Search for dijet resonances in events with three jets from proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract

A search for a narrow resonance, with a mass between 350 and 700 GeV and decaying into a pair of jets, is performed in proton-proton collisions with at least three jets in the final state. The data sample corresponds to an integrated luminosity of 18.3 fb$^{-1}$ collected at $\sqrt{s} = 13$ TeV with the CMS detector. Data are collected with a technique known as "data scouting", in which the events are reconstructed, selected, and recorded at a high rate in a compact form by the high-level trigger. The three-jet final state provides sensitivity to lower values of the dijet mass than in previous searches using the data scouting technique. The spectrum of the dijet invariant mass, from the two jets with largest transverse momenta in the event, is searched for a bump arising from a dijet resonance. No significant excess is found and 95% confidence level upper limits are presented on the production cross section of narrow resonances. The corresponding upper limits on the coupling, of a vector particle interacting only with quarks, is between 0.10 and 0.15 depending on the resonance mass.
1 Introduction

Many models of new physics predict the existence of new massive particles coupling to quarks. The production and decay of these particles into two jets, known as dijets, has been searched for since the first high energy hadron colliders [1–5]. In some models, these particles act as portals linking the standard model (SM) to new sectors of the theory containing dark matter particle candidates [6, 7]. Therefore, the search for dijet resonances at hadron colliders can be interpreted as a search for a dark matter mediator and compared with searches for dark matter from other experiments [8–11].

This note presents a search for dijet resonance in three jet events, which is sensitive to resonance masses between 350 and 700 GeV. The LHC experiments have used various techniques to search for bumps arising from resonances in the dijet invariant mass spectrum. From searches where both jets are individually resolved, the CMS and ATLAS collaborations have set limits for resonances of mass above 600 GeV and 450 GeV, respectively, in 13 TeV proton-proton collisions [12–14] and above 500 and 250 GeV, respectively, in 8 TeV collisions [15, 16]. Another search by the ATLAS collaboration for dijet resonances, produced in association with a photon from initial state radiation (ISR), has set limits in the mass region between 250 and 950 GeV [17]. A search by the CMS collaboration for resonances decaying into two bottom quarks, experimentally identified as b-tagged jets, has set limits in the mass range 325-1200 GeV from proton-proton collision data at 8 TeV [18]. From searches for boosted resonances, decaying into two quarks reconstructed as a single merged jet, the CMS and ATLAS collaborations have set limits in the mass region below 450 GeV and 220 GeV, respectively [19, 20].

We search for vector resonances decaying into two jets using 18.3 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector [21]. To obtain a large trigger efficiency in the mass range 350 – 700 GeV, we explore the three-jet final state, and take advantage of a special high-rate trigger with low thresholds. This search is limited to data collected in the year 2016 in order to take advantage of the low trigger thresholds used in that data period. After 2016, these thresholds were raised in order to limit the trigger rate increase due to the larger instantaneous luminosity and pileup.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. The jets used by this analysis are calo-jets that are reconstructed from the energy deposits in the calorimeter towers, clustered using the anti-$k_T$ algorithm [22, 23] with a distance parameter of 0.4. In this process, the contribution from each calorimeter tower is assigned a momentum, the absolute value and the direction of which are given by the energy measured in the tower, and the coordinates of the tower. The raw jet energy is obtained from the sum of the tower energies, and the raw jet momentum by the vectorial sum of the tower momenta, which results in a nonzero jet mass. The raw jet energies are then corrected to establish a relative uniform response of the calorimeter in $\eta$ and a calibrated absolute response in transverse momentum $p_T$. The calorimetric jet energy resolution is typically 40% at a $p_T$ of 10 GeV, 12% at 100 GeV, and 5% at 1 TeV. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [21].
3 Trigger and simulated samples

Events of interest are selected using a two-tiered trigger system [24]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 µs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

We selected events requiring $H_T > 240\text{ GeV}$ at the L1 trigger and $H_T > 250\text{ GeV}$ at the HLT, where $H_T$ is the scalar sum of the transverse momentum of jets with $p_T > 40\text{ GeV}$ and $|\eta| < 2.5$. The rate of this trigger was about 4 kHz at an instantaneous luminosity of $1 \cdot 10^{34}\text{ cm}^{-2}\text{s}^{-1}$. The amount of data generated by such a high-rate trigger alone using the standard data taking format would have saturated the computing and storage systems of the CMS experiment. For this reason, we used a special data taking which consists of saving only calorimetric jets reconstructed by the HLT computing farm instead of the full detector readout. The size of this reduced data format is about 0.5% of the full size. This technique is known as “data scouting” and was used in previous CMS dijet resonance searches [15].

Data scouting allowed analysis of a very large rate of data passing the HLT trigger, but the overall rate of the CMS L1 trigger was limited. To keep a constant rate, the L1 trigger $H_T$ threshold was increased from 240 to 360 GeV with increasing luminosity during the data taking period. This search is limited to data collected in 2016, which required the lower threshold $H_T > 240\text{ GeV}$, in order to obtain the maximum sensitivity for low mass resonances. From a sample of events collected with a minimum bias trigger, and passing the selection discussed below, we measured a trigger efficiency larger than 99% for dijet mass greater than 290 GeV.

Signal events of a narrow vector resonance decaying into quark-antiquark pairs were generated using MADGRAPH5_aMC@NLO version 2.2.1 generator at leading order (LO) [25, 26], PYTHIA 8.205 generator [27], using a GEANT4-based [28] simulation of the CMS detector. As reference, the signal cross sections are computed for a vector boson decaying into a quark pair, with coupling to quarks $g_q = 0.25$, coupling to dark matter particles $g_{DM} = 1.0$, for a dark matter mass of 1 GeV, using the CTEQ6L1 [29] PDF at leading order.

4 Event reconstruction and selection

The main variable of this analysis is the invariant mass of the two jets originating from the resonance decay. This variable is calculated using jets, reconstructed by the HLT from energy deposits in the calorimeter, passing the selection $p_T > 30\text{ GeV}$ and $|\eta| < 2.5$. Spurious jets originating from instrumental noise are rejected by requiring each jet be detected by both the electromagnetic and hadron calorimeters, with at least 5% of the jet energy in each of the two types of calorimeter. We form “wide jets” by clustering the jets in the event using the anti-$k_T$ algorithm with a distance parameter of 1.1. A similar algorithm using a merging distance $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 1.1$ was employed in previous CMS searches [12, 15], but it only reconstructed two wide jets per event. We apply to the wide jets the same calibrations for the data scouting sample as in the low-mass dijet search of Ref. [12], and select the three wide jets with the highest $p_T$ in the event. We require at least three wide jets with $p_T > 72\text{ GeV}$ in order to have a large trigger efficiency to search for dijet resonances in the mass range 350 – 700 GeV. The $p_T$ threshold of the three-jet selection has been chosen with a method that will be explained in Sec. 5.1.
Since we require at least three wide jets in the event, there are multiple ways to select the dijet, the wide jet pair originating from the resonance decay. We select as the dijet the two wide jets with the largest $p_T$ in the event. This selection is correct in 70% (50%) of simulated signal events with a resonance mass of 700 GeV (350 GeV). Wrong selections are due either to an energetic ISR jet being included in the dijet selection or to an energetic FSR jet emitted with $\Delta R > 1.1$ from the leading jets. We found that alternative criteria — such as selecting the jet pair with the largest vectorial sum $p_T$ — have better performance for resonances produced with a transverse momentum larger than half of their resonance mass. The average transverse momentum of the resonance in simulated signal events passing the event selection is about 150 GeV and, therefore, such alternative criteria have worse performance in the mass range considered in this search. Finally, the two leading wide jets are required to have $|\eta_1 - \eta_2| < 1.1$, to reduce the background which is dominated by $t$-channel production of jets.

5 Dijet mass spectrum fit

Figure 1 shows the dijet mass spectrum ($m_{jj}$). The background is modeled with the following analytic function which is fit to the data in the mass range $290 < m_{jj} < 1000$ GeV

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(p_2x - 1)}{xp_1 + p_3 \log x + p_4 \log^2 x}$$

with $x$ defined as $m_{jj}/\sqrt{s}$ and where $p_0$, $p_1$, $p_2$, and $p_3$ are free parameters. This function is similar to that used by previous dijet searches [12–16], with a modification to the numerator in order to fit a small change in the dijet mass spectrum shape caused by the three-jet selection and by the small trigger inefficiency. The function has been chosen from a pool of functions with a different number of degree of freedom using a Fisher test with a 95% CL [30]. The $\chi^2$ of the fit is 19.3, corresponding to a $p$-value of 0.26. The data is well modeled by the background parameterization and there is no evidence for a dijet resonance.

5.1 Fit range and three-jet selection

The dijet mass bin widths in Fig. 1 are the same as in the previous dijet searches, except for the first bin which is more narrow, starting at a dijet mass value of 290 GeV. This lower bound of the fit range and also the jet $p_T$ threshold for the three-jet selection have been determined by using the distribution of the dijet mass in a control region defined by replacing the $|\eta_1 - \eta_2| < 1.1$ requirement with $|\eta_1 + \eta_2| < 1.1$. The dijet mass in the control region is then calculated after flipping the sign of the pseudorapidity of the second jet — the sign of the $z$-component of the momentum of the sub-leading jet is reversed and then the dijet mass is calculated. The control region contains approximately the same number of background events, 50% less signal events, and with 35% of the observed events in the control region are also in the signal region. Small data-driven corrections (< 5%) are applied as a function of $p_T^1 \cdot p_T^2$ in order for the dijet mass distribution in the control region to resemble that in the signal region. The lower edge of dijet mass included in the search, 290 GeV, has been chosen to be the lowest value of the corrected dijet mass in the control region for which the fit of the background parameterization has a Kolmogorov-Smirnov (KS) probability larger than 33%. The $p_T$ threshold of the three jet selection, 72 GeV, has been chosen to obtain the lowest possible value for the corrected dijet mass in the control region which could be included in the fit and satisfy the same KS test. We verified that a possible signal does not change the choice of the fit range and the three-jet selection.
Figure 1: Dijet mass spectra (points) compared to a fitted parameterization of the background (solid curve) where the fit is performed in the range $290 < m_{jj} < 1000$ GeV. The dashed lines represent the dijet mass distribution from 700, 550, and 400 GeV resonance signals excluded at 95% CL by this analysis.
6 Systematic uncertainties

We search for dijet resonances by performing a simultaneous fit of the dijet mass data in Fig. 1 to the parameterization of the background from Eq. 1 and the signal shape obtained from simulation. The systematic uncertainty is dominated by the uncertainties on the analytic parameters of the background originating from the fit to the data. The other systematic uncertainties are modeled as nuisance parameters using the frequentist approach. The effects of the jet energy scale and resolution uncertainties are taken into account as signal shape uncertainties. We estimated the impact of the parton shower modeling uncertainties in signal simulations to be 10% of the signal yield. The systematic uncertainty on the signal normalization due to the uncertainty on the integrated luminosity is 2.5% [31]. The systematic uncertainty due to the choice of the background function has been estimated from signal injection tests using alternative functions and has been found to be negligible.

7 Results

Figure 2 shows, as a function of resonance mass, observed and expected upper limits at 95% CL on the cross section times acceptance of a vector resonance decaying to jets. The acceptance is calculated as the fraction of signal signal events passing the analysis selection, namely three widejets with $p_T > 72 \text{GeV}$ and $|\eta| < 2.5$, and $|\eta_1 - \eta_2| < 1.1$. Figure 3 shows the limits on the coupling $g'_q$ of a vector resonance that decays only to quarks, defined according to the convention of Ref. [32]. The asymptotic approximation [33] of the modified frequentist CLs method [34, 35] is utilized to set upper limits on signal cross sections, following the prescription described in Ref. [36]. No significant excess is found. Figure 3 shows that the observed upper limits on $g'_q$ are between 350 and 700 GeV. Also shown in Fig. 3 is the value of the coupling $g'_q$ for a DM mediator which decays to dark matter particles of mass 1 GeV, with coupling $g_{DM} = 1$, in addition to decaying to quarks with coupling $g_q=0.25$. This analysis excludes that benchmark model of a DM mediator over the complete mass range 350 to 700 GeV.

8 Summary

A search for narrow vector resonances of mass between 350 and 700 GeV decaying into two jets has been performed in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$. The search used 18.3 fb$^{-1}$ of integrated luminosity collected with the CMS experiment. Data have been taken using a special technique, data scouting, for which the trigger had the lowest possible threshold on the sum of the transverse momenta of the jets in the event. Events with three-jets are used to satisfy the trigger threshold at a lower dijet mass than is possible with only two high $p_T$ jets in the final state. Jets with $\Delta R < 1.1$ have been merged into wide jets. The dijet mass has been calculated from the two leading wide jets with highest transverse momenta. Events have been selected by requiring three wide jets with $p_T > 72 \text{ GeV}$, reconstructed from jets within $|\eta| < 2.5$, and requiring the two wide jets forming the dijet satisfy $|\eta_1 - \eta_2| < 1.1$. The background shape has been fitted by using a parametric function, while the signal shape has been obtained using simulations. The dijet mass distribution has shown no significant peak in the range $290 < m_{jj} < 1000 \text{ GeV}$ and therefore upper limits have been set on the production cross section of a signal. We have set 95% CL upper limits on the coupling to quarks $g'_q$ in the range 0.10 – 0.15 for a vector particle interacting only with quarks. This search excludes a simplified model of interactions between quarks and dark matter particles of mass 1 GeV mediated by a vector boson with coupling strengths of, respectively, $g_q = 0.25$ and $g_{DM} = 1$, and mass between 350 and 700 GeV. Among the searches for resonances decaying into light
The acceptance is calculated for the analysis selection, namely three wide jets with $p_T > 72 \text{ GeV}$ and $|\eta| < 2.5$, and $|\eta_1 - \eta_2| < 1.1$. The observed limits (solid), expected limits (dashed) and their variation at the 1 and 2 standard deviation levels (shaded bands) are shown. The dotted horizontal line shows the expected cross section times acceptance for a DM mediator (see text).

This search sets the most stringent upper limits on coupling to quarks of vector particles with a mass between 350 and 450 GeV.

References


Figure 3: The 95% CL upper limits on the universal quark coupling $g'_q$ as a function of resonance mass for a vector resonance that only couples to quarks. The observed limits (solid), expected limits (dashed) and their variation at the 1 and 2 standard deviation levels (shaded bands) are shown. The dotted horizontal line shows the coupling strength for which the cross section for dijet production in this model is the same as for a DM mediator (see text).


