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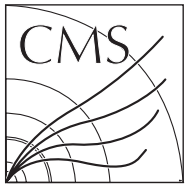

The Compact Muon Solenoid Experiment

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Searches in CMS for new physics in final states with jets

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Abstract

Many new physics models such as compositeness, extra dimensions, extended Higgs sectors, supersymmetric theories, and dark sector extensions, are expected to manifest themselves in the final states with hadronic jets. This note presents searches in CMS for new phenomena in the final states that include jets, focusing on the recent results obtained using the full Run-2 data-set collected at the LHC.

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Searches in CMS for new physics in final states with jets

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Abstract
Many new physics models such as compositeness, extra dimensions, extended Higgs sectors, supersymmetric theories, and dark sector extensions, are expected to manifest themselves in the final states with hadronic jets. This note summarizes searches in CMS for new phenomena in the final states that include jets, focusing on the recent results obtained using the full Run 2 data-set collected at the LHC.

1 Introduction

High energy physics has made leaps of progress, with general purpose collider experiments such as CMS [1] and ATLAS [2] at the Large Hadron Collider (LHC), CERN, playing a crucial part in understanding the nature of the fundamental building blocks of the universe. Despite being our most successful theory of particle physics, the Standard Model (SM) still fails to explain many phenomena such as dark matter, the origin of neutrino mass, matter-antimatter asymmetry, the reason behind three generations of fermions, and more. Many theoretical models involve Beyond the Standard Model (BSM) processes that attempt to provide these explanations and bridge the gaps where the SM falls short.

Many BSM scenarios predict new fermionic or scalar states and, in some cases, introduce new gauge groups. Such particles may couple to Standard Model particles and decay into final states containing quarks and gluons, which manifest in the CMS detector as hadronic jets. The CMS experiment [1] has developed an extensive program dedicated to searching for these signatures. This note presents a selection of recent BSM search results with jet final states, obtained using the CMS Run 2 dataset (2016-2018).

2 General analysis methodology

All the searches described in this note follow a common analysis strategy. The search for new particles which decay into quark or gluon final states can be conducted by first reconstructing the invariant mass of jet final state objects in the CMS detector, followed by identifying localized deviations from the Standard Model expectation that could indicate the presence of new BSM resonances. These BSM signals can either be narrow resonances where the intrinsic width of the new particle is smaller than the detector resolution, or broad resonances. These potential signals are modeled using dedicated Monte Carlo (MC) simulations.

In searches with jet final states, the dominant background arises from QCD multijet processes. Due to large uncertainties which arise from mis-modeling of QCD predictions in simulations, this background is estimated using data-driven methods instead. These data-driven methods typically rely on using fitted parametrized functions to the observed invariant mass distributions to model the QCD distribution, or extrapolating from well defined side-band regions to estimate the QCD background in the main signal sensitive search region. Other SM background processes such as $t\bar{t}$ or V+jets can be estimated using MC simulations.

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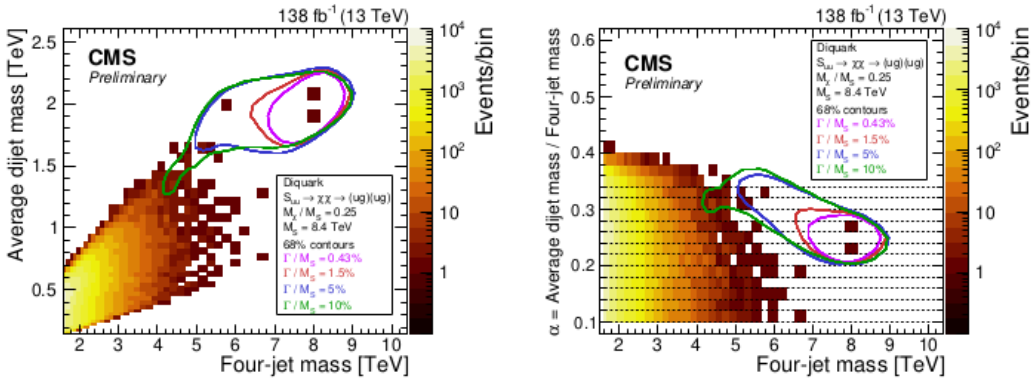

Fig. 1: Event yields are shown as a function of the four-jet mass (m_{4j}) versus the average dijet mass ($< m_{2j} >$) (left) and versus $\alpha = m_{4j} / < m_{2j} >$ (right) overlaid with 68% probability contours from an 8.4 TeV diquark signal decaying to 2.1 TeV vector-like quarks for several assumed widths (0.43%, 1.5%, 5%, 10%). The right plot additionally indicates the thirteen α bins used to construct the four-jet mass spectra (dashed line).

Finally, the estimated signal and background templates are fit to the observed jet invariant mass spectrum, where the systematic uncertainities are included as nuisance parameters in the final fits. Upper limits are set on the signal production cross-sections and statistical signal significance is estimated from the observed data.

3 Search for resonant production of pairs of dijet resonances through broad mediators

Recent CMS and ATLAS searches have investigated the resonant production of pairs of dijet resonances with equal invariant mass (pp $\rightarrow$ Y $\rightarrow$ XX $\rightarrow$ jj jj), with final state consisting of four resolved jets that offer strong sensitivity to physics beyond the Standard Model [3, 4]. These analyses interpret the data in terms of narrow mediators whose natural widths are below 0.5% of their mass. In the CMS search, two events with four-jet invariant masses (m_{4j}) near 8 TeV were observed, yielding a local significance of 3.9σ (global 1.6σ), alongside additional events in both CMS and ATLAS, with masses ranging from m_{4j} of 5.5 to 8 TeV. Fig. 1 (left) shows the observed average dijet mass distribution versus the four jet mass distribution with the full Run 2 CMS data. These additional high-mass events in CMS and ATLAS motivate a reinterpretation of data in terms of broad resonances [5], where the mediator Y is assumed to have a natural width larger than the detector resolution, while the daughter resonance X is assumed to be narrow.

3.1 Analysis strategy and results

This search uses the Diquark model [6] as a benchmark, in which a scalar diquark S_{uu} decays to a pair of vector-like quarks χ, each subsequently decaying to an up quark and a gluon, while limits are also set on the production of S_{dd} diquarks that decay to vector-like quarks w, as shown in Fig. 2. The analysis follows the strategy of the previous CMS narrow-resonance search [3], using the same dataset but fitting for broad resonances with relative widths of 1.5%, 5%, and 10%. A simultaneous fit is performed to the reconstructed four-jet mass distribution in bins of α, which is the ratio of the average dijet mass over the four-jet mass ($< m_{jj} > / m_{4j}$), shown in Fig. 1 (right). The dominant QCD multijet background is estimated using a simultaneous fit of three parametric functions to the four-jet mass distribution across the α bins, implemented through the discrete profiling method.

Model independent 95% CL upper limits are set on the production cross-section for various masses of Y and X resonances, for Y widths up to 10%. Mass limits are also set on diquarks S_{uu} and S_{dd} decaying into vector-like quarks. Fig. 3 (left) shows the 95% CL upper limits on the product of cross-section, branching ratio and acceptance, for a Y of width 10% and M(X)/M(Y) = 0.25, along with the

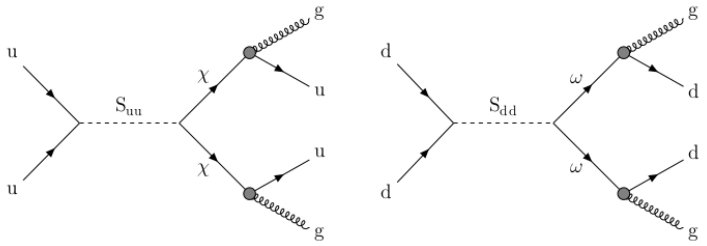

Fig. 2: Production of diquarks decaying to pairs of vector-like quarks, where each evctor-like quark decays into a quark and a gluon.

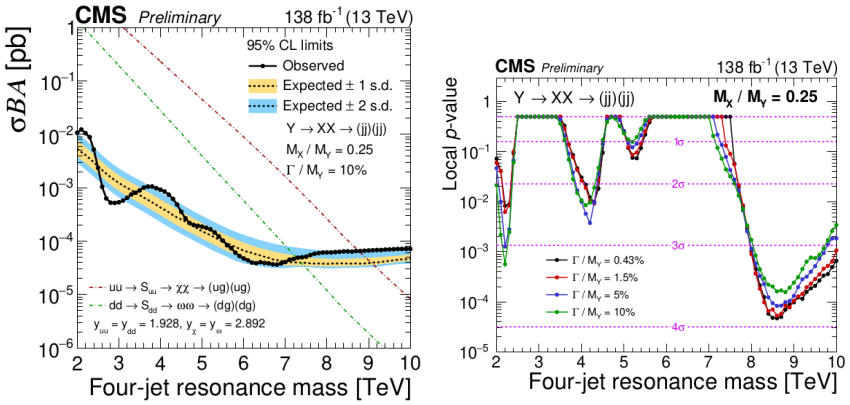

Fig. 3: (left) 95% CL observed and expected upper limits on the product of cross-section, branching ratio and acceptance and (right) observed local p-value for a four-jet resonance Y of relative width 10% and M(X)/M(Y) = 0.25.

predicted theoretical cross-sections for the S_{uu} and S_{dd} diquarks [6].

It is observed that a signal with M(X)/M(Y) = 0.25, M(Y) = 8.6 TeV and with a wide natural width is an equally valid interpretation of the local excess observed in data with the two high mass events. The local signal significance observed for a wide signal is 3.6 σ, for a resonance Y with a relative-width of 10%, as compared to a local significance of 3.9 σ for Y with a relative-width of 0.43 %, as seen in Fig. 3 (right). Moreover, an additional effect is observed at a local significance of 3.9 σ with M(Y) = 3.6 TeV and M(X) = 1 TeV and for a Y with a relative-width of 10%, while a Y resonance with a relative-width of 0.43% yields a local significance of 2.9 σ for the same mass point.

4 Search for dijet resonances with data scouting

A new CMS search is performed for narrow dijet resonances in the intermediate mass range between 600 GeV and 1.8 TeV using the data-scouting technique [7]. Unlike fully reconstructed offline jets, data scouting uses calorimeter information directly from the high-level trigger, enabling us to reach a lower dijet-mass threshold previously inaccessible with common datasets. This search focuses on generic narrow resonances decaying to quark-quark, quark-gluon, and gluon-gluon final states, reconstructed as a dijet, formed by pairs of wide jets. Two leading jets in transverse momentum are used as seeds and jets within a distance of $\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2} < 1.1$ from the seed jets are clustered to form the two wide jets. This clustering technique reduces sensitivity to final-state radiation and improves the dijet mass resolution.

The dominant background is QCD multijet production and it is estimated entirely from data-driven technique by using a smoothly falling parametric functional fit to the dijet mass distribution. A four-parameter modified exponential form is used, which is shown to provide stable fits across all Run-2

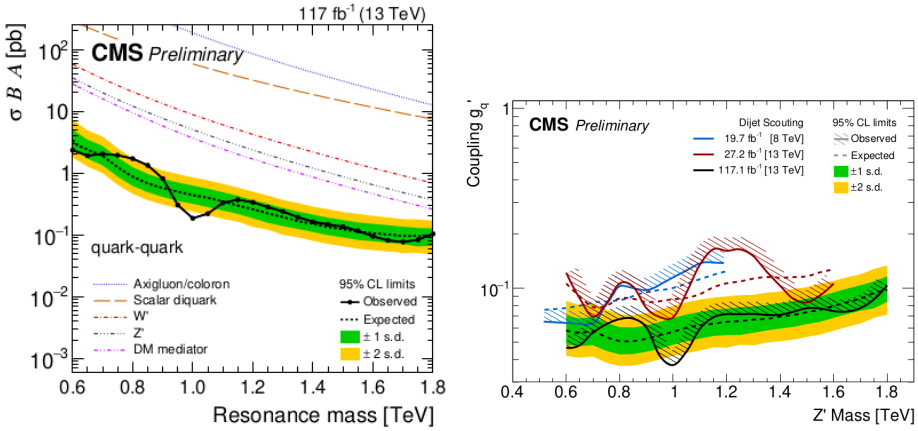

Fig. 4: (Left) 95% CL observed and expected upper limits on the product of cross-section, branching ratio and acceptance for dijet resonances decaying to quark-quark final state. (Right) 95% CL upper limits on the universal quark coupling g'$_q$ as a function of resonance mass for a leptophobic Z' resonance.

data sub-sets. To avoid correlations between potential signal contributions and the background shape, maintain robust statistical results, and ensure that the parametric function accurately models the dijet mass spectra, the Run 2 data is divided into fourteen subsets that are fit simultaneously.

95% CL upper limits are set on the product of the production cross section, branching ratio, and acceptance for narrow qq resonances, as shown in Fig. 4 (left), as well as qg and gg resonances. These generic limits are then interpreted in a variety of benchmark models, including color-octet scalars [8], excited quarks [9,10], new gauge bosons [11], and simplified dark-matter mediators [12,13]. The highest local signal significance is about 2σ at resonance masses near 0.80–0.85 TeV for all final states. In particular, this search achieves the most stringent CMS constraints to date on the universal quark coupling of a leptophobic Z' in the probed mass range, shown in Fig. 4 (right), with sensitivity surpassing that expected from luminosity scaling due to optimized background modeling. Couplings as low as g'$_q$ $\approx$0.04 are excluded for a mediator mass of 1 TeV. Overall, the data is consistent with the Standard Model prediction, and no significant deviations suggestive of new resonances are observed.

5 Search for $T' \to t(bqq)\phi(bb)$ in boosted final state

This CMS search [14] targets vector-like T' quarks decaying to a top quark and a scalar particle ϕ, where the scalar may be either be the Standard Model Higgs boson or a new BSM particle [15], as shown in Fig. 5 (left). The analysis focuses on fully hadronic, highly boosted regime, where both the top quark and the ϕ decay into collimated hadronic jets, resulting in two large-radius jets in the final state. This topology allows the search to cover a wide mass range, with $m(T')$ ranging from 900 GeV to 4 TeV and m(ϕ) between 75 and 500 GeV.

Because of the large Lorentz boost of the top quark and the scalar, this search employs state-of-the-art jet substructure techniques to distinguish the signal from the dominant multijet background. The PARTICLENET [16] discriminator is used to select jets originating either from a boosted top quark or from $\phi \to bb$ decays. In addition, a DEEPAK8 [17] tagger is used to define a control region enriched in semileptonic $t\bar{t}$ events, which helps constrain the resonant $t\bar{t}$ background. The QCD multijet background, which is the dominant background in the signal region, is derived from data using transfer factors extracted from sideband regions, which are defined based on the PARTICLENET and DEEPAK8 tagger scores, as shown in Fig. 5 (right). Smaller backgrounds, including V+jets, are modeled using simulation. A simultaneous liklihood fit of the reconstructed mT' and $m\phi$ spectra is conducted, across both the $t\bar{t}$ control region and the signal region.

No significant deviation from the Standard Model prediction is observed, and the analysis sets

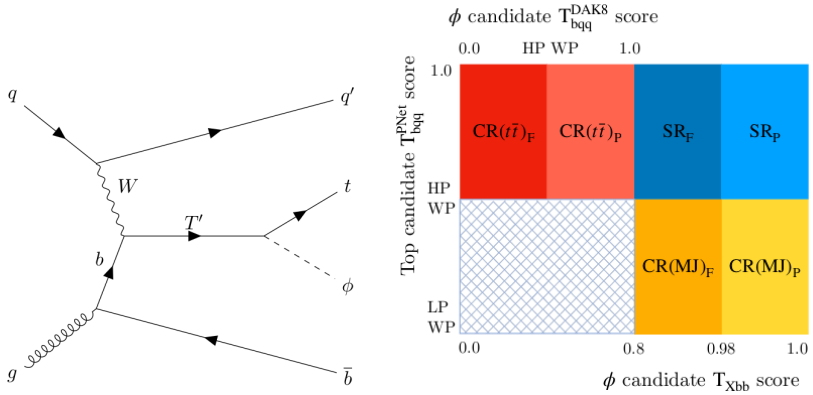

Fig. 5: (Left) Electroweak production of T', decaying to a top quark and a new scalar ϕ, produced in association with a quark and a b-quark. (Right) Categorization of events into the three main regions of the analysis, and their corresponding Pass and Fail regions.

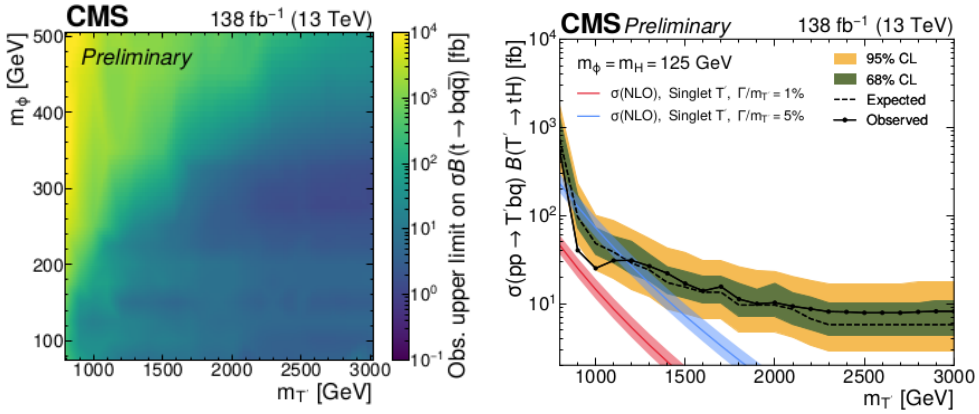

Fig. 6: (Left) 95% CL observed upper limits on the cross-section of $T' \to t\phi$ times the branching ratio of top decaying hadronically, B(t→bqq)). (Right) 95% CL upper limits the product of the production cross section of $T' \to tH$ and branching ratio of B(t→bqq, H→bb) as a function of the T' mass

upper limits on the production cross section of T' quarks for each point in the (mT', $m\phi$) plane. Fig. 6 (left) shows the observed 95% upper limit on the production cross-section of T' times the branching ratio of top decaying hadronically. For the specific case of the $T' \to$ tH decay, the search excludes T' masses below approximately 1.2 TeV at 95% CL for a singlet-like T' with a 5% relative width, as shown in Fig. 6 (right).

6 Summary

This note presents a set of recent CMS searches for new physics in final states containing hadronic jets, using the full Run-2 dataset collected from 2016-2018. The analyses target a variety of Beyond-the-Standard-Model scenarios that predict new particles decaying to quarks or gluons, and employ data-driven techniques to model the dominant QCD multijet background. Results include searches for paired dijet resonances through broad mediators [5], narrow dijet resonances via data scouting [7], and vector-like quark production in boosted topologies [14]. In the paired-dijet search, a broad mediator interpretation is compatible with the two high-mass events observed at m_{4j} of 8 TeV, as well as the other high-mass candidate events observed both by CMS and ATLAS. The dijet search, which employs data-scouting technique, and the T' search which leverages the use of latest jet substructure and tagging techniques, show no significant deviations from the Standard Model expectation.

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