ATLAS+CMS: Boosted topologies (Run1 results, Run2 potential)

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As no sign of beyond the Standard Model physics has yet been observed at the LHC, experimental searches continue to probe ever higher mass scales. The decay of new, heavy resonances can produce highly Lorentz boosted particles, such as top quarks and Higgs or vector bosons. The decay products of these boosted particles are very highly collimated, and novel techniques are needed to identify such decays. In this paper, recent analyses from ATLAS and CMS in the boosted regime are reviewed, with an emphasis on jet substructure techniques and their application.

1 Introduction

Many models of beyond the Standard Model (BSM) physics predict the existence of states which decay to top quarks and Higgs or vector bosons. If the mass difference between the mother and daughter particles is sufficient, the daughter particles are produced with significant Lorentz boost and their decay products will be narrowly collimated. In the event the daughter decays hadronically, the resulting shower produces a "fat" jet with a radius of $R \approx 2m/p_T$, where m and p_T are the mass and transverse momentum of the daughter, respectively.

In order to search for such a decay, one must contend with overwhelming background from QCD interactions. Fortunately, a number of techniques have been proposed in the literature to identify the hadronic decays of top quarks and Higgs and vector bosons. The most powerful handle at our disposal to discriminate between jets from heavy particle decays and those from light quarks and gluons ("QCD jets") is the jet mass. Unfortunately, the jet mass is highly sensitive to pileup and underlying event activity. However, a number of grooming algorithms have been proposed (pruning [1], trimming [2], filtering [3], soft drop [4], etc.) to remove soft and wide angle radiation from the jet clustering history, which significantly pushes the mass distribution for light jets towards zero while having only a minimal effect on jets from heavy particles decays. The effect of grooming on the jet mass distribution [5] and the stability with respect to pileup [6] are shown in Figure 1.

In addition to the mass, a number of jet shape observables are useful for discriminating between QCD jets and those from heavy flavor decays. The k_T-splitting scale [7] and mass drop [3] observables exploit the symmetric nature of heavy particle decays. N-subjettiness (τ_N) variables [8] characterize the consistency of a jet with being composed of N or more subjets. Energy correlation functions [9], quark/gluon likelihood [10], jet charge [11], pull angle [12], and Q-jets volatility [13] are useful as well, among others.

Both ATLAS [14] and CMS [15] have developed b-tagging algorithms optimized for the dense environment inside highly-collimated jets. ATLAS performs b-tagging on standard anti-$\mathrm{k_T}$ R=0.4 jets and then performs a geometric matching to fat jets to tag them. CMS performs

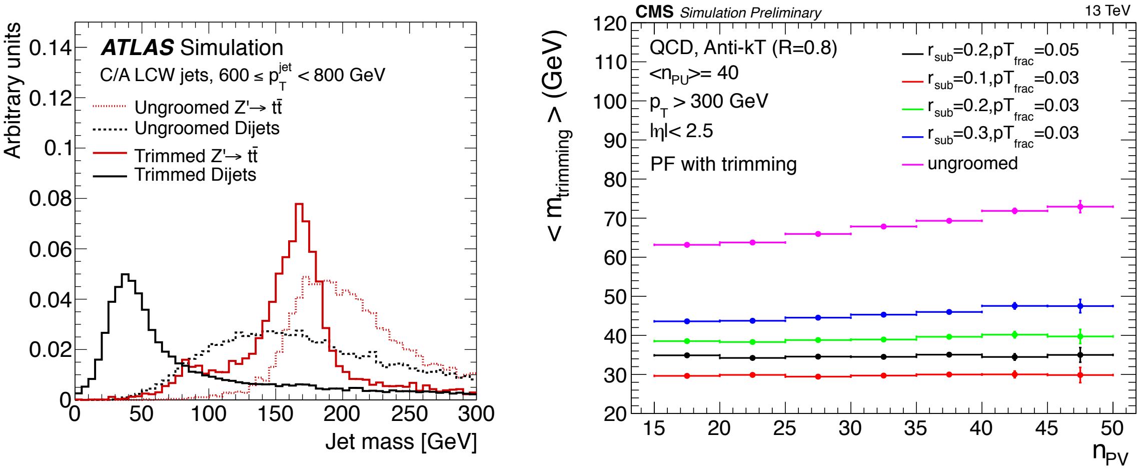

Figure 1 – The jet mass distribution for the leading-p_T jet in simulated $Z' \to t\bar{t}$ and QCD dijet events before and after trimming (left), and the stability of the average jet mass versus pileup for ungroomed and trimmed jets (right).

b-tagging directly on fat jets or subjets, depending on the kinematic regime.

Finally, all of the above techniques can be combined into a dedicated "tagger." This typically involves the application of a groomed mass window requirement along with requirements on the jet substructure. In the case of top and Higgs tagging, b-tagging can also be exploited. The BDRS [3], HEP Top Tagger [16], and CMS Top Tagger [17] are all examples. These top taggers also exploit the presence of a real W boson in the top decay chain, and require a pair of subjets to be compatible with the W mass hypothesis.

2 Analyses in the Boosted Regime

2.1 Searches for Fermion+Fermion Resonances

Both ATLAS and CMS have extensive programs of searches for $Z' \to t\bar{t}$ and $W' \to tb$ resonances. For very high mass resonances with small cross sections, the all-hadronic decay modes with large branching ratios are extremely important. It is also in this regime where jet substructure techniques are most powerful.

CMS has performed a combination of $Z' \to t\bar{t}$ searches in zero, one, and two lepton final states [18]. The all-hadronic channel exhibits a dijet topology. Both high-p_T jets were required to be top-tagged. Separate optimizations were performed in the low and high mass regimes; in the low (high) mass channel, the HEP Top Tagger (CMS Top Tagger) was used, which is based on R=1.5 ($R = 0.8$) jets. Subjet b-tagging was applied, as well as a requirement on the ratio $\tau_{32} = \tau_3/\tau_2$ in the high mass channel.

The dominant background in the all-hadronic final state is QCD dijet production. This background was modeled using a sophisticated data-driven technique. No excess with respect to the background expectation was observed. Model independent 95% confidence level (CL) cross section upper limits are shown in Figure 2, based on a combination of all channels. These were interpreted in the context of a variety of models to obtain mass exclusions. For a narrow leptophobic topcolor [19] Z' resonance with $\Gamma_{Z'}/m_{Z'} = 1.2\%$, masses below 2.4 TeV are excluded.

ATLAS performed a similar search in the lepton+jets final state [20]. Separate optimizations were performed for the cases where the top quark decay products are merged into a single fat jet, or resolved separately. Events were required to contain a high-p_T lepton, at least 1 b-jet and 1 top-jet, and large missing transverse energy ($\not{E}_T$) and transverse mass. Top tagging was performed on trimmed R=1.0 jets, requiring $m > 100$ GeV and k_T-splitting scale $\sqrt{d_{12}} >$ 40 GeV.

The $t\bar{t}$ invariant mass distribution, shown in Figure 2, was used to test for the presence of signal. No significant excess was observed. Like the CMS analysis, 95% CL cross section upper limits were established and interpreted in the context of a variety of models. For a narrow leptophobic topcolor Z' resonance with $\Gamma_{Z'}/m_{Z'} = 1.2\%$, masses below 1.8 TeV are excluded.

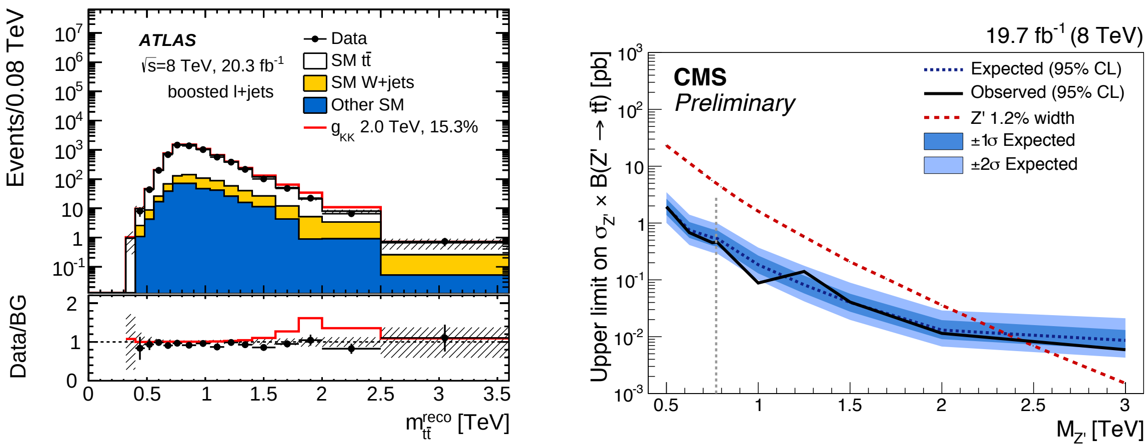

Figure 2 – The ATLAS reconstructed $t\bar{t}$ invariant mass distribution in the boosted channel (left), and the CMS observed 95% CL cross section upper limit (right).

Similar searches have been performed by ATLAS [21] and CMS [22] for $W'{\to}$tb resonances.

2.2 *Searches for Fermion+Boson Resonances*

Many BSM theories predict the existence of fermion+boson resonances; from vector-like quarks in little Higgs models [23; 24], models with extra dimensions [25; 26], and composite Higgs models [25; 26; 27], to excited fermions in composite models [28; 29; 30]. CMS recently performed searches for vector-like top [31] and bottom [32] quark partners, decaying via $T'{\to}\ tH$ and $B'{\to}\ bH$ to all hadronic final states, as well as excited leptons [33] decaying via $\ell^\star \to \ell\gamma/\ell Z$. The search for $\ell^\star \to \ell Z$ considered both leptonic and hadronic Z decays; in the latter case, jet substructure techniques were used to reject the overwhelming Z+jets background.

The all hadronic T' and B' searches were very challenging, requiring sophisticated jet substructure techniques to reject the QCD background. The T' analysis was particularly groundbreaking, as it represented the first use of a Higgs tagger combining both substructure information as well as subjet b-tagging, as well as the first vector-like quark search in an all-hadronic final state.

The search was optimized for T' pair-production, where at least one T' decays via tH to the all hadronic $bbbjj$ final state. Events were selected with at least one top-jet and one Higgs-jet. The top-jets were tagged with the HEP Top Tagger, also requiring a subjet b-tag. R=1.5 jets were Higgs-tagged by requiring a double subjet b-tag and trimmed mass $m > 60$ GeV. Events were categorized based on the number of Higgs-tagged jets in the event, and a joint likelihood was constructed based on the scalar sum of the p_T of all reconstructed jets and the mass of the Higgs-tagged jet. No significant deviation from the background prediction was observed in this likelihood distribution. 95% CL cross section upper limits were derived, and interpreted in the triangular branching ratio space of a vector-like top quark partner, shown in Figure 3.

2.3 *Searches for Diboson Resonances*

A wide variety of diboson resonance searches have been conducted recently by ATLAS [34; 35] and CMS [36; 37; 38; 39] using jet substructure techniques. With the discovery of the

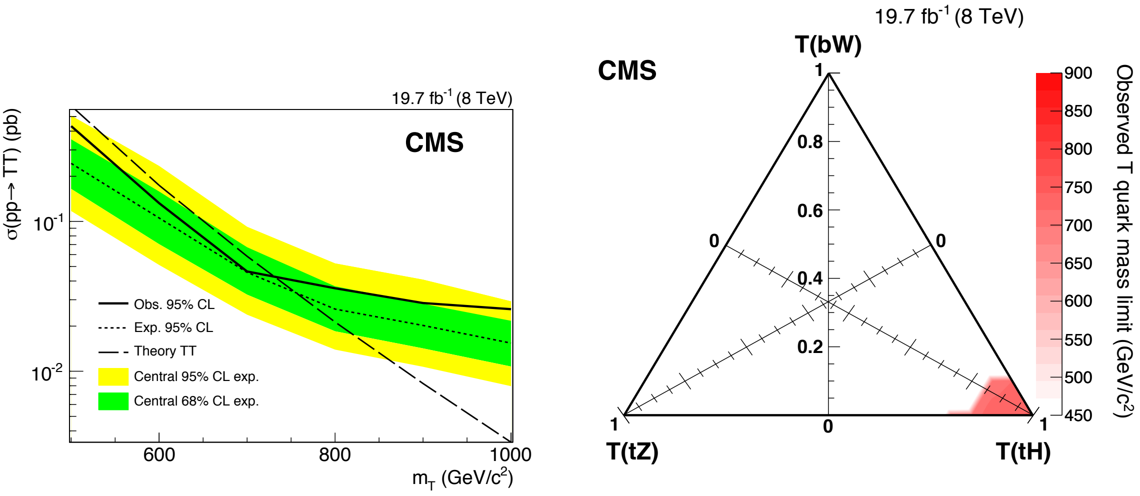

Figure 3 – The 95% CL cross section upper limits for T' pair production (left) and T' mass lower limits (right).

Higgs boson, searches for WH and ZH resonances have become viable and are being pursued vigorously. Initially these searches were focused on the dominant $H \to bb$ decay mode, but in order to maximize search sensitivity recent searches have begun to investigate sub-dominant Higgs decay modes as well.

The first search for a VH resonance in a fully-hadronic final state [36] included channels optimized to select events consistent with $H \to bb$ and $H \to WW \to 4q$ decays of the Higgs boson. This required development of a novel $H \to 4q$ tagger. Pruned R=0.8 jets were used to tag $V \to qq$, $H \to bb$, and $H \to 4q$ decays. In addition to mass window requirements, b-tagging and N-subjettiness information was utilized as well. B-tagging was applied either to the fat jet or the subjets, depending on the geometric separation of the subjets. The $V \to qq$ tagger required the N-subjettiness ratio $\tau_{21} = \tau_2/\tau_1$ to be small, while the $H \to 4q$ tagger instead required the ratio $\tau_{42} = \tau_4/\tau_2$ to be small, owing to the 4-pronged nature of the decay. The t_{42} distribution for the $H \to 4q$ signal and other processes is shown in Figure 4. No significant deviation with respect to the background prediction was observed, and resonance masses below 1.7 TeV were excluded in the Heavy Vector Triplet model [40], as shown in Figure 4.

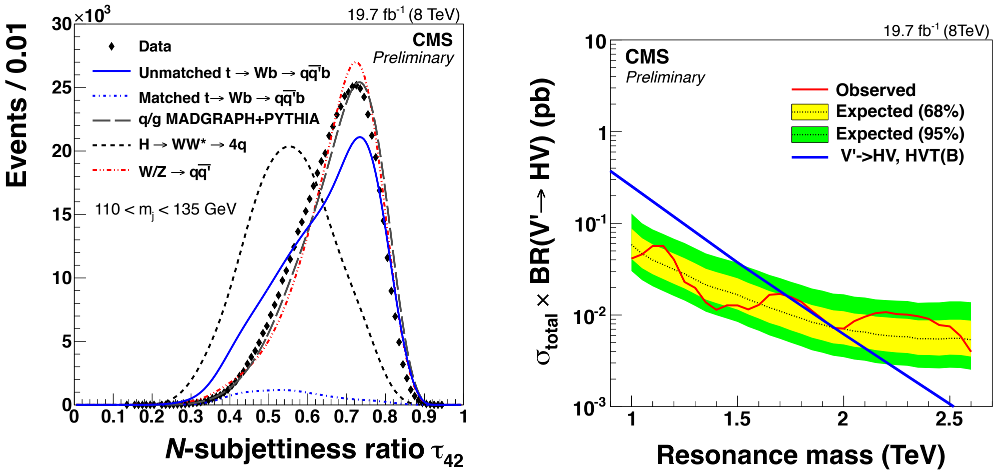

Figure 4 – The τ_{42} distribution for various processes (left) and the 95% CL cross section upper limit for a resonance decaying to VH (right).

Another recent analysis [37], optimized to search for a ZH resonance, developed a novel

$H \to \tau\tau$ tagger. In this analysis, pruned R=0.8 jets were used to tag Z-jets, along with a mass window requirement and a requirement on τ_{21}. The $H \to \tau\tau$ tagger also used pruned R=0.8 jets as a starting point. Jets with a large mass drop $\mu_{1,2} = \max(m_1, m_2)/m_{12}$ were used as inputs to the hadron-plus-strips algorithm [41] with modified isolation requirements. A likelihood-based fit was performed to reconstruct the H candidate from the visible daughters, and a mass window requirement was subsequently applied. Again, no significant deviation from the backrgound prediction was observed.

2.4 Searches for Supersymmetry

Jet substructure techniques have recently found application in high mass stop searches [42; 43]. An ATLAS R-parity violating SUSY search [44] made use of a novel application of jet substructure, so-called "accidental substructure." The analysis was optimized to search for gluon pair production, with cascades containing R-parity violating UDD couplings, ultimately producing 10 or more final state partons.

Figure 5 shows a typical signal event clustered with anti-k$_\mathrm{T}$ R=0.4 and R=1.0 jets. When clustered with R=0.4 jets, 17 unique jets are reconstructed, whereas only 5 jets are reconstructed with the larger R parameter. Unlike the jet substructure applications described above, here the goal is not to capture all the decay products from a heavy parent in a single jet; but rather to capture radiation from partons with different parents that "accidentally" fall in the same fat jet, giving rise to large mass. The observable which then discriminates between signal and background is the scalar sum of the masses (after trimming) of the four leading jets m_J^Σ. This has the advantage over more traditional analyses which rely on the scalar sum of the jet p_T in that it also exploits the rich angular structure of signal events.

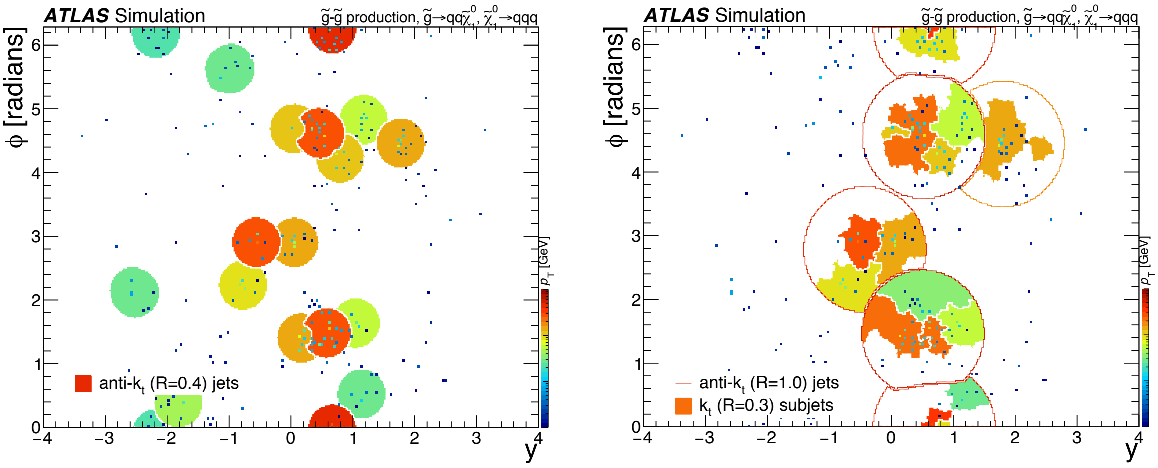

Figure 5 – A signal event clustered with anti-k$_\mathrm{T}$ R=0.4 (left) and anti-k$_\mathrm{T}$ R=1.0 (right) jets.

In addition to containing at least four R=1.0 jets, selected events were required to have a small separation in η between the two leading jets. Backgrounds were modeled with a data-driven approach. The observed m_J^Σ distribution is shown in Figure 6, which agrees well with the background prediction. The resulting 95% CL mass limits in the $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{g}}$ plane are shown in Figure 6.

2.5 Standard Model Measurements

The jet substructure techniques outlined above are now sufficiently-well understood for use in precision measurements. As such, they were recently used in a V+jets cross section measurement [45], as well as a $t\bar{t}$ differential cross section measurement [46]. These measurements were able to extend earlier leptonic measurements to a previously inaccessible kinematic regime.

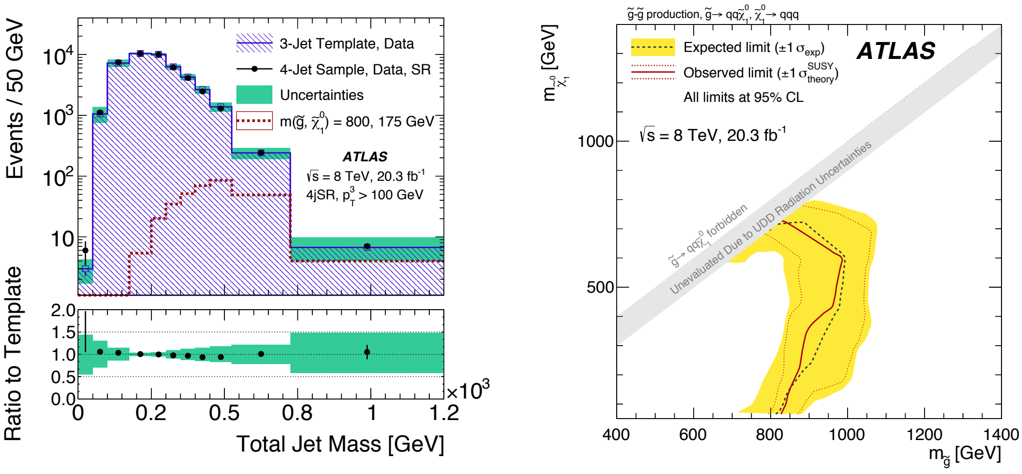

Figure 6 – The predicted and observed m_J^Σ distribution for selected events (left) and the expected and observed 95% CL limits in the $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{g}}$ plane (right).

Previous V+jets cross section measurements in leptonic decay modes only probed the region of phase space with vector boson $p_T < 300$ GeV. In the recent ATLAS analysis [45] based on hadronic decays, the cross section was measured by selecting events with R=0.6 jets with $p_T > 320$ GeV and $|\eta| < 1.9$. A mass window requirement was applied. A further enhancement of the signal sensitivity was obtained with the use of a likelihood discriminant constructed from jet shape variables in the jet rest frame. The V+jets cross section was obtained from a binned, maximum-likelihood fit to the observed jet mass distribution. A value of 8.5 ± 0.8(stat) $\pm$ 1.5(syst) pb was obtained, in reasonable agreement with the NLO theoretical prediction of 5.1 ± 0.5 pb.

3 Conclusion and Outlook

Novel jet substructure techniques proved extremely useful during Run I of the LHC. The sensitivity of many searches was increased significantly though their use, and precision measurements were extended to extreme kinematic regimes. During Run II, ATLAS and CMS will probe yet higher mass scales in the search for new physics. At these scales, heavy particles will be produced with significant boost, making jet substructure techniques essential in many analyses (if they are not already). New challenges will also be presented. Pileup mitigation will be a serious challenge with higher instantaneous luminosity and 25 ns bunch spacing. It will also be challenging to keep all-hadronic trigger rates at acceptable levels without losing significant signal efficiency. Fortunately, the experimental collaborations, with input form the theory community, are already well on their way to addressing these challenges, and jet substructure techniques will remain a powerful tool during Run II of the LHC.

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