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Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: A search for narrow and broad resonances with masses greater than 1.8 TeV decaying to a pair of jets is presented. The search uses proton-proton collision data at $\sqrt{s} = 13$ TeV collected at the LHC, corresponding to an integrated luminosity of 137 fb^{-1}. The background arising from standard model processes is predicted with the fit method used in previous publications and with a new method. The dijet invariant mass spectrum is well described by both data-driven methods, and no significant evidence for the production of new particles is observed. Model independent upper limits are reported on the production cross sections of narrow resonances, and broad resonances with widths up to 55% of the resonance mass. Limits are presented on the masses of narrow resonances from various models: string resonances, scalar diquarks, axigluons, colorons, excited quarks, color-octet scalars, W$'$ and Z$'$ bosons, Randall-Sundrum gravitons, and dark matter mediators. The limits on narrow resonances are improved by 200 to 800 GeV relative to those reported in previous CMS dijet resonance searches. The limits on dark matter mediators are presented as a function of the resonance mass and width, and on the associated coupling strength as a function of the mediator mass. These limits exclude at 95% confidence level a dark matter mediator with a mass of 1.8 TeV and width 1% of its mass or higher, up to one with a mass of 4.8 TeV and a width 45% of its mass or higher.

Keywords: Beyond Standard Model, Hadron-Hadron scattering (experiments)

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Contents

1 Introduction

New particles that decay to pairs of jets and appear as dijet resonances arise in a variety of models. String resonances [1, 2] originate from the Regge excitations of quarks and gluons. Scalar diquarks [3] are predicted by a grand unified theory based on the E_6 gauge symmetry group. Mass-degenerate excited quarks (q^*) [4, 5] appear in quark compositeness models. Axigluons and colorons, axial-vector and vector particles, are expected in the chiral color [6, 7] and the flavor-universal coloron [7, 8] models, respectively. Color-octet scalars [9] appear in dynamical electroweak (EW) symmetry breaking models, such as technicolor. New gauge bosons (W' and Z') can exist with standard model (SM) like or leptophobic couplings [10]. Randall-Sundrum (RS) gravitons are predicted in the RS model of extra dimensions [11]. Dark matter (DM) mediators arise from an interaction between quarks and DM [12–15]. The natural width, Γ, of a new particle increases with its coupling strength to other states, and may vary from narrow to broad, as defined in comparison to the experimental resolution.

This paper describes a model-independent search for a narrow or broad s-channel dijet resonance with a mass above 1.8 TeV, in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV. This search uses data corresponding to an integrated luminosity of 137 fb^{-1} collected in 2016–2018 with the CMS detector at the LHC. Similar searches have been published previously by the ATLAS and CMS Collaborations at $\sqrt{s} = 13$ TeV [16–21], 8 TeV [22–25], and 7 TeV [26–32] using strategies reviewed in ref. [33]. Results of the search are interpreted using as

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benchmarks the models described above. As no excess above the SM was observed, we set limits on the production cross sections of new particles decaying to the parton pairs qq (or $q\overline{q}$), qg, and gg. We then use these limits to constrain the benchmark models, with the same choices of parameters as those that were used in the most recent CMS search [17], which used data corresponding to an integrated luminosity of 36 fb^{-1}. In the color-octet scalar model, the squared anomalous coupling $k_s^2 = 1/2$ [34] is used. For the RS graviton model, the value of the dimensionless coupling $k/\overline{M}_{\mathrm{Pl}}$ is chosen to be 0.1, where k is the curvature scale in the 5-dimensional anti de Sitter space and $\overline{M}_{\mathrm{Pl}}$ is the reduced Planck scale defined as $M_{\mathrm{Pl}}/\sqrt{8\pi}$. For the DM mediator, we follow the recommendations of ref. [15] on model choice and coupling values. We use a simplified model [14] of a spin-1 mediator decaying only to quark-antiquark ($q\overline{q}$) and DM particle pairs, with an unknown mass m_{DM}, and with a universal quark coupling $g_q = 0.25$ and a DM coupling $g_{\mathrm{DM}} = 1.0$.

Similar to past searches, and for dijet mass (m_{jj}) greater than 1.5 TeV, the main background from quantum chromodynamics (QCD) multijet production is predicted by fitting the m_{jj} distribution with an empirical functional form. For $m_{jj} > 2.4$ TeV, a new data-driven method is introduced, which predicts the background from a control region where the pseudorapidity separation of the two jets, $|\Delta\eta|$, is large. This new "ratio method" yields smaller systematic uncertainties when performed in the same dijet mass range as the "fit method", and the sensitivity for broad resonance searches is improved by up to a factor of two depending on the resonance width and mass. In addition, the total integrated luminosity for this search is roughly a factor of four larger than that used by the previous CMS search [17], so the sensitivity of both narrow and broad resonance searches has also increased by up to an additional factor of two.

2 The CMS detector

A detailed description of the CMS detector and its coordinate system, including definitions of the azimuthal angle ϕ and pseudorapidity η, is given in ref. [35]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing an axial magnetic field of 3.8 T. Within the solenoid volume are located the silicon pixel and strip tracker ($|\eta| < 2.4$), and the barrel and endcap calorimeters ($|\eta| < 3.0$), where these latter detectors consist of a lead tungstate crystal electromagnetic calorimeter and a brass and scintillator hadron calorimeter. An iron and quartz-fiber hadron calorimeter is located in the forward region ($3.0 < |\eta| < 5.0$), outside the solenoid volume. The muon detection system covers $|\eta| < 2.4$ with up to four layers of gas-ionization chambers installed outside the solenoid and embedded in the layers of the steel flux-return yoke.

3 Jet reconstruction and event selection

A particle-flow (PF) event algorithm aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector [36]. Particles are classified as muons, electrons, photons, charged hadrons, or neutral hadrons. To reconstruct jets, the anti-k_T algorithm [37, 38] is used

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with a distance parameter of 0.4, as implemented in the FastJet package [39]. At least one reconstructed vertex is required. Charged PF candidates not originating from the primary vertex are removed prior to the jet finding. The candidate vertex with the largest value of summed physics-object p_{T}^2, where p_{T} is the transverse momentum, is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm mentioned above, with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets. For jets, an event-by-event correction based on jet area [40, 41] is applied to the jet energy to remove the estimated contribution from additional collisions in the same or adjacent bunch crossings (pileup).

Events are selected using a two-tier trigger system [42]. Events satisfying loose jet requirements at the first-level (L1) trigger are examined by the high-level trigger (HLT) system. Single-jet triggers that require a jet in the event to exceed a predefined p_{T} threshold are used. Triggers that require H_{T} to exceed a threshold, where H_{T} is the scalar sum of jet p_{T} for all jets in the event with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 3.0$, are also used. The HLT requires: $H_{\mathrm{T}} > 1050\,\mathrm{GeV}$ or at least one jet reconstructed with an increased distance parameter of 0.8 and $p_{\mathrm{T}} > 550\,\mathrm{GeV}$.

The jet momenta and energies are corrected using calibration factors obtained from simulation, test beam results, and pp collision data at $\sqrt{s} = 13\,\mathrm{TeV}$. The methods described in ref. [41] are used and all *in-situ* calibrations are obtained from the current data. Jets are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$. The two jets with the largest p_{T} are defined as the leading jets. Jet identification criteria are applied to remove spurious jets associated with the calorimeter noise as well as those associated with muon and electron candidates that are either misreconstructed or isolated [43]. For all jets, we require that the neutral hadron and photon energies are less than 90% of the total jet energy. For jets within the fiducial tracker coverage, we additionally require the jet to have nonzero charged-hadron energy, and electron and muon energies to be less than 90% and 80% of the total jet energy respectively. An event is rejected if either of the two leading jets fails these jet identification criteria.

Each of the two leading jets is formed into a "wide jet" using an algorithm introduced for previous CMS dijet searches in ref. [23]. This wide-jet algorithm, designed for dijet resonance event reconstruction, reduces the sensitivity of the analysis to gluon radiation (g) from the final-state partons. The two leading jets are used as seeds and the four-vectors of all other jets, if within a distance defined as $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$, are added to the nearest leading jet to obtain two wide jets, which then form the dijet system. The dijet mass is then found as the invariant mass of the system of these two wide jets. The wide-jet algorithm thereby collects hard-gluon radiation found near the leading two final-state partons, in order to improve the dijet mass resolution.

The background from t-channel dijet events has the same angular distribution as Rutherford scattering, approximately proportional to $1/[1 - \tanh(|\Delta\eta|/2)]^2$, which peaks at large values of $|\Delta\eta|$, the pseudorapidity separation of the two jets. The signal region (SR) is defined by requiring $|\Delta\eta| < 1.1$, which maximizes the search sensitivity for isotropic

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decays of dijet resonances in the presence of QCD dijet background. For the ratio method of estimating the background, two control regions (CRs) are defined from events within $1.1 < |\Delta\eta| < 2.6$. The primary control region, $\mathrm{CR_{high}}$, which contains events that satisfy $1.5 < |\Delta\eta| < 2.6$, is used to predict the main QCD background in the SR. The secondary control region, $\mathrm{CR_{middle}}$, which contains events that satisfy $1.1 < |\Delta\eta| < 1.5$, is used to constrain theoretical and experimental systematic uncertainties. The $\mathrm{CR_{high}}$ is defined such that it has four to five times more background events than the SR, and at the same time fewer signal events by a factor of two. The SR is used to search for the presence of resonances and to estimate the QCD background for the fit method.

Events with $m_{\mathrm{jj}} > 1.5\,\mathrm{TeV}$ are selected offline, for which the $|\Delta\eta|$ between the two jets is in the interval $|\Delta\eta| < 2.6$, where the dijet mass and $|\Delta\eta|$ are reconstructed using wide jets. For this selection the combined L1 trigger and HLT was found to be fully efficient, as measured using a sample acquired with an independent trigger requiring at least one muon with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ at the HLT. The $|\Delta\eta| < 1.1$ requirement makes the trigger efficiency increase sharply and plateau at a value of 100% for relatively low values of dijet mass. This is because the jet p_{T} threshold of the trigger at a fixed dijet mass is more easily satisfied at low $|\Delta\eta|$, as seen by the approximate relation $m_{\mathrm{jj}} \approx 2p_{\mathrm{T}} \cosh(|\Delta\eta|/2)$. Hence, the trigger efficiency reaches 100% in the SR at a lower value of dijet mass (1.5 TeV) than in both CRs (2.4 TeV). Therefore the fit method is used for $m_{\mathrm{jj}} > 1.5\,\mathrm{TeV}$ and the ratio method, which requires data from the CRs with 100% trigger efficiency, is used for $m_{\mathrm{jj}} > 2.4\,\mathrm{TeV}$.

4 Data and simulation comparison

As the dominant background for this analysis is expected to be the QCD production of two or more jets, the selected dijet data are compared with QCD predictions. The predictions come from 270 million simulated events produced by the PYTHIA 8.205 [44] program with the CUETP8M1 tune [45, 46] using the parton distribution function (PDF) set NNPDF2.3LO [47], including a GEANT4-based [48] simulation of the CMS detector. The data-over-simulation ratio of event yields is 0.94. This search uses the signal shapes of narrow and broad resonances presented in ref. [17], which are also from a PYTHIA simulation.

The dijet $|\Delta\eta|$ separation between the two wide jets is shown in figure 1. The data distribution shows that dijet production is dominated by t-channel parton exchange, as predicted by QCD, with a production rate that increases with increasing $|\Delta\eta|$. By contrast, most s-channel signals from dijet resonances decrease with increasing $|\Delta\eta|$, as the signal shown does. Figure 1 shows the division of the $|\Delta\eta|$ distribution into the signal and control regions.

Figure 2 shows, for both data and the QCD background, the dijet mass spectra in the signal and control regions, which fall steeply and smoothly as a function of dijet mass. The observed dijet mass distributions are compared to the QCD background prediction from PYTHIA, which simulates processes at leading order (LO).

We inspect the characteristics of the 23 events with $m_{\mathrm{jj}} > 7\,\mathrm{TeV}$, to determine if they have the two-jet topology typical of the QCD background and to check for the presence of detector and reconstruction pathologies, and we find the one unusual event, shown in

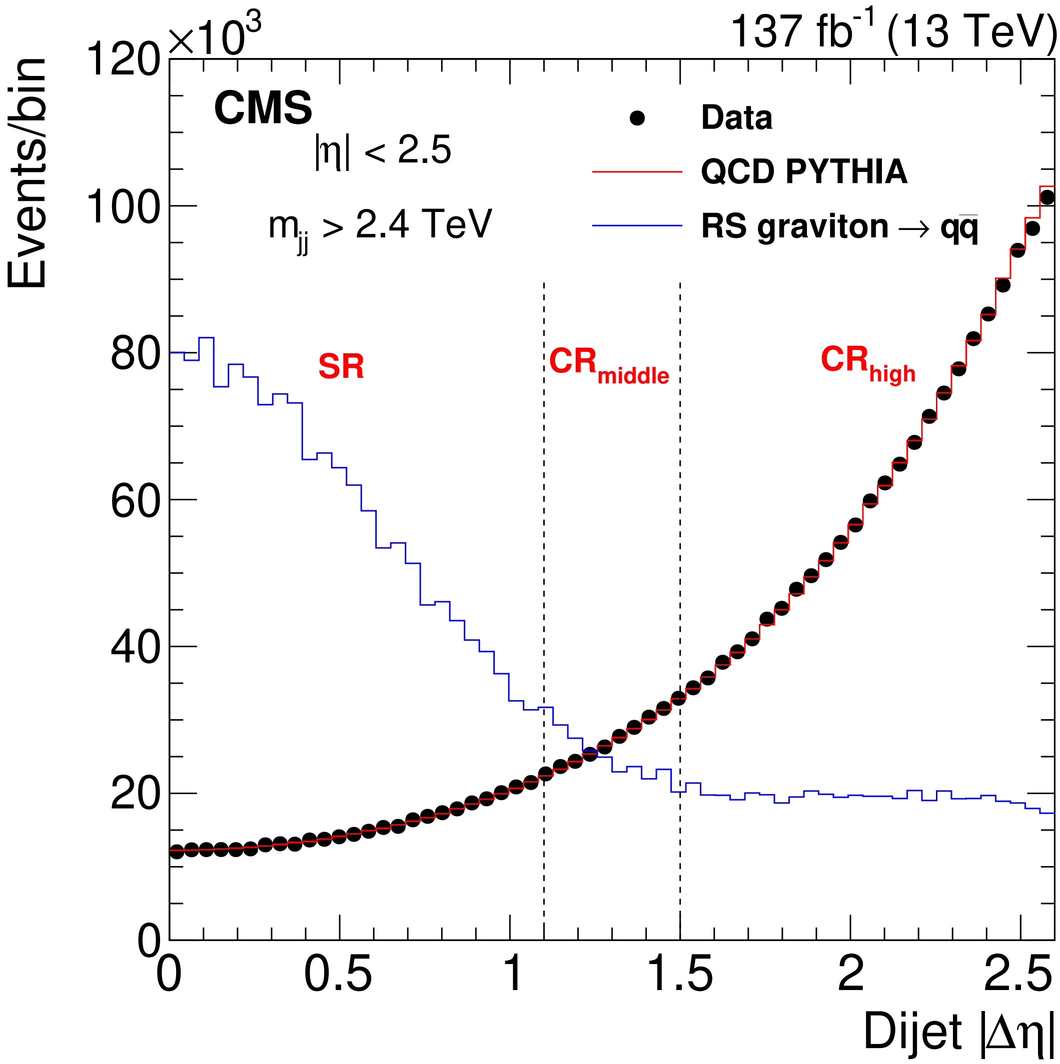

Figure 1. The pseudorapidity separation between the two wide jets for the signal and control regions. Data (black points) are compared to QCD predictions from the PYTHIA MC with detector simulation (red histogram) normalized to data. A signal from an RS graviton decaying into a $q\overline{q}$ pair is also shown (blue histogram) normalized to data.

figure 3. This event is the one with the second highest dijet mass, 8 TeV, and is unusual because it is composed of four jets, in two pairs, which are combined into the two wide jets. It is also unusual because the wide jet mass, equal to the pair mass of the jets, has the same value 1.8 TeV for each of the two wide jets. The leading wide jet has a p_{T} of 3.5 TeV, and the other wide jet has a p_{T} of 3.4 TeV. The wide jets are back-to-back in azimuthal angle ($\Delta\phi = 3.1$) and nearby in pseudorapidity ($|\Delta\eta| = 0.4$). Each one of the two wide jets is composed of two jets with cone size 0.4, with p_{T}, η, and ϕ values as shown in figure 3.

The possibility that this event originates from a resonance decaying to a pair of dijet resonances has been recently explored in a phenomenology paper [49].

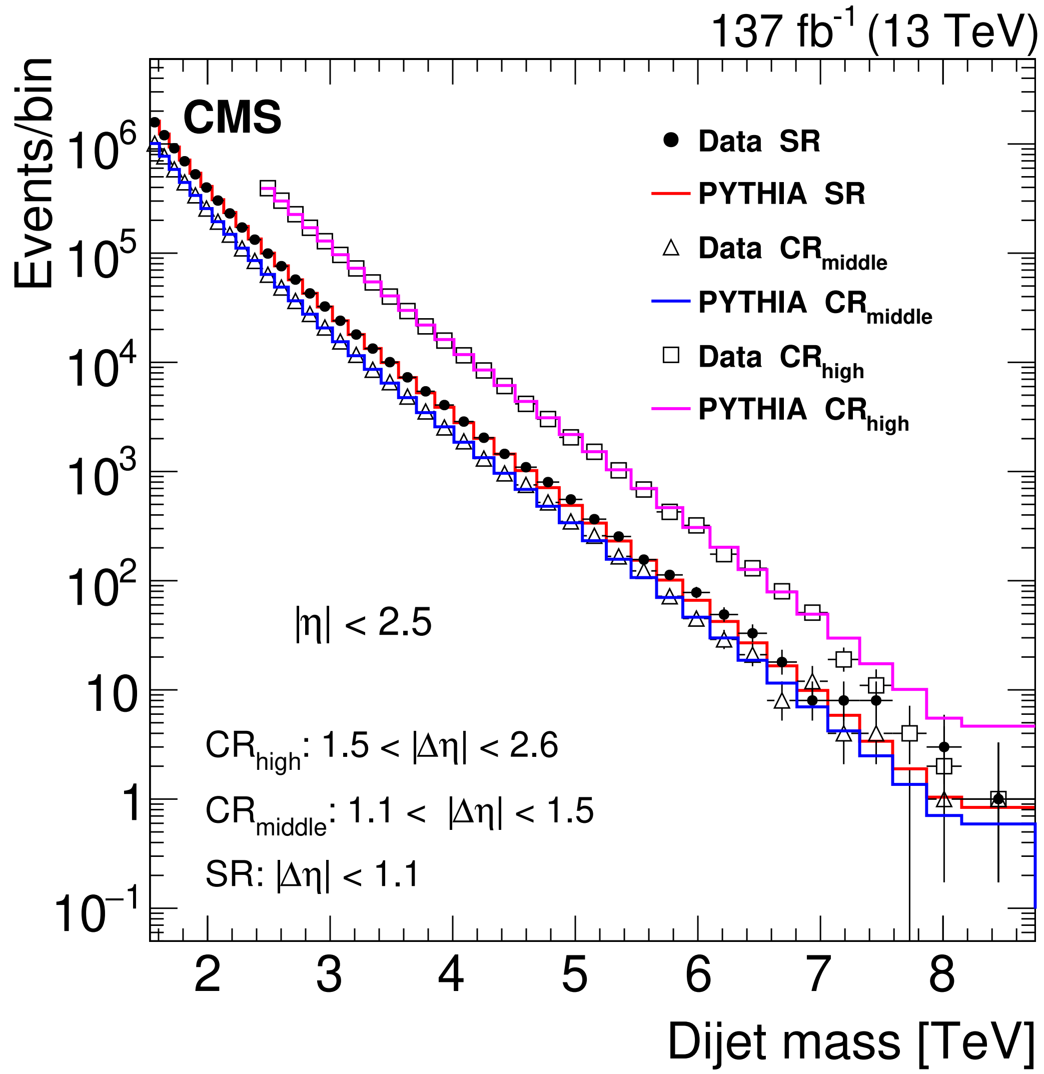

Figure 2. The dijet mass spectra of the data and PYTHIA simulation in the signal region at low $|\Delta\eta|$ (black points and red histogram), control region at middle $|\Delta\eta|$ (triangles and blue histogram), and control region at high $|\Delta\eta|$ (squares and magenta histogram). The simulation is normalized to data.

5 Background prediction methods

In the fit method, utilized here and in previous dijet resonance searches [17, 19–32, 50], the main background in the SR coming from QCD is parametrized with an empirical function of the form

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}, \tag{5.1}$$

where $x = m_{jj}/\sqrt{s}$, and P_0, P_1, P_2, and P_3 are four free parameters. The search for resonances proceeds with fitting the dijet mass distribution in the SR using this background parametrization and the signal template obtained from simulation, a procedure denoted as a signal plus background fit. In this fit, P_0, P_1, P_2, and P_3 are treated as freely

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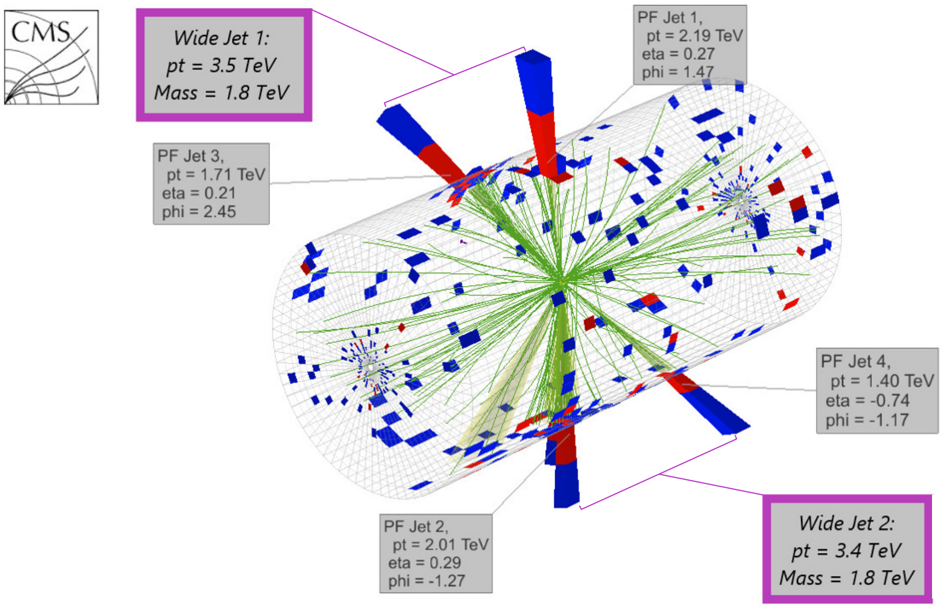

Figure 3. Three-dimensional display of the event with the second-highest dijet invariant mass of 8 TeV. The display shows the energy deposited in the electromagnetic (red) and hadronic (blue) calorimeters and the reconstructed tracks of charged particles (green). The grouping of four observed jets into two wide jets (purple) is discussed in the text.

floating nuisance parameters. In order to examine the compatibility of the data with the background-only description, and the quality of the background prediction, a fit under only the background hypothesis, denoted as a background-only fit, is also performed. The chi-square per the number of degrees of freedom of the background-only fit is $\chi^2/\mathrm{NDF} = 36.63/38$, as shown in figure 5.

The ratio method is a data-driven prediction of the QCD background in the SR, obtained by multiplying the data in $\mathrm{CR_{high}}$ by a mass-dependent transfer factor determined from the simulated angular distribution of QCD dijet production. The transfer factor is the ratio, R, between the simulated dijet mass distribution of background events in the SR and $\mathrm{CR_{high}}$. The method makes use of the following definitions:

$$N(i)^{\mathrm{Prediction}}_{\mathrm{SR}} = R(m_{\mathrm{jj}}/\sqrt{s})N(i)^{\mathrm{Data}}_{\mathrm{CR_{high}}},$$
$$R(m_{\mathrm{jj}}/\sqrt{s}) = C(m_{\mathrm{jj}}/\sqrt{s})N(i)^{\mathrm{Sim.}}_{\mathrm{SR}}/N(i)^{\mathrm{Sim.}}_{\mathrm{CR_{high}}},$$

where $N(i)$ is the number of events in a given bin, i, of dijet mass and $C(m_{\mathrm{jj}}/\sqrt{s})$ is a correction to the simulated transfer factor. This correction is required because, as seen in the upper right panel of figure 4, differences are present between data and the simulation using PYTHIA. These are due to both theoretical and experimental effects. The theoretical effects arise because the PYTHIA simulation uses a QCD calculation at LO, and higher order QCD corrections have some effect, and so do missing EW corrections. Figure 4 shows, with a smaller sample of events, that a better agreement is obtained when these corrections are included, by generating events at next-to-leading order (NLO) in QCD with POWHEG

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v2.0 [51–53] and incorporating an estimate of EW effects [54]. Experimental effects include differences between data and simulation at higher jet pseudorapidities outside the barrel calorimeter region ($|\eta| > 1.3$). The higher-order QCD and EW effects, and the differences between data and simulation at higher jet pseudorapidity values, produce a similar effect on the shape of the transfer factor, affecting mainly the high dijet mass region. We correct the simulated transfer factor to include these effects in a data-driven way, using the second control region, $\mathrm{CR_{middle}}$, which is a $|\Delta\eta|$ sideband to the SR. This second control region contains dijet events with values of jet pseudorapidity very similar to those in the SR, and has a very small signal contamination. As such, the dijet mass distribution of this control region is very similar to that of the SR, and the differences between data and simulation in this control region are caused by similar theoretical and experimental effects as observed in the SR. Hence, this second CR allows the definition of an auxiliary transfer factor, R_{aux}, shown in eq. (5.2).

$$R_{\mathrm{aux}}(i) = N(i)_{\mathrm{CR_{middle}}} / N(i)_{\mathrm{CR_{high}}}. \tag{5.2}$$

We then estimate the correction, C, to the main transfer factor, R, by performing a fit to the data-over-simulation ratio of R_{aux} (eq. (5.3)):

$$R_{\mathrm{aux}}^{\mathrm{Data}} / R_{\mathrm{aux}}^{\mathrm{Sim.}}, \tag{5.3}$$

with the correction parametrized using a two-parameter empirical function, shown in eq. (5.4).

$$C(m_{\mathrm{jj}}/\sqrt{s}) = p_0 + p_1 (m_{\mathrm{jj}}/\sqrt{s})^3. \tag{5.4}$$

The data to simulation ratios of the two transfer factors, R_{aux} and R, along with their background-only fits, performed separately in order to examine their compatibility, are shown in the lower panels of figure 4 and agree to within their uncertainty at 95% confidence level (CL). Specifically, the values of the parameters and their statistical uncertainties from the background-only fits of the data to simulation ratios of R_{aux} are $p_0 = 0.977 \pm 0.004$ and $p_1 = 2.07 \pm 0.33$, and of R are $p_0 = 0.972 \pm 0.004$ and $p_1 = 2.52 \pm 0.28$, and are entirely compatible. This agreement is expected given that the events in $\mathrm{CR_{middle}}$ and SR have, by construction, very similar jet η and m_{jj} distributions. Parameters p_0 and p_1 are treated as free nuisance parameters in the final signal plus background simultaneous fit of the SR, $\mathrm{CR_{middle}}$ and $\mathrm{CR_{high}}$, taking the signal contamination in the control regions into account as described in the next paragraph. The simultaneous background-only fit yields $p_0 = 0.973 \pm 0.003$ and $p_1 = 2.38 \pm 0.23$, consistent with the separate background-only fits shown in figure 4 (lower panels), and with smaller uncertainty. The systematic uncertainty in the background, for both methods, is automatically evaluated via profiling. This effectively refits for the optimal values of the background parameters, allowing them to float freely, for each value of the resonance cross section.

The signal contamination in the CRs depends on the angular distribution of the model. For the models considered in this search, the signal contamination is small compared to the background. This is because we search for dijet resonances produced in the s-channel annihilation of two partons, while the QCD background is predominantly a t-channel process. We assume the signal has the same angular distribution as a vector resonance decaying

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to $q\overline{q}$ pairs. The signal contamination is taken into account in the simultaneous fit. The change in extracted signal is negligible if the angular distribution of any of our other benchmark models is chosen instead. Our benchmark models include scalars coupled to qq or gg pairs, fermions coupled to qg pairs, vectors coupled to $q\overline{q}$ pairs, and tensors coupled to $q\overline{q}$ or gg pairs.

Detailed signal injection tests are performed to investigate the potential bias in each background prediction method, and the bias is found to be negligible when either the fit method or the ratio method is employed. The signal injection tests are performed as follows: pseudo-data distributions are generated, varying the parameters of the background prediction and injecting a signal with a cross section equal to i) zero, ii) the 95% CL observed limit, and iii) two times the 95% CL observed limit. These distributions are created for several resonance masses and widths, spanning the entire range for which results are reported. Then, the same fitting procedure followed in the analysis of the actual data is repeated for each pseudo-data distribution, and the fitted signal cross section, along with its 68% CL standard deviation, is obtained. We examine the distribution of the bias in units of standard deviations, namely the difference between the injected signal cross section and the fitted signal cross section, divided by the standard deviation of the fit. For all resonance masses, widths, and signal strengths considered, the mean bias is less than one half a standard deviation, and in the vast majority of the cases it is well below this criterion. In addition, pseudo-data distributions are generated using different empirical functional forms than the ones used in the actual data fits, and the entire procedure is repeated, again yielding negligible biases.

The ratio method is an independent approach compared to the fit method, yielding consistent results. The ratio method provides a background estimate that is derived primarily from control regions, while the fit method uses only the signal region. The ratio method also provides a background estimate that is more accurate than the fit method. This is because the ratio method fits the data with only two parameters, while the fit method requires four, and because the estimate from the ratio method is additionally constrained by the control region $\mathrm{CR}_{\mathrm{middle}}$. The advantages of this method, as opposed to the fit method, are the following: i) it provides a background estimate independent of the signal region, which results in an independent and less biased value of the observed signal significance, ii) as the resonance width increases the ratio method has smaller background uncertainty compared to the fit method, and hence higher sensitivity. Therefore, we estimate the background using the ratio method instead of the fit method for $m_{\mathrm{jj}} > 2.4\,\mathrm{TeV}$.

Figure 5 shows the dijet mass spectrum, defined as the observed number of events in each bin divided by the integrated luminosity and the bin width. The bin widths depend on the dijet mass and are chosen to correspond to dijet mass resolution. The bin edges were chosen to be the same as those used by previous dijet resonances searches performed by the CMS Collaboration, as introduced in ref. [31]. Figure 5 also shows the background prediction from the fit method, compared to all data, and the background prediction from the ratio method, compared to data with $m_{\mathrm{jj}} > 2.4\,\mathrm{TeV}$. The χ^2/NDF of the background-only fit, masking the signal region, with the ratio method is 42.04/32 as shown in figure 5. The dijet mass spectrum is well modeled by both background prediction methods, which also agree with one another.

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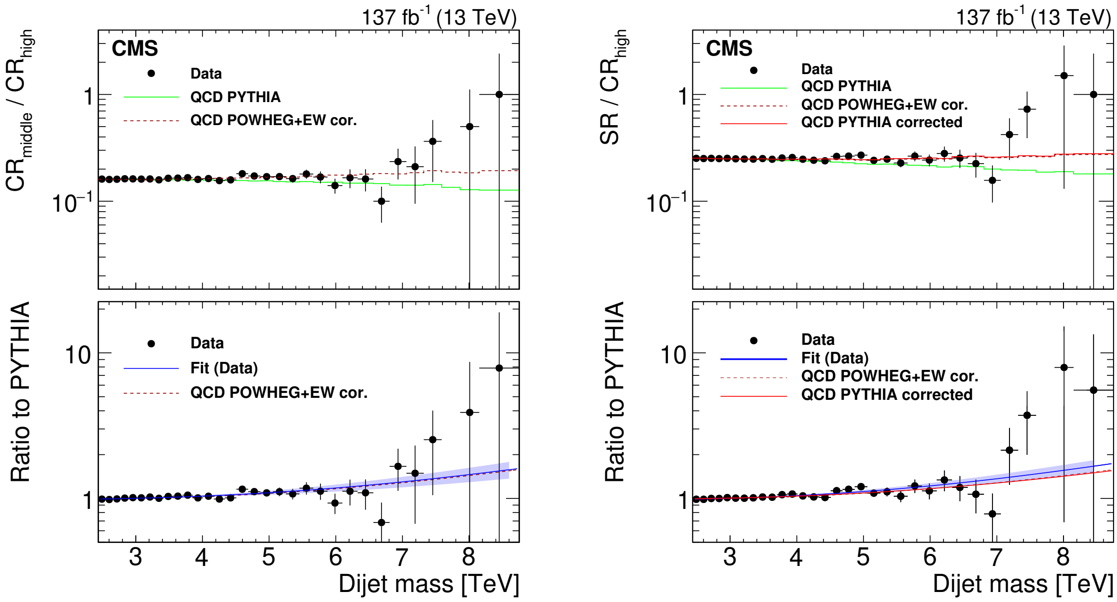

Figure 4. The ratio R_{aux}, the auxiliary transfer factor, calculated for data, PYTHIA, and POWHEG with electroweak corrections (left, upper panel). The double ratio of the same quantities in the upper left panel to R_{aux} from PYTHIA, along with the fit of the double ratio for data with the correction function (left, lower panel). The ratio R, the transfer factor, calculated for data, PYTHIA, POWHEG with electroweak corrections, and corrected PYTHIA (right, upper panel). The double ratio of the same quantities in the upper right panel to R from PYTHIA, along with the fit of the double ratio for data with a correction function, and corrected PYTHIA using $\mathrm{CR}_{\mathrm{middle}}$ (right, lower panel). The fits in the two lower panels agree with each other within their uncertainty at 95% CL (shaded bands).

6 Limits on the resonance cross section, mass, and coupling

We use the dijet mass spectrum from wide jets, the background parameterizations, and the dijet resonance shapes shown previously to set limits on the production cross sections of new particles decaying to the parton pairs qq (or $\mathrm{q\overline{q}}$), qg, and gg. A separate limit is determined for each final state (qq, qg, and gg) because of the dependence of the dijet resonance shape on the types of the two final-state partons.

The dominant sources of systematic uncertainty are the jet energy scale and resolution, the integrated luminosity, and the values of the parameters within the functional form modeling the background shape in the dijet mass distribution. The uncertainty in the jet energy scale is within 2% for all values of the dijet mass and is determined from $\sqrt{s} = 13\,\mathrm{TeV}$ data using the methods described in ref. [41]. This uncertainty is propagated to the limits by shifting the dijet mass shape for the signal by $\pm 2\%$. The uncertainty in the jet energy resolution translates into an uncertainty of 10% in the resolution of the dijet mass [41], and is propagated to the limits by observing the effect of increasing and decreasing by 10% the reconstructed width of the dijet mass shape for the signal. The uncertainty in the integrated luminosity is 2.5% in 2016 [55] and 2018 [56], and 2.3% in 2017 [57], and is propagated to the normalization of the signal. Changes in the values of the parameters

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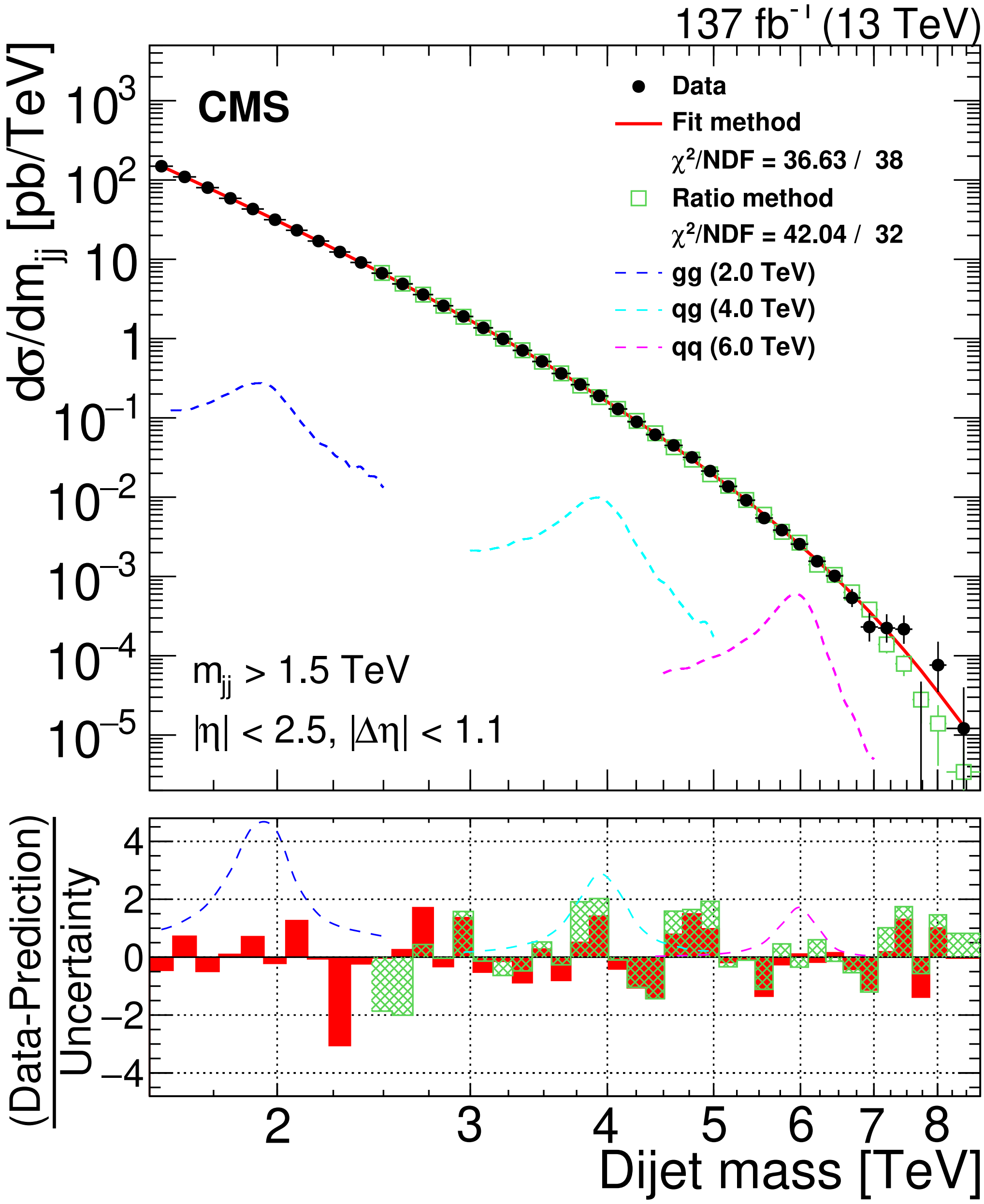

Figure 5. Dijet mass spectrum in the signal region (points) compared to a fitted parameterization of the background (solid line) and the one obtained from the control region (green squares). The lower panel shows the difference between the data and the fitted parametrization (red, solid), and the data and the prediction obtained from the control region (green, hatched), divided by the statistical uncertainty in the data, which for the ratio method includes the statistical uncertainty in the data in the control region. Examples of predicted signals from narrow gluon-gluon, quark-gluon, and quark-quark resonances are shown (dashed coloured lines) with cross sections equal to the observed upper limits at 95% CL.

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describing the background introduce a change in the signal yield, which is accounted for as a systematic uncertainty, as discussed in the next paragraph.

The modified frequentist criterion [58, 59] is used to set upper limits on signal cross sections, following the prescription described in refs. [60, 61] using the asymptotic approximation of the test statistic. We use a multi-bin counting experiment likelihood, which is a product of Poisson distributions corresponding to different bins. We evaluate the likelihood independently at each value of resonance pole mass from 1.8 to 8.7 TeV in 100-GeV steps. The fit method is used to estimate the background for resonance masses from 1.8 to 2.9 TeV, and the ratio method is used for resonance masses from 3.0 to 8.7 TeV. The minimum values of resonance mass for the two methods, 1.8 and 3.0 TeV, are chosen to maintain reasonable acceptances for the minimum m_{jj} requirements, 1.5 and 2.4 TeV, respectively. The sources of systematic uncertainty are implemented as nuisance parameters in the likelihood model, with Gaussian constraints for the jet energy scale and resolution, and log-normal constraints for the integrated luminosity. The background systematic uncertainty, as we described previously, is automatically evaluated via profiling and decreases as the resonance mass increases.

6.1 Narrow resonances

Figures 6 and 7 show the model-independent observed upper limits at 95% confidence level on the product of the cross section (σ), the branching fraction (B), and the acceptance (A) for narrow resonances, with the kinematic requirements $|\Delta\eta| < 1.1$ for the dijet system and $|\eta| < 2.5$ for each jet. The narrow resonance shapes are the ones presented and discussed in detail in a previous publication [17]. The acceptance of the minimum dijet mass requirement in each search, which fully accounts for the overall experimental acceptance, has been evaluated separately for qq, qg, and gg resonances. We include these acceptances in the determination of the limits. Figure 6 also shows the expected limits on σBA and their bands of uncertainty. Figure 7 shows the different limits for qq, qg, and gg resonances, which originate from differences in their line shapes. For the RS graviton, which decays to both $\mathrm{q\overline{q}}$ and gg, we obtain cross section upper limits from the average, weighted by branching fraction, of the limits on quark-quark and gluon-gluon resonances.

Using the statistical methodology discussed earlier, the local significance for qq, qg, and gg resonance signals was measured from 1.8 to 8.7 TeV in steps of 100 GeV. The significance values obtained for qq resonances are shown in figure 8 for both the ratio and the fit methods, and the significances for q g and g g resonances are the same within 0.2 standard deviations. The ratio method usually gives a larger signal significance than the fit method, because it provides a more accurate data-driven background estimate.

All upper limits presented can be compared to the parton-level predictions of $\sigma\, B\, A$, without detector simulation, to determine mass limits on new particles. The model predictions shown in figure 6 are calculated in the narrow-width approximation [33] using the CTEQ6L1 [62] parton distribution function at LO. An NLO correction factor of $K = 1 + 8\pi\alpha_S/9 \approx 1.3$ is applied to the LO predictions for the W' model and $K = 1+(4\alpha_S/6\pi)(1+4\pi^2/3) \approx 1.2$ for the Z' and the DM mediator models [63], where α_S is the strong coupling constant evaluated at a scale equal to the resonance mass. Similarly, for the axigluon and

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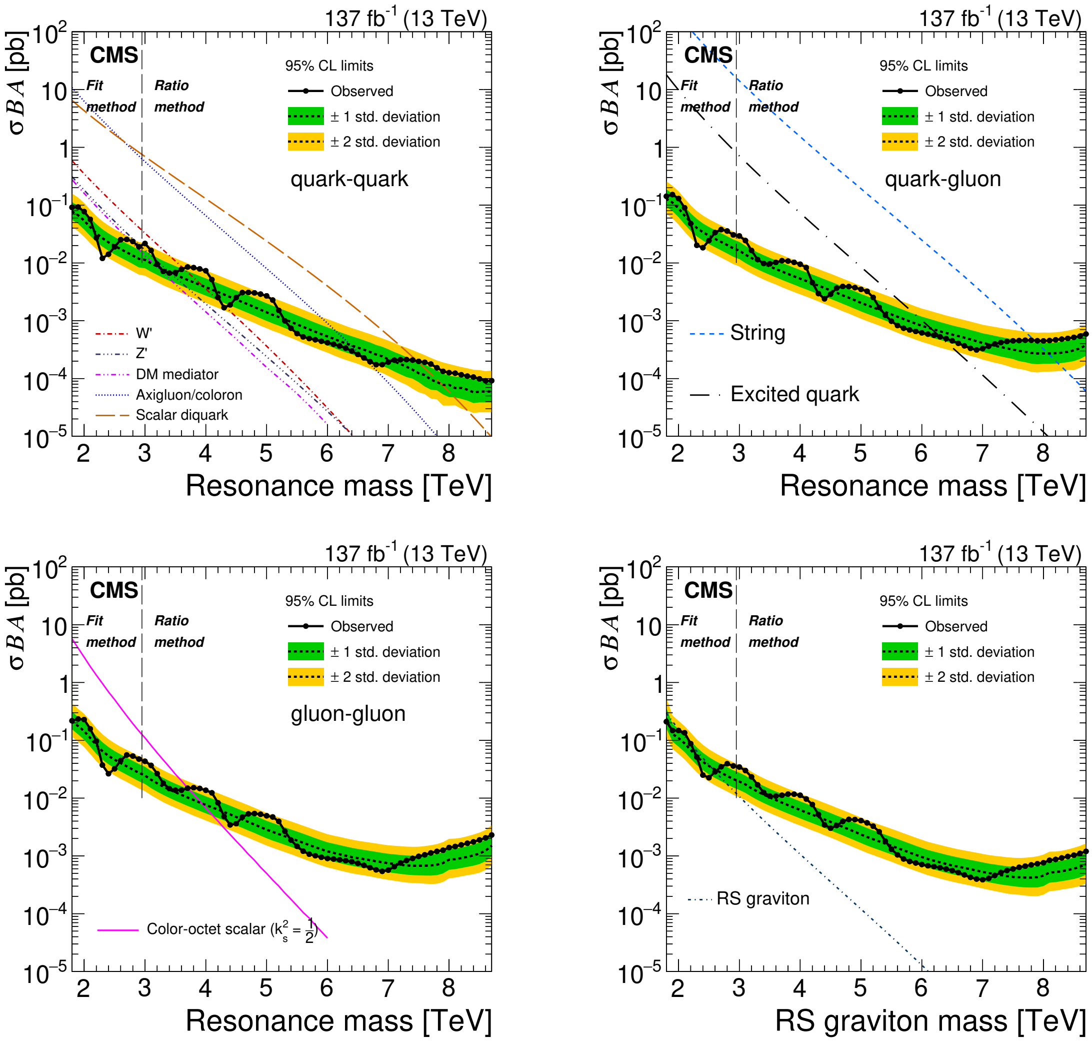

Figure 6. The observed 95% CL upper limits on the product of the cross section, branching fraction, and acceptance for dijet resonances decaying to quark-quark (upper left), quark-gluon (upper right), gluon-gluon (lower left), and for RS gravitons (lower right). The corresponding expected limits (dashed lines) and their variations at the one and two standard deviation levels (shaded bands) are also shown. Limits are compared to predicted cross sections for string resonances [1, 2], excited quarks [4, 5], axigluons [6], colorons [8], scalar diquarks [3], color-octet scalars [9], new gauge bosons W′ and Z′ with SM-like couplings [10], DM mediators for $m_{\mathrm{DM}} = 1\,\mathrm{GeV}$ [14, 15], and RS gravitons [11]. The vertical dashed line indicates the boundary between the regions where the fit method and the ratio method are used to estimate the background.

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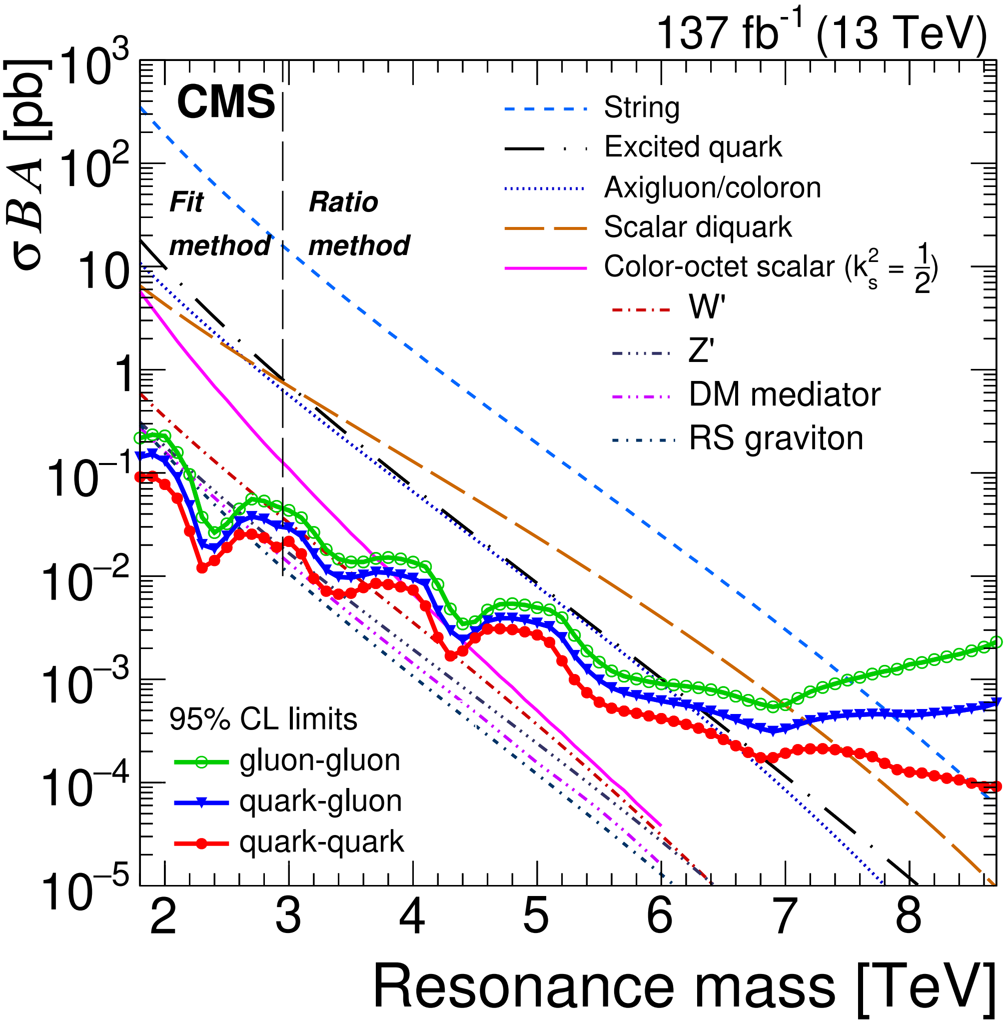

Figure 7. The observed 95% CL upper limits on the product of the cross section, branching fraction, and acceptance for quark-quark, quark-gluon, and gluon-gluon type dijet resonances. Limits are compared to predicted cross sections for string resonances [1, 2], excited quarks [4, 5], axigluons [6], colorons [8], scalar diquarks [3], color-octet scalars [9], new gauge bosons W′ and Z′ with SM-like couplings [10], DM mediators for $m_{\rm DM} = 1\,\text{GeV}$ [14, 15], and RS gravitons [11]. The vertical dashed line indicates the boundary between the regions where the fit method and the ratio method are used to estimate the background.

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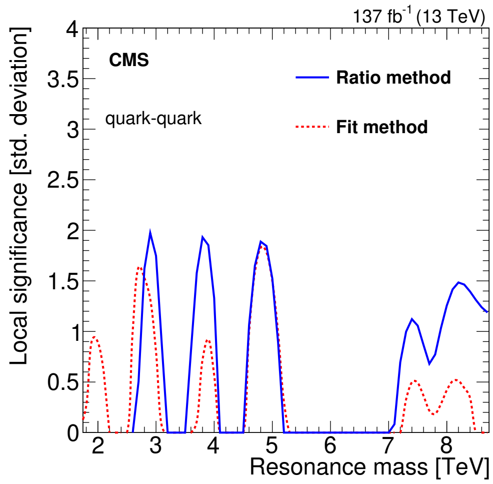

Figure 8. Local significance for a qq resonance with the ratio method (blue line) and the fit method (red dashed line).

Model	Final state	Observed (expected) mass limit [TeV]
String	qg	7.9 (8.1)
Scalar diquark	qq	7.5 (7.9)
Axigluon/coloron	$q\overline{q}$	6.6 (6.4)
Excited quark	qg	6.3 (6.2)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.7 (3.9)
W$'$ SM-like	$q\overline{q}$	3.6 (3.9)
Z$'$ SM-like	$q\overline{q}$	2.9 (3.4)
RS graviton ($k/\overline{M}_{\mathrm{Pl}} = 0.1$)	$q\overline{q}$, gg	2.6 (2.6)
DM mediator ($m_{\mathrm{DM}} = 1\,\mathrm{GeV}$)	$q\overline{q}$	2.8 (3.2)

Table 1. Observed and expected mass limits at 95% CL from this analysis. The listed models are excluded between 1.8 TeV and the indicated mass limit by this analysis. The SM-like Z$'$ resonance is also excluded within the mass interval between 3.1 and 3.3 TeV.

coloron models a correction factor is applied which varies between $K = 1.1$ at a resonance mass of 0.6 TeV and $K = 1.3$ at 8.1 TeV [7]. The branching fraction includes the direct decays of the resonance into the five light quarks and gluons only, excluding top quarks from the decay, although top quarks are included in the calculation of the resonance width. The acceptance is evaluated at the parton level for the resonance decay to two partons. In the case of isotropic decays, the acceptance is $A \approx 0.5$ and is independent of the resonance mass. For a given model, new particles are excluded at 95% CL in mass regions where the theoretical prediction lies at or above the observed upper limit for the appropriate final state of figure 6. Table 1 shows the mass limits on all benchmark models which are extended by 200 to 800 GeV relative to those reported in previous CMS dijet resonance searches [17].

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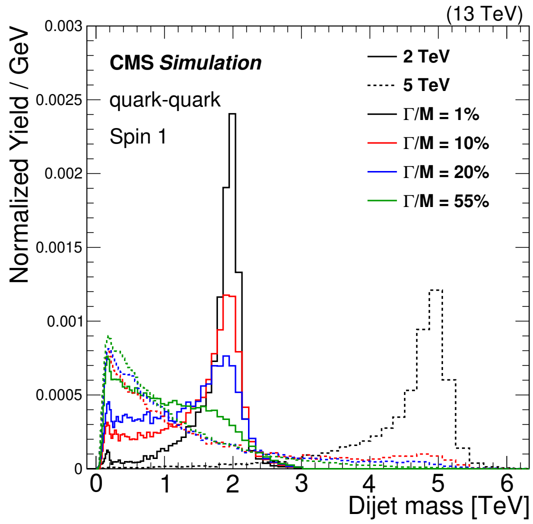

Figure 9. The reconstructed dijet mass spectra for a vector particle decaying to pairs of quarks are shown for a resonance mass of 2 TeV (solid histogram) and 5 TeV (dashed histogram) for various values of intrinsic width, estimated from the MadGraph5 and pythia event generators followed by the simulation of the CMS detector response.

6.2 Broad resonances

We extend the search to cover broad resonances. We use spin-1 resonances decaying to quark-quark pairs with a width up to 55% of the resonance mass, M, as well as spin-2 resonances that decay to quark or gluon pairs with a width up to 30% of the resonance mass. This allows us to be sensitive to more models and larger couplings. The spin-1 resonance results are also used to produce limits on the universal quark coupling of a leptophobic vector mediator of interactions between quarks and DM particles, and limits for a leptophobic Z' that couples to quarks but does not couple to DM particles [12–15]. In order to be sensitive to the largest possible coupling values for these particles, the maximum value of examined widths for spin-1 resonances is increased to 55% of the resonance mass. The additional wider signals are produced in the same way as the narrower ones, using the MadGraph5_amc@nlo v. 2.3.2 [64] generator at LO, and the pythia 8.205 [44] program, followed by a Geant4-based [48] simulation of the CMS detector. For resonance widths up to 30% of their mass, the dijet mass distributions are the ones presented and discussed in detail in ref. [17]. The dijet mass distributions of both wide and narrow spin-1 resonances are shown in figure 9, and exhibit the same behavior as the ones discussed in [17].

The cross section limits in this case are presented as a function of resonance mass and width. In figure 10 we show the observed 95% CL upper limits for various resonance widths, for spin-2 resonances modeled by an RS graviton signal in the quark-quark and gluon-gluon channels, and for spin-1 resonances in the quark-quark channel. The limits weaken as the resonance intrinsic width increases, following the characteristics of the resonance shapes. The spin-1 resonances are significantly broader than the spin-2 resonances. For this reason, their limits are weaker than those of the spin-2 resonances. In figure 10 the cross section

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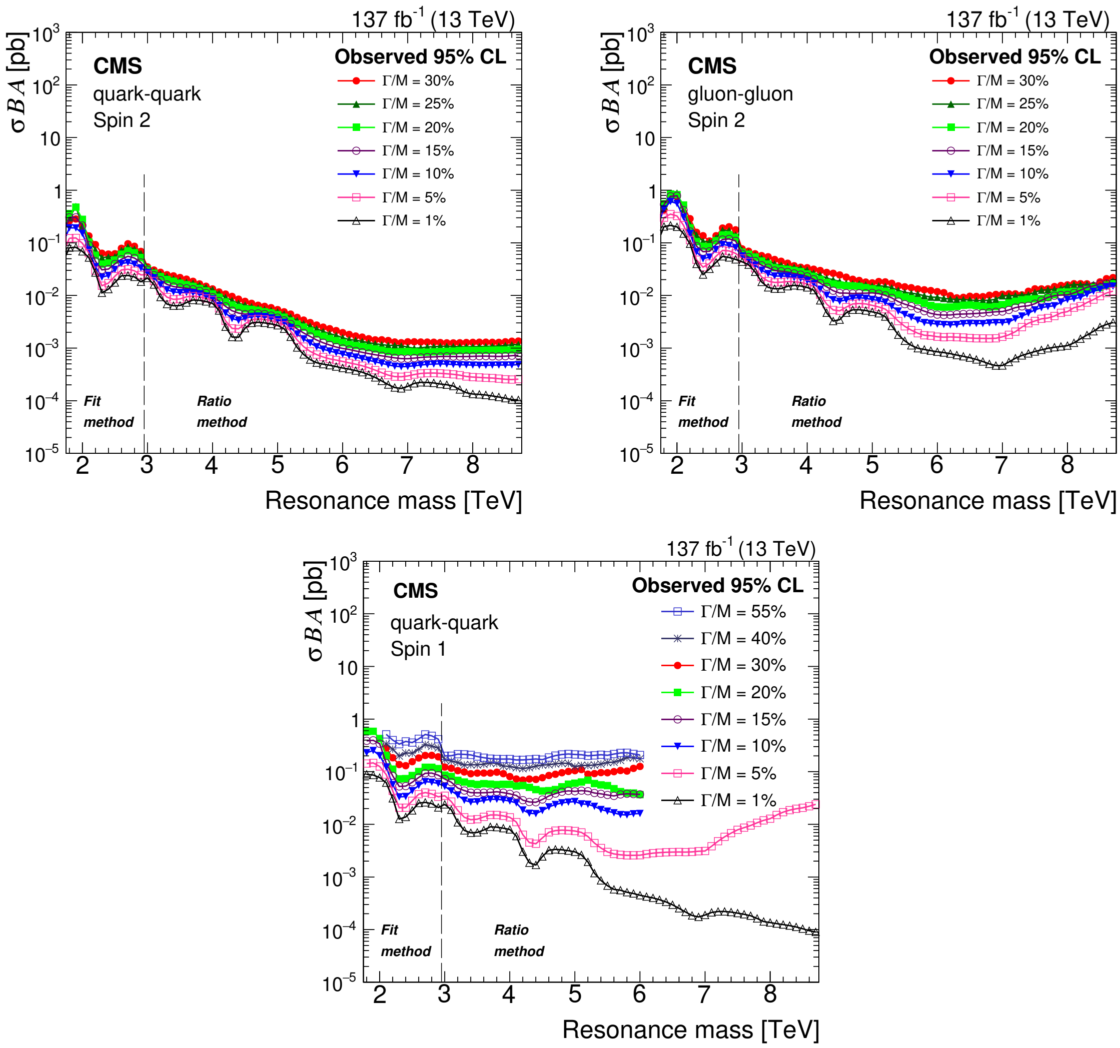

Figure 10. The observed 95% CL upper limits on the product of the cross section, branching fraction, and acceptance for spin-2 resonances produced and decaying in the quark-quark (upper left) and gluon-gluon (upper right) channels, as well as for spin-1 resonances decaying in the quark-quark channel (lower), shown for various values of intrinsic width as a function of resonance mass. The vertical dashed line indicates the boundary between the regions where the fit method and the ratio method are used to estimate the background.

limits at very high mass for spin-1 resonances with $\Gamma/M = 5\%$ increase as the resonance mass increases, while they decrease for $\Gamma/M = 1\%$. This is because, for resonances with widths larger than 1%, the tail to low dijet mass increases significantly as the resonance mass increases, as shown in figure 9.

The limits are presented up to a maximum resonance mass of 8.7 TeV for most models. We do not present limits for the case of spin-1 resonances in the quark-quark channel with masses larger than 6 TeV and $\Gamma/M > 0.1$. These resonances are not part of the search because they have an exceedingly broad and high tail at low dijet mass, as described in ref. [17], which dominates the limit and produces unstable search results. The spin-1 cross

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section limits in figure 10 have been used to derive constraints on the coupling to quarks of mediators of new interactions. We consider two models of a leptophobic mediator which couples to all generations of quarks with the same universal strength. The quark coupling is denoted g'_{q} in the first model, in which the mediator does not couple to DM particles, and denoted g_{q} in the second model, in which the mediator couples to DM particles. For each mediator mass value, the predictions for the cross section of mediator production as a function of the quark coupling are converted to predictions as a function of width. They are then compared to the spin-1 cross section limits from figure 10 to find the excluded values of quark coupling, as a function of mass for a spin-1 resonance. Figure 11 (right) shows upper limits on the coupling g'_{q} as a function of mass for our first model, also known as a leptophobic Z′ resonance [65] that couples only to quarks. In this model the resonance has a width

$$\Gamma_{\mathrm{Med}} = \frac{3(g'_{\mathrm{q}})^2 M_{\mathrm{Med}}}{2\pi}, \tag{6.1}$$

where M_{Med} is the resonance mass and g'_{q} is the universal quark coupling, related to the coupling, g_B, of ref. [65] by $g'_{\mathrm{q}} = g_B/6$. Figure 11 (left) shows upper limits on the coupling g_{q} as a function of mass for our second model, also known as a DM Mediator model, which has a leptophobic spin-1 mediator that couples both to quarks and DM particles [15], and for Dirac DM with a mass $m_{\mathrm{DM}} = 1\,\mathrm{GeV}$ and a coupling $g_{\mathrm{DM}} = 1.0$. The cross section of mediator production for $m_{\mathrm{DM}} = 1\,\mathrm{GeV}$ and $g_{\mathrm{DM}} = 1$ is calculated with MadGraph5_aMC@NLO [64] for mediator masses within the range $1.6 < M_{\mathrm{Med}} < 5.1\,\mathrm{TeV}$ in 0.1 TeV steps and for quark couplings within the range $0.1 < g_{\mathrm{q}} < 1.0$ in 0.1 steps. For these choices, the relationship between the total mediator width, for decays to both quark and DM particles, and g_{q} given in refs. [14, 15] simplifies to

$$\Gamma_{\mathrm{Med}} \approx \frac{(18 g_{\mathrm{q}}^2 + 1) M_{\mathrm{Med}}}{12\pi}. \tag{6.2}$$

The increased sensitivity of the ratio method to wide resonances significantly improves and extends previous limits on DM mediators at large values of Γ/M. For example, for $\Gamma/M = 0.45$, this search excludes DM mediators with mass less than 4.8 TeV, while the observed limit from the earlier searches was 4.0 TeV [17].

7 Summary

A search for resonances decaying into a pair of jets has been performed using proton-proton collision data at $\sqrt{s} = 13\,\mathrm{TeV}$ corresponding to an integrated luminosity of $137\,\mathrm{fb}^{-1}$. The dijet mass spectra are observed to be smoothly falling distributions of events with typically two-jet topology, although one unusual event with a four-jet topology was found at high mass. The background is predicted using two methods. The fit method uses an empirical functional form to fit the background in the signal region, defined by requiring the pseudorapidity separation of two jets in dijet $|\Delta\eta| < 1.1$, while the ratio method uses two control regions at higher values of $|\Delta\eta|$ to predict the background in the signal region. The ratio

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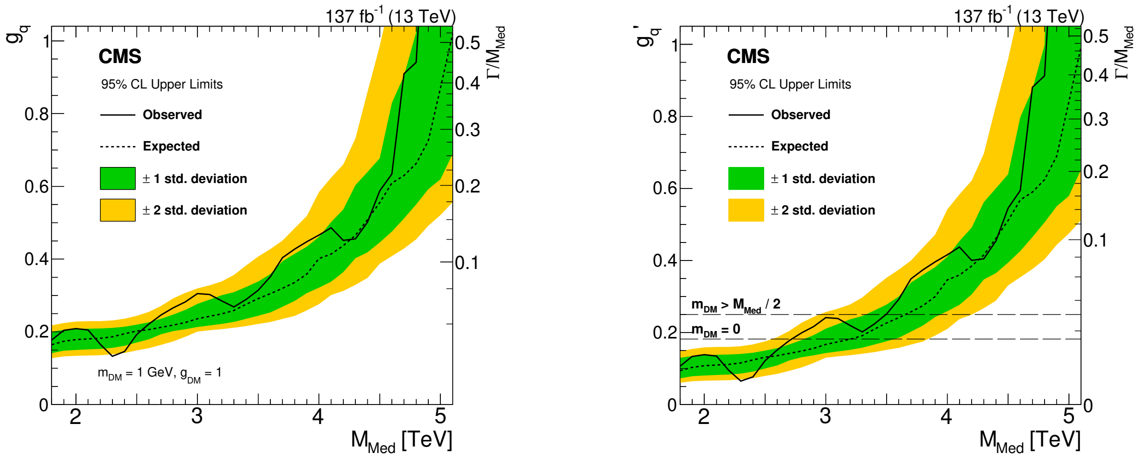

Figure 11. The 95% CL upper limits on the universal quark coupling g_{q} as a function of resonance mass for a vector mediator of interactions between quarks and DM particles (left), and between quarks only (right). The dashed horizontal lines on the right plot show the coupling strength for which the cross section for dijet production in this leptophobic Z' model is the same as for a DM mediator for $g_{\mathrm{q}} = 0.25$. The right vertical axis shows the natural width of the mediator divided by its mass. The expected limits (dashed lines) and their variation at the one and two standard deviation levels (shaded bands) are also shown.

method is a new background prediction method, which is independent of and complementary to the fit method. No evidence for resonant particle production is observed. Generic upper limits are presented on the product of the cross section, the branching fraction, and the acceptance for narrow and broad quark-quark, quark-gluon, and gluon-gluon resonances. The limits are applied to various models of new resonances and yield the following 95% confidence level lower limits on the resonance masses: 7.9 TeV for string resonances, 7.5 TeV for scalar diquarks, 6.6 TeV for axigluons and colorons, 6.3 TeV for excited quarks, 3.7 TeV for color-octet scalars, 3.6 TeV for W' bosons with SM-like couplings, 2.9 TeV and between 3.1 and 3.3 TeV for Z' bosons with SM-like couplings, 2.6 TeV for Randall-Sundrum gravitons, and 2.8 TeV for dark matter (DM) mediators. With this search, limits on narrow resonances are improved by 200 to 800 GeV relative to those reported in previous CMS dijet resonance searches. Limits are also presented for spin-2 resonances with intrinsic widths as large as 30% of the resonance mass, and spin-1 resonances with intrinsic widths as large as 55% of the resonance mass. These limits are used to improve and extend the exclusions of a DM mediator to larger values of the resonance mass and coupling to quarks. In the search for broad resonances, the ratio method provides significantly enhanced sensitivity compared to the fit method, resulting in the exclusion at 95% confidence level of a DM mediator with mass less than 4.8 TeV for a width equal to 45% of the mass, which corresponds to a coupling to quarks $g_{\mathrm{q}} = 0.9$.

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