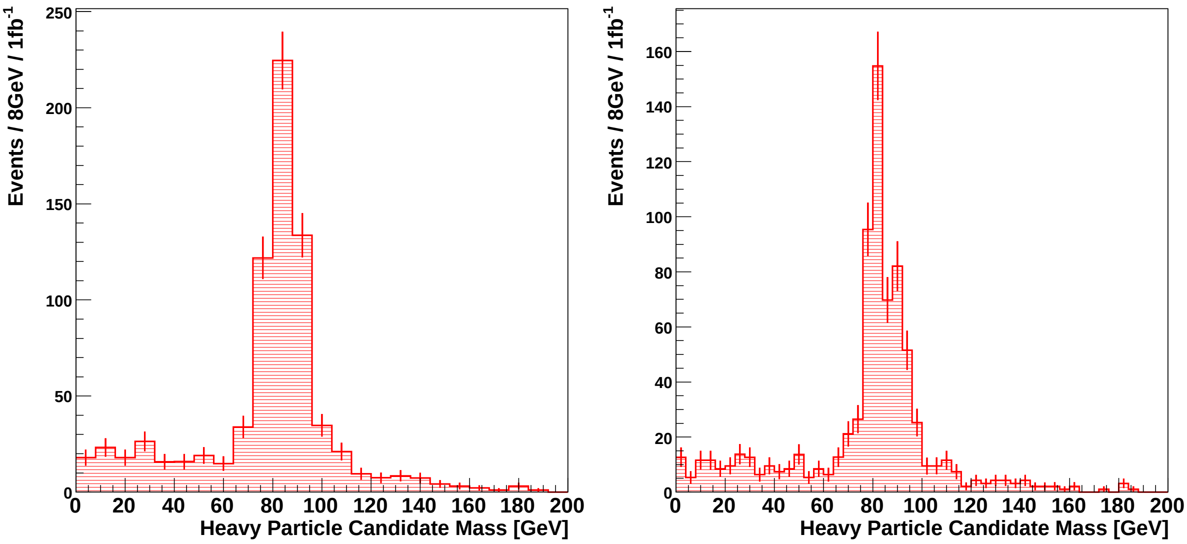

Figure 7: Mass of heavy particle candidates in signal sample only after jet substructure analysis on C-A R=1.2 jets with $p_{\mathrm{T}} > 400$ GeV and $\mu = 1/3$ in 8 GeV bins (left) and 4 GeV bins (right).

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