Search for Dijet Resonances in 7 TeV pp Collisions at CMS

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A search for narrow resonances in the dijet mass spectrum is performed using data corresponding to an integrated luminosity of 2.9 pb^{-1} collected by the CMS experiment at the Large Hadron Collider. Upper limits at the 95% confidence level are presented on the product of the resonance cross section, branching fraction into dijets, and acceptance, separately for decays into quark-quark, quark-gluon, or gluon-gluon pairs. The data exclude new particles predicted in the following models at the 95% confidence level: string resonances, with mass less than 2.50 TeV, excited quarks, with mass less than 1.58 TeV, and axigluons, colorons, and E_6 diquarks, in specific mass intervals. This extends previously published limits on these models.

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Two or more energetic jets arise in proton-proton collisions when partons are scattered with large transverse momenta p_T. The invariant mass spectrum of the two jets with largest p_T (dijets) falls steeply and smoothly, as predicted by quantum chromodynamics (QCD). Many extensions of the standard model predict the existence of new massive objects that couple to quarks (q) and gluons (g), and result in resonant structures in the dijet mass. In this Letter we report a search for narrow resonances in the dijet mass spectrum, measured with the CMS detector [1] at the LHC, at a proton-proton collision energy of $\sqrt{s} = 7$ TeV.

In addition to this generic search, we search for narrow s-channel dijet resonances from eight specific models. First, string resonances (S), which are Regge excitations of quarks and gluons in string theory, with multiple mass-degenerate spin states and quantum numbers [2,3]; string resonances with mass ~2 TeV are expected to decay predominantly to qg (91%) with small amounts of gg (5.5%) and $q\bar{q}$ (3.5%). Second, mass-degenerate excited quarks (q^*), which decay to qg, predicted if quarks are composite [4]; the compositeness scale is set to be equal to the mass of the excited quark. Third, axial vector particles called axigluons (A), which decay to $q\bar{q}$, predicted in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ [5]. Fourth, color-octet colorons (C), also decaying to $q\bar{q}$, predicted by the flavor-universal coloron model embedding the SU(3) symmetry of QCD in a larger gauge group [6]. Fifth, scalar diquarks (D), which decay to qq and $\bar{q}\,\bar{q}$, predicted by a grand unified theory based on the E_6 gauge [7]. Sixth, Randall-Sundrum (RS) gravitons (G), which decay to $q\bar{q}$ and gg, predicted in the RS model of extra dimensions [8]; the value of the dimensionless coupling $\kappa/\bar{M}_{\mathrm{Pl}}$ is chosen to be 0.1. Seventh and eighth, new gauge bosons (W' and Z'), which decay to $q\bar{q}$, predicted by models that propose new gauge symmetries [9]; the W' and Z' resonances are assumed to have standard-model-like couplings.

A detailed description of the CMS experiment can be found elsewhere [1]. The CMS coordinate system has the origin at the center of the detector. The z-axis points along the direction of the counterclockwise beam, with the transverse plane perpendicular to the beam; ϕ is the azimuthal angle in radians, θ is the polar angle, and the pseudorapidity is $\eta \equiv -\ln(\tan[\theta/2])$. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the field volume are the silicon pixel and strip tracker ($|\eta| < 2.4$), and the barrel and end cap calorimeters ($|\eta| < 3$): a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadronic calorimeter (HCAL). Outside the field volume, in the forward region, there is an iron-quartz fiber calorimeter ($3 < |\eta| < 5$). The ECAL and HCAL cells are grouped into towers, projecting radially outward from the origin, for triggering purposes and to facilitate jet reconstruction. In the region $|\eta| < 1.74$ these projective calorimeter towers have segmentation $\Delta\eta = \Delta\phi = 0.087$; the η and ϕ width increases at higher values of η. The energy depositions measured in the ECAL and the HCAL within each projective tower are summed to find the calorimeter tower energy.

The integrated luminosity of the data sample selected for this analysis is $2.9 \pm 0.3\ \mathrm{pb}^{-1}$ [10]. A single-jet trigger is used in both the online hardware-level (L1) and the software-level (HLT) of the trigger system [1] to select an unprescaled sample of events with a nominal jet transverse energy threshold at the HLT of 50 GeV. The trigger efficiency for this analysis is measured from the data to be larger than 99.5% for dijet masses above 220 GeV.

Jets are reconstructed using the anti-k_T algorithm [11] with a distance parameter $R = 0.7$. The reconstructed jet

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energy E is defined as the scalar sum of the calorimeter tower energies inside the jet. The jet momentum $\vec{p}$ is the corresponding vector sum of the tower energies using the tower directions. The E and $\vec{p}$ of a reconstructed jet are corrected as a function of p_T and η for the nonlinearity and inhomogeneity of the calorimeter response. The correction is between 43% and 15% for jets with corrected p_T between 0.1 and 1.0 TeV in the region $|\eta| < 1.3$. The jet energy corrections were determined and validated using simulations, test beam data, and collision data [12].

The dijet system is composed of the two jets with the highest p_T in an event (leading jets). We require that the pseudorapidity separation of the two leading jets, $\Delta\eta = \eta_1 - \eta_2$, satisfies $|\Delta\eta| < 1.3$, and that both jets be in the region $|\eta| < 2.5$. These η cuts maximize the search sensitivity for isotropic decays of dijet resonances in the presence of QCD background. The dijet mass is given by $m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$. We select events with $m > 220$ GeV without any requirements on jet p_T.

To remove possible instrumental and noncollision backgrounds in the selected sample, the following selections are made. Events are required to have a reconstructed primary vertex within $|z| < 24$ cm. For jets, at least 1% of the jet energy must be detected in the ECAL, at most 98% can be measured in a single photodetection device of the HCAL readout, and at most 90% can be measured in a single cell. These criteria, which are fully efficient for dijets, remove 0.1% of the events passing the pseudorapidity constraints and the dijet mass threshold.

Figure 1 presents the inclusive dijet mass distribution for $pp \to 2$ leading jets $+ X$, where X can be anything, including additional jets. We plot the measured differential cross section versus dijet mass in bins approximately equal to the dijet mass resolution. The data are compared to a QCD prediction from PYTHIA [13], which includes a full GEANT simulation [14] of the CMS detector and the jet energy corrections. The prediction uses a renormalization scale $\mu = p_T$ and CTEQ6L1 parton distribution functions [15]. The PYTHIA prediction agrees with the data within the jet energy scale uncertainty, which is the dominant systematic uncertainty. To test the smoothness of our measured cross section as a function of dijet mass, we fit the data with the parametrization

$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}, \quad (1)$$

with four free parameters P_0, P_1, P_2 and P_3. This functional form has been used by prior searches to describe both data and QCD predictions [16,17]. In Fig. 1 we show both the data and the fit, which has a $\chi^2 = 32$ for 31 degrees of freedom. In Fig. 2 we show the ratio between the data and the fit. The data are well described by the smooth parametrization.

We search for narrow resonances, for which the natural resonance width is negligible compared to the CMS dijet mass resolution. Figures 1 and 2 present the predicted dijet mass distribution for string resonances and excited quarks using the PYTHIA Monte Carlo and the CMS detector simulation. The predicted mass distributions exhibit a Gaussian core from jet energy resolution and a tail toward low masses from QCD radiation. This can be seen in Fig. 3, which shows examples of the predicted dijet mass distribution of resonances from three different parton pairings:

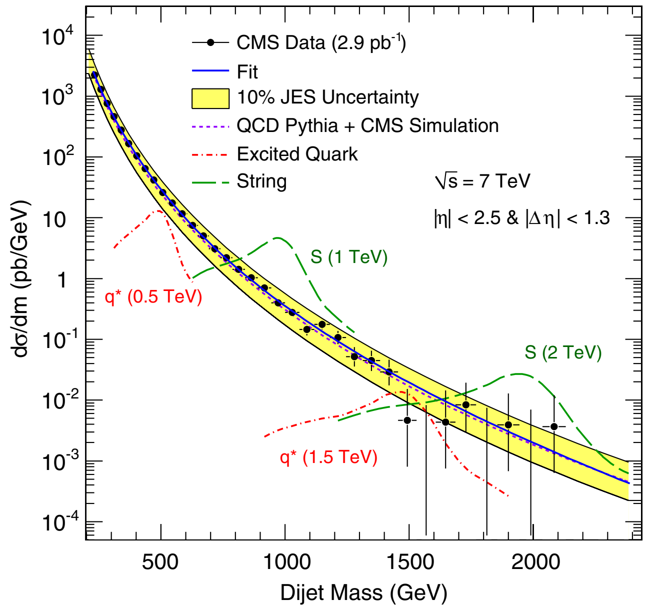

FIG. 1 (color online). Dijet mass spectrum (points) compared to a smooth fit (solid) and to predictions [13] including detector simulation of QCD (short-dashed), excited quark signals (dot-dashed), and string resonance signals (long-dashed). The errors are statistical only. The shaded band shows the effect of a 10% systematic uncertainty in the jet energy scale (JES).

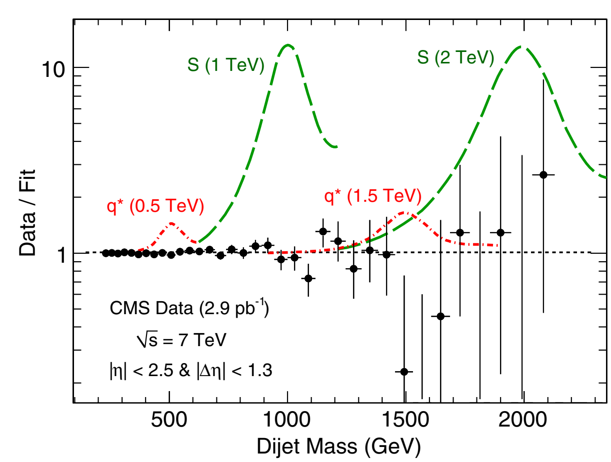

FIG. 2 (color online). Ratio (points) between the dijet mass data and the smooth fit, compared to the simulated ratios for excited quark signals (dot-dashed) and string resonance signals (long-dashed) in the CMS detector. The errors are statistical only.

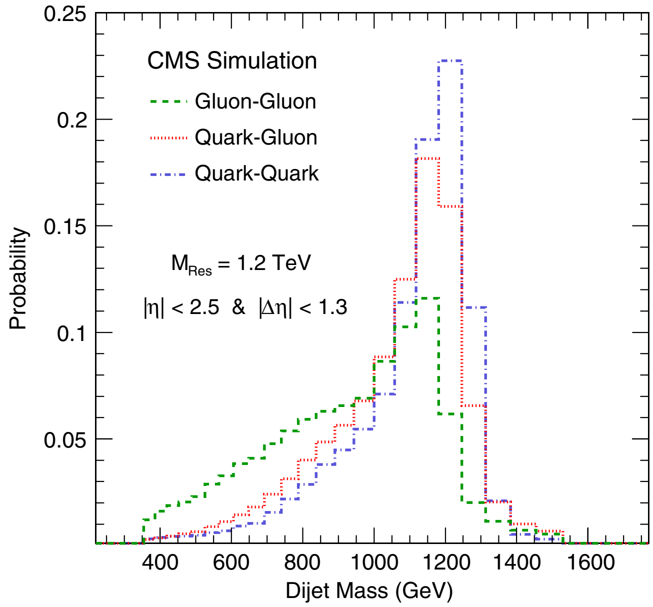

FIG. 3 (color online). Simulation of the expected dijet mass distributions in the CMS detector from a narrow 1.2 TeV resonance of type quark-quark (dot-dashed), quark-gluon (dotted), and gluon-gluon (dashed).

$q\bar{q}$ (or qq) resonances from the process $G \rightarrow q\bar{q}$ [8], qg resonances from $q^* \rightarrow qg$ [4], and gg resonances from $G \rightarrow gg$ [8]. For resonance masses between 0.5 and 2.5 TeV, the dijet mass resolution varies from 8% to 5% for qq, 10% to 6% for qg, and 16% to 10% for gg, respectively. The increase of the width of the measured mass shape and the shift of the mass distribution toward lower masses are enhanced when the number of gluons in the final state is larger, because QCD radiation is larger for gluons than for quarks. The latter also implies that the detector response is lower to gluon jets than to quark jets [18] (jet energy corrections, applied both to data and to simulations, are for the mixture of quark and gluon jets expected in QCD). The distributions in Fig. 3 are generically valid for other resonances with the same parton content and with a natural width small compared to the dijet mass resolution. There is no indication of narrow resonances in our data as shown in Figs. 1 and 2.

We use the dijet mass data points, the background (QCD) parametrization, and the dijet resonance shapes to set specific limits on new particles decaying to the parton pairs qq (or $q\bar{q}$), qg, and gg. For setting upper limits, before accounting for systematic uncertainties, we use a Bayesian formalism with a uniform prior for the signal cross section. We calculate the posterior probability density as a function of resonance cross section, independently at 22 different values of the resonance mass from 0.5 to 2.6 TeV in steps of 0.1 TeV. From this we find initial 95% confidence level (CL) upper limits on the cross section, including only statistical uncertainties. The dominant sources of systematic uncertainty are the jet energy scale (10%), the jet energy resolution (10%), the integrated luminosity (11%), and the background parametrization choice (included by using a different parametrization [19] that also describes the data). The jet energy scale and resolution uncertainties are conservative estimates, consistent with those measured using collision data [12]. To incorporate systematic uncertainties, we then use an approximate technique, which in our application is generally more conservative than a fully Bayesian treatment. The posterior probability density for the cross section is broadened by convoluting it, for each resonance mass, with a Gaussian systematic uncertainty [19]. As a result, the cross section limits including systematic uncertainties increase by 17%–49% depending on the resonance mass and type. Table I lists the generic upper limits at the 95% CL on $\sigma \times \mathrm{BR} \times A$, the product of cross section (σ), branching fraction (BR), and acceptance (A) for the kinematic requirements $|\Delta\eta| < 1.3$ and $|\eta| < 2.5$, for qq, qg, and gg resonances. The acceptance for isotropic decays is $A \approx 0.6$ independent of resonance mass.

In Fig. 4 we compare these upper limits to the model predictions as a function of resonance mass. The predictions are from lowest order calculations of the product $\sigma \times \mathrm{BR} \times A$ using the CTEQ6L1 parton distributions [15]. New particles are excluded at the 95% CL in mass regions for which the theory curve lies above our upper limit for the appropriate pair of partons. We also determine the expected lower limit on the mass of each new particle, for a smooth background in the absence of signal. For string resonances the expected mass limit is 2.40 TeV, and we use the limits on qg resonances to exclude the mass range $0.50 < M(S) < 2.50$ TeV. For comparison, previous measurements [16] imply a limit on string resonances of about 1.4 TeV. For excited quarks the expected

TABLE I. Upper limits at the 95% CL on $\sigma \times \mathrm{BR} \times A$, as a function of the new particle mass, for narrow resonances decaying to dijets with partons of type quark-quark (qq), quark-gluon (qg), and gluon-gluon (gg). The limits apply to the kinematic range where both jets have pseudorapidity $|\eta| < 2.5$ and $|\Delta\eta| < 1.3$.

Mass	Upper limit (pb)			Mass	Upper limit (pb)		
(TeV)	qq	qg	gg	(TeV)	qq	qg	gg
0.5	118	134	206	1.6	3.05	3.72	6.71
0.6	182	229	339	1.7	3.13	3.64	5.88
0.7	90.7	134	281	1.8	2.92	3.41	5.37
0.8	70.8	93.5	177	1.9	2.73	3.15	4.78
0.9	52.7	71.6	142	2.0	2.71	3.02	4.39
1.0	20.3	29.0	71.4	2.1	2.50	2.84	4.15
1.1	17.0	20.1	35.1	2.2	2.20	2.55	3.69
1.2	17.0	20.4	32.5	2.3	1.96	2.28	3.32
1.3	10.5	12.9	22.8	2.4	1.79	2.08	2.94
1.4	6.77	8.71	16.4	2.5	1.67	1.93	2.74
1.5	3.71	5.02	10.3	2.6	1.55	1.80	2.50

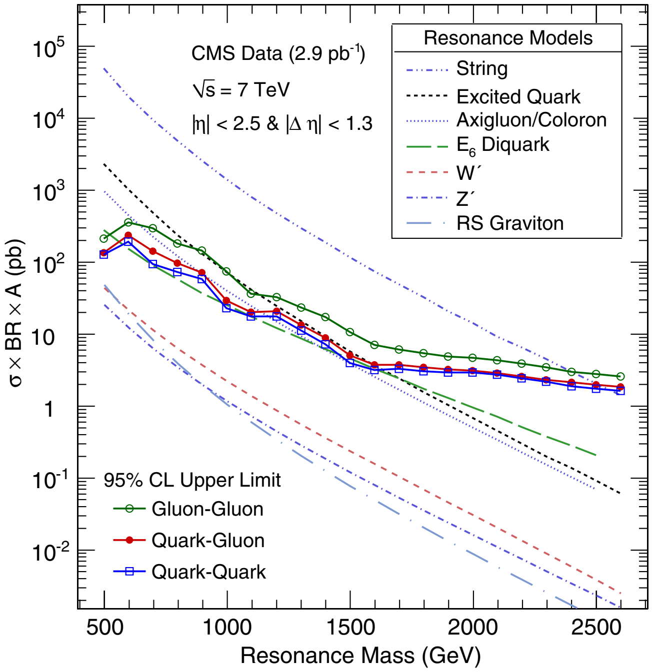

FIG. 4 (color online). 95% CL upper limits on $\sigma \times \mathrm{BR} \times A$ for dijet resonances of type gluon-gluon (open circles), quark-gluon (solid circles), and quark-quark (open boxes), compared to theoretical predictions for string resonances [2], excited quarks [4], axigluons [5], colorons [6], E_6 diquarks [7], new gauge bosons W' and Z' [9], and Randall-Sundrum gravitons [8].

mass limit is 1.32 TeV, and we exclude the mass range $0.50 < M(q^*) < 1.58$ TeV, extending the previous exclusion of $M(q^*) < 1.26$ TeV [16,17,19–22]. For axigluons or colorons the expected mass limit is 1.23 TeV, and we use the limits on qq resonances to exclude the mass intervals $0.50 < M(A) < 1.17$ TeV and $1.47 < M(A) < 1.52$ TeV, extending the previous exclusion of $0.11 < M(A) < 1.25$ TeV [16,19,21,23–25]. For E_6 diquarks the expected mass limit is 1.05 TeV, and we exclude the mass intervals $0.50 < M(D) < 0.58$ TeV, and $0.97 < M(D) < 1.08$ TeV, and $1.45 < M(D) < 1.60$ TeV, extending the previous exclusion of $0.29 < M(D) < 0.63$ TeV [16,19]. For W', Z', and RS gravitons we do not expect any mass limit, and do not exclude any mass intervals with the present data. The systematic uncertainties included in this analysis reduce the excluded upper masses by roughly 0.1 TeV for each type of new particle.

In conclusion, the measured dijet mass spectrum is a smoothly falling distribution as expected within the standard model. We see no evidence for new particle production. Thus we present generic upper limits on $\sigma \times \mathrm{BR} \times A$ that can be applied to any model of dijet resonances, and set specific mass limits on string resonances, excited quarks, axigluons, flavor-universal colorons, and E_6 diquarks, all of which extend previous exclusions.

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