Probing Heavy Dijet Resonances Using Jet Substructure at the LHC

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Abstract

The search for new physics at high energy accelerators has been at the crossroads with very little hint of signals suggesting otherwise. The challenges at a hadronic machine such as the LHC compounds on the fact that final states are swamped with jets which one needs to understand and unravel. A positive step in this direction would be to separate the jets in terms of their gluonic and quark identities, much in similar spirit of distinguishing heavy quark jets from light quark jets that has helped in improving searches for both neutral and charged Higgs bosons at LHC. In this work, we utilise this information using the jet substructure techniques to comment on possible discrimination of new resonances in the all hadronic mode that would be crucial in pinning down new physics signals at HL-LHC, HE-LHC and any future 100 TeV hadron collider.

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Resonance search is one of the most simple and direct ways to establish the presence of new particles at a collider. With high center-of-mass energies available at hadronic colliders such as the Large Hadron Collider (LHC), it serves as a perfect playground for resonance searches of massive particles predicted in many beyond standard model (BSM) scenarios. The LHC energies and available integrated luminosity can help search for these exotic particles beyond 4-5 TeV. The envisaged 100 TeV hadron machine [1] will expectedly improve this range by nearly a factor of magnitude and more so for strongly interacting particles. However, finding a signal for such strongly interacting heavy particles which dominantly decay to either quarks\(^1\), gluons or both against the huge QCD background is very difficult. The major challenge at a hadronic machine such as the LHC compounds on the fact that final states are swamped with jets which one needs to understand and unravel in order to extract signal for new physics in the all hadronic final state. However, there are techniques to reduce these huge QCD background from the signal. There already exist searches for heavy resonances in the dijet channel by CMS [2–7] and ATLAS [8–11]. The experimental collaborations provide an upper limit at 95% C.L. on the cross section for heavy resonance production and decaying to three types of different decay channels, viz. \(qq\), \(qg\), and \(gg\), separately. Although they do not distinguish between quark or gluon jets explicitly in the final state, they have used the line-shape information of the resonance peak, as has been reviewed in Ref. [12] for the three different types of final state to set the limits. In this work we use jet substructure techniques in studying several exotic resonances in the dijet final state and show that in addition to the line-shape, if we can distinguish between the flavour\(^2\) of the jets, existing and future limits on the cross section for heavy resonances can be significantly improved. Thus a good knowledge of discrimination between quark and gluon jets will not only help in improving the resonance searches at the HE-LHC and future 100 TeV machine but also help in pinning down the new physics scenario by giving hints on the interaction Lagrangian.

The recent developments in the study of jet substructure provide us one of the best ways to gather more information from a collider event with large hadronic activity. The use of jet substructure is becoming popular day by day due to the recent developments in both theoretical and experimental understanding of physics inside the jets where perturbative and non-perturbative effects dominate in different regions in the energy scales. It has been shown that theoretical understanding about substructure of a jet can even allow us to differentiate between quark-initiated and gluon-initiated jets to a certain extent [13–17] due to the difference in their radiation pattern inside

\(^1\) Here quark represents both quark and antiquark.
\(^2\) Here flavour means light quark/antiquark and gluon jets.
the jet. Further improvements in this direction can be possible with the use of machine learning techniques which along with the substructure picture of the jets makes the discrimination even more robust and allows us to enhance the discrimination power between quark and gluon jets [18–23]. This quark and gluon tagging can therefore be used to improve the search for resonances in several BSM physics scenarios at the colliders.

While discrimination between a quark and gluon jet would perhaps be a novel approach to identify certain BSM scenarios, in this work we take a slightly different approach. Instead of distinguishing a quark jet from a gluon jet on a jet-by-jet basis, we take an event containing several jets as a whole and the analysis is done on the event variables as well as on the jet substructure observables. The jet substructure observables chosen for quark-gluon discrimination will have different probability distribution for quark and gluon jets. In general, all the jets in a set of events produced at the collider are not entirely quark-initiated or gluon-initiated jets, but certain fraction of them are quark jet or gluon jet contributing to the events. If these fractions are different for signal events from the background events, there will be some degree of distinguishing power between signal and background. Through this work we try and show that even if we do not tag the jets in a particular event as quark or gluon jets, we can still conclude with some confidence whether the event is a signal-like event or a background-like event.

The fraction of quark or gluon jets in a set of events, which we talked about in the last paragraph, can be a fixed fraction generated in each single event or it can be an overall fraction from a set of events. For example, if a strongly interacting heavy fermion (e.g. excited quarks $q^*$) decays to two light-flavoured jets, then one expects that there will be 50% quark jets and 50% gluon jets in each event and hence the fraction will be 50% in the whole set of events for both quark and gluon jets. On the other hand, if a heavy colored boson (e.g. colorons) decays to two light-flavoured jets, it will either decay to a pair of quark or to a pair of gluon jets. Hence the overall fraction of quark jets and gluon jets in the collection of events will be determined by the relative coupling of the heavy boson with a quark pair and a gluon pair. However, note that such a fraction in the events could also originate from non-resonant dijet or multijet production processes at a collider. In fact, the Standard Model (SM) dijet background is a non-resonant production of two light flavoured jets. The probability distribution for jet substructure observables will be same for a given fraction irrespective of whether it originates from every single event or from a collection of events. Thus a closer scrutiny of the events with jet tagging, comparing quark initiated and gluon initiated jets would be crucial in understanding the heavy resonances.

For the jet substructure analysis we first list out the criterion and observables we are interested
in. We classify our requirements based on the event variables and therefore we choose only the simple variables, viz. $p_T$ and $\eta$ of the leading and sub-leading jet (arranged according to larger transverse momenta) and their angular separation $\Delta R(j_1, j_2) = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ defined between the two jets. For the jet substructure observables, we refer to the two types of observables as pointed out in Ref. [14, 16], viz. discrete and continuous observables. The most important ones are:

- Particle and charged particle multiplicity inside a jet [14].

- Les Houches Angularity: $\text{LHA} = \sum_{i \in J} \frac{p_{Ti}}{p_{TJ}} \Delta R(i, J)$ [15, 24].

- Girth: $g = \sum_{i \in J} \frac{p_{Ti}}{p_{TJ}} \Delta R(i, J)^2$ [14].

- Width: $w = \sum_{i \in J} \frac{p_{Ti}}{p_{TJ}} \Delta R(i, J)$ [25–27].

- Two-point energy correlation variables: $e_{\beta} = \sum_{i > j \in J} \frac{p_{Ti}p_{Tj}}{p_{TJ}^2} \Delta R(i, j)^{\beta}$ [28].

- $p_T^2$ weighted jet minor axis ($\sigma_2$) with respect to the jet axis in $\eta - \phi$ plane [16, 29].

- $p_T D = \sum_{i \in J} \sqrt{\frac{p_{Ti}^2}{p_{TJ}^2}}$ [16, 30].

where $R$ is radius parameter of the jet and, in the subscripts, $i, j$ represent the constituents of the jet while $J$ represents the jet.

We know from first principle as well as from data collected in collider experiments that radiation pattern inside a gluon jet differs from that of the light-quark jets. Due to the difference in radiation pattern, many jet substructure observables have been proposed in the literature to discriminate between quark and gluon jets. Though our primary aim in this work is not distinguishing quark jet from a gluon jet, our analysis procedure is still guided by similar jet substructure observables that helps in quark-gluon discrimination. The choices of the observables can be explained as follows.

- Gluon fragments more than a quark due its color factor (color factor ratio is $\frac{C_A}{C_F} = \frac{9}{4}$), which results in higher particle multiplicity in gluon jet compared to a quark jet.

- Charged particle multiplicity is also more in case of gluon jet than in quark jet.

- Gluon fragmentation function is softer than a quark, i.e. constituents of gluon jets tend to be softer than a quark jet. This means $p_T D \to 0$ in the case of a gluon jet while $p_T D \to 1$ in case of quark jet.
- Gluon jets are less collimated compared to quark jets. This gives wider radius for gluon jet with respect to quark jet. So, if the shape of the jets are approximated to an ellipse in $\eta - \phi$ plane, gluon jets tend to have longer minor axis than quark jets.

- Combination of the last two points also tend to give higher values for Girth, Width, LHA and two-point energy correlation variables ($e_\beta$).

![Diagram](image)

FIG. 1. Distribution of jet substructure observables for SM $gg$ events (solid), $qq$ events (dashed), and $qg$ events (dotted). (left) Distribution for girth and (right) distribution for Les Houches Angularity.

To illustrate the difference in the distribution of jet substructure observables between quark and gluon jets, in Fig. 1 we show an area normalized distribution for the two jet substructure observables, both for quark (dashed) and gluon (solid) jets in $(q q)$ and $(g g)$ subprocesses in SM respectively. The jet substructure observables are calculated from the leading jets in the subprocesses. As we can see that the distribution for quark jet is quite different from that of gluon jet. However, for a mixed sample of quark and gluon jets, the distribution will be smeared out. The same two observables are plotted in Fig. 1 for the leading jet in $q g$ events. A selection criteria of $p_{T,j} > 500$ GeV and $|\eta| < 2.5$ for both the jets were imposed on the event sample. Anti-kt algorithm with radius parameter $R = 0.4$ was used for jet clustering. The distribution of the jet substructure observables shown in Fig. 1 are for girth ($g$) and for Les Houches Angularity (LHA). This difference in distribution among quark, gluon and admixture of quark and gluon will form the basis of the analyses to follow.

In this study, we take three different kinds of dijet resonances each of which gives us one of the three types of dijet signals: $qq$, $qg$, or $gg$. For resonances leading to $qq$ final state, each of the jets will be quark-like while it will be gluon-like for $gg$ final state. On the other hand, for $qg$ final state,
its properties will be admixture of those of quark and gluon. Hence, if we consider jet substructure observables of the hardest jet (or second hardest jet), their distribution will be different for these three cases with the observables of $qq$ being far apart from those of $gg$ final state and, for $qg$ final states, the observables will be in-between these two.

In Table I, we list a few important models and the Lagrangians corresponding to these models, e.g. see Refs. [31–33]. A more comprehensive list of all possible colored particle that gives dijet resonances at the LHC can be found in Ref. [34]. We also list in Table I the total cross-sections for these models at 13 TeV LHC for the specific values of the parameters listed in the table. For further analyses, we take coloron model [35–37] for $qq$ resonance, color octet scalar model [38–40] for $gg$ resonance, and excited quark model [41–45] for $qg$ resonance.

![Table I](image)

TABLE I. Examples of resonant particles with the production cross section at 13 TeV LHC for each resonant particle at 2 TeV.

As mentioned in Refs. [14–17], some jet substructure observables are better suited for quark and gluon jet tagging than others. In our work we too perform a thorough investigation of the jet substructure observables to find out which of the observables are best suited for better distinguishing power. We also note that the same jet substructure observables will be equally important in distinguishing the different types of final state events. To highlight this we perform two types of analyses. In the first type of analysis, we try to see how much improvement one can get over the current resonant dijet search by the use of jet substructure observables. In the second analysis, we try to distinguish among the different types of resonances. So our signal in either analysis is that of two jet invariant mass showing a resonant peak at a test mass value of 2 TeV notwithstanding the fact that the results would be true and robust for different values of the mass. The two analyses are differentiated on the fact that the underlying source for backgrounds for them would be markedly different. In the first case we wish to identify the resonance over the SM dijet background as a hint for physics beyond the SM while in the second case, we treat different types of resonant behaviour
To facilitate this study, UFO files were generated corresponding to the Lagrangian listed in Table I using FeynRules2.0 [46, 47]. The parton-level events were then simulated using the UFO files with the help of MadGraph5 [48] with a hard $p_T$ cut to populate the relevant phase space with enough events. The events generated with $p_T > 700$ GeV for both the jets (parton-level) from MadGraph5 were parton showered and hadronized using Pythia8235 [49] with the default tune implemented in Pythia. Jets were clustered using anti-kt algorithm with radius $R = 0.4$ from these showered events with the help of FastJet3.3.2 [50]. We note that detector effects as well as pile-up effects have been ignored in this study. However, one expects that the results may differ by 5-10% if fast detector simulation was considered. In order to reduce the effects of contamination from Underlying Event (UE), many different taggers and groomers have been proposed in the literature e.g. trimming [52], pruning [53, 54], Mass Drop tagger [55] and Soft Drop [56] groomer. In this work, we use the Soft Drop groomer which is a good IRC safe groomer. After jet clustering the Soft Drop groomer was used to groom away the UE with Soft Drop parameter $\beta = 1.0$ and $z_{cut} = 0.1$. Both the jets from each event are required to have $p_T$ more than 800 GeV. The dijet events after satisfying the above condition and with the invariant mass of the dijet lying within 10% of the mass of the resonant particle $X$ ($0.9 M_X < m_{jj} < 1.1 M_X$) are selected for further analysis. All the substructure observables and event variables are constructed after the Soft Drop

3 A systematic comparison with and without Delphes3.3.2 [51] fast simulation for a few jet substructure observables in the case of quark and gluon discrimination is shown in Ref. [23]. The maximum reduction in efficiency is not more than 10% if detector simulation is included.
grooming procedure.

The dijet invariant mass distribution is one way of looking at the parton content of the jets making up the resonance. The line-shape of the resonant mass are different for $qq$, $qg$, and $gg$ resonances as mentioned in Ref. [2]. This is illustrated in Fig. 2. The CMS collaboration has actually used the line shape information to put 95% C.L. upper bound on the three above mentioned configurations of the dijet resonances. A quick comparison of the line-shape plot with Ref. [2] one finds that the $m_{jj}$ distribution is slightly narrower in our case. However, we should not take this comparison seriously since we do not take any kind of pile-up or detector effects. So, the best way to compare and see the improvement is via Receiver Operating Characteristic (ROC) curve. An ROC curve gives the background rejection efficiency, i.e. the fraction of background rejected out of the total background for a given signal efficiency (the fraction of signal accepted out of the total signal). For a single variable, ROC curve can easily be obtained by sliding upper or lower cut on that particular variable and plotting the values of background rejection efficiency versus signal efficiency. However, for complicated distributions or for more than one variable, the ROC curve is not unique. A good multivariate analysis (MVA) gives an optimized classifier variable after combining all the input variables in an optimized way. We can use this classifier variable to draw ROC curves for different signal and background analysis. In this study, we used Boosted Decision Tree (BDT) classifier variable for the rest of the analyses to follow. For the implementation of BDT, the TMVA2.0 [57] package which is built-in in Root6 [58, 59] was used.

With the generated events and variables, we then try to find distinguishing score among the three different types of resonances. Since, in a hadron collider, one cannot really avoid SM QCD background, we would like to first try and distinguish a signal resonance from the huge QCD dijet background. Note that for the SM QCD background, we shall use the same tools and parameters discussed earlier. The properties of the leading and subleading jets of the QCD background will again be a mixture of the properties of pure quark and pure gluon jets. So we expect better discrimination for $qq$ and $gg$ resonances from the SM QCD dijet background. However, we still expect some degree of discrimination for $qg$ resonance since the fraction of quark and gluon will be different for the SM background from the $qg$ resonance, where it is expected to be an admixture of 50% quark and 50% gluon. In order to see that the use of jet substructure observables help in discriminating signal from the background, we first analyse the events with only event variables, viz. $p_T$, $\eta$ of both the jets, $\Delta R(j_1, j_2)$ and $m_{jj}$ for the discrimination of signals from the SM dijet background. We then supplement the analysis by adding jet substructure (JSS) observables, viz. particle multiplicity, charged particle multiplicity, LHA, width, girth, $\epsilon_{0.5}$, $p_T D$, $\sigma_2$ of leading as
FIG. 3. Illustrating the ROC curves (left) for the $gg$ resonance signal against SM the dijet background for analysis with (solid) and without (dashed) jet substructure observables. Variation of Significance Improvement as a function of signal efficiency (right).

well as subleading jets in addition to the simple event variables. We plot the ROC curve in the left panel of Fig. 3 with-JSS (solid) and without-JSS (dashed) observables for $gg$ resonance. We can see quite clearly a very significant improvement if we add JSS observables to the analysis, albeit at the expense of signal efficiency. This can be seen by looking at a Significance Improvement (defined by Eq. 1) curve. If we have $S$ number of signal events and $B$ number of background events, then, for large $S$ and $B$, significance of the signal is defined as $\sigma = \frac{S}{\sqrt{B}}$. To quantify the improvement of using JSS observables, we define a Significance Improvement variable as

$$\text{Significance Improvement} = \frac{\sigma_{\text{JSS}}}{\sigma} = \frac{\epsilon_{\text{JSS}} S}{\epsilon_{S} S} \times \sqrt{\frac{\epsilon_{B}}{\epsilon_{\text{JSS}} B}}$$

where $\sigma$ represents significance, $\epsilon$ represents efficiency. The superscript JSS is for analysis with JSS observables and subscripts $S$ and $B$ represent signal and background respectively. Significance Improvement is plotted as a function of signal efficiency in the right panel of Fig. 3. The improvement in significance is $20 - 80\%$ depending on the values of signal efficiency. It should be noted that for very small signal efficiency, number of events may be so small that the statistical formula for significance, $S/\sqrt{B}$, is not valid anymore. However, for $\epsilon_{S} > 0.05$, the numbers come out to be reasonable with an integrated 40 fb$^{-1}$ luminosity at 13 TeV center-of-mass energy at the LHC.

In the above analysis, the resonance condition on the invariant mass of the dijets has also been applied ($1.8 \text{ TeV} < m_{jj} < 2.2 \text{ TeV}$). While the choice of a window for the resonance mass condition does not affect the signal much, it helps reduce the QCD dijet background to a large extent.

We carry out very similar exercise (analyses) for the other two types of resonant configuration
in the dijet, i.e. the \( qq \) and \( qg \) resonances. The results are shown in Fig. 4. In the left panel of Fig. 4, we plot the ROC curves for the \( qq \) (top) and \( qg \) (bottom) resonance signals against SM dijet background. Significance Improvement as a function of signal efficiency is plotted in the right panel of the figure. We again observe reasonable improvements as seen for \( gg \) resonance. For \( qg \) resonance the improvement is slightly depleted in the range of higher \( \epsilon_S \), compared to the other two cases. This is because both \( qg \) signal and SM dijet background has an admixture of both quark and gluon jet properties in either jet in the dijet event.

Once the signal is identified over the SM background, we can expect to discriminate between the different types of resonances, e.g. \( gg \) resonance from \( qq \) and \( qg \) resonances. We again use BDT for the above discrimination with-JSS and without-JSS observables. The ROC curves for
signal acceptance and background rejection are shown in the left panel of Fig. 5 with-JSS and without-JSS observables. In this part of the analysis, the background no longer implies to the SM dijet background. The convention we set here is that, when any one of the three types of resonance configuration in the dijet is considered to be a signal, the other two resonance channels are considered to be background. In the left panel of Fig. 5, we plot the ROC curves for $gg$ resonance as signal. The ROC curve corresponding to the discrimination from $qq$ with-JSS observables (solid line) is much better compared to the one without-JSS observables (dotted line). The improvement is slightly less when we consider $qg$ resonance as the background since it has a partial gluon jet feature. When considering the $qg$ resonance as background, the ROC curve for the given event variables without-JSS is shown in dash-dot line and the ROC curve with-JSS observables is shown in dashed line. It is clear from the figure that $gg$ can be separated well from $qq$ resonance since signal is pure gluon and background is pure quark in this case. However, the distinguishing power is not as good when applied to separate the $qg$ resonance from $gg$ resonance since $qg$ resonance has around 50% gluon in the event set. Nevertheless, the discrimination score is still significantly high. Here we can see the improvement is much more for the case of jets with-JSS observables from that of jets without-JSS observables. The improvement in signal significance as defined in Eq. (1) is shown in the right panel of Fig. 5. As expected Signal Improvement is much better for $qq$ resonance background compared to $qg$ resonance background. The takeaway from the plot however is the fact that one is able to achieve a robust and pronounced discrimination between the different jet configurations in the dijet resonances over a wide range of signal efficiency parameter
when one uses the JSS observables.

FIG. 6. (left) ROC curves for the $qq$ (top) and $qg$ (bottom) resonance signals for analyses with and without using JSS observables. (right) Significance Improvement for $qq$ (top) and $qg$ (bottom) resonance as a function of signal efficiency.

For the other two resonances, we plotted the ROC curves in the left panel of Fig. 6. The notations and conventions used in the Fig. 6 are similar to that of Fig. 5. The top-left panel is for $qq$ resonance as signal and bottom-left panel is for $qq$ resonance as signal. As expected, for $qq$ resonance as signal the separation is the best against $gg$ resonance background compared to $qg$ resonance as background. In the case of $qg$ resonance, the separation power is relatively less against both the $qq$ and $gg$ resonance. The respective Significance Improvements are shown in the right panels of Fig. 6.

To summarize, we study dijet resonances at LHC and look at the application of jet substructure techniques to such resonances. These resonances may carry different partonic imprints in the jets which will be driven by the spin and color structure of the on-shell particle produced as a resonance.
We note that JSS techniques have become an essential part of today’s collider physics and are being utilized as a very effective tool to understand physics at high energy colliders. Our aim of using jet substructure in this work is to make a statement on the improvements one can achieve in resonant search strategies at the colliders in the dijet final state. However, such an improvement is not restricted to only an exclusive dijet final state but can be applied when final states are of multijet in nature.

Currently, experimental collaborations put 95% C.L. upper limit on the production cross section of different types of resonances, viz. \( gg \), \( qq \), and \( qg \) resonances using only line-shape information of these types of resonances at 13 TeV collider. In this work, we attempt to make use of JSS to improve the existing search strategies of heavy colored resonances in dijet channel. We first show how the jet substructure observables help in discriminating a signal for any of the heavy dijet resonances, viz. \( gg \), \( qq \), and \( qg \), from the SM QCD dijet background. We utilize Boosted Decision Tree (BDT) multivariate classifier for the discrimination. We highlight our results in the form of ROC curves where we find considerable improvement in the ROC curves when we use jet substructure observables in addition to the simple event variables. This suggests that, with the help of jet substructure technique, the search for different types of heavy resonances can be improved to a great extent at the LHC. Furthermore, we also establish and show that distinction between different types of resonances can also be achieved with a better significance if jet substructure observables are used in addition to the event variable. The same technique can also be effectively applied to proposed future high energy machine although analyses with only 13 TeV has been presented in this article.

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