RECEIVED: February 15, 2018

REVISED: March 6, 2018

ACCEPTED: March 6, 2018

PUBLISHED: March 22, 2018

Characterizing boosted dijet resonances with energy correlation functions

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ABSTRACT: Jet Energy Correlation Variables are powerful tools to study jet physics at LHC. We show that a class of such variables, known as Energy Correlation Functions can be used effectively to discover and distinguish a wide variety of boosted light dijet resonances at the LHC through sensitivity to their transverse momentum and color structures.

KEYWORDS: Beyond Standard Model, Hadron-Hadron scattering (experiments), Jet substructure

ARXIV EPRINT: [1710.04661](https://arxiv.org/abs/1710.04661)

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1 Introduction

While LHC has not seen any sign of new physics yet, we are only in the early days of run-2, and regions of parameter space of viable new physics models are yet to be probed. One of the canonical searches where new physics can show up are dijet resonances. For a given resonance mass, the ability to probe smaller couplings to quarks and gluons depends on the amount of data collected and how well one can reduce Standard Model (SM) backgrounds. Sensitivity to light dijet resonances at the LHC, in particular, is limited by the presence of large SM backgrounds that accumulate at a rate which is difficult to manage by currently available trigger and data acquisition systems at ATLAS and CMS. Looking for such resonances produced with high transverse momenta in association with a jet, photon, $W^\pm$ or Z boson (or even in pair production of the resonances) can reduce both signal and background rates thus avoiding trigger threshold limitations. Additionally, for highly boosted light resonances, jet substructure techniques can be applied to further reduce backgrounds.

Recently, using this search strategy, ATLAS [1] and CMS [2] were able to set limits on narrow light vector resonances (specifically a leptophobic Z' [3]), decaying to a pair of jets, in a coupling and mass range (100 – 600) GeV that was not accessible to earlier colliders such as UA2 and CDF. However there are a plethora of possible dijet resonances that could exist: colorons [4], sextet and triplet diquarks [5, 6], excited quarks [7, 8], color-octet scalars [9], massive spin-2 particles [10] to name a few. While substructure techniques can help unearth new resonances, once a light resonance is discovered the primary task becomes understanding the nature of the resonance itself. Among other things, this involves determining the production mechanism (quark or gluon initiated), the final state (quark or gluon jets) and the color representation of the new resonance.

In this paper we demonstrate how Energy Correlation Functions (ECFs) aid in differentiating among numerous types of light dijet resonances.¹ The rest of the paper is organized as follows. In section 2, we describe the choice of certain benchmark models that are being studied in the paper, while in section 3, we describe the event simulation procedure. In section 4 we present and discuss the distributions for various ECFs, moving on to discussing the results in section 5 and finally concluding in section 6.

2 Dijet resonances in new physics models

New dijet resonances may be classified according to their spin and color structure [22]. We exhibit the power of ECF in this regard by examining some benchmark models² listed below:

- A color singlet leptophobic Z' that couples to baryon number via $\frac{g_B}{6}\bar{q}\gamma^\mu q Z'_\mu$ [3].
- A color octet coloron C_μ interacting with quarks through $g_s \tan \theta \bar{q} T^a \gamma^\mu q C_\mu^a$ [4].
- A color sextet diquark (Φ_6^γ) that interacts with pairs of quarks through $\sqrt{2}(\bar{K}_6)_{\gamma}^{ab} \lambda_\Phi \Phi_6^\gamma \bar{u}_{Ra}^c u_{Lb}$ [5, 23].
- A color triplet excited quark (q^*) interacting with quarks and gluons (as well as other gauge bosons) through the interaction term $\frac{1}{2\Lambda} \bar{q}_R^* \sigma^{\mu\nu} [g_s f_S \frac{\lambda^a}{2} G_{\mu\nu}^a] q_L$ [8].
- A massive color singlet, spin 2 object ($X^{\mu\nu}$) that interacts with SM particles through the energy momentum tensor $T_{\mu\nu}$ as $\frac{1}{\Lambda} X^{\mu\nu} T_{\mu\nu}$ [10].
- A color octet (but electroweak singlet) scalar S_8 that interacts with gluons through the field strength tensor as $\frac{g_s d_{ABC} k_s}{\Lambda} S_8^A G_{\mu\nu}^B G^{C,\mu\nu}$ [9, 24].

The above list is by no means exhaustive, but serves to illustrate the utility of this method. Note that each of the above models are different from each other, either through their color structure or their couplings to quarks and gluons. For example notice that although Z' and the Spin-2 resonance are both color singlets, Z' is produced through quarks and decays to quarks, while the Spin-2 resonance are produced through both gluons and quarks, and decays both to quarks and gluons. Moreover, the Spin-2 resonance couples to SM through a higher dimensional operator, and is expected to exhibit a stronger transverse momentum distribution. These features can be revealed through jet observables and used to determine the nature of the resonance. While resonances of different spin can be differentiated on the basis of angular distributions of their decay products, identifying types of resonances on the basis of their color structure is more difficult. Note that the color discriminant variable [23, 25] will not be useful for (relatively) weakly-coupled light resonances since their decay widths are too narrow to be measured at the LHC.

¹Elsewhere we will consider and compare other jet observables such as N-Subjetiness [11–13] and Jet Energy Profiles [14], jet pull [15] and dipolarity [16]. A number of excellent detailed reviews on jet substructure and jet observables exist in the literature detailing the merits of the above [17–21].

²We restrict ourselves to leptophobic models only.

3 Event simulation

We first assess the capability of LHC experiments ATLAS and CMS to discover a light dijet resonance. The signal process of interest is the production of various resonances in association with a jet, viz. ($pp \rightarrow X(\rightarrow jj) + j$; $X \in \{Z'_\mu, C_\mu, \Phi_6, q^*, X^{\mu\nu}, S_8\}$) where the resonance is boosted sufficiently that its decay products lie within a single “fat jet”. Note that we also performed an analogous analysis of the production of the resonances in association with a W boson. However since the production in association with a jet has a much larger cross section and thus a larger sensitivity, we report only this channel in this work. The dominant background originates from QCD multijet events, while W/Z/ $t\bar{t}$ + jets constitute the sub-dominant backgrounds to this channel. We closely follow the CMS analysis [2] in order to estimate our signal to background ratio.

The various resonance models described in section 2 were implemented in **Feynrules** [26]. Parton level events for both signal and background were simulated using **MADGRAPH_AMC@NLO** [27] assuming 13 TeV LHC energy, with subsequent showering and hadronization performed using **PYTHIA8** [28]. We use **FASTJET** [29] to reconstruct jets and calculate ECFs. For QCD/W/Z/ $t\bar{t}$ + jets, where extra jets were simulated, a merging scale of 30 GeV was chosen while showering parton level events using the MLM prescription [30]. Additionally jet energy smearing and detector granularity are simulated using **Delphes3** [31] with parameters similar to CMS. We use the Cambridge-Aachen algorithm [32]³ to construct fat-jets of radius $R = 1.0$ and use the mass-drop tagger [33] to resolve the fat jets into subjets to reconstruct the mass of the resonance X within $M_X \pm 20$ GeV to help reduce the background. Importantly, we find that the mass-drop tagger does not significantly affect JEC distributions of unfiltered signal fat-jets. Further, the acceptance of the tagger does not depend significantly on the nature of the resonance. To enhance the signal to background ratio, we require $H_T = \Sigma p_T > 900$ GeV and $p_T^{\text{fatjet}} > 500$ GeV. We use **MCFM** [34] to determine K-factors for NLO production of the V +jets, $t\bar{t}$ and single top backgrounds. NLO K-factors for the dijet production cross-section were determined using **POWHEGBOX** [35–37]. Further, we use the MLM [30] matching procedure in **PYTHIA8** for multi-jet events that were generated in **MADGRAPH_AMC@NLO**.

For the purpose of demonstration, the mass of the resonance is set to $M_X = 250$ GeV. The current 95 % CL bound on a 250 GeV leptophobic Z' from 35.9 fb⁻¹ of 13 TeV data is $g_b \lesssim 1.5$ ($g_q \lesssim 0.22$), compared with an expected bound of $g_b \lesssim 1.1$ [2]. We therefore consider a Z' resonance with $g_b = 0.6$, which is still allowed by the data. For this coupling, we find that the cross section after all cuts is 25 fb. For all other resonances we adjust the value of the couplings such that for all resonances under consideration, the cross-section after cuts is 25 fb. We find that our total background is ~ 50 pb with the dominant contribution coming from QCD multi-jet processes. We find that with our cuts we expect $S/\sqrt{B} \sim 1.9\sigma$ which is comparable to the expectations of experimental results.

³Note that currently the CMS and ATLAS collaborations use the anti- k_T algorithm to construct fat jets. This however does not alter the conclusions of this analysis.

4 Energy correlation functions

JECs were originally introduced in [38, 39] as a two point correlator, and generalized in [40] as Energy Correlation functions. Studies on ECF have focused on standard model processes, specially to distinguish quark jets from gluon jets. Additionally, ECFs have been shown to be able to differentiate boosted Higgs and top quarks from QCD backgrounds [40]. We simulate distributions for ECFs as implemented in [29]. The input to the ECFs are jet constituents(subjets), defined as *anti* - k_T jets with a radius of 0.1 with smearing implemented a'la ATLAS. They pass all the event selection criterion as defined in the previous section.

The N-point generalized Energy Correlation Function (ECF) is defined as [40],

$$ECF(N, \beta) = \sum_{(i_1 < \dots < i_N \in J)} \prod_{a=1}^N p_{T_{i_a}} \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^N R_{i_b i_c} \right)^\beta. \quad (4.1)$$

The sum runs over all objects (tracks⁴ or calorimeter cells) within a system J (individual jets or all final states of the collision). p_{T_i} is the transverse momentum of each constituent object. The variable $R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\theta_i - \theta_j)^2}$, denotes a pairwise distance measure and is raised to the power β . Here η_i is the pseudo-rapidity while θ_i is the azimuthal angle of particle i . The entire function is infrared and collinear safe for $\beta > 0$.

Using eq. (4.1) one can construct a dimensionless double ratio as

$$C_N^{(\beta)} = \frac{ECF(N+1, \beta) ECF(N-1, \beta)}{ECF(N, \beta)^2}. \quad (4.2)$$

In general, $C_N^{(\beta)}$ quantifies radiation of higher order α_s^n , emerging out of leading order hard sub-jets. In a boosted $Z' \rightarrow j_1 j_2$ like system, if $C_2^{(\beta)} < C_1^{(\beta)}$, the fat jet has two resolved hard subjets, and higher order substructure is mostly soft or collinear. With subsequent soft emissions of the final state, one can assume $p_T^{j_1} \simeq p_T^{j_2} \gg p_T^{j_i}$, where $i > 2$. Thus, the leading approximation can be written as,

$$C_1^{(1)} \simeq R_{12}/4. \quad (4.3)$$

Since $R_{12} \simeq 2m_{Z'}/p_T^j$, $C_1^{(1)}$ is directly related to the boost of the resonance. We show the distribution of $C_1^{(1)}$ for various resonances in figure 1. Since we require $R \leq 1.0$ and $p_T^{\text{fat-jet}} > 500 \text{ GeV}$, we see that $C_1^{(1)} \lesssim 0.25$. Further, since the p_T spectrum is almost identical for all resonances under consideration the distribution for $C_1^{(1)}$ look the same. The p_T distribution for q^* and $X^{\mu\nu}$ are slightly harder (and therefore $C_1^{(1)}$ is shifted to smaller values) since their interactions are mediated by dimension 5 operators. We would also like to point out here that information about the initial state and therefore the nature of the resonance can be gleaned by comparing the p_T distribution for cases when the resonance is produced in association with other particles such as a W -boson. The lower end of the $C_1^{(1)}$ distribution is bounded by detector resolution. This is the minimal separation between subjets that can be resolved, and is encoded in our implementation of the mass drop tagger.

⁴Here we define the ECFs in terms of the individual particles in the “fat jet” in the simulated event, after using the detector simulation as noted above.

Figure 1. The double ratio distribution for $C_1^{(1)}$ for the different kinds of resonances under consideration; Z' in pink (small-dashed), sextet-diquark Φ_6 in black (dotted), Coloron (C_μ) in red (bold,thick), excited quark (q^* , Xquark) in green (large-dashed), Spin-2 ($X^{\mu\nu}$) in blue (bold,thin), scalar color octet (S_8) in black (dot-dashed). The cyan shaded region corresponds to the distribution of the multi-jet background.

Figure 2. The double ratio distributions $C_2^{(2)}$ for the resonances and the multi-jet background.

Higher point moments of the ECF depend crucially on the nature of the resonance, in particular, the color structure not only of the resonance but also its decay products — in particular, since $C_F < C_A$, a color octet will radiate more widely than a color triplet. This implies that the correlator double ratios $C_N^{(\beta)}$ should in general be larger for a color octet than a color triplet and smallest for a color singlet.

In figure 2 we present distributions for the double ratios $C_2^{(2)}$. To understand the behavior of C_2^β ,⁵ consider a simplified scenario of the two body hadronic decay of a resonance

⁵It has been argued in [41, 42] that $D_2^\beta = \frac{ECF(3,\beta)}{(ECF(2,\beta))^3}$ is the optimal variable for identifying two prong substructure. This has been used for LHC in [42].

X with one soft emission — $X \rightarrow 1 + 2 + 3_{\text{soft}}$ where 3_{soft} originates from 1. We also expect the distance measure R_{13} to be small and $p_T^{j1} \simeq p_T^{j2}(=p_T) \gg p_T^{j3}$ in the soft and collinear approximation. $C_2^{(\beta)}$ can then be approximated as

$$C_2^{(\beta)} \simeq \frac{2\varepsilon R_{12}^\beta R_{13}^\beta R_{23}^\beta}{(R_{12}^\beta + \varepsilon R_{13}^\beta + \varepsilon R_{23}^\beta)^2}; \quad (4.4)$$

note that $\varepsilon R_{13} = (p_T^{j3}/p_T)R_{13} \ll 1$ is doubly suppressed since the third jet, 3_{soft} , is both low-momentum and colinear with jet 1. We therefore expect $C_2^{(2)}$ to peak near 0 as seen in figure 2. As discussed earlier, a small $C_2^{(2)}$ implies that the event is mostly a two prong subjet system.⁶

In figure 2 we also see, as expected, that the color singlet Z' has the smallest values for $C_2^{(2)}$ whereas, due to the presence of more radiation, the colored objects have larger values. Although the spin-2 is a color singlet its distribution is not identical to Z' and instead has larger values of $C_2^{(2)}$. This is because the spin-2 predominantly decays to gluons, which themselves produce broader jets (since $C_F < C_A$), whereas the coloron and Z' decays to quarks, which produce narrower radiation patterns. As expected, the color octet scalar resonance has the largest values of $C_2^{(2)}$ since it is itself an octet which decays to a pair of octets (gluons). Also shown in figure 2 is the distribution of $C_{(2)}^2$ for the dominant multi-jet background. We see that its distribution is significantly different from most of the signal distributions and therefore the ECFs can be used not only to discriminate between different signals but also to discriminate signal from background.⁷ The scalar octet behaves most like the QCD multi-jet background since, at low masses, the background is mostly gluonic in origin.

Further discrimination between resonances can be achieved by looking at the distribution for the higher moment correlator $C_3^{(\beta)}$ shown in figure 3. In contrast to $C_2^{(\beta)}$ we see that the peak of the distribution is shifted away from 0. This behavior can be better understood by considering the scenario where $X \rightarrow 1 + 2 + 3_{\text{soft}} + 4_{\text{soft}}$. In this case, we assume that the transverse momentum distribution follows, $p_T^{j1} \simeq p_T^{j2}(=p_T) \gg (p_T^{j3}, p_T^{j4} = p_T)$. We can then approximate $C_3^{(\beta)}$ as (up to order $\varepsilon = \frac{p_T'}{p_T}$)

$$C_3^{(\beta)} \simeq \frac{[(R_{13}R_{14}R_{23}R_{24}R_{34})^\beta]}{[(R_{13}R_{23})^\beta + (R_{14}R_{24})^\beta]^2} + \mathcal{O}(\varepsilon) \quad (4.5)$$

Thus the leading term is not proportional to ε , resulting in the peak that is shifted away from 0, and is determined by the relative opening angles. Similar to what we saw for the lower moment correlator, we find that the distribution of $C_3^{(2)}$ is shifted to larger values depending on the dimensionality of the SU(3) representation of the resonance as well as its decay products. The color singlet Z' decaying to a pair of quarks peaks closer to 0, whereas the distribution for the others, which either are octets or decay to gluons, is shifted away from 0.

⁶Scaling arguments for ECFs and the double ratios have been considered in detail previously in a number of works, in particular [42–44].

⁷CMS [45] uses the variable N2, a generalization of ECF [46] in its search to discriminate between a Z' and background. The behavior of $C_2^{(2)}$, suggests that in addition to enhancing $S/\sqrt{B}$ we can simultaneously use it to discriminate between resonances (S_8 being an exception).

Figure 3. The double ratio distributions for $C_3^{(2)}$ for the resonances and the multi-jet background.

An important point that should be noted finally is the dependence of the ECF on the exponent β . As $\beta \rightarrow 0$, the dependence on the relative angles vanishes, and the ECF double ratio approaches an (approximately) constant value away from 0. The exponent should therefore be viewed as a weighting factor that controls the size of the variation of the ECF. Note that we have not optimized β for maximal discrimination in this analysis. Another aspect that we have not investigated and have reserved for future study is the use of ECFs (or other jet observables) on unfiltered subjects to identify quark and gluonic jets. The ability to discern the decay products of these resonances would further enhance our ability to pinpoint the nature of the resonance.⁸

5 Results and discrimination

In order to test the ability of ECFs to characterize the nature of the resonance we perform a multi-variable likelihood analysis. We do not include $C_1^{(1)}$ in our likelihood function, since we are trying to test the information provided by radiation patterns and not kinematics. We therefore include only $C_2^{(2)}$ and $C_2^{(3)}$ in our likelihood function and test the ability of these two jet observables in differentiating the resonances. Including other correlators or observables in a full multi-variate analysis would further improve the discrimination between various resonances; in this sense our analysis gives a conservative estimate of the method's power. We determine distributions of the likelihood ratio

$$\mathcal{Q} = -2 \log \left(\frac{L(\text{Signal-B} + \text{Background}|\text{data})}{L(\text{Signal-A} + \text{Background}|\text{data})} \right), \quad (5.1)$$

⁸Note that we have not taken pile up into account in our simulations. It is generally known that pile ups can affect Jet observables and substructures significantly. However modern pile up removal techniques like pileup per particle identification” (PUPPI) [47] can significantly mitigate the effect of pile up by using local jet shape information and tracking properties. Such a study goes beyond the scope of a fast simulation analysis performed here and requires a full experimental set up to be able to reliably make a quantitative statement.

Figure 4. The p -values testing hypothetical identities of various resonances as a function of luminosity. Horizontal lines indicate 2 and 3 σ exclusion of the alternate hypothesis. Vertical lines show where $S/\sqrt{B} = 3$ or 4.

by generating pseudo-data. Using the distribution $\mathcal{Q}$, we determine the p -value of excluding the alternate hypothesis.⁹ We include the effects of backgrounds completely but only profile over the various nuisance parameters that arise from detector effects and selection cuts.¹⁰ Our choice of couplings remains the same as detailed in section 3.

The result of our analysis is shown in figure 4. The horizontal dotted lines indicate where one can distinguish between various signal hypotheses at the 2 σ or 3 σ level; for example, one could tell a Z' from an excited quark at the 3 σ level with about 180 fb^{-1} of integrated luminosity. The vertical lines indicate the value $S/\sqrt{B}$ for distinguishing signal over standard model background provided by a given integrated luminosity; for instance, achieving $S/\sqrt{B} = 3$ for our resonances (since we assume the signal size, for all resonances to be 25 fb) would require 720 fb^{-1} of data. The figure shows that the ECFs have information that distinguishes a coloron from a Z' , whereas the weakest discrimination is that between a spin-2 particle and a diquark.

Importantly, although not shown on the figure here we find that all six of our benchmark resonances (color singlet Z' , color octet coloron, color sextet diquark, color triplet excited quark, spin 2 resonance and a color octet scalar) can be discerned from each other. This demonstrates that the ECF method is a powerful tool for discriminating among various color signatures, including production and decay modes, of new light dijet resonances. It therefore warrants further detailed investigation in future work.

⁹We use the median value of the null hypothesis to determine the p -value of the alternate hypothesis. This corresponds to twice the p -value in the CL_s method used in LEP.

¹⁰We emphasize that this likelihood analysis is just an indicator of the utility of ECFs in distinguishing between new dijet resonances. A more accurate analysis would need to be performed by using a full detector simulation and including various nuisance parameters such as standard model background uncertainties.

6 Conclusion

In this paper we assessed the prospects of Energy Correlation Functions to distinguish boosted light dijet resonances. We considered a wide variety of new physics resonances based on their color/spin/coupling structures.¹¹ We concluded that based on the radiation pattern for different resonances (that depends on their color representation) and the transverse momentum distribution of the final states, ECFs can be an effective tool to distinguish a wide variety of new physics resonances once they are discovered. We also observe that they can prove to be an effective handle to suppress SM background. In order to compare the efficacy of ECFs with other observables like jet energy profiles, n-subjetiness etc, a follow up to this work is in progress, where additionally we attempt to find the best possible set of discriminants using neural networks and machine learning techniques. Eventually, in the event of a discovery, these observables will be of paramount importance to experimentalists in order to determine the nature of new physics resonances.

Acknowledgments

This material is based in part upon work supported by the National Science Foundation under Grant No. 1519045. We thank Wade Fisher and Joey Huston for useful discussions.

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¹¹Another observable that could also be useful in this regard is z_g introduced in [48] and further studied in [49]; it probes momentum sharing in splitting, making it sensitive to the spin structure.

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