Characterizing Boosted Dijet Resonances with Jet Energy 
Correlators

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We show that Jet Energy Correlation variables 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.

The LHC is actively seeking dijet resonances. However, 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. Sensi-
tivity 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 cur-
cently available trigger and data acquisition systems at ATLAS and CMS. Looking for 
such resonances produced with high transverse momenta in association with a jet, pho-
ton, $W^\pm$ or $Z$ boson (or even in pair production of the resonances) can reduce both sig-
nal and background rates thus avoiding trigger threshold limitations. Additionally, for 
highly boosted light resonances, jet substructure techniques can be applied to further re-
duce backgrounds.

Recently, using this search strategy, AT-
LAS [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-
occtet scalars [9], massive spin-2 particles [10] 
to name a few. While substructure tech-
niques can unearth new resonances, once a 
light resonance is discovered the primary task 
becomes understanding the nature of the res-
onance itself. In this note we demonstrate 
how Jet Energy Corelators (JECs) aid in dif-
ferentiating between these numerous types of 
resonances.

New dijet resonances may be classified

1 Elsewhere we will consider and compare other jet
according to their spin and color structure [16]. 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 [17, 18] will not be useful for (relatively) weakly-coupled light resonances since their decay widths are too narrow to be measured at the LHC. We exhibit the power of JEC in this regard by examining some benchmark models listed below:

- A color singlet leptophobic $Z'$ that couples to baryon number via $g_6 \bar{q}\gamma^{\mu}qZ'_\mu$ [3].
- A color octet coloron $C_\mu$ interacting with quarks through $g_8 \tan \theta \bar{q} T^a_\mu qC^a_\mu$ [4].
- A color sextet diquark ($\Phi^\gamma_6$) that interacts with pairs of quarks through $\sqrt{2}(\bar{K}_6)^{ab}_\gamma \lambda_\Phi \Phi^\gamma_6 \bar{u}^c_6 qL^a_6 [5, 18]$.  
- A color triplet excited quark ($q^*$) interacting with quarks and gluons (as well as other gauge bosons) through the interaction term $\frac{1}{2\Lambda} \bar{q}_R \sigma_{\mu\nu}[g_8 f_s \bar{L}_s^a G_{\mu\nu}^a] q_L [8]$. 
- 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 $\frac{g_{dABC}k_s}{\Lambda} S^B_8 G^C_{\mu\nu} G^{\mu\nu} [9, 19]$.  

While this list is not exhaustive, these examples serve to illustrate the utility of this method.  

The signal process of interest is the production of various resonances in association with a jet, viz. $(pp \rightarrow X(\rightarrow jj) + j : X \epsilon \{Z'_\mu, C_\mu, \Phi_6, q^*, X^{\mu\nu}, S_8\})^3$, where the resonance is boosted sufficiently that its decay products lie within a single “fat jet”. The dominant background originates from QCD multijet events. The various resonance models were implemented in Feynrules [20]. Parton level events for both signal and background were simulated using MADGRAPH_AMC@NLO [21] assuming 13 TeV LHC energy, with subsequent showering and hadronization performed using PYTHIA8 [22]. We use FASTJET [23] to reconstruct jets and calculate JECs. Additionally jet energy smearing and detector granularity are simulated using Delphes3 [24] with parameters similar to ATLAS. We use the Cambridge-Aachen algorithm [25] to construct fat-jets of radius $R = 1.0$ and use the mass-drop tagger [12] 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  

We also performed an analogous analysis of the production of the resonances in association with a W boson, which will be reported in a future work.
does not depend significantly on the nature of the resonance. We require $H_T = \Sigma p_T > 900$ GeV and $p_T^{\text{fatjet}} > 500$ GeV. We use \textsc{mcfm} \cite{26} 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 \textsc{powhegbox} \cite{27–29}. Further, we use the MLM \cite{30} matching procedure in \textsc{pythia8} \cite{26} to determine K-factors for NLO \textsc{mcfm} QCD backgrounds \cite{33}. 

Studies on JEC have focused on standard model processes, specially to distinguish quark jets from gluon jets. Additionally, JECs have been shown to be able to differentiate boosted Higgs and top quarks from QCD backgrounds \cite{33}. 

The N-point generalized JEC is defined as \cite{33},

$$E CF(N, \beta) = \sum_{(i_1 < \ldots < i_N \in J)} \prod_{a=1}^{N} \frac{\prod_{b=1}^{N} \prod_{c=b+1}^{N} R_{i_1i_2}}{p_{T_i}} \beta$$

\text{(1)}

The sum runs over all objects (tracks\textsuperscript{4} 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 $\beta$. Here $\eta_i$ is the pseudo-rapidity while $\theta_i$ is the azimuthal angle of particle $i$. The entire function is infrared and collinear safe for $\beta > 0$.

Using Eq. 1 one can construct a dimensionless double ratio as

$$C_N^{(\beta)} = \frac{E CF(N + 1, \beta)E CF(N - 1, \beta)}{E CF(N, \beta)^2}$$

\text{(2)}

In general, $C_N^{(\beta)}$ quantifies radiation of higher order $\alpha_s^n$, 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 $p_T^{j_2} \simeq p_T^{j_1} \gg p_T^{j_1}$, where $i > 2$. Thus, the leading approximation can be written as,

$$C_1^{(1)} \simeq R_{12}/4.$$  \text{(3)}

Since $R_{12} \simeq 2m_{Z'}/p_T^{j_1}$, $C_1^{(1)}$ is directly related to the boost of the resonance. We show the distribution of $C_1^{(1)}$ for various resonances in Fig. 1. Since we require $R \leq 1.0$

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

Higher point moments of the JEC 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 $C_{N}^{(2)}$ should in general be larger for a color octet than a color triplet and smallest for a color singlet.

In Fig. 2 we present distributions for the double ratios $C_{2}^{(2)}$. To understand the behavior of $C_{2}^{(2)}$, consider a simplified scenario of the two body hadronic decay of a resonance $X$ with one soft emission– $X \rightarrow 1 + 2 + 3_{\text{soft}}$ where $3_{\text{soft}}$ originates from 1. We also expect the distance measure $R_{13}$ to be small and $p_{T}^{1} \simeq p_{T}^{2} (= p_{T}) \gg p_{T}^{3}$ in the soft and collinear approximation. $C_{2}^{(2)}$ can then be approximated as

$$C_{2}^{(2)} \sim \frac{2\varepsilon R_{12}^{3} R_{13}^{1} R_{23}^{3}}{(R_{12}^{3} + \varepsilon R_{13}^{1} + \varepsilon R_{23}^{3})^{2}}; \quad (4)$$

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

In Fig. 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

![FIG. 1. The double ratio distribution for $C_{1}^{(1)}$ for the different kinds of resonances under consideration; $Z'$ in pink (small-dashed), sextet-diquark $\Phi_{6}$ in black (dotted), Coloron ($C_{\mu}$) 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 (dotted-dashed). The cyan shaded region corresponds to the distribution of the multi-jet background.](image-url)
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 Fig. 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 JECs can be used not only to discriminate between different signals but also to discriminate signal from background.\footnote{CMS \cite{2} uses JEC 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).} 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 Fig. 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, $p_T^1 \simeq p_T^2 (= p_T) \gg (p_T^3, p_T^4 = p_T')$. We can then approximate $C_3^{\beta}$ as (up to order $\varepsilon = \frac{p_T'}{p_T}$)

$$C_3^{(\beta)} \sim \left[\frac{(R_{13}R_{14}R_{23}R_{24}R_{34})^\beta}{(R_{13}R_{23})^\beta + (R_{14}R_{24})^\beta}+ O(\varepsilon)\right]$$

Thus the leading term is not proportional to $\varepsilon$, 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 val-
FIG. 4. The $p$-values testing hypothetical identities of various resonances as a function of luminosity. Horizontal lines indicate 2 and 3 $\sigma$ exclusion of the alternate hypothesis. Vertical lines show where $S/\sqrt{B} = 3$ or 4.

ues 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.

An important point that should be noted finally is the dependence of the JEC on the exponent $\beta$. As $\beta \to 0$, the dependence on the relative angles vanishes, and the JEC 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 JEC. Note that we have not optimized $\beta$ for maximal discrimination in this analysis. Another aspect that we have not investigated and have reserved for future study is the use of JECs (or other jet observables) on unfiltered subjets 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.

In order to test the ability of JECs 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. The result of our analysis is shown in Fig. 4. The horizontal dotted lines indicate where one can distinguish between various signal hypotheses at the 2 $\sigma$ or 3 $\sigma$ level; for example, one could tell a $Z'$ from an excited quark at the 3 $\sigma$ level with about 180 fb$^{-1}$ of integrated luminosity. The vertical lines indicate the value $S/\sqrt{B}$ provided by a given integrated luminosity; for instance, achieving $S/\sqrt{B} = 3$ for our resonances (since we assume the signal size is 25 fb$^{-1}$) would require 720 fb$^{-1}$ of data. The figure shows that it is very easy to tell apart a coloron from a $Z'$, whereas the weakest discrimination is that between a spin-2 and a diquark.

In summary, we conclude that JECs are a powerful tool to both discover and identify new resonances at the LHC.

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