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Search for dijet resonances with data scouting in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: A search is presented for narrow resonances, with a mass between 0.6 and 1.8 TeV, decaying to pairs of jets, in proton-proton collisions at $\sqrt{s} = 13$ TeV. The search is performed using dijets that are reconstructed, selected, and recorded in a compact form by the high-level trigger in a technique referred to as "data scouting", from data collected in 2016–2018 corresponding to an integrated luminosity of 117 fb^{-1}. The dijet mass spectra are well described by a smooth parameterization, and no significant evidence for the production of new particles is observed. Model-independent upper limits are presented on the product of the cross section, branching fraction, and acceptance for the individual cases of narrow quark-quark, quark-gluon, and gluon-gluon resonances, and are compared to the predictions from a variety of models of narrow dijet resonance production. The upper limit on the coupling of a dark matter mediator to quarks is presented as a function of the mediator mass. The sensitivity of this search goes beyond what is expected from statistical scaling with the integrated luminosity alone, as a consequence of the use of fewer parameters in the background function within a more robust statistical procedure.

Keywords: Beyond Standard Model, Hadron-Hadron Scattering, Jets, Particle and Resonance Production

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Contents

1 Introduction

Many theories that extend the standard model (SM) of particle physics predict new particles that decay to pairs of partons, quarks (q) and gluons (g), that hadronize into jets, which manifest themselves as dijet resonances [1–14]. These resonances would appear in experiments as an excess of dijet events on top of a smoothly falling background in the dijet mass (m_{jj}) spectrum. Model-independent searches for these resonances have been conducted at the CERN Large Hadron Collider (LHC) in the following intervals of the dijet mass: high (above 2 TeV), medium (between 0.5 and 2 TeV), and low (below 0.5 TeV). The high-mass searches [15–31] rely on events selected by jet triggers with high thresholds, and the individually resolved jets are reconstructed offline. The low-mass searches use events selected by triggering on initial-state radiation of photons or gluons [32–34], and the highly Lorentz-boosted, merged dijets are also reconstructed offline. This analysis is one of the medium-mass searches [27, 29, 35, 36], which relies on events that are reconstructed, selected, and recorded in a compact form by the high-level trigger (HLT) in a technique referred to as “data scouting” [37]. The compact form and the faster online reconstruction of the individually resolved jets using only calorimeter information allow a higher bandwidth of the trigger and a lower threshold in dijet mass than the high-mass searches. The scouting data sets offer a unique way to probe previously unexplored regions in the dijet mass at lower resonance couplings to quarks and gluons, not otherwise accessible by the full data sets with offline reconstruction.

Dark matter (DM) mediators, hypothetical particles that transmit an interaction between quarks and DM particles, can appear as dijet resonances [11–14]. Since the interaction between DM and ordinary matter is unknown, many models exist. As a benchmark, we choose the simplified model [14] recommended by the LHC DM Working Group to explore the sensitivity to DM from LHC searches. In this model, the DM particle is assumed to be a Dirac fermion, and the particle mediating the interaction is exchanged in the s-channel. This approach provides a coherent framework for analyzing potential interactions and setting limits on DM properties. The simplified model is characterized by four parameters: the

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DM particle mass (M_{DM}), the mediator mass (M_{med}), the universal mediator coupling to quarks (g_{q}), and the mediator coupling to DM particles (g_{DM}). The considered mediator only couples to $\mathrm{q\overline{q}}$ or DM particle pairs. If $M_{\mathrm{DM}} > M_{\mathrm{med}}/2$, the on-shell mediator cannot decay to DM particles, and the dijet cross section (σ) in this case becomes identical to that in a leptophobic Z' model, in which the universal coupling to quarks is g'_{q}.

This paper describes a model-independent search for narrow s-channel dijet resonances with masses between 0.6 and 1.8 TeV. The search is based on proton-proton (pp) collision data at $\sqrt{s} = 13\,\mathrm{TeV}$ collected with data-scouting triggers in 2016–2018 and corresponding to an integrated luminosity of $117\,\mathrm{fb}^{-1}$. We estimate signal significances and set limits on the production cross sections of new particles decaying to the parton pairs qq (or $\mathrm{q\overline{q}}$), qg, and gg. We then use these limits to exclude models of new gauge bosons W' and Z' [1], axigluons [2], excited quarks [3, 5], scalar diquarks [4], colorons [6], and color-octet scalars [9] over the complete mass range considered. In addition, the 95% confidence level (CL) upper limit on the coupling strength g_{q} of DM mediators is presented as a function of M_{med}. The tabulated results for this analysis are provided in the HEPData record [38].

2 The CMS detector and the scouting triggers

A detailed description of the CMS detector and its coordinate system, including definitions of the azimuthal angle ϕ and pseudorapidity η, is given in refs. [39, 40]. 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 ($|\eta| < 2.7$), and the barrel and endcap calorimeters ($|\eta| < 3.0$), where these latter detectors consist of a lead tungstate crystal electromagnetic calorimeter (ECAL), 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 interleaved with layers of the steel flux-return yoke.

In this search we utilize jets formed from energy deposits in the calorimeters, denoted as Calo-jets, in order to benefit from the lowest possible trigger thresholds with the scouting data set. To reconstruct online jets used by the trigger, we employ the anti-k_{T} algorithm [41, 42] with a distance parameter of 0.4, as implemented in the FastJet package [43]. An event-by-event correction based on the jet area [44, 45] is applied to the jet energy to remove the estimated contribution from additional collisions in the same or adjacent bunch crossings (pileup).

Events are recorded using a two-tier trigger system [46, 47]. Events satisfying loose jet requirements at the first level (L1) trigger are examined by the HLT. When an event satisfies the data scouting requirement, the Calo-jets reconstructed at the HLT are saved, along with the event energy density and the missing transverse momentum reconstructed from the calorimeter. The energy density is defined as the median calorimeter energy per unit area calculated for each event in a grid of η-ϕ cells [45].

We apply triggers, which require H_{T} to exceed a threshold, where H_{T} is the scalar sum of transverse momentum (p_{T}) for all jets in the event with $|\eta| < 3.0$. The shorter time for event reconstruction of calorimeter quantities and the reduced event size recorded for

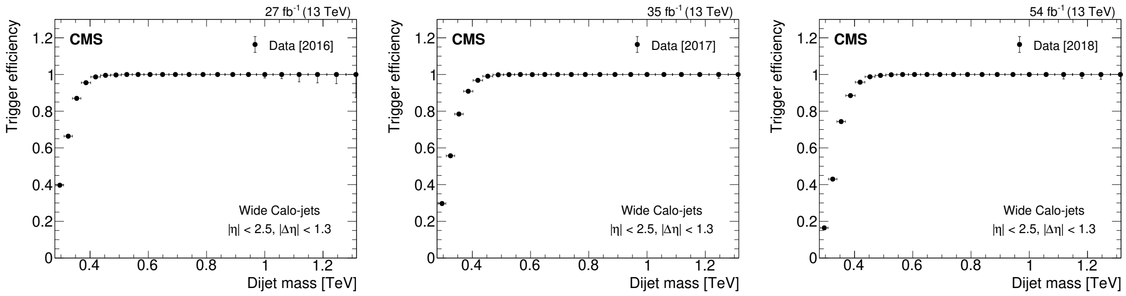

Figure 1. The measured HLT trigger efficiency as a function of the offline dijet mass for wide Calo-jets, defined in section 3, for 2016 (left), 2017 (middle), and 2018 (right) data.

these events allow a reduced $H_{\rm T}$ threshold compared to the searches not utilizing scouting data sets [37]. Calo-jets with $p_{\rm T} > 40\,\text{GeV}$ are used to compute $H_{\rm T}$, and the threshold is set to $H_{\rm T} > 250\,\text{GeV}$. For comparison, when not using scouting, the lowest threshold trigger requires $H_{\rm T} > 1050\,\text{GeV}$.

Two auxiliary scouting trigger paths are used to measure the performance of the main $H_{\rm T}$ trigger. A prescaled L1-only trigger is used to measure the $H_{\rm T}$ trigger efficiency as a function of the dijet mass. This prescaled trigger selects a subset of the events passing the L1 $H_{\rm T}$ requirement without reference to the HLT. An even looser trigger is used to measure the efficiency of the L1 $H_{\rm T}$ seeds. This trigger is seeded by the zero-bias L1 algorithm and requires the presence of at least one Calo-jet at the HLT level. Figure 1 shows the efficiency of the trigger for the 2016, 2017, and 2018 data, demonstrating that the search is fully efficient for events with $m_{\rm jj} \gtrsim 0.5\,\text{TeV}$.

3 Event selection

The jet momenta and energies are corrected using calibration constants obtained from simulation, results from dedicated calibration campaigns with beams, and pp collisions at $\sqrt{s} = 13\,\text{TeV}$ using the methods described in ref. [45]. Jet identification (ID) criteria are applied to remove spurious jets associated with calorimeter noise [48, 49]. The jet ID requires that the jet is detected by both the ECAL and hadron calorimeters, with the fraction 5–95% of jet energy deposited within the ECAL. Jets are required to have $p_{\rm T} > 30\,\text{GeV}$, $|\eta| < 2.5$, and to satisfy the jet ID criteria. The two jets with the highest $p_{\rm T}$ are defined as the leading jets.

Spatially close jets are combined into “wide jets” and used to determine the dijet mass, as in the previous CMS searches [18, 21, 22, 24, 26, 27, 35]. The two leading jets are used as seeds, and the four-vectors of all other jets, if within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$ and satisfying $p_{\rm T} > 30\,\text{GeV}$, are added to the nearest leading jet to obtain two wide jets, which then form the dijet system. 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 dijet mass is the invariant mass of the two wide jets, the square root of the difference of the squared values of the total energy, E, and total momentum vector, $\vec{p}$, of the dijet system: $m_{\rm jj} = [(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2]^{1/2}$.

The background from quantum chromodynamics (QCD) t-channel dijet events has the same angular distribution as the Rutherford scattering, approximately proportional to

$1/[1-\tanh(|\Delta\eta|/2)]^2$, which peaks at large values of $|\Delta\eta|$ and is suppressed by requiring the pseudorapidity of the two wide jets to satisfy $|\Delta\eta| < 1.3$. The above requirements maximize the search sensitivity for isotropic decays of dijet resonances in the presence of QCD dijet background. In addition, the above requirement makes the trigger efficiency, presented in figure 1, reaching 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 $m_{\mathrm{jj}} \approx 2p_{\mathrm{T}}\cosh(|\Delta\eta|/2)$. The Calo-jet energy corrections for the 2016 data were complete, derived from in-situ measurements of the jet response, in contrast to the Calo-jet corrections for 2017 and 2018 data, which were derived from simulation and not verified with data. Therefore, after all the jet corrections and event selections, we apply scale factors to the differential cross sections as a function of dijet mass observed in 2017 and 2018 to ensure consistency with that in the 2016 data.

4 Signal and background modeling

We use independent narrow-resonance shapes for each generic type of final state: qq, qg, and gg. Resonance shapes for these three final states are shown in figure 2, for narrow resonances, generated with the PYTHIA 8.205 [50] Monte Carlo (MC) program with the CUETP8M1 tune [51, 52] and including a GEANT4-based [53] simulation of the CMS detector for scouting reconstruction. The qq resonances are modeled by $\mathrm{q\overline{q}} \to \mathrm{G} \to \mathrm{q\overline{q}}$, the qg resonances are modeled by $\mathrm{qg} \to \mathrm{q}^* \to \mathrm{qg}$, and the gg resonances are modeled by $\mathrm{gg} \to \mathrm{G} \to \mathrm{gg}$, where G is the Randall-Sundrum graviton [7] and q^* is an excited quark [3, 5]. The predicted mass distributions have Gaussian cores from jet energy resolution (JER) and low-mass tails from QCD radiation. The observed width and low-mass tail of the resonance depend on its parton content (qq, qg, or gg). Resonances decaying to gluons, which emit more QCD radiation than quarks, are broader and have a more pronounced tail. The dijet mass resolution within the Gaussian core of gg (qq) resonances in figure 2 varies from 14.0 (10.5)% at a resonance mass of 0.6 TeV to 8.2 (6.7)% at that mass of 1.8 TeV.

All final-state parton signal resonance shapes in 2016, 2017, and 2018 MC simulation agree with each other to within 1–2%, hence, the 2016 shapes are used to set limits and evaluate signal significances for all years.

The background estimation is obtained directly from data, fitting the monotonically and smoothly falling dijet mass spectrum with empirical parametric functions that have been extensively used in previous searches [15–31, 35, 54–56]. Several functions can be considered for this background fit, organized in "families" with increasing numbers of parameters. The fit minimizes the negative log-likelihood function (ΔNLL) of the data and the fitting function. The criteria to choose the optimal fitting function are two-fold. First, the fit must provide a good description of the data with high fit probabilities for all data sets. Second, it must produce stable, continuous ΔNLL curves as a function of the signal strength for each tested resonance mass, as described in the next section, keeping correlations between the signal shapes and the background function parameters at a minimum. The function that satisfied the above criteria and provided the best description of all different data sets is the modified exponential function with four parameters: $p_0 \exp(p_1 x^{p_2} + p_1(1-x)^{p_3})$, where $x = m_{\mathrm{jj}}/\sqrt{s}$ is the independent variable, and the p_i's represent the fit parameters. This fitting approach

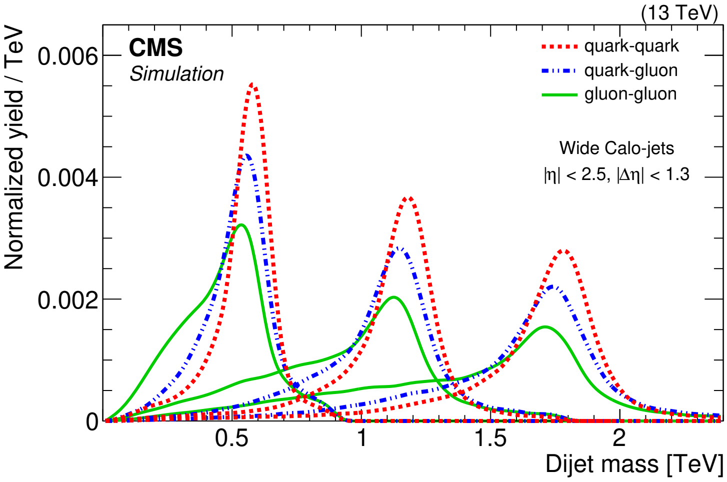

Figure 2. Simulated signal shapes of narrow resonances from parton pairs quark-quark (dotted red curves), quark-gluon (dashed-dotted blue curves), and gluon-gluon (solid green curves) with masses of 0.6, 1.2, and 1.8 TeV. The reconstructed dijet mass spectra are for wide Calo-jets.

yielded stable results with increased sensitivity compared to the previous CMS search [29]. The improved accuracy of our background modeling can be attributed to both the use of a more effective functional form for describing the data and the need for fewer parameters to satisfy Fisher's F-test [57].

Signal injection tests were performed to investigate the potential bias introduced through the choice of background parameterization. As an alternative choice of parameterization we used $p_0(1-x)^{p_1}x^{-(p_2+p_3\ln(x))}$. Pseudo-data were generated, assuming the presence of qq, qg, and gg dijet resonance signals and the alternative parameterization of the background, and then were fit with the nominal parameterization. For all tested resonance masses, final states, background parameterizations, and injected signals, the resulting bias in the extracted signal strength is much smaller than the combined statistical and systematic uncertainty, and therefore, has a negligible impact on the upper limits.

The high statistical precision of the dijet mass spectra made it difficult to get proper fits to the complete Run-2 data sample, or even the individual data-taking years, and to achieve smooth, continuous ΔNLL curves. Parametric background functions could properly describe the spectra only when extra free parameters were introduced, yet these additional free parameters created correlations with the signal shapes and generated discontinuous ΔNLL curves. To alleviate this problem, hence ensuring high goodness-of-fit and consistent behavior across the fitted parameter space, we simultaneously analyzed multiple data samples, each sample with fewer events but the same total events for all samples combined. These samples were the pre-existing "eras" of each year (2016, 2017, 2018) corresponding to different data-taking periods with slightly different running conditions: there were six periods in 2016, four in 2017, and four in 2018. The dijet spectra in these fourteen periods were then fit simultaneously to both the signal and background hypotheses, each yielding individually good fits and producing consistent and well-behaved ΔNLL curves.

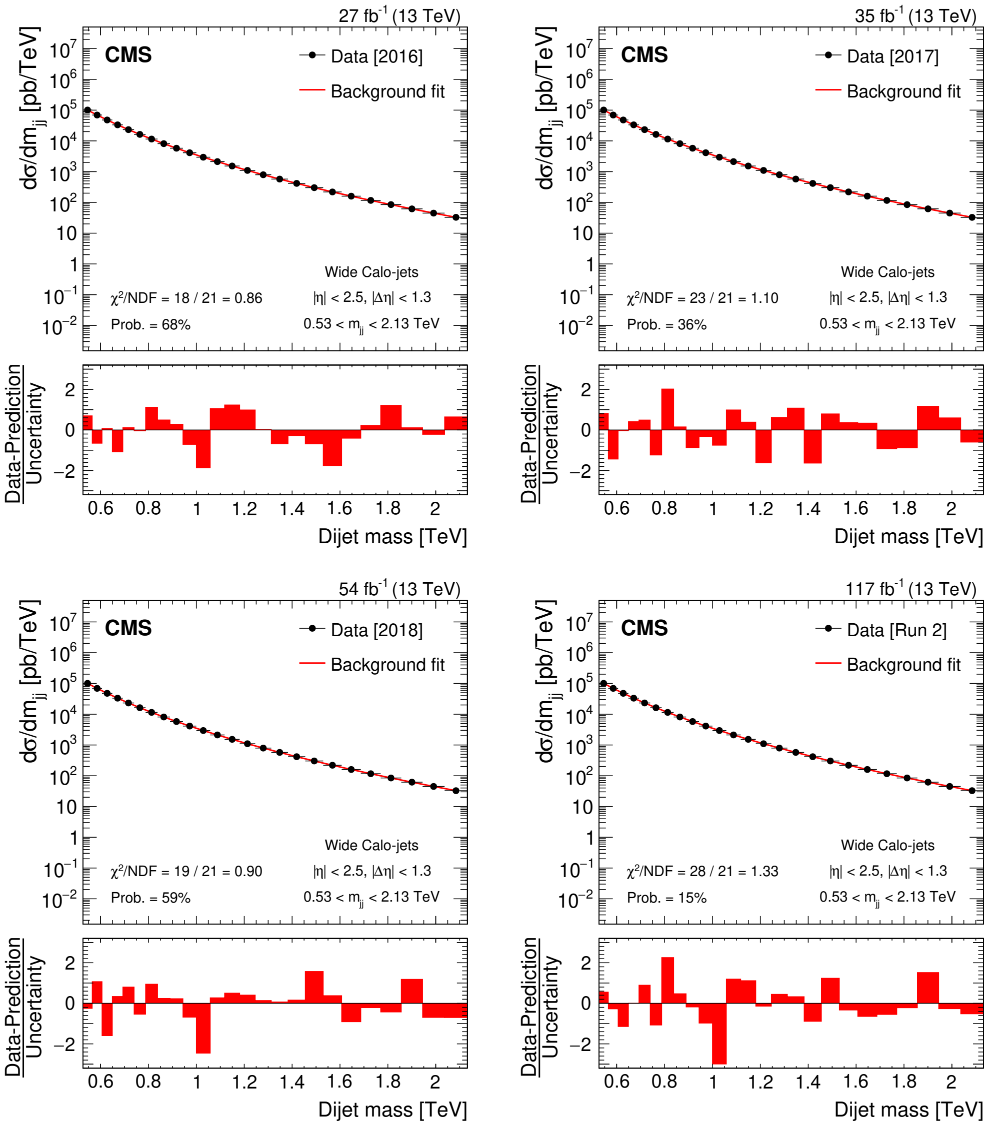

Figure 3. Dijet mass spectra for wide Calo-jets (points) compared to a parameterization of the background (solid curve) for the 2016 (upper left), 2017 (upper right), 2018 (lower left), and the combined (lower right) data sets. The horizontal lines on the data points in the upper panel show variable bin sizes, while the red bars in the lower panels show the bin-by-bin difference between the data and parameterization, normalized to the total uncertainty.

Figure 3 shows the djiet mass spectra from each year, 2016, 2017, 2018, and the sum of all three years (Run-2), along with their background-only fits. The binning of the spectra is based on variable-width bins that increase with m_{jj} and are chosen to be roughly comparable to the dijet mass resolution over the full mass range. The background curves shown are the integrated luminosity weighted sum of the relevant background-only fits from the fourteen data-taking periods within the three years. Also shown are the pulls, defined as the difference between the data and the fitted parameterization, divided by the statistical uncertainty of the data. The dijet mass spectra are well modeled by the background fits, as evidenced by the fit probability and the pulls, and there is no significant evidence for resonant particle production.

5 Statistical procedure

To set limits, we use a multibin counting experiment likelihood, which is a product of Poisson distributions corresponding to different bins. The sources of systematic uncertainty considered are the jet energy scale (JES) and JER, the integrated luminosity, and the values of the parameters within the functional form modeling the background shape in the dijet mass distribution. The background systematic uncertainties are related to the parameters of the functional forms utilized, that were left unconstrained in the fit, and are by far the dominant ones in these searches. The uncertainty in the JES is within 2% for all values of the dijet mass and is determined from $\sqrt{s} = 13\,\text{TeV}$ data using the methods described in ref. [45]. This uncertainty is propagated to the limits by shifting the dijet mass shape for the signal by ±2%. The uncertainty in the JER translates into an uncertainty of 10% in the resolution of the dijet mass [45], and it 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 uncertainties in the integrated luminosities are 1.2% in 2016 [58], 2.3% in 2017 [59], and 2.5% in 2018 [60], and are propagated to the signal normalization.

The test statistic is defined following the LHC CL_s criterion [61, 62] and is implemented using the CMS statistical analysis tool COMBINE [63], which is based on the ROOFIT [64] and ROOSTATS [65] frameworks. In the frequentist paradigm, the systematic uncertainties related to the nuisance parameters are taken into account through profiling (maximization of the likelihood). The sources of systematic uncertainty are implemented as nuisance parameters in the likelihood model. For the background parameterization, parameters are considered as freely floating parameters for each data-taking period independently and uncorrelated across years. Signal modeling uncertainties on JES and JER are implemented with Gaussian constraints, and on the integrated luminosity with log-normal constraints, correlated across years. We then use this test statistic to derive the observed 95% CL upper limit on the signal cross section in the asymptotic approximation [66] and to estimate the local significance.

6 Limits and significance

We use the dijet mass spectrum from wide jets, the background parameterization, and the dijet resonance shapes to set limits on the product of the production cross section (σ), branching fraction (B), and acceptance (A), of new particles decaying to the parton pairs qq (or q$\overline{\text{q}}$), 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. Figure 4 shows the 95% CL asymptotic LHC CL_s limits on σBA for the three considered final states. Therefore, the acceptance of the minimum dijet mass requirement does not appear in the acceptance A.

All upper limits presented can be compared to the parton-level predictions of σBA without detector simulation, to determine mass limits on new particles. The model predictions shown in figure 4 are lowest-order parton-level calculations, as previously discussed [29]. The

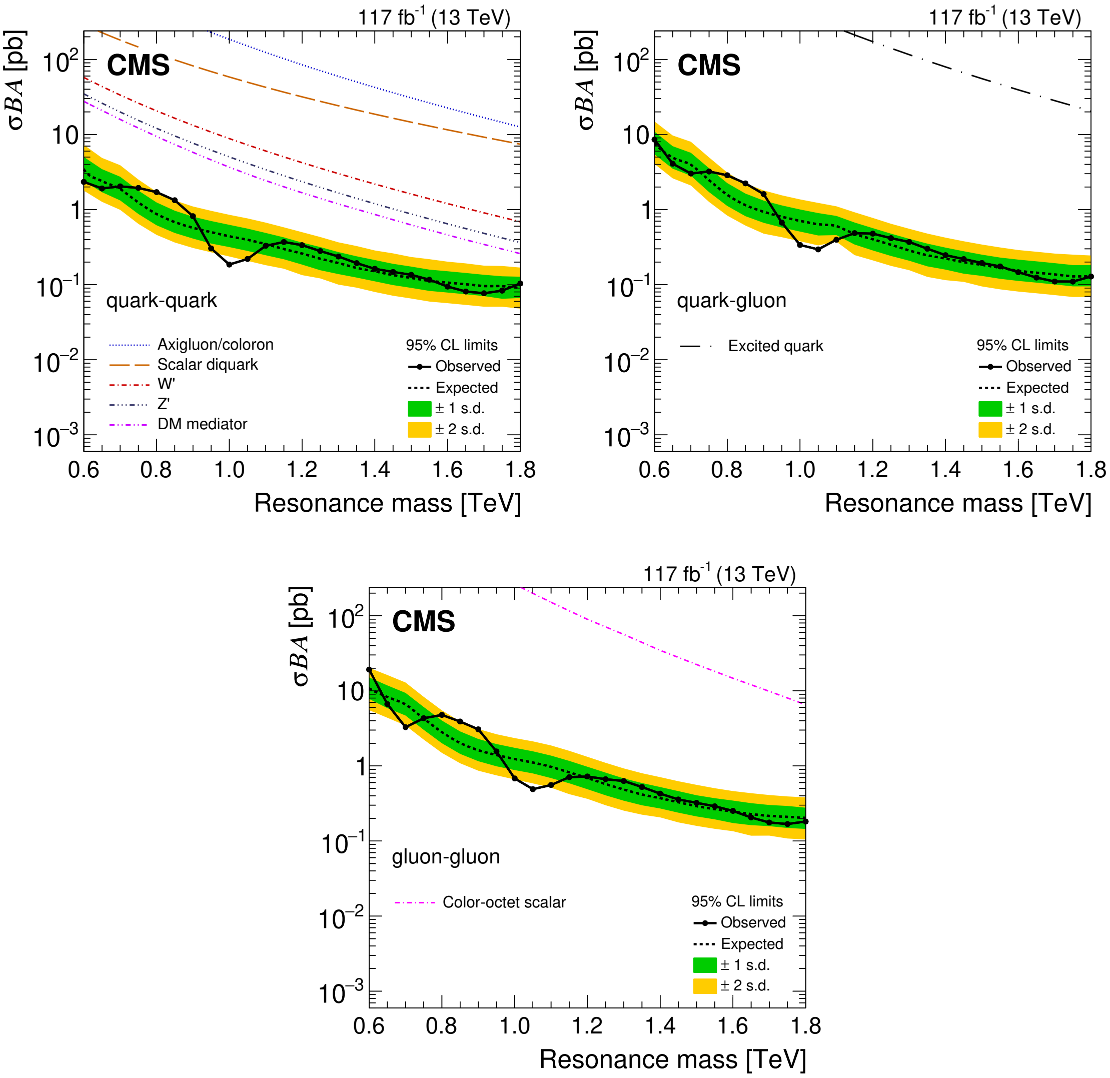

Figure 4. The observed 95% CL upper limits on the product of the cross section (σ), branching fraction (B), and acceptance (A) for dijet resonances decaying to quark-quark (upper left), quark-gluon (upper right), and gluon-gluon (lower). The corresponding expected limits (dashed) and their variations at the 1 and 2 standard deviation levels (shaded bands) are also shown. Limits are compared to the predicted cross sections for new gauge bosons W$'$ and Z$'$ with SM-like couplings [1], axigluons [2], excited quarks [3, 5], scalar diquarks [4], colorons [6], color-octet scalars [9], and DM mediators for the couplings $g_{\mathrm{q}} = 0.25$ and $g_{\mathrm{DM}} = 1$, and dark matter mass $M_{\mathrm{DM}} = 1\,\mathrm{GeV}$ [12, 14].

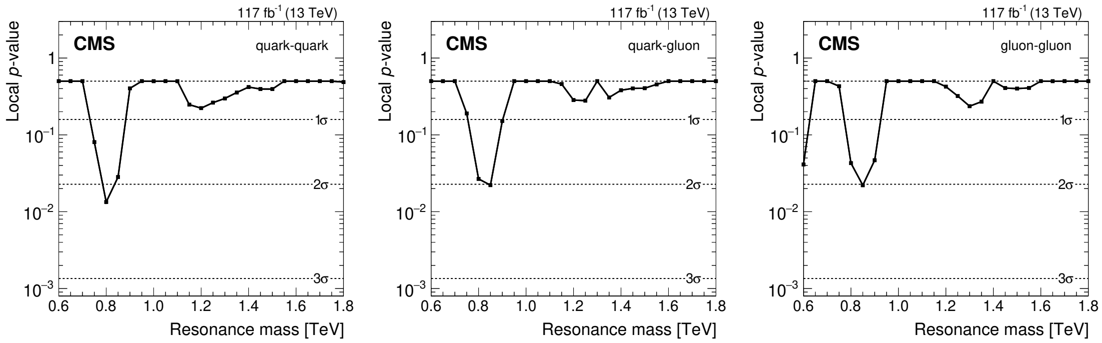

Figure 5. Local p-value, and the corresponding significance in standard deviations, for quark-quark (left), quark-gluon (middle), and gluon-gluon (right) resonances.

acceptance of the minimum dijet mass requirement for each considered signal has been evaluated separately for each final state and has been taken into account by correcting the limits. The acceptance is evaluated at the parton level for the resonance decay to two partons. In the case of isotropic decays, the acceptance is $A \approx 0.6$ 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 4. Between a resonance mass of 0.6 and 1.8 TeV, we exclude all the benchmark models for the coupling values considered, as shown in figure 4.

Figure 5 shows the p-value, a measure of the local significance, as a function of mass for qq, qg, and gg resonances. The highest local significances (lowest p-values), of roughly 2 standard deviations, are observed at resonance masses in the 0.80–0.85 TeV region in all three cases.

7 Limits on dark-matter mediators

Figure 6 presents the excluded values of the universal quark coupling as a function of the Z' boson mass. It shows the significant improvement of the current limits in the coupling versus mass plane with respect to the previously published results from CMS at 8 TeV [35] and 13 TeV [29]. We note that the improvement is beyond what is expected for the statistical component of the limit, which usually scales inversely proportional to the square root of the integrated luminosity. This is a consequence of the new statistical approach, which requires fewer parameters in the empirical functional forms of the background modeling. For the first time, CMS demonstrates sensitivity to coupling values as small as 0.04. Our sensitivity is similar to that from the most recent search by the ATLAS Collaboration [56] based on an integrated luminosity of 132 fb^{-1}. The previous ATLAS search [36], although it used much less integrated luminosity, reported significantly higher sensitivity than the recent CMS and ATLAS searches for Z' masses less than approximately 1 TeV, and has been explicitly superseded by the most recent ATLAS publication [56]. In contrast to the prior ATLAS publication, their most recent paper estimates the important uncertainty in the background in the same way as CMS does, by treating the parameters of the background functional form as nuisances and allowing them to float freely when maximizing the likelihood.

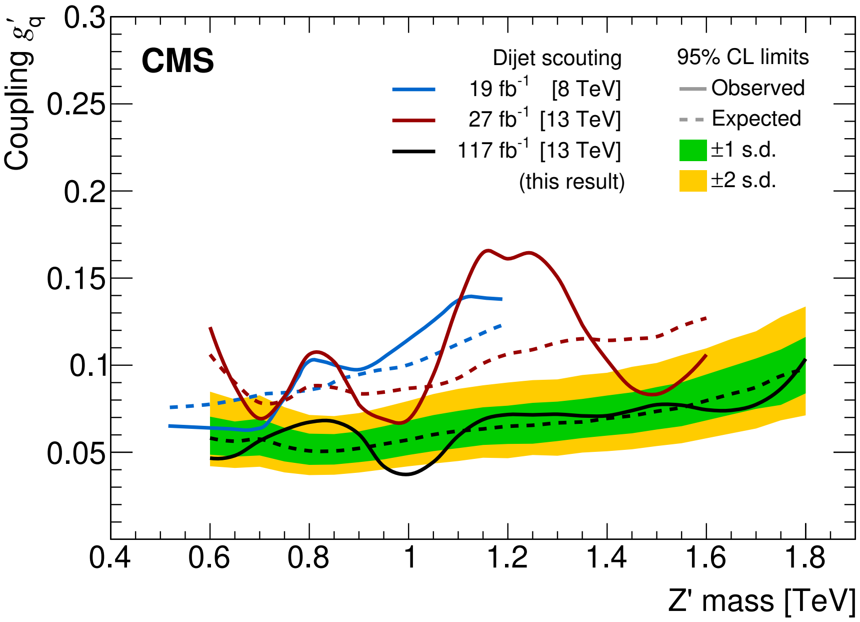

Figure 6. The 95% CL upper limit on the universal quark coupling g'_q as a function of resonance mass for a leptophobic Z′ resonance that only couples to quarks. The observed limits (solid), expected limits (dashed), and their variation at the 1 and 2 standard deviation levels (shaded bands) are shown. Current limits (black) are compared with previously published ones from CMS at 8 TeV [35] (blue) and 13 TeV [29] (red).

8 Summary

Calorimeter jets from data scouting have been used to search for dijet resonances with masses between 0.6 and 1.8 TeV. The dijet mass spectra are observed to be smoothly falling distributions, and no significant evidence for resonant particle production is found. Signal significances and upper limits are presented as functions of the resonance mass, on the product of the cross section, branching fraction, and acceptance, for the individual cases of narrow quark-quark, quark-gluon, and gluon-gluon resonances that are applicable to any model of narrow dijet resonance production. The largest local significance is observed to be 2.2 standard deviations at a quark-quark resonance mass of 0.8 TeV. The limits exclude models of color-octet scalars, excited quarks, axigluons, colorons, scalar diquarks, W′ and Z′ bosons, and dark matter (DM) mediators, for the benchmark choices of the couplings, over the complete mass range considered. The limit on the coupling of DM mediators to quarks, in a simplified model of interactions between quarks and DM, is presented as a function of the mediator mass. The sensitivity of this search goes beyond what is expected from statistical scaling with the integrated luminosity alone, as a consequence of the use of fewer parameters in the background function within a more robust statistical procedure.

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Data Availability Statement. Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

Code Availability Statement. The CMS core software is publicly available on GitHub.

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