Physics Letters B 769 (2017) 520–542

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for dijet resonances in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$ and constraints on dark matter and other models

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ARTICLE INFO

Article history:
Received 11 November 2016
Received in revised form 21 January 2017
Accepted 6 February 2017
Available online 14 February 2017
Editor: M. Doser

Keywords:
CMS
Physics
Search
Exotica
Dijet
Resonance

ABSTRACT

A search is presented for narrow resonances decaying to dijet final states in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$ using data corresponding to an integrated luminosity of $12.9\,\text{fb}^{-1}$. The dijet mass spectrum is well described by a smooth parameterization and no significant evidence for the production of new particles is observed. Upper limits at 95% confidence level are reported on the production cross section for narrow resonances with masses above 0.6 TeV. In the context of specific models, the limits exclude string resonances with masses below 7.4 TeV, scalar diquarks below 6.9 TeV, axigluons and colorons below 5.5 TeV, excited quarks below 5.4 TeV, color-octet scalars below 3.0 TeV, W′ bosons below 2.7 TeV, Z′ bosons below 2.1 TeV and between 2.3 and 2.6 TeV, and RS gravitons below 1.9 TeV. These extend previous limits in the dijet channel. Vector and axial-vector mediators in a simplified model of interactions between quarks and dark matter are excluded below 2.0 TeV. The first limits in the dijet channel on dark matter mediators are presented as functions of dark matter mass and are compared to the exclusions of dark matter in direct detection experiments.

1. Introduction

The dijet mass (m_{jj}) spectrum in proton–proton (pp) collisions arising from the production of partons at high transverse momentum (p_{T}) is predicted by quantum chromodynamics (QCD) to fall smoothly with increasing dijet mass. Many models of physics beyond the standard model (SM) require new particles that couple to quarks (q) and gluons (g) and can be observed as resonances in the dijet mass spectrum. One example is a model in which dark matter (DM) particles couple to quarks through a DM mediator. This mediator can decay to either a pair of DM particles or a pair of jets and therefore can be observed as a dijet resonance [1]. Here, we report a search for narrow dijet resonances, which are those with natural widths that are small compared to the experimental mass resolution.

This letter presents the results of two searches for dijet resonances, using data collected in 2016 with the CMS detector at the CERN LHC in pp collisions at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $12.9\,\text{fb}^{-1}$. The first is a *high-mass* search for resonances with mass above 1.6 TeV using dijet events that are reconstructed offline. Similar high-mass searches were published by CMS and ATLAS at $\sqrt{s} = 13\,\text{TeV}$ [2,3], 8 TeV [4–6], and 7 TeV [7–13] using strategies reviewed in Ref. [14]. The most recently published high-mass searches used data collected in 2015 corresponding to an integrated luminosity of $2.4\,\text{fb}^{-1}$ by CMS [2] and $3.6\,\text{fb}^{-1}$ by ATLAS [3]. The second is a *low-mass* search for resonances with mass between 0.6 and 1.6 TeV using dijet events that are reconstructed, selected, and recorded in a compact form by the high-level trigger (HLT) in a technique called *data scouting* [15]. Data scouting was previously used for a similar low-mass search published by CMS at $\sqrt{s} = 8\,\text{TeV}$ [16].

We present model-independent results and, in addition, consider the following benchmark models of s-channel dijet resonances: string resonances [17,18], scalar diquarks [19], axigluons [20,21], colorons [21,22], excited quarks (q*) [23,24], color-octet scalars [25], new gauge bosons (W′ and Z′) with SM-like or leptophobic couplings [26], DM mediators [27,28], and Randall–Sundrum (RS) gravitons (G) [29]. In the color-octet scalar model the squared anomalous coupling used is $k_s^2 = 1/2$ [30], yielding a width and a cross section that is half the value used in the previous CMS search [2]. Following the recommendations of Ref. [27] the DM mediator in a simplified model [28] is assumed to be a spin-1 particle and to decay only to $\text{q}\bar{\text{q}}$ and pairs of DM particles, with unknown mass m_{DM}, and with a universal quark coupling

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http://dx.doi.org/10.1016/j.physletb.2017.02.012
0370-2693/

$g_q = 0.25$ and a DM coupling $g_{DM} = 1.0$. Otherwise, the specific choices of parameters for the benchmark models are the same as those that were used in previous CMS searches, and can be found in Ref. [7].

2. Jet reconstruction and event selection

The CMS detector and its coordinate system, including the azimuthal angle ϕ and the pseudorapidity η, are described in detail in Ref. [31]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing an axial field of 3.8 T. Within the field volume are located the silicon pixel and strip tracker ($|\eta| < 2.4$) and the barrel and endcap calorimeters ($|\eta| < 3$), which 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 ($3 < |\eta| < 5$), outside the field volume. For triggering purposes and to facilitate jet reconstruction, the calorimeter cells are grouped into towers projecting radially outward from the center of the detector.

A particle-flow (PF) event algorithm reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector [32,33]. Particles are classified as muons, electrons, photons, and either charged or neutral hadrons. Jets are reconstructed either using particle flow, giving *PF-jets*, or from energy deposits in the calorimeters, giving *Calo-jets*. PF-jets reconstructed offline are used in the high-mass search, and Calo-jets reconstructed by the HLT are used in the low-mass search. To reconstruct both types of jets, we use the anti-k_T algorithm [34,35] with a distance parameter of 0.4, as implemented in the FastJet package [36]. For the high-mass search, at least one reconstructed vertex is required. The primary vertex is defined as the vertex with the highest sum of p_T^2 of the associated tracks. For PF-jets, charged PF candidates not originating from the primary vertex are removed prior to the jet finding. For both types of jets, an event-by-event correction based on jet area [37,38] 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. Events satisfying loose jet requirements at the first level (L1) are examined by the HLT. The HLT uses H_T, the scalar sum of the jet p_T from all jets in the event with $|\eta| < 3$ that satisfy a jet p_T requirement, to select events. For the high-mass search, PF-jets with $p_T > 30\,\text{GeV}$ are used to compute H_T, and events are accepted by the HLT if they satisfy the requirement $H_T > 800\,\text{GeV}$. We then select events with $m_{jj} > 1.06\,\text{TeV}$ for which the combined L1 trigger and HLT are found to be fully efficient. For the low-mass search, when an event passes the HLT, the Calo-jets reconstructed at the HLT are saved, along with the event energy density and missing transverse momentum reconstructed from the calorimeter. The shorter time for event reconstruction of calorimeter quantities and the reduced event size recorded for these events allow a reduced H_T threshold compared to the high-mass search. For the low-mass search, Calo-jets with $p_T > 40\,\text{GeV}$ are used to compute H_T, the threshold is $H_T > 250\,\text{GeV}$, and we select events with $m_{jj} > 0.45\,\text{TeV}$ for which the trigger is fully efficient.

The jet momenta and energies are corrected using calibration constants obtained from simulation, test beam results, and pp collision data at $\sqrt{s} = 13\,\text{TeV}$. The methods described in Ref. [38] are used and all *in-situ* calibrations are obtained from the current data. All jets are required to have $p_T > 30\,\text{GeV}$ and $|\eta| < 2.5$. The two jets with largest p_T are defined as the leading jets. Jet identification (ID) criteria are applied to remove spurious jets associated with calorimeter noise. The jet ID for PF-jets is described in Ref. [39]. The jet ID for Calo-jets requires that the jet be detected by both the electromagnetic and hadronic calorimeters with the fraction of jet energy deposited within the electromagnetic calorimeter between 5 and 95% of the total jet energy. An event is rejected if either of the two leading jets fails the jet ID criteria.

Spatially close jets are combined into “wide jets” and used to determine the dijet mass, as in the previous CMS searches [4,6,7,10]. The wide-jet algorithm, designed for dijet resonance event reconstruction, reduces the analysis sensitivity to gluon radiation from the final-state partons. The two leading jets are used as seeds and the four-vectors of all other jets, if within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$, are added to the nearest leading jet to obtain two wide jets, which then form the dijet system. The background from t-channel dijet events peaks at large values of $|\Delta\eta_{jj}|$ and is suppressed by requiring the pseudorapidity separation of the two wide jets to satisfy $|\Delta\eta_{jj}| < 1.3$. The above requirements maximize the search sensitivity for isotropic decays of dijet resonances in the presence of QCD dijet background. For the low-mass search, after wide jet reconstruction and event selection, we use a correction derived from a smaller sample of dijet data to calibrate the wide jets reconstructed from Calo-jets at HLT. With this correction, based on a dijet balance tag-and-probe method similar to that discussed in Ref. [38], the wide jets from Calo-jets have the same response as those reconstructed from PF-jets.

3. Dijet mass spectrum and fit

Fig. 1 shows the dijet mass spectra, defined as the observed number of events in each bin divided by the integrated luminosity and the bin width, with predefined bins of width corresponding to the dijet mass resolution [12]. The highest mass event has a dijet mass of 7.7 TeV. The dijet mass spectra for both the high- and low-mass searches are fit with the following parameterization:

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

where $x = m_{jj}/\sqrt{s}$ and P_0, P_1, P_2, and P_3 are four free parameters. The functional form in Eq. (1) was also used in previous searches [2–13,16,40] to describe the data. In Fig. 1 we show the result of binned maximum likelihood fits, performed independently, which yields the following chi-squared per number of degrees of freedom: $\chi^2/\text{NDF} = 33.3/42$ for the high-mass search and $\chi^2/\text{NDF} = 17.3/22$ for the low-mass search. The dijet mass spectra are well modeled by the background fits. In the lower panels of Fig. 1, in the region of dijet mass between 1.1 and 2.0 TeV, the bin-by-bin differences between the data and the background fit are not identical in the two searches because fluctuations in reconstructed dijet mass for Calo-jets and PF-jets are not completely correlated.

We search for narrow resonances in the dijet mass spectrum. Fig. 1 shows examples of dijet mass distributions for signal events generated with the pythia 8.205 [41] program with the CUETP8M1 tune [42,43] and including a Geant4-based [44] simulation of the CMS detector. The predicted mass distributions have Gaussian cores from jet energy resolution, and tails towards lower mass values primarily from QCD radiation. The contribution of the low mass tail to the lineshape depends on the parton content of the resonance (qq, qg, or gg). Resonances containing gluons, which emit more QCD radiation than quarks, are wider and have a more pronounced tail. The signal distributions shown in Fig. 1 are for qq, qg, and gg resonances with signal cross sections corresponding to the limits at 95% confidence level (CL) obtained by this analysis, as described below. There is no evidence for a narrow resonance in the data. The most significant excess of the data relative to the