PROCEEDINGS OF SCIENCE

Searches for Heavy Hadronic Resonances with the ATLAS and CMS detectors at the LHC

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1. Introduction

New resonances, that couples to quarks and gluons and decay to final states with hadronic jets, can be produced copiously at the Large Hadron Collider (CERN). This review outlines a selection of searches for heavy resonances in hadronic final states performed at the ATLAS and CMS experiments using the proton-proton collision data collected at a center-of-mass energy of 7 TeV (2011) and 8 TeV (2012). A series of points that are deemed important for current and future searches are also discussed.

2. Overview of selected searches in the ATLAS and CMS experiments

The searches for hadronic resonances can be divided into two main categories:

- **Resolved topology** - Searches where the quarks and gluons produced in the final state are each reconstructed at detector level into single, *resolved* hadronic jets. Examples are the single production of a resonance X decaying to a pair of gluons, or the pair production of two resonances X at rest each decaying to a quark-antiquark pair;

- **Boosted topology** - Searches where the quarks and gluons produced in the final state are merged into a single reconstructed jet. A typical example is the decay of a resonance X into a pair of massive particles Y, with $M_X >> M_Y$, and Y decays to a pair of light quarks. In this case the resonance Y will be *boosted* (the resonance has a large momentum compared to its mass) so that a single hadronic jet with a large distance parameter (*wide jet*) encompasses all its decay products. Techniques that exploit the presence of substructure within the *wide jet* are employed to reject background from standard QCD jets and multiple interactions within the same bunch crossing (pile-up).

The quintessential example of hadronic search with resolved jets is the search for heavy resonances in the dijet mass distribution. New particles, or excitations of quarks indicating compositeness, could manifest themselves as narrow 'bumps' in the dijet mass distribution of central leading and subleading jets above the continuum QCD background [5, 6]. The search can be tailored to specific resonances decaying to heavy quark flavors using $b-$tagging for one or both jets [7]. No significant excess over the background has been found for the current ATLAS and CMS analyses, and lower limits are set on the masses of new particles including model-independent Gaussian resonances of varying width. Upper limits on cross section times branching fraction to jets times acceptance of the order of 100, 10, and 1 fb at resonance masses of 1.5, 3, and 4.5 TeV, respectively, are set by both experiments.

Searches for resonances in final states with high jet multiplicity, tailored towards R-Parity Violating supersymmetric signatures (such as 3-body decays into quarks of pair produced gluinos, giving a six jet final state), can be performed in both resolved and boosted regimes [8, 9]. Both experiments select events with six or more jets, but the background estimation techniques for ATLAS and CMS differ. In the resolved channel, ATLAS employs the p_{T} of the sixth jet as a discriminant variable, while CMS performs a 'bump-search' in the three-jet invariant mass. The combinatorial background (from both the QCD background and the signal) penalizes the CMS search and allows the ATLAS search to set more stringent limits. A proof-of-principle boosted jet analysis, although not as sensitive as the resolved one, is also carried on by the ATLAS experiment.

In the case of resonances decaying into pairs of top quarks ($t\bar{t}$) or heavy bosons (WW, ZZ, HH, HZ, ..), the use of jet substructure techniques is crucial to achieve a good background rejection. In these cases, the tops or heavy bosons coming from a TeV-scale resonance are boosted, and therefore their decay products are spatially collimated when reconstructed in the detector.

Specific techniques for top-tagging, based on the presence of three hard energy deposit corresponding to the top decay products, have been employed to distinguish top-jets from jets originated from quarks and gluons that constitute the majority of the QCD background [10, 11, 12, 13]. Both ATLAS and CMS look for heavy resonances decaying in $t\bar{t}$ at 7 and 8 TeV, in semileptonic and all-hadronic top decays [14, 15, 16, 17, 18]. The ATLAS analysis employes b-tagging to further suppress the QCD background and it sets limits starting from a resonance mass of 500 GeV. The CMS analysis, instead, does not use b-tagging and limits are set starting at a resonance mass of 1 TeV. The CMS expected upper limits on the resonance cross section are about a factor 3-4 lower than the ATLAS ones for resonance masses around 2 TeV. A possible reason might be due to the use of b-tagging: on one side, the b-tag requirement allows the ATLAS analysis to start the search at lower resonance masses compared to CMS, by reducing significantly the QCD background; on the other hand, the low b-tag efficiency at high jet p_{T} might penalize the ATLAS search at high resonance masses.

The CMS experiment has also performed a search for RS gravitons decaying to WW/ZZ and W'/Z' decaying to Wq/Zq [19]. This analysis employs W/Z-tagging techniques based on the jet mass and the presence of hard sub-jets to significantly reduce the background and keep a relatively high signal efficiency. Given no excesses above background, limits are set on a number benchmark models.

3. Discussion points

3.1 Jet energy scale in ATLAS and CMS

Resolved searches in ATLAS and CMS employ the anti-k_t jet finding algorithm [1]. The hadronic energy scale is calibrated using a series of corrections derived both from Monte-Carlo simulation and from data [2, 3, 4]. The jet energy scale uncertainty, which dominates among the sources of systematic uncertainty for most of the searches described in this review, is derived using data-driven techniques and has a similar magnitude across jet transverse momenta p_{T} and pseudorapidities η for the two experiments. However, the estimate of the uncertainty for jets above 2 TeV differs between ATLAS and CMS. This is mostly due to different assumptions the two experiments make beyond the p_{T} reach of the $in-situ$ calibration techniques. ATLAS employs conservative uncertainties of particles beyond the range of test beam data ($p >$350 GeV) [21] that leads to an uncertainty of high-momentum particles within jets that is as high as 10%, while CMS uses a flat 3% uncertainty for all particle types and momenta [20]. Further discussion on this point would allow to adopt a homogeneous treatment for the most relevant uncertainty for hadronic searches between the two experiments.

3.2 Setting limits on dijet resonances

The search for hadronic resonances in the dijet mass spectrum present the following differences in the jet reconstruction and the limit-setting procedure between the two experiments:

- ATLAS uses anti-k_t jets with distance parameter equal to 0.6 (AK6), while CMS starts from anti-k_t jets with distance parameter 0.5 (AK5) and then clusters AK5 jets within $\Delta\mathrm{R} = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 1.1$ around the two leading jets, to form two wide jets. This is done to recover energy from final state radiation (FSR).
- CMS uses the Narrow Width Approximation, while ATLAS employs the full template without any truncation;
- the CMS limit is restricted to dijet final states (setting limits on cross-section times acceptance times branching ratio), while the ATLAS search is inclusive and would include in its acceptance e.g. photons from excited quarks as they are reconstructed as jets.

Even though there are no important differences between the mass limits obtained by the two searches, it would be desirable to unify the definitions of one of the benchmark searches for New Phenomena at the LHC for future iterations and possible combinations.

3.3 Trigger strategy for low-mass resonances

In absence of evidence for new physics at the TeV scale so far, searching for new resonances in hadronic final states also with masses between the electroweak ($\approx$ 100 GeV) and the TeV scale, is becoming more and more important for the experimental and the theory community. Due to the steady increase of instantaneous luminosity of the LHC, the trigger thresholds for hadronic triggers are now significantly tighter compared to the LHC startup in 2010. For instance, the 2010 dijet search with the first 3 pb^{-1} of data could start at a dijet mass of $\approx$ 200 GeV, while the same analysis performed in 2012 started at $\approx$ 1 TeV.

In addition to the regular developments for the "core" physics triggers, the ATLAS and CMS experiments have implemented two complementary trigger and data acquisition strategies to mitigate the problem of increased hadronic trigger rate in high luminosity scenarios.

- **ATLAS Delayed Streams and CMS Data Parking** [22] - The "core" physics program of ATLAS and CMS at 8 TeV is realized using data collected at average event rate of few hundred Hz (for an average instantaneous luminosity of $\approx 4 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$). This "core" data is promptly reconstructed (few days) and available during data taking. Extra data (about a factor of 2) has been collected by both experiments to extend physics program, both Standard Model (SM) measurements and beyond-SM (BSM) searches. These new triggers are either a looser version of the core triggers or brand new triggers with small overlap with the rest. This extra data started to be reconstructed after the end of 8 TeV data taking (i.e. delayed reconstruction) when the computing resources became available.
- **CMS Data Scouting** [22] - The idea beyond this novel approach is to collect pp collision events with very low trigger thresholds (such as pT sum of jets in the event above 250 GeV) at high rate (order of kHz) to extend the sensitivity to low-mass resonances decaying to final

states with jets. This is possible only because a reduced event content is stored (for instance calorimeter jets reconstructed during the High Level Trigger processing). No raw data from the detector channels is stored, and therefore the offline reconstruction is not possible in this special stream. Thanks to the reduced size per event, the data acquisition bandwidth (rate $\times$ event size) can be taken under control. This approach was successfully tested by CMS at the end of 2011, improving the limits on low-mass dijet resonances [23]. These triggers were also active during 2012 and the analyses of these data are currently ongoing. The continuos monitoring of this special data stream during the data taking would provide the possibility of extending the standard trigger setup for core physics or data parking / delayed streams in case something interesting shows up in the data scouting analyses.

3.4 New directions in searches with jet substructure

We discuss the searches for heavy resonances X that decay to massive particles Y (such as the SM particles top quark, W, Z, or H) when hadronic decays of Y are considered. The lorentz factor γ of the resonance Y is approximately $M_X/2M_Y$ [24]. By kinematics, a large boost factor implies that the decay products will be predominantly merged into a single reconstructed jet (the ΔR between the decay products is of the order of $2M_Y/p_T^Y$ [12]). If we search for X resonances with a mass greater than ≈ 1.5 TeV, the use of jet substructure techniques becomes mandatory to identify the hadronic boosted decays of Y, since the boosted topology will be by far the dominant one for any SM massive particle Y. The transition region between resolved and boosted topology depends on the mass of the Y particle as well as the jet cone radius.

The jet substructure represents therefore a field where the ATLAS and CMS experiments should invest a lot in view of the startup in 2015 at 14 TeV center-of-mass energy (for searches of new resonances, as well as for the measurement of WW scattering at high $\sqrt{s}$). Much of the success of these searches will depends on the understanding of the "jet grooming" techniques at high jet p_T. These methods are used to reduce the dependence of jet internal properties from pile-up and non-perturbative physics, by rejecting low p_T and large-angle jet constituents during the jet re-clustering process. The current studies show that these algorithms works well in presence of multiple interactions, up to 30 pileup events. These studies should be extended to cover the 50 and 100 pileup interaction scenarios which we expect to face in the 14 TeV data taking.

The MC modeling of the jet substructure variables is fairly good, but could be improved in view of the aforementioned searches and SM measurements to provide a more precise description of the QCD-like backgrounds, as well as to reduce the systematic uncertainties related to the top-tagging and W/Z-tagging efficiency. The 8 TeV data are available to start ramping up this MC tuning work, and the two experiments could already agree upon a certain set of benchmark observables and techniques to be investigated, e.g. using jet mass measurements for different jet-grooming algorithms [26, 27].

The jet substructure is a very active field both in the theoretical development and in the experimental implementation. To conclude, we report below a few more ideas for future applications of jet substructure methods in the LHC analyses which were discussed during the conference:

- **N-subjettiness** - A promising jet substructure observable, which have been recently started to be used in both ATLAS and CMS, is the *N-subjettiness* [28, 29, 30]. This observable quantities the compatibility of a jet with the hypothesis that it is formed by "N" main sub-structures (for example N=2 could identify two quarks from a W decay), by exploiting the p_{T} of the jet constituents and the ΔR between the jet constituents and the "N" axes representing the hypothesized subjets. The ratio of *N1-subjettiness* and *N2-subjettiness* is a powerful discriminator between jets containing "N1" and "N2" sub-structures.

- **Jet charge** - The idea of using of a weighted sum of the charges of a jet's constituents, to distinguish among jets with different charges, have been recently reprised for the LHC [31]. Potential applications include measuring electroweak quantum numbers of hadronically-decaying resonances or supersymmetric particles, as well as Standard Model tests, such as jet charge in dijet events or in hadronically-decaying W bosons in top-antitop pair events.

- **Energy and angular resolution of subjets** - We consider a massive, boosted SM particle Y (for example a W) decaying to a pair of quarks that merge into a single reconstructed wide jet. The reconstruction of the 4-momenta of the two subjets within the wide jet is important if one wants to measure the polarization of the particle Y in boosted regime. One important application is the WW scattering at large invariant mass of the diboson system, where the goal is to isolate the longitudinal scattering amplitude from the transverse one, as highlighted in Ref. [32]. To accomplish this task the energy and angular resolution of subjets reconstructed within the wide jet should be studied in detail, as well as their dependence on the momentum of the particle Y and on the pileup environment.

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References

[1] M. Cacciari, G. P. Salam, and G. Soyez, *The anti-k_t jet clustering algorithm*, *JHEP* **04** (2008) 063, [arXiv:0802.1189].

[2] ATLAS Collaboration, *Jet energy scale and its systematic uncertainty in proton-proton collisions at sqrt(s)=7 TeV with atlas 2011 data*, ATLAS-CONF-2013-004, CERN, Jan, 2013.

[3] CMS Collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS*, *Journal of Instrumentation* **6** (2011), no. 11 P11002.

[4] ATLAS Collaboration, *Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV*, *Eur.Phys.J.* **C73** (2013) 2304, [arXiv:1112.6426].

[5] CMS Collaboration, *Search for narrow resonances using the dijet mass spectrum with 19.6fb-1 of pp collisions at sqrts=8 TeV*, CMS-PAS-EXO-12-059, CERN, 2013.

[6] ATLAS Collaboration, *Search for new phenomena in the dijet mass distribution updated using 13.0 fb^{-1} of pp collisions at sqrts = 8 TeV collected by the ATLAS detector*, ATLAS-CONF-2012-148, CERN, Nov, 2012.

[7] CMS Collaboration, *Search for heavy resonances decaying into bb and bg final states in pp collisions at sqrt(s) = 8 TeV*, CMS-PAS-EXO-12-023, CERN, 2013.

[8] CMS Collaboration, *Search for three-jet resonances in pp collisions at*, *Physics Letters B* **718** (2012), no. 2 329 – 347.

[9] ATLAS Collaboration, *Search for pair production of massive particles decaying into three quarks with the ATLAS detector in* $\sqrt{s} = 7$ TeV *pp collisions at the lhc*, *Journal of High Energy Physics* **2012** (2012), no. 12 1–42.

[10] D. E. Kaplan, K. Rehermann, M. D. Schwartz, and B. Tweedie, *Top Tagging: A Method for Identifying Boosted Hadronically Decaying Top Quarks*, *Phys.Rev.Lett.* **101** (2008) 142001, [arXiv:0806.0848].

[11] T. Plehn, M. Spannowsky, M. Takeuchi, and D. Zerwas, *Stop Reconstruction with Tagged Tops*, *JHEP* **1010** (2010) 078, [arXiv:1006.2833].

[12] ATLAS Collaboration, *Performance of large-r jets and jet substructure reconstruction with the atlas detector*, ATLAS-CONF-2012-065, CERN, Jul, 2012.

[13] L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, and I. Sung, *Template Overlap Method for Massive Jets*, *Phys.Rev.* **D82** (2010) 054034, [arXiv:1006.2035].

[14] CMS Collaboration, *Search for anomalous* $t\bar{t}$ *production in the highly-boosted all-hadronic final state*, *Journal of High Energy Physics* **2012** (2012), no. 9 1–41.

[15] ATLAS Collaboration, *Search for resonances decaying into top-quark pairs using fully hadronic decays in pp collisions with ATLAS at* $\sqrt{s}$*=7 TeV*, *Journal of High Energy Physics* **2013** (2013), no. 1 1–50.

[16] CMS Collaboration, *Search for anomalous top quark pair production in the boosted all-hadronic final state using pp collisions at sqrt(s) = 8 TeV*, CMS-PAS-B2G-12-005, CERN, 2013.

[17] *A search for* $t\bar{t}$ *resonances in the lepton plus jets final state with atlas using 14 fb*^{1} *of pp collisions at* $\sqrt{s} = 8$ *TeV*, ATLAS-CONF-2013-052, CERN, Geneva, May, 2013.

[18] CMS Collaboration, *Search for ttbar resonances in semileptonic final state*, CMS-PAS-B2G-12-006, CERN, 2013.

[19] CMS Collaboration, *Search for heavy resonances in the W/Z-tagged dijet mass spectrum in pp collisions at 7 TeV*, arXiv:1212.1910.

[20] CMS Collaboration, *Single-particle response in the CMS calorimeters*, CMS-PAS-JME-10-008, CERN, 2010.

[21] ATLAS Collaboration, *Single hadron response measurement and calorimeter jet energy scale uncertainty with the ATLAS detector at the LHC*, *Eur.Phys.J.* **C73** (2013) 2305, [arXiv:1203.1302].

[22] CMS Collaboration, *Data Parking and Data Scouting at the CMS Experiment*, CMS-DP-2012-022, CERN, 2012.

[23] CMS Collaboration, *Search for Narrow Resonances using the Dijet Mass Spectrum in pp Collisions at* $\sqrt{s} = 7$ *TeV*, CMS-PAS-EXO-11-094, CERN, 2012.

[24] M. Gouzevitch, A. Oliveira, J. Rojo, R. Rosenfeld, G. Salam and V. Sanz, *Scale-invariant resonance tagging in multijet events and new physics in Higgs pair production*, [arXiv:1303.6636].

[25] M. Cacciari, J. Rojo, G. P. Salam, and G. Soyez, *Quantifying the performance of jet definitions for kinematic reconstruction at the LHC*, *JHEP* **0812** (2008) 032, [arXiv:0810.1304].

[26] CMS Collaboration, *Studies of jet mass in dijet and W/Z+jet events*, [arXiv:1303.4811].

[27] ATLAS Collaboration, *Jet mass and substructure of inclusive jets in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS experiment*, *JHEP* **1205** (2012) 128, [arXiv:1203.4606].

[28] Stewart, Iain W. and Tackmann, Frank J. and Waalewijn, Wouter J., *N-Jettiness: An Inclusive Event Shape to Veto Jets*, *Phys.Rev.Lett.* **105** (2010), 092002.

[29] Thaler, Jesse and Van Tilburg, Ken, *Identifying Boosted Objects with N-subjettiness*, *Journal of High Energy Physics* **1103** (2011), 015.

[30] Thaler, Jesse and Van Tilburg, Ken, *Maximizing Boosted Top Identification by Minimizing N-subjettiness*, *Journal of High Energy Physics* **1202** (2012), 093.

[31] D. Krohn, M. D. Schwartz, T. Lin and W. J. Waalewijn, *Jet Charge at the LHC*, [arXiv:1209.2421].

[32] T. Han, D. Krohn, L. -T. Wang and W. Zhu, *New Physics Signals in Longitudinal Gauge Boson Scattering at the LHC*, [arXiv:0911.3656].