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 (*fat jet*) encompasses all its decay products. Techniques that exploit the presence of substructure within the *fat 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 pT 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

- Some details on high-pT JES [20][21]
- 2 plots side by side: background rejection after boson tagging and one of the limit plots
- Encourage more work on both sides to make consistent assumptions

3.2 Setting limits on hadronic resonances

- Refer to earlier plots
- Differences: full template/narrow width, inclusive vs dijet-only search
- Recommend to unify definition for 14 TeV (combination)? [22]

3.3 Data for low-mass resonances

- One/two-sentence description of need to look lower in mjj, hadronic rate problems, delayed triggers and parked data
- one plot only: CMS 2011 low-mass extension

3.4 New directions in searches with jet substructure

- Justification on why substructure necessary at 14 TeV (and not for 8 TeV Higgs yet)
- Need for MC generator support and benchmarks among experiments [23][24]
- New ideas:
  - Q/g tagging for lower masses
  - Tools for W' and Z': jet charge and angle between subjets (angular correlations?)
- Open questions:
  - Particle flow and substructure
  - High-lumi and substructure

4. Conclusions

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