PROCEEDINGS OF SCIENCE

Searches for new phenomena using jets at CMS

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Many new physics models such as quark compositeness, extra dimensions, extended Higgs sectors, supersymmetric theories and dark sector extensions are expected to manifest themselves in the final states with hadronic jets. Emphasis is placed on CMS searches for new phenomena in the final states that include jets, focusing on the recent results obtained using the full Run-II data-set collected at the LHC.

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1. Introduction

There are several extensions of the standard model (SM) predicting the existence of new resonances that couple to quarks. Proton-proton collisions produced by the LHC at CERN provide an excellent opportunity to search for such resonances.

In this document we will discuss three searches performed by the CMS experiment [1] that look for a dark matter mediator that decays into quarks in different mass regimes, from the very low at 50-450 GeV to the very high at 2.0-8.5 TeV.

2. Low mass regime - Boosted dijet search

The sensitivity of conventional searches for dijet resonances below 1 TeV is limited by high trigger thresholds and by the huge expected SM backgrounds, dominantly from events consisting of jets produced through the strong interaction (QCD multijet events).

The boosted dijet search [2] avoids these difficulties by looking for light leptophobic vector (Z') resonances decaying to a quark-antiquark pair, produced in association with a high transverse momentum (p_T) jet from initial state radiation (ISR). The ISR requirement ensures that the event has enough energy to satisfy trigger requirements either by the ISR jet or by the resonance.

2.1 Low mass regime - Analysis strategy

This search focuses on events in which a high-p_T jet from a merged Z' → qq recoils against another high-p_T ISR jet. The most energetic jet in the event is assumed to correspond to the resonance and is reconstructed as a single "fat" jet. The physics observable of the analysis is the jet mass, groomed with the softdrop algorithm (m_{SD}) [3, 4] which reduces the jet mass of QCD background jets by removing soft gluon radiation contributions while keeping the jet mass of merged decays mostly unchanged. In addition to the groomed jet mass, two more variables are used to discriminate the two-prong signal events from the mostly one-prong background ones, the p_T invariant variable ρ [3, 5] and the jet sub-structure variable N_2^1 [6]. The search is performed by looking for a resonance in the soft-drop mass distribution over background contributions dominated by QCD multijet events and smaller contributions from W $(q'\bar{q})$+jets, Z$(q\bar{q})$+jets, and top quark background processes. The dominant QCD background is estimated from data, using control regions defined by events failing the jet-substructure criteria.

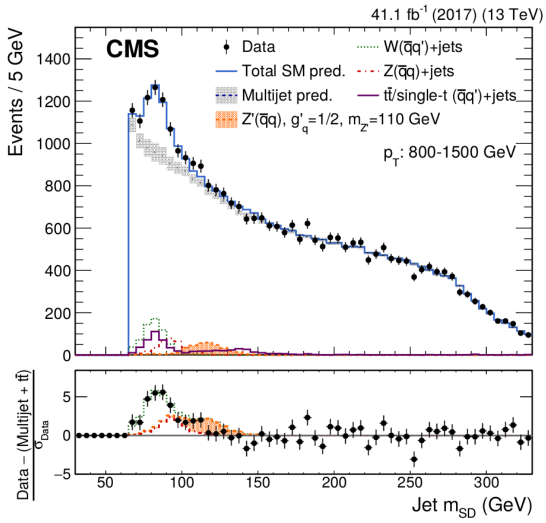


Figure 1: Jet m_{SD} distribution for the 800-1500 GeV p_T category of the fit. Data and the different background predictions are shown. In the bottom panel, the ratio of the data to its statistical uncertainty, after subtracting the non-resonant backgrounds, is also shown [2].

2.2 Low mass regime - Results

A binned maximum likelihood fit to the shape of the observed m_{SD} distribution is performed using the sum of the Z' signal, W, Z, tt, and QCD contributions. Search for a signal from a Z' resonance in the mass range from 50 to 450 GeV is performed. The fit is performed simultaneously in the signal and control regions of five jet p_T categories. In Figure 1 the jet m_{SD} distribution of the data is compared to the final fit, for a specific jet p_T category, while the different background contributions are shown separately.

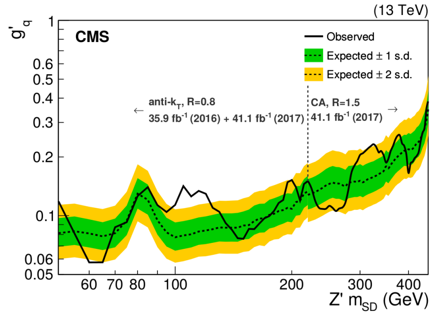


Figure 2: Upper limits at 95% CL on the coupling g_q' as a function of the resonance mass. The observed limits (solid), expected limits (dashed), and their variations (shaded bands) are shown [2].

The results are interpreted in terms of 95% confidence level (CL) upper limits on the production cross section of a Z' resonance which are then translated into the coupling $g_{q'}$ as a function of the boson mass (Fig. 2). Using both the 2016 and 2017 results, the search provides the most sensitive limits to date for masses 50-300 GeV while using only the 2017 data this search is the first one to probe the region up to 450 GeV with jet sub-structure techniques.

3. Intermediate mass regime - Resolved dijet search

Resolved dijet searches are looking for resonances decaying into quarks or gluons (s-channel production) in the dijet mass (m_{jj}) distribution of the two most energetic jets. The main background originates from QCD multijet events (t-channel production). This analysis [7] is using a special data-taking technique called data scouting, which consists of saving only the calorimeter-based jets reconstructed by the software trigger system in CMS, allowing the analysis of much larger rate of data.

3.1 Intermediate mass regime - Analysis strategy

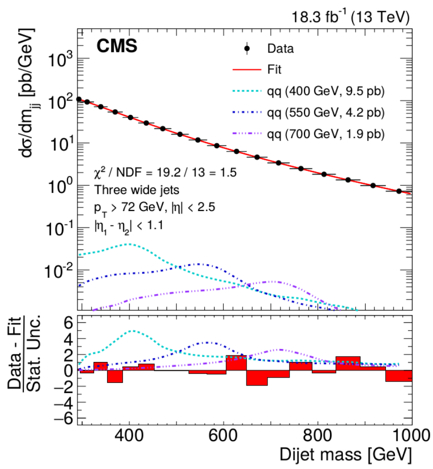


Figure 3: Dijet mass spectrum (points) compared to a fitted parameterization of the background (solid curve). The lower panel shows the difference between the data and the fitted parametrization, divided by the statistical uncertainty of the data [7].

In order to increase sensitivity to even lower resonance masses with respect to the trigger requirements, this search selects events with at least three jets in the final state. The two most energetic jets are assumed to correspond to the resonance and the third is attributed to either initial or final state radiation.

The smoothly falling QCD background is modeled by the empirical parametrization 1, where x is defined as $m_{jj}/\sqrt{s}$, and p_0 , p_1, p_2, p_3, and p_4 are free floating parameters of the fit.

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(p_2x-1)}{x^{p_1+p_3logx+p4log^2x}} \quad (1)$$

3.2 Intermediate mass regime - Results

Figure 3 shows the m_{jj} spectrum of the data along with the background-only parametric fit. The signal templates used in the final signal+background fits are obtained using simulation. The result of the signal+background fit is interpreted in terms of 95% confidence level (CL) upper limits on the production cross section and coupling strength of a dark matter mediator that decays both to 1 GeV dark matter particles and quarks. Figure 4 compares the upper limits on the cross section and the coupling g_q', respectively, with the predictions of a model with a DM mediator that decays to DM particles with masses of 1 GeV, and also decays to quarks.

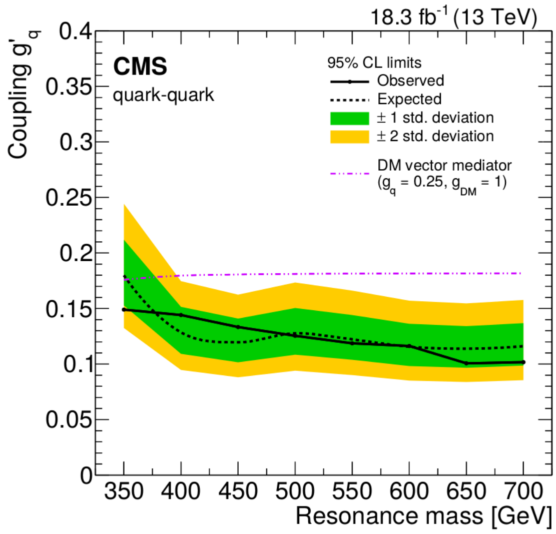


Figure 4: Upper limits at 95% CL on the universal quark coupling g_q', as a function of resonance mass, for a narrow vector resonance that only couples to quarks. The observed limits (solid curve), expected limits (dashed curve) and their variation (shaded bands) are shown [7].

4. High mass regime - Resolved dijet analysis

The high mass dijet search in CMS [8], searches for dijet resonances in the m_{jj} distribution over a smoothly falling QCD background, similarly to what was described in section 3.

4.1 High mass regime - Analysis strategy

The background is estimated with two orthogonal approaches: a parametric fit on the data similar to the one described in section 3.1 and a novel data-driven technique (the ratio method) which predicts the QCD background using control regions, that significantly reduces systematic uncertainties. The signal region (SR) and the two control regions (CR_{middle} and CR_{high}) are defined with respect to the pseudorapidity separation between the two jets ($|\Delta\eta|$) as shown in Figure 5. The ratio method predicts the QCD background in the SR by multiplying the data in CR_{high} by a mass-dependent transfer factor determined from the simulated angular distribution of QCD dijet production. The transfer factor is corrected for missing NLO and electroweak effects in the simulation using data in CR_{middle}.

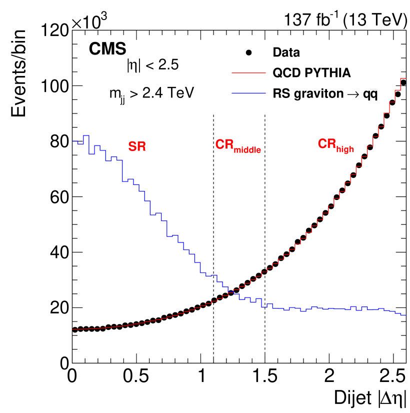


Figure 5: The $|\Delta\eta|$ between the two jets for the signal and control regions. Data (black points), QCD predictions from PYTHIA simulation (red histogram) and a RS graviton signal decaying to a qq pair are shown (blue histogram) normalized to data [8].

4.2 High mass regime - Results

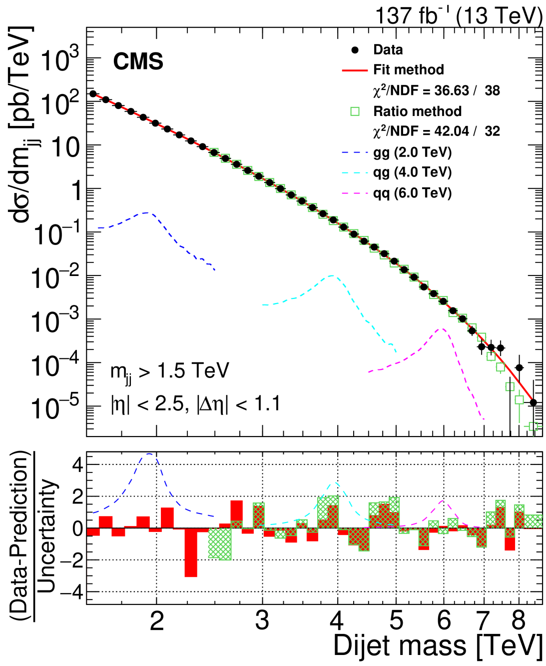


Figure 6: The m_{jj} spectrum in the SR (points) compared to the background predictions (solid line and green squares). The lower panel shows the difference between the data and the predictions divided by the statistical uncertainty in the data [8].

Figure 6 shows the dijet mass spectrum of the data and compares it to the background predictions of the two approaches. Both approaches describe the data well and agree with each other. The search for resonances proceeds with fitting the dijet mass distribution in the SR using the background predictions and signal templates obtained from simulation, a procedure denoted as a signal plus background fit. The results from the signal plus background fits are used to set upper limits on the production cross sections of new particles decaying to the parton pairs qq (or $q\bar{q}$), qg, and gg. Figure 7 shows the different observed limits at 95 % CL for qq, qg, and gg resonances whose natural width is much smaller than the experimental resolution (narrow resonances). Differences between the limits of each final state arises from differences in the signal templates.

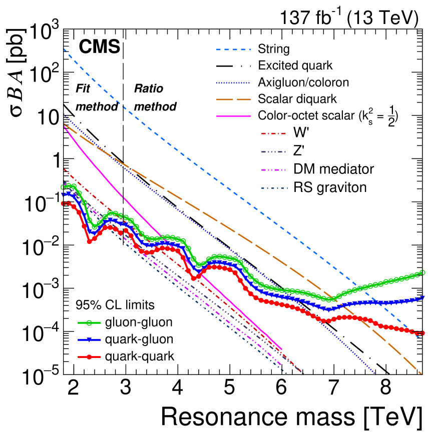
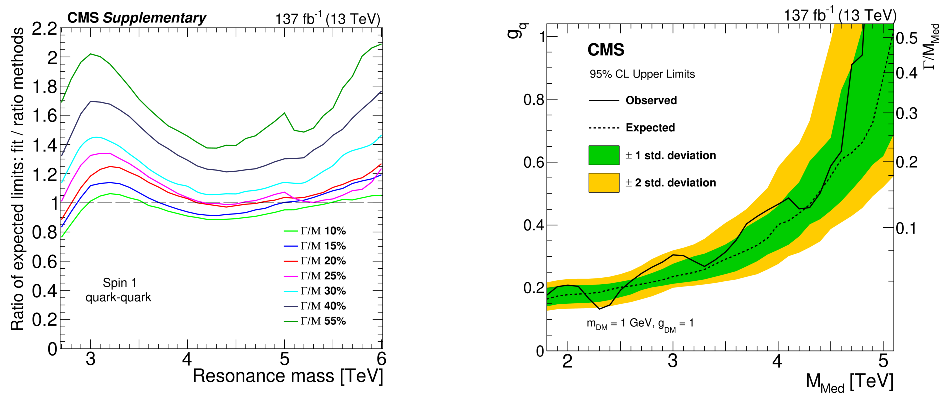


Figure 7: The observed 95% CL upper limits on the cross section for qq, qg, and gg type dijet resonances. Limits are compared to predicted cross sections for various benchmark new physics models [8].

This search is also covering resonances whose natural width is larger than the experimental resolution (broad resonances), searching for spin-1 resonances decaying to quark-quark pairs with a width up to 55% of the resonance mass as well as spin-2 resonances that decay to quark or gluon pairs with a width up to 30% of the resonance mass. As the resonance width increases the ratio method has smaller background uncertainty compared to the fit method, and hence higher sensitivity. Figure 8a shows the ratio of the expected limits obtained using the fit method as the background prediction divided by the expected limits using the ratio method for broad spin-1 resonances, where it is obvious that ratio method provides better limits by a factor up to 2 for the largest widths. The cross section limits of spin-1 broad resonances are used to set upper limits on the coupling g_q as a function of mass for a leptophobic, spin-1, dark matter (DM) mediator that couples both to quarks and DM particles of 1 GeV mass and a coupling g_{DM} = 1.0 (Figure 8b).



(a) Ratio of the expected limits obtained using the fit method as the background prediction divided by the expected limits using the ratio method for broad spin-1 resonances [8].

(b) 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 [8].

Figure 8

5. Summary

The analysis strategies and results of three very powerful dijet searches in CMS have been discussed, covering a wide range of resonance masses, from 50 GeV to 8.5 TeV. The boosted dijet search and the resolved dijet search in the intermediate mass regime provide the most sensitive results to date for resonance masses 50-300 GeV and 350-450 GeV respectively. The high mass search introduced a novel data-driven estimation for the QCD background, significantly reducing systematic uncertainties, resulting in the exclusion at 95% CL of a dark matter mediator up to 4.8 TeV for a width equal to 45% of the mass, corresponding to a coupling to quarks $g_q = 0.9$.

References

[1] S. Chatrchyan *et al.*, “The CMS Experiment at the CERN LHC,” *JINST*, vol. 3, p. S08004, 2008.

[2] A. M. Sirunyan *et al.*, “Search for low mass vector resonances decaying into quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV,” *Phys. Rev. D*, vol. 100, p. 112007, Dec 2019.

[3] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, “Towards an understanding of jet substructure,” *JHEP*, vol. 09, p. 029, 2013.

[4] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, “Soft Drop,” *JHEP*, vol. 05, p. 146, 2014.

[5] J. Dolen, P. Harris, S. Marzani, S. Rappoccio, and N. Tran, “Thinking outside the ROCs: Designing Decorrelated Taggers (DDT) for jet substructure,” *JHEP*, vol. 05, p. 156, 2016.

[6] I. Moult, L. Necib, and J. Thaler, “New Angles on Energy Correlation Functions,” *JHEP*, vol. 12, p. 153, 2016.

[7] A. M. Sirunyan *et al.*, “Search for dijet resonances using events with three jets in proton-proton collisions at $\sqrt{s} = 13$ TeV,” *Phys. Lett. B*, vol. 805, p. 135448, 2020.

[8] A. M. Sirunyan *et al.*, “Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s} = 13$ TeV,” *JHEP*, vol. 05, p. 033, 2020.