

Searches with Boosted Topologies at the LHC

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Several models of physics Beyond the Standard Model predict new heavy particles that can decay to boosted W,Z,H bosons or top quarks, that is, with a transverse momentum that considerably exceeds their rest mass. This is a new kinematic regime where classical reconstruction approach relying on one-to-one jet to parton assignment is not adequate anymore. New techniques for the reconstruction of such objects at the LHC have been recently developed and successfully applied to analyses based on the Run I data at 8 TeV allowing to significantly extend the sensitivity of BSM searches. These new reconstruction approaches are now even more crucial for the incoming Run II at 13 TeV.

1 Introduction

The LHC has crossed a new energy frontier, where searches for new physics Beyond the Standard Model (BSM) typically involve the production of massive new particles that decay into final state object with very large transverse momenta (p_T). In this regime the resulting hadronic decay products from bosons (W,Z,H) or top quarks can be collimated and fall into a single reconstructed jet. In this case the selection based on a one to one correspondence between hadrons and jet will start to fail and new reconstruction techniques need to be employed to identify ("tag") the particle originating the reconstructed jet. Here we will show the basic concepts underlying these new methods and how they improve significantly the reach for searches of new heavy particles predicted in various BSM models.

2 Jet Grooming Strategies

Jet substructure analyses are able to distinguish the "fat"-jets, which form when highly boosted bosons or top quarks decay hadronically, from the large QCD background. A sophisticated set of tools have been developed to try to answer the following two questions. The first one, to disentangle if the jet mass is due to the decay of a massive particle or simply a consequence of the QCD emissions. The second, when the jet is indeed coming from the decay of a massive object, to disentangle the particles coming from the massive object itself from those coming from the initial state radiation (ISR) or underlying event (UE) or pile-up (PU). These factors are essential

for achieving a good mass resolution. The methods developed to address these questions are dedicated to clean away uncorrelated radiation within a jet and identify sub-jets within the candidate jet. Jet grooming refers to the elimination of uncorrelated UE/PU radiation from a target jet. Various forms of grooming have been developed. "Pruning"¹ involves reclustering the jet under scrutiny throwing away the particles that are both soft and emitted at a wide angle. In the "filtering"² approach the constituents are reclustered into subjets with a smaller cone, $\Delta R = 0.3$, then only the N (where N is fixed) hardest subjets are kept. Another technique called "trimming"³ quite similar to filtering in the sense that it also recluster the jet components using a smaller cone, but keeps all the sub-jets if above a certain scale.

3 Boosted W and Z tagging

For an electroweak boson (W or Z) with a $p_T \geq 200 \text{ GeV}/c^2$ a jet reconstructed with a large cone of $\Delta R \approx 1.0$ contains most of the decay products. The main observable to identify a V-jet^{4,5} is the mass of the jet itself once improved with grooming methods such as those described above. A good W-tagging performance is achieved selecting pruned jet masses between $60 \text{ GeV}/c^2$ and $100 \text{ GeV}/c^2$. Additional improvements can be obtained by exploiting the information from the jet substructure such as the likelihood of having two-prongs in the jet. Moreover, the jet substructure can be further exploited to extend the concept of charge tagging also to boosted Ws. A distribution of a very pure sample of boosted Ws from $t\bar{t}$ events in data is shown in Fig.1.

4 Searches with boosted bosons

4.1 Diboson

Several theories of BSM physics predict the existence of resonances with masses above 1 TeV that decay into a quark and a W or Z vector boson or into pairs of vector bosons. Given the mass range of the heavy particles being searched the analyses combine a mixture of resolved and boosted reconstruction depending on the kinematical regime. While all the possible final states have been studied by ATLAS⁶ and CMS^{7,8,9}, we focus here on the semileptonic case where one of the bosons decays leptonically (with one or two leptons in the final state) while the other decays hadronically and is V-tagged, or the fully hadronic case with one or two V-tagged jets. In general, the selection profits of the capability of identifying one or more V-tagged jets in order to suppress the large QCD or V+jets background. The final result is obtained doing a bump search over a smooth fit of the distribution of the invariant mass of the two bosons $M(VV)$, thus employing a fully data driven background estimate. Various strategies are employed to improve the sensitivity at even larger masses (where the reconstruction efficiency starts to degrade) playing with the quality requirement of the V-tag itself, to select samples with different purities. The exclusions limits are extracted for several models of excited quarks, Randall-Sundrum Gravitons, or W' .

4.2 Dark Matter

One essential part of the Dark Matter search program is the search for pair production of WIMPs at particle colliders such as the LHC via some unknown intermediate state. The final state WIMPs would be invisible to the detectors but the events can be detected if there is an associated initial-state radiation of a SM particle. In the case where the up-type and down-type coupling of this operator have opposite signs [$C(u) = -C(d)$] the mono-W-boson production can become the dominant process. In particular ATLAS¹⁰ has searched for the production of large momentum W or Z bosons decaying hadronically and reconstructed as a single massive jet in association with large missing transverse energy. The results of this search are presented as

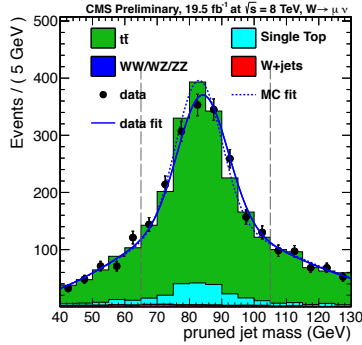


Figure 1 – Pruned jet mass distribution in a muon semi-leptonic $t\bar{t}$ control sample, passing the W-tagging selection

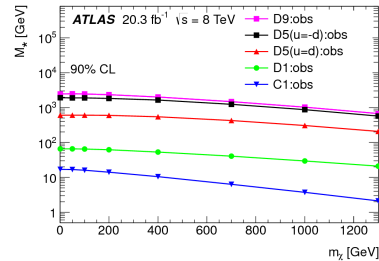


Figure 2 – Observed limits on the effective theory mass scale M^* as a function of m_χ at 90% C.L. from combined mono-boson signals

limits sets on the mass scale of the effective field theories that describe the interactions of the dark matter and standard model particles, see Fig.2 and on the cross section of Higgs production and decay to invisible particles. In addition, this analysis allows to put cross section limits on the anomalous production of W or Z bosons with large missing transverse momentum.

5 Boosted Top Tagging

The top quark decays (in the Standard Model) almost always in a W and a b quark. The decay of the W hence determines if the final state is leptonic or hadronic. In the case of top quark produced with a significant boost the traditional reconstruction techniques become inefficient, either because of the requirement on lepton isolation is not valid anymore once the lepton is close to the jet from the b hadronization, either because the three jets start becoming very close to each other. Depending on the boost of the top quark we can identify three different regimes in the case of an hadronic decay: resolved (with three separately reconstructed jets with a smaller cone), partially resolved (where the W jets are reconstructed in a single cone and identified with substructure technique as described above), or fully boosted where the three jets from the top decay need to be disentangled with substructure techniques applied to a larger cone jet. Several algorithms have been developed for top-tagging^{11,12,13} and have been successfully applied in the analyses. The most important aspect though is that their performance have been measured and validated on real data given the very large production of $t\bar{t}$ events at the LHC. The agreement between the data and MonteCarlo prediction is impressive and shows the very good control and understanding of these sophisticated techniques, see Fig.3.

5.1 B-tagging in Boosted Jets

The next step in order to better exploit the hadronic decays of boosted bosons or top quarks is to develop techniques to be able to identify the presence of b -jets inside the jet substructure. As for all new developments, several approaches are being followed at the moment. The first one is based on the simple application of traditional b -tagging algorithms to the whole list of tracks present in a "fat"-jet, regardless of the substructure details. This approach however starts to fail at higher boosts, in particular for the case of double b -tagging, as it can happen for a $H \rightarrow b\bar{b}$ decay. A better approach seems to be instead the application of b -tagging algorithm only to the specific set of tracks belonging to the different sub-jets: for instance in the case of a t -tagged jet, the request of an additional sub-jet b -tagged provides a reduction of a factor ten of the QCD background while keeping 70% of the efficiency¹⁴.

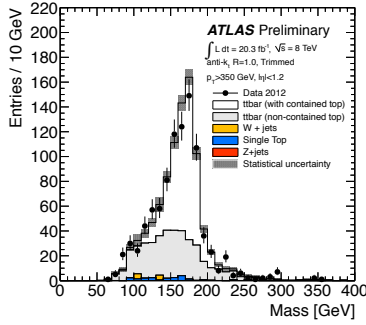


Figure 3 – Jet mass for leading t -tagged jet in a data sample enriched in $t\bar{t}$ semi-leptonic events

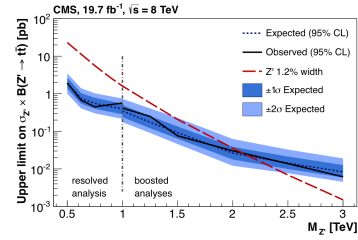


Figure 4 – The 95% CL upper limits on the production cross section times branching fraction as a function of $M(t\bar{t})$ for Z' resonances with $\Gamma(Z')/M(Z')=1.2\%$ compared to theory predictions.

6 Searches for new $t\bar{t}$ Resonances

A mix of resolved and boosted analysis approach has been applied to the search for heavy resonances (Z') decaying into $t\bar{t}$ pairs^{15,16,17}. These new particles are expected in several theories such as topcolor models¹⁸, chiral color models¹⁹ and Randall-Sundrum models with warped extra dimensions²⁰. The resolved approach has a sensitivity up to about a Z' mass of 1 TeV where the boosted approach start becoming more significant, see Fig.4. This implies not only the use of jet substructure techniques for the hadronic decays of the top quark, but also a different treatment of top leptonic decays, since at higher boosts the lepton is no more isolated from the accompanying b jet. Combining these different approaches the limits obtained reach a sensitivity in the range of 2 to 2.5 TeV for various models of Z' with different width hypothesis or Randall-Sundrum KK Gluons.

7 Searches for Vector Like Quarks

If a more traditional "fourth generation" has been essentially ruled out, heavier partners of the third generation quarks appear still as a very compelling extension of the standard model. They exist in several models such as the Two Higgs Doublet Model (2HDM), Little Higgs or Extra Dimension. These new partners can behave as isospin singlet, double or triplet and they can display normal $(+\frac{1}{3}, -\frac{2}{3})$ or exotic charge $(+\frac{5}{3}, -\frac{4}{3})$. In some models the couplings with the third generation quarks are enhanced, which leads to very interesting final states containing boosted vector and Higgs bosons and top quarks. In particular it should be noted that these final states are rich in number of leptons, jets, b -jets and boosted objects, but not a significant amount of transverse missing energy (hence complementary to typical SUSY searches in similar final states). Both the CMS and ATLAS collaboration have covered the overall parameter space for the search of pair produced B' and T' ^{21,22,23,24}. Various recent analyses consider multi-lepton and multi-V-tagged final states, in some cases with an explicit reconstruction of the heavy object invariant mass as a discriminant, reaching strongest exclusion limit for the $T'(B')$ around 800 GeV/ c^2 for specific cases.

8 Perspectives for Run II

Looking forward to the next data taking period, Run II, at a higher centre-of-mass energy of 13 TeV and given the very large masses already excluded for several new particles with the Run I data, it becomes clear that the techniques for the reconstruction of boosted bosons and top quarks will become even more critical. Two aspects should be considered early on. The first one is the performance of the different algorithms as a function of the number of additional interactions (pile-up) that might become significant depending on the luminosity achieved by

the LHC. It is comforting to see that preliminary studies already show a certain robustness even in challenging conditions. The second one is the capability of making this algorithms sufficiently fast to be able to use them at the level of the trigger selection. The possibility of having trigger paths selecting boosted objects would significantly increase the efficiency for searches for heavy exotic objects in hadronic final state that would otherwise suffer of increasingly large rates from the QCD processes.

9 Conclusions

The discovery frontier for new heavy objects that will be produced at the LHC in Run II relies heavily on the capability of the experiments to profit of the new kinematical regime of final states with boosted W, Z or Higgs bosons and top quark. This implies the development of new reconstructions techniques that allow to disentangle the jet substructure and its possible heavy flavor content and distinguish merged jets from hadronic decays of bosons and top quarks from normal QCD jets. Several of these algorithms have been already validated and used for new particles searches on the Run I data at 8 TeV by ATLAS and CMS significantly extending the sensitivity reach of the analyses.

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