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

Caterina Doglioni, Francesco Santanastasio*
University of Geneva and CERN
E-mail: caterina.doglioni@cern.ch, francesco.santanastasio@cern.ch

This review focuses on a series of searches for new resonances decaying to hadronic final states in the ATLAS and CMS experiments. Searches for dijet resonances, R-Parity Violating SUSY gluinos and resonances decaying in boosted top pairs and heavy bosons using jet substructure techniques are outlined, and differences between the search strategies of the two experiments are highlighted. Issues relevant for measurements to be performed with the increased center-of-mass and luminosity at the LHC after 2015 are also raised for further discussion.

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*Speaker.

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1. Introduction

New resonances, coupling to quarks and gluons and decaying to hadronic final states, 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 LHC 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 in two main categories:

- **Resolved topology** - Searches where the quarks and gluons produced in the final state are 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 encompasses all its decay products. Techniques that exploit the presence of substructure within this jet are employed to reject background from standard QCD jets and reduce the dependence on 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 [1, 2]. The search can be tailored to specific resonances decaying to heavy quark flavors using $b-$tagging for one or both jets [3]. No significant excess over the background has been found in the current ATLAS and CMS searches, and lower limits are set on the masses of new particles including model-independent Gaussian resonances of varying width. Upper limits of the order of 100, 10 and 1 fb at are set on cross section times branching fraction to jets times acceptance for resonance masses of 1.5, 3, and 4.5 TeV, respectively.

Searches for resonances in final states with high jet multiplicity, optimized for R-Parity Violating supersymmetric signatures (3-body decays into quarks of pair produced gluinos, giving a six jet final state), can be performed in both resolved and boosted regimes [4, 5]. Both experiments select events with six or more jets, but the background estimation techniques differ in ATLAS and CMS. In the resolved channel, ATLAS employs the p_{T} of the sixth jet as a discriminant variable, while CMS performs a 'bump-hunt' 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 out by the ATLAS experiment [5].

In the case of resonances decaying into pairs of top quarks ($t\bar{t}$) or heavy bosons (e.g. WW, ZZ, HH, HZ, ..), the use of jet substructure techniques is crucial to achieve a good background rejection. In these cases, the top quarks or heavy bosons coming from a TeV-scale resonance would be boosted, and therefore their decay products would be spatially collimated 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 [6, 7, 8, 9]. Both ATLAS and CMS look for heavy resonances decaying in $t\bar{t}$ in both 7 and 8 TeV data, in semileptonic and all-hadronic top decays [10, 11, 12, 13, 14]. The ATLAS analysis employs $b-$tagging to further suppress the QCD background and 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. In the case of the 7 TeV analysis, 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. The top-tagging technique (requiring the presence of $b-$tagged jets) used by ATLAS allows the search to start 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} and the more conservative treatment of uncertainties could reduce the sensitivity of 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 [15]. This analysis employs W/Z-tagging techniques based on the jet mass and the presence of hard sub-jets to significantly reduce the background, while keeping 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 [16]. The hadronic energy scale is calibrated using a series of corrections derived from both Monte-Carlo simulation and from data [17, 18, 19]. 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 made 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) [20] which lead to an uncertainty as high as 10% for high-momentum particles within jets, while CMS uses a flat 3% uncertainty for all particle types and momenta [21]. Further discussion on this point would allow to adopt a coherent treatment for the most relevant uncertainty for hadronic searches between the two experiments, paving the way for possible combinations of the result.

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3.2 Setting limits on dijet resonances

The search for hadronic resonances in the dijet mass spectrum presents 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.

- CMS uses the Narrow Width Approximation to define the resonance cross-section and signal template, while ATLAS employs the full simulated 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, low cross-section resonances in hadronic final states with masses between the electroweak ($\approx$ 100 GeV) and the TeV scale, becomes increasingly important for the experimental and the theory community. Due to the steady increase of instantaneous luminosity of the LHC and to the large rates of final states containing jets, the trigger thresholds for hadronic triggers are now significantly higher compared to the LHC startup in 2010. As an example, the 2010 dijet search with the first 3 pb^{-1} of data could be performed starting from a dijet mass of $\approx$ 200 GeV, while the same analysis performed in 2012 could only start at $\approx$ 1 TeV due to the high prescales of lower jet p_{T} triggers.

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 uses data collected at the average event rate of few hundred Hz (for an average instantaneous luminosity of $\approx 4 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$). The "core" data are promptly reconstructed (within a few days) and are available during data taking. Additional data (about a factor of 2) have been collected by both experiments to extend the physics programs, both in terms of Standard Model (SM) measurements and beyond-SM (BSM) searches. These new triggers can be implemented as either a looser version of the core triggers or as brand new triggers with small overlap with the rest. The additional data are reconstructed after the end of 8 TeV data taking (delayed reconstruction), as soon as the computing resources become available.

- **CMS Data Scouting** [22] - The idea beyond this novel approach is to collect pp collision events with very low trigger thresholds (such as p_T sum of jets in the event above 250 GeV) at a 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 only calorimeter jets reconstructed during the High Level Trigger processing). No raw data from the detector channels are stored, and therefore the offline reconstruction is not possible in this special stream. However, thanks to the reduced per-event size, the data acquisition bandwidth (rate $\times$ event size) can be kept under control. This approach was successfully tested by CMS at the end of 2011, and lead to an improvement in the limits on low-mass dijet resonances [23]. These triggers were also enabled during 2012 and the analyses of these data are currently ongoing. The continuous monitoring of this special data stream during the data taking would provide the possibility of dynamically extending the standard trigger setup, both for core physics and for special triggers, in case unexpected phenomena appear.

3.4 New directions in searches with jet substructure

Searches for heavy resonances X that decay to massive particles Y (such as the top quark, W, Z, or H in the SM), with Y decaying in hadrons, have been also considered in the discussion. The Lorentz factor γ (boost factor) of the resonance Y is approximately $M_X/2M_Y$ [24]. Due to the kinematics of the event, 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 $2M_Y/p_T^Y$ [8]). When searching for resonances X with a mass greater than $\approx$ 1.5 TeV, the use of jet substructure techniques becomes mandatory to identify the dominant hadronic boosted decays of massive SM particles Y. Therefore, ATLAS and CMS experiments should invest in the study of substructure techniques in view of the startup at 14 TeV center-of-mass energy. Those techniques could benefit the searches of new resonances, as well as the measurement of WW scattering at high $\sqrt{s}$.

Much of the success of these searches will depend on the understanding of jet substructure and of jet grooming techniques at high jet p_T. Grooming techniques such as trimming [25] or pruning [26, 27] 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. Current studies [28] show that these algorithms work well in presence of multiple interactions, up to 30 pile-up events. These studies should be extended to cover the 50 and 100 pile-up interaction scenarios which we expect to face in the 14 TeV data taking.

The MC modeling of the jet substructure variables and backgrounds to searches in the boosted regime could also be improved in view of the aforementioned searches. SM measurements could provide a more precise description of the QCD-like backgrounds, and help reducing the systematic uncertainties related to the top-tagging and W/Z-tagging efficiency. 8 TeV data are available to proceed with 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 [29, 30].

Jet substructure is currently a very active field both in terms of theoretical development and in experimental implementation. To conclude, we report below two ideas for future applications of jet substructure methods in the LHC analyses which were discussed during the workshop:

- **Jet charge** - The idea of using of a weighted sum of the charges of the constituents of a jet, to distinguish among jets with different charges, have been recently discussed in the context of 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 jet with a large distance parameter. The reconstruction of the 4-momenta of the two subjets within this 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 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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